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Uncertainty in Morphological Sediment Budgeting of Rivers

by

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ABSTRACT

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Repeat topographic surveys are often used to monitor geomorphological change in rivers. Such surveys can yield Digital elevation models (DEMs), which are differenced against each other to produce spatially distributed maps of elevation changes called DEMs of difference (DoD). Both areal and volumetric budgets of erosion and deposition can be calculated from DoDs. However, questions arise about the reliability of the analyses and what they mean. This thesis presents two new methodological advances to address these two uncertainties.

The question of reliabilities (reliability uncertainty) was addressed through the development of a flexible technique for estimating the spatially variable surface representation uncertainties in individual DEMs. A fuzzy inference system is used to quantify uncertainty in DEMs and the individual error estimates are propagated into the DoD on a cell-by-cell basis. This is converted into a probabilistic estimate of DoD uncertainty. This estimate can be improved using Bayes theorem and an analysis of the spatial coherence of erosion and deposition units within the DoD. The resulting probabilistic estimate of DoD uncertainty reflects the spatial variability of uncertainty, and can be used to threshold the DoD at user-specified confidence intervals. This addresses reliability by allowing the distinction between real and undetectable changes.

The question of what the thresholded DoDs mean, geomorphically, is a fundamental one and what originally motivated the development of morphological sediment budgeting techniques. Herein, a range of masking tools were developed, which allow the quantitative interrogation of these rich spatial datasets and their patterns based on various classification systems and/or the expert-judgment of a trained geomorphologist. The tools extend the traditional DoD interpretation of whether a reach is net aggradational or net degradational to a detailed quantitative segregation of the DoD budget into the mechanisms responsible for the changes at the bar-scale.

The utility of both these methodological developments were tested on three different 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 the application of these tools in the three different settings is the sharp contrast between which geomorphological mechanisms of change are dominant in areal versus volumetric terms. The tools extend what can reliably be inferred about geomorphological change from repeat topographic surveys.

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Preface

Some of the work presented in this thesis has been submitted for publication in peer-reviewed literature. Portions of the review in Chapter 2, is appearing in Wheaton *et al.* (2008), which acts as an introductory book chapter in an edited volume on *River Restoration: Managing the Uncertainty in Restoring Physical Habitat.* I was responsible for the research and primary writing of the manuscript.

Where data or analyses have been provided by others or prepared collaboratively, appropriate acknowledgments and/or citations are provided. Although I am grateful for the assistance and contributions of the many collaborators who have helped with this thesis, the originality of the material presented in this thesis is consistent with the requirements for doctoral research.

NOTE: If you are viewing a PDF version of this document, you will find that all the cross-referencing, indexing and footnoting throughout the thesis is hyperlinked allowing easy navigation between sections. For example, to navigate ahead to the first chapter, you can click on the one in Chapter 1.

Acknowledgements

Any time I try to write a list of people to acknowledge, I forget someone important. For example, in my Masters Thesis acknowledgments, I actually forgot to thank one of my supervisors and key collaborators, Joe Merz. Thus, the acknowledgments here are by no means a comprehensive attempt to thank everyone who helped make this a reality. I therefore first extend my apologies and thanks to the numerous individuals who helped me *finally* make this thesis a reality but that I failed to mention below.

My primary supervisors, David Sear and Steve Darby, both deserve medals for their patience and countless hours of help and ideas in the field, office, pub, and remote assistance since I took a lectureship in Aberystwyth two years ago. Their better halves have also been extremely supportive. I would like to thank my secondary supervisors from the Centre for Ecology and Hydrology, Mike Acreman and Douglas Booker, for their input and assistance with establishing the conceptual basis for this work. Although James Brasington was not one of my four official supervisors, he might as well have been for he has generously invested an enormous amount of time helping me with the research. Without his help, the research would not have been possible. I know of few PhD students who can claim to have been graced with the support of four to five supervisors. Amazingly, the advice they gave only occasionally contradicted each other.

Funding for this PhD was provided through a studentship, jointly funded by the School of Geography at the University of Southampton and the Centre for Ecology and Hydrology at Wallingford. An Overseas Research Studentship award from U.K. Universities made up the funding gap for international fees. Additional funding was generously provided by the Hydrology Section of the American Geophysical Union who awarded me the Horton Research Grant for Ph.D. Students in 2005, and the Saint Helena Community Forum who funded field work on Sulphur Creek, California in 2006. I am grateful to all these organisations for making this possible.

Indirectly, the Institute of Geography and Earth Sciences at Aberystwyth University helped support this PhD by graciously paying my salary and patiently wait for over two years for me to finish this thesis. I owe all my colleagues at Aberystwyth a huge thank you for giving me space and picking up my slack to allow me to finish.

As the three study sites used in the thesis involved funding and support from very different sources and teams of people, acknowledgments for each of the specific study sites can be found in § A.3 (River Feshie), § F.2 (Sulphur Creek) and § G.5 (Mokelumne River).

Key informant interviews with a number of individuals who gave their time and thoughts were instrumental for identifying the key issues with respect to uncertainty. These included: Andrew Brookes, Jacobs Consultancy; Paul Carling, University of Southampton; Mike Clark, University of Southampton; Mark Diamond, UK Environment Agency; Martin Doyle, University of North Carolina; Henry Pollack, author of *Uncertain Science Uncertain World*; Giles Foody, formerly University of Southampton; Nick Jackson, Centre for Ecology and Hydrology;

Matt Kondolf, University of California at Berkeley; Jeffrey Mount, University of California at Davis; Douglas Shields, US Department of Agriculture; Kevin Skinner, Jacobs Consultancy, Ltd.; Phillip Williams, Phillip Williams and Associates; among others. I also wish to thank the over 500 participants in the International River Restoration Survey (Wheaton *et al.* 2006), whose views have helped obtain a clearer synopsis of the restoration community.

At Southampton, I would like to thank Jim Milne for his countless hours and expertise on any and everything related to programming and web-editing, his excellent help in the field, and for his failed attempt to teach an American how to play and appreciate cricket with a piece of driftwood and a tennis ball on a beach in California. I owe Charlie Kerr enormously for help with everything IT related. Thank you to Paul Carling who was an excellent sounding board at the pub, and the reason Aberystwyth even considered hiring me. In addition, Paul's excellent editorial comments and proofreading of the thesis were very helpful. Paul Carling and David Gilvear both gave very helpful feedback and I thank them for a stimulating and engaging viva. I thank Mike Clark for his insight and wisdom during the upgrade process. I would also like to thank all of the excellent support staff at the School of Geography (e.g. Stef Webb, Adam Corres, Maggie Harris, Denise Pompa, Ruth Calver...), who really make Southampton a great place to study. I also thank all of the School of Geography postgraduates (particularly Julian Leyland), who aside from exchanging ideas with, were great company at the pub.

Although not reported in this thesis, a significant portion of the PhD was spent attempting to develop a morphodynamic model and I owe James Brasington, Tom Coulthard, Marco van de Wiel, Christel Prudhomme and Mike Bithel many thanks for their time helping me pursue this.

Finally, I would like to thank my entire family for their amazing support and patience while I indulged myself in this PhD. You all made sacrifices to allow me to pursue this, and I am forever indebted to you for that. Adrea, in particular you have been so amazingly patient and understanding. Luke and Cadel, you kept me smiling even when things were dragging on. Anne, Mom and Dad thanks for everything. Even Booker, my dog, has been a great sounding board for ideas and a most enthusiastic assistant in the field (despite his selective hearing).

Thank you everyone. I am very grateful.

List of Acronyms

- 1D: One Dimensional
- 2.5D: Two and a half Dimensional
- 2D: Two Dimensional
- 3D: Three Dimensional
- CFD: Computational Fluid Dynamics
- CoD: Classification of Difference
- DEM: Digital Elevation Model
- DEMs: Digital Elevation Models
- dGPS: differential Global Positioning System
- DoD: DEM of Difference
- DoDs: DEMs of Difference
- DSS: Decision Support Systems
- ECD: Elevation Change Distribution
- FIS: Fuzzy Inference System
- GHSI: Global Habitat Suitability Index
- HSC: Habitat Suitability Curve
- HSI: Habitat Suitability Index
- $_{min}$LoD: Minimum Level of Detection
- PHR: Physical Habitat Restoration
- rtkGPS: real-time kinematic Global Positioning System
- SHIRA: Spawning Habitat Integrated Rehabilitation Approach
- SHR: Spawning Habitat Rehabilitation

Dedicated to my family, who put up with me 'almost being done' for way too long.

Part I

The Problem

Chapter 1

Thesis Aims and Objectives

1.1 Chapter Purpose

The purpose of this chapter is to define the problem of uncertainty in relation to monitoring geomorphological change in rivers using morphological sediment budgeting and to present the aim and objectives of this thesis. The motivation for considering this problem is borne out of increasingly popular efforts to restore rivers for salmon. There are many other potential motivations for considering this problem, ranging from basic research in fluvial geomorphology and/or GIS to monitoring applications in different environments that rely on repeat topographic surveys, to validating morphodynamic models. However, this work is primarily derived from the starting point of making meaningful interpretations in a river restoration monitoring context. This context is elaborated in this chapter as a basis for the aim and objectives that will be addressed. Finally, a basic outline of the organisation of the thesis is provided.

1.2 Introduction to Problem

There is a distinction between the motivating problem of salmonid restoration, which is one justification of this work in a broader context, and the more specific research problems this thesis is poised to address. The former is an incredibly complex environmental problem with physical, ecological and socio-political dimensions. The latter problems are largely methodological challenges associated with long-term geomorphological monitoring. These issues are becoming increasingly prevalent as more money is spent on restoration efforts in rivers, more attention is given to monitoring, and expectations grow about what monitoring can say about what benefits (if any) the restoration efforts provided. These separate problems are described, below.

1.2.1 Motivating Problem: Monitoring Physical Habitat Restoration

Salmon have been an iconic cultural symbol to many societies for centuries (Lackey 1997, Ormerod 2003, Ruckelshaus *et al.* 2002). The well-documented decline of wild salmon over the past century throughout North America and Europe (Yoshiyama *et al.* 1998, Williams *et al.* 1989, WWF 2001) has been attributed to a large number of factors. These include:

- *Overfishing* of oceans, estuaries and rivers (Costanza *et al.* 1998, Parrish *et al.* 1998);
- Declines in favourable *oceanic conditions* (Coronado & Hilborn 1998, Francis & Sibley 1991), partly due to climate change (Friedland *et al.* 2003, Friedland 1998, Hansen & Quinn 1998);
- *Aquaculture* and *hatchery stocking* both of which have ecological consequences (e.g. competition for habitat with wild stocks) and genetic consequences such as interbreeding (Youngson & Verspoor 1998, WWF 2001);
- *Habitat loss* through direct channel modifications and *anthropogenic barriers to migration* such as dams, diversion structures and culverts (Sheer & Steel 2006, Mesa & Magie 2006, Gibson *et al.* 2005);
- *Habitat degradation* from dams and instream mining (Kondolf 1997, Beechie *et al.* 2001, Gilvear *et al.* 2002), reduced flow regimes due to water abstraction (Jungwirth *et al.* 1993, Poff *et al.* 1997, Mesa & Magie 2006, Petts 1996), pollution (Hendry *et al.* 2003) engineering modifications to river channels (WWF 2001), and disturbances (e.g. fine sediment infiltration, or scour to burial depth of eggs) leading to poor embryonic survival in spawning habitat (Greig *et al.* 2007).

Broad societal and political interest in salmonids has lead to a wealth of research, environmental policy and management responses aimed at restoring populations of salmonids to something approaching their former glory (Lackey 2003*b*, Ruckelshaus *et al.* 2002). Social values influenced by sport-fishing, nostalgia of the abundance of salmon 'when I was a child', and culinary preference for salmonids have driven these processes as much or more than a scientific agenda per se (Lackey 2001). While many authors have put forth legitimate and eloquent critiques of such a single-species approach to restoration (Pitcher 2001, Enberg *et al.* 2006), salmonid restoration activities remain immensely popular (Lackey 2003*a*). Sometimes, such efforts are described as ecosystem restoration based on the argument that salmonids are keystone species to ecosystems and therefore a good indicator of overall ecosystem health (Willson & Halupka 1995, Hilderbrand *et al.* 2004). Garibaldi & Turner (2004) take a less apologetic stance and consider salmonids to be an example of a cultural keystone species, thus justifying the restoration emphasis on salmonids based on social and economic values alone.

Restoring salmonid populations in Europe and North America is a major sub-set of river restoration activities, which are now practised throughout the world (Wheaton *et al.* 2006). It follows logically that to restore salmonid populations, the factors that have led to their

FIGURE 1.1: Despite all the rhetoric calling for 'catchment-scale restoration', most PHR involves active intervention (i.e. construction of habitat features) at the reach scale as shown here. In this case gravel is being placed in a channel downstream of a dam to construct riffle and bar habitats for salmon. Photo from PHR in 2001 on the Mokelumne River, California (photo by Author).

decline need to be addressed (listed above). Ruckelshaus *et al.* (2002) argued that restoration scientists are continuing to place too much emphasis on studying what has caused the decline of salmonids and too little on what are the likely consequences of alternative approaches today to restoring salmon.

Much of the effort to restore salmonid populations has focused exclusively on restoration of their physical habitat[1] in rivers (Brookes *et al.* 1996, Kondolf 2000, Wheaton *et al.* 2004*b*). A typical example of these sorts of activities is shown in Figure 1.1. Physical habitat restoration (PHR) has persisted and remained extremely popular not because it is necessarily the most effective, but because it leads to tractable environmental management projects (Barinaga 1996). The logic behind PHR is rather simple. It is assumed or hoped that the availability of adequate quality physical habitat is a limiting factor for these species (Kondolf 2000). Therefore, if one improves the quality and/or increases the availability of such habitat, this should at a minimum mean that physical habitat is less of a limiting factor. The hope is that PHR will lead to an increase in the salmonid population, but clearly many other factors[2] during their anadromous life-cycle may prove equally important.

[1]The restoration of physical habitat in rivers and streams has many names (e.g. instream habitat improvement, habitat rehabilitation, habitat enhancement, gravel augmentation, riffle construction, habitat structures, LWD and boulder placement, etc.) and even more different approaches to implementation. For consistency, in this thesis the term physical habitat restoration (PHR) will be used.

[2]The bulleted list of impacts to wild salmonid stocks on the previous page provides some insight into these 'other' factors. PHR in rivers only addresses habitat quality and quantity issues during their adult-spawning, embryonic, juvenile and freshwater-migratory life stages.

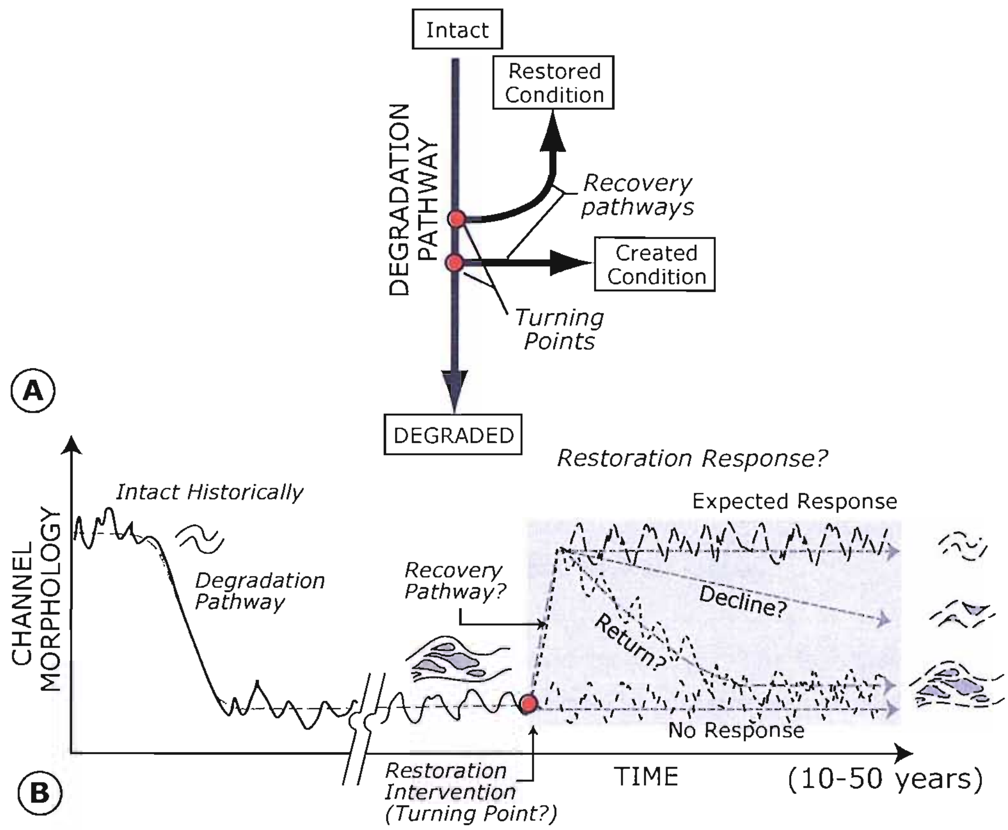


FIGURE 1.2: A simplified illustration of uncertainty in channel morphology response to a restoration intervention (B) in relation to a recovery diagram (A). In (A), recovery from a degradation pathway is possible through a recovery pathway to either a former condition or a created condition. In (B), the uncertain response to restoration intervention is illustrated with an example of attempted restoration from a braided to meandering channel type (gray shaded area). However, the range of potential responses reflect uncertainty as to whether the river response will be a full recovery as planned (top), some degradation to a different state or return to the degraded state (middle), or whether the system will not actually respond to the restoration intervention at all. Note that this is not to suggest that a meandering plan form is better or worse than a braided plan from from a salmonid physical habitat perspective. Figure (A) adapted from Brierley & Fryirs (2005, p. 326) and figure (B) adapted from Sear (1994).

However, as was established in Wheaton *et al.* (2008), numerous uncertainties are inherent in trying to restore physical habitat for salmonids. These span scientific uncertainties as well as socio-political uncertainties. One of the most fundamental uncertainties with respect to the effectiveness of PHR relates to the significance of geomorphological change (Bradford *et al.* 2005, Dorava *et al.* 2001, Beechie *et al.* 2001). Figure 1.2 illustrates conceptually three possible trajectories following a restoration intervention. There are actually infinite possibilities but these are bounded by what is plausible for the system. By definition, a restoration intervention is expected to result in a change (hopefully, but not necessarily, from worse to better). Almost all restoration is project-based, and projects typically have a starting point and an end-point. This often results in an expectation that following the initial change in response to a restoration, the channel will remain 'restored' (e.g. Path 1 in Figure 1.2) and only minor changes may be expected to follow (Kondolf *et al.* 1996, Hughes *et al.* 2005). Such expectations are particularly prominent in form-based, and reference reach approaches so popular in restoration practise (Shields *et al.* 2003, Kondolf 1995). Two simple questions follow:

1. Should a river subjected to a PHR intervention be expected to change (geomorphologically) beyond the intervention itself?
2. If changes do occur, what influence will they have on salmon?

Both questions depend on what precisely is meant by change. The first question is related to uncertainty about the future, in that any expectation is essentially an implicit prediction. More simply, a geomorphologist might argue that 'of course the river will change', but the rates of change and timespan a geomorphologist may consider might extend beyond typical environmental management time frames. Similarly, a landscape ecologist might argue that a dynamic *shifting habitat mosaic* is a fundamental process attribute of the fluvial environment and essential to ecosystem health (Stanford *et al.* 2005, Lorang *et al.* 2005, Whited *et al.* 2007). However, PHR practitioners and stakeholders often envisage their *improvements* as a semi-permanent fix that is providing high quality, but static, habitat features (Kondolf *et al.* 1996). Hughes *et al.* (2005) argued that river managers feel they need to be able to predict how a river will respond to its management and subsequently view a river that is changing as an unacceptable, uncertain risk.

The second question has to do with how change is interpreted and responded to. While this question can be assessed objectively, it may be inherently value-laden in its focus on salmonids over other ecosystem members. For better or worse, one objective approach the restoration science community has advocated that indirectly addresses the above two questions is simply to carry out long-term monitoring and observe the changes than ensue post-restoration intervention.

1.2.2 Problem of Focus

The primary uncertainties of interest in this thesis are those associated with monitoring geomorphological changes. These physical changes to the fluvial landscape are an expression of the system dynamics and disturbances (either natural or anthropogenic) to which it is subjected. In turn, such dynamics exert a fundamental control on ecosystem health (Ward *et al.* 2002, Stanford *et al.* 1996, Bilbly *et al.* 2003). Fluvial geomorphologists have a conceptual understanding of how various processes interact to bring about such change in rivers (Church 2002, Lane & Richards 1997). However quantifying the rates of geomorphological change from observations, predicting change with models, and interpreting the significance of change are all topical research concerns that are far from being 'solved' problems (Church 2006, Cao & Carling 2002*b*). While there is much merit in continuing to pursue such lines of research[3], this thesis is primarily concerned with articulating the uncertainties associated with analyses that are readily available to researchers and practitioners, and evaluating the significance of that uncertainty.

Repeat topographic surveying through time has rapidly emerged over the past decade as a tractable means of monitoring geomorphological changes in rivers and is the focus of this thesis. With this increased popularity and availability, there is a need[4] to better understand how observed or anticipated geomorphological changes matter to salmonids, and to assess whether or not our uncertainty about such changes is significant to making such an appraisal. Put another way, the thesis is that key attributes of geomorphology and its change through time are relevant to physical habitat for salmonids and their restoration, but uncertainties in their quantification and interpretation have not yet been adequately accounted.

1.3 Aim and Objectives of Thesis

This thesis aims to develop the means to make more reliable and meaningful interpretations of repeat topographic surveys collected to monitor geomorphological change in rivers. The relevance of this aim to fish habitat restoration is fundamental.[5] In the simplest terms, it is not known how a river will change following a restoration intervention.[6] Any geomorphological changes to a river will result in some alteration of physical habitat. So long as the design was appropriate and the construction successful, the restoration alteration presumably (but not necessarily) results in an improvement in physical habitat. The changes that follow from there present numerous uncertainties. As suggested in the preceding section

[3]Indeed, a secondary motivation within this thesis is to improve our ability to measure, predict and/or interpret geomorphological change.

[4]This assertion is justified later in § 1.3.2 and § 3.2.

[5]The aim deliberately makes no reference to river restoration or PHR, as the methods that would be used to address this aim should have equal relevance in a restoration versus non-restoration context. Hence, it is unnecessary to restrict focus only to geomorphological changes that take place following river restoration.

[6]Never mind whether that change is in response to the restoration intervention or whether the change would have occurred regardless of the intervention (i.e. explanation). This is another way of saying we can not predict the future with certainty.

(§ 1.2), from a salmonid PHR perspective it is unclear whether such changes have any net impact, are bad, are good or whether they might even be necessary to sustain habitat quality (Dorava *et al.* 2001).

This aim can be focused into two objectives, one that focuses on the *reliability* problem and one that focuses on the *meaningful* problem:

1. Develop a technique for quantifying uncertainty in estimating geomorphological change from repeat topographic surveys
2. Develop a tool for making more meaningful mechanistic geomorphological interpretation of changes suggested by repeat topographic surveys

These objectives are explained briefly in the following subsections and are more exhaustively justified in Chapter 3.1. A central theme in both objectives will be more explicitly exploiting information recorded in the spatial structure of repeat topographic survey datasets.

1.3.1 Objective 1: Reliability of Monitoring Geomorphological Change

Develop a technique for quantifying uncertainty in estimating geomorphological change from repeat topographic surveys

There are many ways to monitor geomorphological change, but one of the simplest is to conduct repeat topographic surveys and infer the processes from the net change. For example, the quantification of geomorphological change can be estimated from observations of change through comparison of topographic surfaces (Leopold *et al.* 2005, Brasington *et al.* 2000) or aerial photographs (Gilvear & Winterbottom 1992, Kondolf & Larson 1995) at different points in time. Such techniques are particularly prominent in restoration monitoring as they do not require continuous monitoring and temporal sampling frequency[7] can be tailored to individual questions, budgets and constraints as necessary.

Historically, two repeat surveying techniques have acted as the hallmark monitoring protocols of the fluvial geomorphologist. Either plan form changes to estimate areas of change were reported from analysis of historical and or contemporary aerial photographs and maps (Gilvear & Winterbottom 1992, Graf 2000); or a mix of repeat longitudinal profiles, reoccupation of cross sections and plan form surveys were used to estimate volume of change (Lane *et al.* 1994). In the late 1980s and early 1990s, pioneering research papers came out suggesting the use of repeat topographic surveys for monitoring geomorphological change (Carson & Griffiths 1989, ?), pointing out the benefits of visualising changes spatially by using what Brasington *et al.* (2000) called four dimensional monitoring (3 spatial dimensions and 1 temporal). By 2000, the

[7] Most typically, survey frequency is on annual, decadal or more arbitrary intervals. However, the techniques can be employed on intervals as short as hours to days, so long as enough time is alloted to complete the survey between intervals and that the surface is not changing during the survey itself.

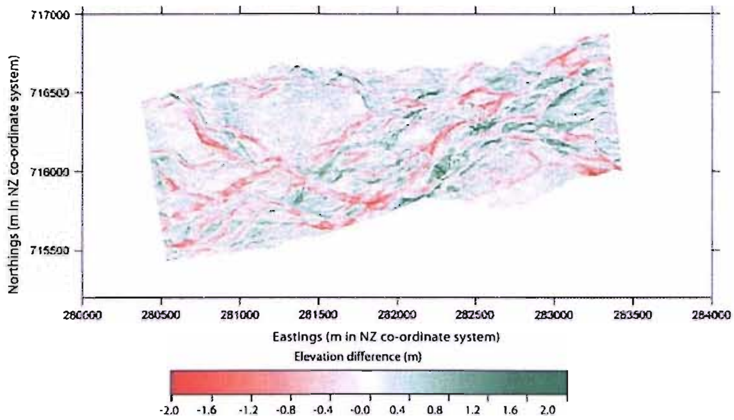


FIGURE 1.3: An example of a DoD from the Waimakariri River, South Island, New Zealand. Figure reproduced from Lane *et al.* (2003).

level of sophistication in surveying methods had grown dramatically with notable developments tn processing this data from Milne & Sear (1997) and Brasington *et al.* (2000) and what became known as the morphological approach[8] had emerged as a recognised technique. The technique will be reviewed in Chapter 3, but for now it is pointed out that the primary graphical output is a DEM (digital elevation model) of difference or DoD (e.g. Figure 1.3); whereas the primary metric is a reporting of net volumetric aggradation or degradation.

Since 1996, there has been notable initial discussion and analysis in the peer-reviewed literature on the uncertainty inherent in representing surface topography and how this propagates through to sediment budget estimates in the morphological approach (Brasington *et al.* 2003, Westaway *et al.* 2000, Lane *et al.* 2003, Fuller *et al.* 2003, e.g.). This emphasis is understandable as given the advancing surveying technologies and relatively new approach, one would like to be able to segregate the proportion of the calculated changes that can be safely assumed to be real versus those that can not be distinguished from noise. In all of these studies, the uncertainty almost entirely has been represented as spatially uniform (for computational convenience) and a minimum level of detection has been defined. This approach generally leads to an over-prediction of errors in many areas and under-prediction of errors in others. The net result is that typically 65% to 85% of the changes predicted by the morphological method are thrown-away because real changes below these thresholds are indistingushable from noise.

It is postulated that there are meaningful geomorphological changes being discarded through minimum level of detection analyses that could be better distinguished from this noise. So there exists a large gap between the negligent approach of ignoring the role of uncertainty in the analysis and the conservative approach of discarding information below some minimum level of detection. The more pervasive practice when using the morphological method is to ignore these

[8]This is also commonly referred to as morphological sediment budgeting, DEM-differencing, and repeat topographic surveying.

uncertainties altogether. This thesis will develop a new technique that attempts to quantify the influence of surface representation uncertainty on the morphological method in a more comprehensive and spatially variable way, with the intention of recovering more information than current minimum level of detection methods afford. This approach is proposed as an extension to previous work, which disregards the spatial structure of such uncertainty.

While it is well known that DEM representation is central to hydrological and geomorphological analysis (Brooks & McDonnell 2000, Oksanen & Sarjakoski 2006), it is also critical to PHR. From a physical habitat perspective, the geomorphology can be captured with a topographic surface model and characterisation of the composition of that surface (i.e. grain size distribution). The geomorphology in combination with the hydraulic flow conditions, and water quality (e.g. temperature, dissolved and suspended load) define physical habitat (Clifford *et al.* 2008). Thus, knowledge of the uncertainty in the topographic representation is equated to knowledge about uncertainty of one of the central defining components of physical habitat.

1.3.2 Objective 2: Meaningful Geomorphological Interpretations

Develop a tool for making more meaningful mechanistic geomorphological interpretation of changes suggested by repeat topographic surveys

While the literature advancing the morphological approach has contributed to the visualisation of net morphological change (e.g. Figure 1.3), and gross reach-scale quantifications of sediment budgets, little emphasis has been placed on using the wealth of spatially-explicit quantitative data buried within a DoD to make meaningful quantitative geomorphological interpretations. Most interpretations that have been made are largely of a qualitative nature.[9] While gross reach-scale interpretations are useful, there is a wealth of more detailed spatially-distributed information captured in these topographic surveys that can be used to directly infer mechanisms of change due to specific geomorphological processes (e.g. bank erosion, bar development, pool scour, pool filling, confluence scour, bar dissection, floodplain deposition, etc.).[10] Thus, new techniques are needed to help better interrogate the spatial data sets that are now so readily acquirable and available. Put another way, the morphological approach currently yields a quantification of the storage components of a sediment budget at the reach-scale. This objective seeks to segregate this sediment budget into both its mechanistic process components and morphological unit components at the geomorphic unit[11] scale. Moreover, the uncertainty propagated through to this analysis from the original DoD can, and will, also be explicitly accounted for.

[9] The exact same problem is prevalent in the reporting of model results from hydraulic, and morphodynamic simulations. The techniques developed for interrogating spatial data sets of observations might have equal utility in interrogating spatial data sets from simulation models.

[10] Sear & Milne (2000), Milne & Sear (1997), Brasington *et al.* (2003) and Lane *et al.* (2003) present some promising techniques for extracting this more detailed process information. These are reviewed in Chapter 3 in more detail, where it is argued that this can be taken much further.

[11] This is also known as the bar-scale. The 'geomorphic unit' is a River Styles Framework spatial scale, which was developed by Thomson *et al.* (2001) and is discussed briefly in § 3.2.

The geomorphological process interpretation (quantitative or qualitative) that has accompanied analyses using the morphological method, is relatively unsophisticated in comparison to strictly qualitative geomorphological observations of change historically reported in the literature (Ferguson & Werritty 1983, e.g). Perhaps it is the relative ease with which a morphological analysis and colourful figures can be produced in now widely available GIS and CAD packages that has taken the emphasis away from sensible geomorphological interpretations of the observations. Geomorphology has historically struggled with its characterisation as too qualitative, and has sought in the past three decades to demonstrate that it can be quantitative (Church 1996, Sherman 1996). Quantitative analysis like morphological sediment budgeting are fine, but ultimately are of little use in themselves unless they can be used to help make better interpretations of the processes responsible for shaping the morphologies observed.

It is postulated that specific signatures of geomorphological change should be recognisable from more detailed analyses and process inferences of morphological sediment budgets. For example, elevation change distributions are a simple way of looking at either the areal or volumetric distribution of changes in a morphological sediment budget (Lane *et al.* 2003). These can be looked at for the gross sediment budget of the entire area of analysis. However, these distributions could be split into their component parts by specific mechanisms of change (e.g. bank erosion, pool scour, floodplain deposition, bar development) or by areal units (e.g. specific sub-reaches or morphological units). Each of these decompositions might have a specific recognisable signature of geomorphological change as represented in its elevation change distribution. For example, a bank erosion signature should be entirely skewed on the erosional side of the elevation change distribution (Figure 1.4). Moreover, such a segregation of the total budget would allow an appraisal of which mechanisms of change are responsible for doing the most geomorphological work within a study reach.

From a physical habitat perspective, geomorphological interpretations at a reach-scale are interesting in setting the context. However, physical habitat is experienced by salmonids at the hydraulic unit (patch) and geomorphic unit (bar) scale (Wheaton *et al.* 2004*c*, Crowder & Diplas 2000). Thus, it would be much more useful to have a quantitative geomorphological interpretation at this scale. If the techniques called for above can be developed, they provide precisely this sort of quantitative, process-based information. This approach could reveal a key to explicitly and quantitatively make a link between geomorphological processes and physical habitat for salmonids. This link has been conceptually touted in the literature as fundamental for some time (Arscott *et al.* 2002, Stanford *et al.* 2005). However, relatively little has been done to elucidate it explicitly and quantitatively (Kerle *et al.* 2002).[12]

[12] Notable exceptions include contributions from the Floodplain Ecology and Biodiversity Research Group at EAWAG, Switzerland (Tockner *et al.* 2006, e.g.), The University of Montana's Flathead Lake Biological Station (Stanford *et al.* 2005, e.g.), and the University of Stirling's Fluvial Geomorphology and Hydroecology Research Group in the School of Biological and Environmental Sciences (Gilvear *et al.* 2004, e.g.). However, the quantitative links between geomorphological dynamics and ecology have been primarily focused on vegetation communities and macroinvertbrates as opposed to salmonids.

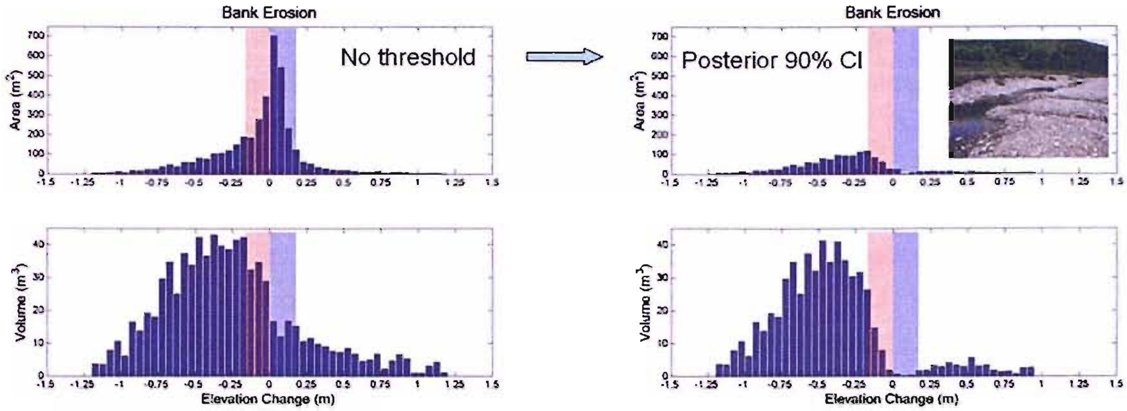


FIGURE 1.4: An example of an elevation change distribution for bank erosion derived from a DoD, with (LHS) and without (RHS) an uncertainty analysis applied. The top distributions are by area subjected to erosion, the bottom distributions are by volume. The light blue and red bands represent the portion of the distribution that would be discarded if a 15 cm minimum level of detection was applied. In this example from the River Feshie, bank erosion occurs in only 3% of the reach (aerially), yet contributes between 35 and 40% of the total sediment budget and roughly 20% of the total erosion. Banks are consistently in areas of higher DoD uncertainty; therefore bank erosion estimates can vary significantly (hence the incorrect inclusion of depostion on a bank erosion distribution). Figure reproduced from Wheaton *et al.* (2004*a*).

1.4 Thesis Organization

This section briefly outlines the organization of the thesis. The thesis is organised into four parts. Part I identifies the problem of uncertainty about geomorphological change in salmonid PHR, articulates the aims and objectives and provides appropriate reviews of the relevant literature. Part II seeks to achieve the two stated objectives through methodological development and forms the substantive original contribution of the thesis. Part III uses contrasting monitoring datasets at three case study sites to demonstrate and evaluate the said techniques. Finally, Part IV briefly synthesises the substantive outputs of Part II and Part III as well as highlighting the relevance to PHR and future research possibilities. Additionally there are a collection of appendices that are not central to supporting the basic narrative of the thesis, but provide the reader with additional depth, raw data and analyses for reference. The remainder of this section elaborates on the chapters that comprise each part.

In Part I, this chapter concisely sets the context for the entire thesis by laying out the basic problems, the thesis statement and the aim and objectives that follow from these. In Chapter 2 a much broader view of the problems outlined in this chapter are presented. The purpose of that review is to establish the vast scope of the problem of uncertainty in relationship to monitoring geomorphological change and provide a more constructive framework for understanding and communicating uncertainty therein. Chapter 3 returns to a more focused review that justifies the selection of methods that are used and developed. The chapter starts with a review of the spatial scale of the problem, then discusses the rationale behind the individual objectives, wrapping up with a justification of the study sites used in Part III.

Part II is comprised of Chapters 4 and 5. The chapters are each stand-alone methodological contributions that address objectives one (See section 1.3.1, and two (See section 1.3.2) respectively. Briefly, Chapter 4, presents the development and testing of a new method for quantifying surface representation uncertainty in digital elevation models (DEMs) and their subsequent impact on morphological sediment budget results. Chapter 5 builds on this by segregating the morphological sediment budget into coherent spatial components, that help explain the mechanisms of change quantitatively. In other words, the fluvial processes responsible for the observed change are inferred from the differences and quantified. While Chapter 4 uses data from one of the study sites to assist in the methodological development, Chapter 5 is a much more concise and conceptually simple development, whose application is reserved for Part III.

While Part II may appear to accomplish the objectives of the thesis, these ideas need to be grounded and tested in some contrasting real-world examples. In Part III this is provided by using the developed methods to narrate stories of geomorphological change using data sets from three contrasting study sites. This is done for Sulphur Creek in Chapter 6, the Mokelumne River in Chapter 7, and the River Feshie in Chapter 8, in order of increasing complexity of the nature of change. Collectively, these stories demonstrate the thesis aim of making more reliable and meaningful interpretations of repeat topographic surveys collected to monitor geomorphological change for different reasons in three very different rivers.

Part IV brings the reader back from the methodological development of Part II and the stories told in Part III to the original motivation of PHR for salmonids discussed in Part I. Only a single discussion and conclusion chapter (Chapter 9) comprises Part IV. The chapter synthesises what has been done and includes a forward looking discussion of potential future research. In Chapter 9 the significance of these contributions in relationship to PHR as well as under their own scientific merits is also laid out. Finally, the chapter provides a concise summary of the primary findings.

Several appendices are also provided. These include the presentation of additional or primary datasets referred to but not presented in the thesis, as well as some more detailed information on the case study sites.

Chapter 2

A Broader Context for Uncertainty

2.1 Introduction

The topic of uncertainties is riddled with complexity and confusion. In section 1.2, the reliability and interpretation uncertainties associated with monitoring geomorphological changes and morphological sediment budgeting were highlighted as the fundamental uncertainties of interest in this thesis. While this is perfectly reasonable, a more holistic consideration of uncertainties would provide a more robust context for understanding what these uncertainties mean, where they stem from and their significance. Thus, the purpose of this chapter is to unravel the ambiguities surrounding uncertainty about monitoring geomorphological change. To do this, some nomenclature, and a typology for uncertainty, are presented to delineate the scope of uncertainty (§ 2.2). Then, existing uncertainty tools in the sciences are reviewed (§ 2.3), highlighting the sparse examples of explicit recognition of uncertainty in PHR where appropriate.[1] With the broad scope of uncertainty outlined, as well as the potential and/or shortcomings of existing techniques for communicating and dealing with uncertainty already available, the specific question of uncertainty about geomorphological change is revisited (§ 2.4). It is then argued that a basic philosophical strategy for dealing with uncertainty is needed (§ 2.5) to allow both the individual researchers and PHR practitioners to:

- Explore the potential significance (both in terms of unforeseen consequences and welcome surprises) or insignificance of uncertainties.
- Effectively communicate uncertainties
- Eventually make adaptive, but transparent, decisions in the face of uncertainty

Finally, it is argued that amongst the various available strategies for dealing with uncertainty, the only strategy that might meet the above criteria is one of embracing uncertainty. The

[1] For a broader review of uncertainty tools in environmental management as well as the sciences, the reader is referred to Wheaton *et al.* (2008).

suggestion is that this framework would be equally applicable to both research problems like the one addressed here, and broader environmental management problems like PHR.

2.2 Uncertainty Unraveled

To unravel what confusion may exist in the mind of the reader about uncertainty and to better place this work in context, some basics about uncertainty are reviewed in this section. First, some of the confusing nomenclature for uncertainties and related misconceptions are addressed (§ 2.2.1). Next, an existing typology for uncertainty is used to define uncertainty (§ 2.2.2). Lastly, the question of how knowledge and uncertainty relate is addressed (§ 2.2.3).

2.2.1 A Lexicon of Uncertainty

In the simplest sense, uncertainty can be a lack of sureness about something or someone (Merriam-Webster 1994). However, uncertainty can be more than simply a lack of knowledge. It persists even in areas where knowledge is quite extensive; and knowledge does not necessarily equate to truth or certainty (Van Asselt & Rotmans 2002). There are at least 24 potential synonyms for the noun uncertainty and 27 synonyms for the adjective uncertain (Table 2.1). There are a number of concepts related to uncertainty, but which differ from uncertainty itself. That is, these concepts may stem from or be influenced by uncertainties, but are not themselves uncertainties. A non-exhaustive selection of these concepts are considered briefly below. It is important to understand that although the semantics discussed here are based on a review of the uncertainty literature, definitions and opinions with regards to uncertainty are inconsistent, contradictory and uncertain themselves.

Accuracy- Accuracy refers to correctness or freedom from errors. In measurements, accuracy refers to how close an individual measurement is to the 'true' or 'correct' value (Brown *et al.* 1994). The classic accuracy analogy is the location of darts on a dart board - the closer the darts are to the bull's-eye, the more accurate. If one can be certain about both the 'true' value (e.g. the position of the bull's-eye) and the value of the individual measurement (e.g. the position of the dart), then the accuracy is actually a certainty. In practice, accuracy statements are uncertain because 'true' values are often assumed and measurements have limited precision.

Confidence- Confidence in something (such as a statement, a hypothesis, a measurement, a feeling or a notion) relates to the degree of belief or level of certainty. Confidence levels, for example, describe the probability that a given population parameter estimate falls within a designated continuous statistical confidence interval.

Divergence- Divergence describes a situation when similar causes produce dissimilar effects (Schumm 1991). Divergence relates to uncertainty in situations where problems of cause and process are under consideration.

Synonyms of Uncertainty	Synonyms of Uncertain
Ambiguity	Ambiguous
Indeterminacy	Causeless
Capriciousness	Capricious
Chance	Probabilistic
–	Deferred
Danger	Dangerous
Disbelief	Disbelieving
Doubt	Doubtful
Equivocation	Equivocal
–	Erratic
Expectation	–
Future condition	–
Hesitation	Hesitant
Ignorance	Ignorant
Improbability	Improbable
Indecision	Indecisive
Indeterminacy	Indeterminant
Insecurity	Insecure
Irresolution	–
Obscurity	Obscure
Surprise	Surprising
–	Unauthentic
Unintelligibility	Unintelligible
–	Unexplained
–	Questionable
Vacillation	Vacillating
Vagueness	Vague
–	Undecided
Unsureness	Unsure
Unpredictability	Unpredictable

TABLE 2.1: Potential synonyms of the noun 'Uncertainty' and the adjective 'Uncertain.'

Error- Error is the difference between a measured or calculated value and a 'true' value. In every day conversation, an error is a mistake. In science, error is the metric by which accuracy is reported and is not a synonym for uncertainty (Ellison *et al.* 2000). A 'true' value is certain by definition. If one knows the error between the 'true' value and a measured or calculated value there is no uncertainty in principle. However, in practice 'true' values are often not known and instead assumed to be 'true'; and the measured or calculated value also may have a degree of uncertainty. Hence error becomes representative of uncertainty. Once errors are calculated, it can be helpful to consider whether the error is systematic or random. Systematic errors stem from consistent mistakes and are often constant or predictable, because they affect the mean of a sample (i.e. bias, Trochim, 2000). Systematic errors potentially can be constrained as their source is identifiable. By contrast, random errors only influence the variability of a sample (not the mean), and are generally unpredictable or unconstrainable (Trochim 2000).

Exactness- Exactness is really a synonym for accuracy. However, it is worth pointing out that exactness has quite a different meaning to exact. Exact statements or exact numbers, in principle, have no uncertainty about them. They are statements of truth. By contrast, exactness is a relative measurement assigned to inexact statements or values (i.e. those with some uncertainty).

Expectation- Expectation has to do with anticipation of probable or certain events. Uncertainty fundamentally relates to expectations. When uncertainties are unknown, not fully considered or ignored, the degree that our expectations may be unrealistic will generally increase.

Equifinality- Equifinality (also referred to as convergence), arises when different processes and causes produce similar effects (Schumm 1991). This is the opposite phenomenon of divergence. In a modeling context, Beven (1996*a*) and Beven (1996*b*) suggest that 'the consequences of equifinality are uncertainty in inference and prediction.' In a social context, a potentially limitless range of possibilities may lead to a single event, such as the election or defeat of a politician.

Precision- Precision is a measure of how closely individual measurements or calculations match one another (Brown *et al.* 1994). Recalling the dart board analogy, a precisely thrown set of darts will cluster around one another, but may be nowhere near the bull's-eye. In measurement, the precision of an instrument refers to the finest-scalar unit the instrument can resolve. Precision is related to uncertainty in that it defines a detection threshold, below which differences can not be discerned.

Reliability- In social sciences, reliability is related to the quality of information or measurement (Trochim 2000). In systems engineering, reliability is the chance that a system or element will operate to a specified level of performance for a specified period under specified environmental conditions. Reliability is an important concept in engineering design for assessing thresholds of failure.

Repeatability- Repeatability can be viewed as either the ability to reproduce the same measurement, result or calculation or the variability in repeated measurements, results or calculations.

Probability (%)	Uncertainty
<1	Extremely unlikely
1 to 10	Little chance or very unlikely
10 to 33	Some chance or unlikely
33 to 66	Medium likelihood
66 to 90	Likely or probable
90 to 99	Very likely or very probable
> 99	Virtual Certainty

TABLE 2.2: Probabilistic Uncertainty. From Pollack (2003).

Uncertainty can simply limit repeatability or increase variability.

Risk- Risk is a measure of likelihood that a undesirable event or hazard will occur (Merriam-Webster 1994). Ward (1998) credited Knight (1921) for making the important clarification between risk and the type of uncertainty for which there exists 'no valid basis of any kind for classifying instances':

> 'He used the term "risk" for situations in which an individual may not know the outcome of an event, but can form realistic expectations of the probabilities of the various possible outcomes based either on mathematical calculations or the history of previous occurrences.'

Newson & Clark (2008) contrasted risk (with 'known' impacts and probabilities) with uncertainty (with 'known' impacts but 'unknown' probabilities) and ignorance (with 'unknown' impacts and probabilities).

Sensitivity- Sensitivity refers to either the ability or susceptibility of something or someone to change (Allison & Thomas 1993). Sensitivity is closely related to the concepts of resistance to change and thresholds for change, which all have important implications in geomorphology and ecology (Brunsden 1993). As resistance to change and thresholds for change are uncertain quantities, sensitivity too is an uncertain concept.

It is worth noting that uncertainty itself, and all the related concepts outlined above are described in terms of their 'degree'. That is, none of these concepts are simple Aristotelian two-valued logic concepts (e.g. true-false). Each concept is measured along a continuum of values with end-members that may be described in terms of Aristotelian two-valued logic. For example, the end-members of uncertainty might be total uncertainty (complete irreducible ignorance) and certainty. However, a large range of uncertainty measures exist on the continuum between those two end members. In a sustainable, adaptive management context, Newson & Clark (2008) described uncertainty and the related concepts of risk[2] and ignorance in terms of knowledge of impacts and probabilities. Table 2.2 describes uncertainty measures in terms of probabilistic notions.

[2]See risk definition on page 18.

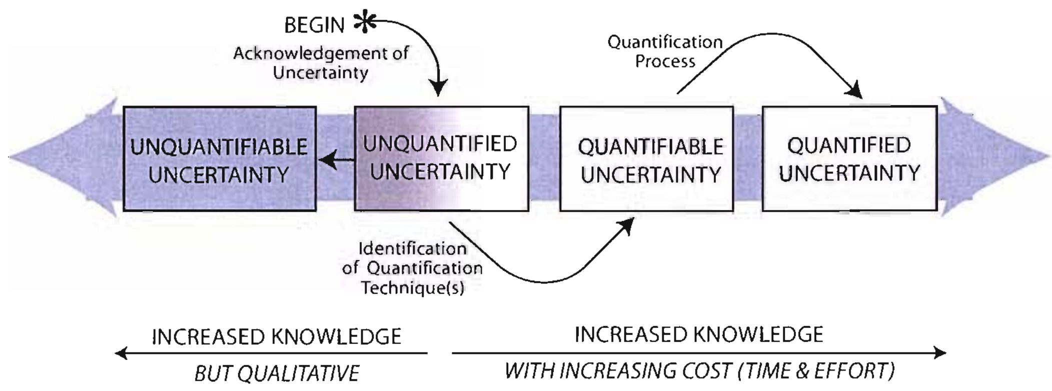


FIGURE 2.1: The Quantifiable Continuum of Uncertainty. Notice that once uncertainties are acknowledged as unquantified uncertainties, increased knowledge about the uncertainties will determine their position on the continuum.

While probabilistic uncertainty is a quantification of uncertainty, not all uncertainty is quantifiable. To quantify uncertainty it is necessary to estimate the degree of our limited knowledge. Whereas if irreducible ignorance is considered as one extreme of uncertainty, it is difficult at best to estimate the degree of something that is not even known to exist. Within this broad view of uncertainty, uncertainty might be considered along a continuum that reflects our ability to quantify it (Figure 2.1). At one end of the continuum are 'unquantifiable' uncertainties; somewhere further along would be 'unquantified' uncertainties (those that in principle could be either un-quantifiable or quantifiable) and 'quantified' uncertainties would be further along the continuum yet.

In summary, when uncertainty is mentioned casually, it is difficult to discern whether this is a reference to limited knowledge, a lack of knowledge altogether or one of the above-mentioned concepts that are influenced by uncertainty. Moreover, the above-mentioned concepts are highly inter-related and easily confused. Similar to vague, pseudo-scientific buzzwords and catch-all phrases like holistic and integrated, uncertainty alone has little meaning until its details are unraveled and an attempt to understand it is made.

2.2.2 An Existing Typology for Uncertainty

Classification is often used as an alternative to formal definition of uncertainty because uncertainty is so hard to define (Van Asselt & Rotmans 2002). The utility of any typology or classification system is ultimately dependent on its application (Kondolf 1995, Lewin 2001). Rotmans & Van Asselt (2001, p. 112) astutely pointed out, 'there is not one overall typology that satisfactorily covers all sorts of uncertainties, but that there are many possible typologies'. For example, the Intergovernmental Panel on Climate Change (IPCC) defined guidelines for all working group authors of the Fourth Assessment Report of the IPCC - *Climate Change 2007* that included a rather simple typology for uncertainty (Table 2.3). The important point

Type	**Indicative examples of sources**	**Typical approaches or considerations**
Unpredictability	Projections of human behaviour not easily amenable to prediction (e.g. evolution of political systems). Chaotic components of complex systems.	Use of scenarios spanning a plausible range, clearly stating assumptions, limits considered, and subjective judgments. Ranges from ensembles of model runs.
Structural uncertainty	Inadequate models, incomplete or competing conceptual frameworks, lack of agreement on model structure, ambiguous system boundaries or definitions, significant processes or relationships wrongly specified or not considered.	Specify assumptions and system definitions clearly, compare models with observations for a range of conditions, assess maturity of the underlying science and degree to which understanding is based on fundamental concepts tested in other areas.
Value uncertainty	Missing, inaccurate or non-representative data, inappropriate spatial or temporal resolution, poorly known or changing model parameters.	Analysis of statistical properties of sets of values (observations, model ensemble results, etc); bootstrap and hierarchical statistical tests; comparison of models with observations.

TABLE 2.3: A simple typology of uncertainties used by the IPCC. From the Appendix (WMC & UNEP 2005) of the IPCC (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*

is that the typology is fit for its purpose. The IPCC typology needed to be clear when communicating uncertainty to a very diverse audience from mixed lay and technical backgrounds (IPCC 2007).

In the context of this thesis and review, a typology was sought which considered sources of uncertainty and did not unnecessarily ignore any type of uncertainty. Thus, the existing Van Asselt (2000) typology was chosen over others in the literature because of its generic and holistic consideration of uncertainty. The typology arose out of Integrated Assessment modeling, which attempts to account for all relevant aspects of particular societal problems with an ultimate aim of providing decision support. Integrated Assessment includes interactions between social, economic, institutional and environmental dimensions and are instrumental in long-term policy analysis (Lempert *et al.* 2003). The most common examples are global climate change models that run under various scenarios of each dimension (Rotmans & Van Asselt 2001). The typology was first introduced in detail in Van Asselt (2000) and concisely reviewed in Rotmans & Van Asselt (2001) and Van Asselt & Rotmans (2002). At the highest level, two sources of uncertainty exist: uncertainty due to variability and uncertainty due to limited knowledge (Figure 2.2). Van Asselt & Rotmans (2002, pp. 78-89) provided the following helpful distinctions and references to similar terminology:

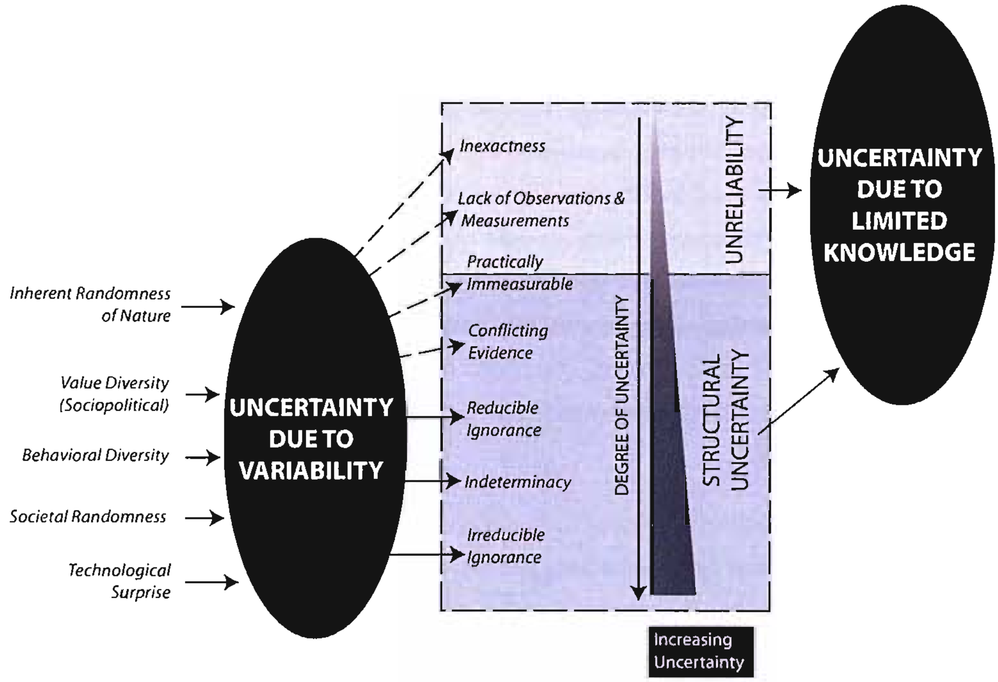


FIGURE 2.2: Typology for sources and degree of uncertainty. Adapted from Van Asselt's (2000) proposed typology for uncertainties in integrated assessment.

Variability. 'The system/process under consideration can behave in different ways or is valued differently. Variability is an attribute of reality (ontological). Also referred to as "objective uncertainty" (Natke & Ben-Haim 1996), "stochastic uncertainty" (Helton 1994), "primary uncertainty" (Koopmans 1957), "external uncertainty" (Kahneman & Tversky 1982), "unpredictability"(IPCC 2007) or "random uncertainty" (Henrion & Fischhoff 1986).'

Limited knowledge. 'Limited knowledge is a property of the analysts performing the study and/or of our state of knowledge (epistemological). Also referred to as "subjective uncertainty" (Natke & Ben-Haim 1996, Helton 1994), "incompleteness of the information"(von Schomberg 1993), "informative uncertainty" (van Witteloostuijn 1987, Bandemer & Gottwald 1995, Natke & Ben-Haim 1996), "secondary uncertainty" (Koopmans 1957) or "internal uncertainty" (Kahneman & Tversky 1982).

Van Asselt & Rotmans (2002) presented uncertainty due to variability first as these uncertainties ultimately combine to contribute to uncertainty due to limited knowledge. Environmental management is concerned with the inherently variable natural and managed systems. Knowledge about natural change and variability in ecosystems, fluvial systems and hydrological systems is incomplete and hence contributes to uncertainty due to limited knowledge in, for example, river basin management and river restoration (Wissmar & Bisson 2003*a*). Five distinct subclasses of uncertainty due to variability are proposed: inherent natural randomness, value diversity (socio-political), behavioral diversity, societal randomness, and technological surprise. Inherent natural randomness is attributed to 'the non-linear, chaotic, and unpredictable nature of natural processes'. Natural variability of river systems should be a fundamental consideration in integrated river basin management and was reviewed thoroughly in Wissmar & Bisson (2003*b*). Value diversity, behavioral diversity and societal randomness each contribute to uncertainties in environmental management, particularly through stakeholder negotiations, public support, project funding, policy-making and individual perspectives. Technological surprises result from new breakthroughs in technology, which may provide unforeseen benefits and/or bring unforeseen consequences.

Van Asselt & Rotmans (2002) separated seven types of uncertainty due to limited knowledge. Unlike uncertainties due to variability, uncertainties due to limited knowledge are thought to map out along a continuum that reflects the relative degree of uncertainty. At the highest degree of uncertainty are four 'structural uncertainties'. Starting with the highest degree, Van Asselt & Rotmans (2002) identified:

- Irreducible ignorance- 'We cannot know.'
- Indeterminacy- 'We will never know.'
- Reducible ignorance- 'We do not know what we do not know.'
- Conflicting evidence- Knowledge is not fact but interpretation, and interpretations frequently contradict and challenge each other. 'We don't know what we know.'

Van Asselt & Rotmans (2002) then proposed a transition into 'unreliability' uncertainties of a relatively lesser degree:

- Practically immeasurable- A lack of data or information is always a reality in studying natural systems. Not only are many natural phenomena incredibly difficult or impossible to measure, all are fundamentally limited by problems of temporal and spatial resolution, up-scaling and averaging (Kavvas 1999). 'We know what we don't know'-(Van Asselt & Rotmans 2002).
- Lack of Observations and Measurements- Although in principle this is easy to identify and augment, in practice this is always a factor. Borrowing from Van Asselt & Rotmans (2002): 'could have, should have, would have, but didn't.'
- Inexactness- Related to lack of precision, lack of accuracy, measurement and calculation errors. Under Klir and Yuan's (1995) typology, these are considered 'fuzziness' or vagueness.

The Van Asselt (2000) typology is both more general and detailed than other typologies such as Klir & Yuan (1995). However, all provide a reasonable means to deal with the first step to understanding uncertainty. Namely, they allow a systematic identification of sources and types of uncertainties that could work in either individual river restoration projects or international policy-making on water and environmental management. In practice, it is recognized that the semantics of uncertainty will always be interpreted differently in different professional contexts (Newson & Clark 2008). However, within the context of this thesis the Van Asselt (2000) typology and associated meanings will be used consistently. In this thesis, the uncertainties that matter are unreliability uncertainties associated with DEM differencing and structural uncertainties associated with making geomorphological interpretations of DoDs.

2.2.3 How Knowledge and Uncertainty Relate

Much of modern science is based on the premise that as the scientific knowledge base develops, unique causal relationships will be discovered, and uncertainty will subsequently decrease (Wilson 2001, Spedding 1997). In other words, a positivist view (Van Asselt & Rotmans 2002). Openshaw (1996) contended that as knowledge increases, uncertainty decreases. Brookes *et al.* (1998) made the more restrictive but contradictory generalisation that 'as knowledge relating to rivers and their floodplains increases, uncertainty is increased rather than decreased.' In reality, there is no unique relationship between uncertainty and knowledge (Van Asselt & Rotmans 2002). It is a highly contextual relationship dependent on the type of uncertainty (i.e. uncertainty due to lack of knowledge versus variability) and the specific circumstances under consideration. Jamieson (1996) pointed out that uncertainty is not a fixed quantity and is not always reduced by scientific research. Openshaw (1996) suggested that although 'normal science is predicated on the belief that knowledge and information reduce uncertainty,' Zadeh's principle of incompatibility suggests the exact opposite is true for complex systems. Figure 2.3 elaborates on these examples of the potential relationships between knowledge and uncertainty by showing the influence of the source of uncertainty.

Now that the basic terminology of uncertainty is established, it is helpful to review the existing tools available within science (see § 2.3) to communicate these uncertainties.[3] Given the daunting scope of uncertainty when considered in such broad terms, it makes sense that each of these tools will only address specific classes of uncertainty (Anderson *et al.* 2003). The scientific tools review is necessary to identify the scope of possible tools available for dealing with unreliability and structural uncertainties this thesis aims to address.

[3] This review is extended to include environmental management tools in Wheaton *et al.* (2008).

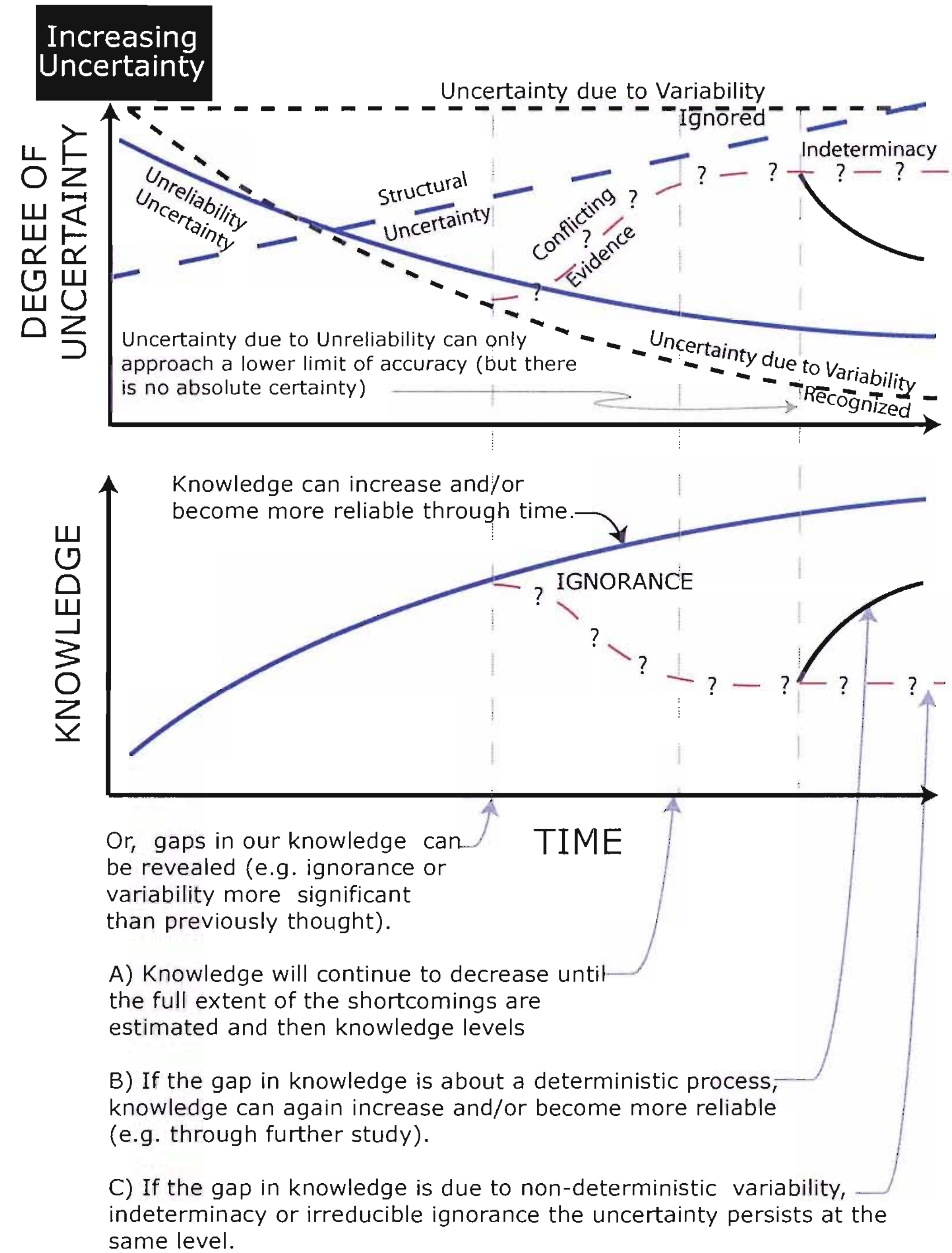


FIGURE 2.3: Some potential hypothesized relationships between knowledge and uncertainty through time. Contrary to the argument of the positivist, no unique inverse relationship between uncertainty and knowledge exists. See § 2.2.2 and Figure 2.2 for definitions of uncertainty types.

2.3 Scientific Tools for Communicating Uncertainty in Observations and Models

In this section, some of the basic ways to represent and treat uncertainties, primarily in a quantitative fashion, are briefly reviewed. In fluvial geomorphology, observations and models are the primary quantitative tools from which interpretations are made. Each produce uncertain quantities and are subject to uncertain interpretations. Most treatments of these uncertainties have grown out of traditional scientific disciplines (e.g. chemistry, physics and mathematics) and classical theories therein (e.g. classical set theory and probability theory). Some of the more recent treatments come from applied sciences (e.g. engineering, economics and policy-sciences). As will be shown, with the notable exception of fuzzy-set theory, most of these treatments are limited to certain classes of problems and types of uncertainty (Klir & Yuan 1995). These are primarily unreliability uncertainties due to limited information (i.e. inexactness, lack of observations and measurements). This section is meant to briefly introduce the range of treatments available and some of the issues associated with each treatment[4].

2.3.1 Metrics of Uncertainty as Expressions of Societal Values

There is no unique metric by which uncertainty can be measured or expressed. All attempts to quantify uncertainty in science or environmental management are expressions of societal or scientific community values. That is uncertainty is expressed in units or terms based on specific interests and subsequent perceived importance. For example, structural engineers may express their uncertainty about the seismic integrity of a bridge in terms of a range of stress and strain thresholds or tolerances; a planner would view this uncertainty in terms of factors of safety; a geologist expresses this uncertainty in terms of a probability of an earth-quake occurring; and the insurance agent expresses their uncertainty in terms of risk levels. Ultimately, it is assumed that the decision maker understands each of these metrics and their ramifications. Scientists may communicate to their peers or restoration practitioners technically using metrics of uncertainty that are convenient and/or conventional. However, when scientists communicate uncertainty to decision makers, stakeholders and the general public, it is imperative that they use metrics that are easily understood and directly related to the societal goals driving the restoration. For example, Stewardson & Rutherfurd (2008) expressed their uncertainty in specifying flushing flows that would turn over a gravel bed to maintain habitat quality in terms of a range of discharges. This novel yet simple example is easily communicated to dam operators and in the case of the Goulburn River, Australia, revealed that the range of uncertainty was actually outside the feasible availability of water.

[4] In so far as they apply to the restoration of degraded river systems.

2.3.2 Communicating Uncertainty in Observations

2.3.2.1 Measurement Uncertainty

Arguably the most familiar and ubiquitous treatments of uncertainty are those that deal specifically with measurement uncertainties. This branch of treatments focuses exclusively on uncertainty due to inexactness, which is typically represented in the form of errors (Routledge 1998). Detailed guidelines and international standards for accounting and constraining measurement uncertainty already exist (Taylor & Kuyatt 1994, ISO 1995). In quantitative chemical analysis for example, Ellison *et al.* (2000) defined uncertainty as: 'A parameter associated with a measured value that characterises the dispersion of values reasonably attributed to the measurand.' In this view, uncertainty in measurement does not imply doubt, but rather expresses confidence in the validity of measurements (i.e. measurement of error). The two primary types of errors, random (or chance) and systematic (or bias) errors, were already introduced in section 2.2.1 and guidelines for standard statistical techniques to address these are readily available (Routledge 1998). Instead of reviewing the straight forward methods themselves, Routledge (1998) pointed out that to apply statistical techniques in error analysis it is assumed that the data 'contain no systematic component, are independent, have a constant standard deviation and feature a distribution that follows a normal curve.' Routledge (1998) explained that if any of these assumptions are violated, 'standard statistical analyses may not work properly.' These assumptions frequently are violated but employed anyway. Many of these methods were developed for relatively routine measurements in controlled or laboratory environments (e.g. chemistry, physics).

Rivers are rather poor examples of controlled environments and present large challenges to constraining measurement uncertainties. This statement is not to suggest that such techniques have no utility in rivers. Herschy (2002), for example, proposed a practical method for expressing uncertainty in current meter measurements for estimates of discharge. Wilcock (2001) contrasted trade-offs in measurement errors and formula errors (based on measurements) for bedload transport which can vary over multiple orders of magnitude. Brasington *et al.* (2000) and Brasington *et al.* (2003) compared errors in digital elevation model surface representation of river beds from field-collected (rtkGPS) and remotely-sensed (aerial photogrammetry) survey data. Although measurement errors are frequently used to represent uncertainty in river studies, it is important to recognise that such techniques only focus on a specific form of uncertainty, and understand the limitations of statistical techniques based on potentially invalid assumptions.

2.3.2.2 Statistical and Probabilistic Methods

Klir & Yuan (1995) credited the modern view of uncertainty to physicists in the late 19th century who were interested in studying processes at the molecular level. The magnitude of individual particles and processes at that scale prompted the development of statistical methods, which substitute individuals in a population with their statistical averages. Klir & Yuan (1995) went on to say that calculus (the mathematical tool of choice in classical Newtonian mechanics that includes no uncertainty) was replaced in molecular physics by probability theory, which accounts for uncertainty of a specific type. Statistical techniques require a high degree of randomness and a large number of variables. The key to representing uncertainty with probabilistic methods largely boils down to: how well one can represent the uncertain process or population of interest with a probability density function (PDF). A well known example of a PDF is the Gaussian bell-curve of a normal distribution. Uncertainty is then represented as a probability derived from this PDF (Table 2.2). In general, if the PDF representation is good, accounting for uncertainty is straight forward. The problem is that complex natural processes and populations are not always necessarily well represented by PDFs.

2.3.2.3 Fuzzy Set Theory

The quantitative treatments of uncertainty discussed thus far have all been represented in terms of crisp sets of numbers, for which membership is unambiguous and standard classical mathematics apply. For example, the crisp set of numbers A might be defined as:

$$A = \{1, 2, 3\} \tag{2.1}$$

The members of set A are simply 1, 2 and 3, whereas 4 or any other number are not. Crisp sets have distinct or crisp boundaries between membership and non-membership. In reality, and especially in the case of river restoration, not all situations are adequately represented by absolute membership criteria (Bandemer & Gottwald 1995). Zadeh (1965) first proposed fuzzy sets, whose boundaries are imprecise. Membership in a fuzzy set is not simply a matter of yes or no, but a question of degree (Klir & Yuan 1995). Fuzzy set theory is then a more flexible theory, of which classical set theory is simply a special case. In fuzzy set theory, a membership function is used to indicate the degree or grade of membership, μ_A, of a particular value to a set, where μ_A can be any value from 0 to 1: 1 indicates definite membership, 0 indicates definite non-membership, values in between are degrees of membership. The utility of this is illustrated well with the example of a simple linguistic classification system of temperature (Figure 2.4). In a crisp representation, the terms 'hot' and 'cold' must correspond to a specific range of temperature values. In a fuzzy representation, where membership equals one (the top of the trapezoid in this case) there is absolute membership in the class. However, where membership is between 0 and 1 (the legs of the trapezoid) the temperature boundaries vary according to the vagueness of the description 'hot' or 'cold', and can even overlap with each other. Hence, the added flexibility of a membership function allows representation of uncertainty (in this case stemming from the linguistic terminology 'hot' and 'cold').

At first glance, the specification of a membership function appears to be quite similar to the assignment of a PDF. However, recall that the assumptions behind assignments of a PDF

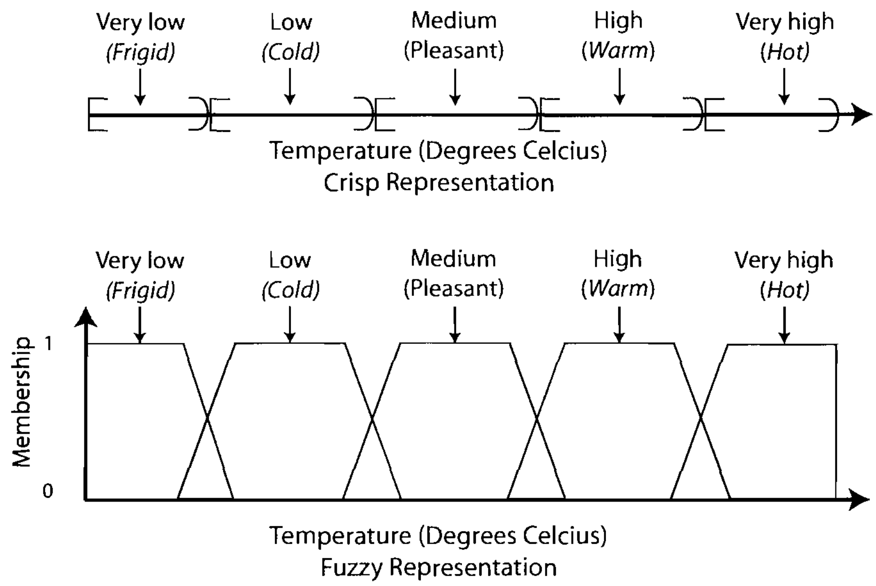


FIGURE 2.4: Crisp versus fuzzy, representations of a temperature classification. Adapted from Klir and Yuan (1995).

are highly restrictive; whereas fuzzy set theory is very flexible (Johnson & Heil 1996, Schulz & Huwe 1999). Thus, the range of problems that can be addressed with fuzzy techniques is potentially larger. Johnson & Heil (1996) presented one of the first applications of fuzzy set theory to fluvial geomorphology and river restoration through the example of bankfull discharge. The concept of bankfull discharge was introduced by Leopold & Maddock (1953) and has become one of the most popular and arguably misapplied concepts in river restoration (Doyle *et al.* 1999). The bankfull discharge concept and subsequent quantification of bankfull depth, discharge, and bankfull shear stress are all subject to numerous uncertainties. In particular, uncertainties due to the vagueness of the bankfull definition[5] and subjectivity in selecting a representative value make a crisp representation of bankfull conditions questionable. To acknowledge and quantify the implications of these uncertainties, Johnson & Heil (1996) represented their field estimates of bankfull depth, calculations of boundary shear stress and theoretical estimates of critical shear stress as fuzzy numbers and performed subsequent calculations of bankfull discharge, sediment transport and stream classification with fuzzy mathematical operations. Their subsequent calculations showed, for example, that for a degree of belief $\alpha = 0$, the excess shear stress was $\tau_e = [3.7, 24.3]$ N/m^2, whereas for a degree of belief $\alpha = 1$, the excess shear stress was $\tau_e = 4.2$ N/m^2. In other words, the fuzzy representation reports its highest degree of belief as 4.2 N/m^2, but plausible values of excess shear stress can be anywhere between 3.7 and 24.3 N/m^2 (a roughly 6-fold range). The flexibility of fuzzy set theory, allowed Johnson & Heil (1996) to simply and explicitly quantify their uncertainties without potentially invalidating the assumptions required of probabilistic or statistical representations of uncertainty.

[5]Johnson & Heil (1996) reported over 16 bankfull definitions exist.

2.3.3 Communicating Uncertainty in Environmental Models

Uncertainty in modeling is a rich topic but differs from uncertainty models. The latter are a subclass of models that try to predict and propagate calculated uncertainties (Ayyub & Gupta 1994). First, an overview of the sources of uncertainty in environmental models is provided.

Cao & Carling (2002*a*) pinpointed the crux of the problem with uncertainties in alluvial river models:

> 'River scientists and engineers do not have full confidence in making reliable and accurate simulations of sediment transport, whilst the users' community is moving toward a position where rapid impact-modeling and decision-making are required with decision support models and hydroinformatics tools.'

Uncertainty in environmental models has attracted much well-deserved attention in the recent literature, including examples from climatic models (Zapert *et al.* 1998), ecological models (Horssen *et al.* 2002), vadose-zone models (Schulz & Huwe 1999), hydrological models (Binley *et al.* 1991)), hill-slope erosion models (Brazier *et al.* 2001), flood-conveyance models (Wohl 1998, Samuels *et al.* 2003), sediment transport models (Reckhow 2003), bank erosion models (Darby & Thorne 1996), and consideration of parametric uncertainty (McIntyre *et al.* 2002). In a benchmark review of *structural uncertainties* in mathematical modeling of alluvial rivers, Cao and Carling (2003 a & b) attribute the uncertainties in river modeling to '1) poor assumptions in model formulations; 2) simplified numerical procedures; 3) the implementation of sediment relationships of questionable validity; and 4) the problematic use of model calibration and verification as assertions of model veracity.' Clifford *et al.* (2008) pointed out that the hydrological, geomorphological and ecohydraulic linkages are conceptually well understood, but highlight that:

> 'giving precise values to quantities and timings of material and energy transfers, and accounting for feedbacks between them, gives rise to uncertainty at all scales.'

In their review of Integrated Assessment Models (including global circulation models) Rotmans & Van Asselt (2001) considered how unreliability uncertainty and structural uncertainty[6] influence modeling (Table 2.4). They explain how these uncertainties produce technical uncertainties (uncertainties in model quantities), methodological uncertainties (uncertainty about model form) and epistemological uncertainties (uncertainty about model completeness). Modeling uncertainties will never be fully understood or reduced down to a set of insignificant quantities. The point of considering uncertainties in environmental models used in river restoration is not to necessarily improve the predictive capability of models, but to realise the limitations of models. Hence, model predictions provide valuable and uncertain information in much the same was as a DSS helps inform decisions, rather than making them.

[6] Recall, unreliability and structural uncertainties are types of uncertainty due to limited knowledge; see Figure 2.2, page 21.

Type of Uncertainty	Influence on Modelling	Source of Uncertainty
Technical	Uncertainty in input data Parameter uncertainties	Inexactness Lack of Observations or Measurements
Methodological	Uncertain equations Model structure uncertainties	Conflicting evidence Phenomena practically immeasurable
Epistemological	Uncertain levels of confidence Uncertain about model validity Uncertain about model validity	Reducible Ignorance Indeterminacy Uncertainty due to variability

TABLE 2.4: Influence of Uncertainties on Modeling. Note that a) Technical uncertainties are related to model quantities; b) Methodological uncertainties are related to model form; and c) Epistemological uncertainties are related to model completeness. Adapted from Van Asselt & Rotmans (2002, Figure 5).

Klir & Yuan (1995) pointed out that maximising model usefulness is a function of three interrelated characteristics of the model: complexity, credibility and uncertainty. Paradoxically, they argue that:

> 'Usually (but not always) undesirable when considered alone, uncertainty becomes very valuable when considered in connection to the other characteristics of systems models: in general, allowing more uncertainty tends to reduce complexity and increase credibility of the resulting model.'

This highlights the fundamental trade-offs that the developers of all models have to consider. At what point does increased complexity (often achieved through the use of additional, often poorly constrained, parameters), cease to provide more valuable predictions? In a witty commentary, Stuart (2007) speaks of his own 'parameter abuse', while contrasting attempts to quantify uncertainty in models in an effort to make them more useful (Beven & Binley 1992), still striving toward development of models 'that are not only useful but truthful.' Ultimately, uncertainty in any model is primarily relevant to the user and what they are attempting to use the model for (i.e. the 'fit for purpose' question). Thus, making a model 'more useful' is as much about the philosophical treatment of uncertainty[7] as the technicalities of the model itself.

2.3.3.1 Probabilistic Uncertainty Representation in Models

The majority of environmental models used in river restoration (hydrological, hydraulic, eco-hydraulic, etc.) are spatially distributed and prone to structural uncertainty in spatial averaging. In physically-based hydrological models, for example, hydrologists are challenged with the daunting task of representing dynamic non-linear hydrological processes in heterogeneous catchments through some up-scaled form of the conservation equations (Singh &

[7]This is discussed in § 2.5.

Woolhiser 2002). Beven (1996*b*) pointed out the futility in attempting to produce an optimal model from piecemeal aggregation of plot- and point-scale theories and field data to up-scaled model domains. When point-scale conservation equations are up-scaled to the computational grid scale (10^1-10^3 m), spatial averaging of parameters estimated at individual points (e.g. soil characteristics, elevation, etc.) implicitly introduces uncertainty over what is actually a highly heterogeneous area. Furthermore, the equations are partial differential equations without deterministic solutions and can hence only be solved numerically. If one ignores the structural uncertainties[8], Kavvas (2003) argued that the uncertainty in the point-scale parameter estimates can be represented stochastically (with their probability distribution functions), and proposes non-linear stochastic partial differential equations at the point scale to represent the uncertainty. He then shows that the ensemble averages (PDFs and means) of the point-scale parameters are explicitly represented in the up-scaled forms of the conservation equations. Kavvas' approach is conceptually satisfying in its explicit accounting for uncertainty, but the calculus of stochastic partial differential equations is hardly a simple matter. Nonetheless, Kavvas (2003) showed that for some hydrological processes, the up-scaling process actually produces ordinary differential equations (as opposed to partial), hence permitting a analytical solution. The point of this example is that sophisticated stochastic and probabilistic techniques exist for dealing with uncertainty. However, their current practicality in the context of PHR practice is questionable as most researchers and practitioners are unlikely to understand or adopt such techniques.

Levy *et al.* (2000) suggested that probability models of uncertainty are frequently inappropriate for dealing with uncertainty in natural systems where extreme events play a crucial role. This is because the assumptions of probabilistic models are frequently violated (Anderson 1998). Petterman & Peters (1998) suggested that classical statistical hypothesis testing, use of standard errors of parameter estimates and 95% confidence limits are not adequate characterisations of uncertainty for decision-making in ecosystem management. Bergerud & Reed (1998) made the same warnings, and add significance tests, P-values and the frequentist paradigm to the statistical toolkit they claim is inadequate in ecosystem management. Klir & Yuan (1995) contrasted statistical methods with traditional analytical methods (e.g. calculus) to map out the two extremes of problems that analytical and statistical techniques can address:

> 'While analytical methods based upon calculus are applicable only to problems involving a very small number of variables that are related to one another in a predictable way, the applicability of statistical methods has exactly opposite characteristics: they require a very large number of variables and a very high degree of randomness. These two types of methods are thus highly complementary. When one type excels, the other totally fails... Most problems are somewhere between these two extremes: they involve nonlinear systems with large numbers of components and rich interactions among the components, which are usually nondeterministic, but not as a result of randomness that could yield meaningful statistical averages.'

[8]Structural uncertainties here are referring to the structure of the model (i.e. which processes are represented with which equations).

Under certain circumstances probabilistic representation of parameter uncertainties (technical uncertainties) are useful in EM. However, due to the strict assumptions that need to be met for probabilistic models to remain valid, this can narrow range of problems they are appropriate for.

2.3.3.2 Bayesian Frameworks

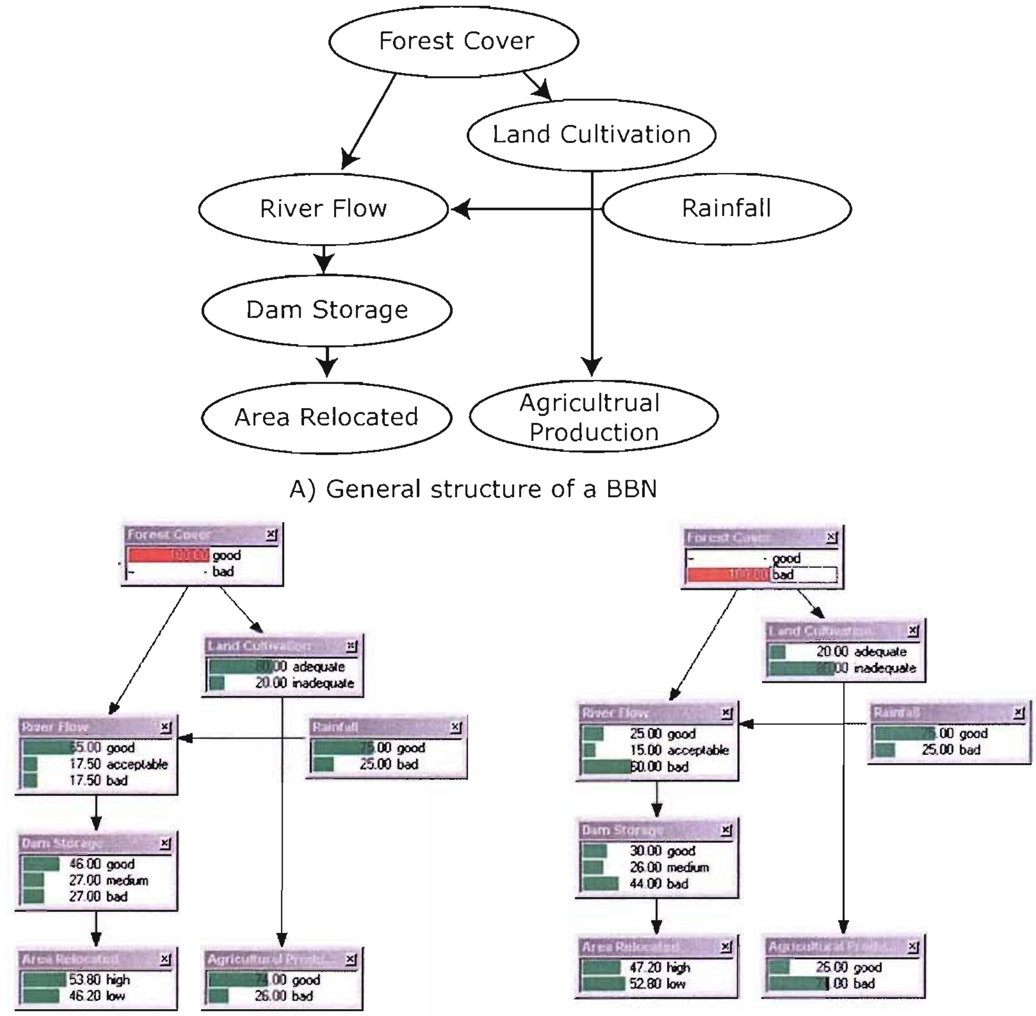
Bayesian frameworks are mentioned briefly here as a subclass of the probabilistic methods discussed above. Bayesian frameworks allow the user to assign a 'degree of belief' or probability to uncertain information. For example, instead of calculating a mean model parameter value from a large number of field measurement, classical Bayesian inference is used to estimate probability distributions from *a priori* information of physically reasonably values for unknown model parameters (Balakrishnan *et al.* 2003). Although this approach is practical in computationally efficient environmental models, it can be cumbersome in a growing class of computationally intensive models (e.g. 3D CFD models). However, Balakrishnan *et al.* (2003) developed a complex Bayesian modeling framework for reducing uncertainty in environmental 3-D numerical models, which creatively bypasses some of the traditional computational barriers.

Bayesian frameworks have proved useful beyond simply representing parametric uncertainty in environmental models and have found extensive application as decision support systems in EM, engineering and medicine (Addin & Jensen 2004). This is largely because of the flexibility they afford the user in incorporating their existing knowledge. Varis (1997) suggested that Bayesian analysis can be extended from the parameter space to the hypothesis space in decision theory by any of three dominant approaches: decision trees, influence diagrams and belief networks. An example of a Bayesian belief network is shown in Figure 2.5.

Addin & Jensen (2004) provided an excellent overview of how to develop Bayesian belief networks for EM decision support systems. They describe the techniques as merging qualitative information in a graphical form (causal graph) that specifies conditional relationships between a system's variables, with quantitative conditional probabilities. Because the actual probabilities are not known a subjective probability might be estimated using Bayesian inference (Bergerud & Reed 1998). However, among the shortcomings of Bayesian frameworks are the assumptions that the causality within a system is known (Addin & Jensen 2004). Even though uncertainty is explicitly represented in the probabilities, the structural uncertainty in the validity of the belief network is difficult to assess (P.comm. Nick Jackson, CEH, 2004).

2.3.3.3 Monte Carlo Models

In environmental models, Monte Carlo simulations can be used to incorporate uncertainty. Typically, a random number generator is used to select a set of model parameter values (known as an ensemble) that span the full range of plausible parameter values in the parameter space.



A) General structure of a BBN

B) BBN with Probability Tables in case "Forest Cover" is "good"

C) BBN with Probability Tables in case "Forest Cover" is "bad"

FIGURE 2.5: A simple Bayesian Belief Network adapted from Addin & Jensen (2004) representing part of a complex environmental management system.

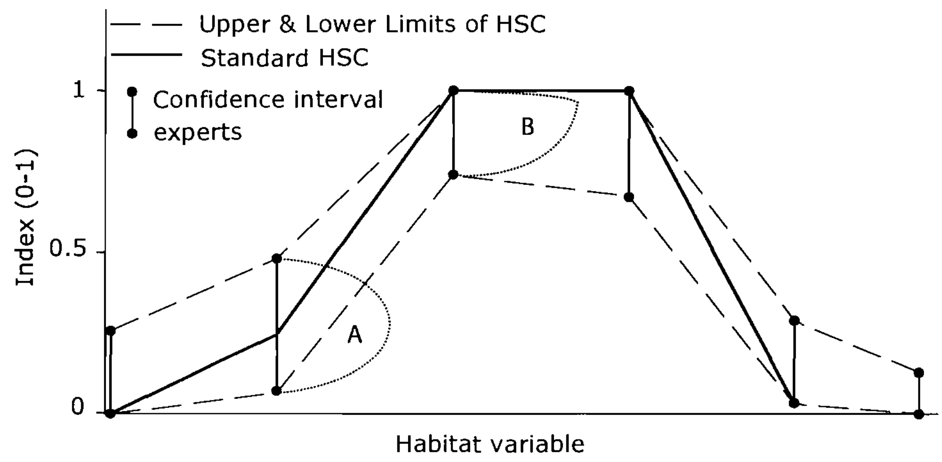


FIGURE 2.6: Illustration of the uncertainty in a habitat suitability curve. The solid line represents a typical HSC, and the dashed lines represent upper and lower limits of uncertainty. The uncertainty can be described as symmetrical (A) or asymmetrical (B) probability distributions, depending on the average (i.e. the parameters of the original model), the minimum and the maximum of the interval (based on expert judgment). Figure adapted from Van der Lee *et al.* (2006).

The model is then run repeatedly (typically 10^2s to 10^5s of times) under the ensemble scenarios defined by these randomly selected parameters. Unlike a typical sensitivity analysis, which may only explore the maximum, minimum and expected parameter values, a Monte Carlo analysis provides a fuller exploration of the parameter space. The uncertainty in parameter estimates can then be represented by a statistical analysis of the parameter influences on model results.

A prime example, in an EM context, is the GLUE (General Likelihood Uncertainty Estimation) framework developed by Beven & Binley (1992) originally for hydrological rainfall-runoff models. The GLUE framework has been applied to hydrological, hydrodynamic and dispersion models. Monte Carlo simulations as used in GLUE are helpful not only for considering parametric uncertainties, but also structural uncertainties in models giving rise to equifinality[9] of different model structures (Beven 1996*a*, Hankin *et al.* 2001). Within this context, equifinality is used to reject the notion of an 'optimal' model (Binley *et al.* 1991, Zak & Beven 1999, Brazier *et al.* 2000, Brazier *et al.* 2001). Beven (1996*b*) advocated instead disaggregating the information to reveal that multiple reasonable model structures exist, which are rather elegantly explained by our uncertainties.

Monte Carlo analyses have also been used in ecohydraulic modelling to explore how uncertainties in habitat suitability curves (HSCs) influence the predictions of habitat suitability models (Figure 2.6. HSCs are used to define physical habitat preference (as inferred by observation of a species utilising a particular habitat) for specific abiotic physical variables (e.g. water depth, velocity, substrate size, percent cover, temperature, etc.). Van der Lee *et al.* (2006) used a Monte Carlo analysis to explore the impact of uncertainty in HSC model inputs on a model

[9]See section 2.2.1, Page 2.2.1 for description of equifinality (i.e. the same result for different reasons).

of lake habitat suitability for fennel pondweed (*Potamogeton pectinatus*). The input HSCs were water depth, water transparency, wind fetch and orthophosphate concentration, which were all combined to define an overall Habitat Suitability Index.[10] Figure 2.7 highlights the net outputs of an ensemble of 2000 simulations. While Van der Lee *et al.* (2006) found that there were substantial uncertainties in the use of HSCs to drive habitat suitability models, they still concluded that their use as tools in EM may still be acceptable. They suggested that uncertainty analyses should become 'standard procedure' in EM projects, but cautioned that the use of Monte Carlo analysis was very computationally demanding and labour-intensive.

As computational power has increased, so to has the application of Monte Carlo methods to environmental modelling problems (Binley *et al.* 1991, Hankin *et al.* 2001, Osidele *et al.* 2003, Wechsler & Kroll 2006, Wu & Tsang 2004, Beechie *et al.* 2006, Cox *et al.* 2004, e.g.). However, Stuart (2007) cautions that sophisticated Monte Carlo techniques (e.g. GLUE) are pragmatic calibration techniques for environmental models, but that they only address the symptom of parametric uncertainty without really considering the root cause of structural uncertainty in the model formulation and how tenuous the response functions are themselves.

2.3.3.4 Fuzzy Models

Fuzzy set theory is the foundation for a wide range of related topics: fuzzy arithmetic, fuzzy relationships, fuzzy logic, possibility theory, which are used in fuzzy models (Bandemer & Gottwald 1995). In Klir & Yuan (1995) an attempt was made to compile a bibliography of all relevant books and articles relating to fuzzy set theory and its applications as of 1995 (organized by disciplines). Of the over 1700 references predating 1995, only three were for ecological applications, four for environmental applications and seven for earthquake studies; whereas sixty-one references addressed uncertainty measures specifically.

When research for this thesis originally commenced, several article searches under ISI Web of Science[11] were performed to see if more recent contributions might have since bridged this apparent gap (Table 2.5). Although these searches were by no means exhaustive and the results were not exhaustively compared; they highlighted a rich body of literature and well developed multidisciplinary theory to deal specifically with uncertainty dating back to the 1960s. Although fuzzy applications in GIS and environmental sciences were starting to grow, they seemed to be under utilized in river restoration as of January 2004. At that time, Wheaton *et al.* (2008) postulated that fuzzy methods were under-utilised in river restoration science, and there was tremendous scope for their application. The same searches were repeated in June 2007 and have subsequently revealed a substantial increase in the number of publications in environmental science and management using fuzzy methods (compare column 2 and 3 in Table 2.5). With the search terms 'fuzzy and rivers' and 'fuzzy and watersheds', there were 485% and 370% increases respectively in the total number of articles in just a 3 year period!

[10] The minimum of the input HSCs was used to define the overall habitat suitability index, hence highlighting the areas where habitat was limiting.

[11] Web of science can be accessed at `http://wok.mimas.ac.uk/`.

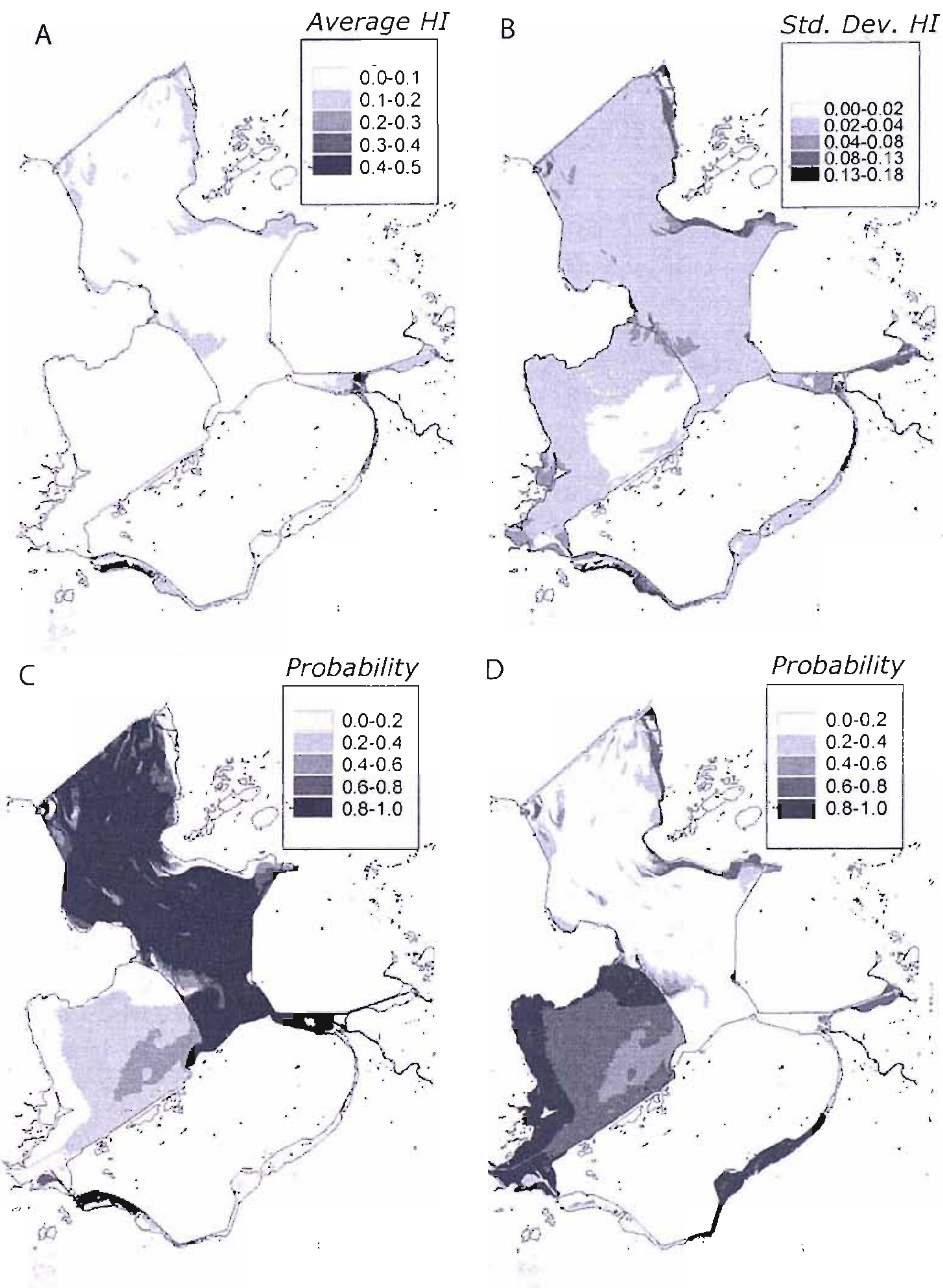


FIGURE 2.7: Summary outputs of lake habitat suitability model for fennel pondweed (*Potamogeton pectinatus*) from a Monte Carlo ensemble of 2000 simulations. a) Average habitat suitability (on a scale from poorest at 0 to highest at 1) per grid cell. b) Standard deviation of habitat suitability with model and input uncertainty. c) The probability (0-1) that water depth is limiting factor of habitat suitability. d) The probability (0-1) that orthophosphate concentration is limiting factor of habitat suitability. Figure adapted from Van der Lee *et al.* (2006, Figures 3 & 4).

Search Terms	Jan. 2004	Jun. 2007	Comments
'fuzzy AND environmental management'	15	19	Only 4 for river basin management
'fuzzy AND geomorphology'	8	9	Only one fluvial geomorphology
'fuzzy AND rivers'	7	34	All in Decision Support, GIS and Remote Sensing in 2004
'fuzzy AND watershed'	20	74	Primarily GIS and Remote Sensing in 2004; expanding into hydrological modelling and other areas
'fuzzy AND fish'	45	82	Only 12 of 82 were related specifically to salmon
'fuzzy AND river management'	3	6	Including Clayton (2002) and Clark & Richards (2002) referenced elsewhere in this chapter.
'fuzzy AND river restoration'	0	2	In 2004, search failed to produce the only two papers known of on fuzzy applications to river restoration: (Johnson & Heil 1996, Schneider & Jorde 2003).
'fuzzy AND engineering'	702	979	Includes civil, environmental, mechanical and electrical engineering
'fuzzy'	22,607	33,658	NA

TABLE 2.5: Number of matches of some selected ISI Web of Science Searches for 'Fuzzy' peer reviewed literature in applications related to river restoration and comparison with fuzzy applications in engineering and articles in general.

A promising example of fuzzy modeling in river restoration has emerged in an ecohydraulic habitat suitability model similar to PHABSIM, which was developed using fuzzy logic as an alternative or augmentation to traditional habitat suitability curves (Schneider & Jorde 2003). The simulation model, CASiMiR (Computer Aided Simulation Model for Instream Flow Requirements), can run as a sub-model inside existing 1D, 2D or 3D hydrodynamic models and adds a flow regime module, river bed module and aquatic zone module. CASiMiR allows the user to incorporate 'expert knowledge' to evaluate habitat quality numerically, which Schneider & Jorde (2003) asserted is more readily available than habitat suitability curves and much more flexible in implementation. Schneider & Jorde (2003) report that fuzzy-rule based models generally perform better than traditional habitat suitability curve-based models in comparison studies. The model has been applied successfully to assess river restoration, determine instream flow requirements, and habitat suitability requirements for numerous fish and macroinvertebrate species (Clayton 2002, Kerle *et al.* 2002, Schneider & Jorde 2003, Mouton *et al.* 2007).

In an interesting review of the uncertainties that forest managers are faced with, Petterman & Peters (1998) tip toed around the numerous shortcomings of traditional statistical, probabilistic, Bayesian and classical decision-analysis techniques, while still advocating their use. Petterman & Peters (1998) made the reasonable argument that in the apparent absence of any other tools, such tools for coping with uncertainty have utility to managers if their limitations are well understood. It is important to highlight with caveats the relevance of all tools for dealing with specific types of uncertainties under specific assumptions. However, among statisticians there seems a pervading assumption that probabilistic and statistical techniques are the *only* way to represent uncertainty (e.g. Balakrishnan et al. 2003). There seems to be at least equal, if not more extensive, promise in applying a host of fuzzy applications to environmental management problems such as river restoration. In the same volume (Sit & Taylor 1998), Routledge (1998) astutely highlighted some of the difficulties in producing quantitative measures of imprecise concepts (e.g. biodiversity), yet focuses again on the traditional statistical and probabilistic techniques to do so.

Putting imprecise and complex concepts in numerical form is exactly what fuzzy techniques are intended to do (Bandemer & Gottwald 1995, Openshaw 1996, Klir & Yuan 1995, Zadeh 1996). Zadeh (1996) suggested that the advantage of fuzzy logic over other methodologies (e.g. 'predicate logic, possibility theory, neural network theory, Bayesian networks and classic control') is that fuzzy logic is simply 'computing with words.' Fuzzy logic offers in both scientific and management contexts a way to convert expert opinions into linguistic variables and expressions, which may later be 'defuzzified' to crisp numbers.

While trying to argue that human geographers should embrace the fuzzy science paradigm in order to bring credibility (equated with quantitative analysis) to their science, Openshaw (1996) summarised four advantages of fuzzy techniques from Klir & Yuan (1995):

1. 'It provides a means of expressing irreducible observation and measurement uncertainties in whatever form they appear.'

2. 'It offers far greater resources for managing complexity; indeed, the greater the complexity the greater the superiority of fuzzy methods.
3. 'It offers considerably greater expressive power, allowing it to deal effectively with a broad class of problems; in particular it has the capability of dealing in mathematical terms with problems that require the use of natural language.
4. 'The new paradigm has a greater capability of capturing human common sense reasoning and other aspects of human cognition and intuition so that they can be included rather than excluded from computer systems.

This is not to suggest that fuzzy techniques are the ultimate, unique solution to all the world's management problems. Instead, they seem to show promise that is only starting to be explored in PHR and/or monitoring geomorphological changes.

2.4 Uncertainty about Change

From the preceding review of scientific research tools (§ 2.3) for dealing with uncertainty, it is clear there are a wealth of potential methods that can be used to better understand uncertainty about geomorphological change and its influence on fish habitat. There is also tremendous scope for the improvement of existing tools, employment of existing tools in new and novel applications and the development of additional tools altogether. How uncertainty about change is treated is as much a philosophical issue as it is a technical one. The perspective[12] from which one is considering uncertainty about change will strongly influence how one addresses this problem.

The degree of uncertainty varies across the different knowledge bases central to implementation of PHR (Figure 2.8). The varying degree of uncertainty is partly related to the relative degree of uncertainty due to natural variability in each knowledge base, but is also strongly influenced by the relative complexity of physical, versus ecological, versus social systems (Van Asselt & Rotmans 2002). It could be argued that because of their relative magnitude, socio-political uncertainties trump all the other uncertainties (Teng & Belfrage 2004, e.g.). In river restoration projects, socio-political uncertainties manifest themselves largely as communication and expectation uncertainties from restoration motives and objectives. However, it is postulated that uncertainties in the geomorphology and ecology knowledge bases[13] will propagate into the socio-political uncertainties and act to exacerbate them further. At this juncture, it is worth revisiting the basic aim and objectives of this thesis (§ 1.3).

Recall that the motivation for this thesis grows out of the very applied context of PHR, for salmonids. However, the aim makes no specific reference to PHR as the question of

[12]For example, as a practitioner designing restoration projects; a manager in a river basin management context; or as a researcher in an applied research context.

[13]The geomorphology and ecology knowledge bases are the areas that this thesis specifically tries to build upon.

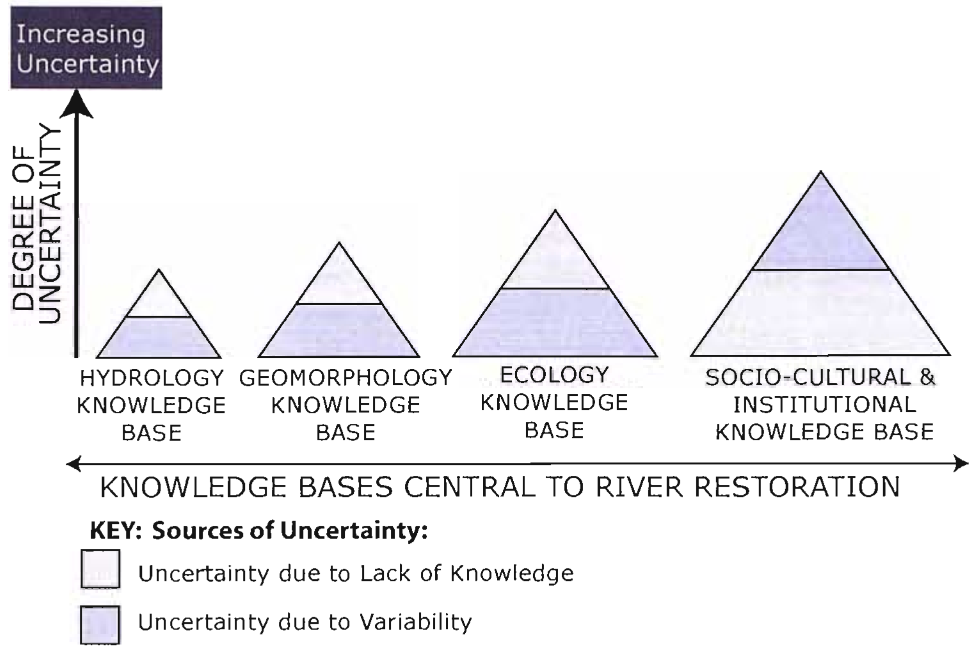


FIGURE 2.8: Relative degree and type of uncertainties in the primary knowledge bases central to physical habitat restoration for salmonids. The idea for this figure was adapted from Van Asselt & Rotmans (2002, Figure 6).

significance of uncertainty about change has a fundamental relevance beyond just this specific issue. On the surface, objectives one (§ 1.3.1) and two (§ 1.3.2) are simply about expanding the knowledge base of geomorphology. Insofar as the specific methodological tools that fall out of delivering these objectives might be used by PHR practitioners, the thesis might provide specific techniques for communicating uncertainties in a meaningful way to decision makers and stakeholders; hence addressing the potentially larger uncertainties inherent in the socio-political and institutional knowledge bases. However, for PHR, it is emphasised that a few tools for specific uncertainty problems still pale in importance to the basic philosophical treatment of uncertainty that decision makers and societies choose to adopt. Closely related to the philosophical treatment of uncertainty is the nature of response to change. This response at one extreme might be characterised as a catastrophic decline and at another extreme it may be seen as adaptive resilience (Janssen *et al.* 2007, Vincent 2007, Berkes 2007). The philosophical treatment of uncertainty is not the focus of this thesis[14], but it is the focus of the next section.

Before that digression, the primary sources of uncertainty about change from a geomorphological perspective are briefly reviewed. Uncertainty about changes through time at a particular location in space are fundamentally either about postdiction,[15] prediction,[16] observing process[17] or some combination. Schumm (1991) argued that there are ten problems encountered

[14]Indeed, the philosophical treatment of uncertainty is dealt with more thoroughly by others (Priddy 1999, Pollack 2003, Popper 1968, e.g.).
[15]Explaining how things came to be the way they are.
[16]Explaining how things will come to be in the future
[17]Explaining how forces and phenomena acting in the present are changing the landscape.

Problem	Schumm's Description
1. Time	'involving both absolute duration and relative time spans'
2. Space	'involving scale and size'
3. Location	'the site of concern within a natural system'
4. Convergence	(a.k.a. equifinality), 'the production of similar results from different processes and causes'
5. Divergence	'the production of different results from similar processes and causes'
6. Efficiency	'the variable efficiency and work accomplished by a process'
7. Multiplicity	'the multiple explanations that combine to influence and cause natural phenomena'
8. Singularity	'the natural variability among like things'
9. Sensitivity	'the susceptibility of a system to change'
10. Complexity	'the complex behavior of a system that has been subject to altered conditions'

TABLE 2.6: Schumm's 10 Ways to be Wrong. Compiled with reference to Schumm (1991). See Schumm (1991) for full description of each.

when trying to extrapolate past changes to the earth from observations of modern conditions (Table 2.6). Convergence, divergence and sensitivity were all mentioned earlier (page 2.2.1) as generic concepts closely related to uncertainty. Methods to quantify geomorphological changes directly are fundamentally limited by *unreliability uncertainties*[18] associated with field observations (Kirkby 1996). Numerical models that attempt to predict geomorphological changes are even more uncertain owing in part to the *inherent natural variability* of such physical processes as well as both *structural* and *unreliability uncertainties* in our models (Coulthard 1999, Cardwell & Ellis 1996, Zak & Beven 1999). Thus, anticipating what geomorphological changes to expect in the context of PHR is strongly contingent on both *uncertainties due to variability* and *limited knowledge.*

2.5 Philosophical Treatments of Uncertainty

So is all this uncertainty bad? By this point, it should be clear that uncertainty in PHR is a ubiquitous fact of life (Graf *et al.* 2008). However, whether this is good, bad or otherwise and what should be done about it have not yet been considered. Different segments of society view uncertainty in very different ways, depending on the context (Lemons & Victor 2008). As already mentioned, humans are quite comfortable with the uncertainties of life in an intuitive and non-explicit sense (Pollack 2003, Anderson *et al.* 2003). However, uncertainty in policy and science, especially as reported in the media (Riebeek 2002), are very different contexts to daily life. Referring back to the synonyms of uncertainty and uncertain in Table 2.1, one

[18]Namely, *inexactness, lack of observations and practically immeasurable* types of uncertainties (Star 2 in Figure 2.11).

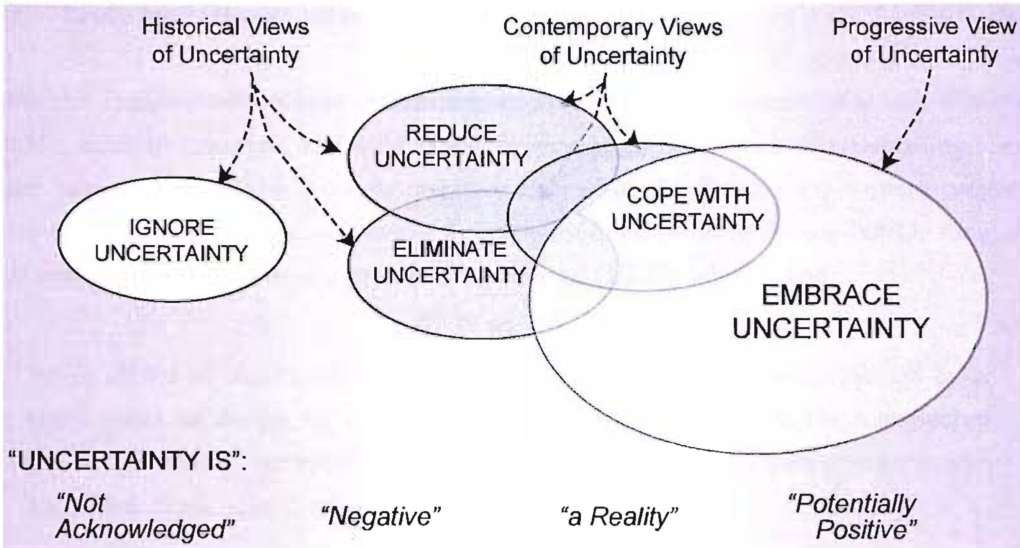


FIGURE 2.9: Five Philosophical Attitudes Toward Uncertainty. The Venn diagram is meant to illustrate the overlap between contemporary attitudes toward uncertainty. Note that ignoring uncertainty shares no overlap with contemporary attitudes toward uncertainty.

would logically conclude that uncertainty is bad. With the notable exception of 'surprise' the rest of the synonyms have a generally negative connotation. Interestingly, of the terms related to uncertainty: accuracy, confidence, exactness, expectation, precision, reliability and repeatability, all carry generally positive connotations; whereas divergence, error, equifinality, risk, sensitivity and variability may be perceived as negative. The choice of what to do about the uncertainty is a philosophical question. Five potential philosophical treatments of uncertainty are proposed in Figure 2.9.

1. Ignore uncertainty
2. Eliminate uncertainty
3. Reduce Uncertainty
4. Cope with Uncertainty
5. Embrace Uncertainty

Each of these philosophies were reviewed in detail in Wheaton *et al.* (2008) and linked to current attitudes within different segments of the PHR community. Wheaton *et al.* (2008) argued that embracing uncertainty was the most productive and realistic way forward and that philosophical treatment is reviewed here.

2.5.1 Embrace Uncertainty

Despite the apparent advantages of efforts to cope with or reduce uncertainty over eliminating it, all the other philosophies still fundamentally view uncertainty as a negative thing. Several authors have departed from a purely negative view of uncertainty toward a more progressive view of embracing uncertainty (Newson & Clark 2008, Johnson & Brown 2001). One of the earlier proponents of this view appears to be Holling (1978), who argued:

> 'while efforts to reduce uncertainty are admirable...... if not accompanied by an equal effort to design for uncertainty and obtain benefits from the unexpected, the best of predictive models will only lead to larger problems arising more quickly and more often' -(in: Levy et al., 2000).

Klir & Yuan (1995) considered uncertainty in modeling as 'an important commodity..., which can be traded for gains in the other essential characteristics of models.' Other authors have suggested that a recognition that not all uncertainty is bad will be increasingly important to decision-makers who are forced to make decisions in the face of uncertainty (Clark & Richards 2002, Pollack 2003). Especially in long-term policy analysis (next 20-100 years)[19], decision makers are faced with what Lempert *et al.* (2003) referred to as 'deep uncertainty'. Johnson & Brown (2001) argued that explicitly incorporating uncertainty into restoration design and the decision-making process allows the practitioner to consider multiple causes and hypothesized fixes; thereby reducing the potential for project failure and ultimately reducing costs. Throughout this chapter it has been argued that uncertainty is not necessarily a bad thing, but ignorance of it can foster unrealistic expectations. Chapman & Ward (2002) argued that uncertainty can be viewed not just as a risk, but also as an opportunity. Uncertainty due to natural variability, in say flow regime, can be a particularly good thing, for example by promoting habitat heterogeneity and biodiversity (Montgomery & Bolton 2003, Clifford *et al.* 2008).

In Figure 2.10, the notions of embracing uncertainty in the context of the Van Asselt (2000) typology are synthesised. This approach embraces uncertainty as information and its potential for helping avoid risks, or embracing unforeseen opportunities. Notice that all uncertainties are not treated uniformly but instead are segregated by their source (i.e. due to limited knowledge or due to variability) and type. Anderson *et al.* (2003) astutely pointed out that environmental management problems are so diverse that a single approach is unlikely to be appropriate for all. Thus, Chamberlin's (1890) idea of multiple working-hypotheses is emerging in environmental management through advocating pluralistic approaches (e.g. Lempert et al. 2003; Van Asselt and Rotmans 1996). The embracing uncertainty framework proposed here embraces that very point by simply structuring a range of questions and possible management decisions based on the specific uncertainties at hand. In the spirit of 'sustainable uncertainty' as proposed by

[19]Which are precisely the time scales that the restoration literature has been suggesting the restoration community needs to move toward (see § ??).

Newson & Clark (2008), this is not at all a rigid framework, but instead a loose and adaptive guide built around an uncertainty typology. Unlike the four other philosophical treatments of uncertainty, this allows the restoration scientist, practitioner or decision-maker to:

- explore the potential significance (both in terms of unforeseen consequences and welcome surprises) or insignificance of uncertainties.
- effectively communicate uncertainties
- eventually make adaptive, but transparent, decisions in the face of uncertainty

2.6 Conclusion

In this chapter a very broad picture of uncertainty has been painted. A typology for discriminating uncertainty was reviewed (§ 2.2.2) that allows one to separate uncertainties that can lead to unforeseen and undesirable consequences from uncertainties that lead to potentially welcome surprises (e.g. a shifting habitat mosaic). The significance of reliability and interpretation of uncertainties in this thesis is largely situation-specific and, to date, unexplored.

This review was intended to help unravel the ambiguities around uncertainties about monitoring geomorphological change and recast them as useful pieces of information. More importantly, the typology and embracing uncertainty framework provide a context to articulate what type of uncertainty is addressed in this thesis and how it is approached philosophically. Traditional scientific research typically has focused on a narrow class of uncertainties and adopted the *eliminate* and *reduce* uncertainty philosophies. Out of the decision-making arena has emerged the pragmatic view of *coping with uncertainty*. However, it was concluded that *embracing uncertainty* could also help transcend the scientific research and decision making boundaries in river restoration. In this thesis, the embracing uncertainty framework may be used as a philosophical approach to the basic problem of uncertainty from morphological sediment budgeting in rivers.

The specific types of uncertainties that this thesis will address are highlighted with stars in the 'embracing uncertainty' framework of Figure 2.11. Returning to the thesis aim and objectives in § 1.3, a *reliability* problem and a *meaningfulness* problem were identified with respect to morphological sediment budgeting. The premise is that one of the primary sources of these two types of uncertainties is limited knowledge due to *reducible ignorance* (Star 4 in Figure 2.11). That is, a more complete understanding and articulation of these uncertainties through research, should transform the uncertainty resulting from ignorance to a useful statement of the magnitude of unreliabilities inherent in data or analyses (Star 2 in Figure 2.11). Of central importance to both the *reliability* and the *meaningfulness* problem are uncertainties due to natural variability (Star 1 in Figure 2.11). Specifically, spatial variability in surface representation uncertainty and spatial coherence in erosion and deposition patterns could be

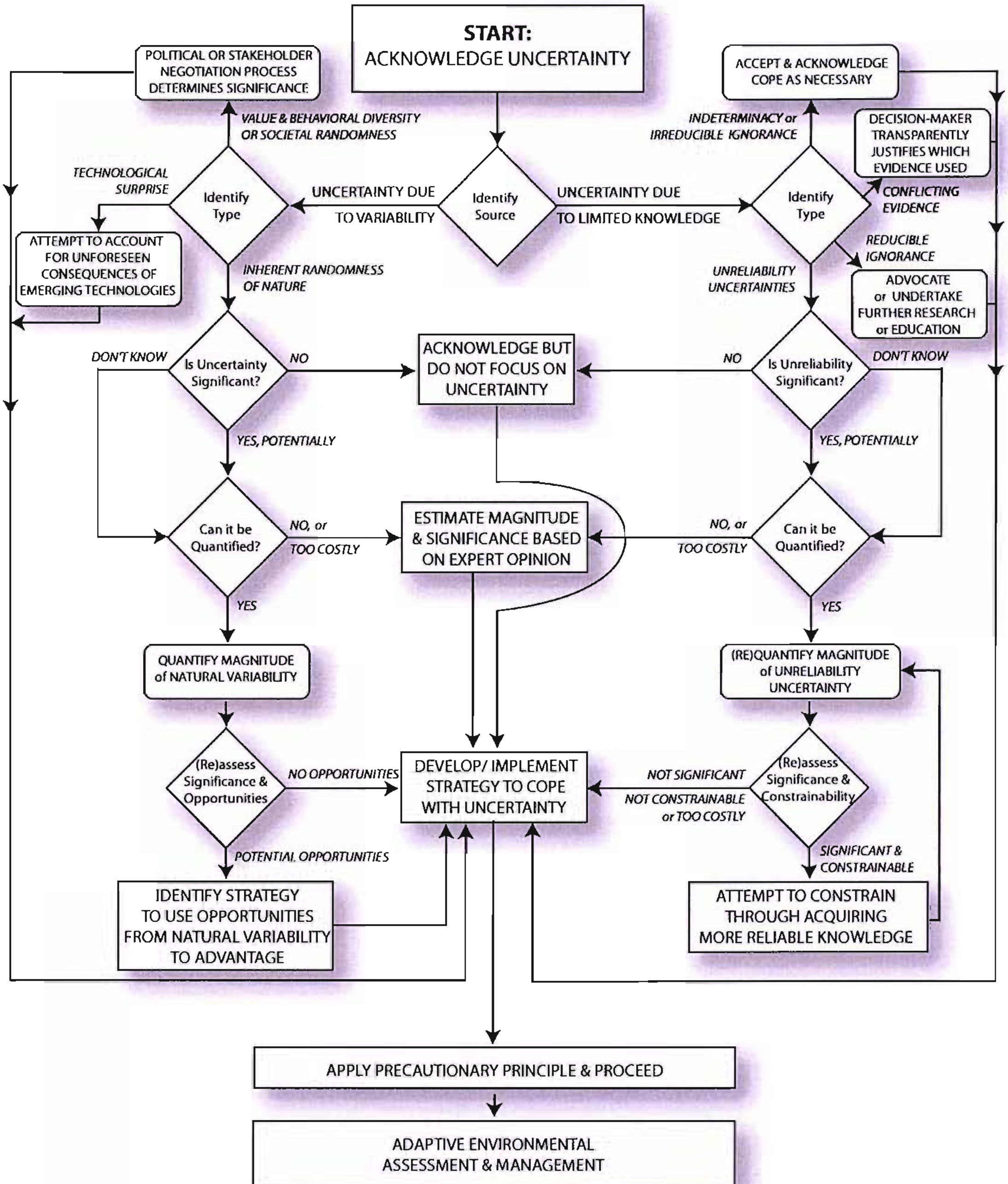


FIGURE 2.10: Embrace Uncertainty Strategy. Framework for embracing uncertainty in decision making process. This framework relies on the Van Asselt (2000) typology of uncertainty.

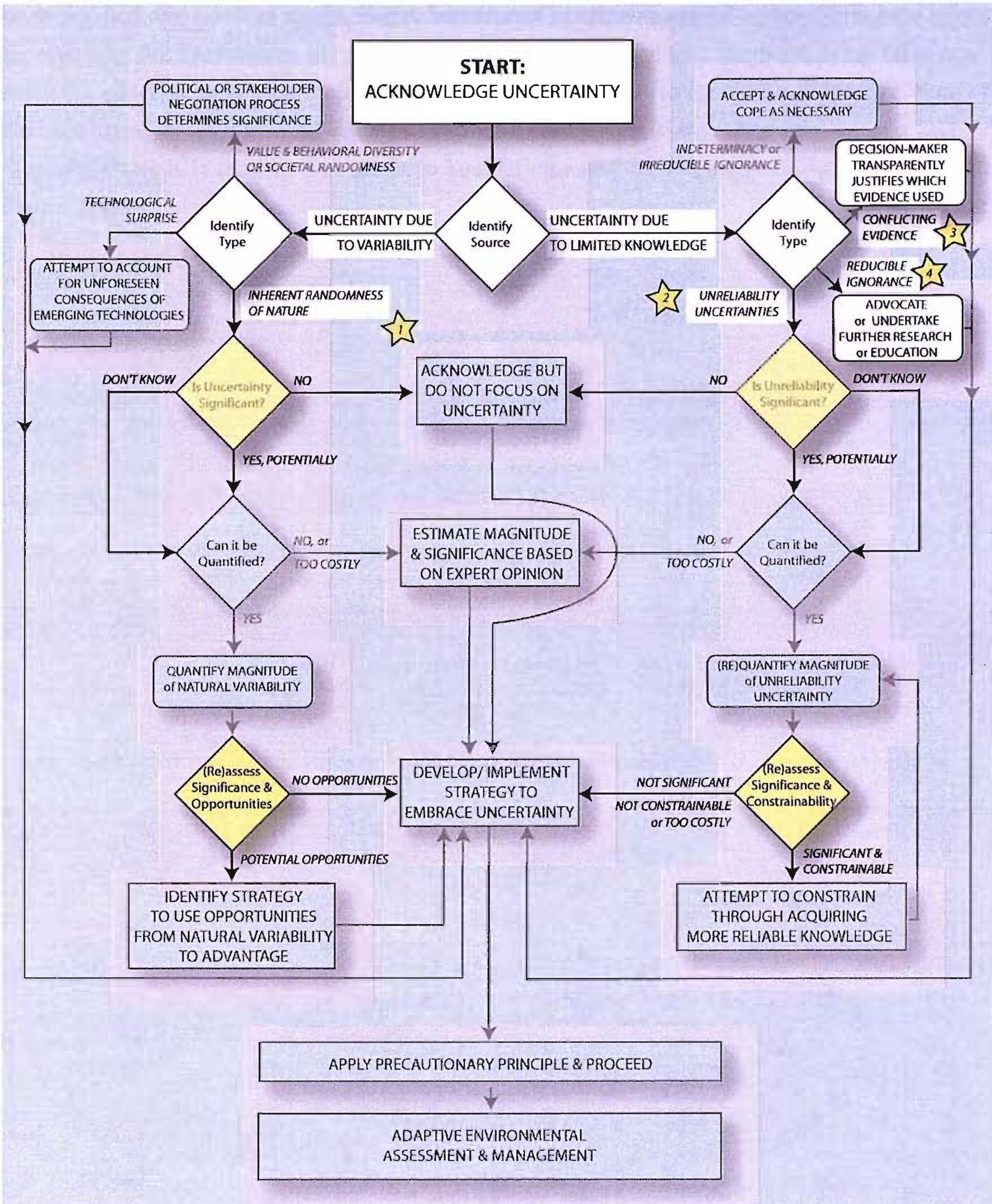


FIGURE 2.11: Aim and Uncertainties Addressed in this Thesis. The aim of assessing the significance of uncertainty is highlighted in yellow within the 'embracing uncertainty' framework. The types of uncertainties addressed are labeled with numbered stars one through four, and referenced in the text. The rest of the framework is grayed out (see Figure 2.10).

better characterised and used to better constrain geomorphological change calculations and interpretations. Additionally, any techniques used to monitor geomorphological changes or predict geomorphological changes are prone to *unreliability uncertainties*, many of which can be quantified and some of which might be reduced or constrained. The emphasis here is not on reducing the uncertainty in topographic surveying, but instead on quantifying its magnitude in a way that enables a more informed judgment on the quality of calculated and inferred changes from inter-comparing surveys. Without considering these uncertainties, the quality of interpretations is suspect and prone to conflicting evidence and suggestions (e.g. Star 3 in Figure 2.11).

Chapter 3

Thesis Rationale and Scope

3.1 Chapter Purpose

From the preceding uncertainty review, it is clear that no shortage of research opportunities exists. Chapter 1 already established that the specific research opportunities to be exploited in this thesis are concerned with uncertainties surrounding morphological sediment budgeting. This chapter focuses on elucidating the scientific rationale and scope of this work[1] in relation to the focus of this thesis. Specifically, this chapter's purpose is to provide a scientific rationale for each objective, identifying:

- What is already known and where are the knowledge gaps?
- How this thesis will extend the body of existing work, thereby establishing its original contributions.

Secondarily, this chapter seeks to articulate more clearly the links between geomorphological changes and physical habitat for salmon and explain how this lends itself to a focus at particular spatial scales. The latter of these secondary chapter aims will be the starting point. The two objectives will then be worked through to develop the justifications defined above. Finally, the selection of study sites will be discussed. Upon conclusion, the reader should have a clear understanding as to why Parts II and III unfold the way they do.

3.2 Introduction - An Appropriate Scale

No theme unites geomorphologists in their quest to better understand the Earth quite like scale (Schumm & Lichty 1965). The selection of *appropriate* space and time (spatiotemporal) scale(s) is fundamental to all geomorphological inquiry. Church (1996, p. 153) pointed out

[1]Recall that Chapter 1 provided a practical and societal justification in terms of PHR for salmonids.

that 'it is perfectly reasonable for more than one spatiotemporally delimited paradigm to be pursued within a science at any given time.' Thus, the section sub-heading (*an appropriate scale?*) may be misleading insofar as it could suggest a single spatio-temporal scale of inquiry is *most* appropriate. Different spatio-temporal scales of inquiry are going to yield different types of insight into particular questions as well as present their own limitations (Levin 1992). When considering scale, both the extent and resolution need to be identified. In the context of space, extent refers to the total volume, area or length under consideration; whereas in temporal terms extent is synonymous with total duration of analysis. In spatial terms, resolution refers to the length scale of the smallest resolved unit within a measured area (e.g. the grid cell size in a raster image or dataset). With respect to time, resolution refers to frequency at which something is observed, recorded or calculated over the entire duration under consideration. In this section the spatiotemporal scales used in this thesis are explained and justified.

3.2.1 Spatial Scale

The primary spatial scales examined within this thesis span the hydraulic unit (patch) to the reach scale (Figure 3.1).[2] These scales are inherited partly by the morphological method itself, which involves topographic surveying over reach scale extents but resolves habitat features at the hydraulic unit and geomorphic unit scale. However other justifications include the scale of PHR, and the scale at which individual salmonids experience and utilize habitat. Each of these are discussed briefly in the following paragraphs.

The morphological method is usually applied at reach scales. It can be deployed using one dimensional (e.g. cross-section and long profiles) or two dimensional (e.g. topographic survey) perspectives (Fuller *et al.* 2003, Leclerc *et al.* 1995). Previously, the cost (in survey and computational time) of two-dimensional methods was often deemed too expensive to warrant its application, even though the resulting spatially distributed results yielded much more useful information (Wheaton *et al.* 2004c). With recent improvements in computational power and surveying technology,[3] the relative cost of higher-dimensional methods has become practically affordable in research and many applied settings. As such, the focus in this thesis is on two-dimensional morphological methods applied over the reach scale (10^2 to 10^4 m), and resolved at the hydraulic unit scale (10^{-1} to 10^0 m).

The spatial scale at which restoration is carried out is predominantly the reach scale (Wheaton *et al.* 2006, Bernhardt *et al.* 2005). Even if PHR projects are placed in a catchment-scale context, their implementation will still largely be at reach scales and subsequent long-term

[2]Throughout this thesis, the River Styles Framework will be used for descriptions of spatial scales, such as hydraulic units (Brierley & Fryirs 2005, Thomson *et al.* 2001). The framework is based on a nested hierarchy of geoecological associations. The scales in order are ecoregion (largest), catchment, landscape unit, reach, geomorphic unit, hydraulic unit, and microhabitat (smallest; e.g. patch). Each spatial unit is comprised of an assemblage of the units from the next smaller scale (e.g. a reach may comprise bar, riffle and pool geomorphic units). Moreover, the classification system has been shown to be ecologically meaningful, with different assemblages of macroinvertbrate communities selecting for specific microhabitat and hydraulic unit assemblages (Thomson *et al.* 2003).

[3]See § 3.3.1 for explanation of improvements in surveying technology.

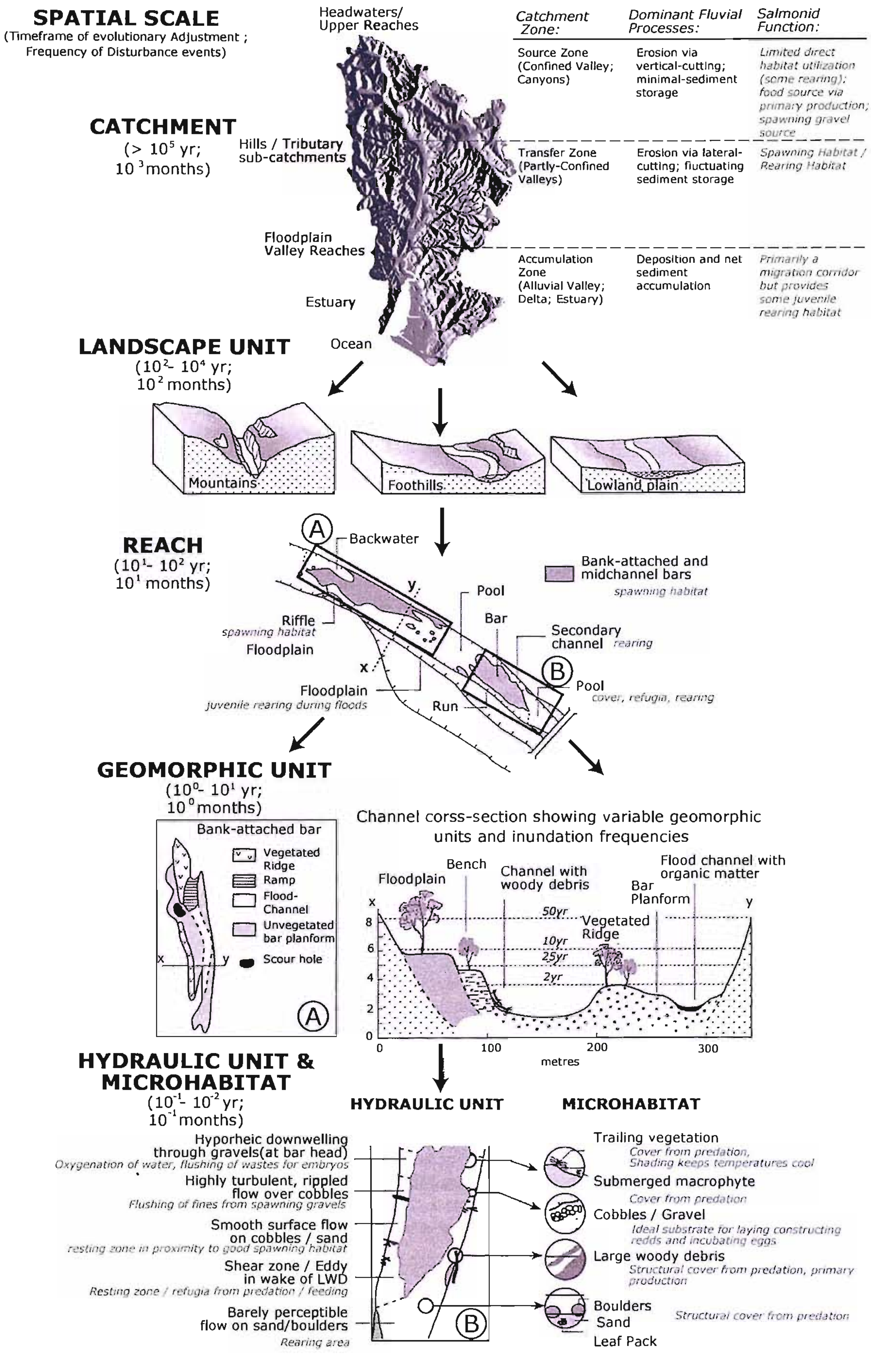


FIGURE 3.1: Example of a catchment-framed nested hierarchy of spatial scales and associated salmonid functions. Figure adapted from Brierley & Fryirs (2005).

monitoring will likely also be primarily conducted at this scale. Repeat topographic, habitat, and habitat utilization surveys are likely to form part of post project appraisals and monitoring for PHR (Downs & Kondolf 2002). It follows that the morphological method will be one of the more prominent methods for analysing this monitoring data and assessing project performance (Pasternack *et al.* 2004, Wheaton *et al.* 2004*c*). Thus, PHR and its monitoring act to provide a pragmatic justification for focusing on reach scales in this research. Moreover, the restoration science community is likely to play a key role in implementing these monitoring programmes (Wohl *et al.* 2005, Palmer & Bernhardt 2006, Newson & Large 2006).

The spatial scale at which a salmon (Atlantic or Pacific) experiences its habitat is minimally defined (resolution) by the size (fork length) of the fish itself and maximally defined by its range (extent). Thus, when studying salmon, the spatial scale most appropriate for studying salmon varies with lifestage.[4] Before aelvins emerge out of their natal gravel substrate, they measure only about 1.5 to 2.5 cm in length and tend not to venture any further than the extent of the interstitial pore space within the egg pocket of the redd their mother constructed. Upon emerging as fry, fork lengths vary from roughly 3 to 7 cm but their spatial range expands dramatically (up to the length-scale of the accessible river) as generally they make their way downstream feeding as frequently as permissible and trying to avoid predation. Through their juvenile development (parr), eventually they can reach fork-lengths of up to 12 to 20 cm before entering the oceans as smolts. Once in the ocean, their range grows dramatically by several orders of magnitude (Figure 3.2). By the time salmonids make their journey back to freshwater as adults they are typically 30-80 cm in length, with some well over 100 cm. Depending on the size and physiographic setting of the river system, adult salmon may travel anywhere from 5 kilometers to 500 kilometers (e.g. Columbia River) upstream to reach their natal spawning grounds.

From a riverine physical habitat perspective, only the embryonic and adult spawning life-stages will be considered in this thesis. As most ecohydraulic models are driven by computational fluid dynamics (CFD) hydraulic flow models that do not account for hyporheic exchange, ecohydraulic modelling is usually restricted to rearing and adult life-stages.[5] The resolution at which salmon experience their habitat during spawning lifestages is on the order of 10^0 cm to 10^2 cm (i.e. microhabitat to hydraulic unit in Figure 3.1) and their range tends to be within the reach scale that they are migrating through.[6] During spawning, the female will construct a redd that is between 1 and 17 square meters in size (Figure 3.3), but she may inhabit multiple adjacent geomorphic units (e.g. a pool and a riffle) while guarding her nest (McPhee & Quinn 1998, Moore *et al.* 2004). Egg pockets are typically found at depths from 8 to 43 cm beneath the original bed elevation (McPhee & Quinn 1998). Thus, during spawning

[4] Lengths also vary between species (e.g. *Salmo salar* - Atlantic versus *Oncorhynchus tschawytscha* - Chinook). The approximate sizes listed here are generalisations for Atlantic salmon primarily from Swansburg *et al.* (2002) and Jonsson (1991), but the relative proportions for habitat purposes are similar for most salmonid species.

[5] See Greig *et al.* (2007) for promising recent developments with respect to modelling and monitoring processes responsible for embryonic survival of salmonids and Fleckenstein *et al.* (2006) for modelling groundwater-surfacewater interactions in the context of maintaining minimum flows necessary for migration.

[6] This is justified in the previous paragraph, based on typical ranges for fish sizes across various salmonid species.

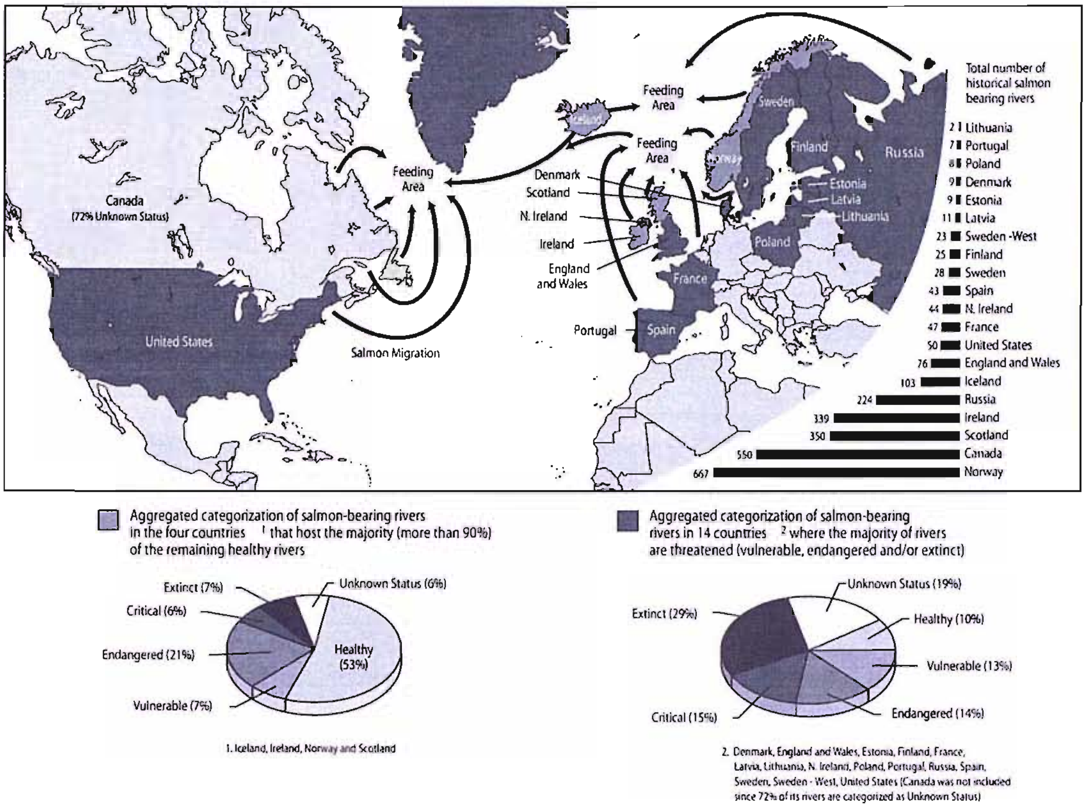


FIGURE 3.2: Map depicting the range of wild Atlantic Salmon (*Salmo salar*) as of 2000 from WWF (2001) study. Their known oceanic migration patterns are depicted by the arrows, and the status of their runs are aggregated by country. Figure reproduced from WWF (2001).

females are capable of altering local bed morphology and hydraulics and thus creating their own hydraulic units (Gottesfeld *et al.* 2004, Merz *et al.* 2006).

The critical factors during juvenile out-migration, and adult upstream migration are barriers or obstacles to migration (e.g. dams, culverts, hydro-electric turbines, natural water-falls) as well as provision of refugia along the migration route.[7] Refugia largely is manifested as habitat heterogeneity elements at the hydraulic unit and microhabitat scales (Figure 3.1). These heterogeneity elements come in a variety of forms including large woody debris, boulder complexes, cobble clusters, irregularly shaped banks and overhanging vegetation. Functionally, the heterogeneity elements provide a) *shear-zones*, which furnish an area of slow moving water in proximity to a zone of fast moving water that are critical for energy conservation (especially when migrating upstream or spawning) and feeding; and b) *structural cover*, which makes available a location to hide from predators as well as as a shading function that acts to keep water temperatures cooler (Sullivan *et al.* 2006, Wheaton *et al.* 2004*e*).

Although the spatial scale at which a salmon experiences and utilizes its habitat is a logical spatial scale to consider, the physical state of that habitat is clearly the product of a complex

[7]Provision of refugia in close proximity to spawning and rearing habitat is known to be a key factor in determining utilization in these lifestages as well (Wheaton *et al.* 2004*e*, Power & Dietrich 2002).

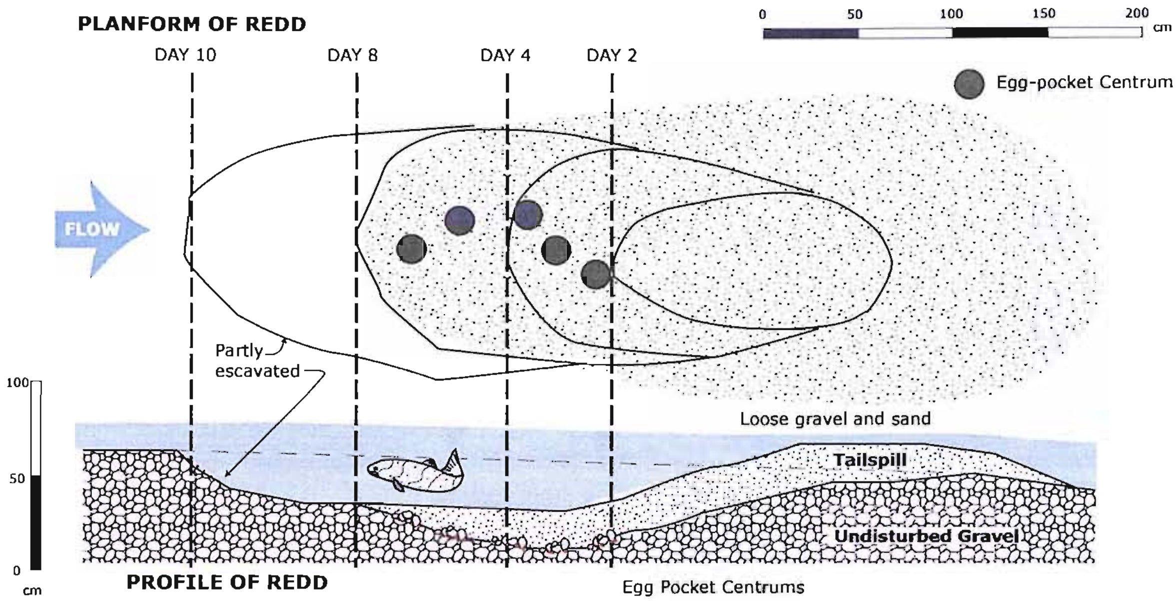


FIGURE 3.3: Schematic of salmonid redd highlighting spatial scale of physical habitat and temporal scale of nest construction. Figure adapted from Chapman (1988).

interaction of physical processes over a hierarchical range of spatial scales (Figure 3.1). For example, in the top half of Figure 3.4 the physical factors thought to influence a female salmon's selection of a site to construct a redd in are defined in relationship to the biological factors. In this thesis, the geomorphological processes that result in a rearrangement, alteration or redistribution of geomorphic unit assemblages that collectively comprise a reach will be inferred on the basis of evidence of change. While these changes are the result both of Newtonian grain-scale mechanics and events occurring at larger landscape, catchment and regional scales (Church 2006), such scales are beyond the scope of this thesis.

3.2.2 Temporal Scale

The temporal scales under consideration should span both the geomorphological processes responsible for changing physical habitat and the life cycle of the salmon potentially using the habitat. In both cases, issues of timing, frequency and duration are explored briefly below and used to demonstrate how the temporal scales considered here were arrived at.

Fluvial change in gravel-bed rivers[8] is limited to relatively infrequent competent flows (Church 2006) that are driven by hydrological events (storms). The timing and magnitude of such events tend to broadly follow seasonal trends, but are generally unpredictable and often treated as stochastic (Pasternack 1999). Fluvial processes occur across a wide range of temporal scales ranging from fractions of a second (e.g. grain entrainment, turbulence) to thousands of years

[8]Focus is restricted to gravel-bed rivers as this is the primary physical habitat utilized for rearing and spawning salmonids (Montgomery *et al.* 1999, Payne & Lapointe 1997).

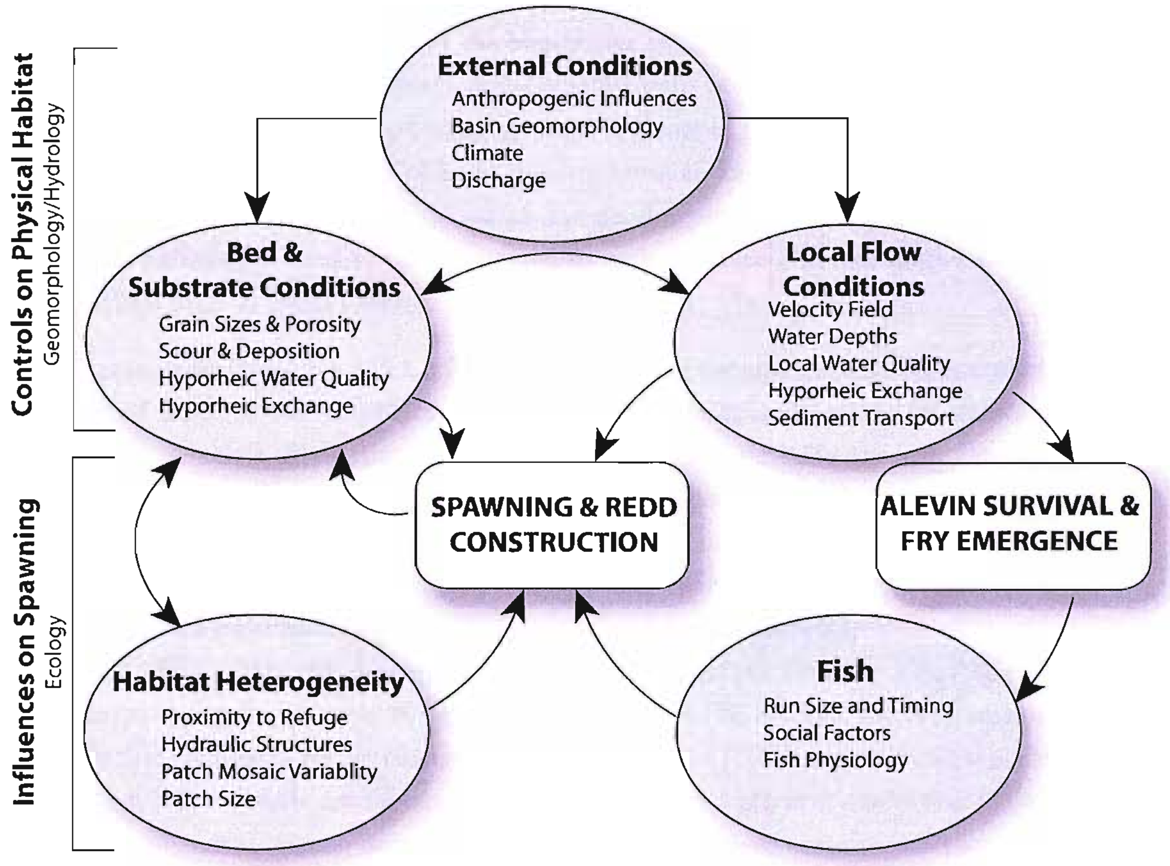


FIGURE 3.4: Conceptual model of factors influencing salmonid spawning site selection. Figure reproduced from Wheaton *et al.* (2004*c*). See also Gilvear *et al.* (2002, Figure 1) for a slightly more comprehensive conceptual model focused just on the abiotic factors (top half).

(e.g. meander belt migration). All processes occur through time and can be described by rates. If a rate happens to be temporally constant and completely time invariant (rare in nature), the time-scale over which it is measured is irrelevant. However, rates that vary through time present a problem in that their approximation is a function of the choice of sampling frequency. In practise, a sampling frequency is usually chosen that is thought to capture the dynamics of interest adequately. For example, to characterise flow turbulence statistics in a natural channel, measuring velocity at circa 25 Hz for circa 200 seconds may be deemed necessary (Carling *et al.* 2002). Nevertheless, any attempt to measure a rate requires an implicit decision about averaging through time. There is a *structural uncertainty* in making this implicit decision, that is separate from the *unreliability uncertainty* in actually making the measurement itself (Herschy 2002). The temporal resolution of measurements should not be so coarse that it averages out dynamics that are essential for understanding the process being measured (Lawler 2005). However, with increased temporal resolution it may be hard to disentangle the essential trend from the time series (not to mention the increased cost).

With respect to the morphological method, the only processes typically quantitatively inferred are gross volumetric estimates of net erosion and net deposition (i.e. storage change), and in rare cases sediment transport fluxes at the boundaries are measured. However, a skilled geomorphologist can look at an assemblage of geomorphic units at two points in time and qualitatively describe the evolution of morphological units in terms of mechanisms like bank erosion, floodplain accretion, progradation of bars, channel avulsion, channel incision, channel filling, confluence pool scour, and various forms of bar development (Ferguson & Werritty 1983, e.g.). Geomorphologists used to be unashamed to make detailed and informative qualitative interpretations such as these (Sherman 1996).

As postulated under Objective 2 (§ 1.3.2), such inferences of net change could be quantitatively teased out of DoDs in the morphological method. However, it is important to reiterate that the inference, whether qualitative or quantitative, can only describe the net change that occurs between two arbitrary observation points in time. For example, what during the first observation appeared to be a channel and at the second observation appears to be a mid channel bar, would be inferred as a net process of mid-channel bar development. However, the bar may have a more complex sedimentological history, for example a series of channel scour and channel filling events that eventually ended in net deposition. Similarly a surface that did not appear to change at all could in fact have been subjected to multiple suites of erosion and deposition that resulted in no net change. Lindsay & Ashmore (2002) explored the implications of different survey intervals on the morphological method for a physical model and found that 'volumetric compensation' can occur if there are 'switches' between erosion or deposition and back again between surveys. Thus in providing a net reporting of change, the morphological method is conservative in recording how much work was actually done. As multiple plausible pathways can explain the final system state, this is an example of equifinality[9], a *structural uncertainty*. There may be other forms of evidence that can be used in conjunction with the morphological method to constrain the range of plausible explanations that converge to produce the current morphology (e.g. flow records, surface age, sedimentological evidence).

From a physical habitat perspective, there are situations in which the equifinality and potential 'compensation' hidden beneath a measurement of net change is unimportant. So long as the change in habitat did not occur when the fish was utilizing it, the only thing that matters is the net result. This is clearly dependent on flow and water quality in addition to just morphology. However, in terms of temporal scale considerations, the question arises *when* and *how* would a salmon be utilizing habitat during a time when the habitat is changing (i.e. competent floods)? It is accepted generally that salmon seek refugia during big floods by taking advantage of shear-zone refugia and or utilizing slower flowing water on inundated floodplains[10] (Lin *et al.* 2006). However, this is primarily inferred from observations of fish returning to the same habitats after a flood as opposed to direct observation (Jeffres *et al.* 2006). Still, as long as habitat heterogeneity elements exist to provide shear zone refugia, the precise nature of the change during the event may be unimportant for rearing juveniles and/or adult salmon. However, salmon embryos live in the bottom of an egg pocket (Figure 3.3) anywhere between 8 and 43

[9]See § 2.2.1.

[10]Though, stranding on the recession of the flood on the floodplain can be a problem for some juveniles (Sommer *et al.* 2001, Sommer *et al.* 2005).

cm beneath the bed of the channel. At the embryonic life-stage salmon are unable to actively seek refugia during a flood by their own accord. Thus they are vulnerable to three types of geomorphological change during their incubation period (2-8 months) in the gravels:

- **Infiltration of fine sediment into the interstitial pore space**- Slows or blocks intragravel (hyporheic) flow, which is essential for providing clean oxygenated water to the redds as well as flushing metabolic wastes from the redds out of the egg pocket (Brunke 1999, Milhous 1998, Vaux 1962, Greig *et al.* 2007)
- **Deposition of sediment over redd** - If deposition consists of a layer of fines, it can form a seal that limits intragravel flow and acts as a barrier to emergence; secondarily, deposition increases the burial depth and therefore the distance through the interstitial pore space that the aelvins will have to travel to emerge (Chapman 1988)
- **Scour of bed to egg-burial depth** - Eggs either damaged from impacts with bedload or entrained into flow where likelihood for deposition into a 'safe' incubation environment is very low (Lapointe *et al.* 2000, Montgomery *et al.* 1996, Lisle & Lewis 1992)

The sampling frequency for morphological analysis (e.g. repeat surveys) was chosen to coincide with the typical types of monitoring that constitute 'long-term'[11] monitoring of fluvial systems. A mix of event-based (before and after) and annual frequencies will hence be employed in the study design. The duration of analyses will be entirely opportunistic, taking advantage of as long of a record up to the present as possible (up to 60 years with historical aerial photos). Superimposed on these seemingly arbitrary sampling regimes is the natural flow and event record of the study site(s). As the study period for various sites ranges from 5 years to decades, it is long enough to exhibit a range of competent floods at the study site(s), and variability between years leading to different signatures of geomorphological change. In summary, the temporal resolution will be a mixture of event-based and annual, whereas the temporal range will vary from an event to half a decade.

3.3 Rationale for Monitoring Geomorphological Change

Objective 1: *Develop a technique for quantifying uncertainty in estimating geomorphological change from repeat topographic surveys*

3.3.1 Background

Asking a geomorphologist to justify why they monitor geomorphological change is like asking a medical doctor why they try to heal patients. It is simply what geomorphologists do. However, the question deserves some more serious attention for an audience that may be

[11] Recalling that 'long-term' in a restoration context means $\geq$3-5 years.

motivated more by the restoration of salmon populations. The crux of the matter was put forth as the primary hypothesis of this work: key attributes of geomorphology and its change through time are relevant to physical habitat for salmonids and their restoration, but uncertainties in their quantification and interpretation have not been adequately accounted. In this section, the scientific rationale for monitoring geomorphological change in rivers from a strictly geomorphological perspective is considered.

3.3.1.1 'We Can'

Although not the most convincing scientific argument, one of the very real pragmatic arguments for why geomorphologists are increasingly monitoring geomorphological change is simply because 'we can'. This is more meaningful when placed in the context that previous methods of monitoring geomorphological change directly (e.g. cross-sections and long profiles) were more laborious and yielded less information; whereas today, there are a wealth of ground-based and remotely-sensed methods for monitoring surface topography (a primary expression of morphology) readily available. The technologies have been developed independently in the surveying industry and research sectors, but the scientific geomorphological community has played in active role in developing and promoting the application of these technologies to address geomorphological problems. As geomorphologists are finally becoming successful in convincing river basin managers and decision makers that geomorphology matters (Sear & Newson 2003, Gilvear 1999, Newson & Large 2006, Newson 2002, Clark *et al.* 1997, Kondolf 2000), there are now two demands the scientific geomorphological community has brought upon itself:

1. Tools: Provision of suitable techniques and methods
2. Robustness: Assessing the uncertainty in applying tools

There is often a lag-time on the order of 5 to 10 years between those techniques that are the standard of practice in scientific research versus industry (Price 1965, Faulkner 1994). This lag appears particularly true with respect to monitoring geomorphological change. Five years ago, a topographic survey was a rare find in consulting reports for restoration projects. Most practitioners argued they were simply too expensive and too time-consuming to use on most projects (p. comm., Pasternack, 2004). Today, this has changed and topographic surveying is becoming the standard of practice and is called for routinely in the design and initial post-project assessment phases, as well as increasingly being specified in those rare projects that happen to have monitoring programmes. The relevance, then, of this objective in a restoration context is extremely timely as practitioners will need both to understand the significance of uncertainty in inferring changes between repeat surveys, but also are in need of a tractable method for quantifying it.

One of the factors that has made repeat topographic survey a more tenable option is the rapid technological advancement of surveying techniques over the past decade and the affordability of such technology on a commercial scale. Today, geomorphologists have a host of survey technologies to choose from using either remotely sensed aerial approaches such as aerial photogrammetry (Lane *et al.* 2003, Gilvear *et al.* 2004, Heritage *et al.* 1998) and LiDAR (Charlton *et al.* 2003, French 2003), or ground-based approaches, such as fully-robotic and auto-tracking total-stations (Fuller *et al.* 2003, Valle & Pasternack 2005), real-time kinematic global positioning systems (rtkGPS) - (Brasington *et al.* 2000) and the rapidly emerging ground-based laser scanning systems (Heritage & Hetherington 2007). Ten years ago, aerial LiDAR was a hot new research tool, five years ago it was still 'cutting-edge' to do research using LiDAR technology (Baltsavias 1999), now it has become so widely available it is standard practice in a research context (e.g. ARSF[12] & NCALM[13]).

Over the past decade on the ground-based survey front, the acquisition time of individual points (easting, northing, elevation), has been slashed using both GPS and total station surveys from something on the order of a maximum of 1 point every 5-10 seconds, down to 1 point every 0.2 - 1 second [14]. Back in the summer of 1992, when Lane *et al.* (1994) were using the latest tacheometric survey technology (i.e. a data-logging total station), they reported a *maximum* acquisition rate of 1 point every 15 seconds using 'rapid tacheometric survey'. Considering the operator on the instrument had to manually adjust the total station and site up on the prism for every point, this is a pretty good pace. Today, the limiting factor is actually how quickly the rod-person can move from one position to the next, as opposed to how quickly points can be acquired, calculated and stored by the instrument. While GPS rovers have always only required a single operator, total stations historically demanded a 2-person survey crew (one person on instrument, one person on the rod). As of about a decade ago, total stations became available in a robotic mode, whereby a single person can fully operate the total station via a radio-linked controller from the rod (relies on auto-tracking technology). What this means, is that topographic surveys can either be run with just a single person, or multiple people can be running simultaneously (e.g. multiple GPS rovers operation at once), both of which increase productivity. Terrestrial laser scanning acquires points at rates three to four orders of magnitude greater than conventional ground based methods (1000-50,000 points/second). The net result of all these advances, is that literally several orders of magnitude more data can be collected in a fraction of the time it used to take (McLean & Church 1999). These advances aside, it is argued there is still a relative lack of appreciation for the quality of the data provided from different sources relative to what it is being used for (Marks & Bates 2000). Furthermore, clarity is required on how to actually make appropriate use of such data (Lane & Chandler 2003), whatever its uncertainties are.

[12] NERC's Airborne Research & Survey Facility (ARSF): `http://arsf.nerc.ac.uk/`

[13] NSF's National Center for Airborne Laser Mapping (NCALM): `http://www.ncalm.ufl.edu/`

[14] In the case of total stations, this is thanks to the advent and subsequent improvement of automatic reflector/prism tracking devices, whereby the instrument constantly keeps a lock on the target as it is moving, so that all the operator needs to do is press a button to acquire the point instead of individually manually adjusting the instrument for each point to align on the centre of the prism. In the case of GPS, with a real-time kinematic setup (rtkGPS), one can acquire centimeter-scale accuracy on individual points with occupation times of less than 1 second.

It is thus speculated that the use of the morphological method for monitoring geomorphological change will continue to grow in both scientific research and restoration practice. Indeed, Brasington & Smart (2003) attribute the 'surge' in interest in the morphological method to advances both in the survey technology and digital elevation modelling. Thus, the need for a robust methodology that can be applied on a project-by-project basis to determine whether the data is of adequate quality to distinguish apparent observed changes from noise should be in demand (Lane *et al.* 2003). Geomorphology has moved from an era where it was data poor and fundamentally could not get enough measurements (Meentemeyer 1989), to an era where it is data rich but does not have the analytical means or tools to interrogate this data (Lane & Chandler 2003, Brasington & Smart 2003).

3.3.1.2 The Morphological Method

The process of estimating geomorphological change from repeat topographic surveys has come to be known as the morphological method.[15] It has its roots in one-dimensional cross section and long-profile monitoring (Brewer & Passmore 2002, Martin & Church 1995), but has now become the standard in two-dimensional topographic surveys. Some call topographic surface models three dimensional (Lane *et al.* 1994), but as the topographic surface models used in the morphological method only ascribe a single elevation value to every location in x-y cartesian space they are considered here to be two dimensional. Complex digital terrain models that allow multiple elevations to be defined for every cartesian x-y coordinate, are truly three dimensional. By contrast, cross-sectional and long-profile derived budgets (Brewer & Passmore 2002, Goff & Ashmore 1994), are one dimensional in that they only account for elevation change along one horizontal dimension. Moreover, this convention is consistent with the distinction between 1D (cross-sectionally averaged), 2D (depth-averaged) and 3D hydraulic models. Such semantics aside, the 2D form of the morphological method is a relatively simple technique by which, geomorphological changes at a single location between two points in time are inferred by differencing (subtracting) the surface elevations of the old surface from the new surface (Figure 3.5). In the case of gridded digital elevation models (DEMs), so long as the grid resolutions and locations are consistent the elevation change is actually a direct subtraction between corresponding cells in each DEM. More complicated algorithms exist for differencing TINed (Triangular Irregular Network) surfaces. The resulting DEM of Difference (DoD), shows elevation changes. To convert this to volumetric change, the elevation changes are multiplied by the area of the grid cells.

The morphological method has primarily been developed within the fluvial geomorphological community. Here the technique has been shown to have utility not just in monitoring applications, but also physical modelling (Brasington & Smart 2003, e.g.), and it is regularly used to interpret the results of morphodynamic and landscape evolution models. However, the morphological method has applications beyond just fluvial geomorphology, and has been employed

[15] Many investigators refer to the morphological method as 'DEM-differencing', whereas McLean & Church (1999) refer to it as the 'sediment budget approach.'

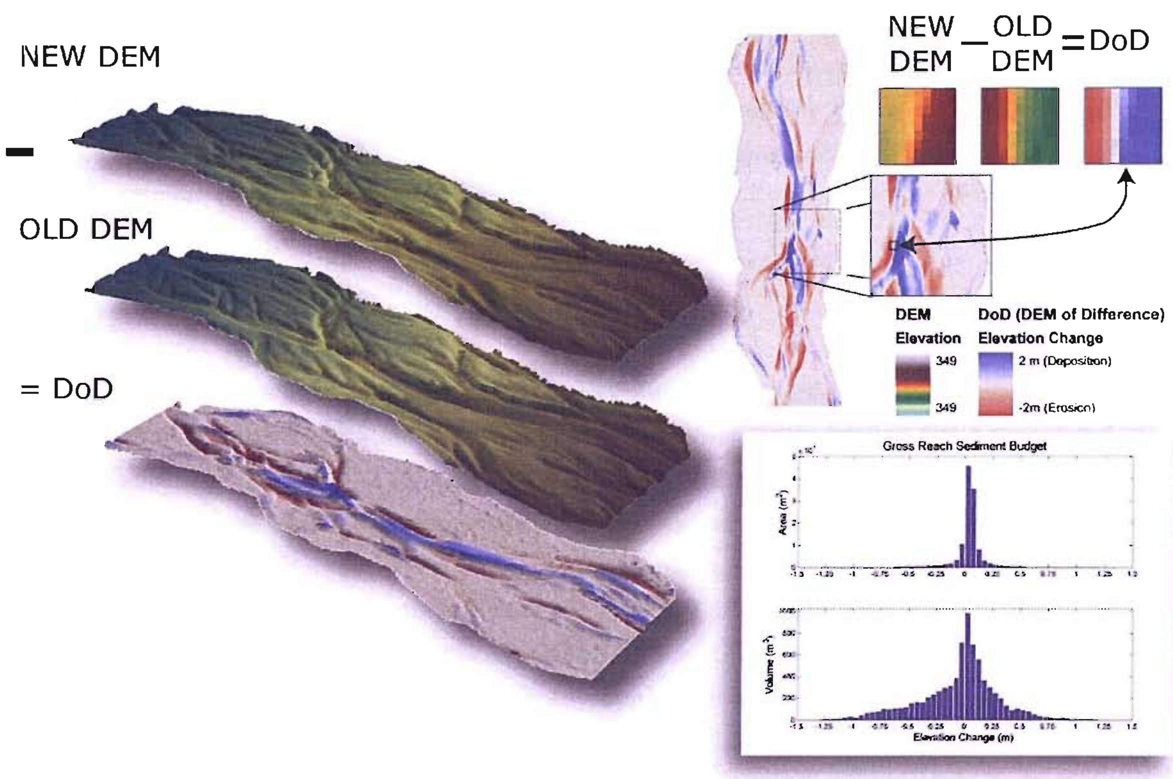


FIGURE 3.5: A Schematic of the morphological method. On the left, an example of a DoD (bottom) derived from the two DEMs above it is shown. In the upper right, a plan form perspective of that DoD is shown, and and the inset maps show how the DoD is calculated on a cell-by-cell basis by subtracting the elevation values in the older DEM from the newer DEM. In the lower right is an example of an areal (top) and volumetric (bottom) elevation change distribution from the same DoD.

by numerous investigators in other disciplines.[16] For example, Eeckhaut *et al.* (2007) used the technique to detect landslides over a 125 km^2 forested region using seven repeat LiDAR surveys. Hubbard *et al.* (2000) and Rippin *et al.* (2003) used the morphological method to infer changes in glacial ice from repeat aerial photography. In glaciology, DEM differencing has been used largely for ice mass balance calculations, but at generally much coarser resolutions[17] than in the fluvial environment (Keutterling & Thomas 2006). Smith *et al.* (2000) used the morphological approach to estimate over 38 x 10^6 m^3 of net sediment deposition and 25 x 10^6 m^3 of net erosion from a jökulhlaup in Skeioararsandur, Iceland. Dunn *et al.* (2001) attempted to use the morphological method to infer changes from volcano-tectonic events over sections of fast spreading sea-floor ridges from repeat bathymetric surveys of a 300-km-long section of the southern East Pacific Rise. Thus, the morphological method is of interest to a variety of disciplines. Moreover, part of the versatility of the technique comes from the fact it can be applied to DEMs derived from all topographic survey techniques as well as landscape evolution and morphodynamic models.[18]

3.3.2 Knowledge Gaps

Although the morphological method itself is relatively simple to apply, a host of uncertainties are associated with its application. Many of these are *unreliability uncertainties* associated with the process of topographic surveying (e.g. survey instrument precision, sampling design, point density, etc.), the sampling interval between surveys, interpolation methods to construct a surface elevation model and how these uncertainties propagate into the calculation of a DEM of difference and ultimately a sediment budget. Actually, there has been a lot of focus on uncertainty in the morphological method within the scientific literature (Lane & Chandler 2003). With any 'new' technique,[19] there is an initial excitement about the technology and its potential applications, and then a period of robustness testing. This testing has taken a variety of forms which are discussed below.

The morphological method has concerned investigators, as the vertical scale of change in many physiographic settings is relatively small in magnitude; such that if uncertainty in the surface representation is greater than or of equal magnitude to the change itself, it is difficult to distinguish the change from noise. Although there have been varying degrees of sophistication in accounting for surface representation uncertainty and propagating this into the DoD calculation, all of the approaches have been based on defining a minimum level of detection ($_{min}$LoD). This is relatively sensible as it establishes a threshold across which calculated changes should either be discarded or treated with skepticism.

[16]The 'morphological method' name appears to be a phrase coined and used withing fluvial geomorphology, but is also referred to as DEM-differencing.

[17]Whereas DEM differencing in fluvial applications tends to based on grid resolutions of 0.5 to 5 meters, 'high-resolution' for glaciers has been c. 20 m. The majority of glaciology DEMs for DEM differencing are from photogrammetry or satellite derived data.

[18]Refer back to § 3.3.1.1 for review of survey techniques and head to § 4.7.4 for discussion of applicability of DoD Uncertainty Analysis techniques developed to different survey techniques.

[19]The application of the morphological method in two dimensions was new in the early 1990's.

The primary problem with the $_{min}$LoD approach is that it throws away meaningful geomorphological changes with the noise. Clearly elevation changes lower than the arbitrary $_{min}$LoD take place. At one level, the use of $_{min}$LoD will always be an inherent limitation of the morphological method. However, the pervasive assumption that a single $_{min}$LoD is appropriate to apply in a spatially uniform manner across an entire DoD is seriously flawed. (Lane *et al.* 2003) appear to be the only investigators[20] who have recognised the spatial variability of the error function and attempted to account for this. However, Lane *et al.* (2003) only recognised a difference between survey techniques and assigned different $_{min}$LoD for areas that were wet versus dry and surveyed with photogrammetry. When propagated into the DoD, this produced four classes of $_{min}$LoD between subsequent surveys: wet $\Rightarrow$ wet, wet $\Rightarrow$ dry, dry $\Rightarrow$ dry and dry $\Rightarrow$ wet.

Clearly, there is more than just the survey method (e.g. GPS vs. aerial photogrammetry) and whether the surface is wet or dry that leads to spatial variation in the surface representation uncertainty. For example, should the uncertainty in the surface representation for a dry, flat, bare, smooth dirt floodplain surface be the same as a submerged, steep, thickly vegetated and highly irregular cut bank? Under best practice, the $_{min}$LoD is determined by the poorest quality area (conservative). This has the unintended consequence of discarding information in precisely those areas where geomorphological changes are likely to be of lower magnitude, such as shallow deposition on bar tops, and often have lower $_{min}$LoDs (Brasington *et al.* 2003). Thus, the primary knowledge gap can be summed up as a data retrieval problem. The conceptual knowledge and the raw data exist, but it is not know how to account for uncertainty without being overly conservative.

It is postulated that there are meaningful geomorphological changes being discarded through minimum level of detection analyses that could be better distinguished from this noise. This thesis therefore seeks to extend the work of Lane *et al.* (2003), Brasington *et al.* (2003) and Lindsay & Ashmore (2002) (among others) at accounting for uncertainty in the morphological method to try to recover some of this information loss. A fuller consideration of the factors leading to surface representation uncertainty will be made and this will be used to define spatially variable $_{min}$LoD in Chapter 4.

3.4 Rationale for Geomorphological Process Interpretations

Objective 2: *Develop a tool for making more meaningful mechanistic geomorphological interpretation of changes suggested by repeat topographic surveys*

Despite the considerable focus that uncertainty in DEM differencing of the morphological method has received, the actual geomorphological interpretations associated with the 2D morphological method have been rather disappointing. One might have hoped that with the new found wealth of spatially-distributed '3D' data, geomorphological interpretation might have

[20] Excepting the author and his co-investigators (Wheaton *et al.* 2004*a*, Brasington *et al.* 2004).

improved as a result. Despite many authors highlighting the benefits of the 2D morphological method in providing spatially distributed estimates of geomorphological dynamics and even inferring spatial patterns of bedload transport rates (Fuller *et al.* 2003, Lane *et al.* 1994, Brasington *et al.* 2000, Brasington *et al.* 2003), the majority of authors quickly discard the spatial data and opt for a spatially averaged reporting of gross reach-scale erosion, deposition and net change (notable exceptions are Lane *et al.* (1995) and Martin & Church (1995)). Virtually all the publications provide plots of DoDs (e.g. Figures 1.3 and 3.5) that tend to illustrate coherent patterns in the change. Lane *et al.* (2003) raised this very point, but nevertheless focused on extending the spatial extent of coverage of the survey to something previously unattempted with the 2D (DEM-differencing) incarnation of the morphological method in the fluvial setting. Ironically, given that most geomorphological interpretation of the morphological analysis has been qualitative, extending the spatial extent of analysis only exacerbates the problem of morphological unit-scale evolution being overlooked. The point here is not to criticise the important contributions of these past authors, but simply to point out that a detailed geomorphological interpretation of DEM-differences has not been the emphasis of past studies.

If one looks at 1D applications of the morphological method, the techniques are more mature and established (Leopold 1973, e.g.). Therein greater clarity and emphasis has been placed on making meaningful morphological interpretations across reaches, albeit at the bar-scale (Brewer & Passmore 2002, Fuller *et al.* 2002, e.g.). Brewer & Passmore (2002) separated one-dimensional[21] morphological methods into the plan-form budget, the channel-profile budget and the morphological budget (an integration of plan form and cross-sectional data). Some authors have segregated their study reaches into arbitrary control volumes (divided by cross sections) arranged in series in the streamwise direction, and quantitatively reported the rates of change between each control volume (Lindsay & Ashmore 2002, McLean & Church 1999, Church *et al.* 2001).[22] By contrast, Sear & Milne (2000) and Milne & Sear (1997) have looked closer at segregating budgets using a GIS by morphological units.

It is worth summarising the more detailed attempts to describe the geomorphological processes captured in DoD. A relatively common technique for interpreting DoDs has been to segregate their reach into arbitrary control volumes, computing cells or sub-reaches (each divided by cross sections) arranged in series in the streamwise direction, and quantitatively report the rates of change between each control volume (Lindsay & Ashmore 2002, McLean & Church 1999, Church *et al.* 2001, Lane *et al.* 1994, Brewer & Passmore 2002, e.g.). Lindsay & Ashmore (2002, Figure 11) schematically described four processes they observed taking place from DoD of a flume-based physical model of braided river development: a) lateral migration (to medial bar); b) lateral migration of channel followed by widening; c) avulsion into abandon channel; d) avulsion at a diffluence. Their observations were particularly helpful in the context of trying to determine whether net reported changes were masking 'compensation' episodes of aggradation or scour. Brewer & Passmore (2002) identified similar masking problems with one-

[21]They actually refer to these as three-dimensional techniques, but the nomenclature introduced in § 3.3.1.2 is used here for consistency.

[22]See also later discussion in § 5.2.1.1 and Figure 5.1.

dimensional approaches and pointed out that any sediment transport estimate derived from the morphological method would be conservative. Villard & Church (2005) used an echo-sounder to collect bathymetry biweekly over a three month period on the Fraser River Estuary in British Columbia and used a morphological approach to produce DoDs. Their geomorphological interpretation was focused on bar and dune development (individual morphological units) in primarily a qualitative fashion, but they then took transects of subsets of the data to compare dune geometry between surveys. Returning to gravel bed river reaches of the Fraser, Church *et al.* (2001) did go to the effort of manually coding individual DoD pixels in terms of morphological changes over a 70 km reach as:

- channel ⇒ bar surface (fill)
- channel ⇒ island or floodplain surface (fill)
- bar surface ⇒ island or floodplain surface (fill)
- bar surface ⇒ channel (scour)
- island or floodplain surface ⇒ bar surface (scour)
- island or floodplain surface ⇒ channel (scour)

This procedure allowed them to segregate their sediment budget into dominant processes, but they also use it to assess errors in the sediment budget. Milne & Sear (1997) took a slightly different approach and classified contiguous zones of erosion and deposition due to lateral channel migration to quantify bank erosion and point bar development.

As of 2008, Milne & Sear (1997) and Church *et al.* (2001) appear to be the only two studies that have attempted to segregate the DoD budget into specific geomorphological processes. In both studies the morphological interpretation analysis described here was not the main emphasis of the study. Both the approaches by Milne & Sear (1997) and Church *et al.* (2001) can be thought of as classification of difference (CoD) approaches in that they classify the morphology between surveys and then ascribe process to the unique categories of a change in classification that result (Wheaton *et al.* 2004*a*). The logic for this is probably inherited from repeat plan form surveys (often derived from aerial photo analysis), in which the morphological units are classified and then intercompared in a GIS (Graf 2000, Gaeuman *et al.* 2003). Such an approach clearly has utility in interpreting DoD but requires further research and development. In particular, would such an approach need to be entirely manually based or are semi-automated or automated procedures available?

The morphological approach was touted initially for the promise it showed in providing an alternative means of estimating sediment transport rates and producing reach scale sediment budgets (Lane *et al.* 1994). Very few authors have actually reported sediment transport rates from studies using the morphological method. To do so from the morphological approach, a known sediment transport boundary condition needs to be specified (McLean & Church 1999).

As such field measurements of bedload transport rates at the input boundary of a study reach are sparse and difficult to acquire, these data are not typically available. Hence, very few investigators have actually been able to calculate bedload transport rates in conjunction with the morphological method. As far as preparing sediment budgets, the morphological method only directly yields the change in storage terms, without actually defining the flux terms. As reported by McLean & Church (1999), the basic conservation of mass equation for sediment can be used to express the relationship between morphological change and sediment transport:

$$Q_{bi} - Q_{bo} = (1 - \eta) dV_b/dt \tag{3.1}$$

Where Q_{bi} and Q_{bo} are volumetric rates of transport of bed material coming into and leaving the control volume respectively; η is the bed sediment porosity; and V_b is the volume of bed material stored in the reach. While η can be approximated relatively easily from field measurements, dV_b/dt is derived from a DoD (dt is the change in time between surveys). In the context of this thesis, not knowing the bedload transport rate and subsequently being unable to complete the sediment budget (Eq.3.1) is not entirely problematic. From a geomorphological perspective, quantitative information about the rates of specific processes from just the storage terms of the budget is good enough for assessing the relative role of specific processes. From a physical habitat perspective, no data yet exist that relates bedload transport rates to salmonid activity or physical habitat changes, although Gibbins *et al.* (2007) are starting to provide some of the first empirical information on such a relationship in the context of the ability of macroinvertebrates to utilise and colonise patches of the bed.

This research will address two facets of the knowledge gaps identified above. First, morphological interpretations of DoDs, akin to the work of Ferguson & Werritty (1983), are lacking in the literature. Second, semi-automated techniques for making detailed morphological interpretations of DoDs do not exist currently. Even though manual segregation of the DoD and sediment budget into specific processes and the evolution of specific morphological units would be very insightful, thus far there has been extremely little published work on this. Perhaps the morphological interpretation has been over-looked, because such a process was seen as too laborious. If so, this provides further support for the need to develop semi-automated techniques to help encourage geomorphologists to actually make geomorphological interpretations.

It is postulated that specific signatures of geomorphological change should be recognisable from more detailed analyses and process inferences of morphological sediment budgets. This research will attempt to develop this concept through drawing from the more descriptive roots of geomorphology coupled to semi-automated procedures that quantify the observed changes. This development will come in part by extending the work of Milne & Sear (1997) and Church *et al.* (2001) as discussed above.

A B C

FIGURE 3.6: Contextual photos of three study sites used in this thesis. A. River Feshie, Scotland. B. Sulphur Creek, California. C. Mokelumne River, California.

3.5 Study Site Selection

This thesis is adopting a very methodological focus and as such the selection of a study site or sites is of secondary importance to the narrative. The primary criteria for study site selection is how well the study site will facilitate achievement of the three separate objectives of the thesis. In particular, a study site that allows rigorous testing of the methods being developed through available data and/or original data that could be acquired over the course of the study is of paramount importance. While it may be convenient to choose a study site or sites that fulfill all of the individual criteria for each objective, it is not essential.

The common thread that connects all of the thesis objectives together under the thesis aim is that of geomorphological change. More specifically, the methodological focus of the thesis is centred on how geomorphological change is monitored using repeat topographic surveys. Thus, the most fundamental criteria is that either repeat topographic surveys existed or could be acquired for the study site. Moreover, a site that is sufficiently active to exhibit geomorphological dynamics and changes over the study period would be desirable.[23] Although one of the primary motivations for the thesis is PHR (see § 1.2), the aim and objectives make no specific reference to PHR. Thus a study site that had been subjected to restoration, was planned for restoration, or would make a good candidate for restoration is not necessarily a requirement (although may be desirable).

Three study sites were chosen which meet all of the criteria described above:

1. Sulphur Creek[24], in the Napa Valley, California, USA

[23]However, as site that experiences no change is also a good test of the DoD as well (see § 4.3.1.4).

[24]Note that 'Sulphur', as opposed to 'sulfur' is the *correct* local place-name spelling for historical reasons (Grossinger *et al.* 2003).

2. Mokelumne River on edge of Central Valley, California, USA
3. River Feshie, in Cairngorms, Scotland, UK

An overview photo of each of the study sites and their respective locations in the UK and California are shown in Figure 3.6. More detailed location and vicinity maps as well as a complete study site description of each can be found in Appendices F (Sulphur Creek), G (Mokelumne River) and A (River Feshie).

In terms of meeting each of the specific thesis objectives[25], not every study site was required for every objective in Parts II and III. Only the Feshie is used in Chapter 4. Further justifications for each study site are outlined in § 5.3. All three study sites are used as case studies to apply the DoD uncertainty analysis and geomorphological interpretation techniques in Part III.

Although detailed individual study site descriptions are provided in the appendices and the use of study sites is rationalised in each chapter, it is helpful to concisely contrast the primary differences between the sites before proceeding into Part II. Table 3.1 does exactly this with respect to the primary physical attributes of the study sites. Each site occupies a relatively small reach in the context of their broader parent catchments, but reaches that represent fundamental transitions in geomorphological behavior from upstream reaches. As such, they are areas that exhibit interesting geomorphological responses. In terms of the presence of salmonids and physical habitat, each study site hosts physical habitat capable of supporting salmonids. Table 3.2 shows the primary differences, as well as highlighting the most obvious geographic difference between the UK and California study sites in supporting Atlantic species of salmon (Atlantic salmon: *Salmo salar*) versus Pacific species (Steelhead: *Oncorhynchus mykiss*; and Chinook:*Oncorhynchus tshawytscha*). Although the Feshie is part of the Spey Catchment, which supports one of the healthiest populations of Atlantic salmon in western Europe (SEPA 2003); the extent of the run on the Feshie actually is not well documented.[26] Grant *et al.* (2006) pointed out that headwater tributaries like the Feshie have experienced notable declines in the numbers of spawning salmon over the past 30 years, despite availability of 'good' quality spawning habitat not being a limiting factor in the Feshie. By contrast, salmonids and their habitat utilisation in Sulphur Creek (Koehler 2003*a*, SFBWQB 2002, Liedy *et al.* 2003) and the Mokelumne (CDFG 1991, Merz & Setka 2004, Merz *et al.* 2004) have been well documented and physical habitat is known to be a limiting factor in both systems.

[25]Objective 1 (§ 1.3.1) corresponds to Chapter 4. Objective 2 (§ 1.3.2) corresponds to Chapter 5.

[26]Grant *et al.* (2007) and Grant *et al.* (2006) have collected the only known spawning surveys on the Feshie in 2005 and 2006 at the study site, but these are as of yet unavailable with publication of that data currently in preparation (p. comm Gibbins & Soulsby, 2007).

Study Site:	River Feshie	Sulphur Creek	Mokelumne River
Location	Highlands, Cairngorms National Park, Scotland, UK	Coast Range, Napa Valley, California, USA	Edge of Sierra Nevada Foot-Hills/Central Valley, California, USA
Physiographic Setting	Formerly glaciated valley, Highland mountain and moorland setting	Broad alluvial fan protruding into alluvial valley of Napa River from a rugged and steep catchment	Transition from foothills to vast valley from a former inland sea
Catchment Size	231 km^2	25 km^2	1700 km^2
Catchment Upstream of Study Reach	113 km^2	21 km^2	1497 km^2
Catchment Elevation Range	1262 m to 232 m	833 m to 51 m	3050 m to 0 m
Tributary to:	River Spey (> 3000 km^2); drains to Atlantic via North Sea	Napa River (1103 km^2); drains to Pacific via San Francisco Bay	San Joaquin River (40,840 km^2); drains to Pacific via San Francisco Bay
Reach Strahler Stream Order	4	3	5
Reach Length	1000 m	350 m	500 m
Average Active Channel Width	250 m (braid plain)	40 m	35 m
Plan form	Minor Braiding (2-3 active channels)/wandering	Alternate bar morphology, with wandering tendencies where width is less-confined	Single-thread
Average Annual Precipitation	1268 mm (Feshie Bridge)	886 mm (headwaters)	254 mm (Central Valley) to 1195 mm (headwaters)
Flow Regime	Natural, perennial, relatively flashy system with major flood events primarily in Fall to Winter with a smaller number in late spring from snowmelt	Natural, intermittent flows, defined by summer drought, flashy spring and winter floods, no large dams and only minor abstractions	Spring snow-melt dominated hydrograph, with distinct summer drought; flow regime dramatically altered and reduced by over 28 large dams and 2 major dams
Q_5 & Q_{100}	80.4 & 141.4 cumecs (Feshie Bridge)	NA & 94 cumecs (FEMA 1998)	282 & 1200 cumecs (Pre-Dam) 115 & 300 cumecs (Post Dam)
Geomorphological Regime	Active incision and reworking of braidplain and fluvio-glacial deposits	Tectonically active; relatively high sediment yields through an artificially stable channel across its alluvial fan	Minimal natural sediment transport, heavily armoured, highly artificial
Sediment Supply	Abundant, primarily from fluvio-glacial valley deposits and hillslope process	Abundant sediment yield from upper catchment as well as local supply in alluvial fan	Supply limited, No sediment passes Camanche Dam; local supply limited due to former mining and sediment starvation
Valley Setting	Unconfined, flanked by fluvio-glacial terraces	Artificially confined, channel and inset-floodplain cut into alluvial fan surface	Partially confined by mix of local rock outcrops and man-made levees
Repeat Topographic Surveys	7 years; annual surveys	Single high magnitude event (before and after)	5 years; Pre and Post SHR projects

TABLE 3.1: Summary comparison of relevant physical attributes of study sites used in this thesis.

Study Site:	River Feshie	Sulphur Creek	Mokelumne River
Salmonids Present	Atlantic salmon (*Salmo salar*)	steelhead (*Oncorhynchus mykiss*); occasional stray chinook (*Oncorhynchus tshawytscha*)	fall-run chinook (*Oncorhynchus tshawytscha*); Steelhead (*Oncorhynchus mykiss*)
Riparian Setting	Active braidplain, with older surfaces colonised	Minimal riparian vegetation, adjacent industrial landuse, engineering structures	Thin riparian corridor, tall overstory, artificially stable vegetation and incised channel due to regulated flow regime
Habitat Utilisation of Study Reach	some spawning, primarily in groundwater fed side channels	steelhead : migration corridor; chinook: spawning	Spawning, rearing, migration
Redd Surveys	Only 2 years of surveys (unavailable)	steelhead: not applicable; Chinook: only 1 year (Wheaton 2005)	Weekly surveys during spawning season from 1994 to 2007 (average of 915 redds annually)
Typical Spawning Flows (Fall)	3 to 6 cumecs	0.5 to 2.0 cumecs	8 to 12 cumecs
Juvenile Surveys	unknown	9 sparse historical surveys (Liedy *et al.* 2003)	Irregular EBMUD and CDFG surveys
Run Size	unknown	unknown	c. 12,000 annually (video-monitored)
Limiting Factor for Salmonids	Unknown/ probably not physical habitat	Reliable spawning and out-migration flows; rearing habitat (Koehler 2003*a*, SFBWQB 2002)	Spawning habitat (CDFG 1991)
SHR Projects?	None (no need)	NRCS Project in 2003	EBMUD projects in 1997, 1998, 1999, 2003, 2004, 2005, 2006

TABLE 3.2: Summary comparison of relevant salmonid utilisation, physical habitat characteristics and respective data availability for the study sites used in this thesis.

3.6 Conclusion

The scientific justification for the research aim and objectives identified in Chapter 1 have been explained in terms of past studies and knowledge gaps. It was also discussed how the spatial scale of focus will resolve hydraulic unit and geomorphic unit scale features over reach scale extents. The temporal scales of interest will be a mixture of event based, annual and decadal resolutions. Uncertainty in morphological change associated with DEM differencing and the morphological method has been shown to be a topical research interest within which the spatially uniform application of minimum levels of detection appears to be unnecessarily discarding large amounts of meaningful change. A more sophisticated and flexible model of surface representation uncertainty will be developed in Chapter 4. While DoD uncertainty has received considerable attention in the literature, the geomorphological interpretations of DoDs have by comparison not been investigated in detail, particularly at scales of ecological relevance to fish (e.g. at the hydraulic and geomorphic unit scales). Techniques to fill this interpretive void will be developed in Chapter 5. The reader is reminded that the scientific justification for the thesis aim and objectives are independent to the physical habitat restoration justifications that are the motivation for this thesis. This theme will be revisited in Part IV.

Part II

Methodological Developments

Chapter 4

Accounting for DEM Uncertainty in Morphological Sediment Budgeting

4.1 Introduction

With recent advances in ground-based and remotely-sensed surveying technologies[1], the rapid acquisition of topographic data in the fluvial environment is now possible at spatial resolutions and extents previously unimaginable (Lane *et al.* 2003). These advances make monitoring geomorphological changes and estimating fluvial sediment budgets through repeat topographic surveys and application of the morphological method[2] a tractable, affordable approach not just for research purposes, but also for long-term monitoring associated with river basin management and river restoration schemes (e.g. physical habitat restoration for salmonids[3]). The morphological method historically has been applied primarily from repeat surveys of river plan form, cross-sections and/or longitudinal profiles (Brewer & Passmore 2002). However, from the early 1990s, the morphological method was expanded to the use of repeat topographic surveys from which digital elevation models (DEMs) could be constructed and differenced to produce DEMs of Difference (DoDs).[4] This chapter focuses exclusively on the 2D application of the morphological method using DoD.[5]

As stated in § 3.3.2, uncertainty in DoD application of the morphological method has already received considerable attention in terms of assessing the reliability of the approach. One of the primary driving questions behind these efforts was, given the uncertainty inherent in representing the earth's surface with a DEM, is it possible to distinguish real geomorphological changes from noise? The reliability of morphologically inferred sediment budgets is controlled by: a) uncertainty in the flux boundary conditions; b) survey frequency; and c) DEM quality.

[1]These include ground-based GPS, total station surveying and terrestrial laser scanning as well as airborne LiDAR and photogrammetry. See § 3.3.1.1 for more background.

[2]See § 3.3.1.2 for description of the morphological method

[3]For context on PHR, see Part I. Few direct references to PHR will be made in this chapter.

[4]See Figure 3.5.

[5]See § 3.3.1.2 for distinction between 1D and 2D.

Most studies involving DEM differencing have not dealt with quantifying the bedload transport fluxes at the boundaries (e.g. Lane et al. 2003, Brasington et al. 2000, Fuller et al. 2003).[6] In a laboratory setting, Lindsay & Ashmore (2002) focused on the issue of survey frequency and identified compensation mechanisms that result in net changes captured at coarser survey frequencies, which mask the true magnitude of geomorphological change. This work helped establish more robustly what has been generally accepted - that DEM differencing generally produces conservative estimates of total change. To date, most research interest has focused on evaluating the uncertainty in budget estimates due to DEM errors. These arise as a largely unknown function of survey point quality, sampling strategy, surface composition, topographic complexity and interpolation methods. This chapter is focused on improving the understanding of DEM uncertainty and how it propagates into DoD calculations.

A commonly adopted procedure for managing DEM uncertainties involves specifying a minimum level of detection threshold ($_{min}$LoD) to distinguish actual surface changes from the inherent noise. Determination of the $_{min}$LoD requires both a theory of change detection and a metric of DEM quality (Brasington *et al.* 2000, Lane *et al.* 2003). Typically this is achieved by applying the classical statistical theory of errors and a measure of DEM precision derived from check data or point precision estimates. Research presented here aims to demonstrate that simple thresholding may, however, significantly degrade the information that can be optimally retrieved through DEM differencing. Analyses are based on five annual topographic surveys, which span a four year period on the River Feshie in the Scottish Highlands. The surveys consist of high-quality rtkGPS data and a limited amount of total station acquired data.

The purpose of this Chapter is to achieve Objective 1 (see § 1.3.1) through the development of a new technique that quantifies the influence of surface representation uncertainty on sediment budgets derived from DEM differencing. In so doing, spatial variability is accounted for in a more comprehensive way. The new methodology for change detection presented incorporates: (i) a stepwise analysis for quantifying spatial variability in surface representation uncertainty arising during DEM construction; (ii) the development of a spatial coherence delineation tool to group areas of scour and fill; and (iii) alternative methods for analysing change data which relax the assumptions of the LOD approach. These latter strategies explicitly incorporate uncertainties in DEM data and permit sediment budget calculations to be presented in a probabilistic framework.

The chapter is organised as follows. First the Feshie study site, which is introduced in § 3.5, will be described. All the examples used in this chapter will be made with reference to the Feshie. Next, an extensive review of contrasting approaches to quantifying DEM surface representation uncertainty in the context of morphological sediment budgeting is presented (§ 4.3). There is particular emphasis on the shortcomings of various approaches, and on how various elements of some of the approaches might be improved upon. That review sets the stage for the methodological developments presented here in § 4.4. This is divided into two primary contributions, a spatially variable quantification of uncertainty (§ 4.4.1) and an

[6] Lane *et al.* (1995) and Martin & Church (1995) are notable exceptions.

analysis of spatially coherent erosion and deposition units (§ 4.4.2). The development of a DoD Uncertainty Analysis software program using these methodological developments is presented next (§ 4.5). The software package has six different pathways through its application, which represent the various contrasting approaches reviewed earlier as well as the methodological developments presented in this chapter. Those pathways are then used as a framework to compare and contrast the different techniques all using the Feshie datasets. The chapter closes with a discussion of the main findings, some of the problems and what can be done in the future to address these.

Before delving into this lengthy chapter riddled with specifics about uncertainty, it is helpful to point out precisely what types of uncertainties are and are not addressed in this chapter. This can be done in the context of the Van Asselt (2000) typology discussed in § 2.2.2. The chapter is primarily concerned with quantifying surface representation uncertainty in DEMs. This is an uncertainty due to limited knowledge (e.g. inexactness, lack of observations & measurements, and/or practically immeasurable) that primarily arises out of unreliabilities from the surveying process and technology, and is exacerbated during the surface interpolation process. Only the vertical or elevation uncertainty of the DEM is considered directly. There are many uncertainties that combine to create elevation uncertainties and most of these are discussed in some way in this chapter. However, the focus is on developing a tractable method of quantifying uncertainties that could be applied given any raw topographic survey data (i.e. and x,y,z point cloud). This means that where uncertainties can be identified but not quantified readily, a conservative estimate of their magnitude will be made. The end goal is to propagate the estimated uncertainty in two DEMs into a DoD, to differentiate between those DoD calculated changes that are thought to be real versus those that can not be distinguished from noise. As described above, techniques to do this already exist but because they are spatially uniform tend to be more conservative than necessary overall, but too liberal in certain areas. This chapter seeks to improve upon this.

4.2 River Feshie Study Site

To develop this new technique, a dataset of high-resolution repeat topographic surveys from a system that was sufficiently dynamic to exhibit a range of styles of geomorphological change over a reasonable duration study period (e.g. 3 or more years) was necessary. Moreover, while lower quality datasets could prove a good test of the methods developed, it is preferable to have high quality data sets that can be degraded or used as benchmarks[7]. While monitoring with repeat topographic surveys is becoming more popular, there are actually very few data sets in the world that meet all of the above criteria. Particularly the criteria of 'sufficiently dynamic' within a 'study period' will tend to restrict the focus to particularly active river styles (e.g. braided). Thomas (2006, Chapter 7) identified seven rivers where data were emerging from such intensive high resolution monitoring campaigns, but only five of these involved

[7]Benchmarks is used here to mean a basis for comparison as opposed to a semi-permanent survey marker.

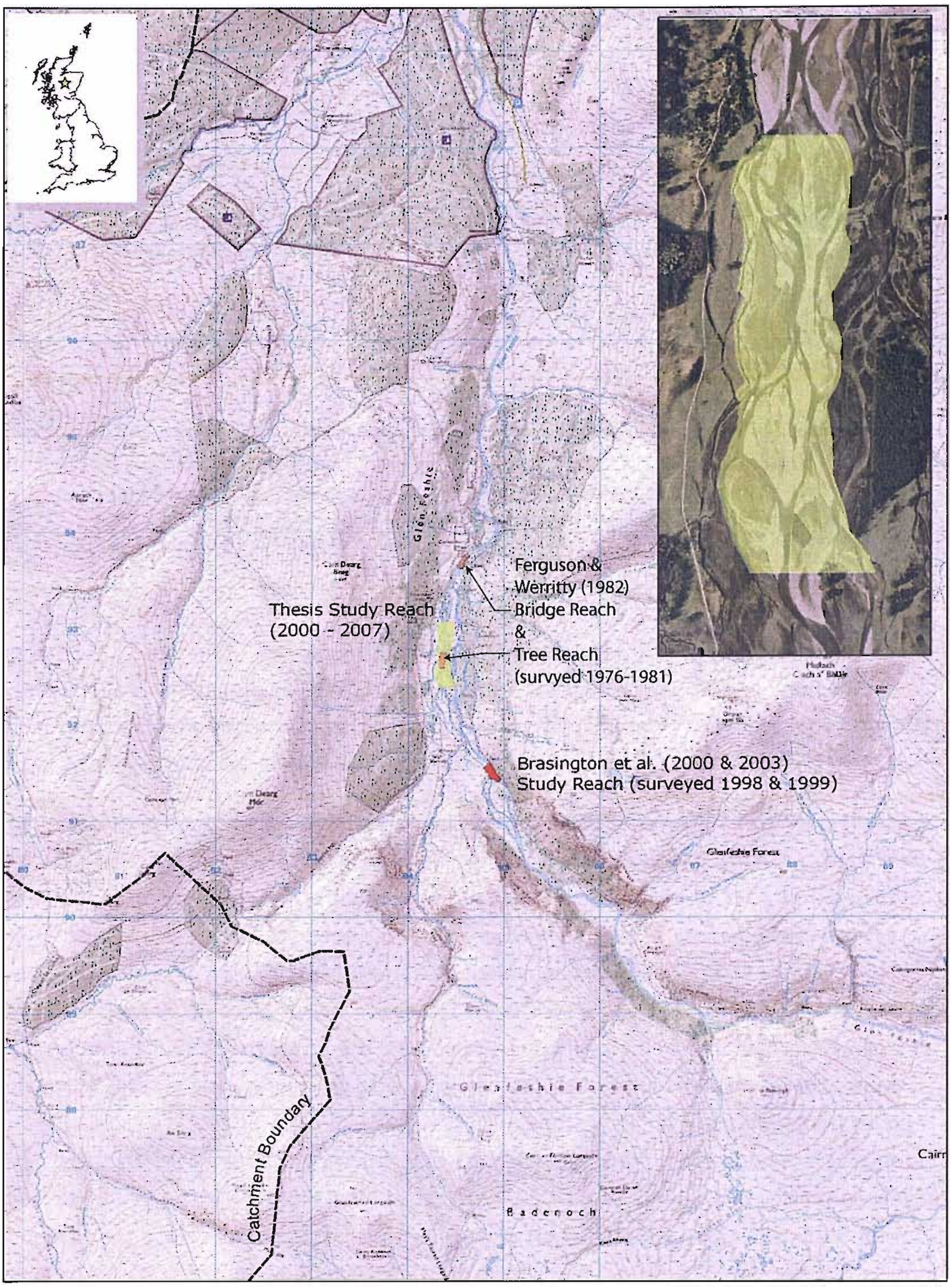


FIGURE 4.1: Vicinity Map for River Feshie Study Site. The thesis study site is depicted in yellow on both the Ordnance Survey 1:25,000 map (background hillshade derived from NextMap 5m DTM data flown in 2005) and the aerial photograph from 2005.

River	Survey Type	Duration	Investigators
River Feshie, Cairngorm Mountains, Scotland	GPS,TS and AP	1998-2007	(Brasington *et al.* 2000, Brasington *et al.* 2003)
Sunwapta River, Alberta, Canada	OP and TS	1999 (daily)	(Chandler *et al.* 2002)
Waimakariri River, South Island, New Zealand	AP and LiDAR	1999-2000	(Lane *et al.* 2003, Westaway *et al.* 2003)
South Saskatchewan River, Saskatchewan, Canada	LiDAR	2003- 2004	(Thomas 2006)
Platte River, Nebraska, USA	LiDAR	2002 and 2005	(Kinzel *et al.* 2006a, 2006b)
Mokelumne River, California, USA	TS	1999 to 2007	(Merz *et al.* 2006)

TABLE 4.1: The 'Benchmark' Repeat Topographic Survey Data Sets. Compiled with reference to Thomas (2006, Chapter 7). Abbreviations: aerial photogrammetry (AP), oblique photogrammetry (OP) total station (TS), differential GPS (GPS), Light Detection and Ranging (LiDAR).

repeat surveys (Table 4.1). Although other data sets exist, few, if any, ground-based survey data sets in the world match the detail and scope of the benchmark dataset from the River Feshie in the Cairngorm Mountains of Scotland (Figure 4.1).The study site was introduced in § 3.5 and further details are provided in Appendix A.

For the purposes of analyses in this chapter, data were analysed from 2003 to 2007, reflecting four analysis periods. Although topographic survey data for the study reach also existed from 2000 and 2002, for consistency the analyses in this chapter are limited to 2003 through 2007. The 2000 survey was an aerial photogrammetric survey, unlike the ground-based surveys of the other years, plus there was a gap year (2001) when no topographic data were collected.[8] The spatial extent of the 2002 survey was only 73% of that of the 2003 through 2007 surveys (8.5 as opposed to 11.6 hectares), and an analysis mask[9] including the 2002 survey would exclude an interesting zone of activity at the top (south) end of the reach surveyed in each of the other years. The 2003 through 2006 surveys were entirely rtk-GPS ground based surveys whereas the 2007 survey was augmented with total station data. Each survey consisted of between 34,000 and 51,000 points over an 11.5 to 14.5 hectare survey area with an average point density of about 0.24 points/m^2 over all surveys (see Table C.1 and Appendix C for full details of surveys).

[8]The methods developed in this chapter are actually well suited to dealing with topographic data collected using different methods. However, this chapter's scope was limited to dealing with the simpler case of consistent methods; so as to not complicate the narrative associated with the methodological development.

[9]The intersection of all survey areas.

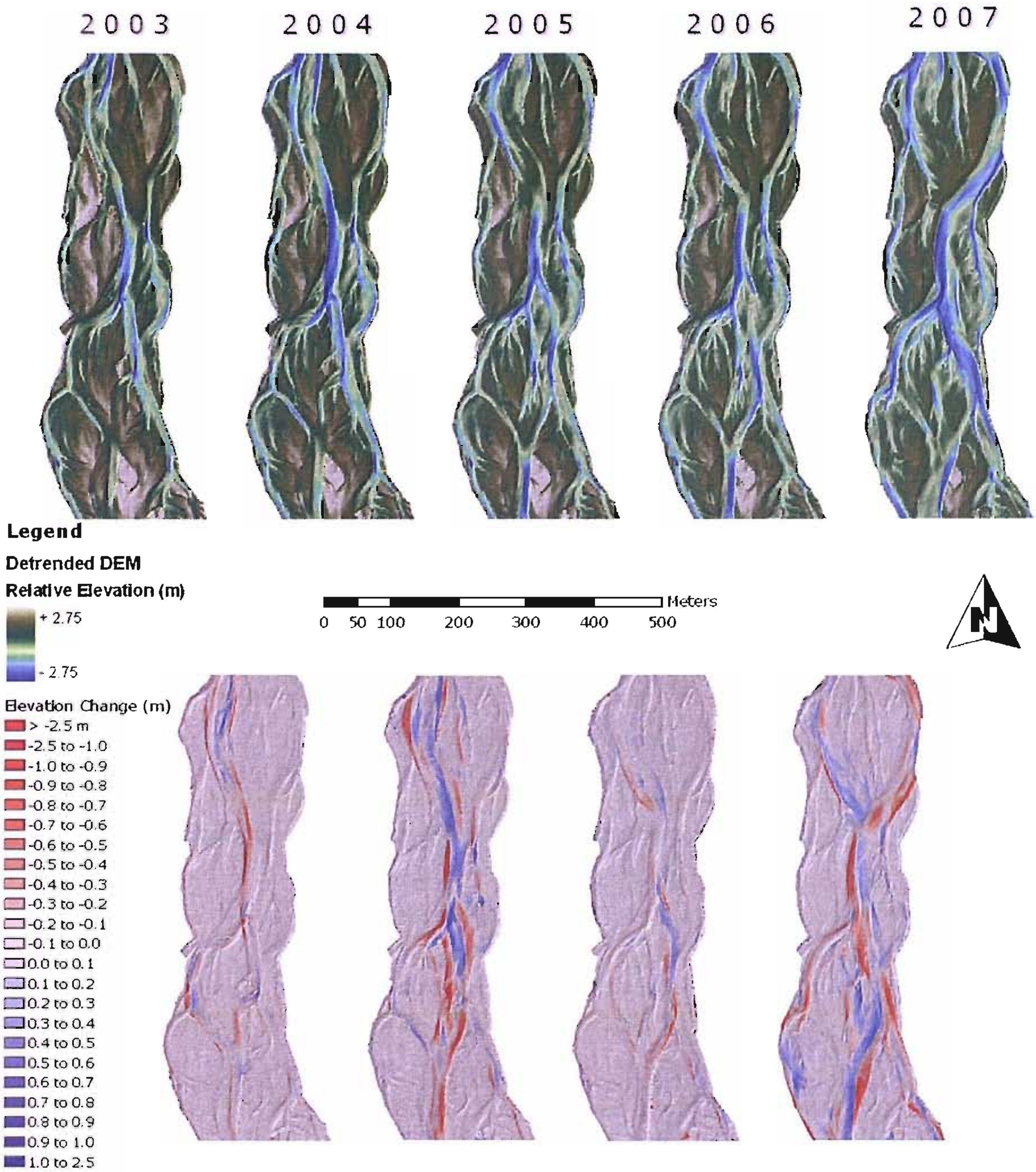


FIGURE 4.2: Detrended DEMs and DoD for 2003 to 2007. Note that the hillshades from the more recent year in the DoD are shown behind the DoD for context. For details on how the DEMs were created and detrended see Appendix C.

4.3 Contrasting Approaches

There are many contrasting approaches that have been used or could be used to construct a new technique that quantifies the influence of surface representation uncertainty on sediment budgets derived from DEM differencing. In this section, these approaches are contrasted and knowledge gaps identified. Regardless of the approach used, the process can be divided into three steps:

1. Quantifying the surface representation uncertainty in the individual DEM surfaces that are being compared
2. Propagating the identified uncertainties into the DoD
3. Assessing the significance of the propagated uncertainty

The next three subsections address the contrasting approaches that have been or could be used to address each of the above steps. As described in § 3.3.1.2, the DoD version of the morphological method involves the simple mathematical operation of subtracting the elevations in the older surface from the elevations in the newer surface. This difference can be converted to a volumetric estimate of change by multiplying the calculated elevation change in each grid cell by the grid resolution (area) and summed as desired to compare deposition and erosion. This simple technique was applied to the five years of DEMs at the four annual analysis intervals, and the mapped changes are shown in comparison to the original detrended[10] DEMs in Figure 4.2.

4.3.1 Quantifying Surface Representation Uncertainty

There are a wide variety of ways to quantify uncertainties in the terrain surface representation of vector topographic survey data (i.e. x,y,z point clouds) as it is manifested in DEMs like those shown in Figure 4.2. Here, surface representation uncertainty will be denoted as $\delta(z)$, assuming the horizontal components are negligible.[11] We use $\delta(z)$ as follows:

$$Z_{Actual} = Z_{DEM} \pm \delta(z) \tag{4.1}$$

where Z_{Actual} is the true value of elevation at some point in space that is approximated with the best guess Z_{DEM} of that elevation value as represented in the DEM. The approaches for approximating $\delta(z)$ range from as simple as assuming that the manufacturer reported

[10] The detrending process used is described in § C.4 and full page figures of the detrended DEMs can be viewed as well.

[11] It has been customary in the literature to only consider vertical or elevation uncertainty ($\delta(z)$). Given that the resolution of DEMs typically used in DEM differencing are typically at least an order of magnitude greater than the horizontal positional uncertainty components ($\delta(x)$ and $\delta(y)$) of individual survey points, assuming horizontal positional uncertainty (δ) is negligible is quite reasonable. Thus, only elevation uncertainty ($\delta(z)$) is considered in this thesis as the dominant influence on surface representation uncertainty.

instrument precision rating is a good indication of $\delta(z)$, to attempts at complete error budgets (Lichti *et al.* 2005). It is important to recognise that the $\delta(z)$ of an output like an interpolated DEM surface is the result of propagated errors from the inputs (e.g. instrument precision, measurement errors in individual points), and structural uncertainties[12] in the sampling (e.g. point density, sampling pattern) and surface interpolation methods (e.g. TIN, inverse distance weighted, natural neighbours, spline, Kriging etc.). Unfortunately, all these components can not be measured or necessarily known, and therefore no deterministic or statistical approach can fully account for $\delta(z)$. Thus, the subset of tractable approaches reviewed here each represent various ways of approximating $\delta(z)$.

4.3.1.1 Repeat Observation of Control Points

One of the simplest ways to treat $\delta(z)$ is to assume that it is spatially uniform and estimate its magnitude a) theoretically, b) from empirical experiments, or c) from numerical simulations. For example, with photogrammetric, total station and GPS surveys one can make repeat observations of fixed control points over the course of a survey and look at the variance between the measurements (Brasington *et al.* 2000, Lane *et al.* 2003, Brasington & Smart 2003). If one assumes that the variance or range (more conservatively) in observations of a control point (that itself is assumed not to have moved) is indicative of the uncertainty in acquiring an individual topographic survey point, this may be reasonably used to approximate $\delta(z)$. A similar set of experiments were conducted over three years for the Feshie GPS surveys and the summary results are tabulated in table 4.2. The results show mean positional standard deviations (σ)on the order of 2 cm and a mean vertical standard deviation (σ) of about 1 cm. For change detection in the vertical, à la Brasington *et al.* (2000) this suggests that for the Feshie GPS surveys a measurement limit of ± 4 cm 95% of the time (2σ) is reasonable.[13] This is consistent with the GPS vertical measurement limits of ± 5.2 cm 95% of the time reported by Brasington *et al.* (2000), using older technology and fewer available satelites in the late 1990s (also on the Feshie).

4.3.1.2 Error Budgets

Although the assumptions in the approach of taking summary statistics from control points to characterise $\delta(z)$ may not be entirely correct, they do provide a tractable approximation to the problem. A more thorough alternative is to try to construct a detailed error budget for all the components of error (Lichti *et al.* 2005, Baltsavias 1999). Such an approach involves quantifying the error contribution for each identified component. For example, one source of error in GPS surveys is the positional accuracy of a point due to satellite and base station geometry at the time of measurement. Most GPS packages provide an estimate of point quality. From 204,657 GPS observations collected from 2003-2007 on the Feshie, the

[12]See § 2.2.2.

[13]Jumping ahead to § 4.3.3, using a measurement limit of 2σ is the equivalent of applying a 95% confidence interval threshold.

	2004	2005	2006	Combined
σ_μ Easting (m)	0.015	0.034	0.007	0.020
σ_μ Northing (m)	0.014	0.037	0.012	0.020
σ_μ Elevation (m)	0.007	0.018	0.004	0.010
n Repeat Observations	257	110	15	382
n of Control Points	6	5	5	16

TABLE 4.2: Variance in repeat GPS observation of control points over three years (n=382 observations). Standard deviations (σ) of each coordinate component were calculated for each control point and then averaged over the number of control points to produce σ_μ. The fifth column shows an average standard deviation for each coordinate component that was weighted by the number of observations from that year (row 5).

reported 3D point quality ranged from 0.004 m to 0.642 m with a μ of 0.017 m and σ of 0.007 m. In ground-based surveys where a detail pole[14] is used, another component of error is introduced by the extent to which the operator was holding the pole plumb when the point was recorded. In Appendix D this component of error is considered both theoretically and through an empirical experiment. It was found that this would typically only account for 5-10 mm of $\delta(z)$, but can be considered negligible in gravel bed rivers.[15] Two problems arise from continuing down this track of error budgeting. The first is the question of what is the appropriate method for propagating the component sources of error to estimate $\delta(z)$? Most conservatively, errors can be considered additive such that:

$$\delta(z) \approx \delta(z)_1 + \delta(z)_2 + \ldots + \delta(z)_n \tag{4.2}$$

where $\delta(z)_n$ is the nth component of errors and there are n components of error (Taylor 1997). However, if the component errors ($\delta(z)_n$) are independent and subject only to random uncertainties, Eq. 4.2 is an over-prediction of uncertainty and a quadratic sum can be used instead (Taylor 1997, pp. 57-60):

$$\delta(z) = \sqrt{(\delta(z)_1)^2 + (\delta(z)_2)^2 + \ldots + (\delta(z)_n)^2} \tag{4.3}$$

The second challenge is whether or not all the identifiable components of error can be detected. For example, Lane *et al.* (1994, Table II) attempted to identify the *major* causes of error impacting individual survey point quality from photogrammetric and total-station surveys. They distinguished between *random* (determining precision), *gross* (determining reliability), and *systematic* (determining accuracy) errors, but point out that a number of the identifiable errors are undetected[16] (e.g. detail pole not held plumb, detail pole driven into the sediment) implying that the error budget could never be complete. While conducting error budgets as exhaustively as is permissible with available data is a worthwhile exercise, it is often impractical

[14]Detail poles are also sometimes referred to as survey rods. See Figure 4.5A, C and D for example.
[15]See § D.5 for explanation.
[16]These errors are undetected as opposed to undetectable, as they can be identified and potentially measured, but it is not practical to do so in a operational sense.

to complete with the basic topographic survey data alone. Thus, there is a need to quantify DEM $\delta(z)$ not just for tightly controlled experimental surveys, but for any topographic survey acquired with any technique that is to be used in DEM differencing.

4.3.1.3 Bootstrap Experiments

Another way of trying to estimate surface representation uncertainties is through different statistical resampling techniques, such as bootstrapping. Any TIN or DEM is constructed from a finite sample of an infinite number of actual elevation values that represent the population (surface). The principle is that if the sample is sufficiently large (i.e. higher point density than necessary to capture topography), a sub-sample can be removed from the dataset and the DEM reconstructed without it. This removed sub-sample can then be used in a variety of ways to estimate the sampling distribution through comparison. For example, Brasington *et al.* (2000, pp.987-988) performed such an experiment to explore whether $\delta(z)$ was dependent on surface grain roughness. They performed pebble counts to characterise grain roughness and then identified a subsample area of the DEM characterised by two distinct roughnesses and higher point densities than necessary. They randomly sorted the survey points in this subsample and split the dataset into two, from which two DEMs were constructed. They then differenced the two DEMs, and observed higher elevation differences where the surface roughness was greater, but noted that the mean absolute differences were not dissimilar to the elevation uncertainty suggested from the repeat control point observations (§ 4.3.1.1).

In this study, a simple bootstrapping experiment was conducted to infer elevation uncertainty ($\delta(z)$). As the 2003 survey data contained the highest point density (Table C.1), it was chosen for resampling. A random sample of 10% of the 51,080 points was taken and removed from the data set. A TIN was reconstructed from the thinned dataset and coverted to a 1 metre DEM.[17] The elevations of the 5108 subsample points (Z_{XY}) then were compared to the DEM values (Z_{DEM}). The mean difference ($\overline{|Z_{XY} - Z_{DEM}|}$) was taken to be an indication of elevation uncertainty ($\delta(z)$).The experiment was repeated three times with three different random subsamples to check that the results were consistent (Table 4.3). Absolute differences of upto 87 cm were observed, with the mean absolute differences at approximately 6 cm. This is substantially higher than the 1 cm (1σ) suggested by the repeat control point observations in § 4.3.1.1 as a proxy for $\delta(z)$.

To assess whether there was any spatial structure in the suggested elevation uncertainty, the sub-sampled survey points from all three experiments were overlaid on the DEM of the reach with their point symbols coloured and scaled to the magnitude of their calculated absolute elevation differences (Figure 4.3). From Figure 4.3A, there appears to be a clear pattern of the highest absolute elevation differences being located strictly along grade-breaks and steep banks, with medium values tending to be concentrated in channels, and the low values tending to be located toward the flat exposed bar-tops and floodplain surfaces. From Figure 4.3B, it

[17]The same resolution used for all the DoD analyses (see § C.3).

	Sample 1	Sample 2	Sample 3	3 Combined
$\lvert Z_{XY} - Z_{DEM}\rvert_\mu$	0.062	0.060	0.064	0.062
$\lvert Z_{XY} - Z_{DEM}\rvert_{Max}$	0.763	0.780	0.872	0.872
$\lvert Z_{XY} - Z_{DEM}\rvert_\sigma$	0.076	0.073	0.080	0.076

TABLE 4.3: Basic statistics (in metres) from three bootstrap experiments for estimating elevation uncertainty ($\delta(z)$) from absolute elevation difference ($\lvert Z_{XY} - Z_{DEM}\rvert$, see text). Row 1 is the mean, row 2 is the maximum and row 3 is the standard deviation. Note, $\lvert Z_{XY} - Z_{DEM}\rvert_{Min}$ is 0.

Slope Range ⇒	0 to 2	2 to 5	5 to 10	10 to 20	20 to 100
$\lvert Z_{XY} - Z_{DEM}\rvert_\mu$	0.033	0.039	0.050	0.075	0.149
$\lvert Z_{XY} - Z_{DEM}\rvert_{Max}$	0.245	0.276	0.427	0.515	0.763
$\lvert Z_{XY} - Z_{DEM}\rvert_\sigma$	0.029	0.034	0.047	0.068	0.143

TABLE 4.4: Summary statistics from bootstrap experiment for estimating elevation uncertainty ($\delta(z)$) segregated by slope. Row 1 is the mean, row 2 is the maximum and row 3 is the standard deviation. Note, $\lvert Z_{XY} - Z_{DEM}\rvert_{Min}$ is 0.

is also clear that even when the DEM is built with only 90% of the data, it still reasonably represents the surveyed elevations.

To consider whether the absolute elevation differences were directly attributable to other known metrics for the data that may contribute to $\delta(z)$ (e.g. point density, slope, water depth[18], GPS 3D Point Quality[19]), the individual survey metrics were also plotted against absolute elevation difference (Figure 4.4). Interestingly, the relationships between these individual metrics and their absolute elevation differences from the experiments are not obvious. Point density shows the clearest and most intuitive relationship, with high point densities correlated to lower differences and low point densities spanning a wide range of generally higher elevation differences. On the basis of the spatial patterns, slope might be expected to show the strongest indication of a relationship with higher differences expected at higher slopes. However, graphically the scatter plot is not convincing. There are at least two explanations for why these relationships are not more obvious. The first is that the concentration of data points are heavily biased by the distributions of the metrics themselves. For example, the vast majority of the reach has low slopes (hence large concentration of points at low slopes), leaving far fewer points at higher slopes to indicate whether or not a meaningful relationship exists. A more recognisable relationship emerges if the absolute elevation difference statistics are segregated into bins by slope (Table 4.4).

[18]Where water depths are deep, it may be difficult to judge the bottom and/or hold the rod steady.

[19]Most GPS devices, allow you to calculate a 3D error vector, which is the resultant of residuals for each point in the easting, northing and elevation, as calculated from all measurements taken during an individual point acquisition. It is primarily a reflection of a) satellite geometry and b) how steadily the operator is holding the detail pole.

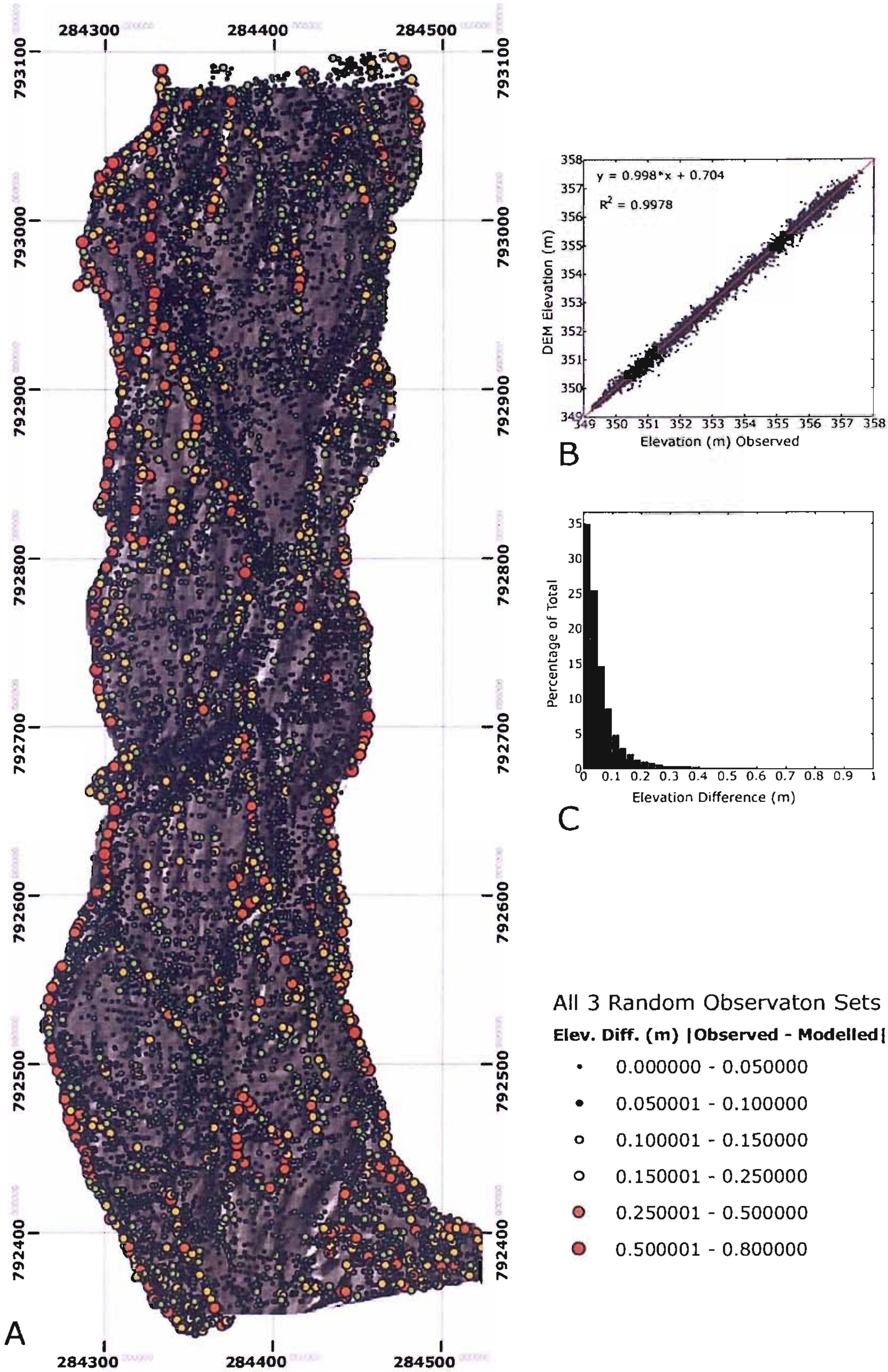


FIGURE 4.3: Combined results of three numerical experiments for estimating elevation uncertainty (see text for details) A) Map of location and magnitude of absolute elevation differences (assumed representative of $\delta(z)$) from random samples; B) Comparison of observed versus modelled elevations at random sample locations (red line is 1:1 line); C) Distribution of absolute elevation differences.

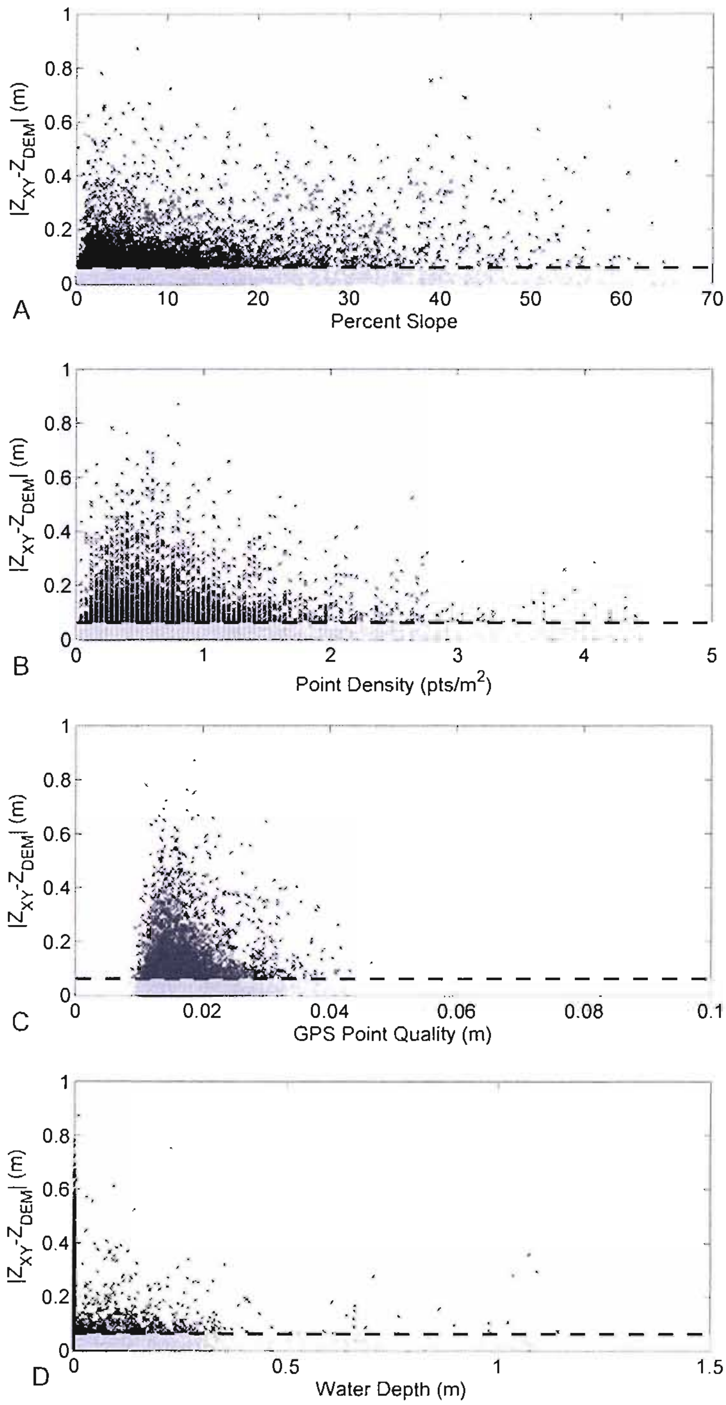


FIGURE 4.4: Results from bootstrapping experiments. Individual survey metrics are compared against elevation differences (taken to be elevation error) for A) Local DEM Surface Slope; B) Survey Point Density; C) GPS Point Quality Metric; and D) Water Depth. For reference, the area faded out beneath the dashed line represents a $_{min}$LoD threshold as estimated from § 4.3.1.1 (2σ) to delineate the portion of the distribution that can not be distinguished from noise (bottom).

4.3.1.4 Repeat Survey Experiments

An alternative to bootstrapping-type exercises for characterising $\delta(z)$ is to simply repeat the exact same topographic survey multiple times over a surface that has not changed and look at the variation between surveys (Brasington & Smart 2003). In August of 2004, a series of repeat survey experiments of fluvial surfaces that were known not to have changed[20] were conducted in the Feshie to estimate the magnitude of elevation uncertainty in DEMs as well as what components were primarily responsible for contributing to it. The experiments were conducted at two sites within the study reach and these are depicted in Figure 4.5 D, E and F. These sites were referred to as the 'Confluence Site' (located just upstream of the confluence of two main channels) and the 'Dry Bar Site', and their locations in relationship to each other are shown in Figure 4.6A. Below, the experiments and the results are described separately.

The first of these experiments, at the 'Confluence Site', involved seven resurveys of a subset of the study reach. As shown in Table 4.5, the number of points in each survey and point density (Pt ρ), were broadly equivalent across all surveys. The site was chosen as it exhibited a range of the common morphological features encountered in the study site (e.g. active channel, steep cut bank, flat bar tops, vegetating bar). The spatial stratification of points collected was designed to mimic the regular survey (rough grid 2-3 metre spacing with separate survey of grade breaks and major morphological features). The individual survey points for each survey are shown in Figure 4.6B with different colours and symbols. The first two surveys (Exp1A$_{Normal}$ and Exp1B$_{Normal}$) were executed exactly as the normal topographic survey would have been. During the second of these, a simple sub-experiment was performed to assess whether ground-based GPS and total station surveying with a detail pole systematically samples points on gravel surfaces on tops of grains or the voids between grains (the discrepancy highlighted in Figure 4.5 A versus B). During the GPS topographic survey, the surveyor placed the detail pole on the gravel-bed to acquire a point using their standard technique and not paying any particular attention to precise placement of the tip. After the detail pole was placed, the surveyor than looked at the placement of the tip and recorded whether it happened to fall in the voids between grains or on top of a fully-exposed grain at the surface. Over 83% (125 of 150) observations were recorded in the voids between grains. On sandy and vegetated surfaces, this systematic over-sampling of lower elevations at the surface is likely to be even more pronounced with a standard pointed-tip detail pole, as it penetrates deeper into the subsurface. After this observation, the next four repeat surveys were altered slightly to capture the maximum $\delta(z)$ (or potentially a grain roughness signal[21]) as a result of systematic bias towards sampling in voids or on the tops of grains. The spatial stratification of points was carried out exactly as described above, but in the first two surveys (Exp2A$_{Voids}$ and Exp2B$_{Voids}$) the operator deliberately placed the survey tip in voids and on the second two (Exp3A$_{HPs}$ and Exp3B$_{HPs}$) deliberately sampled on the tops of grains.

A wide range of analyses were performed on the data from the Confluence Site repeat surveys.

[20]Surveys conducted over the space of a couple hours during low (non-competent) flows.
[21]See Appendix E for roughness extraction.

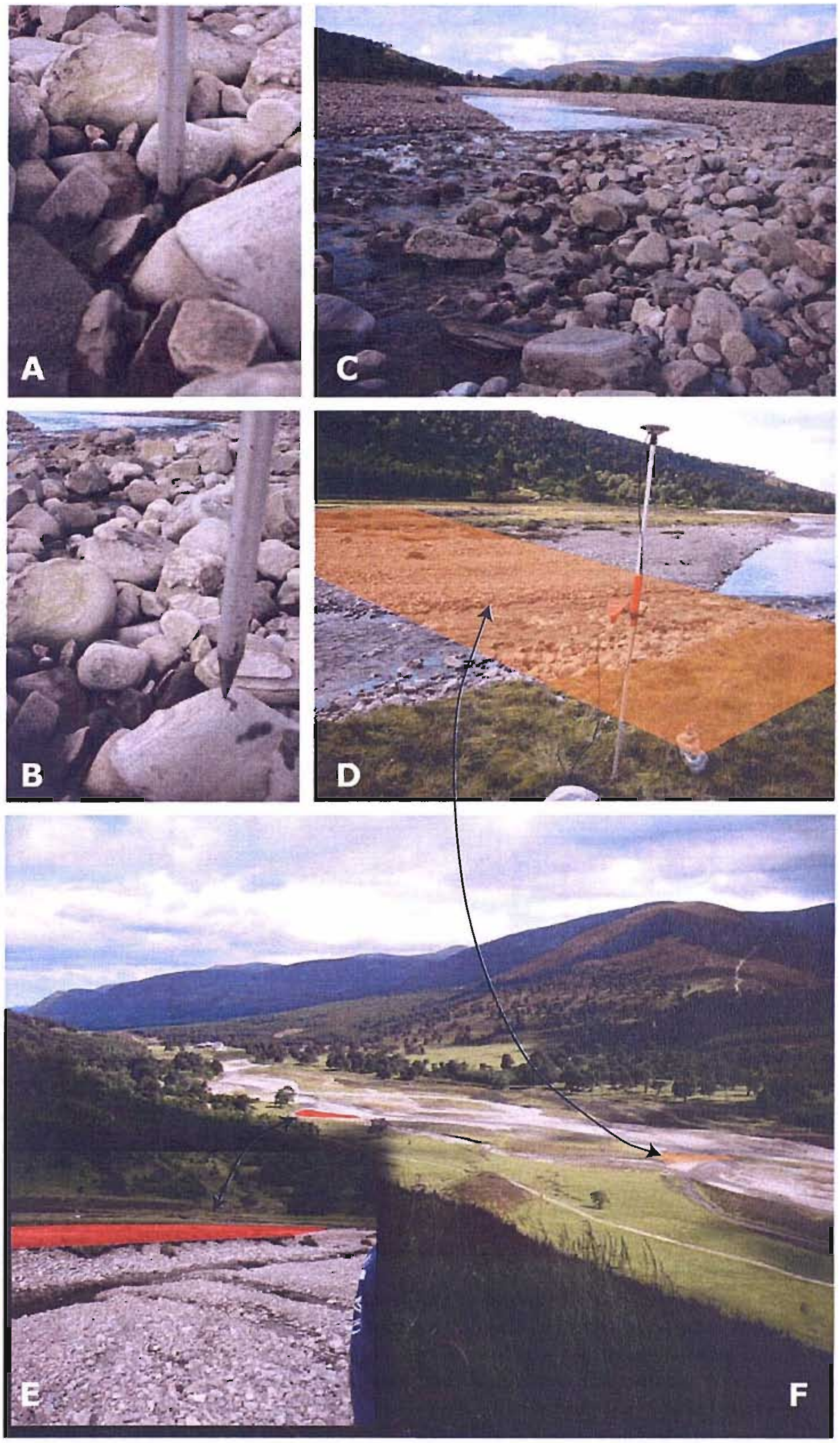


FIGURE 4.5: Photos depicting conditions and locations of repeat survey experiments. A and B highlight the difference between survey points collected within voids (A) as opposed to on top of grains (B). C and D show the nature of the morphology and surface roughness at the Confluence Site Experiment. E shows the exposed and vegetating bar top of the Dry Bar Site Experiment. F shows the location of the two experiment sites (Dry Bar in red and Confluence in orange), within the study reach (flow is from right to left).

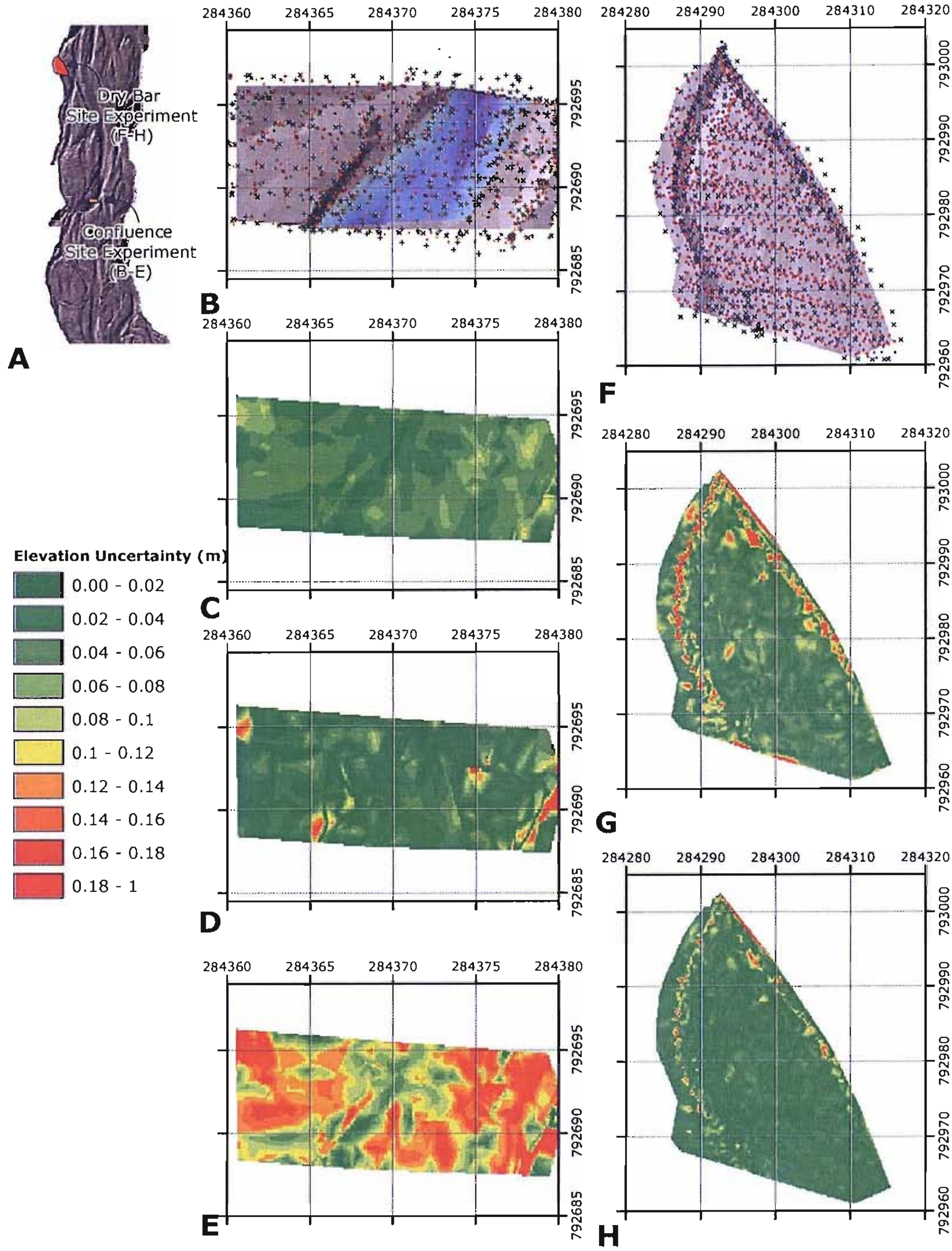


FIGURE 4.6: Summary results of repeat survey experiments. A) Study sites are shown within the 2004 study reach. B) Depicts the morphology, water depth and sample locations for the seven repeat surveys performed at the Confluence Site. C) Elevation uncertainty as derived from standard deviation of all seven repeat survey DEMs constructed with explicit grade break feature codes in the TINs at the Confluence Site. D) Elevation uncertainty as derived from standard deviation of all seven repeat survey DEMs constructed with out explicit grade break feature codes in the TINs at the Confluence Site. E) Elevation uncertainty as derived from the difference between the maximum of high points and the minimum of low points (see text) at Confluence Site. F) Depicts the morphology and sample locations for the three repeat surveys performed at the Dry Bar Site. G) Elevation uncertainty as derived from the difference between the maximum of high points and the minimum of low points (see text) at the Dry Bar Site. H) Elevation uncertainty as derived from standard deviation of three repeat surveys at the Dry Bar Site.

Experiment	n Points	n GB Points	% in Voids	Pt ρ
Exp1A$_{Normal}$	172	34	?	0.735
Exp1B$_{Normal}$	227	59	84%	0.970
Exp2A$_{Voids}$	169	34	100%	0.722
Exp2B$_{Voids}$	178	26	100%	0.761
Exp3A$_{HPs}$	198	35	0%	0.846
Exp3B$_{HPs}$	166	36	0%	0.709
Regular Survey	186	0	?	0.795

TABLE 4.5: Magnitude and point density of 2004 repeat surveys at Confluence Site.

The results of three of these are highlighted in Figure 4.6 C, D and E and the corresponding histograms are shown in Figure 4.7. DEMs of 25 cm resolution were prepared (as opposed to 1 m) for all the surveys as described in Appendix C. First DEMs were derived from TINs built including grade breaks.[22] The DEMs were then reconstructed without including the grade-break points to ascertain whether this additional survey detail improved overall surface representation. A variety of ArcGIS Spatial Analyst tools were used to make basic inter-comparisons of the DEMs. These included a) the maximum absolute elevation difference in each grid cell between all surveys (replicates with and without grade break points); b) the standard deviation of elevation in each grid cell between surveys; and c) the average of DoD values (between pairs of surveys). These were repeated using the following samples: i) all seven surveys; ii) just the regular surveys; iii) just the high point surveys; and iv) just the void point surveys.

The difference between Figure 4.6 C and D highlights the importance of including grade break points in the survey. Both results show a spatial structure of elevation uncertainty with higher magnitudes in areas of topographic complexity or higher surface roughness. The influence of including the grade breaks is clear in its influence on the maximum elevation uncertainties (12 cm vs. 30 cm). However, their histograms (Figure 4.7 A and B) tell a rather different story with the relative magnitude of elevation uncertainty slightly higher when the grade break points are included (μ = 4.4 cm) versus not (μ = 3.0 cm). Figure 4.6 E highlights the maximum absolute elevation difference between all surveys and shows a spatial structure consistent with that in Figure 4.6 C and D. However, the magnitude is substantially greater (μ = 12 cm) and the distribution is probably showing a strong reflection of the grain size distribution and surface roughness in addition to the more standard surface representation uncertainties.

At the second site, the 'Dry Bar Site', a simpler single experiment was conducted to explore whether there was a difference in elevation uncertainty between a fairly flat and relatively smooth vegetating dry bar top, and the steep banks that demarcated the bar's boundary. Only two repeat surveys were conducted in addition to the original (total of three), and these were performed by different operators[23] using the 'same' sampling strategy (Figure 4.6F).

[22]Normally explicit grade breaks using 3D polylines are not undertaken as it is too laborious for this scale of mapping. Moreover, if point density is high enough and grade breaks captured in the survey, the morphology is reasonably represented.

[23]Note the reach surveys are all performed by a team of 3-7 surveyors, with multiple GPS rovers running.

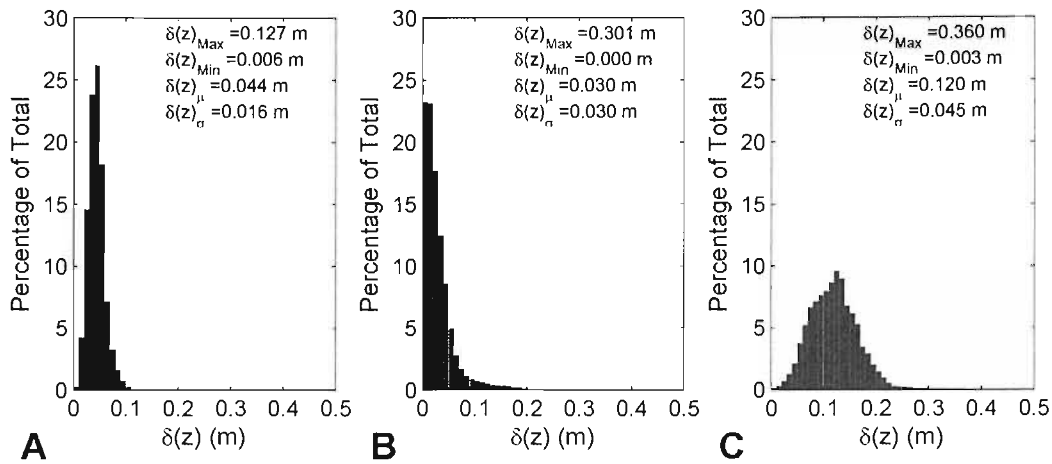


FIGURE 4.7: Histograms of elevation uncertainty ($\delta(z)$) for experiments at Confluence Site. A) Elevation uncertainty as derived from standard deviation of all seven repeat survey DEMs constructed with explicit grade break feature codes in the TINs. B) Elevation uncertainty as derived from the standard deviation of all seven repeat survey DEMs constructed with out explicit grade break feature codes in the TINs. C) Elevation uncertainty as derived from the difference between the maximum of high points and the minimum of low points (see text).

DEMs were constructed of all three surveys as per normal with a 1 metre grid resolution. Comparisons between the surfaces included a) the maximum absolute elevation difference in each grid cell between the three surveys; b) the standard deviation of elevation in each grid cell between the three surveys; and c) the average of three DoD values. The spatial results of a) and b) are highlighted in Figure 4.6 G and H, respectively, and the corresponding histograms are shown in Figure 4.8. Spatially, this experiment highlights the intuitively obvious - higher elevation uncertainty ($\delta(z) > 10$ cm) on the steep banks and lower uncertainty (10 cm $> \delta(z) > 2$ cm)on the relatively smooth vegetating bar top. The mean absolute elevation difference was 4.8 cm ($\sigma = 5.4$ cm) and the mean standard deviation of elevations was 2.4 cm.

Both experiments highlight a strong spatial organisation of elevation uncertainty magnitudes. Moreover, the mean magnitudes of $\delta(z)$ are broadly consistent with those reported in the literature (Brasington *et al.* 2000, e.g.) and in previous sub-sections using different techniques. The spatial structure may be compelling, and the factors contributing to these patterns (e.g. combination of grain roughness, point density, morphology, etc.) may be apparent and straight-forward to describe. However, these experiments provide little insight as to how one could decompose the uncertainty into its component parts (the purpose of this § 4.3.1) or, construct a model of that uncertainty from its component parts (the purpose of the next § 4.3.2).

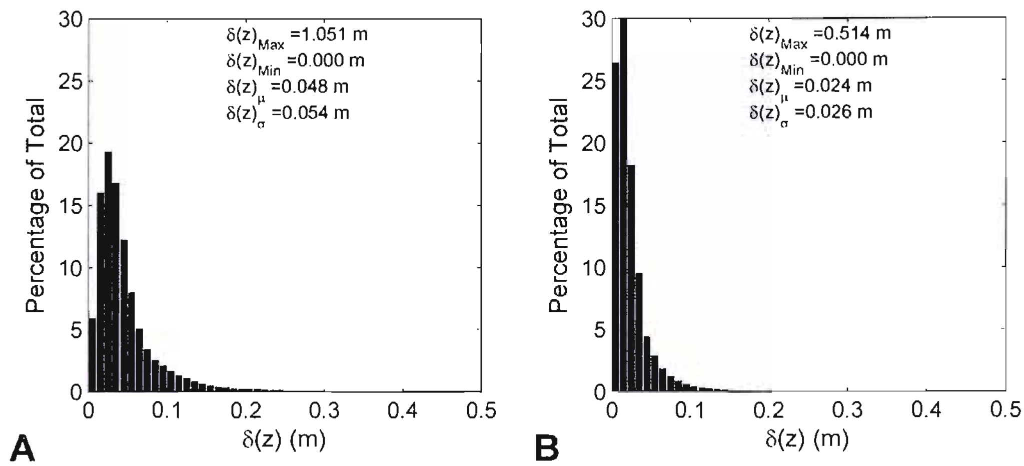


FIGURE 4.8: Histograms of elevation uncertainty ($\delta(z)$) for experiments at Dry Bar Site. A) Elevation uncertainty as derived from the difference between the maximum of high points and the minimum of low points. B) Elevation uncertainty as derived from standard deviation of three repeat surveys.

4.3.1.5 Other Methods

A non exhaustive selection of contrasting approaches to estimating elevation uncertainty in DEMs has been presented in this section. Most of the techniques, as they have been applied in the past, have the aim of collapsing the elevation uncertainty down to a single global metric. However, elevation uncertainty exhibits spatial variability that could exert a strong influence on morphological sediment budget results and interpretations. There are potentially other approaches to representing elevation uncertainty. For example, Lodwick & Santos (2003) build terrain models (not of the Earth's surface, but it could be applied as such) with fuzzy surfaces. Therein, each elevation of the surface is represented by a fuzzy number and membership function as opposed to a single crisp value. The fuzzy number expresses the range of uncertainty in the elevation values. Similarly, one might represent each elevation in a DEM with its own probability distribution. Fuzzy models may afford some degree of flexibility over probabilistic models.[24] Chappell *et al.* (2003), used a more traditional geostatistical technique and modeled topography with Kriging surfaces, which explicitly incorporate a spatially variable estimate of uncertainty. An unfortunate by-product of this approach is that it does not preserve the actual surveyed point elevations in the final surface like a simple TIN-based technique. In the case of high-resolution ground-based surveys that specifically capture morphological grade breaks, a Kriging interpolation technique may not work as well as it does on much coarser resolution datasets that are typical in geostatistics. Although all of these approaches provide a means of expressing elevation uncertainty, neither of these approaches fundamentally provides a mechanism to systematically and robustly quantify the elevation uncertainty. If one is going to revert back to more simplistic spatially uniform estimates of elevation uncertainty, than there

[24] In terms of the assumptions required for valid application. See § 2.3.2.3 for discussion as to why.

is no need to use a complex surface model to represent it. The error budgeting alternative requires inputs that are not readily available and a degree of mathematical numeracy that many geomorphologists and restoration practitioners (primary users of the morphological method) may lack. Thus, a more tractable approach that could estimate spatially variable elevation uncertainty patterns on the basis of readily available information would be preferable.

4.3.2 Propagating Uncertainty into DoD

The significance of error or uncertainty[25] propagation from the individual DEMs into the DoD is related to the issue of separating real changes (e.g. due to geomorphological processes) from spurious changes that arise due to DEM uncertainty. Once the errors in the individual surface DEMs have been estimated, Brasington *et al.* (2000) showed they can be propagated by:

$$E_{DoD} = \sqrt{(\epsilon_{new})^2 + (\epsilon_{old})^2} \tag{4.4}$$

where E_{DoD} is the combined error, and ϵ_{new} and ϵ_{old} are the individual errors in DEM$_{new}$ and DEM$_{old}$ respectively.[26] Two fundamental points arise when operationalising error propagation in DEM-differencing:

1. What error should be propagated?
2. How should the total propagated error be used to assess the DoD?

Brasington *et al.* (2000) were amongst the first to spell out the conceptual framework for error propagation in DEM-differencing that addresses these questions. The error to be propagated was in part the subject of the previous sub-section[27], but, as was demonstrated there are no shortage of methodological choices (*structural uncertainty*) as to how to define this error (e.g. spatially variable vs. uniform).

To extend the $_{min}$LoD for DEM differencing into a probabilistic framework, Lane *et al.* (2003) followed the framework outlined by Taylor (1997). Such a framework allows one to assess the probability that DoD predicted changes are real and instead of thresholding with an elevation $_{min}$LoD, one can probabilistically define a confidence interval $_{min}$LoD threshold based on what probability the user is willing to accept that changes may be real.[28] As probabilities are a form of expressing uncertainties that most people are accustomed to, casting DoD analyses in a probabilistic framework has conceptual appeal. The methods used in this chapter adopt this probabilistic framework and, as such, the derivation of a form of equations 4.3 and 4.4

[25]The terms 'uncertainty' and 'error' are used interchangeably here. As explained in § 2.2.1, an error is technically not an uncertainty but a metric for accuracy and can only be calculated if the *true* value is known. In the practise of DEM-differencing, the true value is not known and errors can only be estimated and used as an expression of uncertainty. Thus, it is assumed that $\delta(z) \cong \epsilon_z$.

[26]This is nothing more than a specific application of the quadratic error formula presented in Eq. 4.3.

[27]See § 4.3.1.

[28]This idea is developed in the next sub-section.

outlined by Lane *et al.* (2003) is reviewed here and elaborated with reference to Burrough & McDonnell (1998) and Taylor (1997).

The result of mathematical operations[29] between two or more quantities are subject to the uncertainties in the input quantities (A_i). Consider the general operation:

$$B = f(A_i) \tag{4.5}$$

where the output B is an arithmetic function relating the input variables A_1, A_2, ... A_n. The question is how do uncertainties in the input variables manifest themselves or propagate into the output, B? Or formulaically:

$$B + \delta(b) = f\left((A_1 + \delta(a_1)) + (A_2 + \delta(a_2)) + \ldots + (A_n + \delta(a_n))\right)) \tag{4.6}$$

where $\delta(b)$ and $\delta(a_i)$ represent the error associated with the output B and inputs A_i respectively. If it is reasonable to assume that the error terms ($\delta(a_i)$) in the input variables (A_i) are random, unbiased and uncorrelated, the errors can be reliably treated as normally distributed and quantified in terms of their mean (μ) and standard deviation (σ).[30] For the simple case of a mathematical operation like DEM-differencing ($b = a_1 - a_2$), where both the true values of a_1 and a_2 are zero, Taylor (1997) showed that the probability of sampling a specific value of a_1 can be found as:

$$Prob(a_1) \propto \exp\left(\frac{-a_1^2}{2\sigma_{a_1}^2}\right) \tag{4.7}$$

and a_2 as:

$$Prob(a_2) \propto \exp\left(\frac{-a_2^2}{2\sigma_{a_2}^2}\right) \tag{4.8}$$

and the probability of simultaneously sampling any a_1 or a_2 is:

$$Prob(a_1, a_2) \propto \exp\left[-12 \cdot \left(\frac{a_1^2}{\sigma_{a_1}^2} - \frac{a_2^2}{\sigma_{a_2}^2}\right)\right] \tag{4.9}$$

It follows from Eq. 4.9 that the values of $(a_1 - a_2)$ are distributed as $\sqrt{\sigma_{a_1}^2 + \sigma_{a_2}^2}$ and the uncertainty term $\delta(b)$ from Eq. 4.6 can be estimated as:[31]

$$\delta(b) = \sigma_b = \sqrt{\sigma_{a_1}^2 + \sigma_{a_2}^2} \tag{4.10}$$

Note that in this special case of subtraction, the probabilistic framework reduces down to Eq. 4.10, which is of the same form as Eq. 4.4.[32]

In summary, when the input quantities a_1 and a_2 are the elevation uncertainties $\delta(z_1)$ and $\delta(z_2)$ (corresponding to an older DEM_1 and newer DEM_2 respectively), Eq. 4.10 provides

[29] Such as simple subtraction as in DEM-differencing.

[30] This assumption is justified in Lane *et al.* (2003, pp. 253-254) on the basis that systematic errors are removed from the raw point data ahead of time.

[31] Applies only for the simple case of subtraction or addition of two input quantities (a_1 and a_2).

[32] This is the familiar error propagation formula: the total error is equal to the square root of the sum of squares of the individual errors.

a general solution for the propagation of elevation uncertainties into the DoD to produce $\delta(DoD)$. Most authors and practitioners have taken the elevation uncertainties ($\delta(z_1)$ and $\delta(z_2)$) to be spatially uniform (e.g. Brasington *et al.* 2000, thereby calculating a global DoD uncertainty metric ($\delta(DoD)$).

This assumption of spatial homogeneity is not necessary, as Eq. 4.10 can actually be applied on a cell by cell basis for each DoD cell providing a spatially heterogeneous estimate of DoD uncertainty (Brasington *et al.* 2004). However elegant this may be, the practical challenge then returns to the task of quantifying surface representation uncertainty in § 4.3.1 on a cell-by-cell basis. Lane *et al.* (2003) and Westaway *et al.* (2003) take a slightly simpler approach of differentiating elevation uncertainties ($\delta(z)$) into spatial regions on the basis of whether or not the DEM cell is subaerial (dry) or subaqueous (wet). Their DEMs were derived from aerial photogrammetry with standard photogrammetric procedures used for deriving the DEM in subaerial contexts. However, deriving a DEM for the subaqueous fraction relies on either retaining a generally much lower density of photogrammetrically matched points under water and then applying some sort of refraction correction (Westaway *et al.* 2000, Westaway *et al.* 2001, e.g.) or estimating the water-depth from the image reflectance (assuming a correlation between reflectance and water-depth) and subtracting this from the photogrammetrically determined water surface elevation (Winterbottom & Gilvear 1997, Gilvear *et al.* 1995, Brasington *et al.* 2003). In either method, the ($\delta(z)$) for the subaqueous portion is higher. Recognising this, Lane *et al.* (2003) defined four error propagation classes: wet ⇒ wet, wet ⇒ dry, dry ⇒ dry and dry ⇒ wet. This is a perfectly reasonable approach to account for spatial differences due to DEM construction differences between years. However, experiments such as those reported in § 4.3.1.3 and § 4.3.1.4 suggest that there is an even stronger spatial structure present in DEM elevation uncertainties ($\delta(z)$) that is related to the morphology, surface roughness, point sampling patterns, and other factors. How to derive this spatial structure in a robust and tractable manner remains an unanswered question.

4.3.3 Assessing the Significance of DoD Uncertainty

The significance of propagated DEM uncertainty into uncertainty in DoD predicted elevation changes can be expressed in at least three ways. First, if an elevation $_{min}$LoD threshold is defined,[33] its significance is that all changes below this threshold are assumed not to be real as they can not be distinguished from noise. The simplest way to illustrate the significance of this uncertainty is by comparing the influence of various $_{min}$LoD thresholds on DoDs and their elevation change distributions (Figure 4.9). The more uncertain the DEMs (and hence the higher the $_{min}$LoD threshold), the more information is lost from the budget. Clearly, we would expect elevation differences to occur across a continuum of values as suggested by the raw DoD. However, the significance of the uncertainty is the inability to reliably detect these lower magnitude elevation changes below the $_{min}$LoD threshold.

[33] This can be defined in a variety of ways (e.g. empirically: § 4.3.1.1; theoretically).

Second, if fuzzy DEM surfaces were used (e.g. Lodwick & Santos 2003), the DoD itself is a fuzzy surface and each elevation difference is a fuzzy number.[34] Thus, the fuzzy surface expresses the uncertainty in DoD values and the method one chooses to defuzzify that surface into a crisp representation (single valued best estimate) determines the significance.

Third, as eluded to in the previous section, a probabilistic representation of DoD uncertainty ($\delta(DoD)$) can be defined, and a statistical significance confidence interval can be used to either threshold or weight the DoD predicted changes. As most people are more familiar with conceptualising uncertainties as probabilities (as opposed to fuzzy numbers), a probabilistic framework is adopted in this thesis. As such, a method used here of calculating probabilities using inferential statistics is described briefly below.

Referring back to the previous section, Eq. 4.10 provides a basis for inferring the statistical significance of a calculated difference between two quantities. The two quantities of interest here are the elevations (z_{DEM_1} and z_{DEM_2}) at two different times, which are differenced to produce the DoD. In this case, a null hypothesis can be formulated that any observed difference ($z_{DEM_2} - z_{DEM_1}$) is simply due to chance measurement error. Thus, the observed difference can be represented as a t-score:

$$t = \frac{|z_{DEM_2} - z_{DEM_1}|}{\sigma_{DoD}} \tag{4.11}$$

where σ_{DoD} is the propagated uncertainty term from Eq. 4.10, which quantifies the measured elevation difference in terms of the characteristic uncertainty, σ_{DoD}. The probability of a difference occurring purely due to chance measurement error can then be calculated by relating the t-statistic to the cumulative distribution function (CDF) for t.[35] For problems based on large samples used to determine σ_{DoD}, the t distribution is almost identical to the normal distribution, so that a difference, $z_{DEM_2} - z_{DEM_1}$, giving $t = 1$ can be treated as significant at the 68% confidence limit and $t = 1.96$ is significant at the 95% confidence limit assuming a two-tailed test.

The significance of observed differences based on a probability transformation of Eq. 4.11 can be applied across all the cells of a regular gridded DEM provided that either σ_{DoD} is assumed to be globally homogeneous, or known locally and assumed spatially independent. Even if the propagated DoD uncertainty is spatially uniform, σ_{DoD}, the probability that the change is real will vary spatially. This is illustrated in Figure 4.10. As the t-score is a function of the actual DoD magnitude (which does vary spatially), whether the propagated DoD uncertainty (σ_{DoD}) varies spatially or not, the calculated probability will vary spatially. To date, applications of this method to sediment budgeting with DEMs have generally treated σ_{DoD} as spatially uniform.[36] However, if the propagated DoD uncertainty, σ_{DoD}, can be defined as spatially variable (e.g. calculated independently for each cell), then a t-score and probability can be

[34] See § 2.3.2.3 for explanation of fuzzy numbers.

[35] In this thesis, the *tcdf* function in Matlab's Statistics Toolbox was used to perform this integration and calculate a probability.

[36] Excepting Lane *et al.* (2003), which was described in the previous sub-section.

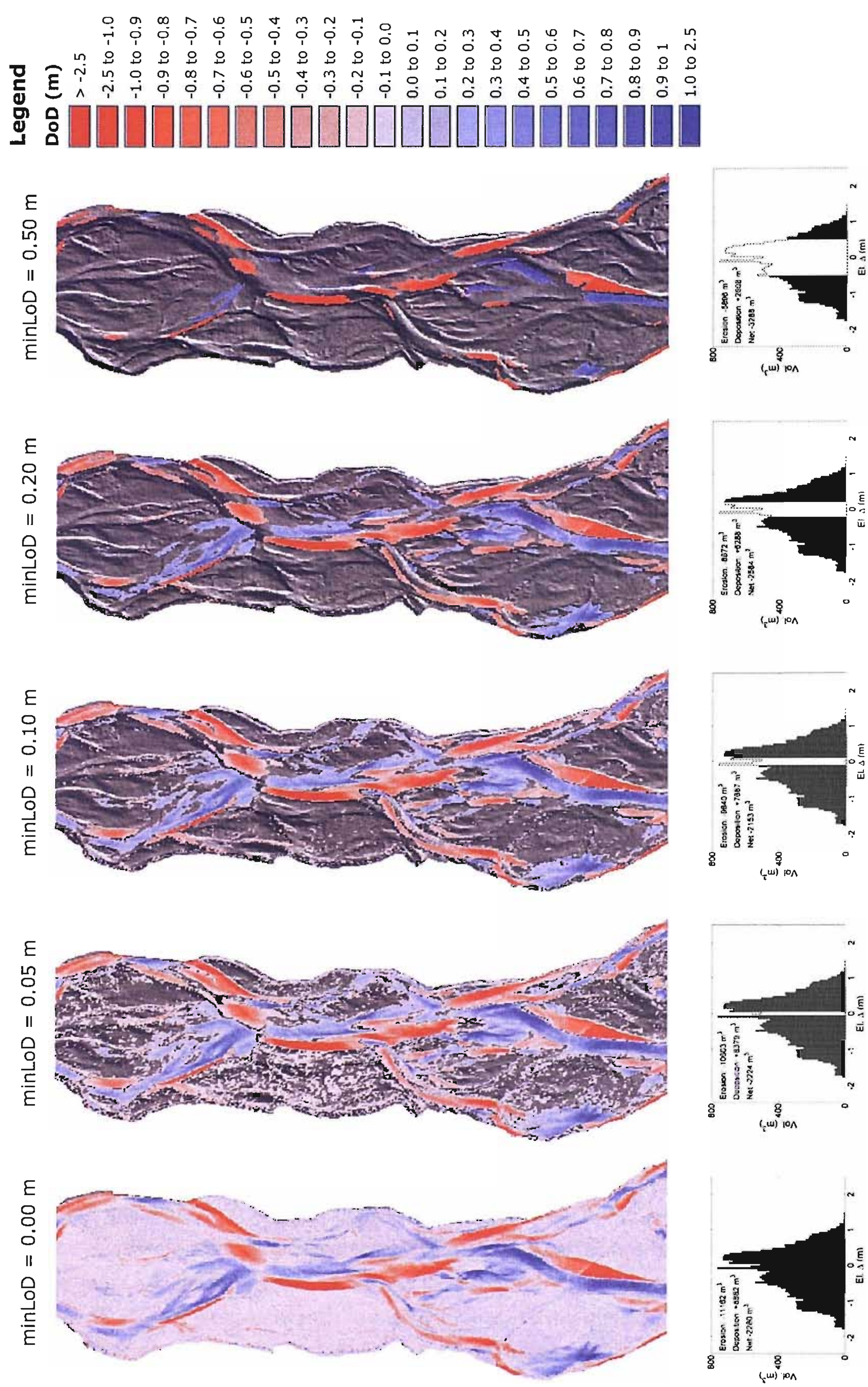


FIGURE 4.9: Example of significance of elevation ${}_{min}$LoD threshold on DoD budget for 2007-2006 DoD. The DoD maps are shown on top and the elevation change (El. Δ) distributions are shown below. The gross unthresholded DoD is shown on the far left, and moving toward the right progressively more conservative (i.e. higher $\delta(DoD)$ and ${}_{min}$LoD) are shown.

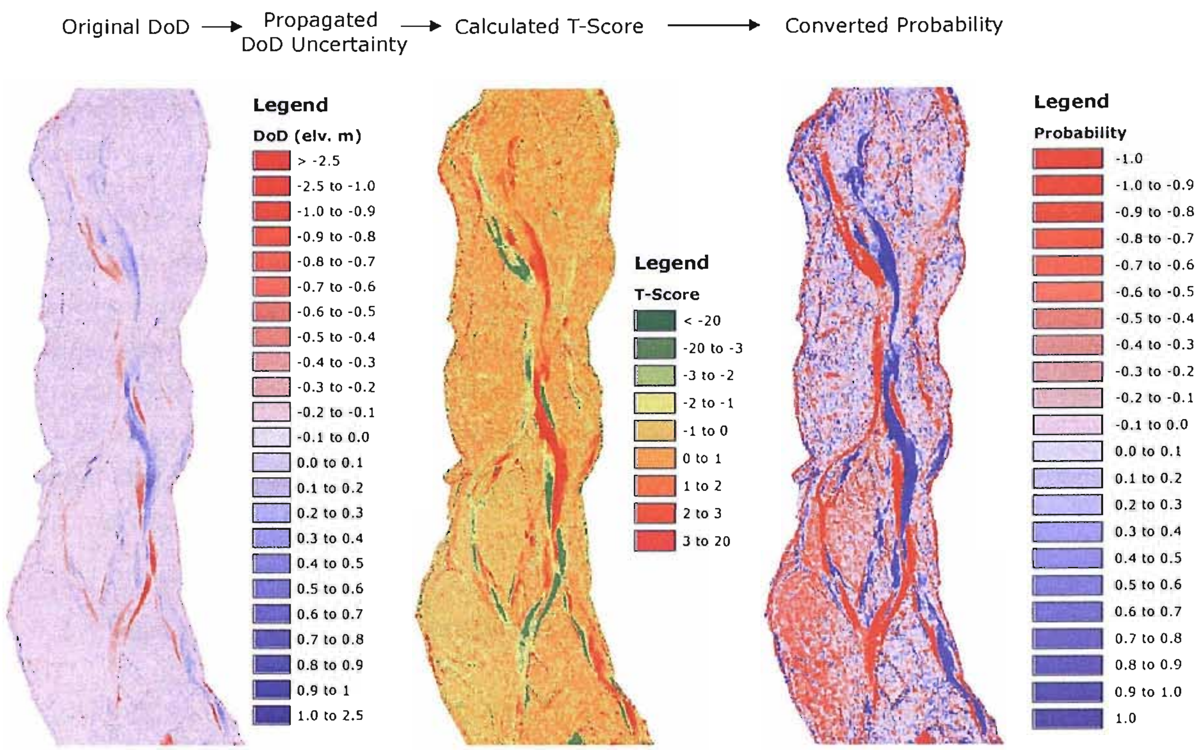


FIGURE 4.10: Illustration of the calculation of the probability that DoD predicted changes are real for 2006-2005 DoD. Given a DoD (left), and some spatially uniform propagated DoD uncertainty, σ_{DoD} (calculated as 0.085 cm in this example from Eq. 4.10: $0.085 = \sqrt{0.06^2 + 0.06^2}$), a T-score can be calculated directly from Eq. 4.11 (middle), and then converted to a probability (right). Note that both positive and negative probabilities are shown, with erosional probabilities denoted by a negative sign to distinguish them from depositional probabilities (positive).

calculated accordingly to reflect this spatial variability. Thus the same challenge, of deriving this spatial structure in a robust and tractable manner, emerges again.

4.4 Methodological Development

Working off the premise that meaningful geomorphological changes are being unnecessarily discarded through $_{min}$LoD analyses, the spatial structure of elevation uncertainty (currently unaccounted for) becomes fundamentally important. Specifically, if one can identify regions of the DoD where $\delta(DoD)$ is lower than currently presumed, a less restrictive $_{min}$LoD may be applied and information about geomorphological changes that are likely to be real can be recovered (e.g. bar tops subjected to broad shallow sheets of deposition). Similarly, in areas where $\delta(DoD)$ is probably substantially higher than currently presumed (e.g. steep banks), a more restrictive $_{min}$LoD may be applied to more accurately adjust volumetric estimates of change to reflect this higher uncertainty. As Brasington *et al.* (2003) pointed out, the problem with spatially uniform $_{min}$LoD is that they influence different processes in different ways. A process like bank erosion has an elevation change distribution (ECD) that is entirely erosional but spans a large range of elevation change magnitudes (reflecting primarily differences in bank heights). Whereas a process like overbank deposition tends to exhibit a peaked ECD concentrated toward low-magnitude elevation changes that may well fall below a $_{min}$LoD threshold.

There are two original methodological contributions presented in this Chapter that were developed to address Objective 1 (see § 1.3.1) and the above problems. As emphasised in the previous section (§ 4.3), one of these is the development of a flexible and robust technique for estimating spatially variable surface representation uncertainties. The second was based on the recognition that erosion and deposition patterns tend to exhibit strong spatial coherence (i.e. contiguous zones of erosion or deposition as opposed to chequerboard patterns of erosion and deposition more indicative of noise). The next two sections describe the techniques developed and their justification.

4.4.1 Spatially Variable Uncertainty Quantification

Returning to the experiments in § 4.3.1.3 and § 4.3.1.4, figures 4.3 and 4.6 highlight a strong spatial bias in elevation uncertainty. Any experienced topographic surveyor could describe this bias in rather simple terms. Essentially, areas that are steep, have low survey point density, and high surface roughness (e.g. cobbles and boulders), have very high elevation uncertainty; whereas areas that are flat, have relatively high survey point density and are smooth have low elevation uncertainty. When elevation uncertainty is characterised by a spatially uniform value and this is used to define a minimum level of detection for change in elevations, the $_{min}$LoD is typically either defined based on an average value, which fundamentally discards more information than it should in areas where actual elevation uncertainty is lower, and does not discard enough information in areas where elevation uncertainty is higher. When a more conservative approach is employed and a higher $_{min}$LoD defined, even more information about potentially meaningful geomorphological changes is discarded. These simple observations form the premise for trying to quantify the spatial variability of elevation uncertainty. The crux of the problem is that the various components of elevation uncertainty are collinear variables and do not exhibit a simple, deterministic relationship to elevation uncertainty. Although an expert can identify the various factors that contribute to elevation uncertainty, a deterministic model of this elevation uncertainty can not be constructed. For these reasons, a more heuristic approach was attempted herein.

Chen *et al.* (1999*b*) and Chen *et al.* (1999*a*) contrast fuzzy and probabilistic models in terms of the type of uncertainty they are capable of describing. Whereas probabilistic models primarily describe random variability in parameters, fuzzy models primarily deal with vagueness in parameters. Although the assumptions on the nature of the statistics behind probabilistic models of uncertainty can be stretched in order to apply them, such applications can lead to serious errors (Chen *et al.* 1999*b*). By contrast, fuzzy models require very few assumptions and can be applied when relatively little is known about the uncertainty, or what is known can only be articulated linguistically as opposed to directly measured (Bandemer & Gottwald 1995, Klir

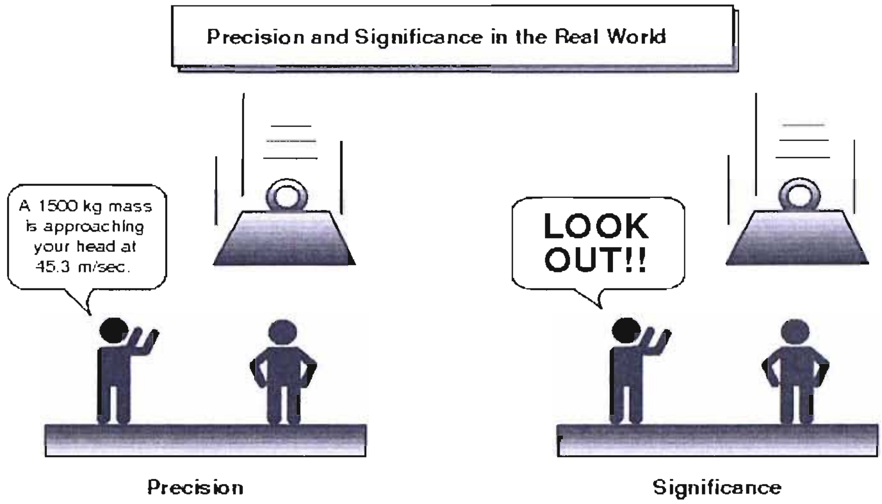


FIGURE 4.11: A cartoon contrasting precision and significance from Jang & Gulley (2007).

& Yuan 1995). One of the subsets of fuzzy set theory is fuzzy logic, and one of the tools that grows out of fuzzy logic is the fuzzy inference system. Fuzzy logic is often described as a trade-off between significance and precision as wittily illustrated in Figure 4.11 from Jang & Gulley (2007). The detail of the preceding section may obscure the fundamental motivation for considering uncertainty in DEMs - knowledge of how reliable geomorphological interpretations based on these DEMs are. As the cartoon suggests, the geomorphologist may not necessarily need to know the precise magnitude of elevation uncertainty from every minuscule component (e.g. due to slightly tilted detail pole) of the error budget. What is important is the significance of the total uncertainty on the geomorphological interpretation. Fuzzy inference systems are convenient frameworks for taking the information that is known (inputs) and producing an appropriate output (Jang & Gulley 2007). In the case of topographic surveys, something is always known about the survey sampling (e.g. point density) and the morphology (slope), and in some cases there may be additional information (e.g. roughness from facies maps, point quality from GPS). The fundamental quantity of interest is the elevation uncertainty $\delta(z)$. From empirical work (e.g. § 4.3.1), a reasonable understanding exists of the range and general magnitude of elevation uncertainties associated with various types of surveying. Here, a fuzzy inference system (FIS) is developed that accepts the inputs that are readily available and produces a $\delta(z)$ output that is calibrated to the range of empirically determined values. Matlab's Fuzzy Logic Toolbox, developed by Jang & Gulley (2007), was used to implement this FIS.

The fuzzy inference system consists of four components:

- Specification of FIS type, fuzzy operation methods, rule implication method, aggregation method and defuzzification method (if applicable)
- Definition of fuzzy membership functions for the inputs

- Definition of rules relating inputs to outputs
- Definition of fuzzy membership function for the output

Throughout the FIS analyses the most common default specifications for FIS type (Mamandi), fuzzy operation methods (And method: maximum), rule implication method (minimum), aggregation method (maximum) and defuzzification method (centroid) were used. In the next few sub-sections, the definition of the other three components will be described.

4.4.1.1 Fuzzy Inputs and Output

Fuzzy membership functions were described previously in § 2.3.2.3 in Chapter 2. Although fuzzy membership functions can come in a wide array of shapes, the most common forms are triangular and trapezoidal membership functions (Jorde & Schneider 2004). Fuzzy inference system outputs tend not to show that much sensitivity to membership function shape (Klir & Yuan 1995, Jang & Gulley 2007). The process of defining membership functions for a variable can be thought of in two parts. First, the number of linguistic adjectives that might be used to characterise the variable being described needs to be identified. For the inputs used here (slope, point density and point quality), the simple adjectives 'high', 'medium' and 'low' were deemed adequate to define rules from.[37] However, in principle any and as many adjectives as the user finds helpful are permissible. The second part consists of defining the membership function that will describe the range of values covered by each adjective for the input or output. The membership functions used throughout this thesis are shown in Figure 4.12. For the input variables, as long as the membership functions span the range of encountered values for that variable, the exact specification of their membership functions is not very critical (Klir & Yuan 1995, Jang & Gulley 2007). What is more important is that the expert defining the rule system knows what values the adjectives correspond to and develops their rules in accordance with those perceptions. For the output variable ($\delta(z)$ in this case), the second part is more critical. Here, the output membership functions need to correspond to realistic output values. The experiments reported in § 4.3.1 were used to check the magnitude of predicted elevation uncertainty by the FIS.

4.4.1.2 FIS Rules

Rule definition for the FIS is simply a process of linguistically relating the inputs (using their different adjectives defined above) to a single adjective for the output. For example, if 3D point quality is high, slope is low, and point density is high, then elevation uncertainty is low. By contrast if 3D point quality is low, slope is high, and point density is low, then elevation uncertainty is extreme. Both a generic 2-rule FIS (Table 4.6) based on point density and slope inputs, and a 3-rule FIS (Table 4.7), which incorporates GPS 3D Point Quality are

[37] If too many adjectives are used, far more rules need to be defined.

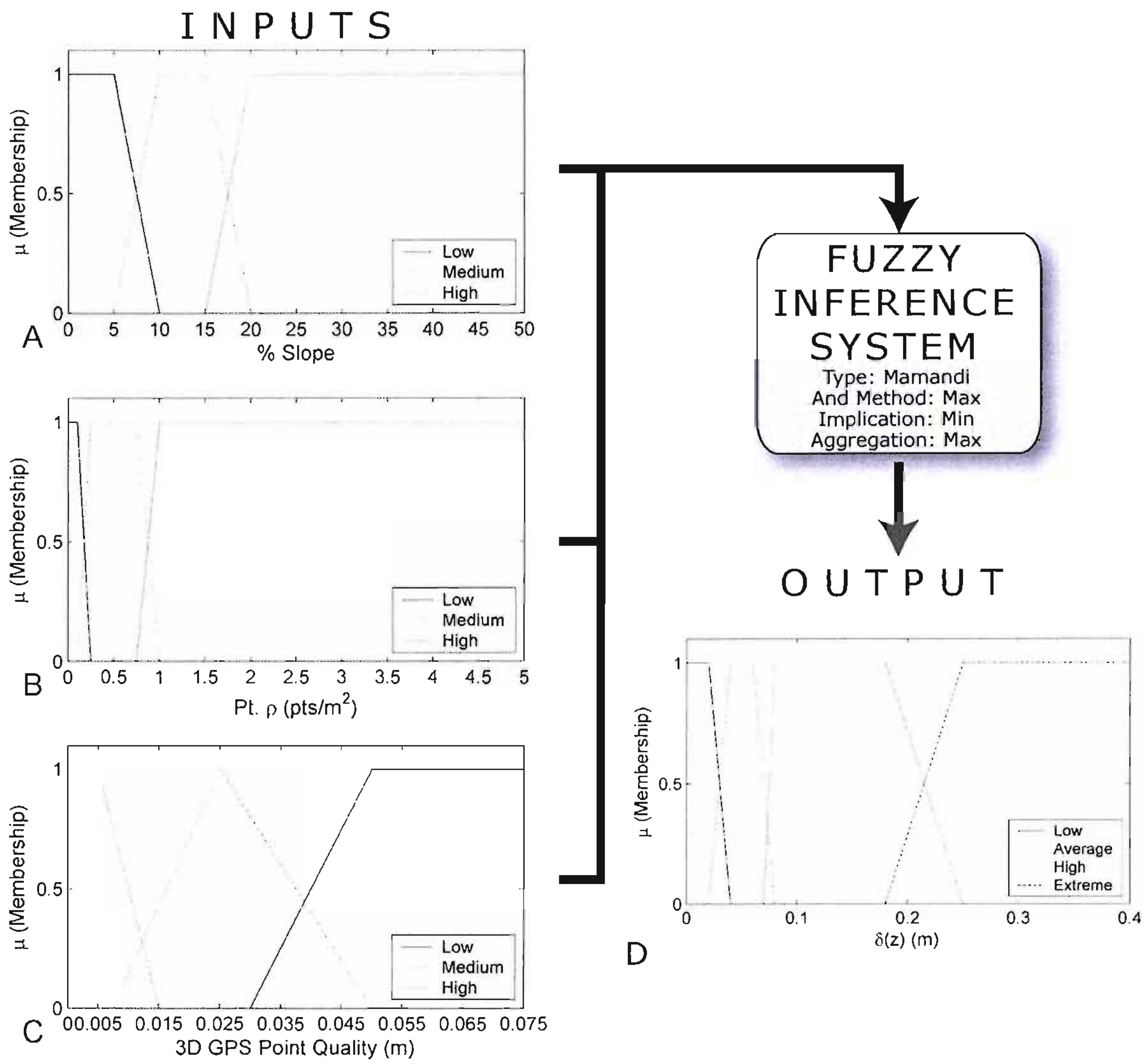


FIGURE 4.12: Input and Output Fuzzy Membership Functions used in this chapter. Inputs: A) Slope; B) Point Density; and C) Point Quality. Output: D) Elevation Uncertainty $\delta(z)$.

Rule:	Inputs		Output
	Slope %	Pt. ρ m/pts^2	$\delta(z)$ m
1	Low	Low	Average
2	Low	Medium	Low
3	Low	High	Low
4	Medium	Low	High
5	Medium	Medium	High
6	Medium	High	Average
7	High	Low	Extreme
8	High	Medium	High
9	High	High	High

TABLE 4.6: A two input fuzzy inference system for elevation uncertainty ($\delta(z)$). The two inputs are percent slope and point density.

reported here. The 2-rule system is proposed as applicable to any topographic survey using any technique as the point density and slope inputs can be derived from any raw XYZ vector topographic survey data set.[38] In both systems, slope was the dominant input controlling $\delta(z)$.

A number of other FIS rule systems were developed and experimented with including varying combinations of the above inputs as well as surface roughness and water depth. The FISs including water depth were not used for the case of the Feshie surveys as water depths were generally shallow and could not be shown empirically to have any sensible relationship to $\delta(z)$ (Figure 4.4). Roughness probably almost certainly exerts an important control on the magnitude of $\delta(z)$. Viable techniques for estimating roughness with facies maps include textural image analysis (Carbonneau *et al.* 2003), and/or retrievals from terrestrial laser scan data (Vericat *et al.* 2007). Any of these could be meaningfully incorporated into an FIS rule system. However, such alternatives were not available for all years from the Feshie (only 2007) and the aim of the chapter was to develop a system that could be implemented from any raw x,y,z survey point data. As such, an attempt was made to derive a meaningful map of surface roughness from the topographic survey data. It was found that the resolution of the survey data was too coarse to reliably estimate roughness.[39] Of key importance is that a user can flexibly define additional inputs and rules that are tailored to the specifics of their application. Alternatively, the generic 2-rule system defined here should provide a better approximation of $\delta(z)$ than existing spatially uniform assumptions.

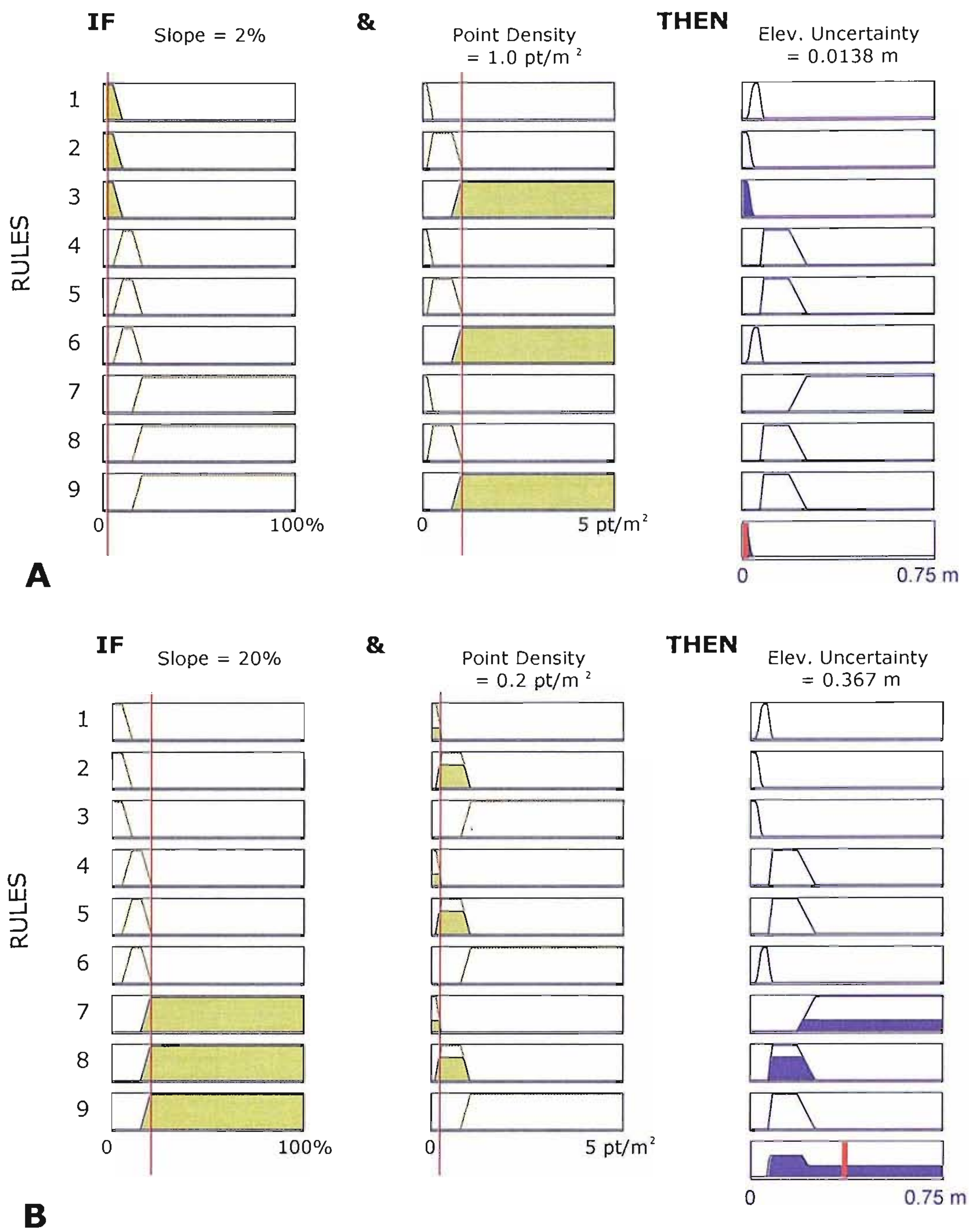


FIGURE 4.13: Two examples of the total consequence of the two input fuzzy inference system. A) A 'low' elevation uncertainty situation. B) A 'high' elevation uncertainty situation. In both situations, the total consequence of the relevant rules are aggregated to the shape that appears in the lower right corner. This aggregated fuzzy output is then defuzzified (using a centroid method) to produce a crisp estimate of elevation uncertainty. The thin red vertical lines represent the input values for the two examples. When a rule is applicable, the mass of the membership function it intersects is highlighted yellow. The output membership function is shaded blue, only when it has two applicable inputs.

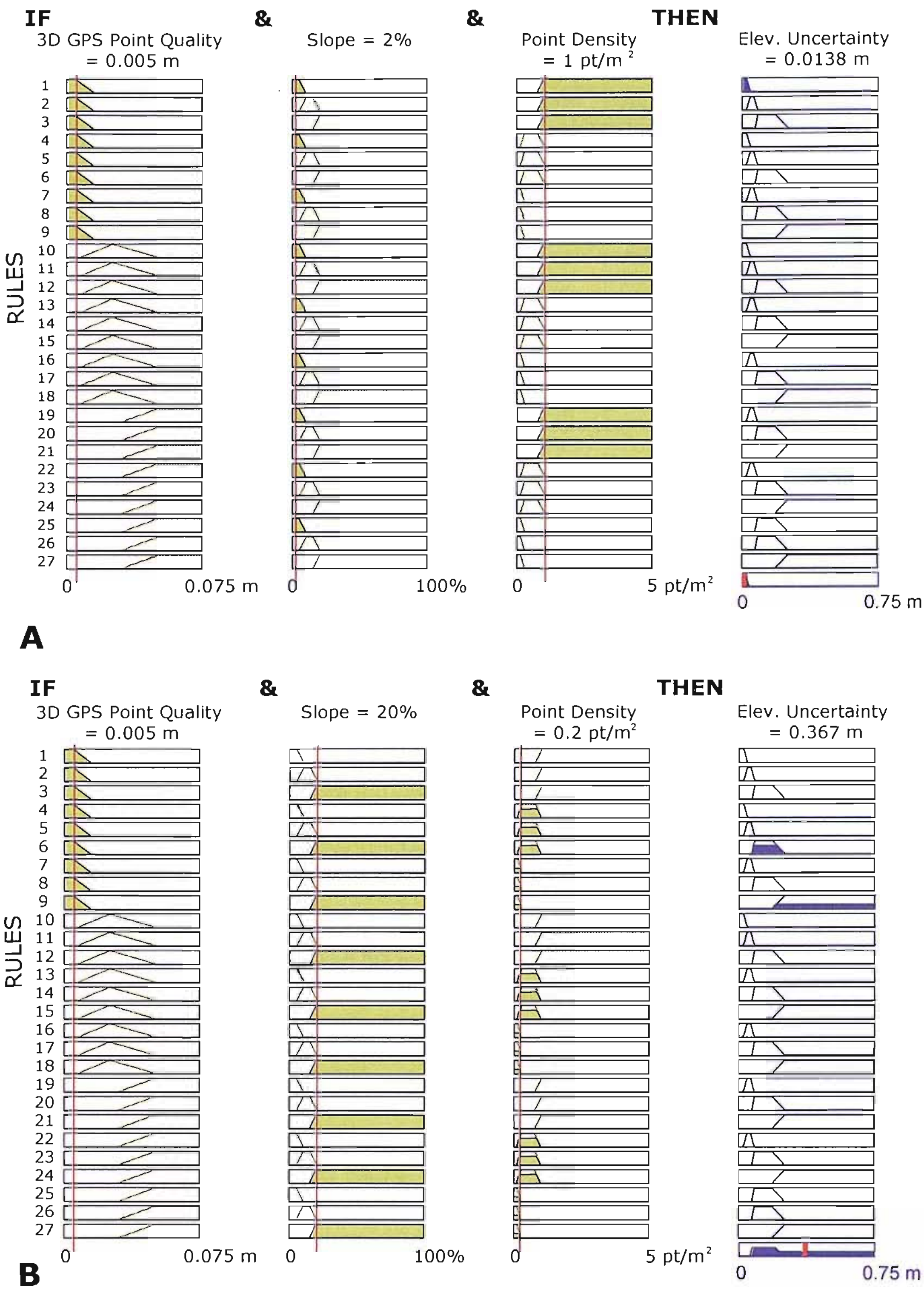


FIGURE 4.14: Two examples of the total consequence of the three input fuzzy inference system. A) A 'low' elevation uncertainty situation. B) A 'high' elevation uncertainty situation. In both situations, the total consequence of the relevant rules are aggregated to the shape that appears in the lower right corner. This aggregated fuzzy output is then defuzzified (using a centroid method) to produce a crisp estimate of elevation uncertainty.

Rule:	Inputs			Output
	3D P.Q. m	Slope %	Pt. ρ m/pts^2	$\delta(z)$ m
1	High	Low	High	Low
2	High	Medium	High	Average
3	High	High	High	High
4	High	Low	Medium	Low
5	High	Medium	Medium	Average
6	High	High	Medium	High
7	High	Low	Low	Average
8	High	Medium	Low	High
9	High	High	Low	Extreme
10	Medium	Low	High	Low
11	Medium	Medium	High	Average
12	Medium	High	High	High
13	Medium	Low	Medium	Average
14	Medium	Medium	Medium	High
15	Medium	High	Medium	Extreme
16	Medium	Low	Low	Average
17	Medium	Medium	Low	High
18	Medium	High	Low	Extreme
19	Low	Low	High	Average
20	Low	Medium	High	High
21	Low	High	High	Extreme
22	Low	Low	Medium	Average
23	Low	Medium	Medium	High
24	Low	High	Medium	Extreme
25	Low	Low	Low	High
26	Low	Medium	Low	High
27	Low	High	Low	Extreme

TABLE 4.7: A three input fuzzy inference system for elevation uncertainty ($\delta(z)$). The three inputs are GPS reported 3D point quality, percent slope and point density.

4.4.1.3 Application of FIS

A fuzzy inference diagram is the standard technique for illustrating how a specific fuzzy inference system actually works. In Figure 4.13 an illustration of the implementation of the two-rule FIS is shown whereas Figure 4.14 depicts the three-rule FIS. In both figures, two examples are shown. Both contrast the same point density and slope inputs. The first step in the process involves the calculation of the degree of fulfillment of each individual rule (implication method) to produce the output membership function for each applicable rule (left to right on the diagrams). Next, the total consequence of all the applicable[40] rules is calculated

[38]While the rule system would stay the same, the elevation uncertainty output membership functions may need to be calibrated to reflect the survey method or site conditions.

[39]These attempts are reported in Appendix E.

[40]There will generally always be some inapplicable rules for every input combination (e.g. if the rule is based on an input being high and the input only has membership in the low and medium classes, then the rule is not

(aggregation method). This resulting total consequence membership function expresses the full range of uncertainty in the output predicted by the FIS. Finally, if desired, the total consequence membership function can be defuzzified into a crisp output (single value) of elevation uncertainty. This process is repeated on a cell-by-cell basis for every cell in the raster.

To illustrate how this method is carried out over two entire DEMs used for a DoD calculation to estimate the spatial variability of elevation uncertainty, an example from 2006-2005 is illustrated in Figure 4.15. Unlike Figure 4.10 (§ 4.3.3), where the probability map was calculated from a spatially uniform estimate of $\delta(z)$ for each DEM and a consequently spatially uniform estimate of $\delta(DoD)$, in Figure 4.15 the $\delta(z)$ are spatially variable. The individual FIS predictions of elevation uncertainty, $\delta(z)$ are propagated into the DoD precisely as described in § 4.3.2 using Eq. 4.10, but this time on a cell by cell basis to reflect the spatial variability. The resulting raster of propagated elevation uncertainty, $\delta(DoD)$, is then combined with the original DoD to calculate a T-score using Eq. 4.11, again on a cell-by-cell basis, in an analogous fashion to that shown in the Figure 4.10 illustration. The result is the probability map on the far right of Figure 4.15. This probability map can then be used to threshold or weight the DoD calculations at any user desired threshold as described in § 4.3.3.

Finally, now that the method of deriving a spatially variable estimate of $\delta(z)$ has been fully described and illustrated, the FIS outputs based on the 3-Rule and 2-Rule system and used in the remainder of this thesis are presented in Figure 4.16. The spatial structure in $\delta(z)$ for the individual DEMs depicts a pattern reflective of the observations from the empirical experiments in Figures 4.3 and 4.6. The three rule system discriminates the steep areas with a slightly larger magnitude of $\delta(z)$ across the reach. However, both produce a consistent and coherent result.

Before moving on, it is worth throwing up a cautionary note about propagating FIS estimated $\delta(z)$ from two DEMs into a DoD. The framework in which this uncertainty was propagated to produce Figure 4.15, for example, was that spelled out in § 4.3.2. Notably, this is a probabilistic framework. Using the FIS in that error propagation framework assumes that the FIS can produce a reasonable approximation of error. In strict statistical terms, this is theoretically murky territory.[41] However, it is argued here that the output produced from the FIS is just as reasonable and robust as any of the variety of crude estimates reported in § 4.3.1 that other authors have used and already vetted through the peer-review literature. Making these assumptions allows the DoD uncertainty to be expressed probabilistically, which has practical utility in communicating uncertainty in terms that readers and users understand.[42]

applicable).

[41] This is 'murky' because theoretically errors are supposed to be calculated based on a comparison between known values and observations. In practise, known values do not exist and even statisticians stretch their own rules to get a workable estimate of error.

[42] Even though fuzzy logic has become a mature branch of mathematics, it is still not familiar to most scientists (Klir & Yuan 1995, Jang & Gulley 2007).

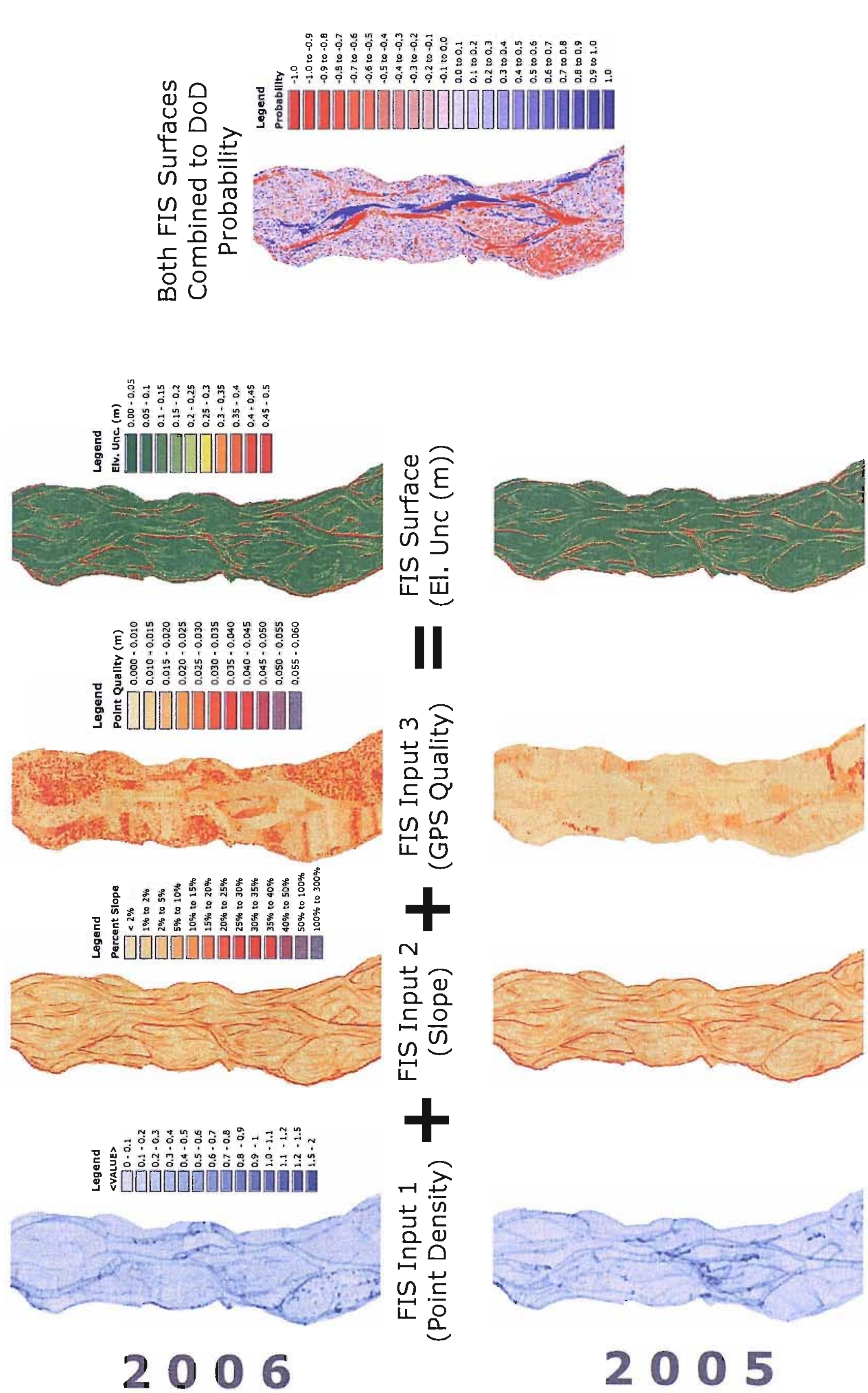


FIGURE 4.15: Illustration of FIS Construction and resulting Probability Map for 2006-2005 DoD. The top shows the 2006 inputs and the bottom shows the 2005 inputs. The left hand three inputs combine together as inputs into the three rule FIS to produce the defuzzified FIS prediction of elevation uncertainty. Both predictions of elevation uncertainty combine to produce the probability map that DoD changes are real. Note: El. Unc. is an abbreviation for elevation uncertainty ($\delta(z)$).

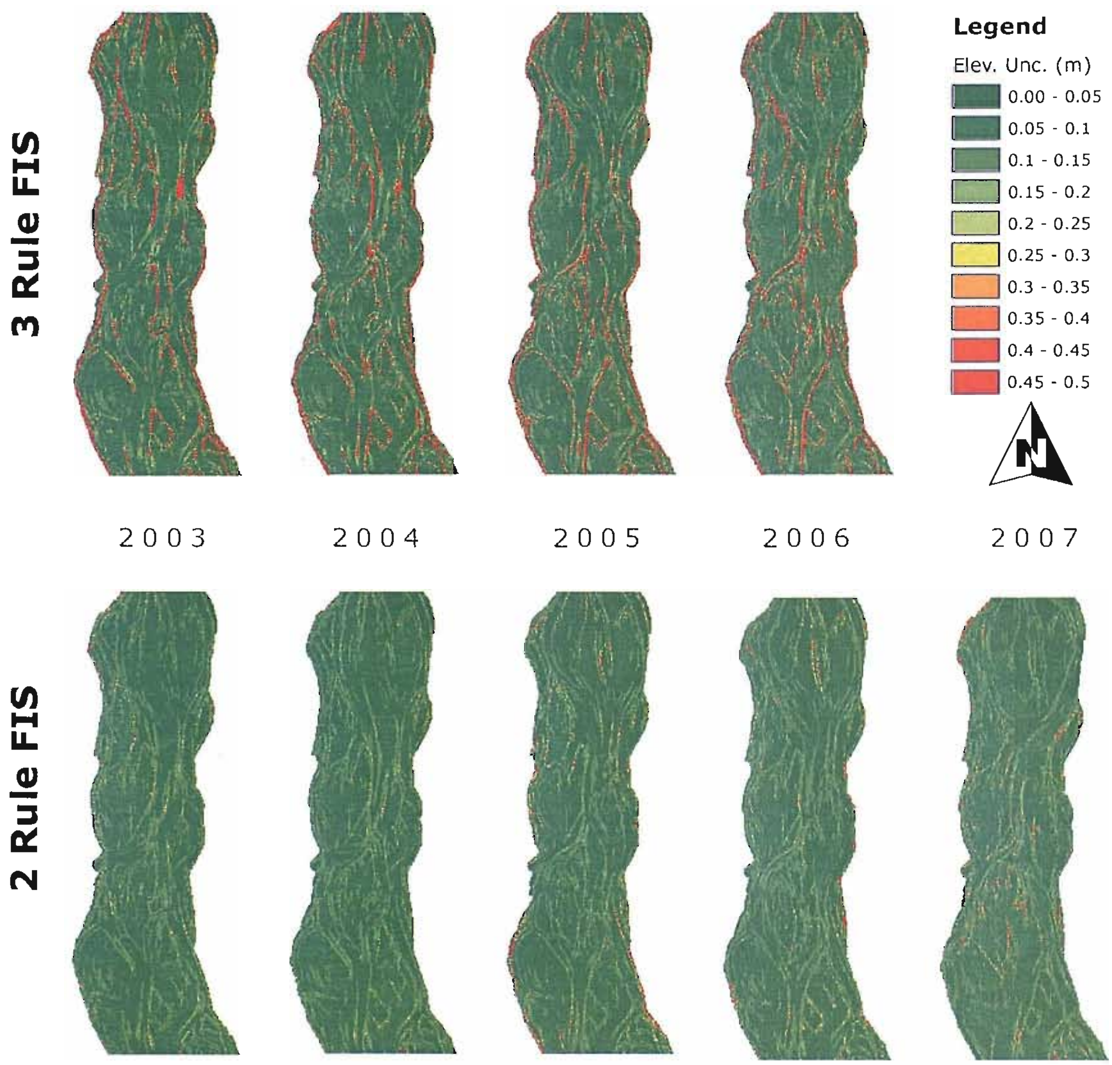


FIGURE 4.16: Comparison of 3-Rule (top) and 2-Rule FIS predicted $\delta(z)$ surfaces. Note that as an no point quality data was available for 2007, only the 2 rule output is shown.

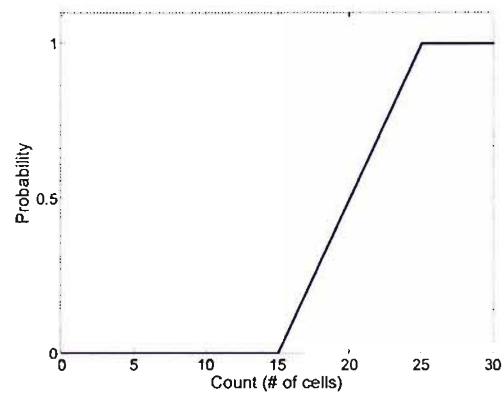


FIGURE 4.17: Example of a linear transform function from the spatial contiguity index to probability.

4.4.2 Spatially Coherent Erosion and Deposition Units

An alternative (or complementary) approach to using a FIS to estimate spatial variability could be developed based on the observation that erosion and deposition tends to occur in spatially coherent patterns. For example, in Figure 4.2 the DoDs do not exhibit erosion and deposition patterns that are pixelated like a chequerboard of random noise. Instead there are coherent contiguous units of erosion and deposition that are generally elongated and stretched in a streamwise orientation. For example, many of the bank erosion units are long thin crescent shaped units with rather sharp boundaries; whereas many of the depositional units are slightly broader in width and more diffuse at their boundaries. If these areas of contiguous and coherent changes could be identified or classified, then DoD predicted elevation changes within those units could be assigned a higher probability of being real and areas outside could be assigned a lower probability. To operationalise this approach requires both a technique for adjusting the probability estimate that DoD change is real based on this new information, as well as a method for defining these regions throughout the reach. These are described in the next two subsections.

4.4.2.1 Defining Coherent Units

A simple technique of defining coherent units of areas of erosion and deposition would be to visually identify them on a DoD map (e.g. Figure 4.2) and manually digitize the areas of interest. A binary treatment of areas 'inside' and 'outside' the units could be applied, whereby those 'inside' are assigned some higher probability approaching 1, and those 'outside' are assigned some lower probability approaching 0. In the context of geomorphological interpretation (e.g. Chapter 5) such a simple, but labour-intensive, approach may be acceptable or even desirable. However, in the context of developing a tractable methodology for uncertainty analysis that can be applied with available information and in a relatively automated fashion, a more sophisticated approach is desirable.

A simple, but automated technique for delineating these units is to run a moving window across the DoD raster and count the number of neighboring cells that the DoD predicts are erosional versus depositional. These counts are used as indices of spatial contiguity, where cells entirely embedded within regions of erosion or deposition record 100% similar neighbours. Separate indices for erosion and deposition are calculated.[43] This simple local neighbourhood analysis algorithm was written in Matlab and an example of the type of results it produces is shown in Figure 4.18. Unlike above, where a binary assignment of a high probability or low probability can be made, here some sort of transform function must be defined to differentiate cells likely to be in a unit from those not likely to be within a unit. The logic for a transform function is as follows. If the centre cell is predicted to be erosional, and all the cells around it are erosional, then it is highly likely that the cell actually is erosional. However, if the centre cell is depositional, and all the cells around it are erosional, it is highly unlikely the cell is actually depositional. Those cases in between have more intermediate probabilities. Thus,the index of contiguity is linearly transformed into the probability that each cell belongs either to a class of erosion or deposition, as follows (for a 5 x 5 window):

$$p(A|E_j) = \frac{\sum_{i=1}^{n=25} x - x_{min}}{x_{max} - x_{min}} \tag{4.12}$$

where x is a unit vector (-1 if cell is erosional, + 1 if cell is deposition), and x_{max} and x_{min} are upper and lower thresholds taken to define the number of cells at which the probability becomes 1 and 0 respectively. For most of the analyses reported here using 5x5 windows, a default value of x_{max} was defined as 25 (i.e. all cells same class) and x_{min} was defined as 15 (Figure 4.17). Figure 4.18 shows an example comparison of erosional and deposition neighbourhood analyses calculated using a 5x5 versus 7x7 window. Windows can be of various sizes (e.g. 3x3, 5x5, 7x7, 9x9), but given the DEM resolution of 1 metre used here, and the scale of contiguous erosional and depositional units that are to be resolved (e.g. bar scale), 5x5 and 7x7 were deemed the most appropriate. The boundaries appear slightly sharper for the 5x5 window, as suggested by the sharper contrasts between the dark (high count) and light (low count) areas. What this means is that the 5x5 is a stronger discriminator of those areas of lower probability of reflecting real changes. However, the purpose of the spatial coherence filter is to recover meaningful low-magnitude changes, primarily on the periphery of spatially contiguous units. A closer look at these 'sharper' boundaries reveals that the 5x5 window is showing higher relative counts then the 7x7 window along these boundaries. Thus, the 'dark' areas are expanded, hence doing a slightly better job of 'recovering' these low magnitude changes at the boundaries. On this basis, the 5x5 window was used in all subsequent analyses reported here.[44]

[43]This is to avoid the possibility that a particular cell may lie close to a sharp boundary between erosion and depostion areas. If erosional counts were treated as negative and depositional counts were treated as positive, a single index may therefore record an index close to zero, not because of not having any similar neighbours but because the number of cells from both classes cancel each other out.

[44]Note that this is a grid-resolution dependent analysis and all the analyses reported here are on 1 metre resolution grids.

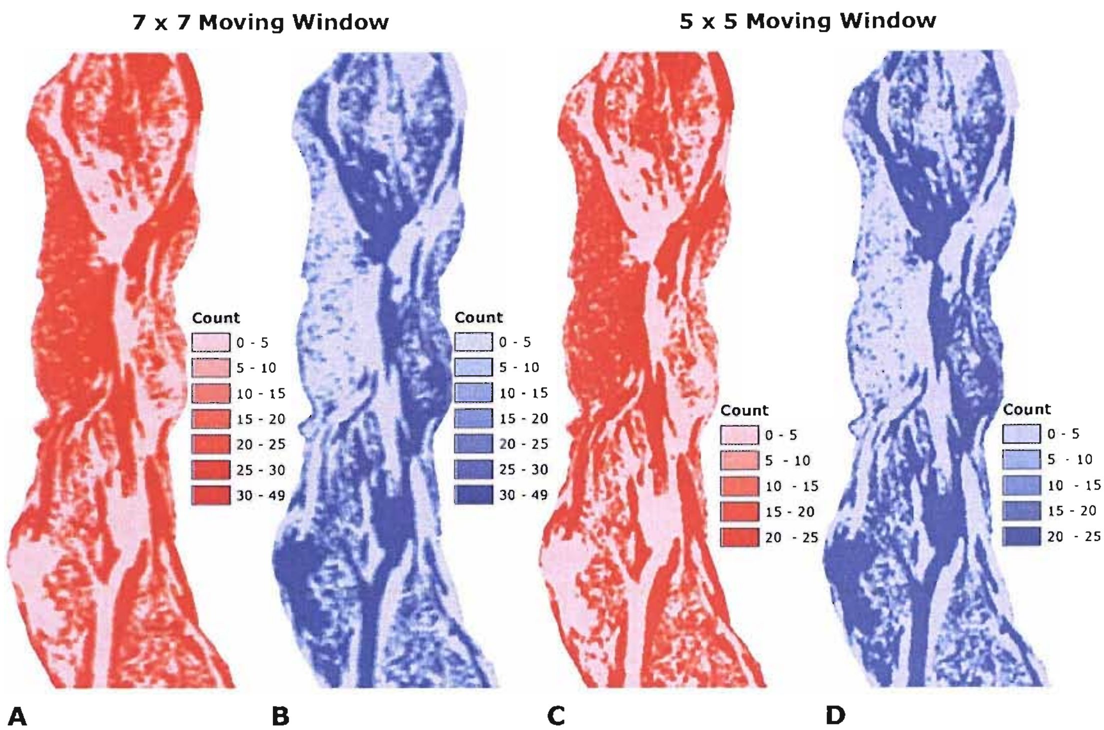


FIGURE 4.18: Example of comparison between 5x5 and 7x7 neighbourhood analysis window on the erosion and deposition contiguity indices. Data shown is based on the 2007-2006 DoD. A. 7x7 Erosion Neighbourhood Analysis; B. 7x7 Deposition Neighbourhood Analysis; C. 5x5 Erosion Neighbourhood Analysis; and D 5x5 Deposition Neighbourhood Analysis.

4.4.2.2 Updating the Probability

Two techniques have been presented for defining a probability that DoD changes are real on the basis of either a spatially uniform estimate of $\delta(z)$ (e.g. Figure 4.10) or a spatially variable estimate of $\delta(z)$ using the FIS (e.g. Figure 4.15). Here, a separate probability that change is real based on the spatially coherent patterns of erosion and deposition has been calculated using Eq. 4.12.[45] Bayes Theorem provides a simple way of updating the former probability (a Priori) based on this additional (conditional) probability. The analysis needs to be conducted for erosion and deposition classes separately and then the results can be combined to produce an overall probability map akin to Figure 4.10 and Figure 4.15. Here, the application of Bayes Theorem is described only for the erosional case to illustrate the concepts (it is exactly the same for the depositional case).

The original a priori probability ($p(E_j)$) that the DoD predicted elevation change is significant can be updated by calculating a conditional posterior probability ($p(E_j|A)$) that a vertical elevation difference is significant, given the probability ($p(A|E_j)$) revealed from its spatial

[45] It is possible to threshold the DoD with a $_{min}$LoD confidence interval based on this probability defined solely on spatial coherence, but this is not explored here. The closest thing to this is what will be referred to later as a pathway 5 analysis, which uses Bayesian updating of a spatially uniform estimate of $\delta(z)$ (§ 4.5).

index analysis. In this case:

$$p(E_j|A) = \frac{p(A|E_j) \cdot p(E_j)}{p(A)} \tag{4.13}$$

where $p(A)$ is the conditional probability that the cell is erosional given its spatial context within an area of erosion. This is defined as:

$$p(A) = p(A|E_j) \cdot p(E_j) + p(A|E_i) \cdot p(E_i) \tag{4.14}$$

where the $_j$ subscript refers to a probability that a change is significant and the $_i$ subscript refers to the probability that a change is insignificant.[46] Thus, the updated probability can be calculated knowing just two probabilities: the a priori probability ($p(E_j)$) and this conditional spatial index probability ($p(A|E_j)$).

4.4.2.3 Application

To illustrate the application of Bayesian updating based on spatial contiguity index, it is helpful to use both an example at a single cell and then on the entire DoD raster. First, consider an example of a calculation at a single cell, where the DoD predicted elevation change for that cell is -0.153 m. The a priori significance must be measured relative to the propagated uncertainty from the two input DEMs into DoD ($\delta(DoD)$). In this example, let $\delta(DoD) = 0.153$ m. Thus, using Eq. 4.11, the t-score is equal to 1 such that the a priori probability that this change is significant is $p(E_j) = 0.68$, and would thus be rejected at the 90% confidence interval. For the same cell, assume that the local neighborhood analysis found that 21 of the DoD cells in the 5 x 5 cell neighborhood window predicted erosion. From Eq. 4.12, this gives a spatial index probability of $p(A|E_j) = 0.85$.[47] The inverse probabilities of both analyses, that the change is insignificant, are therefore ($p(A|E_i) = 1 - 0.85 = 0.15$ and $p(E_i) = 1 - 0.68 = 0.32$, respectively. Substituting this back into Eq. 4.14 and substituting that into Eq. 4.13 yields:

$$0.91 = \frac{0.85 \cdot 0.68}{(0.85 \cdot 0.68) + (0.15 \cdot 0.32)} \tag{4.15}$$

so, the posterior probability that the cell is erosional has now risen and is significant at the 90% CI.

Extending this application from the single cell to every cell in a raster is straight forward. The 2007-2006 DoD will be used as an example. An a priori DoD probability grid is supplied from either a spatially uniform analysis of $\delta(DoD)$ (e.g. Figure 4.10) or a spatially variable analysis of $\delta(DoD)$ (e.g. Figure 4.15). A spatial contiguity index is produced for erosional and depositional grids as in Figure 4.18. Using a transform function (e.g. Figure 4.17), this is converted into a probability. Following the steps outlined in the previous paragraph, Bayes

[46] If the probability of significance is known (j), the probability of insignificance (i) is automatically known as they are inversely related ($i = 1 - j$).

[47] For this example, the probability is being defined by the spatial coherence detection analysis.

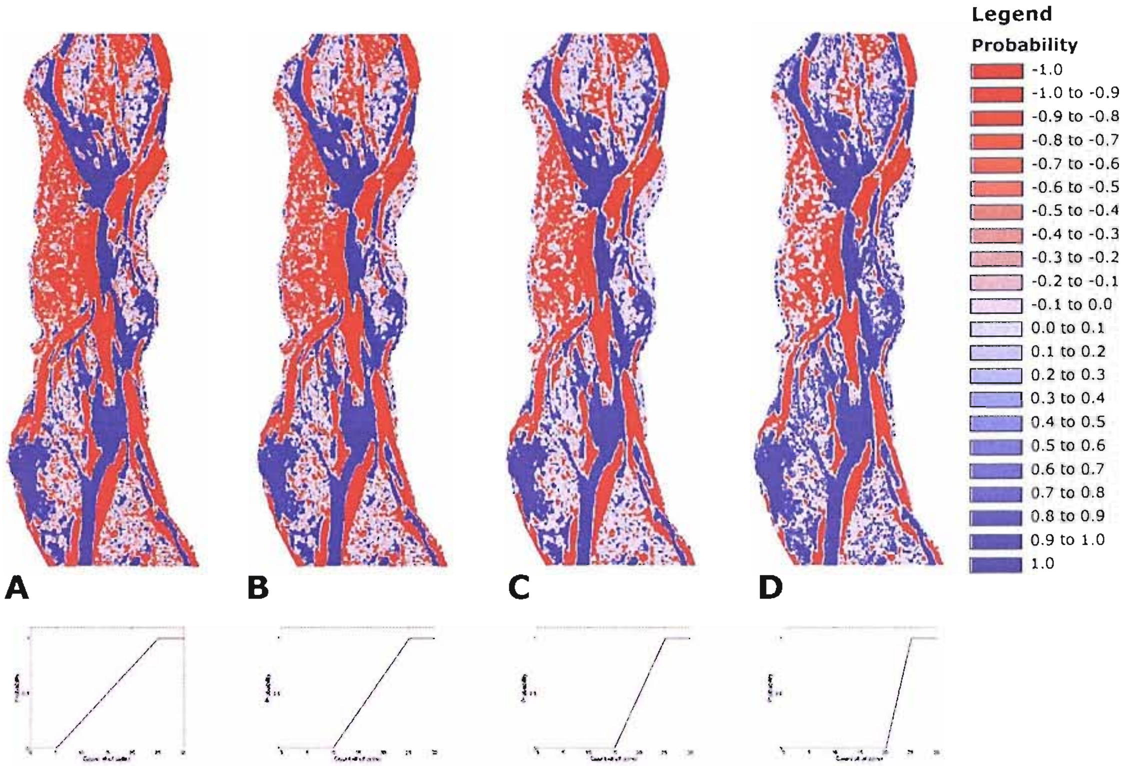


FIGURE 4.19: Sensitivity of DoD probability updated using spatial coherence index to lower limit of transform function. Example shown is using the 2007-2006 DoD. The transform function is shown on the bottom (refer to Figure 4.17 for larger view) and corresponds to a lower limit of 5, 10, 15, and 20 for A, B, C and D respectively.

Theorem is applied on a cell by cell basis. Figure 4.19 shows an example of the sensitivity of the DoD probability grid to the transform function (shown on the bottom) used. In this example, only the lower limit on counts of cells was varied (between 5 and 20 in a 5x5 moving window), while the upper limit was held fixed at 25 (i.e. all cells depositional). Although the differences are subtle at the resolution shown above, one can still notice more lightly shaded areas (representing lower probabilities) as you move to the right in Figure 4.19. That is as the lower limit on the threshold transform function is increased, the probability transform function is more restrictive and acts more as a binary function. It is reassuring that the main units of change are insensitive to the thresholds, and relaxing the lower limit seems to pick up more around the edges. Areas exhibiting a pattern of deposition and erosion resembling a chequerboard are somewhat suspect (primarily braidplain). In these zones, a lower limit of 15 seemed (Figure 4.19C) seemed to be the best discriminator (i.e. it assigned these areas lower probabilities).

4.5 DoD Uncertainty Analysis Software Development

By combining the variety of DoD uncertainty analysis techniques outlined in § 4.3 and § 4.4, there are a wide array of options and pathways to follow for assessing the significance of uncertainty to morphological sediment budgets. The primary pathway developed in this chapter involves:

1. Calculation of a DoD from two DEMs
2. Calculation of spatially variable $\delta(z)$ in each of the input DEMs using an FIS (§ 4.4.1)
3. Propagation of FIS-predicted $\delta(z)$ from each DEM into DoD $\delta(DoD)$ (§ 4.3.2)
4. Conversion of $\delta(DoD)$ to a DoD probability grid using a T-Test (§ 4.3.3)
5. Bayesian updating of DoD probability grid based on a spatial contiguity index (§ 4.4.2)
6. Assessment of significance of $\delta(DoD)$ by applying a confidence interval $_{min}$LoD threshold to DoD

However, to assess how this method performs in comparison to existing or alternative methods it is helpful to have a framework for making such comparisons. A wizard-driven graphical user interface was developed in Matlab. The primary reasons for developing the software were to automate and more clearly define the DoD analysis process, reduce the likelihood of errors common with manual analyses, and provide a means of running batch analyses to conduct sensitivity analyses and inter-comparisons. A secondary reason was to provide an analysis package that other users could use and/or modify if they wish to employ the methods developed in this chapter.[48] The program was developed in Matlab because it is a simple and flexible development environment with lots of in-built functionality. Programs can be entirely hard-coded (with no user inputs), command prompt driven (with user inputs at the command line), dialog box driven (with user inputs in wizard-type pop up windows), or a full graphical user interface (GUI with all user inputs controlled from main window or pop ups). In this instance, a dialog box driven application was developed that walks the user through a series of choices and inputs that transparently reflect the options already discussed in how to implement the DoD uncertainty analysis. The program can also be run in a batch mode, which automatically applies the inputs and parameters based on a batch configuration file. The most concise way of describing this software application is with the flow-chart in Figure 4.20.

As the flow-chart suggests, there are a number of pathways through this program and in Table 4.8, the six primary pathways are identified. For reference the 'primary' pathway discussed above coincides with Pathway 4. In the next section (§ 4.6), each pathway will be described

[48]While the Matlab code is complete and available to interested parties by contacting the author, it requires both Matlab and the Fuzzy Logic Toolbox. A platform independent stand-alone application, and an ArcGIS toolbar plug-in are currently under development, which will offer the full functionality of the existing Matlab code. When development and testing is complete for all three applications, they will be released together as open source code software under the GNU Public License.

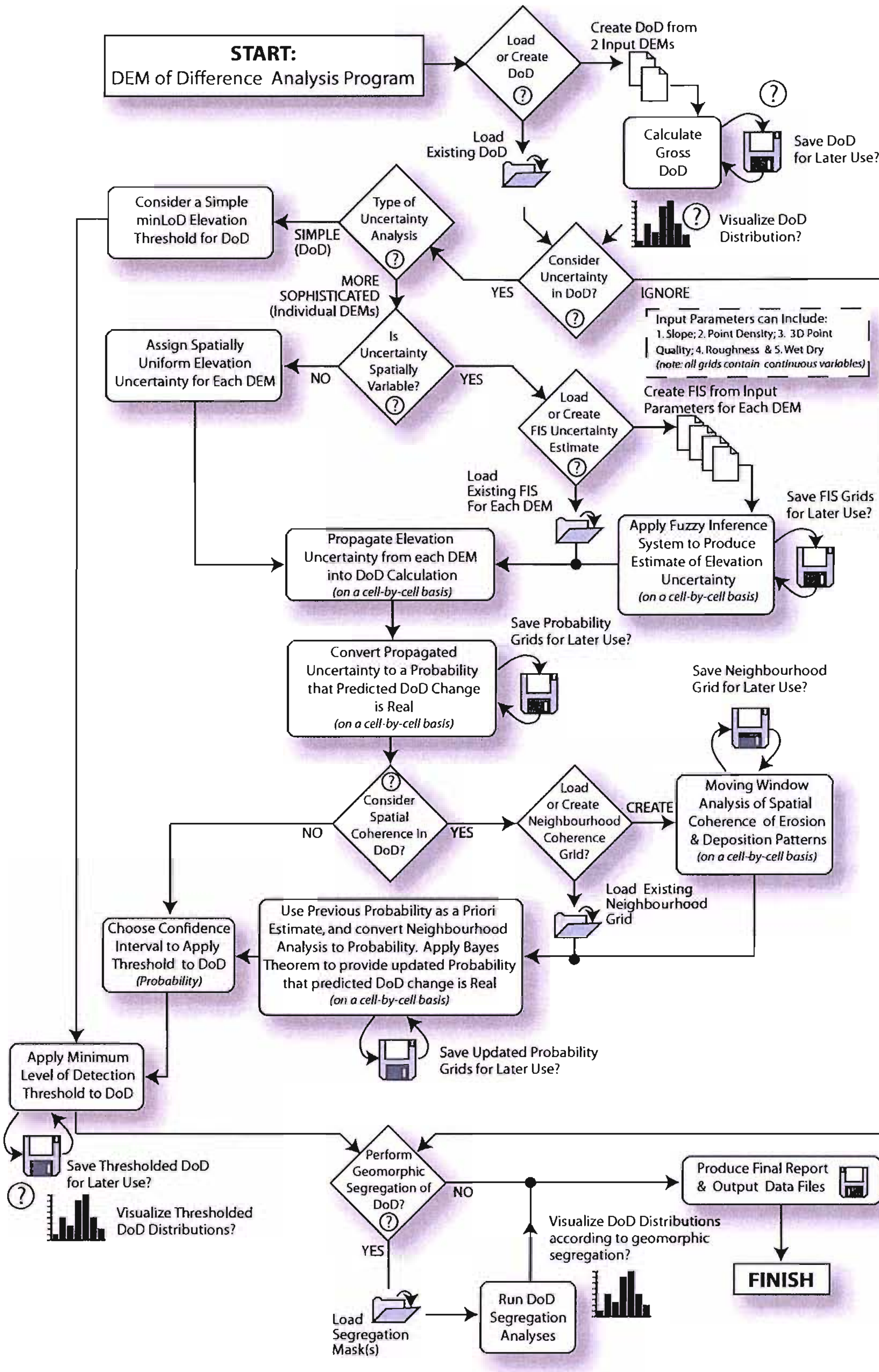


FIGURE 4.20: This flow chart depicts the various pathways through the DoD Analysis 2.0 Wizard and represents five different ways of considering the influence of DEM uncertainty on DoD sediment budgets.

	Pathway					
Sub-Method:	1	2	3	4	5	6
Gross DoD Analysis?	Y	Y	Y	Y	Y	Y
Simple $_{min}$LoD Elevation Threshold for DoD?	N	Y	N	N	N	N
Spatially Uniform: separate $\delta(z)$ for each DEM?	N	N	N	N	Y	Y
Spatially Variable: FIS defined $\delta(z)$ for each DEM?	N	N	Y	Y	N	N
Bayesian Updating Based on Spatial Contiguity Index?	N	N	N	Y	Y	N
Probabilistic $_{min}$LoD Confidence Interval Threshold for DoD?	N	N	Y	Y	Y	Y
Figure:	4.21	4.23	4.27	4.28	4.34	4.35

TABLE 4.8: Contrasting Pathways Through DoD Uncertainty Analysis. Refer to the figures for more detail.

briefly and results presented. The purpose of this is to present the primary results (Pathway 4) in comparison to alternative methods and disentangle which aspects of the multifaceted method are responsible for producing what types of information. This is intended to facilitate an objective appraisal of the developed approach. In trying to infer which method(s) might be the most appropriate, two recurring themes will be 1) the plausibility of the results and 2) the information loss or recovery. In terms of plausibility, the contrasting results will be critiqued to determine to what extent they seem to be geomorphologically reasonable. In terms of information loss and recovery, all the uncertainty analyses presented here are based on thresholding of some form to differentiate between changes that a) can be assumed to be meaningful and b) changes that can not be distinguished from noise or uncertainty. As such all DoD sediment budgets subjected to this kind of uncertainty analysis will report a lower magnitude of change (i.e. information loss). The premise of this chapter is that many uncertainty analyses are discarding meaningful information that is likely to encompass real geomorphological changes. Thus, to what extent these new techniques can recover information relative to the gross budget is a metric by which they can and will be judged.

4.6 Application to the Feshie

In this section the application of five different types of DoD uncertainty analysis to the Feshie 2003 to 2007 data sets is presented. The analyses follow pathways outlined in the previous section (Table 4.8). Pathway 1 (§ 4.6.1), which represents the gross DoD with no uncertainty analysis, is presented first as a benchmark for comparison. The bulk of the emphasis however will be placed on Pathway 4 (§ 4.6.3), which represents the most comprehensive form of uncertainty analysis presented.

DoD Period	Volumetric			Percent Coverage of Reach		
	Erosion m^3	Deposition m^3	Net Change m^3	Erosion %	Deposition %	Total %
2007-2006	11162.0	8882.3	-2279.7	50.2%	49.5%	99.7%
2006-2005	4538.5	3167.1	-1371.3	54.1%	45.0%	99.0%
2005-2004	8307.9	7029.7	-1278.2	46.8%	52.5%	99.2%
2004-2003	4975.5	3072.2	-1903.3	56.4%	43.2%	99.5%

TABLE 4.9: Gross DoD Budget Results following a Pathway 1 analysis (no uncertainty accounting).

4.6.1 Pathway 1

The simplest and most typical form of DoD Analysis is represented as Pathway 1 in Figure 4.21. Pathway 1 involves just a basic DoD calculation and gross budget analysis, but includes no consideration of uncertainty. The summary map results from all the DoDs under a Pathway 1 analysis was already reported in Figure 4.2. Similar types of figures have been commonly reported in the literature (Fuller *et al.* 2003, Brasington *et al.* 2003, Brasington *et al.* 2000, Lane *et al.* 2003, e.g.). On the basis of a visual inspection of these figures, the changes they illustrate seem perfectly plausible and relatively coherent.[49] It appears that the two 'wet' years (2004 to 2005 and 2006 to 2007) produced much more extensive changes, whereas the other years resulted in relatively minor adjustments. From this coarse reach view, there do not appear to be any obvious busts[50] in the data or pixelated/noisy areas. In general the highest magnitude erosion (red) appears along the outside bends of channels suggesting bank erosion, with some additional concentrated erosion in pools (particularly at confluences), as well as some lower areas of erosion primarily concentrated in channels and chutes.[51] Deposition (blue) seems to be occurring in channel areas in the form of bar development and in lower magnitude sheets as overbank deposition. From a geomorphological perspective, there is nothing out of the ordinary to suggest that uncertainties in these data are causing too much of a problem. However, the reader is reminded that this is one of the most extensive, high resolution repeat survey data sets of its types, and this crude visual inspection may yield very different interpretations from other data sets.

The same results are presented in Figure 4.22 as both areal and volumetric elevation change distributions. The areal distributions (left hand side of Figure 4.22) are simply histograms showing the total area that experienced a given magnitude of elevation change in each bin. Without careful inspection, the areal distributions can be somewhat misleading. For the four analysis periods, they all appear to be broadly similar normal distributions roughly centred around an elevation change of 0 metres, loosely implying equilibrium conditions. If one is to use the total area[52] of erosion and deposition as an indication of whether the reach is tending

[49]Note that there are only two colour classes for changes less than 10 cm in magnitude.

[50]'Busts' is a surveying term used to describe mistakes.

[51]The geomorphological interpretation is not the focus of this chapter, and will be addressed in detail in Chapter 5.

[52]Reported in upper left hand corner of distributions in Figure 4.22.

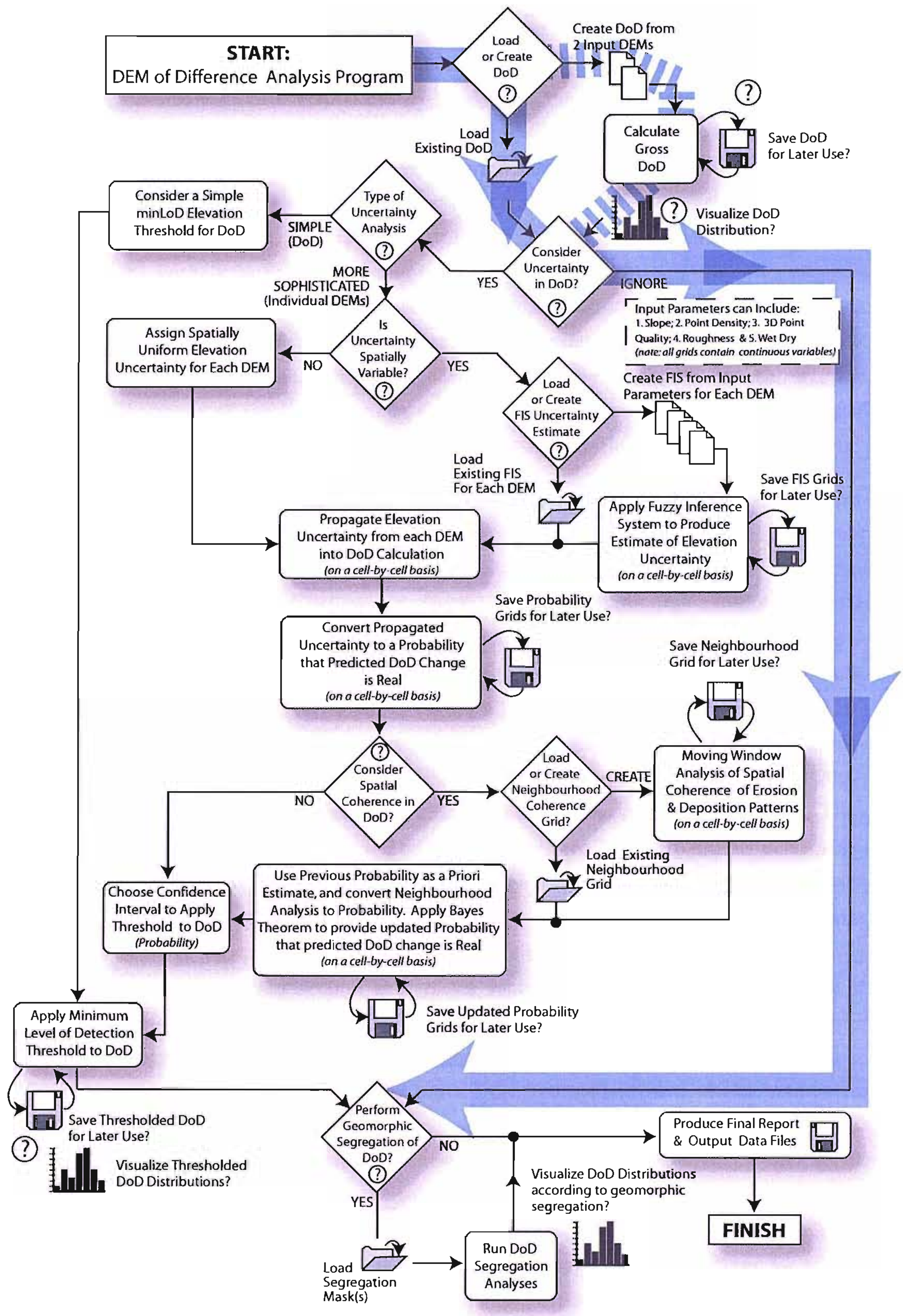


FIGURE 4.21: Pathway 1 through DoD Analysis 2.0 is depicted in blue.

toward aggradation or degradation, one would conclude that from 2004 to 2005 (Figure 4.22E) the reach was slightly aggradational (54,095 m^2 of erosion versus 60,710 m^2 of deposition) and in the remaining years it appears slightly degradational.[53] Columns 5-7 of Table 4.9 report these areas as a percentage of the total survey reach. On the basis of these observations of the areal distribution alone, are the changes suggested plausible? Note that in every DoD, over 99% of the reach was suggested to have experienced geomorphological change. Given that over the five year study period the entire survey reach was never completely inundated and there are substantial zones of elevated vegetating and vegetated bar surfaces and islands (see Appendix B) with little field evidence of geomorphological change, this suggestion is highly suspect.[54] It is also interesting to note that the total volumetric changes throughout the study period (Column 4 of Table 4.9) suggest that the reach is consistently degradational with net erosion on the order 1200 to 2300 m^3 each year. The net change is between 8% and 24% of the total volume of estimated change each year. Thus, the suggestion from the areal distributions that 2004 to 2005 might have been slightly aggradational is at least confusing.

Perhaps the volumetric elevation change distributions (left hand side of Figure 4.22) can provide some clarification? In comparing the volumetric and areal distributions, it is apparent the volumetric distributions are much better discriminators of the different styles of change between analysis periods. As the volumetric distribution reflects the area multiplied by the magnitude of elevation change (i.e. the x-axis), the areal and volumetric distributions look quite similar near the middle but dramatically different the further away from zero one gets. The two relatively quiet years (2003 to 2004: Figure 4.22H and 2005 to 2006: Figure 4.22D) have relatively similar shape and magnitude, single-peak distributions with a slight degradational bias. The two larger magnitude years (2004 to 2005: Figure 4.22F and 2006 to 2007: Figure 4.22B) boast much more interesting distributions with at least three peaks each. They each have a high peak in the middle centred roughly around zero. 2006 to 2007 is particularly interesting in that it has a very high and concentrated peak of low magnitude deposition with a much more spread out ridge of erosion spanning a wide range of magnitudes. These latter characteristics seem to be quite plausible geomorphological signatures, but the consistently highest magnitude peak centred around zero raises some fundamental questions. While it is certainly plausible that a high percentage of the areal distribution will be centred around zero,[55] is there necessarily any reason that this phenomenon should hold for the volumetric distributions as well? For the high peak to remain centred around zero in the volumetric distributions would mean that a large relative proportion of the reach would have to be undergoing changes of very low magnitude, because these are being multiplied by such small elevation changes. In contrast, for a peak to develop around a higher magnitude area, requires a relatively small surface area to change, because these are being multiplied by much larger elevation changes. While there are plausible geomorphological explanations for such a high peak to persist so consistently, this feature is highly suspect in light of the observations from the areal distributions about the unrealistically high percentage of the reach undergoing

[53]Note, see also discussion in § 8.4.1 about areal and volumetric dominance reversals.

[54]This question is addressed more rigorously under the geomorphological interpretation in Chapter 8.

[55]Because erosional and depositional processes will occur over a continuum of elevation change magnitudes.

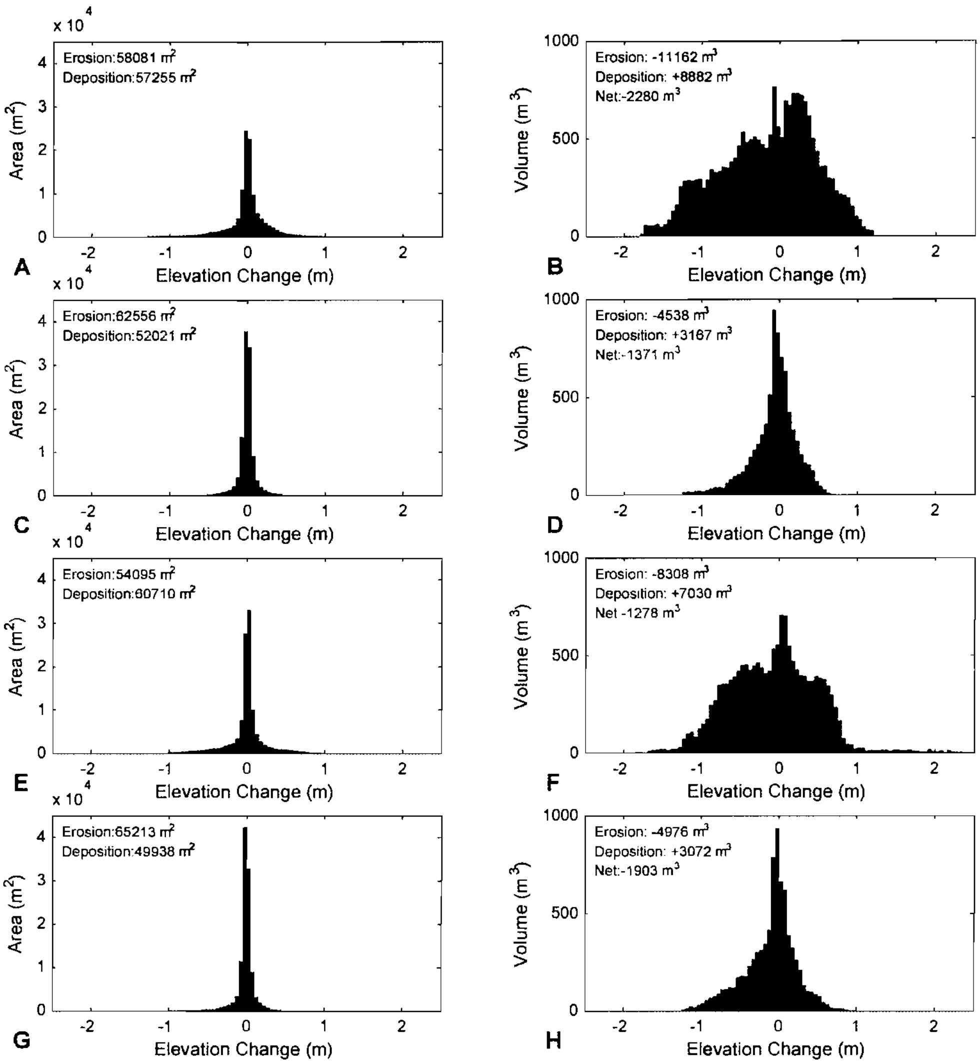


FIGURE 4.22: Comparison of areal and volumetric DoD Distributions (2007-2003). Each row represents a different analysis period (A and B are 2007-2006; C and D are 2006-2005; E and F are 2005-2004; G and H are 2004-2003). The left-hand column represents the gross un-thresholded areal DoD distribution, whereas the right-hand column represents the un-thresholded volumetric DoD distribution. Note, this represents pathway 1 through DoD Analysis 2.0 (see Figure 4.21) with no uncertainty analysis.

	Areally Changes under				Volumetrically Changes under			
DoD Period	5 cm	10 cm	15 cm	20 cm	5 cm	10 cm	15 cm	20 cm
2007-2006	41%	59%	67%	73%	5%	13%	18%	24%
2006-2005	63%	82%	89%	92%	20%	40%	52%	61%
2005-2004	53%	68%	75%	79%	8%	16%	23%	28%
2004-2003	65%	83%	88%	92%	20%	37%	47%	55%
Mean	55%	73%	80%	84%	13%	27%	35%	42%

TABLE 4.10: Areal and Volumetric Percentages of the DoD Elevation Change distributions beneath various elevation thresholds (centred $\pm\, x$ cm around 0).

changes.

Contributing to this concern about such large and persistent peaks centred around zero in both the areal and volumetric distributions are the findings about DEM errors and elevation uncertainty developed in § 4.3 and § 4.4. Putting a plausible geomorphological explanation for the peak aside, is it merely a coincidence that $\delta(DoD)$ is centred around zero and on the order of 6 to 15 cm? Table 4.10 shows the percentage of these elevation change distributions that are beneath various magnitudes from 5 to 20 cm. Returning to the 10 cm $_{min}$LoD that Brasington *et al.* (2000) established for GPS surveys, it is rather concerning that on average over 73% of the total area where changes are predicted and approximately 27% of the total volume of change predicted lie beneath this threshold. When returning to our initial visual inspection of the DoDs in Figure 4.2, what percentage of the reach might be estimated to be actively changing (geomorphically)? Is 25% a reasonable guess (the inverse of the average area under the threshold)?[56]

In summary, these DoDs derived from high quality, high resolution GPS surveys appear to be producing some reasonable spatial patterns of change, but there are serious concerns raised about the reliability of the magnitude and proportions of predicted changes from standard DoD analyses. In the next section, a standard uncertainty analysis will be applied to see to what extent it can address some of the concerns raised above.

4.6.2 Pathway 2

Pathway 2, depicted in Figure 4.23, is the simplest and most common form of uncertainty analysis used in the literature to date. The method was developed by Brasington *et al.* (2000) and was described in § 4.3.1.1. By some means (e.g. repeat control point observations), a $_{min}$LoD elevation threshold is defined. Brasington *et al.* (2000) suggested a detection limit of 10 cm for rtkGPS surveys such as this one, and the various methods employed (§ 4.3.1) of empirically establishing $\delta(z)$ support this. Figure 4.24 shows the DoD maps for each year with a 10 cm $_{min}$LoD elevation threshold applied. Figure 4.23 depicts the same analyses (right hand

[56] In actuality, this valley is probably best approximated by the total inundated area, which varies from year to as a function of flows. This question is dealt with in Chapter 8.

column) as volumetric elevation change distributions in relationship to the non-thresholded DoD. In terms of information loss[57] from a 10 cm $_{min}$LoD, this has actually already been reported in percentage terms in columns 3 and 7 of Table 4.10. As much as 83% of the reach is assumed not to have experienced any *detectable*[58] geomorphological change under the assumption of a 10 cm $_{min}$LoD. Moreover, upto 40% of the total volume ($\mu = 27\%$) of DoD predicted changes are considered indistinguishable from error.

Although a 10 cm $_{min}$LoD has been established as a reasonable threshold for these data, there is an outstanding question as to whether the 'revised' result under this form of uncertainty analysis is any more geomorphologically plausible than that of the original DoD under pathway 1? As the spatial extent of changes depicted in Figure 4.24 is much more compact around areas of observed changes in the field, it appears visually more satisfying. On all four thresholded DoD maps, there are a fair number of pixelated areas and non-coherent patches of change on the map. It is difficult to discern whether these are an artifact of the thresholding process, but there is no convincing geomorphological justification for their presence.[59] The DoD maps exhibit some sharp boundaries between zones of change and zones that have not changed. Such boundaries do exist in fluvial environments at the edge of channels, or along areas that have been inundated with flowing water. However, the many contiguous areas of erosion and deposition in the DoD map (particularly in areas of in-channel change - e.g. transition from point bar deposition to pool scour) are no longer contiguous, purely as an artifact of the thresholding process.

The elevation change distributions (Figure 4.25) accurately portray the simplicity of the Pathway 2 approach, but leave a conceptually dissatisfying geomorphological picture. Surely, the influence of elevation errors will influence the entire range of magnitudes of elevation change and not just those below some defined threshold.[60] The elevation change distributions could be easily misinterpreted as implying that no changes take place below the $_{min}$LoD threshold. As already discussed in the pathway 1 subsection (§ 4.6.1), it is known that elevation changes span a continuum of magnitudes starting from zero. It probably can be concluded that the results produced by a pathway 2 analysis are more realistic than the unthresholded DoD in terms of both magnitude and spatial extent. However, it is also probably safe to suggest that they are conservative in areal (spatial extent) terms. It is difficult to say whether the total volume of change is conservative relative to reality as the low magnitude changes being thresholded out may not account for much volumetrically.

In the absence of better information about uncertainty, it is difficult with a pathway 2 analysis to assess how well the revised volumetric magnitudes represent reality. All that can be done is to explore the sensitivity of those estimates to different threshold values. An example

[57] Information 'loss' is defined here as elevation changes predicted by the gross DoD, that have been thresholded out. The information lost will inevitably include an unknown mix of meaningful geomorphological changes and errors. The point is that uncertainty about the precise magnitude of those errors prevents distinguishing these changes from errors.

[58] Detectable with the DoD method!

[59] There may be perfectly reasonable bioperturbation explanations (e.g. plant growth, decomposition of organic material, burrowing animals, grazing or trampling) for small-scale local elevation changes.

[60] However, the influence of those errors will diminish with increasing elevation change magnitude.

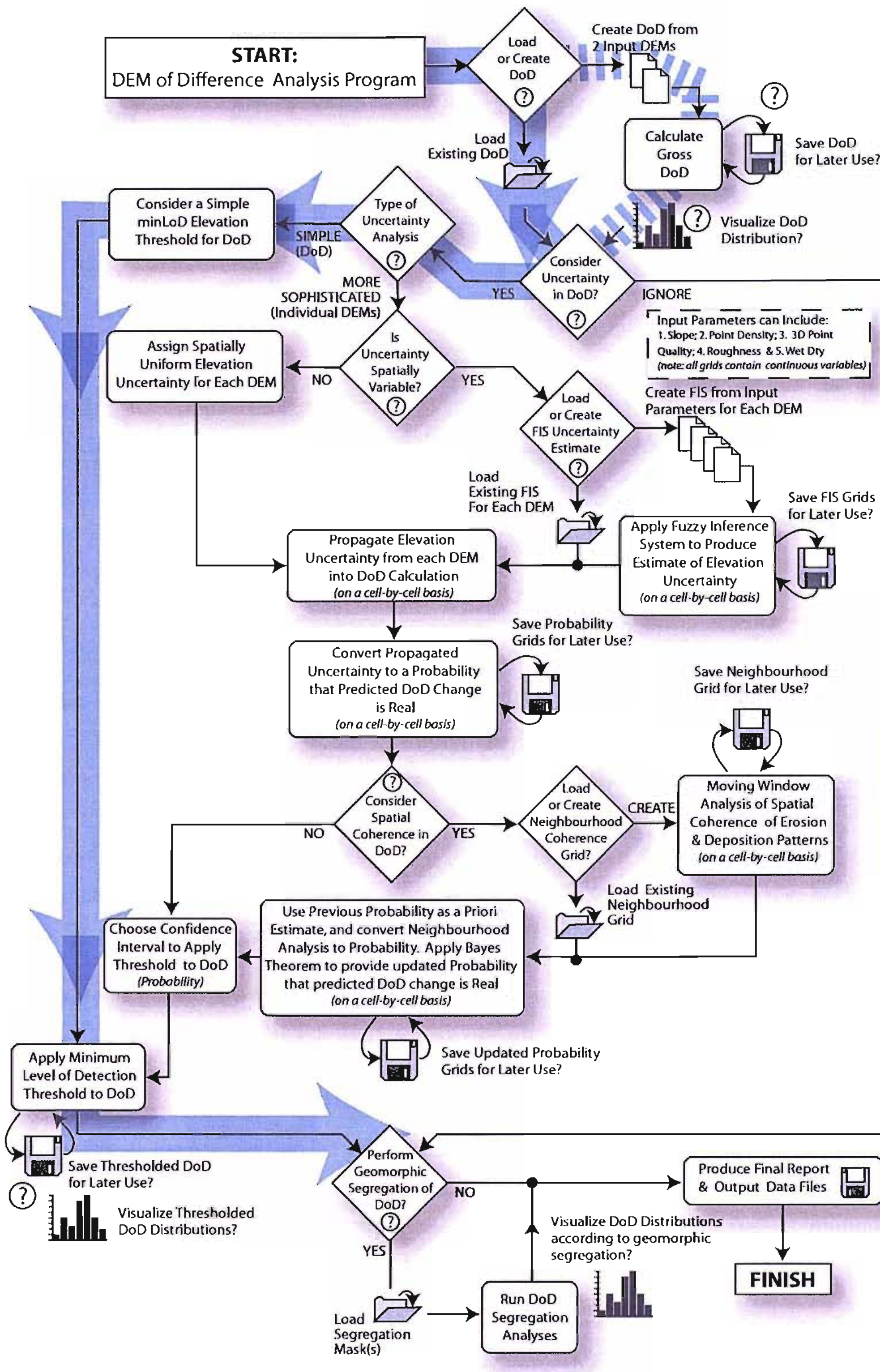


FIGURE 4.23: Pathway 2 through DoD Analysis 2.0 is depicted in blue.

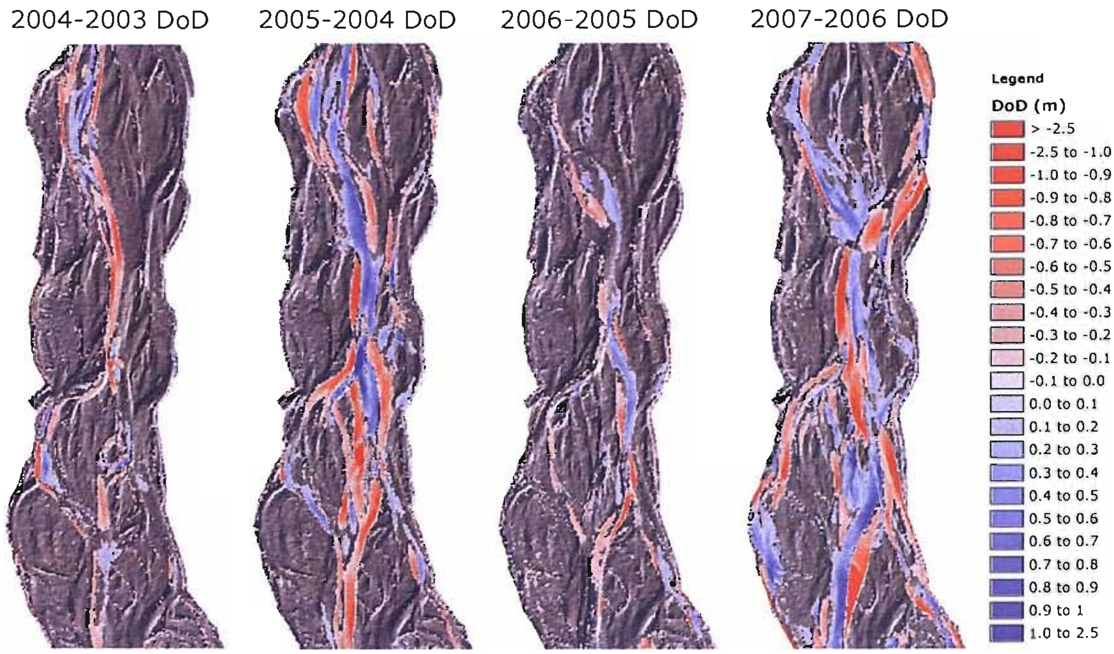


FIGURE 4.24: DoDs with a simple 10 cm $_{min}$LoD elevation threshold applied (Pathway 2). Hillshades from the more recent year's DEM are shown in the background for context.

of this was reported earlier in Figure 4.9 for the 2007-2006 DoD. Therein, a comparison of four $_{min}$LoD thresholds was depicted spanning the lowest justifiable $_{min}$LoD (5 cm) up to a $_{min}$LoD that may be appropriate for a poor quality photogrammetry or LiDAR surveys (50 cm). The higher threshold values certainly remove the 'pixelated' effect, but at the expense of a large number of meaningful changes. The bottom of Figure 4.9 also depicts how dramatic the influence on the elevation change distribution is. At 20 cm, 24% of the budget is lost (Table 4.10).

The example in Figure 4.9 represents a subsample of a sensitivity analysis to $_{min}$LoD from 60 separate pathway 2 analyses. For that sensitivity analysis, ten analyses in 5 cm increments were performed for each change period (Figure 4.26).[61] The information loss patterns are broadly consistent across all years and only in 2003-2002 (Figure 4.26E) do they result in a reversal between net deposition to net erosion.[62] Although Figure 4.26B and Figure 4.26F have a slight suggestion of information loss flattening out above 30 cm $_{min}$LoD, there is no clear inflection point in this set of analyses above which information loss is minimised. A similar finding for the Feshie was presented in Williams (2004).

Brasington *et al.* (2003) noted that fluvial deposition often tends to take place in more spatially extensive but lower magnitude (e.g. 2-3 D_{90}) increments than fluvial erosion, which tends to be more concentrated spatially and of greater magnitude. They then suggested that deposition

[61] In this experiment, analyses were included from the 2002-2000, and 2003-2002 datasets in addition to the four primarily reported in this chapter.

[62] It is an interesting side note that the two years not included in the analysis are mildly aggradational whereas the four included all suggest degradation.

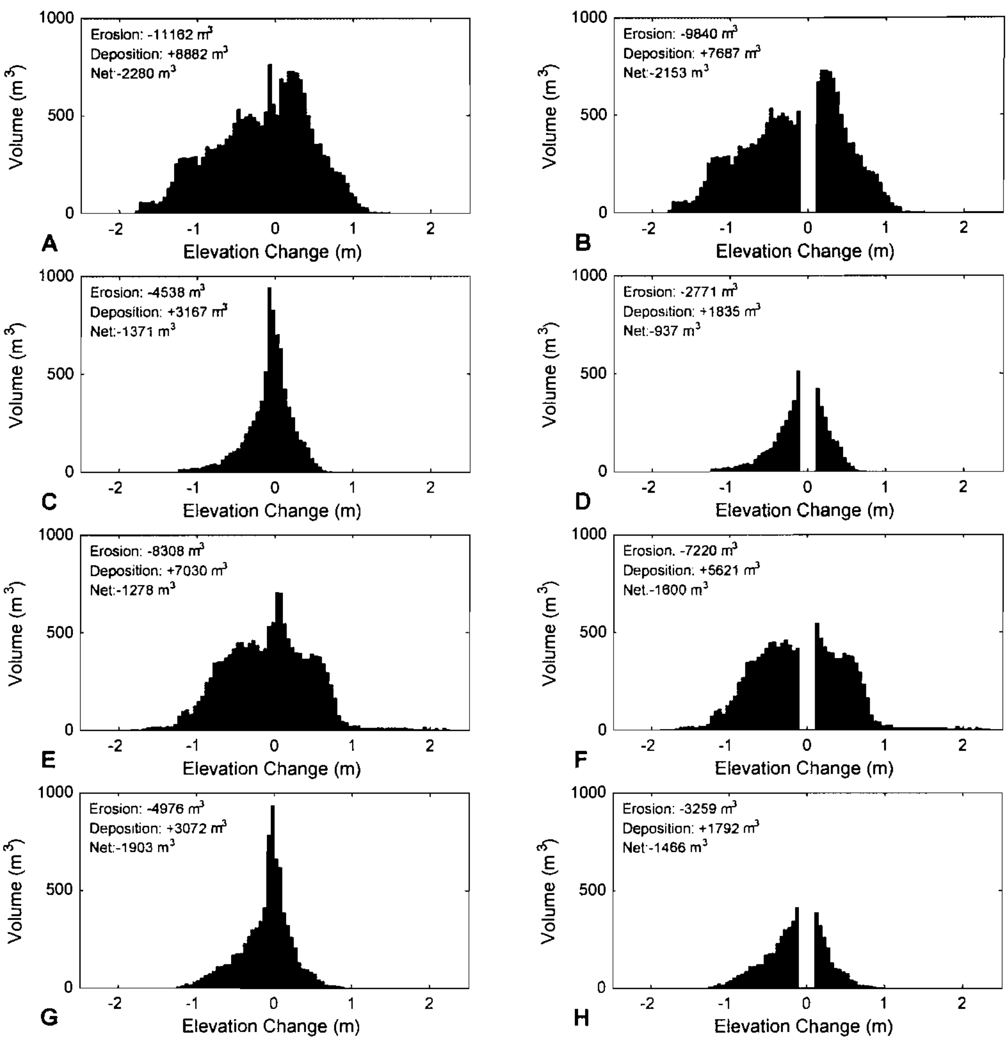


FIGURE 4.25: Application of Pathway 2 on volumetric DoD distributions (2007-2003). Each row represents a different analysis period (A and B are 2007-2006; C and D are 2006-2005; E and F are 2005-2004; G and H are 2004-2003). The left-hand column represents the gross unthresholded DoD, whereas the right-hand column represents the application of a a simple 10 cm $_{min}$LoD via pathway 2 (see Figure 4.23).

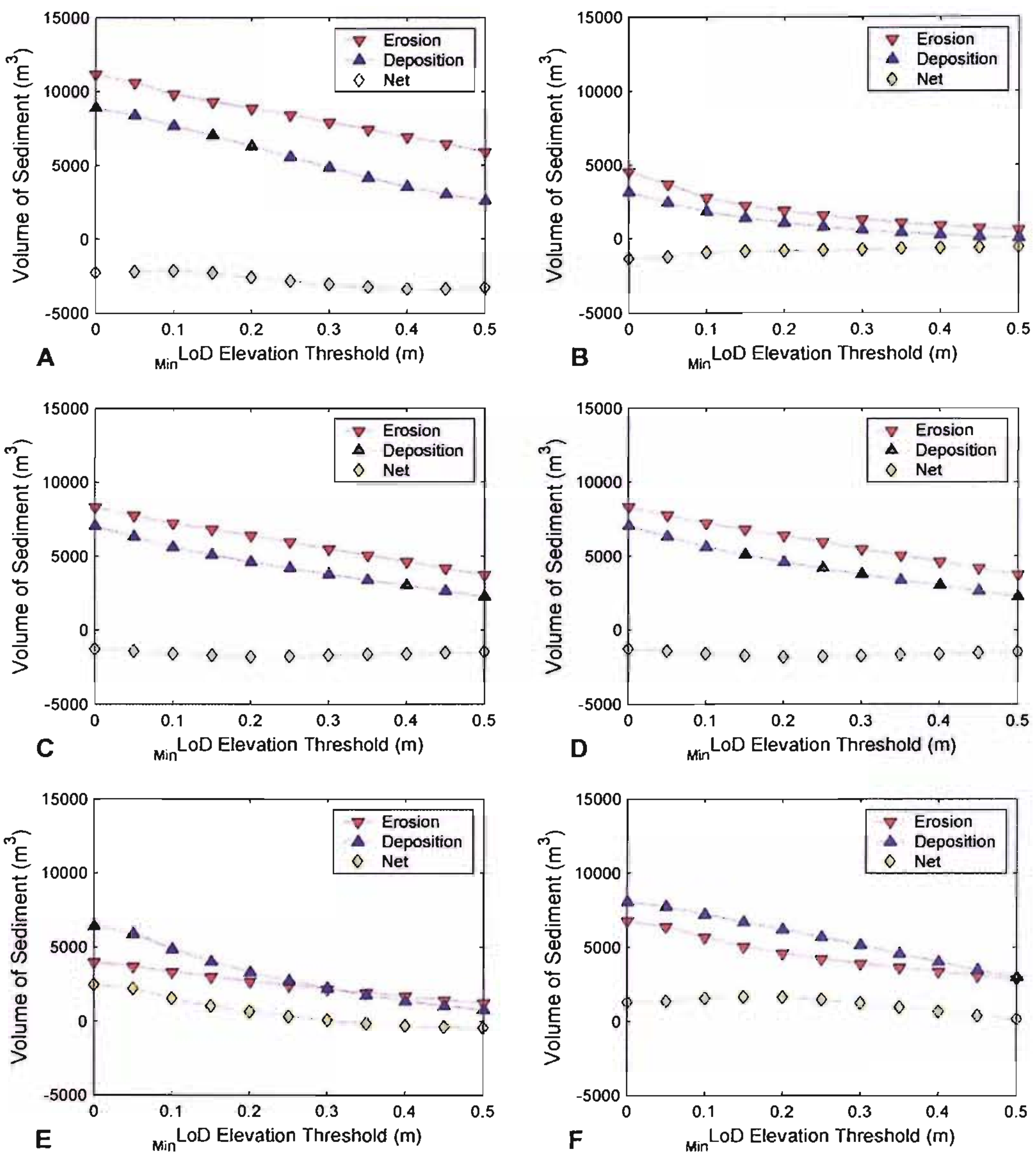


FIGURE 4.26: An example of gross sediment budget sensitivity to different simple elevation threshold minimum levels of detection. Derived from ten sets of analyses in each interval in 5 cm $_{min}$LoD increments from 5 cm to 50 cm. Analysis Intervals: A) 2007-2006, B) 2006-2005, C) 2005-2004, D) 2004-2003, E) 2003-2002, F) 2002-2000. Note the gross non-thresholded values are plotted at a $_{min}$LoD of 0 m to indicate information loss.

may be more susceptible to information loss via a $_{min}$LoD thresholding technique centred around zero. Given this, one might have expected to see a steeper curve for erosion than deposition in Figure 4.9. However, the curves were fairly consistently parallel across the analyses. As only two runs in each year (points at 5 cm and 10 cm) were within this 2 to 3 D_{90} depositional sheet range, there is very little resolution to resolve such a difference.

In summary, pathway 2 provides a simple means of accounting for uncertainty in DoD calculations but the results produce a rather high degree of information loss. Without a more sophisticated understanding of the uncertainty, it is difficult to decipher how much of this information loss is necessary versus overly conservative. The next section applies a more sophisticated model of $\delta(z)$ using the methodology developed earlier in the chapter.

4.6.3 Pathways 3 and 4

The distinction between pathways 3 and 4 is illustrated in Figures 4.27 and 4.28. Both Pathways 3 and 4 use a spatially variable analysis of DEM $\delta(z)$ based on § 4.4.1. However, pathway 4 includes the spatial contiguity analysis described in § 4.4.2.[63] Figure 4.29 shows the summary map results of all DoDs with a 95% confidence interval $_{min}$LoD threshold applied. The same results are presented in Figure 4.30 as elevation change distributions. Focusing first on the pathway 3 elevation change distributions (left hand side of Figure 4.30), the distribution shapes are rather different than those simply thresholded using a pathway 2 analysis (Figure 4.25). Instead of consisting of a distribution with its middle chopped out, the FIS-based distriubtions look like discrete erosional and depositional distributions. Applying the spatially variable uncertainty has the effect of recovering some information down to a lower limit as implied in the membership function of the 'low' $\delta(z)$ class (Figure 4.12), but also selectively recovers and discards information across the whole range of elevation change magnitudes. In terms of plausibility, the elevation change distributions suffer from some of the same shortcomings highlighted in the previous section for the pathway 2 derived distributions, but to a lesser degree. It is conceptually appealing that more conservative threhsolds have been applied where $\delta(DoD)$ is greater and less conservative thresholds applied where δ(DoD) is less, and the distributions certainly reflect an adjustment based on this principle.

Shifting attention now from the distributions to the DoD map for Pathway 3 (top of Figure 4.29), in comparison to Pathway 2 these show some noticeable improvements in terms of geomorphological plausibility. First, the number of pixelated areas on the floodplain has been reduced dramatically. The primary coherent units of erosion and deposition have grown around their edges (reflecting the picking up of some lower magnitude changes). This has particularly helped improve contiguity between erosion and deposition units, but it could still be improved. Although Pathway 3 has recovered a small volume of lower magnitude changes, it has not done a particularly good job of recovering much in the way of meaningful low

[63] In the DoD Uncertainty Analysis Program, when a Pathway 4 analysis is chosen, a complete Pathway 3 analysis is done any way.

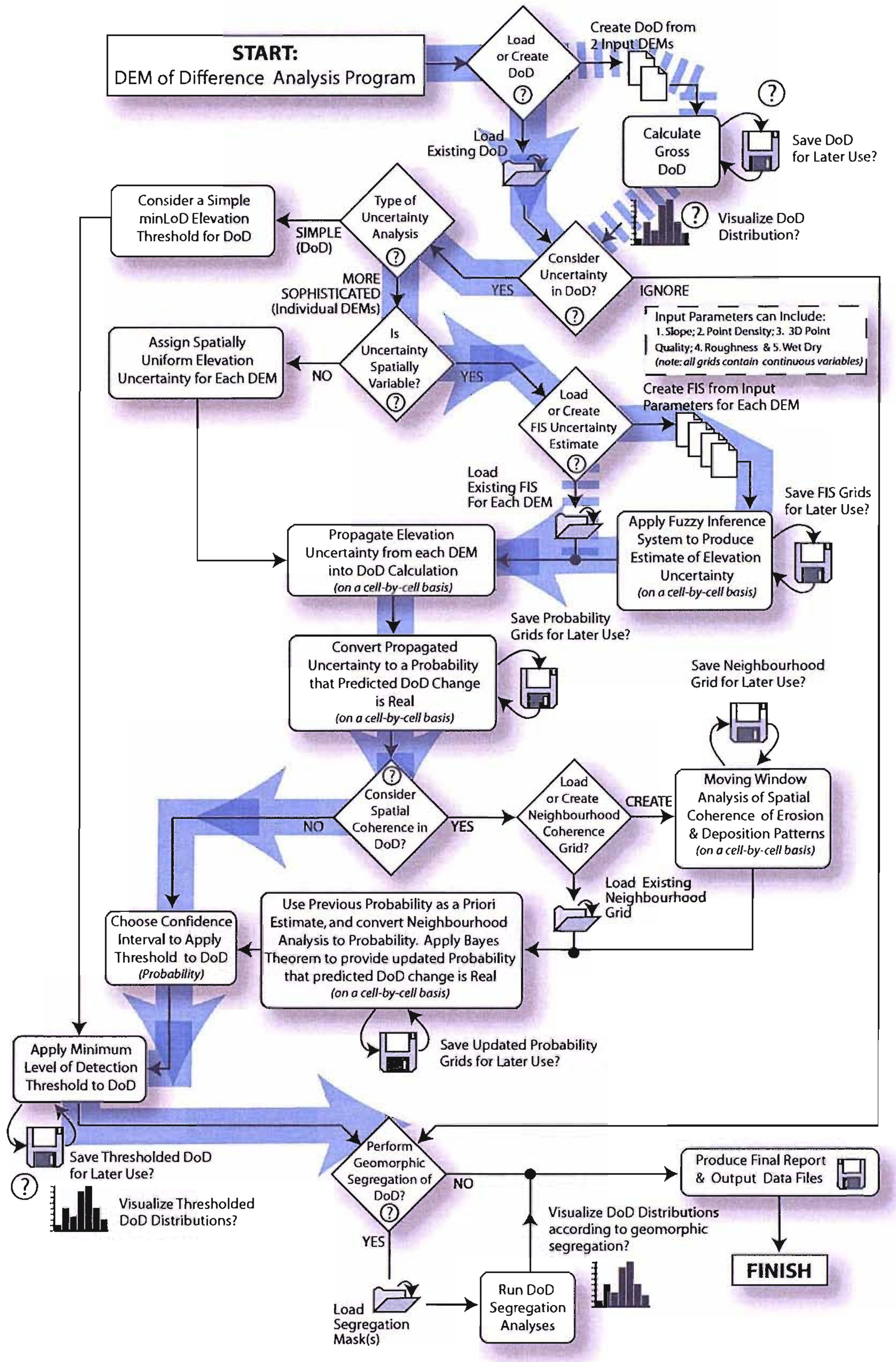


FIGURE 4.27: Pathway 3 through DoD Analysis 2.0 is depicted in blue.

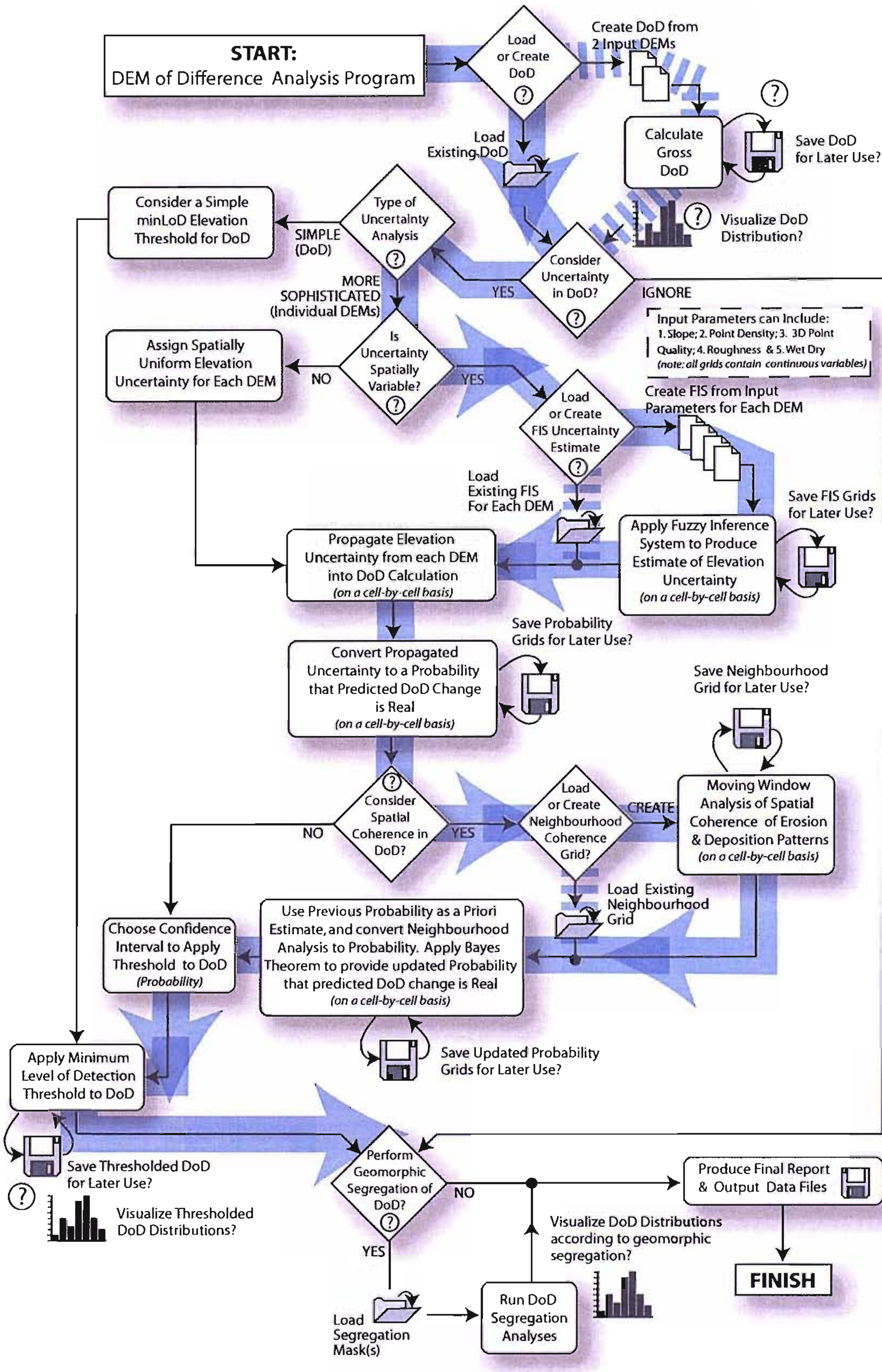


FIGURE 4.28: Pathway 4 through DoD Analysis 2.0 is depicted in blue.

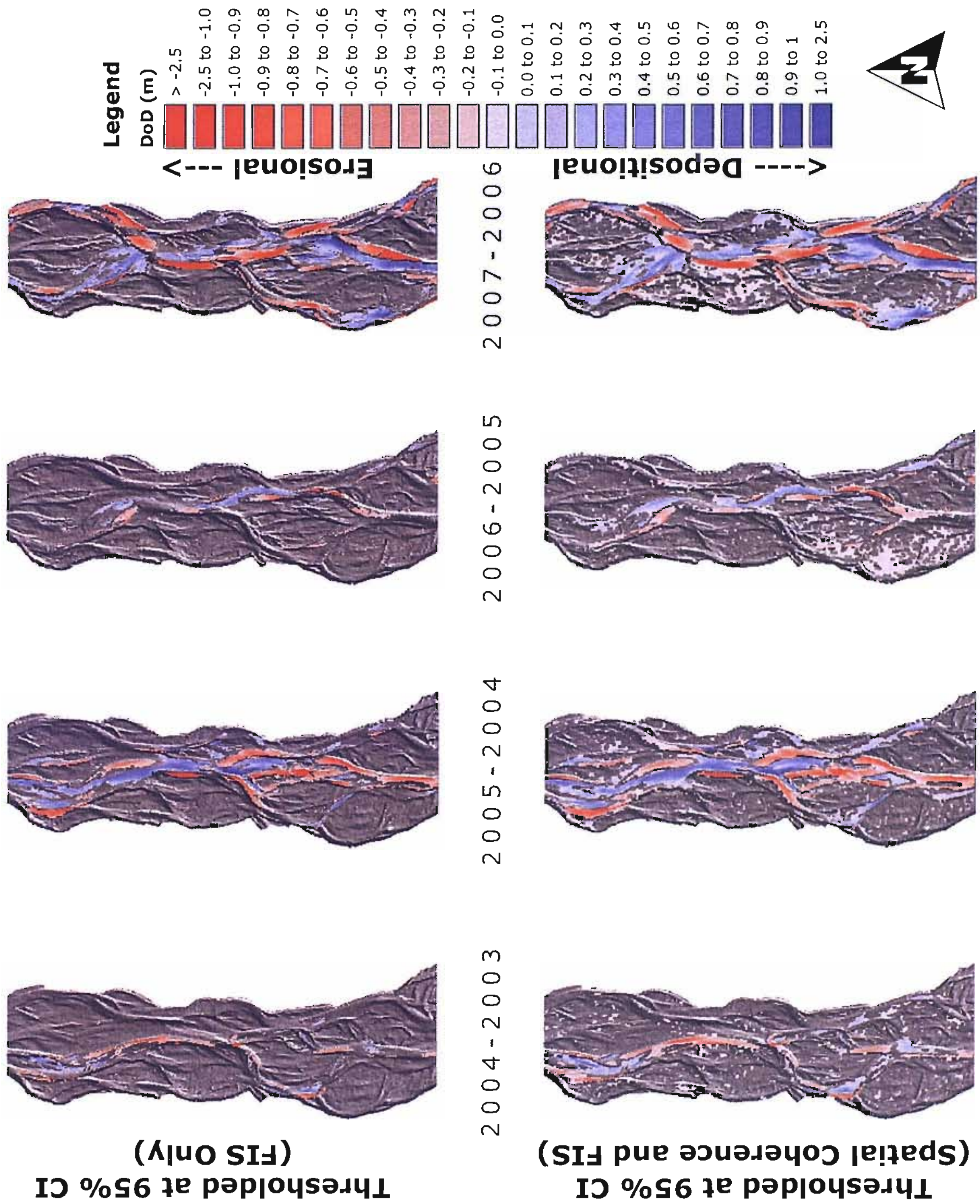


FIGURE 4.29: Comparison of thresholded DoDs (at 95% Cofidence Interval) based on applying FIS through Pathway 3 (top) and applying Bayesian updating using the Spatial Contiguity Index through Pathway 4 (bottom) for all annual DoDs from 2007-2003. The hillshade from the more recent year's DEM underlies the DoD for context.

magnitude elevation changes across the floodplain. This result is likely because these changes really are below the lowest $_{min}$LoD limits.

By comparison, pathway 4 (top of Figure 4.29) does appear to recover substantial areas of floodplain deposition based on the spatial contiguity index. Some of the smaller areas are on the verge of looking like a smoothed pixelated mess, but some of the larger units are in coherent patterns (e.g. splays) that could plausibly reflect actual overbank deposition. Pathway 4 also significantly increases the spatial extent of the individual erosion and deposition units again toward their actual extent in the areas where there is strong field evidence of such change taking place. Thus, from the DoD maps, pathway 4 seems to qualitatively represent a substantial improvement over pathways 1, 2 and 3.

Returning to the elevation change distributions for pathway 4 (right hand side of Figure 4.30), the distribution shapes still emulate the parent distributions from pathway 3 on the left hand side of Figure 4.30. However, the total volumes in these pathway 4 distributions have substantially increased over their pathway 3 counterparts representing a significant information recovery.[64] What is particularly pleasing about the information recovery is not the magnitude of recovery but that it has successfully bridged the gap between the discrete erosional and depositional halves of the distribution, such that even changes hovering around zero are now represented in the distribution.

For reference, it is helpful to compare the DoD probability grids produced by pathways 3 versus 4 prior to any thresholding. Figure 4.31 shows these maps for all four analysis periods. The most striking difference between the probability maps is the degree of smoothing and removal of the 'pixelated' look from pathway 3. When the spatial contiguity index is used with the Bayesian updating, it in essence acts like a low-pass filter smoothing the spatial probability distribution and highlighting coherent regions (Burrough & McDonnell 1998).

To explore to what extent the conclusions above hinge on the somewhat arbitrary selection of a reasonably conservative 95% confidence interval[65] a sensitivity analysis of the pathway 4 DoDs was performed. A total of 44 analyses across the four analysis periods were performed (11 each), in 5% increments from 50% (liberal), up to 95% and then including 99% (conservative). The results are summarised in Figure 4.32. The original gross budget estimates (pathway 1) are plotted in the background as straight lines to give an indication of information loss. One of the most striking differences between this sensitivity analysis and that under pathway 2 presented in Figure 4.26 is how much less sensitive the pathway 4 analysis seems to be to the full range of threshold values.[66] The high magnitude years (2007-2006: Figure 4.32A and 2005-2004: Figure 4.32C) show much more sensitivity than the lower magnitude years, particularly above 90%. Once again, 2006-2005 (Figure 4.32B) shows some sensitivity at higher thresholds to the overall interpretation of net aggradation or degrdation.

[64] The discussion of information loss and recovery for pathways 3 and 4 will be reserved for the next section when Table 4.11 is presented.

[65] Lane *et al.* (2003), for example, use a 68% confidence interval.

[66] i.e. the curves in Figure 4.32 have much gentler slopes than in Figure 4.26. The threshold values are $_{min}$LoD elevations in the pathway 2 analysis and confidence interval values in the pathway 4 analysis.

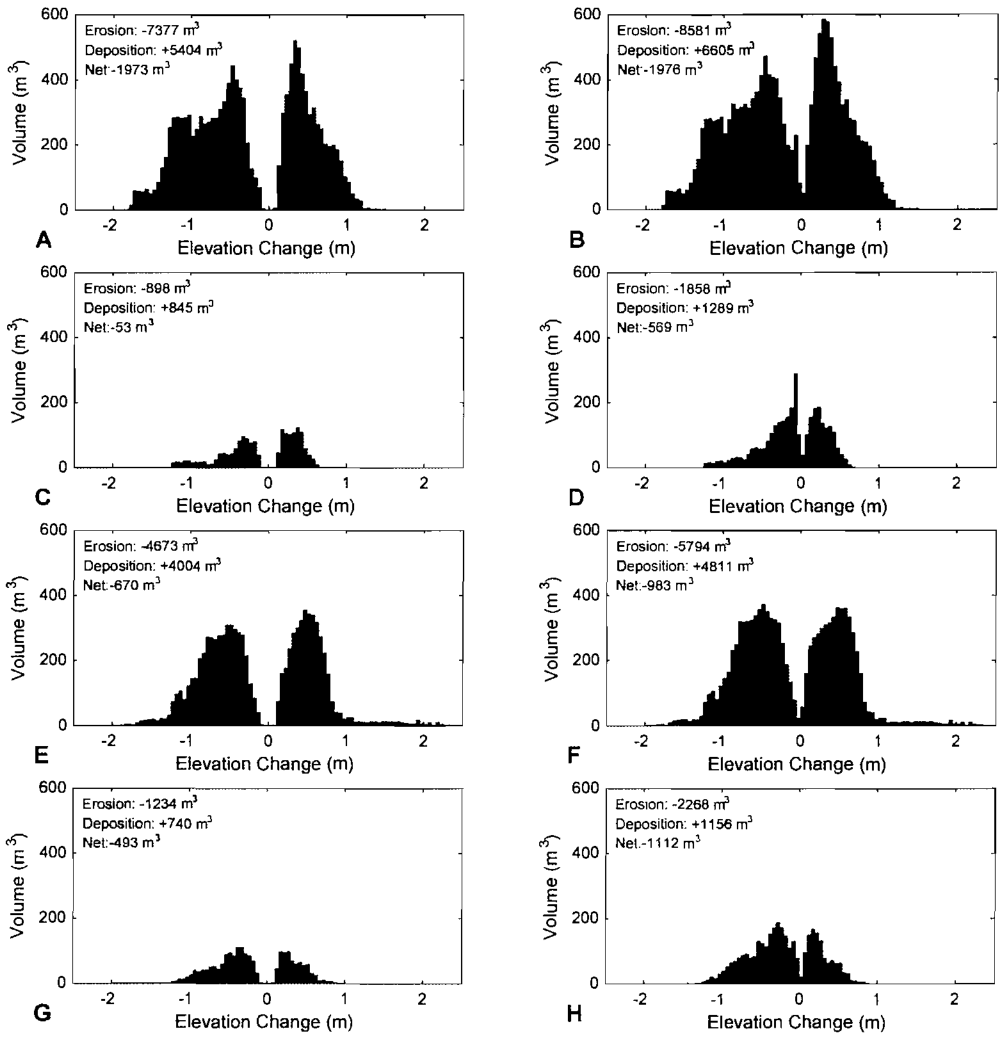


FIGURE 4.30: Application of Pathways 3 (left) and 4 (right) on volumetric DoD distributions (2007-2003). Each row represents a different analysis period (A and B are 2007-2006; C and D are 2006-2005; E and F are 2005-2004; G and H are 2004-2003). The left-hand column represents the volumetric DoD distribution with a FIS applied and thresholded at a 95% confidence interval (see Figure 4.22 for gross distributions); whereas the right-hand column represents the volumetric DoD distribution with both a FIS and Bayesian updating using the Spatial Contiguity Index applied and thresholded at a 95% confidence interval via pathway 4 (see Figure 4.28).

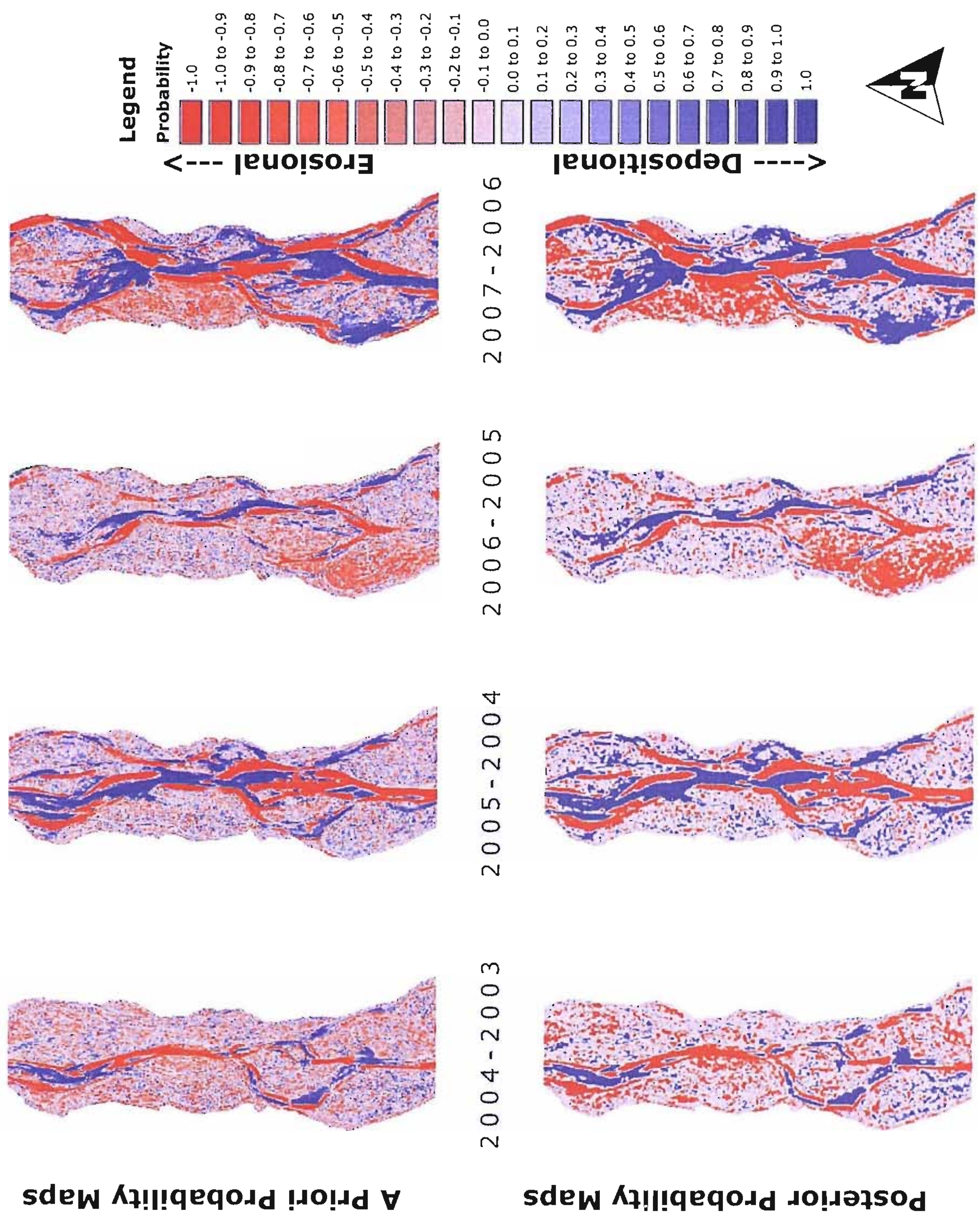


FIGURE 4.31: Comparison of a priori (top) and posterior probabilities (bottom) for all annual DoDs from 2007-2003. The top shows the probabilities that DoD-predicted changes are real based on the application of the FIS, whereas the bottom shows probabilities based on Bayesian updating from the spatial contiguity index. Note that darker colours indicate a higher probability and lighter colours a lower probability.

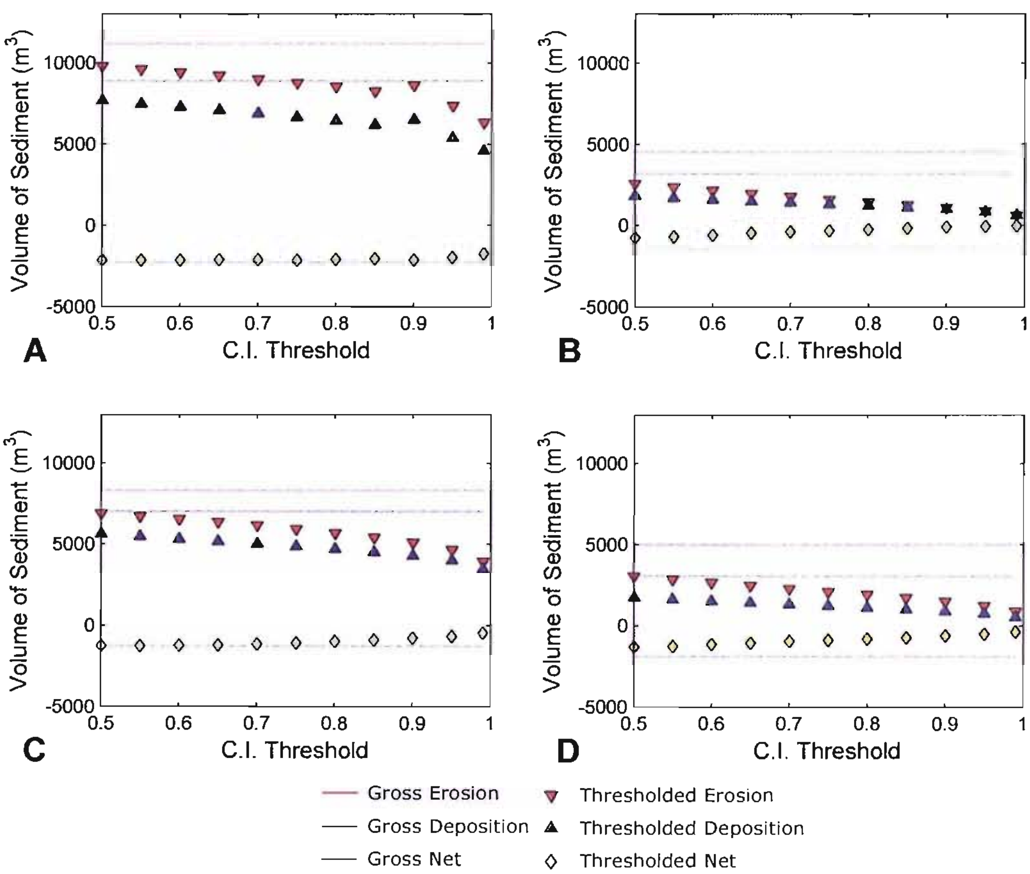


FIGURE 4.32: An example of pathway 4 sediment budget sensitivity to different confidence interval thresholds. Analysis Intervals: A) 2007-2006, B) 2006-2005, C) 2005-2004, D) 2004-2003. Note the gross non-thresholded values are plotted as a series of horizontal reference lines to indicate relative information loss.

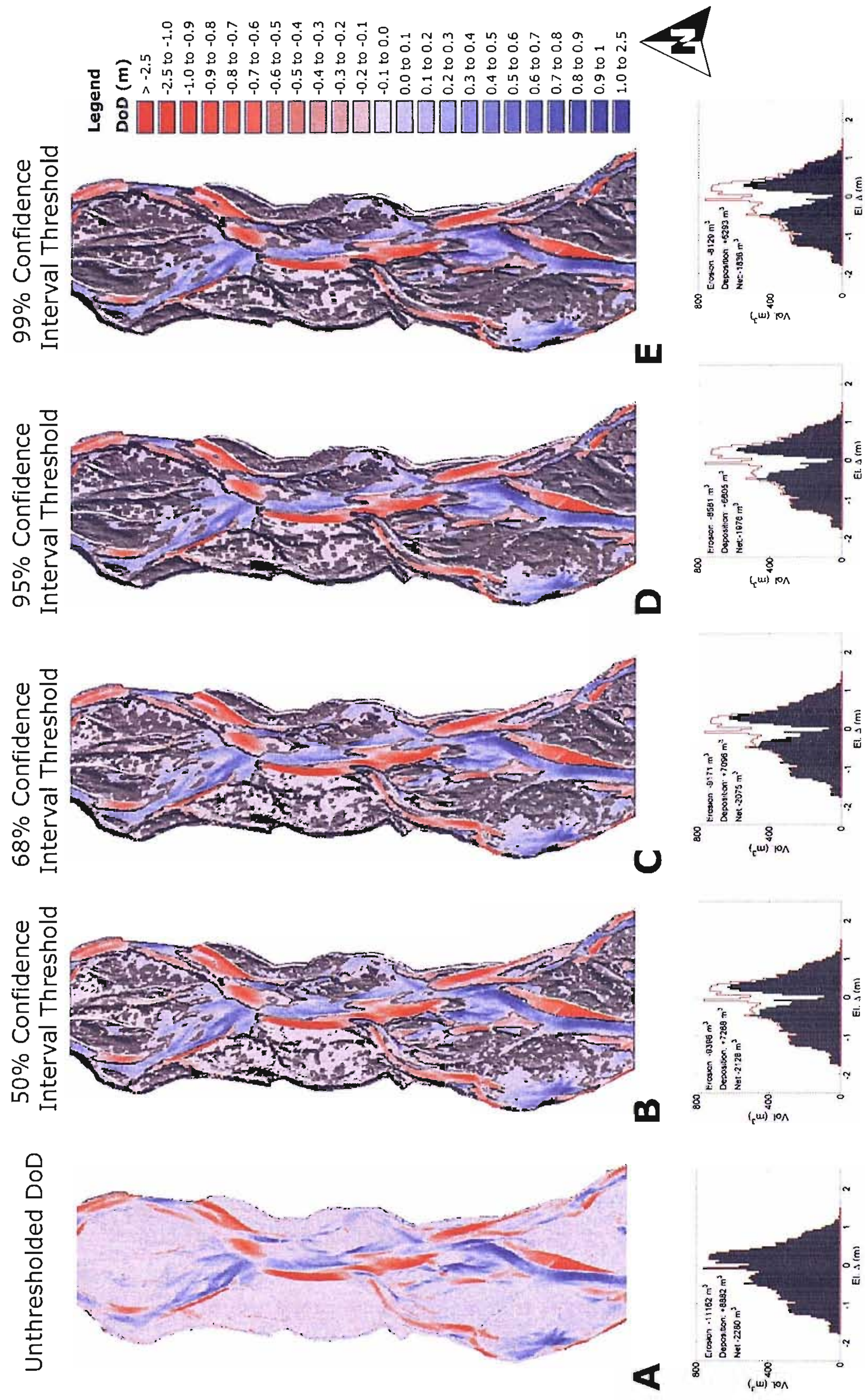


FIGURE 4.33: An example of DoD sensitivity to confidence interval threshold minimum levels of detection. Derived from ten sets of analyses in each interval in 5 cm $_{min}$LoD increments from 5 cm to 50 cm. Confidence Intervals: A) Unthresholded, B) 50% CI, C) 68% CI, (σ), D) 95% CI (2σ), E) 99% CI. Note the gross non-thresholded values are plotted in red on each volumetric elevation change distribution (bottom) to indicate information loss.

To illustrate the influence that different confidence interval ${}_{min}$LoD thresholds have on spatial patterns and elevation change distributions, a selection of common threshold values for the 2007-2006 DoD are shown in Figure 4.33. For reference, the unthresholded DoD and its distribution are shown in Figure 4.33A. The general shape of the elevation change distributions hardly differs across the whole range of confidence intervals. Even the magnitude of information loss does not vary dramatically across the range, with 17% total information loss from the original for the 50% confidence interval and 28% total information loss from the original for the 99% confidnece interval. In terms of spatial patterns, the 50% confidence interval certainly recovers a much higher degree of floodplain and bar top deposition. Further analysis is required to establish to what extent these correlate to areas that were inundated in 2006 to 2007, but there does seem to be a striking similarity between these patterns and those produced by hydraulic simulation of floodplain inundation (Cox *et al.* Submitted).

In summary, the results from pathway 4 are not perfect, but are quite encouraging and seem to be a) producing more geomorphologically plausible results than pathways 1 and 2, b) producing more meaningful uncertainty representations, and c) seem reasonably resilient to the selection of a confidence interval for thresholding.

4.6.4 Pathway 5 and 6

As a final test of how pathway 4 is performing in terms of information recovery, some simple summary statistics from all pathways will be reviewed. To do this, pathways 5 and 6, which are outlined in Figures 4.34 and 4.35 respectively, need to be understood. Pathway 5 is intended to separate the influence of Bayesian updating based on the spatial contiguity index from the spatially variable FIS uncertainty analysis. Instead of using a spatially variable $\delta(z)$ analysis, a spatially uniform $\delta(z)$ is specified for each DEM and a priori probability maps are defined as described in § 4.3.3 and depicted in Figure 4.10. The pathway 5 analysis should be helpful in determining to what extent the Bayesian updating is responsible for information recovery by comparing it to a pathway 6 analysis. The pathway 6 analysis is exactly the same as a pathway 5 analysis but it does not include any Bayesian updating of the DoD probability grid. The effect of a pathway 6 analysis on the DoD distributions is exactly the same as a pathway 2 analysis (i.e. a simple ${}_{min}$LoD elevation threshold being applied), the only difference is that the threshold is defined probabilistically in terms of a confidence interval. As such, a pathway 6 analysis is useful for a user who prefers to think of thresholds probabilistically, but in reality identical results can be achieved following pathway 2. As the primary purpose of these pathways is for end-member comparison with pathway 4 to help explain how it works, focus is restricted here to just the summary DoD results in pathway 5 and 6 from a set of eight analyses thresholded at a 95% confidence interval.

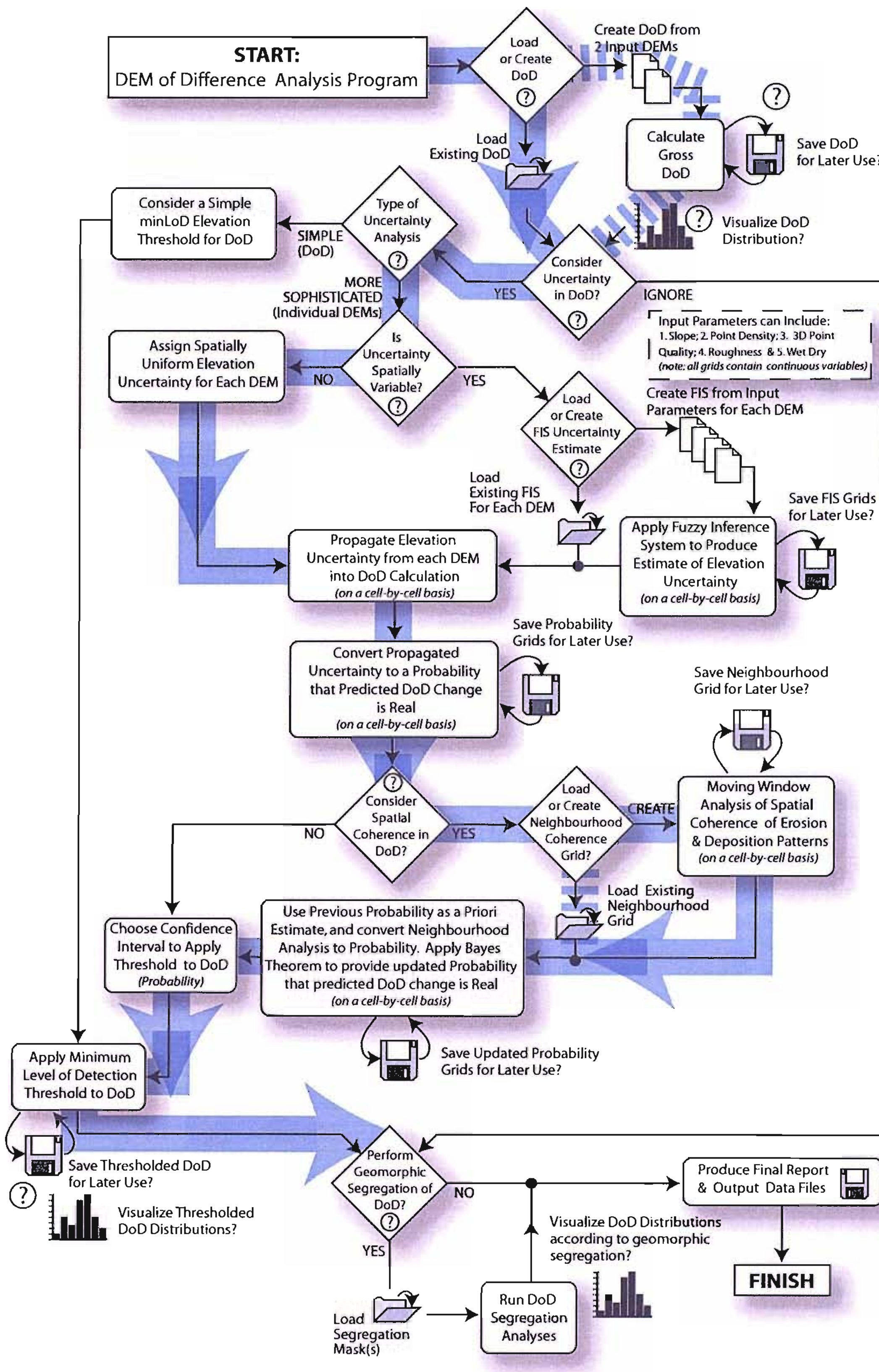


FIGURE 4.34: Pathway 5 through DoD Analysis 2.0 is depicted in blue.

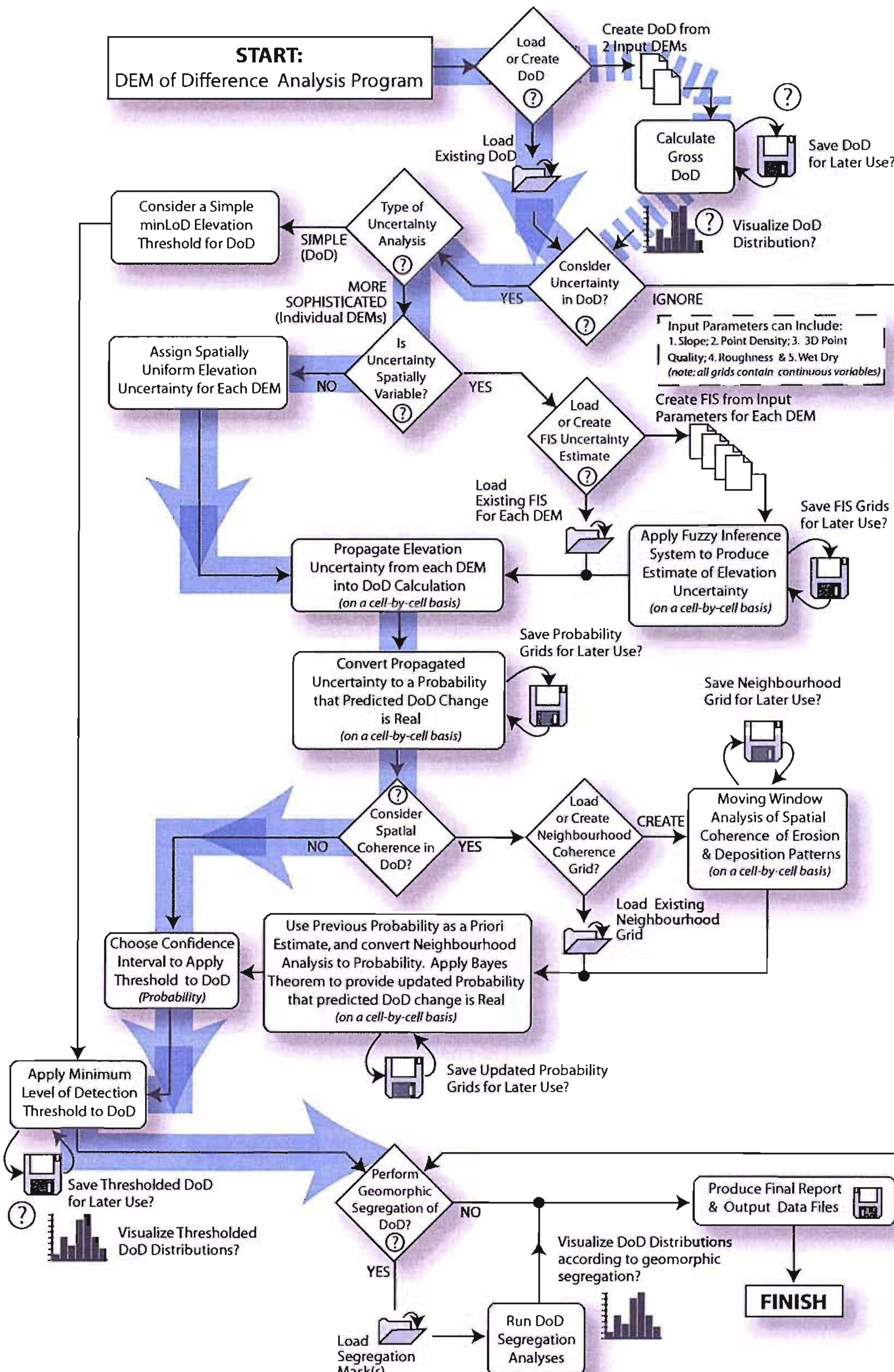


FIGURE 4.35: Pathway 6 through DoD Analysis 2.0 is depicted in blue.

	DoD Change			Percentage Loss From Original		
DoD	Erosion m^3	Deposition m^3	Net m^3	Erosion %	Deposition %	Total %
	Pathway 1					
2007-2006	11162.0	8882.3	-2279.7	NA	NA	NA
2006-2005	4538.5	3167.1	-1371.3	NA	NA	NA
2005-2004	8307.9	7029.7	-1278.2	NA	NA	NA
2004-2003	4975.5	3072.2	-1903.3	NA	NA	NA
μ:	7246.0	5537.8	-1708.2	NA	NA	NA
	Pathway 2 (10 cm $_{min}$Lod)					
2007-2006	9840.0	7687.0	-2153.0	12%	13%	13%
2006-2005	2771.4	1834.8	-936.6	39%	42%	40%
2005-2004	7220.4	5620.7	-1599.7	13%	20%	16%
2004-2003	3258.8	1792.4	-1466.3	35%	42%	37%
μ:	5772.6	4233.7	-1538.9	25%	29%	27%
	Pathway 3 (95% CI)					
2007-2006	7376.7	5403.7	-1973.0	34%	39%	36%
2006-2005	898.4	845.1	-53.3	80%	73%	77%
2005-2004	4673.4	4003.8	-669.7	44%	43%	43%
2004-2003	1233.5	740.5	-493.1	75%	76%	75%
μ:	3545.5	2748.3	-797.2	58%	58%	58%
	Pathway 4 (95% CI)					
2007-2006	8581.0	6605.3	-1975.7	23%	26%	24%
2006-2005	1857.8	1288.5	-569.3	59%	59%	59%
2005-2004	5794.0	4810.8	-983.2	30%	32%	31%
2004-2003	2268.1	1156.1	-1111.9	54%	62%	57%
μ:	4625.2	3465.2	-1160.0	42%	45%	43%
	Pathway 5 (95% CI)					
2007-2006	9382.7	7265.5	-2117.2	16%	18%	17%
2006-2005	2554.5	1513.7	-1040.9	44%	52%	47%
2005-2004	6710.2	5293.6	-1416.6	19%	25%	22%
2004-2003	2977.6	1414.6	-1563.0	40%	54%	45%
μ:	5406.3	3871.8	-1534.4	30%	37%	33%
	Pathway 6 (95% CI)					
2007-2006	9172.1	6788.5	-2383.5	18%	24%	20%
2006-2005	2131.2	1301.4	-829.7	53%	59%	55%
2005-2004	6664.6	4905.4	-1759.2	20%	30%	25%
2004-2003	2725.6	1288.5	-1437.1	45%	58%	50%
μ:	5173.3	3570.9	-1602.4	34%	43%	38%

TABLE 4.11: Volumetric DoD results and information loss for all pathways and all years (using 95% confidence interval for pathways 3 through 6). Mean values across all four periods are also reported. Note: percentage total loss from original is calculated from the total volume of change, not the net volume of change.

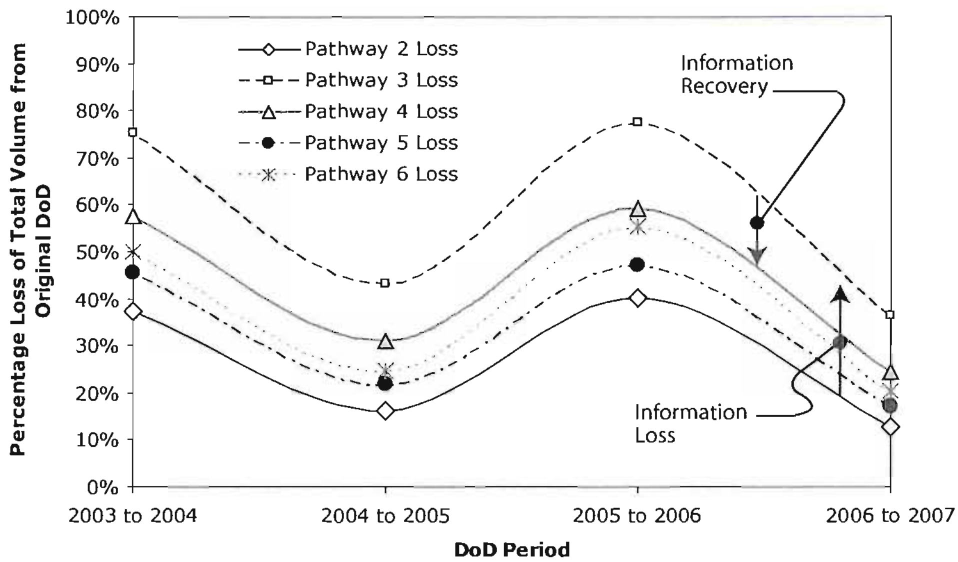


FIGURE 4.36: Graphical summary of total volumetric information loss by pathway for each year (data taken from Table 4.11). The reference Pathway 2 shown is a 10 cm $_{min}$LoD, whereas all the other pathways shown are based on a 95% confidence interval threshold.

4.6.5 Pathways Compared

Table 4.11 summarises the gross DoD volumes of all six pathways and the corresponding information loss from the original unthresholded DoD (pathway 1). Information loss was calculated simply as one minus the ratio of the volume of predicted volumetric change for the current pathway divided by the original unthresholded volumetric change. Total information loss refers to the same ratio but is based on the sum of erosion and deposition volumes as opposed to net volumes. Across the information loss statistics for every pathway, there is only a maximum difference of 8% within a pathway between erosion, depositon and total information loss, and a mode of 3%. As such, the discussion here will focus just on the total information loss statistic.

Total information loss across all the DoD analyses in all pathways ranged from as little as 13% to as much as 77% ($\mu = 40\%$). Caution should be excercised in interpreting gross information loss as an indication of how well various pathways are peforming. These summary results give little insight into what fraction or type of information was 'recovered' or lost like the elevation change distributions do. However, it is difficult to describe overall trends across 24 different elevation change distributions, and for that these statistics can be helpful. Regardless of pathway, the high magnitude years (2006 to 2007 and 2004 to 2005) consistently produced the lowest information loss (typically roughly half of the other years). This is probably seen easiest in Figure 4.36, which summarises just the total information loss by pathway. The peaks correspond to the low magnitude change years and the troughs to the high magnitude change years.

Pathway 2 generally produced the lowest information loss ($\mu = 27\%$), but as discussed in § 4.6.2 this seems to be at the expense of geomorphological plausiblity and by means of an overly simplistic model of uncertainty. Pathway 3 by contrast, generally produced the highest information loss ($\mu = 58\%$), but with the aid of a more sophisticated model $\delta(z)$. Pathway 4 was quite effective at recovering much of the information lost in pathway 3 ($\mu = 43\%$, roughly 16% recovery on average.). As pathway 5 ($\mu = 33\%$) involved only a spatially uniform analysis of elevation uncertainty before applying Bayesian updating with the spatial contiguity index, it had less lost ground to recover than pathway 4. This lesser 'lost ground' for pathway 5 is crudely characterised by pathway 6 ($\mu = 38\%$).In an analgous fashion to how pathway 3 provides the low point of information loss for pathway 4; pathway 6 produces the a priori probability for pathway 5). In so doing, pathway 5 again proved effective at recovering information from its a priori estimate (pathway 6), recovering 5% on average. Although the mean information loss for pathways 5 and 6 are lower than pathways 3 and 4, this is again accomplished by means of an overly simplistic spatially uniform uncertainty model. Thus, pathway 4 emerges as the new preferred approach.

4.7 Further Discussion

This chapter has mixed discussion with methods and results throughout. However, there are several broader discussion points that have not been addressed, which help bring together this topic of quantifying DoD uncertainty. These are addressed in the next few subsections. Further discussion can be found in Chapter 9.

4.7.1 A New Preferred Methodology

The preferred methodology used in the literature thus far has been a $_{min}$LoD technique (i.e. Pathway 2 or 6), primarily because it is a reasonable, tractable approach. With the development of the DoD Uncertainty Analysis Software, that approach is even simpler to robustly apply. However, on the basis of geomorphological plausibility[67] and recovery of otherwise discarded information likely to be real, the pathway 4 analysis has emerged as the preferred method here. One of the advantages of the pathway 3 and 4 analyses, which use a FIS to estimate spatially variable uncertainties, is that they allow the relaxation of detection levels in areas like smooth, flat floodplains, and they make detection levels more stringent in areas like steep banks. This allows a much more realistic estimation of surface representation uncertainty then a spatially uniform approach (e.g. pathways 2, 5 or 6). With the pathway 4 analysis, these estimates can be relaxed or strengthened further on the basis of the spatial coherence of erosion and deposition units. With the DoD Uncertainty Analysis Software, it is no harder to apply a pathway 4 analysis then any other analyses, and it is simple to run analyses of all pathways to inter-compare differences.

[67] The geomorphological interpretation and plausibility of this dataset will be explored more fully in Chapter 8.

4.7.2 Why Bother?

Perhaps one of the most direct questions, which this chapter has sidestepped thus far, is given that a DoD is known to generally be a conservative estimate of the total magnitude of change[68], and given that any uncertainty analysis is going to reduce that estimate, why bother? That is, even if an unthresholded DoD overestimates the actual volume of net change in the storage terms in a sediment budget (equation 3.1), surely this should be closer to the actual value of total sediment moved. There are at least three compelling reasons to undertake an uncertainty analysis in spite of the above argument.

First, it is misleading to imply that a DoD can provide an estimate of the total volume of material moved for sediment budgeting purposes. A DoD will reflect changes in storage due to fluxes within the DoD control volume as well as fluxes of material moving across the control volume boundaries. However, a DoD provides no direct measurement of these fluxes. At best a DoD can only provide an approximation of the storage terms in a sediment budget, and in reality it only actually reflects the *net* storage terms. Under the most ideal circumstances, where a DoD is capturing only changes from a single event that was known to only produce uni-directional changes, the DoD is a reasonable estimate of the change in storage. However, in many cases, there is a more complex history of changes that have taken place between the two surveys that can locally reflect varying episodes of cut and fill (Lindsay & Ashmore 2002). Thus, it is important to be clear that what can be calculated from a DoD is a net change in storage and recognise that uncertainties in that estimate still need to be considered.

Second, even if the volume of change from a raw DoD was an under-estimate of the total magnitude of change, it could be a grossly misleading over-estimate or misrepresentation of the net volume of change. Without some form of uncertainty analysis these misrepresentations would go undetected, and one can not be confident that the changes calculated are meaningful.

Finally, the simplest answer is because the unthresholded DoD is simply not geomorphologically plausible. The odds of recording the exact same elevation at the exact same point, when that point has certainly not moved are next to zero.[69] This is a reflection of simple measurement error (an unreliability uncertainty due to limited knowledge). However, in many DoDs, like the Feshie, there are large areas captured in the survey that will have experienced no detectable change. For example, a floodplain that has not been inundated has no agent for geomorphological change (assuming that aeolian processes are not a factor). When resurveyed, such areas in theory should show no change. However, in practise measurement and interpolation errors mean that every cell in a DoD of an unchanged surface will show some changes.[70]

[68]A DoD only captures the net change in storage between two points in time. It does not quantify the flux terms (e.g. sediment transport). It can also conceal changes that might have taken place, but were since erased by more recent changes (e.g. building of a bar-feature that erodes away before next survey).

[69]This is what the repeat observation of control points attempts to measure (§ 4.3.1.1).

[70]This is what the repeat survey experiments showed (§ 4.3.1.4).

4.7.3 Interpolation Errors

In this context, interpolation errors in DEMs manifest themselves primarily in two ways. One is as a result of the TINing process and the other is in the rasterization process. Are these errors significant and are they dealt with in the DoD uncertainty analyses proposed?

Recall that TINs are the most common and reliable form of representing high-resolution topographic data, which has been collected to capture morphological grade-breaks (French & Clifford 2000). The TIN itself is particularly prone to misrepresenting surface topography where low point density and greater topographic complexity combine. The use of an FIS that accounts for both point density and slope is an implicit attempt to account for such TIN interpolations. It is not explicit, in that it does not fundamentally address the root causes of interpolation errors (i.e. over generalisation) and does not improve the TIN. All the process does is allow an estimation of the extent to which TIN interpolation errors might be contributing to surface representation uncertainty.

There are further interpolation errors introduced in the process of linearly resampling the TIN onto a raster (grid) DEM. These errors are minimised when an grid resolution is chosen that is similar or finer than the point density of the survey. As point density varies, there is always an expensive trade-off between finer resolution rasters and associated increased computational overhead. One way to identify appropriate grid resolutions, so as to minimise such interpolation errors, is to look at the sensitivity (through information loss) of DEM budgets to grid resolutions. For the Feshie, a 1 m resolution DEM seemed to minimise information loss, while maintaining the detail of bar scale morphology and a computationally efficient grid size to preform the 1000's of analyses reported here.[71] Alternative TIN-based differencing schemes do exist and are used in commercial applications like Surfer and Autodesk's Land Desktop and have been used in the literature (Lane *et al.* 1994, Merz *et al.* 2006, e.g.). However, to apply the sort of uncertainty analysis used here, would be algorithmically much more complicated to apply and difficult to maintain flexibility for extension in the future. As such, the simpler raster-based algorithms were adopted here and adequately high grid resolutions were used.

4.7.4 Application to Other Survey Methods

All of the analyses presented in this chapter were based on ground-based survey techniques like rtkGPS and total station surveying. Other popular techniques of monitoring topography in fluvial environments include aerial photogrammetry (Gilvear *et al.* 2004, Westaway *et al.* 2001), and airborne-LiDaR (Charlton *et al.* 2003). In addition, terrestrial laser scanning (or ground-based LiDaR) is rapidly emerging as a viable monitoring tool in the fluvial environment (Brasington *et al.* 2007, Milan *et al.* 2007, Heritage & Hetherington 2007), capable of capturing

[71] For reference, an unattended pathway 4 analysis (in batch mode, not waiting for user inputs), could be undertaken in about 2 minutes on a 1.7 Ghz laptop with 2 GB of RAM and running XP Pro. When running in wizard mode, it took a trained user between 5 and 10 minutes. The most time-consuming process is data preparation.

topographic data at resolutions on the order of 10^3 points per square metre as opposed to 10^0 points per square metre. All three of these techniques have challenges capturing accurate topography in subaqueous environments[72] and vegetated environments as compared with ground-based GPS and total station surveying. However, they can be applied at exceptionally high resolutions over spatial extents similar to that with ground-based methods, or at quite reasonable resolutions over much greater spatial extents (Lane & Chandler 2003). Increasingly, a mix of surveying technologies is used to build a complete data set for one survey (e.g. mixing GPS and LiDAR data). Also, in a monitoring context, different repeat surveys may have been collected using different techniques. As such, the uncertainty estimation methods here would be much more useful if they could be applied independently to any survey methods, and then propagated into the DoD.

Using a two-rule system, as long as the raw point-data were available from such surveys, the DoD uncertainty techniques developed here should be applicable. Some slight calibration of the membership functions might be needed, but at a minimum these could be calibrated to provide a reasonable (if not conservative) first order estimate of surface representation uncertainty. However, these estimates could be improved considerably by extending the rule system to factor in data specific to these individual techniques. For example, most photogrammetry packages provide residuals for each point that could be incorporated, or information from aerial photographs like the presence of vegetation could usefully be incorporated into an FIS rule base. From LiDAR surveys, information about the lag between first and second pulse, could be used not just as a proxy for vegetation height, but explicitly incorporated into the rule system as an uncertainty input. The specific application of the DoD Uncertainty Analysis techniques to other survey methods requires further research, but the basic principles[73] should be widely applicable.

4.7.5 Application to Non-Fluvial Environments

The focus here has been on application of DoD uncertainty techniques to improve morphological sediment budgeting in fluvial environments. However, as mentioned in § 3.3.1.2, there are many other monitoring contexts where DEM-differencing is being used. In civil engineering, comparison of as-built surveys against pre-project surveys has long been used to check cut and fill volumes against grading plans (Webb & Haupt 2003). In glaciology, repeat topographic surveys are used to perform mass-balance calculations, and look at more detailed processing of ice calving (Hubbard *et al.* 2000, Rippin *et al.* 2003, Keutterling & Thomas 2006). In general, no form of uncertainty analysis has accompanied such applications of DEM differencing in glaciology (p. comm B. Hubbard, 2007). In hillslope geomorphology, differencing of LiDAR and photogrammetry surveys can be used to look at geomorphological change from landslides (Eeckhaut *et al.* 2007). Virtually any geomorphological process that shapes the Earth's surface

[72] Most commercially available LiDAR does not penetrate the water surface.

[73] 1. Using an FIS and spatial coherence filter to independently estimate surface representation uncertainty in individual DEMs; 2. Propagate uncertainty from different DEMs separately into the DoD and represent uncertainty probabilistically.

in a manner that produces a magnitude of change larger than minimum detection limits has the potential to be studied using DEM differencing.

As with applying the DoD uncertainty analysis techniques to different surveying technologies, the basic principles should still apply. Specific calibration and/or extension of the rule systems would be necessary, but straight forward to implement. It is likely that because of the lower resolution of topographic data sources in hillslope geomorphology, glaciology and oceanography applications, that more of the budget would be discarded as a result of relatively high minimum levels of detection. All the same, such an analysis is necessary to determine whether anything reliable can be said about change from repeat surveys in such environments. It is speculated that this might suggest better quality and higher resolution datasets are necessary for many applications.

4.8 Conclusion

The purpose of this chapter was to introduce and test a new technique for quantifying uncertainty in estimating geomorphological change from repeat topographic surveys. The premise for the chapter was that there were meaningful geomorphological changes being discarded through minimum level of detection analyses that could be better distinguished from noise through a more sophisticated model of DEM surface representation uncertainty. To test the validity of this premise, the approach developed (culminating in pathway 4) was compared against a baseline of existing approaches (pathways 1, 2 and 6).[74] A significant portion of the chapter was focused on contrasting the variety of existing approaches used (§ 4.3) and explaining how elements of these approaches would be employed here. The original developments from this chapter are three fold:

1. Development of a spatially variable model of elevation uncertainty based on a flexible and robust fuzzy inference system (§ 4.4.1)
2. Development of a spatial contiguity index to account for the spatial coherence exhibited in fluvial patterns of erosion and deposition (§ 4.4.2)
3. Development of a software application for performing a complete DoD uncertainty analysis (§ 4.5)

The new approach was applied to five years of high resolution repeat GPS surveys of the semi-braided River Feshie, Cairngorm Mountains, Scotland. The various pathways outlined through the software application developed were used as a framework for comparing the relative strengths and weakness of the developed and existing approaches. The main criteria used to judge the relative performance of the different analyses were the geomorphological plausibility of the results and the degree to which they recover information likely to be describing real

[74] Refer to Table 4.8 for explanation of pathways.

changes and discard information that is probably noise. From an inter-comparison of the plausibility of all the pathways, pathway 4 (the advocated developed approach) appears to produce the most coherent and believable results. On the basis of just information loss pathway 2 (representing the standard existing approach) with a 10 cm $_{min}$LoD performs best, and pathway 3 (representing a developed approach, which considers the spatial variability of DEM uncertainty) performs the worse. However, pathway 3 is much more plausible then Pathway 2. When pathway 3 is extended to incorporate the spatial coherence of erosional and depositional units (i.e. a pathway 4 analysis) it recovers 15%, on average, of the information lost in going from a Pathway 3 to Pathway 2 analsyis. Thus, on a combination of geomorphological plausibility and recovery of coherent information, the developed pathway 4 analysis appears to perform best.

The DoD uncertainty analysis tools are simple to apply to any topographic data set and the underlying rule systems in pathway 3 and pathway 4 analysis are straight-forward to calibrate to different field settings. The analysis framework is designed to give a robust spatial-variable estimate of DEM uncertainty from any raw topographic point data. However, the framework is flexible and easy to extend to include more rules and factors (e.g. roughness) known to influence surface representation uncertainty if they are available.

Chapter 5

Geomorphological Interpretations of Morphological Sediment Budgeting

5.1 Introduction

The focus on morphological sediment budgeting from DEM differencing has been largely methodological in the literature thus far (Lane *et al.* 2003, Brasington *et al.* 2000, Brasington *et al.* 2003, Fuller *et al.* 2003). As in Chapter 4, this emphasis has been based on demonstrating to what extent DoD calculated changes can be distinguished from noise (i.e. considering uncertainty). This is a natural and necessary progression for an emerging technology. However, a by-product of that focus has been a lack of emphasis on the original reason that the method was developed in the first place, namely to aid in making more meaningful interpretations of geomorphological changes.[1] More than 10 years after Lane *et al.* (1994) reported DEM-differencing as a new development, it is time to return to the question of what can be learned from DoDs.

In this brief chapter, it is asserted that a more explicit quantification of inferred fluvial processes and mechanisms of change can be derived from DEM differencing. It is postulated that geomorphological interpretation is largely a process of informed story telling and inference, based on the best available evidence (Rhoads & Thorn 1996*a*). As Schumm (1991) eloquently pointed out in a student text-book, there are many ways to be wrong when making geomorphological interpretations. In the context of interpreting DoDs, one of the fundamental ways to get it wrong is through misinterpretation of unreliability uncertainties due to limited knowledge about the magnitude of surface representation error. Some confidence in the DoDs being derived is now afforded by the more detailed assessment of uncertainties and methodological development outlined in Chapter 4. In terms of the embracing uncertainty framework outlined in Figure 2.10, a potentially significant unreliability uncertainty has been identified and quantified, and a way to assess its significance and constrain it has been developed.

[1] This claim was justified in § 3.4.

With this analysis addressed, the task of interpreting geomorphological changes is subject to other types of uncertainties due to limited knowledge like indeterminacy, conflicting evidence and reducible ignorance (refer back to Figure 2.2 and § 2.2.2 for explanations). These are structural as opposed to unreliability uncertainties. As outlined in Figure 2.10, there is little that can be done about indeterminacy or conflicting evidence other than to transparently acknowledge it. However, there is more detail locked up in DoDs about the mechanisms of change than have been exploited to date in the literature. It is argued that this is a form of reducible ignorance that just needs some simple tools to improve our understanding. The resulting interpretations of 'why' and 'how' will be open to debate between individual geomorphologists and always subject to uncertainties. That is not of concern here. The focus here is on better describing 'what' information is in a DoD.

The purpose of this chapter is to provide the methodological description of some simple masking tools that can be used to segregate a DoD budget. No results will be presented here, and instead these tools will be put to the test in three separate case studies in Part III. This chapter is separated into the methodological development of the masks, the extension of the DoD Uncertainty Analysis Software to include these tools, and a justification of the study sites used in Part III.

5.2 Methodological Development - The Mask

One of the easily overlooked attributes of a DoD is the explicit information about the spatial patterns of geomorphological change inherent in the maps themselves. Although the geomorphological literature on DoD-based monitoring has to date placed little emphasis on these spatial patterns, the premise of this chapter is that those spatial patterns captured in the DoD are fundamentally what will allow a more detailed and meaningful geomorphological interpretation of observed changes. Whereas any individual DEM only represents a snap shot in time of the Earth's surface, a DoD actually says something about the spatial and historical contingencies (Phillips 2001) that have coalesced to produce the more recent morphology. Ultimately, the utility of the geomorphological interpretations made from the DoD will only be as good as the ability of the investigator to make sense of the spatio-temporal puzzle that the DoD represents. Three case study examples of how this can be done will comprise the bulk of the remainder of this thesis. First, in this chapter, both a method and a tool to implement these interpretations are needed. The method will be to apply a spatial mask, and the tool will be an extension of the DoD Analysis Software developed in § 4.5 that segregates the DoD results according to this spatial mask. The next two sub-sections briefly describe these conceptually simple but interpretatively powerful methodological developments.

5.2.1 Defining the Masks

In the context of GIS, a mask[2] is a sub area of an entire dataset that will be included in an analysis. If the mask is defined with vector data it is a polygon, or if it is defined as a raster it is the collection of cells with the same integer value within that raster. For the purposes of this chapter, the *masks* that will be used should have a specific geomorphological meaning - either relating to a specific style of change, an inferred geomorphological process, or a particular morphological characteristic. The *analysis* that will be performed on the data (or DoD) that fall within that *mask* will be identical to those performed in the previous chapter (i.e. calculation of areal and volumetric elevation change distributions and summary statistics). To segregate the DoD analysis by multiple masks is a simple matter of aggregating the discrete masks (polygons or unique integer values within a grid) into a single mutually exclusive classification. This subsection is concerned with defining sensible ways to perform this classification.

Classification of landscapes and landforms has a rich history that can be drawn on for interpreting changes in rivers. Although earlier attempts at geomorphological classification exist, Davis (1885) was one of the most effective early advocates for the concept of landscape classification as a unifying theme for geography (Beckinsale 1976). In Davis (1902) he laid out an agenda for the basis of classification in geography, while in Davis (1915) he crystallised this agenda into his framework for geographical analysis based on classification. Today countless classification schemes for fluvial landscapes exist at a range of spatial scales (e.g. Leopold & Wolman 1957, Kemp *et al.* 2000, Montgomery & Buffington 1997, EA 2003, Newson *et al.* 1998, Schumm 1977, Rosgen 1996), including multi-scalar classifications (e.g. Brierley & Fryirs 2000, Maddock 1999, Lewin 2001, Wiens 2002). Each classification scheme has its own limitations and the classifications themselves are arguably less important than the interpretations they help facilitate (Kondolf 1995). The widespread availability and ease of use of GIS has made spatial classification commonplace (Demers 1991, Marchi & Dalla Fontana 2005, Burrough & McDonnell 1998).

Although landscape classification is well established, it is still subject to scrutiny. Rhoads & Thorn (1996*b*, p. 120) have highlighted long-standing philosophical debates on the basis for classification that draw into question the actual presence of sharp or distinct boundaries between all classes (or natural kinds). Wilson & Burrough (1999) outline a variety of fuzzy classification techniques, which allow these inherent ambiguities and uncertainties in landscape classification to be represented. (Wood 1996) and Schmidt & Hewitt (2004) provide elegant examples of how fuzzy landscape classifications at regional and catchment scales can be derived from a morphometric analysis of a digital elevation model alone. At the morphological unit scale, such automated classifications have not yet been proved. Although fuzzy classifications are straightforward to apply (Burrough & McDonnell 1998, Deng 2007, Wilson & Burrough 1999), their application as masks is not as elegant and can cloud the rather simple interpretations of DoDs deemed as a necessary first step in this chapter. While, this debate it

[2]Also commonly referred to as an analysis mask. See ESRI GIS Dictionary (2007).

is interesting and alternative fuzzy classification methods might show some promise, they are peripheral to the focus of this chapter.

With regards to classification, the real question of relevance to morphological sediment budgeting is whether existing classification systems can be used to interpret a DoD or whether new classification systems might be needed. A range of classification techniques were experimented with. No single classification system is universally applicable or useful in all fluvial environments (Newson *et al.* 1998, Kondolf 1995). In any particular case study, there will be a range of useful and appropriate classification systems that may be used. These may be existing systems, or bespoke systems developed by the investigator(s) for the particular application and questions at hand. As such, a plurality of classification techniques used in parallel is advocated as opposed to any particular one. Below, a subset of classification types (as opposed to specific classification systems) deemed to yield the most useful information are described. First considerations in applying standard classifications are discussed. Next, the concept of a classification of difference (CoD) is introduced. Next, a DoD-specific classification is suggested, and finally some masks relevant to salmonid ecology are proposed.

5.2.1.1 Standard Classifications

As suggested above, their are no shortage of fluvial and/or habitat classifications at reach and sub-reach (geomorphic unit) scales. The individual classes in all of these classifications can be useful in interpreting DoD captured changes, provided that the classification system is relevant to the study site. In particular, an appropriate upper limit needs to be chosen for the spatial scale and resolution of the classification being applied. It is important that the spatial scale of the classification system is finer than the spatial extent of the DEMs. For example, the geomorphic unit scale classification within the River Styles hierarchy (see Figure 3.1) is a perfectly coherent scale to apply a meaningful mask from for most ground-based fluvial repeat topographic surveys. Similarly, the reach scale classification may be sensible provided that the survey is large enough to span multiple reach types (e.g. contrast in DoD results between braided and meandering reaches).

With regards to a lower-limit for an appropriate spatial scale of classification to use for budget segregation, the spatial extent should be coarser than the resolution of the topographic survey, but the resolution of individual units should not exceed the resolution of the topographic survey. Within River Styles, the hydraulic unit scale classification is approaching the lower limit of a sensible scale of segregation or masking for most topographic surveys,[3] but may be justified provided that the survey resolution is adequate. By contrast, few if any fluvial DoDs would be sensibly segregated by landscape scale classification as the fluvial environment itself represents a single landscape unit. However, a landscape scale mask from a catchment scale DoD or landscape evolution model, may be perfectly reasonable.

The one type of mask that has routinely been applied to DoDs in the literature is a sub-reach

[3]Terrestrial laser scanning perhaps being an exception (Milan *et al.* 2007).

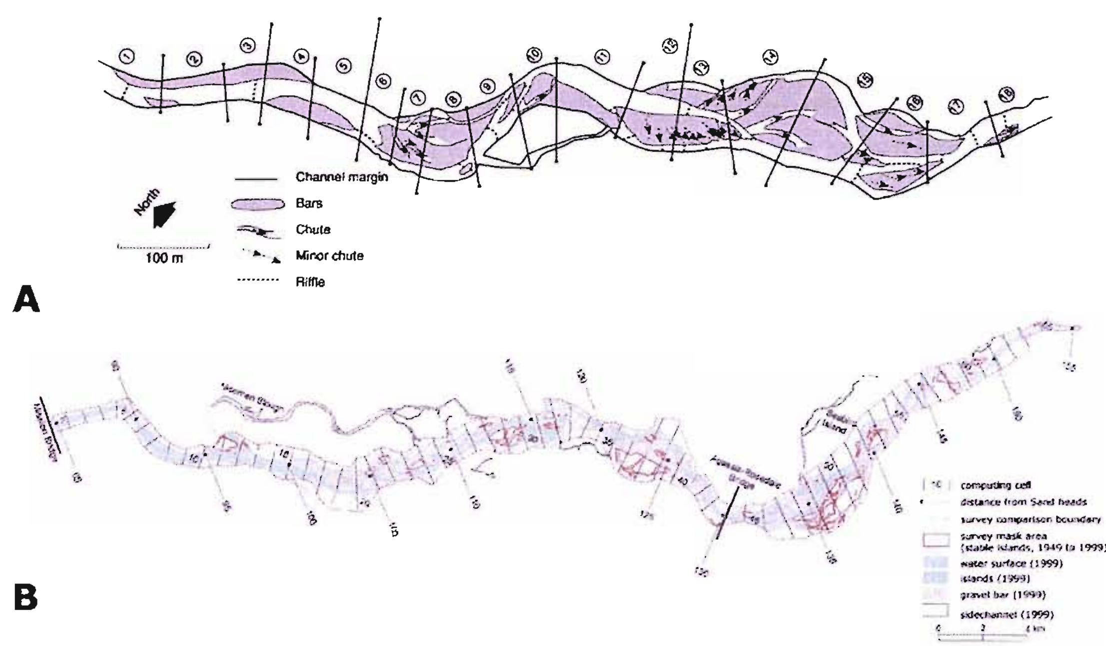


FIGURE 5.1: Examples of sub-reach masks applied to DoDs in the literature. A) A 1.5 km study reach on the River Coquet, United Kingdom, which was DEM-differenced from 1999 to 2000 by Fuller *et al.* (2003). the reach was subdivided into 18 analysis masks (referred to as sub-reaches; sub-figure adapted from Fuller *et al.* (2003, Figure 1)). B) A 70 km study reach on the Fraser River, British Columbia, which was DEM-differenced from 1952 to 1984 and 1984 to 1999 by Church *et al.* (2001) and McLean & Church (1999). The reach was subdivided into 65 analysis masks (referred to as computing cells; Sub-figure adapted from Church *et al.* (2001, Figure 3)).

classification (Figure 5.1).[4] Most authors apply a gross application of the sediment continuity equation (Equation 3.1) to these masks in an attempt to look at net downstream transfer rates between sub-reaches (Fuller *et al.* 2003, McLean & Church 1999, Church *et al.* 2001, e.g.). Additionally, using sub-reach masks can be helpful for inter-comparing a) the relative gross magnitude of change, b) the nature of change (aggradational, degradational) and c) the style of change (elevation change distributions) between sub-reaches. Here, the application of such masks is extended both through c) and the uncertainty analysis techniques from Chapter 4.

Another useful mask that has been discussed in the literature (Brewer & Passmore 2002, Fuller *et al.* 2003, Fuller *et al.* 2002, e.g.) is the use of individual morphological units as masks. Brewer & Passmore (2002, Figure 3) first presented the concept of segregating the morphological sediment budget by morphological units (e.g. point bars, riffles, etc.) in the context of their 'morphological budget', which integrates both channel cross section and plan form data. Although such a mask could be extremely useful for looking at the magnitude, nature and style of change to specific morphological units, Brewer & Passmore (2002) and authors who have followed the technique (Brewer & Passmore 2002, Fuller *et al.* 2003, Fuller *et al.* 2002, e.g.) never actually report the data from individual morphological units. Instead,

[4]Although not typically referred to as analysis masks or a classification, in practical terms they are. These techniques were discussed briefly in § 3.4 - third paragraph.

the emphasis has been on simply summing the net changes from each morphological unit within a sub-reach (which is useful in itself). Moreover, this method of segregating the sediment budget by morphological units has only-been reported (by summation) for the combination of plan form and cross-section data and does not appear to have been reported explicitly for DEM differencing. Thus, simply extending this useful concept proposed by Brewer & Passmore (2002) to DEM-differencing and looking more closely at trends within and between distinct types of morphological units will be an original contribution helpful for improving geomorphological interpretation of DoDs.

Virtually all existing classification systems for fluvial environments are applied as static snapshots in time. Even a multi-scalar classification (e.g. River Styles or Alluvial Systematics) is only multi-scalar in the spatial sense, and is temporally-fixed, representing an assessment of the system at one particular point in time. This observation is not to suggest such classifications are not useful, or that such systems do not include categories that naturally imply something about the formation and history of a particular form or feature. The point is raised to highlight what information a standard geomorphological or habitat classification applied as an analysis mask for a DoD provides.

Careful consideration needs to be given to whether the mask applied to the DoD is derived from the more recent or older DEM. A mask applied to the DoD from the older DEM will reveal something about what changes took place to things as they were. For example, one could ask questions about how much deposition or erosion took place on what was a pool or what was a riffle and use that to infer how these features were reshaped (i.e. what was their fate?). Conversely, a mask applied to the DoD derived from the more recent DEM gives insight into what changes took place to produce the more recent morphology.[5] For example, did the pools captured in the more recent survey get there by preservation (e.g. no net elevation change) or active carving (e.g. scour)? Both masks derived from the older and newer DEMs yield useful information on their own, but together they can be used to piece together a fuller understanding of the changes.

5.2.1.2 Classification of Difference

As an alternative to a classification derived from the newer or older DEM in a DoD, a classification can be derived based on both. This technique will be referred to as a classification of difference (CoD), a preliminary form of which was presented by Wheaton *et al.* (2004*a*). The CoD requires two input classifications: one derived from the newer and one from the older DEM. Both classifications should be based on the same classification system. A CoD mask is then created for every possible combination of categories from old to new in the classification. For example a simple binary classification of each DEM in the DoD into areas of wet and dry (Brasington *et al.* 2003, Lane *et al.* 2003, e.g.) could be input to produce four unique output classes: wet ⇒ wet, wet ⇒ dry, dry ⇒ dry and dry ⇒ wet.

[5] This is what the Brewer & Passmore (2002) technique used.

For a classification system with n categories, n^2 CoD masks (output classes) will be produced. Of the n^2 masks, n will always represent no class change categories, and the remainder $(n^2 - n)$ will represent changes from one type to another. However, just because a cell in the DoD is classified by the CoD as a no class change, does not mean it did not experience geomorphological change. For example, a cell that was originally classified as a channel could experience significant erosion or deposition, yet still remain a channel. Conversely, just because a cell is classified by the CoD as a class change, does not necessarily mean it experienced net elevation change (i.e. geomorphological change can occur at a given location without the topography at the location necessarily changing). For example, due to an avulsion a cell that was previously classified as a channel may become an abandoned channel without any elevation change actually occurring in that cell. In such instances, the requisite is that some type of elevation change took place in the vicinity (e.g. plugging at the head of the abandon channel) for the geomorphological change to occur without an elevation change taking place.

5.2.1.3 Geomorphological Interpretation Classification

After experimenting with numerous combinations of standard classifications, bespoke classifications and CoDs, a slightly different type of classification type was developed. The classification is based on the qualitative interpretations[6] a trained geomorphologist makes when inspecting a site in the field and describing the evidence of change before them. Those qualitative observations can be articulated into a classified map of different types of changes, which is then overlaid as an expert-derived analysis mask (albeit subjective) onto the DoD. This type of classification allows the transformation of qualitative observations into a quantitative segregation of the DoD.

Most experienced fluvial geomorphologists are comfortable going to a field site after a flood and describing what they think happened on the basis of visual evidence of erosion and deposition. For example, they might identify areas where bank erosion occurred or areas where 'fresh' gravel was deposited to produce or accentuate a bar. Based on the relative areal extent of such changes, some might even be happy to speculate about the relative magnitude of each change and which was more dominant. This style of interpretation (Ferguson & Werritty 1983, e.g.) is actually very focused on the processes responsible for the change, but as it is qualitative it is difficult to test the resulting hypotheses and assumptions. If these interpretations are translated onto a map, they become masks from which the DoD can be segregated. Moreover, the quantitative results can be used to test the original hypotheses and assumptions made.

These interpretations need not be based on field observation alone. Ideally, they are formulated in a GIS using a combination of all the available evidence (i.e. layers). For example, in this chapter a mix of the DoD, both input DEMs, before and after aerial photographs, geomorphological classifications before and after, as well as CoDs were used in addition to field

[6]See § 9.3 for a discussion of the robustness of these interpretations.

observations. Collectively, they allow the investigator to cast judgment on what categories of change were taking place and captured by the DoD with reasonable confidence. As with any classification system, it is important that the available evidence is used to make consistent interpretations. The individual categories of change used to produce this type of classification will vary from site to site depending on the dominant processes. It is important to draw a conceptual distinction between categories of change and the fluvial processes responsible for producing that change. The two are intimately related, but they are not necessarily the same.

5.2.1.4 Ecologically Relevant Masks

There are at least three types of ecologically relevant masks that might be used to explore the implications of geomorphological changes on salmonids. The first is a physical habitat classification mask, and this can be applied either as a standard classification (§ 5.2.1.1) or a classification of difference (§ 5.2.1.2). Secondly, redd surveys showing the locations and areal extent of spawning activity could be used as a mask. This might be used to look at the impact of a flood during the incubation period or, if surveys were detailed enough, how much sediment was moved from the process of redd construction. Finally, ecohydraulic habitat suitability models might be used as a mask. They could be used to draw correlations between the quality of habitat and the types of change it experiences (i.e. a standard classification), or to look at how changes in morphology relate to changes in habitat quality (i.e. classification of difference).

5.2.2 Geomorphological Interpretation Software Extension

The DoD Uncertainty Analysis Software developed in § 4.5 has resulted in an expandable and easy to use analysis package for considering the influence of DEM uncertainty on DoD predictions. In this chapter, the application of spatial masks to DoD outputs from this software (e.g. a pathway 4 analysis) are advocated. It is desirable to report the relative magnitudes of change in each mask class, produce elevation change distributions for each mask class, save consistently formatted figures, and produce some summary reports with basic statistics. As will be shown in the next three chapters, these basic outputs will dramatically improve the robustness and scope of geomorphological interpretations that can be made from DoDs. While these tasks are straight-forward to apply manually, they are time-consuming and manually produced outputs are highly susceptible to inadvertent errors given their repetitive nature. Thus, again, a software program to automate these tasks was developed partly to reduce likelihood of errors in the analysis, but primarily to extend the scope of analyses that could be performed.

As with before, a secondary motivation was to produce an easy to use software application to facilitate these types of analyses by trained geomorphological researchers and practitioners. Ideally, the user would be able to run one set of DoD analyses based on all their available intersecting data. Instead of using a different clipping boundary geared to the question of

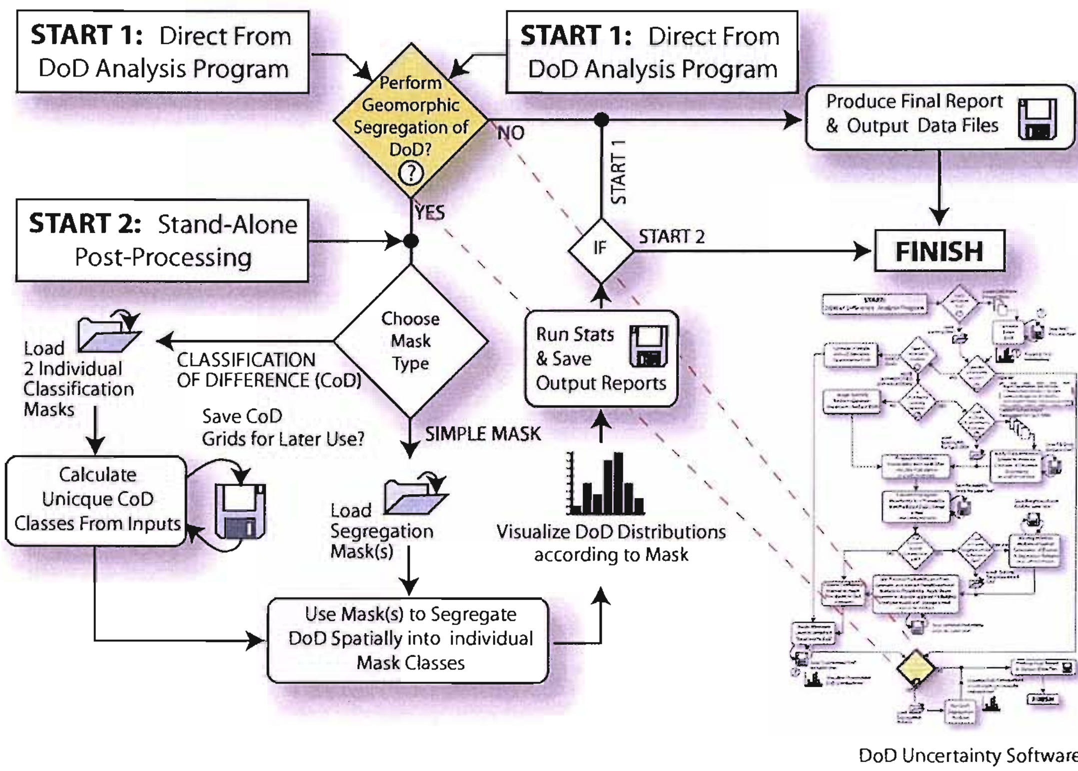


FIGURE 5.2: Flow chart showing geomorphological analysis extension to DoD Uncertainty Software. The inset figure of the DoD Uncertainty Software in the lower right is for reference (for full size see Figure 4.20).

interest and then having to rerun DoD analyses for every clipping boundary, the user should be able to run the analysis once for all the data, and then ask whatever questions they wish of it by masking the dataset in different ways. This reduces the likelihood for inadvertent user errors by eliminating the need to repeat the same analyses.

An extension to the DoD was again developed in Matlab as a dialog box driven application. As shown in the extension flowchart (Figure 5.2), the extension can be run as part of any pathway[7] straight out of the DoD Uncertainty Analysis Software (Start 1 in Figure 5.2). Alternatively, any DoD or thresholded DoD raster can be loaded independently and the geomorphological analysis run as a stand-alone application (Start 2 in Figure 5.2). The extension can also be run in a batch mode, which automatically applies the inputs and parameters based on a batch configuration file.

Within this extension, two types of masks can be applied based on the options discussed in the previous section. The simpler of the two, segregates the DoD based on the number of unique integers in the single raster integer input grid. The more complicated (CoD) produces unique categories based on two input raster integer input grids (one associated with the old DEM and one with the new DEM). In principle any classification system could be applied (e.g. River Styles (Brierley & Fryirs 2000); see § 3.2.1) with any number of classes. The only requirement

[7]See § 4.6 for description of different pathways.

for the CoD approach is that the same classification system is used for each input. However, as the number of output classes in a CoD is the square of the number of input classes, even a straight forward classification with 10 input classes will have 100 output classes!

Masks can be derived in any GIS package using a variety of techniques. One simple work flow for manual classification is to draw vector polygons (e.g. shapefiles in ArcGIS) to classify the DEMs or DoD and then convert these to a raster integer grid where the integer corresponds to the class. In this Geomorphological Interpretation Software Extension, the user is prompted to type in descriptive tags that correspond to each of the unique integer values it finds in the loaded raster(s). The extension then uses these tags to label figures, produce output reports and output tables that will make sense to the user.

The way the extension works is rather simple, but results in huge time-savings over trying to attempt this methodology manually. For each unique integer value in the mask (i.e. class in the classification), it visits every cell in the raster mask and checks if its value matches the current value. If it does, it takes the elevation change defined by the DoD in the corresponding DoD cell and adds it to the elevation change distribution for this class. After looping through the entire raster, a complete elevation change distribution is produced for that class and the same summary statistics regarding areal and volumetric changes developed in Chapter 4 are produced. The process is repeated for every unique class and then an inter-comparison of the relative magnitude and styles of change in each class are calculated. The results are saved in a series of output elevation change distribution figures, a pie chart, a summary text report and tables. All the raw data from the elevation change distributions are saved in *.csv tables to allow additional analyses.

It is important to emphasise that this software extension does not make or automate any geomorphological interpretation itself. Instead, the application simply facilitates analysis of the DoD based on a classification done externally and provided as an input. That classification, in principle, can be anything from an entirely objective algorithm-based classification, to a more subjective expert-based classification. There is no single correct classification (Newson *et al.* 1998), and each will yield different information and unique insight into the changes reflected in the DoD. After reliability uncertainties in the DoD have been accounted for, the sensible interpretation of the DoD, rightly, remains the responsibility of the trained geomorphological practitioner using the software.

5.3 Study Sites

To demonstrate the utility of the proposed methodological development in different environments, it will be useful to test its application at study sites where completely different styles of change are taking place. As described in § 3.5, the three study sites used in this thesis are Sulphur Creek[8] in California, the Mokelumne River[9] in California, and the River

[8]See Appendix F for complete study site description of Sulphur Creek.
[9]See Appendix G for complete study site description of the Mokelumne River.

Feshie[10] in Scotland (Figure 3.6). The three study sites span a range of physiographic settings with contrasting anthropogenic influences (refer back to Table 3.1) that make for an interesting inter-comparison. For example, both the River Feshie and Sulphur Creek have completely unregulated flow regimes with no major abstractions or dams located upstream of the study sites (Soulsby *et al.* 2006, Grossinger *et al.* 2003). Both sites also boast relatively[11] dynamically changing channels with high sediment loads (Pearce *et al.* 2003, Katzel & Larsen 1999, Brasington *et al.* 2000, Ferguson & Werritty 1983). These characteristics are in sharp contrast to the heavily regulated flow regime of the Mokelumne River, which no longer receives any sediment load from upstream (Merz *et al.* 2006). However, both the Mokelumne River and Sulphur Creek study sites have been subjected to over a century of heavy direct engineering intervention including artificial bank armouring and extensive gravel mining (Merz *et al.* 2006, Grossinger *et al.* 2003). Gravel mining has since stopped in both systems and both sites have been subjected to 'restoration' interventions and efforts. The Feshie by contrast is one of only four sites in the UK that is a Site of Special Scientific Interest (SSSI) because of the natural value and character of its fluvial features (i.e. only contemporary example of an undisturbed braided river in UK).

From a geomorphological monitoring perspective, the three study sites define three of the more typical styles of contemporary fluvial geomorphological monitoring using repeat topographic surveying. Namely:

- Sulphur Creek represents an example of short-term, event-based, monitoring
- The Mokelumne River represents an example of monitoring associated with reach-scale restoration, consisting of pre-project, as-built and repeated post project appraisal[12] surveys as part of a long-term monitoring programme
- The River Feshie represents an example of a long-term, annual resurveying effort in a relatively dynamic system

Although other types of repeat topographic survey monitoring exist over both shorter (e.g. hourly or daily) and longer (e.g. decadal) survey intervals, these three examples are arguably a reasonable cross-section of most common forms.

In terms of explaining the geomorphological regime and the changes the repeat surveys are capturing at each of these sites, there is a progression in terms of complexity. As the data at the Sulphur Creek study site captures change due to a single major storm event, it represents the simplest of the three. The Mokelumne River is slightly more complex in that the data represent both changes due to a PHR intervention (placed gravel) and subsequent adjustment of the constructed features by minor fluvial reworking. The Mokelumne also represents seven surveys associated with four PHR projects, providing a more rigorous assessment of the methodology.

[10] See Appendix A for complete study site description of the River Feshie.

[11] Relative to other streams and rivers in their respective regions.

[12] See Downs & Kondolf (2002) for description of post project appraisals (PPA) and Wheaton *et al.* (2004*c*, p. 9-10) for monitoring typically associated with PHR projects.

However, the Mokelumne River site is a highly artificial system directly controlled by a heavily regulated flow regime and as such the changes due to geomorphological processes are relatively minor. The Feshie by contrast boasts two periods of minor changes and two periods of substantial change.[13] Thus the next three chapters in Part III will provide varying examples of geomorphological change on Sulphur Creek (Chapter 6), the Mokelumne (Chapter 7), and the Feshie (Chapter 8) respectively, in order of increasing complexity of the nature of change. The simplest case on Sulphur Creek will be used to compare variations in the methodology, whereas the other two will focus more on the geomorphological interpretation.

5.4 Conclusion

This short chapter has outlined some simple masking techniques and categories of masks that can be used to segregate a DoD into discrete classes and make a more informed geomorphological interpretation. The masks proposed included a range of standard classification masks, a classification of difference, a geomorphological interpretation mask, as well as a few ecologically relevant masks. These tools were built into an extension of the DoD Uncertainty Analysis Software. They will be applied to three different case studies in Part III to provide contrasting examples of change.

[13]This *substantial change* is characterised by regular inundation of over 75% of the active braid plain at the site and subsequent reworking and activation of braid plain materials.

Part III

Case Studies: Three Examples of Geomorphic Change

Chapter 6

Sulphur Creek - Event-Based Monitoring: Case of the New Year's Eve Flood

6.1 Introduction

The effectiveness of fluvial geomorphological monitoring with repeat topographic surveying is hampered by an inability to predict when geomorphologically competent floods will occur. Usually, an arbitrary survey interval is chosen (e.g. monthly, seasonal, annual, decadal or sparser resurveys) and it is hoped that the events which drive significant change fall meaningfully within the analysis interval. Alternatively, fluvial geomorphologists might work in relatively dynamic systems where the change is so frequent that weekly, daily or even hourly surveys will capture the change (Milan *et al.* 2007, Lane *et al.* 1994, e.g.). Or, in the case of regulated rivers, if geomorphologists are able to work with dam operators, they may have the luxury of designing their own events and monitoring experiments (Henson *et al.* 2007, Jeffres *et al.* 2006, Batalla *et al.* 2006, e.g.). Very rarely, the geomorphologist may just happen to do a topographic survey right before a big event and then have the opportunity to resurvey it afterward, before the signature of the event is masked by further flows. Sulphur Creek presented the author with one such fortuitous opportunity after a baseline topographic survey was performed in December of 2005 for a separate modeling study. Shortly after the survey, Northern California was deluged by the New Year's Eve Storm.

The purpose of this chapter is to offer the first of the three case studies that are used to demonstrate the utility of the methods developed in this thesis (Part II). More specifically, the morphological method and the DoD Uncertainty Analysis developed in Chapter 4 are used to derive a thresholded DoD for the New Year's Eve Storm. The focus will then be on how to use the masking technique outlined in Chapter 5 to make a meaningful interpretation of the DoD. This first case study on Sulphur Creek was selected because the DoD record there covers only a single event with a relatively simple geomorphological response. Moreover, because there is just a single analysis period it lends itself nicely to comparing and contrasting different methods of mask definition without getting bogged down in the details of contrasting changes across multiple analysis periods[1]. First the New Year's Eve Storm is explained as the sole driver of observed DoD changes in this example. Following that, the three different techniques described in § 5.2.1 are used to interpret the associated geomorphological changes. Finally, the potential impact of the event on incubating salmonid embryos will be explored.

6.2 Study Site Context

The study site was introduced in § 3.5 and is described in more detail in Appendix F. Here, a minimal description is provided to define the study site specifically and give the necessary context for understanding the changes that took place in response to a single large storm event.

Figure 6.1 shows the basic context of the study site with a series of oblique aerial photos. The study reach functions largely as a transition reach, funneling Sulphur Creek's width and character from a wandering/semi-braided stream incised within its former alluvial fan to a heavily modified, overly-narrow, and incised channel through an urban corridor. Four structures within this transition reach can act as grade control:

- A concrete grade control structure spanning part of left hand anabranch at the upstream limit of the study reach (GC1 in Figure 6.1A & C)
- Crane Street Bridge at the top of the transition reach, which is comprised of three box culverts and a concrete sill (GC2 in Figure 6.1A & C)
- A concrete grade control structure in the middle of the study reach, spanning the entire channel and banks (GC3 in Figure 6.1A & C)
- Main Street Bridge at the bottom of the transition reach, which has a concrete sill (GC5 not shown in figure)

The entire study reach and the 1.5 km wandering/semi-braided reach that extends upstream of Crane Street Bridge to the Heath Canyon Confluence were gravel mined from roughly 1910 to 1999 (Grossinger *et al.* 2003, Pearce *et al.* 2003). Mining was probably more intense initially to 'fix' the river into its present course (Pearce *et al.* 2003, p.6). However, from at least the 1950's to the present, both the quarry receipts (p. comm Jack and Harold Varozza, 2005) and the relative lack of incision over time suggest that extractions amounted to little more than removal of the annual sediment yield from the upper catchment (Grossinger *et al.* 2003, p. 46). Quarry receipts were available from 1998 and 1994,[2] and showed 5572 m^3 and 4630 m^3

[1]Both the Mokelumne (Chapter 7) and the Feshie (Chapter 8) case studies involve multiple analysis periods.
[2]The rest of the receipts were lost when Sulphur Creek flooded the quarry offices.

FIGURE 6.1: Oblique context aerial photography of study site (taken 8th February 2006 following New Year's Flood). A. Photograph of majority of study site (depicted in dashed yellow line). B. Photograph looking east over Sulphur Creek's relic alluvial fan and City of Saint Helena. C. Photograph looking upstream showing study site in relationship to formerly gravel mined reach (upstream) and transition reach (downstream). D. Location map of study site within Sulphur Creek Catchment.

of gravel being mined respectively. Harold Varozza (p. comm, 2005), who owned the quarry and oversaw mining operations since the 1950's, confirmed that gravel extraction amounts varied from year to year, but he estimated it was probably always between 8000 and 11,000 tons per year (approx. 4373 m^3 to 6013 m^3 per year).[3] The mining activity is remarkably consistent with an average annual load of 7456 m^3 calculated from a PWA (2003, Figure 8, pp. 46-50) estimate of 432,432 m^3 of total sediment delivery from the upper Catchment (74% coming from debris landslides).

Despite the relative abundance of annually replenished gravels in Sulphur Creek, gravel mining has never approached the same intensity of mining operations in nearby rivers like the Russian River with deep mining pits and huge gravel deficits (Kondolf *et al.* 2001, e.g.). The nature of the mining operations on Sulphur Creek during their height is evident in the aerial photograph from 1974 in Figure 6.2. As the photo suggests, gravel mining was areally extensive, extending from the gravel yard in the foreground all the way to Heath Canyon. However, gravel mining

[3]Note these figures differ from the rough figures reported from the same source in Grossinger *et al.* (2003, p. 40). However, the basic story and its net impact are the same.

FIGURE 6.2: Oblique 1974 aerial photo looking upstream at study reach (red). Crane Street Bridge had not yet been built (location shown in dashed black), and what have become grade control structures (GC3 and GC4) more recently were formerly low-water crossings for the gravel mining operations. Extensive bank protection is also evident along the much of the reach.

was primarily a bar skimming operation without any concentrated deep excavations or mining pits (p. comm Varozzas).[4] The staging piles in the foreground of Figure 6.2 give some idea as to what 8000 to 11,000 tons of gravel looks like when piled 5 to 10 metres high. Varozza explained that Sulphur Creek was never mined to the same extent because the Sulphur Creek gravel was simply too soft, and so did not meet engineering specifications for use in concrete and asphaltic-concrete mixes (primary uses of aggregate). As such Sulphur Creek gravel could primarily only be used for road-base, which once the valley's primary infrastructure was in place there was limited demand for. The parent geology in the upper-catchment is dominated by highly weathered and metamorphosed shales, sandstones, conglomerates, cherts, greenstones and metagraywacke of the Franciscan Complex melange (Graymer *et al.* 2007). Aside from the high rates of active tectonic uplift in the catchment, these rock types are highly susceptible to erosion with the steeper slopes prone to catastrophic failure by landsliding induced by both heavy rainfall and earthquake shaking events (PWA 2003, pp. 8-9).

From the cessation of gravel mining in 1999 to 2002, the Varozzas (p. comm), cited in Grossinger *et al.* (2003, p. 40), anecdotally reported that as much as 1.5 metres had accumulated locally in parts of the study reach. These observations led Grossinger *et al.* (2003)

[4]Aerial photos from 1942, 1953, 1958 and 1965 suggest that at least for the last 60 years of mining operations the approach was similar.

and Pearce *et al.* (2003) to speculate that the bed of the formerly gravel mined reach would continue to aggrade and without some removal (natural or mechanical), sediment could choke the channel and lead to increased flooding (through reduced channel capacity) and even trigger reoccupation of other parts of the alluvial fan. This conjecture leads to some interesting questions about the ability of Sulphur Creek in its current configuration through Saint Helena to store versus transfer the high sediment loads delivered to it from upstream. The past century of gravel mining is a clear indication that this reach is able to accommodate and transfer through its length the gravel delivered to it from upstream. However, the heavily incised and constricted (by urban encroachment, engineering structures and artificially stable riparian growth) reach downstream has adjusted to a complete lack of sediment delivered to it from upstream during the gravel mining years. Thus, will sediment accumulate at the head of this reach and exacerbate flooding as speculated, or will sediment be adequately delivered through the confined city reach to the Napa River? As advocated in Grossinger *et al.* (2003) and Pearce *et al.* (2003), this is precisely the sort of problem that requires geomorphological monitoring. This study contributes one aspect of that story showing the impact of large events. Further long-term monitoring is needed.

6.3 New Year's Eve Storm

The first half of December, 2005, was notably dry for the season in the Sulphur Creek watershed, with most catchments in the region still dry and most streams still trickling along at their summer baseflows. By mid-December, a series of typical winter storms hit the area over a two week period bringing in moisture and cold fronts off the North Pacific typical for the season (Figure 6.4A). Those storms did not produce any flooding, but did set up antecedent conditions in the area of completely saturated soils prior to the New Year's Eve Storm. On Friday, December 30th 2005, temperatures rose as a warm front blew in off the jet-stream from the southwest Pacific carrying with it extensive moisture (Hall 2006, Blanchard 2006, AP 2005). In the 24 hour period that followed, most of Northern California experienced torrential rainfall and extensive flooding on par with the 1997 floods and not exceeded since the 1986 floods.

The most intense rainfall volumes for the region were recorded just 8 km south of Sulphur Creek on Mount Veeder with 243 mm falling in a 24 hour period (Figure 6.3). In the headwaters of Sulphur Creek, over 195 mm fell in a 31 hour period (185 mm in a 24 hour period). In the Miller *et al.* (1973) regional precipitation frequency atlas, a 2-year 24-hour event for the study area is estimated at approximately 125 mm, a 25-year 24-hour event is roughly 200 mm, and a 100-year 24-hour event is roughly 249 mm. There are three active rain gauges in the Sulphur Creek Catchment, and a hyetograph from the SH4 gauge in the headwaters is shown in Figure 6.4A. Based on hourly rainfall data over a 24 hour period from the SH4 gauge dating back to 1948, the 24-hour event has a recurrence interval somewhere between 9.8 and 14.8 years.[5]

[5]The range in this estimate is because it is unclear from the records whether this is the fourth, fifth or sixth largest 24 hour rainfall event over the past 60 years as 1995, 1971 and this 2005 event all report roughly

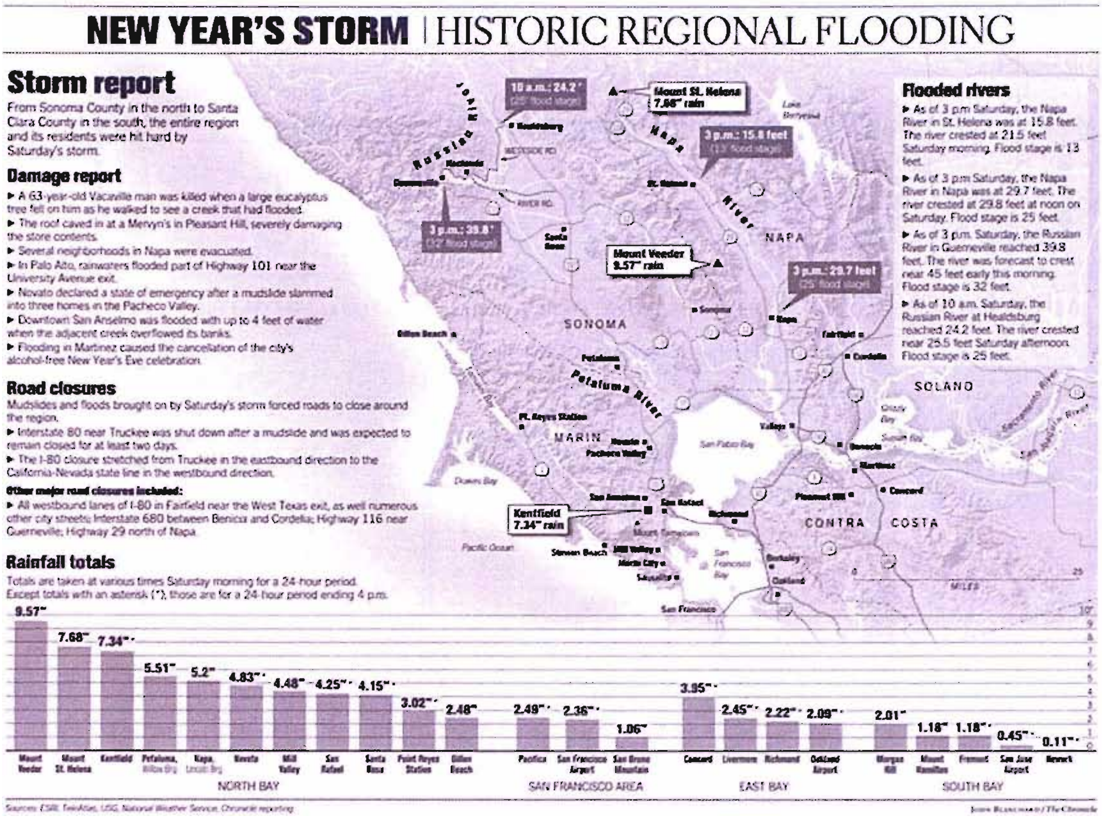


FIGURE 6.3: Newspaper clipping from the San Francisco Chronicle of Sunday, 1st of January, 2006 showing regional significance of the New Year's Storm Event. Figure from Blanchard (2006).

There were no active[6] flow gauges in place on Sulphur Creek during the 2005 New Year's Eve Flood. However, a stage gauge from an unrated section just upstream of the confluence with Heath Canyon on the main-stem was operational during the event and shows a peak of 2.31 m above an arbitrary datum (Figure 6.5). A USGS flow gauge (Station STH) does exist on the Napa River just downstream of the confluence with Sulphur Creek and shows the response of the Napa River to the New Year's Eve storm (Figure 6.4). The local and national press reported that a new peak stage had been recorded for the Napa River at Saint Helena of 6.57 m (flood stage being at 4.42 m) compared to the previous record of 5.64 m recorded on 22 February 1986 (Figure 6.4C). However, the new peak can not be compared directly to the 'previous flood stage record' as the gauge was moved roughly a mile upstream to its current location in 2005.

equivalent totals. (largest events in 1^{st} 1993, 2^{nd} 1997, 3^{rd} 1955, and 4^{th} through 6^{th} tie between 1995, 1971 and 2005). The data were not available in a format enabling calculation of recurrence intervals based on storm-event totals.

[6]The USGS operated a flow gauge on the main stem of Sulphur Creek for one year (1966-1967) just upstream of the confluence with Heath Canyon and before the gravel mining reach (USGS Station 11455950 available from National Water Information System: `http://nwis.waterdata.usgs.gov/nwis/`). Beginning in 2000, the Napa Valley Regional Rainfall and Stream Monitoring System (`http://napa.onerain.com/home.php`) reoccupied this gauge but are only measuring stage and rainfall, and the cross section is no longer rated. The stage data is intermittent and certain periods produce highly suspect and unreliable results for this cross section. Stage data during the New Year's Eve storm were sensible, but in the month following the event the data were nonsensical.

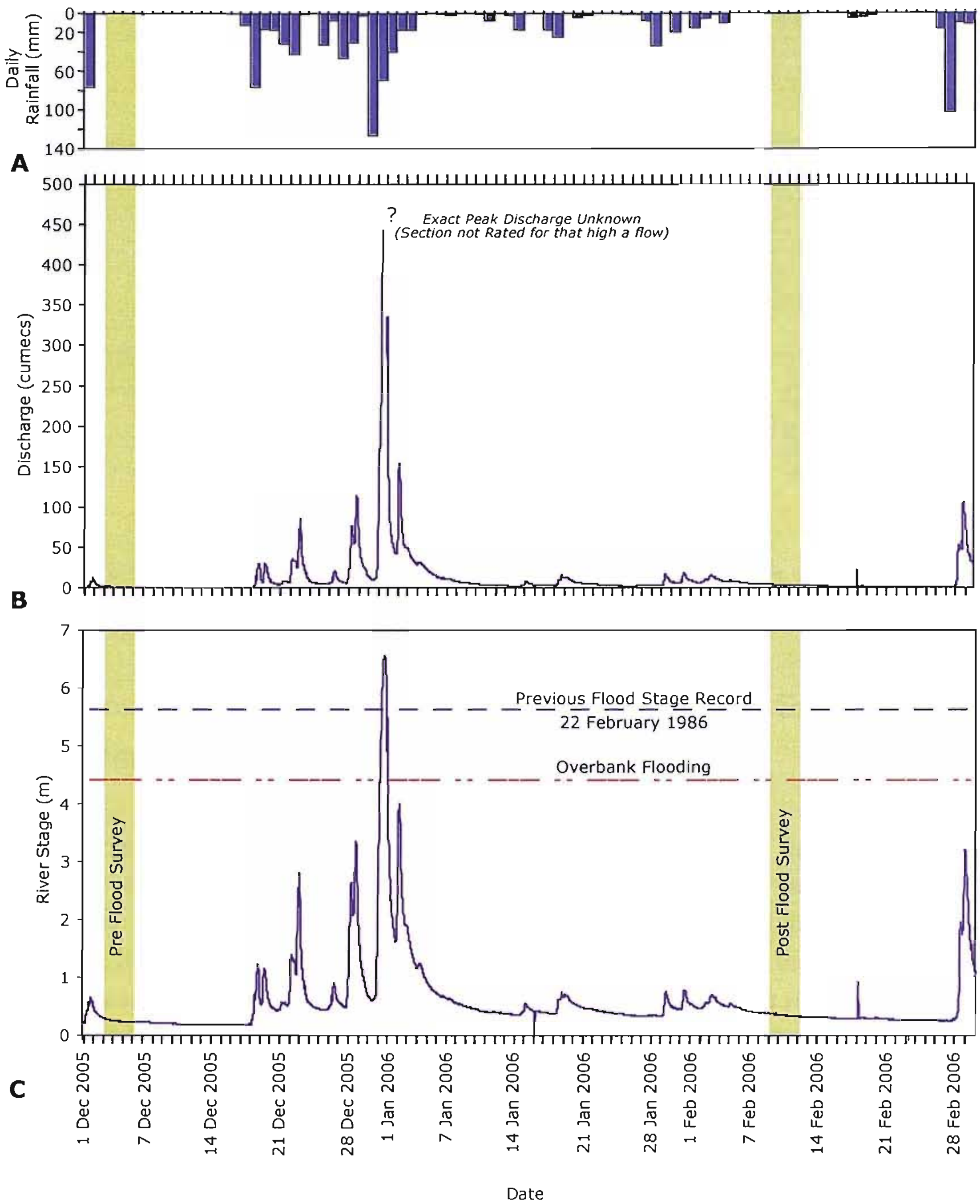


FIGURE 6.4: Contextual hyetograph and hydrographs for month preceding and two months following the 2005 New Year's Eve Storm. The topographic survey periods are shown in yellow. A. Hyetograph of total daily rainfall for California Department of Water Resources Station SH4, located in the headwaters of Sulphur Creek. B. Discharge and C. Stage for **Napa River** (Sulphur Creek is unrated) immediately downstream of confluence with Sulphur Creek (from Napa Valley Regional Rainfall and Stream Monitoring System).

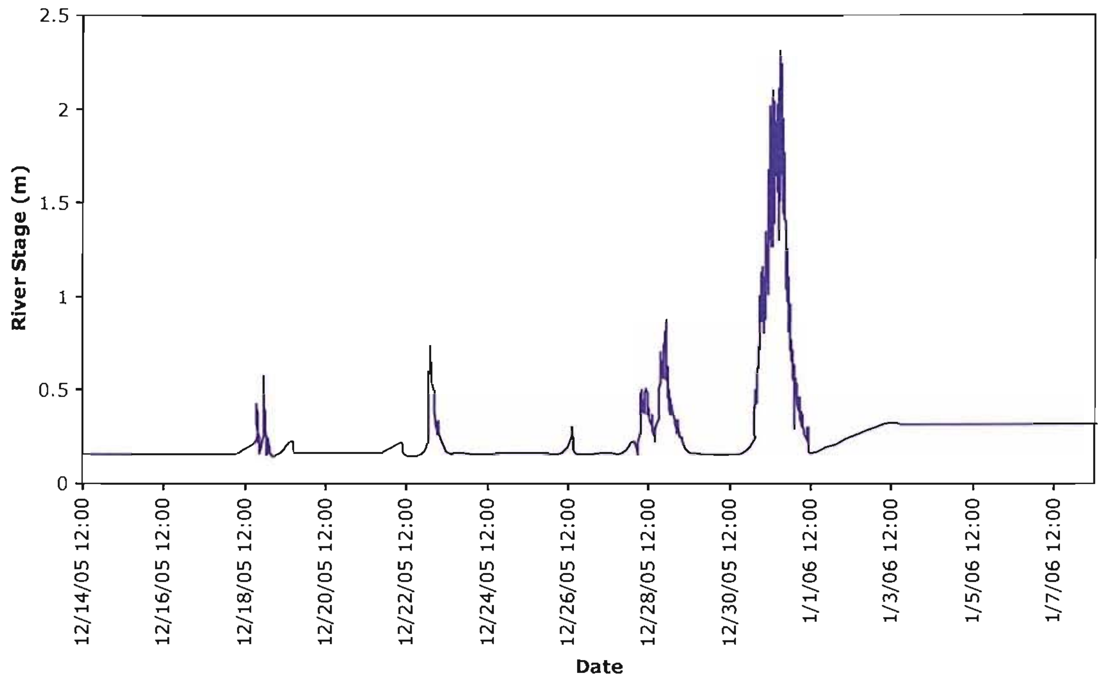


FIGURE 6.5: Stage hydrograph on Sulphur Creek upstream of Heath Canyon confluence during New Year's Eve Flood (from USGS Station STH).

6.4 Geomorphological Impact of the New Year's Eve Storm on Study Reach

While adequate records to estimate the recurrence interval of the New Year's Eve flood on Sulphur Creek do not exist,[7] the geomorphological consequences of this magnitude of event is quite clear in the study reach. The flood has reset the channel and portions of the riparian corridor. Figure 6.6 show the common signatures of this style of event in terms of large areas of fresh sediment deposition, a decrease in the amount of in-channel and riparian vegetation and debris (through both removal and burial), and overall simplification of morphological unit structure and habitat heterogeneity.

Figure 6.7 shows a simple geomorphic unit classification of the study reach prior to and following the event. The December 2005 classification shows a complex mix of morphologies and habitat types that are consistent with the character of a wandering/semi-braided channel. Namely, there are a large number of exposed bars (both central and lateral) with channel bifurcations and confluences around them. There is a characteristic lack of deep-pool habitat consistent with observations by Koehler (2003*b*), Pearce *et al.* (2003) and a channel of this nature with such high sediment loads. The noteworthy exception is the presence of a deep pool downstream of a concrete grade control structure and major artificial channel and floodplain width constriction in the middle of the study reach (GC3 in Figure 6.1A & C). The channel is

[7]The recurrence interval estimate from the rainfall records calculated in the previous section will likely differ from a flow-based estimate.

FIGURE 6.6: Aerial Photographs of Sulphur Creek Before and After New Year's Flood. Aerial photographs (3 cm resolution) acquired from blimp photography taken at site by the author and collaborators. Photographs were ortho-rectified based on extensive ground-control network and mosaiced using ArcGIS by author. Flow direction is up the page.

confined to an inset corridor/floodplain, which was excavated into the alluvial fan fill. Along the left-bank are three bank-protection features labeled as engineering structures. The rest of the engineering structures shown are rock-rip rap spurs oriented upstream on both sides of the main channel in the bottom half of the reach. These structures, in combination with a riparian vegetation planting scheme, represent a Natural Resource Conservation Service restoration project that was constructed in 2003 (p. comm Varozzas). According to the project coordinator (p. comm P. Blake), the structures were intended to prevent bank erosion and force a deep channel thalweg (for fish passage) to persist in the centre of the channel. Given that the reach was established to be aggrading and there were no local bank erosion problems, the design basis is questionable. After less than two years (by December 2005), half of these structures had been buried by gravel and the remainder were only partially exposed.

Following the New Years Flood, a large slug of sediment was deposited throughout the study area simplifying the arrangement of geomorphic units considerably (Figure 6.7). Upstream of the Crane Street Bridge, the persistent central bar feature grew considerably, prograding downstream toward the bridge and shifting the channel confluence by roughly 15 metres (Figure 6.8). The reach downstream of the bridge, but upstream of the grade control structure (GC3), what had been a vegetating floodplain (or former lateral bar) on the inside bend, was engulfed in gravel deposition and became a large lateral gravel bar (Figure 6.9). The channel filled and homogenized considerably in this sub-reach with a small pool being almost entirely filled. A persistent grade differential of 20 to 50 cm has existed between the reach upstream and downstream of GC3 for at least the past decade. This event erased any suggestion of that grade difference, completely filling the former pools downstream. The channel thalweg through this 'restored' reach was shifted from its central position to river left and aggraded considerably. Together with the lateral bar that formed on river right, deposition through the 'restoration' reach buried all but the highest protrusions of the rip rap boulders on the constructed spurs.

It is clear from field evidence, the aerial photographs and geomorphic unit classification that there were substantial changes as a result of this single flood event. However, the details of those changes and their magnitude can not be reliably inferred without some quantitative analysis. From the photographs (Figures 6.8) it is clear that some areas experienced as much as 1.5 metres of deposition, but how those local highs translate across the entire reach is difficult to infer. It is probably safe to say from the above evidence alone that the event was dominated by deposition, but what proportion of the event was erosional is not as easy to estimate. It is also difficult to say for sure what the dominant style of change was. Although there is widespread bar development, could pool and channel filling account for more volumetrically? There are other interesting questions about how the magnitude of deposition from this event compares to historical estimates of annual gravel extraction or average annual sediment loads.

One way to address these questions is through the use of repeat topographic surveys (before and after the event) and application of the morphological method.[8] The next section presents

[8]Refer to § 3.3.1.2 for review.

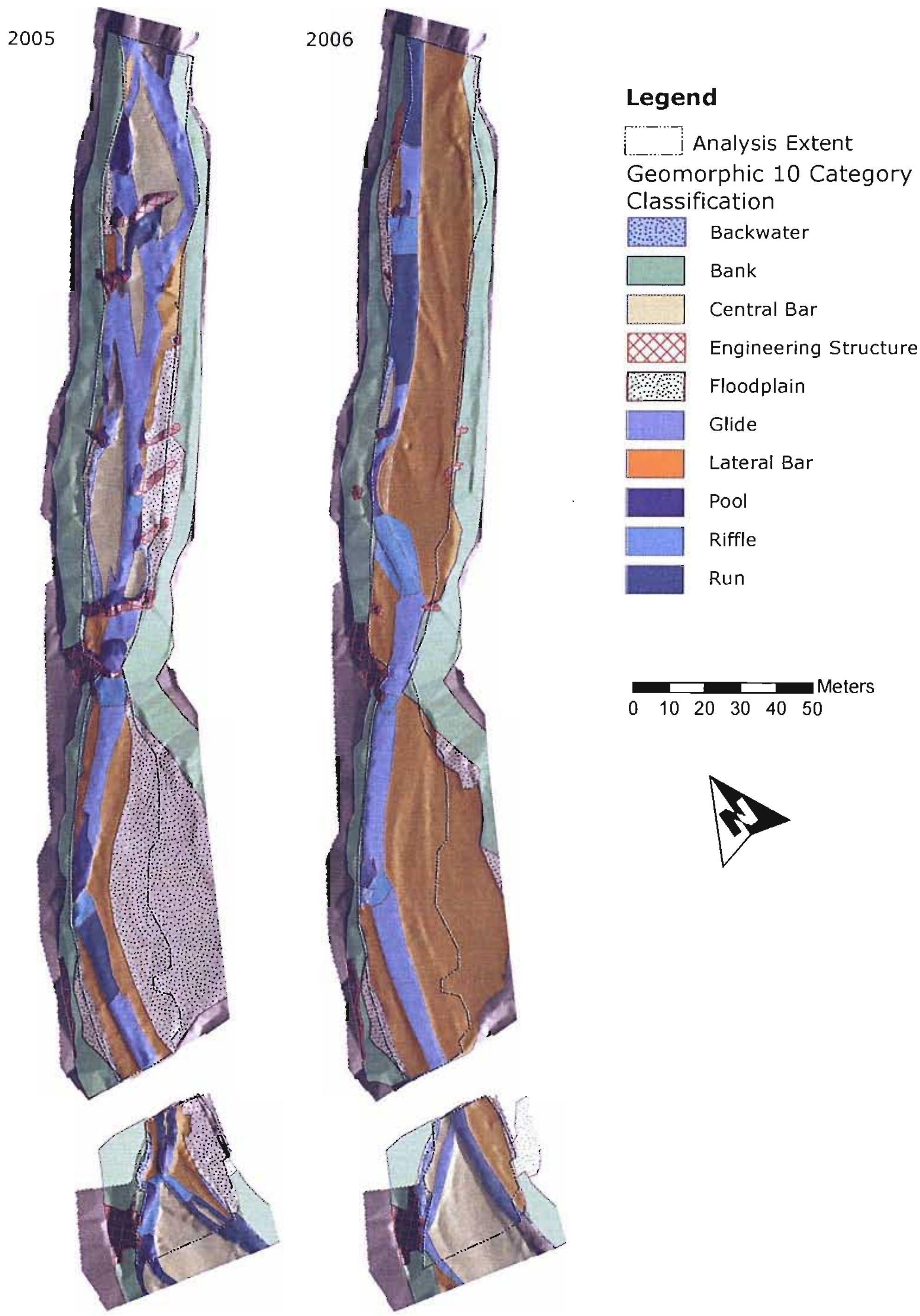


FIGURE 6.7: Geomorphic unit classification of study reach before and after New Years Flood. These are expert-based classifications based on a mix of field observations, aerial photography (Figure 6.6) and topography. Flow direction is up the page.

FIGURE 6.8: Photograph sequence of central bar development looking upstream from Crane Street Bridge as a result of New Year's Storm, before (top), during (middle), and after (bottom) the storm. Photographs taken by Wayne Leong.

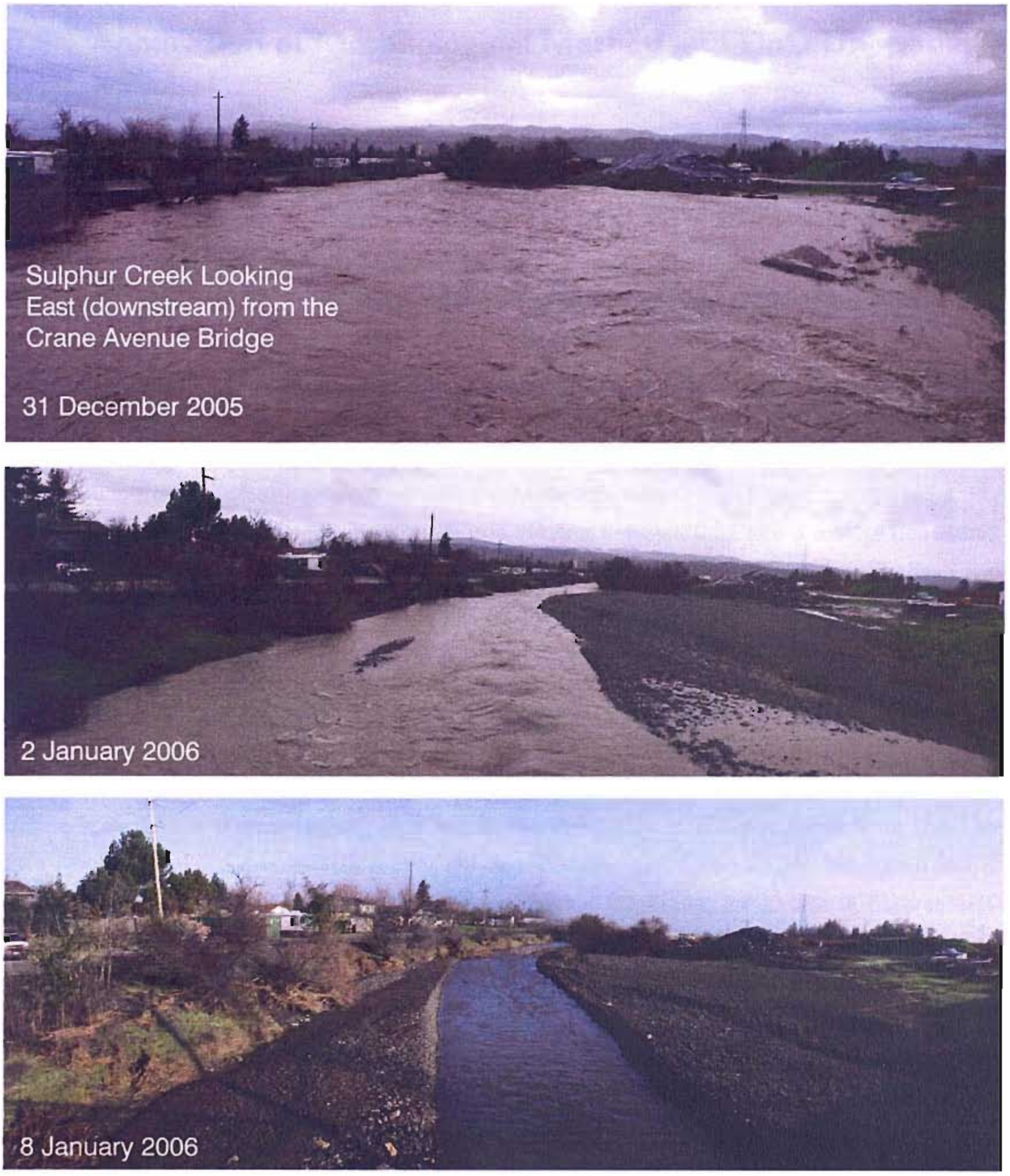


FIGURE 6.9: Photograph sequence of recession of New Year's Storm looking downstream from Crane Street Bridge during the peak (top), recession stage (middle), and post-flood (bottom). Photographs taken by Wayne Leong.

the results of the application of the morphological method and DoD uncertainty analysis as was developed in Chapter 4. However, it is § 6.6 which really returns to this question of sensible, quantitative geomorphological interpretation.

6.5 Application of Morphological Method and DoD Uncertainty Analysis

As indicated earlier[9], a topographic survey of the study site was carried out just prior to and following the New Year's Eve Storm. Figure 6.4 indicates the timing of these surveys with yellow bars in relationship to rainfall and flows in the area. The pre flood survey was conducted from the 3^{rd} to 5^{th} of December 2005 and the post flood survey was conducted from the 9^{th} to 11^{th} of February 2006. The pre project survey consisted of 3619 points, and the post project survey consisted of 8989 points (spatial extent was greater than study site reported here). Both surveys were conducted primarily with a reflectorless Leica TCRP1205 total station, but the second survey was augmented with two survey-grade differential rtkGPS rovers (Leica GPS1200 system). A feature based sampling scheme was adopted with points collected along all major grade breaks and then on a rough grid varying between 0.25 and 3 metres depending on the topographic complexity. The study site is delineated by the intersection of these two surveys, which is a roughly 0.70 hectare area defined primarily by the survey extent of the pre project survey.

The resulting point clouds from the two surveys are shown in Figures 6.10 A and D overlaid on top of the derived point density (pts. per square metre). A simple TIN-based interpolation was used to produce surface models of the survey data. The resolution of the survey data relative to the scale of the morphological units led to the derivation of a raster DEM from the TIN at a resolution of 0.5 metres. Hillshades derived from the respective DEMs are shown in the background of Figure 6.7. Slope analyses derived from the DEMs are shown in Figures 6.10 B and E. The slope analyses and point density grids were both derived at 0.5 metres and used as inputs into the fuzzy inference system (FIS) portion of the Pathway 4 DoD Uncertainty Analysis.[10] The same rule system reported in Table 4.6 was used. The resulting FIS spatially variable estimates of elevation uncertainty were used in conjunction with a spatial coherence filter[11] under the pathway 4 analysis and on their own under the pathway 3 analysis to derive DoD probability maps from which the DoD's were thresholded. DoDs were thresholded fairly conservatively at 95% confidence intervals. The resulting thresholded and unthresholded DoDs and their elevation change distributions (ECDs) are shown in Figure 6.11A.

According to the raw DoD, roughly 79% of the 0.68 hectare surface area of the study area expereinced deposition and the rest expereinced erosion. The areal elevation change distribution in Figure 6.11D reflects this strong spatial bias towards deposition with a primary areal

[9]See § 6.1
[10]See § 4.6.3 for explanation.
[11]See § 4.4.2.

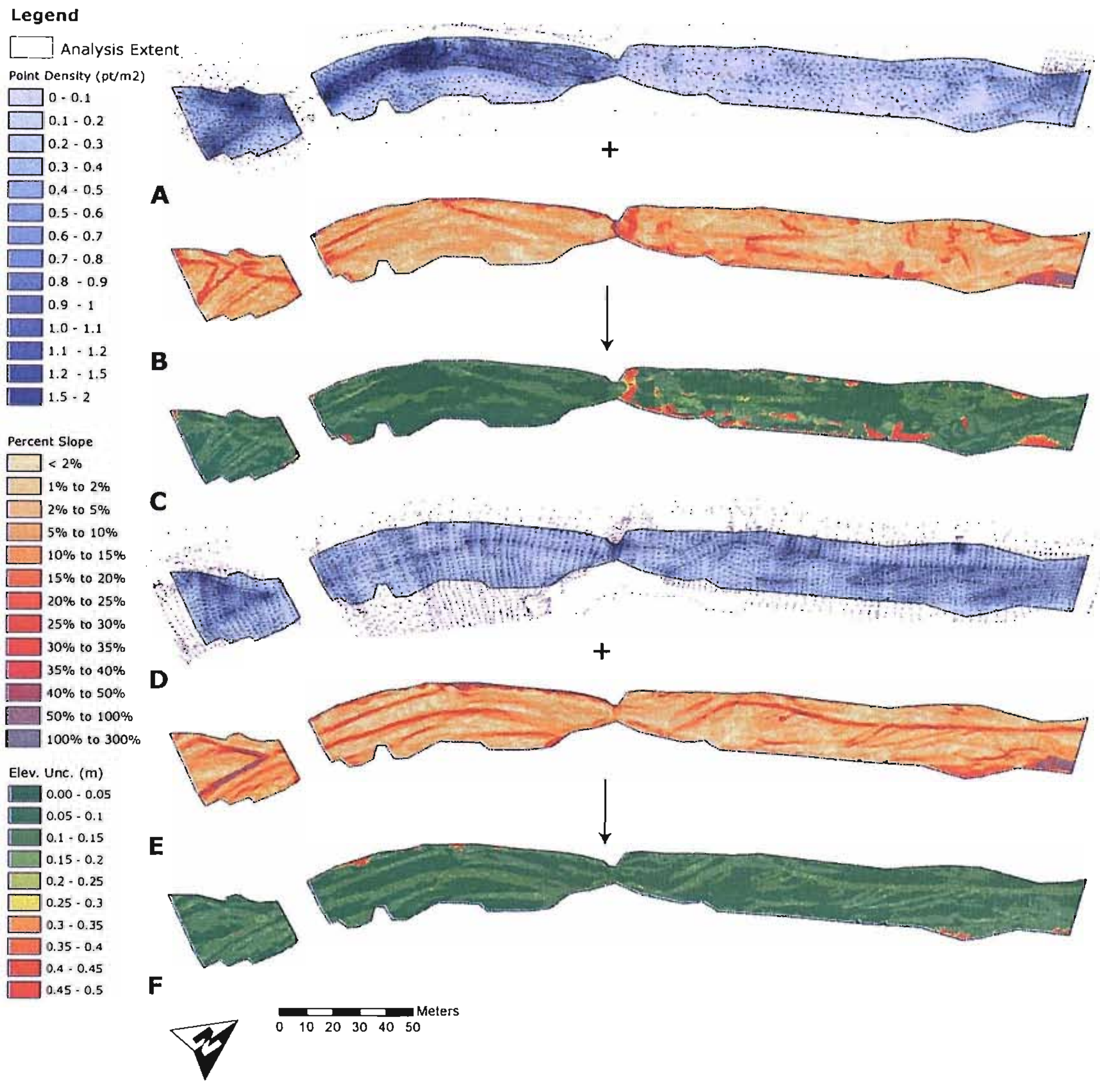


FIGURE 6.10: FIS-derived elevation uncertainty surface for Sulphur Creek and inputs. A, B, D and E represent FIS inputs of point density (A & D) and percent slope (B & E). C and F are the FIS-derived elevation uncertainty grids for 2005 survey (prior to New Year's Flood) and 2006 (following New Year's Flood).

	Erosion	Deposition	Total Change	Net Change
	Area (m^2)			
Unthresholded DoD	1450.5	5398.3	6848.8	NA
PW3 Thresholded DoD	375.3	3289	3664.3	NA
PW4 Thresholded DoD	700.3	4295.3	4995.6	NA
	Volume (m^3)			
Unthresholded DoD	214.4	2163	2377.4	1948.6
PW3 Thresholded DoD	84.6	1704.6	1789.2	1620
PW4 Thresholded DoD	142.2	1995.3	2137.5	1853.1

TABLE 6.1: Comparison of gross areal and volumetric DoD budget values for pathway 1 (unthresholded), 3 and 4 analyses.

peak of deposition of 15 to 25 cm and a secondary peak at 55 to 65 cm. When transformed to a volumetric distribution, the distribution becomes bimodal with a very minor erosional peak and a dominant bimodal peak centred around the secondary areal peak at 55 to 65 cm (Figure 6.11E). The raw unthresholded DoD suggests that 2163 m^3 of deposition and 214 m^3 of erosion took place reflecting the strongly aggradational response of the study reach to the New Year's Eve storm.

Following the DoD uncertainty analysis developed in Chapter 4, the Pathway 3 uncertainty analysis (Figures 6.11 B, F and G) draws into question 39% of the area of predicted deposition and 74% of the area of predicted erosion from the raw DoD. This consequently trims the predicted total volume of erosion down to 84.6 m^3 and the total volume of deposition down to 1794.6 m^3, still retaining the strong depositional signal (Figure 6.11 G). As was consistently the case in Chapter 4, the spatial coherence analysis reflected in Pathway 4 recovers a significant proportion of these changes as meaningful (Figures 6.11 C, H and I). In areal terms, the Pathway 4 analysis suggests that 72% of the DoD actually experienced changes signficant enough to be distingusihed from noise. The Pathway 4 analysis (Figure 6.11 I) represents a volumetric sediment budget with 95% confidence that the changes being showed can be distinguished from noise. For the storm, the change in storage under this budget works out to 142.2 m^3 of erosion and 1995.3 m^3 of deposition. These values are summarised in Table 6.1. In contrast to the results from the Feshie presented in Chapter 4, there is not a huge difference between the pathway 4 thresholded values and the unthresholded values. This is explained the large proportion of the budget representing high magnitude elevation changes (Figure 6.11E, G and I). These areas are subsequently above most $_{min}$LoD thresholds. The primary question of this chapter, is how does one segregate this budget, which has been thresholded to account for uncertainty (Pathway 4), to make a more detailed meaningful interpretation of what changes took place?

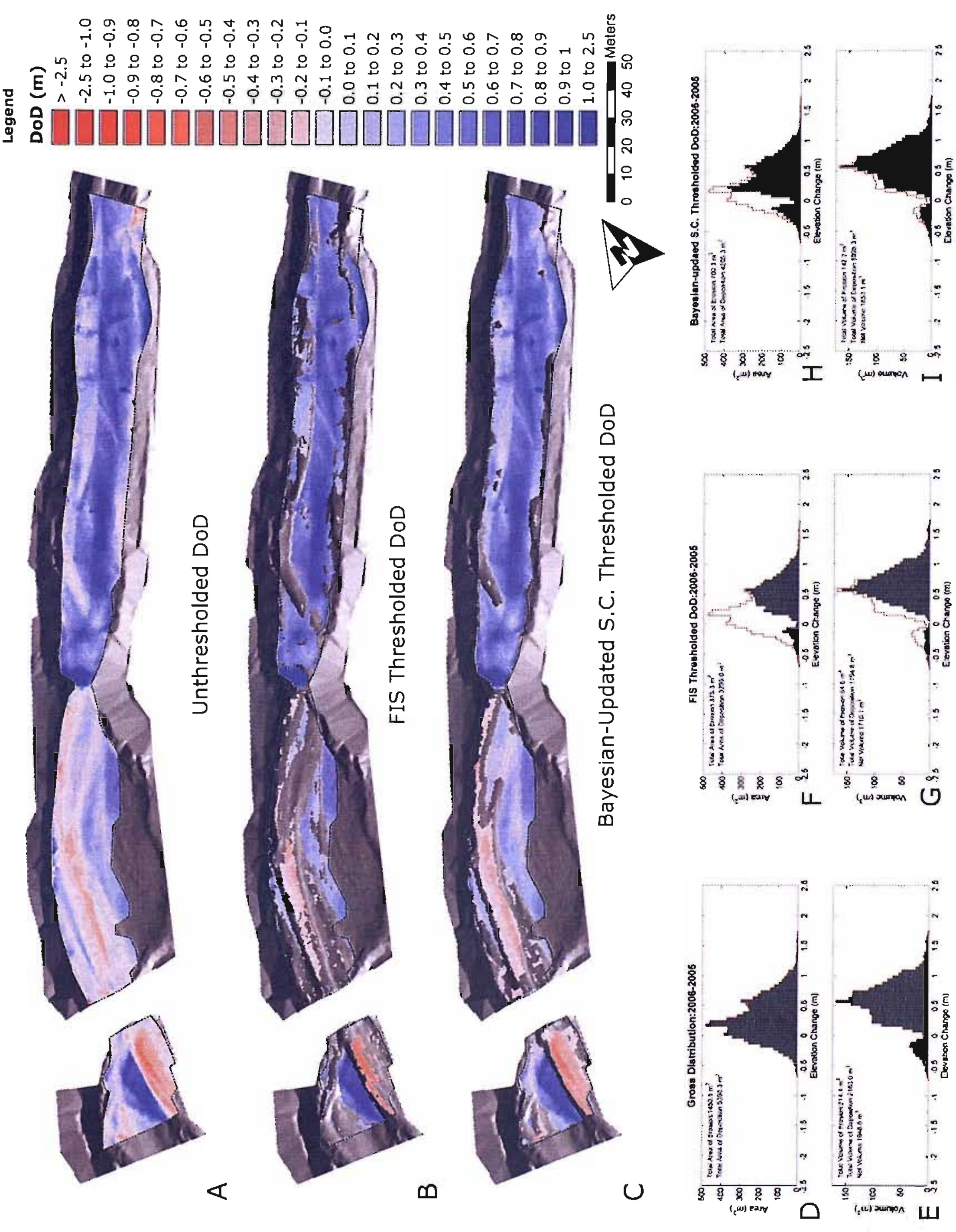


FIGURE 6.11: DoD for New Year's Eve Flood on Sulphur Creek. A. Unthresholded DoD (D. areal and E. volumetric elevation change distributions); B. Pathway 3 FIS thresholded DoD based on a 95% confidence interval (F. areal and G. volumetric elevation change distributions); C. Pathway 4, Bayesian updated spatial contiguity index thresholded DoD based on a 95% confidence interval (H. areal and I. volumetric elevation change distributions). Flow direction is up the page.

6.6 Different Techniques to Interpret the DoD

As laid out in § 5.2.1, here the Pathway 4 thresholded DoD (Figures 6.11 C, H and I) will be segregated in a variety of ways. First, the study reach is divided into logical sub reaches acting as a type of standard classification (§ 6.6.1). Next, a simple geomorphological classification before and after is used to derive a classification of difference (§ 6.6.2). Finally, an expert-based geomorphological interpretation of the DoD is derived (§ 6.6.3).

6.6.1 Sub Reach Segregation

The study reach divides logically into three subreaches delimited by the presence of four engineering structures (Figure 6.1).[12] At the top end of the reach, from GC1 to GC2 (Crane Street Bridge) is a very interesting central bar complex that represents the downstream end of the wandering/semi-braided reach. This sub-reach is delineated in light blue in Figure 6.12A and corresponds to the volumetric elevation change distribution in Figure 6.12E. Moving downstream of the Crane Street Bridge[13], and extending downstream to the next grade control structure (GC3) another sub-reach is defined. This sub-reach is shaded in dark green in Figure 6.12A and corresponds to the volumetric elevation change distribution in Figure 6.12D. Moving downstream again, from GC3 to the end of the reach (where Varozza Bridge crosses) is the third sub-reach. This sub-reach is shaded gold in Figure 6.12A and corresponds to the volumetric elevation change distribution in Figure 6.12C. Below, the DOD-derived morphological budgets segregated by these three sub-reach masks are described.[14]

The sub-reach upstream of Crane Street Bridge boasts a dynamic bar complex that has persisted in one form or another since Crane Street Bridge was constructed in the 1970s (for evidence, see aerial photographs[15] from 1974 1982, 1987, 1993, 2002, 2003, 2005 and 2006). The central bar complex grew and prograded downstream during the New Year's Eve Flood (Figure 6.8). This central bar growth is characterised by two distinctive depositional signatures in its volumetric elevation change distribution (E2 and E3 in Figure 6.12E). The first (E2) is a broadly evenly distributed signature over fill depths from 0 to 0.75m, representing the morphologically flat bar-top, that was extended over a mix of morphologies creating a diversity of fill depths. The second (E3) is a much narrower and peaked signature, which peaks at 1.05 m and falls sharply to a maximum fill depth of 1.25 m. This signature is characteristic of the large fill depths over the former channel as the bar prograded and subsequent sculpting of the right hand side of this bar by the lower-stage recession flood producing the distinctive grade break seen later in Figure 6.16A. Like the entire reach, the erosional signal of this sub-reach (74.5 m^3) was dwarfed by the deposition (187.2 m^3). Although this sub-reach only represents 12% of the 0.5 hectare study reach and the bar development comprises only 9% of the total

[12] These engineering structures were described in § 6.1.

[13] The Crane Street Bridge (GC2) consists of three parallel box arch Culverts (see Figure 6.16A), each roughly 2.5 metres in height, approximately 6 metres in width, 1 metre apart and each with a concrete sill.

[14] Refer to § 5.2.1.1 for background.

[15] Aerial photographs from 1982, 1993 and 2002 are shown in § F.1; 2005 and 2006 are shown in Figure 6.6.

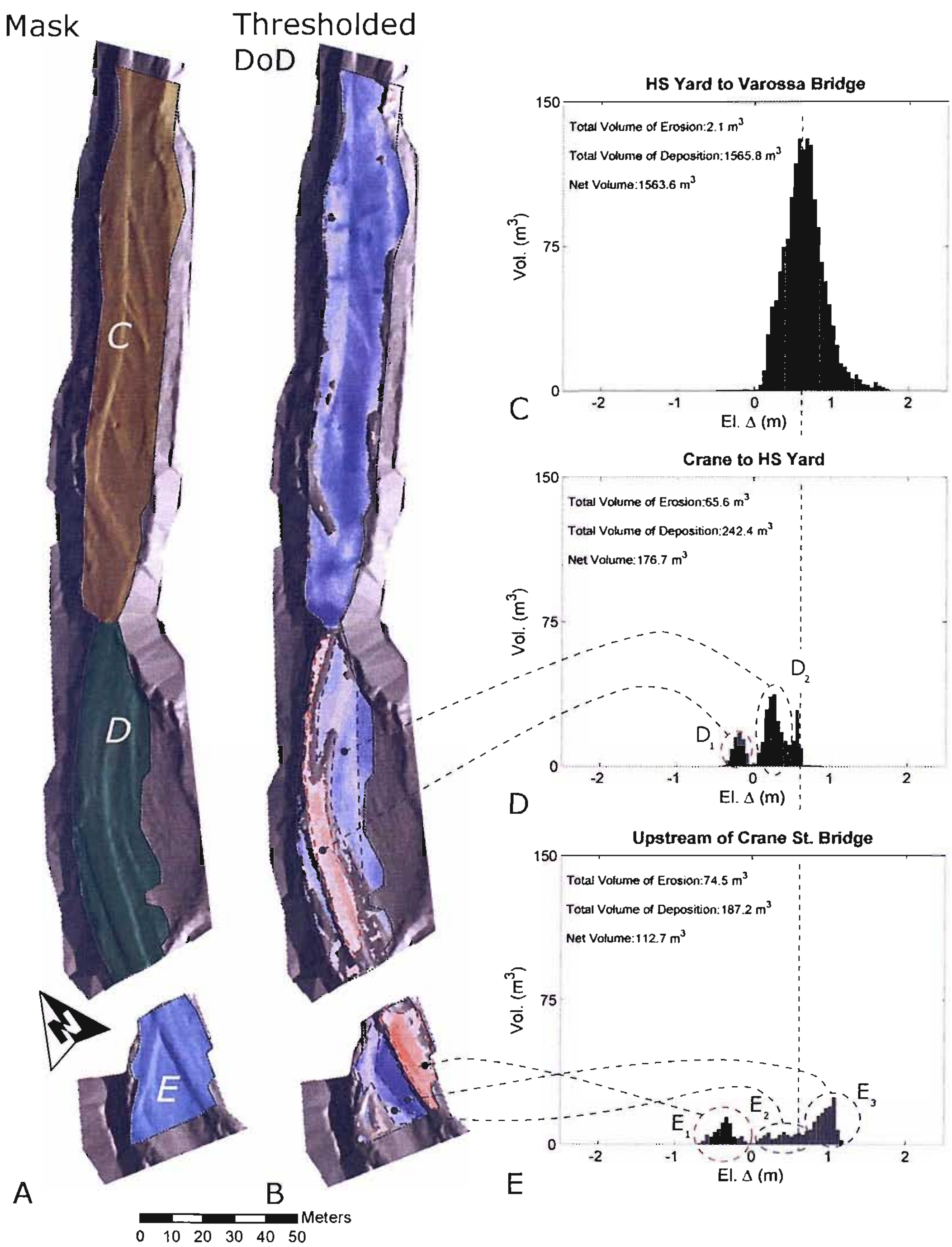


FIGURE 6.12: Segregation of DoD into three distinct subreaches delimited by engineering structures, which act as grade control and/or constrictions. A. The three masks: Harold Smith Yard to Varozza Bridge (*C*), Crane Street Bridge to Harold Smith Yard (*D*), Upstream of Crane Street Bridge (*E*). B. The thresholded DoD (Pathway 4 analysis at a 95% confidence interval threshold; flow direction is up the page; see also Figure 6.11C for shading legend). C - E. Corresponding elevation change distributions for each reach segment.

volume of deposition in the reach, 52% of the total volume of erosion that took place in the study reach was within this subreach. The erosional distribution (E1 in Figure 6.12E) is broadly distributed from 0 to 70 cm with a peak around 35 cm. This erosional signature is a reflection of the shifting of the right-hand anabranch channel further to the right in response to the growth of the central bar, which buried much of the former channel. As the channel is forced into one or more of the three box culverts, this erosion is strongly controlled by the presence of the grade control structures and the relatively armoured banks in this reach. These structural constraints mean that for the subreach to accommodate such extensive central bar development, some erosion is necessary to maintain the relatively steep channel gradient dictated by the two grade control structures.

The sub-reach from Crane Street Bridge to the Harold Smith Yard consists of a single thread channel on a very broad right-hand bend. The sub-reach is confined on river left by a reasonably well vegetated, terrace bench, which itself is flanked on its left with an artificially stable bank with intermittent concrete and rip-rap revetments. By contrast, the sub-reach is completely unconfined on river right and the broad inside bend gives rise to a high-stage secondary flow cell in floods (top picture in Figure 6.9). Within this zone, the dominant depositional signal for the sub-reach rebuilt the lateral bar (in place of the vegetating floodplain/bar) with a broad sheet of deposition. As the pre-flood and post flood topography are both broadly similar morphologies with gentle slopes this sheet of deposition is characterised by a narrow elevation change distribution (D2 in Figure 6.12D) with a strong peak at about 25 cm. A second depositional peak at 55 to 60 cm represents the extension of this flat lateral bar over a former high-stage channel that dissected the lateral bar at its downstream end. Even though deposition in this sub-reach is substantial, it only comprises 12% of the total volume of deposition in the reach. By contrast, 46% of the total volume of erosion exists within this subreach and this is represented in the erosional fraction of the ECD (D1 in Figure 6.12D). This 65.6 m^3 of erosion is relatively shallow with a peak of about 20 cm and is the result of the channel shifting to the right and eroding into the pre-existing lateral bar on river right. The reason for this shift is a knock-on effect of the central bar growth in the upstream subreach. Recall that Crane Street Bridge consists of three box culverts. Prior to the New Years Eve Flood, the thawleg occupied the left hand box culvert. The growth of the central bar upstream, shifted this thawleg into the central box culvert, which in turn funneled a jet of water during the flood directly into the existing lateral bar, shifting the channel to the right.

The third sub-reach (restoration or Harold Smith Yard reach) exhibited a reasonable amount of habitat heterogeneity and morphological diversity prior to the New Year's Flood. This was erased by roughly 1565.8 m^3 of deposition in the sub-reach (78% of the total reach). Only 429.6 m^3 was eroded from the two upstream subreaches, so at least 73% of this material had to come from further upstream. Erosion was negligble in this subreach, only 2.1 m^3 being detected. The relatively straight and gently sloping channel in this subreach is moderately confined by artificially stable banks on both sides (this reach did not expereince overbank flooding). During high-stage events, overbank flooding occurs immediately downstream of this reach as the channel quickly transitions into a narrow, incised and confined channel that can not accomodate the flows from upstream. The combination of low bed slopes in this subreach and a backwater from the transition downstream creates a relatively shallow energy grade line in this reach providing the last substantial accommodation space and opportunity for significant deposition on Sulphur Creek before it reaches the Napa River, roughly 2 km dowstream. Deposition in this subreach appears to have produced a broad-flat plane bed morphology parallel to the energy grade line, that was subsequently resculpted by the flood recession flows, carving out a new shallow thawleg on river left. The elevation change distribution is only slightly asymmetric, with a long tail up into 1.75 m fill reflecting the filling of the pools. The peak is centred around a 55 to 70 cm fill, but the full width of the distribution represents the varied depth of this flat fill burying the relatively diverse pre-flood morphology.

In summary, the simple segregation of the reach into three subreaches with different morphological responses is a helpful mask for disentangling the mechanisms of change buried in the gross reach-scale DoD.

6.6.2 Classification of Difference

Although better and more detailed individual morphological classifications exist (e.g. Figure 6.7), to illustrate the concept of a classification of difference (CoD)[16] a simple three category classification is used here. The three classes are bank, channel and bar. Here, a bank is defined as anything with a local slope over 10% that acts to confine the channel; a channel is defined as anything that is submerged (in the low-flow aerial photography of Figure 6.6); and a bar consists of exposed, unsubmerged, areas within the boundaries of the banks.[17]

In Figure 6.13 the pre-flood (left) and post-flood (middle) morphologies are shown together with the resulting CoD (right). The classifications were derived from the aerial photography (Figure 6.6) and DEMs before and after the flood. Even this simple classification highlights the simplification of the morphology and habitat structure in response to the New Year's Eve Flood previously described by more sophisticated classifications in Figure 6.7. The nine categories of change that fall out of the CoD reflect three no-class changes (i.e. where the morphology type has remained the same following the flood) and six class changes. On the basis of surface area, 60% of the reach preserved its classification (i.e. the three no class change categories); whereas 40% experienced a class change (i.e. the six class change categories). The two most dominant categories by surface area were the Bar→Bar and the Bar→Channel categories[18], at 42% and 24% respectively.

When the CoD is used as a budget mask, the relative magnitude of volumetric change in each CoD category can be assessed (Table 6.2).[19] Figure 6.14D depicts the relative percentage

[16] Refer to § 5.2.1.2 for background.

[17] As with many fluvial classifications, this one is clearly stage dependent.

[18] Recall that a channel in this simple classification a channel is defined as anything that is submerged, and may indeed be a submerged bar. This large percentage of Bar→Channel, is a reflection of the active channel shifting its course and occupying formerly exposed bars.

[19] Slight discrepancies between the total volumes in Table 6.2 and Table 6.1 are not errors but a reflection of the CoD masks not completely covering the analysis extent (typical throughout).

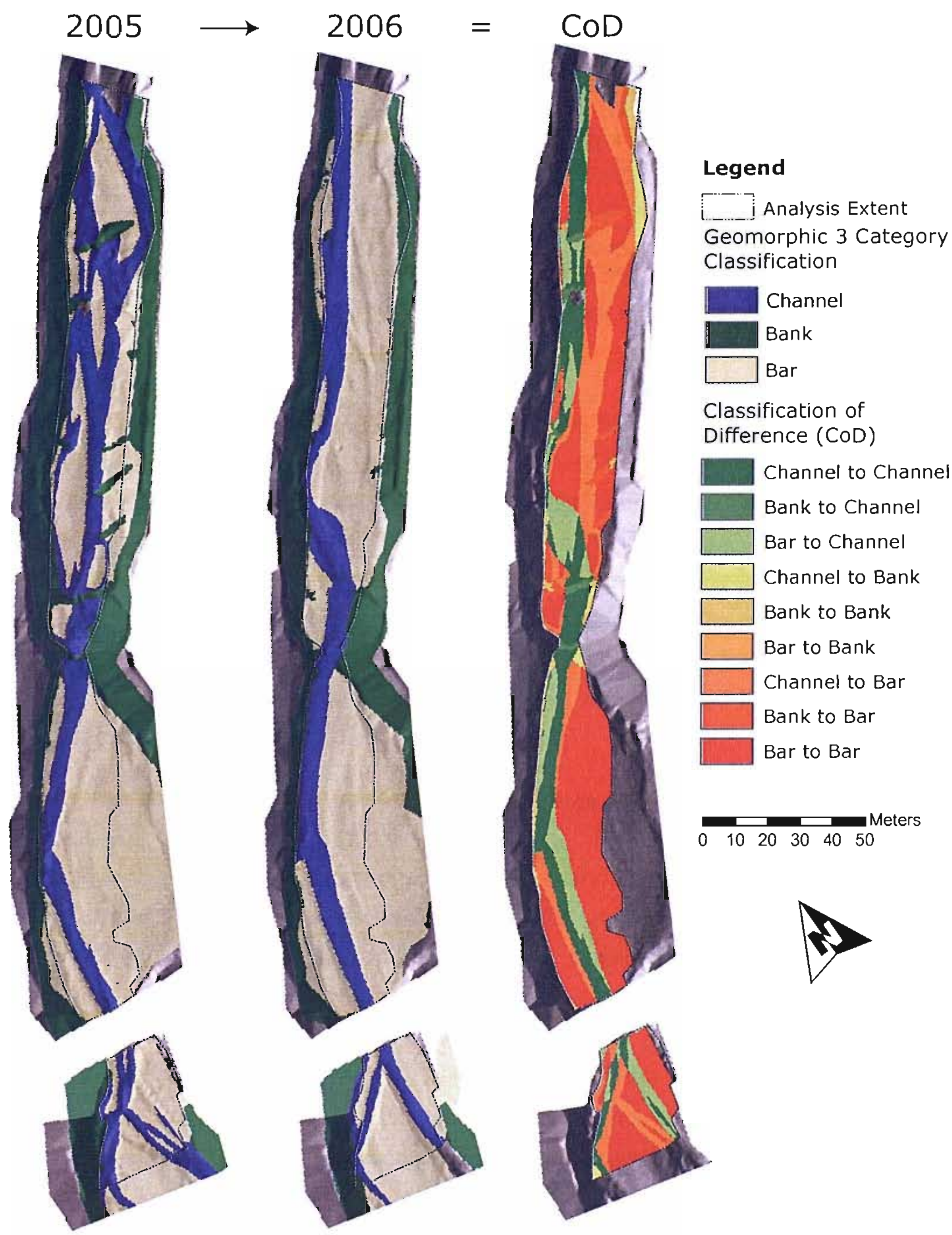


FIGURE 6.13: A CoD (right) based on a simple three-category classification scheme applied to the pre (left) and post (middle) flood surveys. Flow direction is up the page.

CoD Name	Pct. of Total	Erosion	Deposition	Total	Net
	%	Volume (m^3)			
Channel→Channel	12.24	22.6	236.0	258.6	213.4
Channel→Bank	1.08	0.4	22.4	22.7	22.0
Channel→Bar	6.58	77.5	61.6	139.0	-15.9
Bank→Channel	2.11	0.0	44.6	44.6	44.6
Bank→Bank	1.12	1.3	22.5	23.8	21.2
Bank→Bar	0.09	0.0	1.9	1.9	1.9
Bar→Channel	33.53	0.5	708.2	708.7	707.7
Bar→Bank	4.22	0.1	89.0	89.2	88.9
Bar→Bar	39.04	38.3	786.9	825.2	748.5
	TOTAL:	140.7	1973.0	2113.7	1832.3

TABLE 6.2: DoD volumetric budget segregation based on three-class CoD categories.

of change that took place in each CoD class. Here, the Bar→Bar category comes out on top again with 37% of the total volume of sediment moved consisting of bar growth through deposition. Over 93% of the volumetric changes are depositional, with the erosion in all nine of the categories comprising less than 7% of the total volumetric change. Its elevation change distribution (Figure 6.14C) shows a small amount (38.3 m^3) of bar degradation in comparision to the dominant signal of bar development (786.9 m^3), which includes fills of up to 1.3 m. The Bar→Channel category still sits at second in terms of volumetric change but narrows the gap between itself and the Bar→Bar category (compared with the areal percentages) coming in at 34% of the total volumetric change.

Interestingly, the Bar→Channel category's elevation change distribution (Figure 6.14B) is entirely depositional, contrary to what one might expect. This suggests that as opposed to the new channels being cut into existing bars and the channel bed elevation either remaining constant or downcutting, the new channels were formed at a later stage in the flood after significant volumes of deposition had raised bed levels. Possible mechanisms of channel development that explain the presence of a channel created through deposition as opposed to channel carving include:

- A plane bed channel was deposited at an elevation roughly equal to the adjacent lateral bars and was built up until the flood peak; as flows receded preferential flow carved out the new channel where the bar once existed, but were unable to excavate down to the original bar top elevation.[20]
- The channel was formed on top of the former bar entirely by depositional processes. However, the rate of deposition on the adjacent lateral bars was simply much greater, producing the elevation differential between the bar and the channel.

[20]This is an example of a *negatively biased budgets* through local *compensation* of scour and fill (Lindsay & Ashmore 2002, p. 28), and was reviewed briefly in § 3.2.2.

Given the evidence of erosion along the margins of these channels in this CoD category (e.g. Figure 6.9 bottom), the former mechanism seems more likely or at least dominant.

The elevation change distributions (ECDs) for all nine categories in the CoD are shown in Figure 6.15. The five ECDs, which include the bank category, are of relatively low total magnitude and reflect the relative lack of change at the channel margins. Interestingly, these five ECDs all show fairly broad distributions typically spanning fill depths up to and over a metre. The largest magnitude changes and most interesting ECDs comprise the four corners of Figure 6.15 and represent changes to bars and/or channels. The Bar→Channel and Bar→Bar ECDs were described previously. The Channel→Channel ECD shows an interesting bimodal distribution. One of the peaks represents the erosional fraction (22.6 m^3) with a peak at 10-15 cm of scour and in-channel scour not exceeding 40 cm. The more substantial depositional fraction (236.0 m^3) peaks quickly at 20-30 cm of shallow channel deposition and then exhibits a broad shallow tail with fill depths up to 1.7 m. This signature is characteristic of a channel that previously exhibited a fair degree of morphological diversity (e.g. pools and riffles) but has experienced substantial aggradation across the board leaving relatively homogeneous plane-bed and glide morphologies. The Channel→Bar ECD represents the most balanced ECD of all 9 CoD categories, with 77.5 $m^3$of erosion and 61.6 m^3 of deposition. The erosional fraction is associated entirely with the shifting of the channel within the middle sub-reach in Figure 6.12. The depositional fraction is primarily from burying of the channel by bar development in the upstream and downstream subreaches.

The simple CoD gives a different type of insight into the nature of change than the sub-reach classification. Specifically it helps distinguish the styles and magnitudes of change associated with specific morphological units. When more sophisticated input classifications are used (e.g. $>$ 3 classes), further details are yielded. However, as the CoD will always have n^2 categories, an input classification that is too complicated may yield results that are difficult to interpret. However, as was the case in this example, experimentation with different CoDs has shown that a small subset of the total number of classes typically dominates in terms of the magnitude of volumetric changes.

6.6.3 Expert-Based Geomorphological Interpretation

One of the problems with the CoD approach is that the categories of change do not necessarily relate consistently to the processes and mechanisms that are driving that change. For example, Wheaton *et al.* (2004*a*) tried to relate CoD categories directly to specific processes like bank erosion. Their CoD was derived from a similar bar, bank, channel 3-category classification. One example Wheaton *et al.* (2004*a*) postulated was that the CoD class Bank→Channel should represent the process of bank erosion. Although, this appeared to generally be the case (as indicated by a predominantly erosional ECD), there were still substantial areas of deposition reflected in the DoD (obviously not bank erosion) and there were other areas of the DoD that clearly reflected bank erosion that were not detected (typically in the erosional fraction of Bank→Bank). Unfortunately, for other processes like bar development, the story

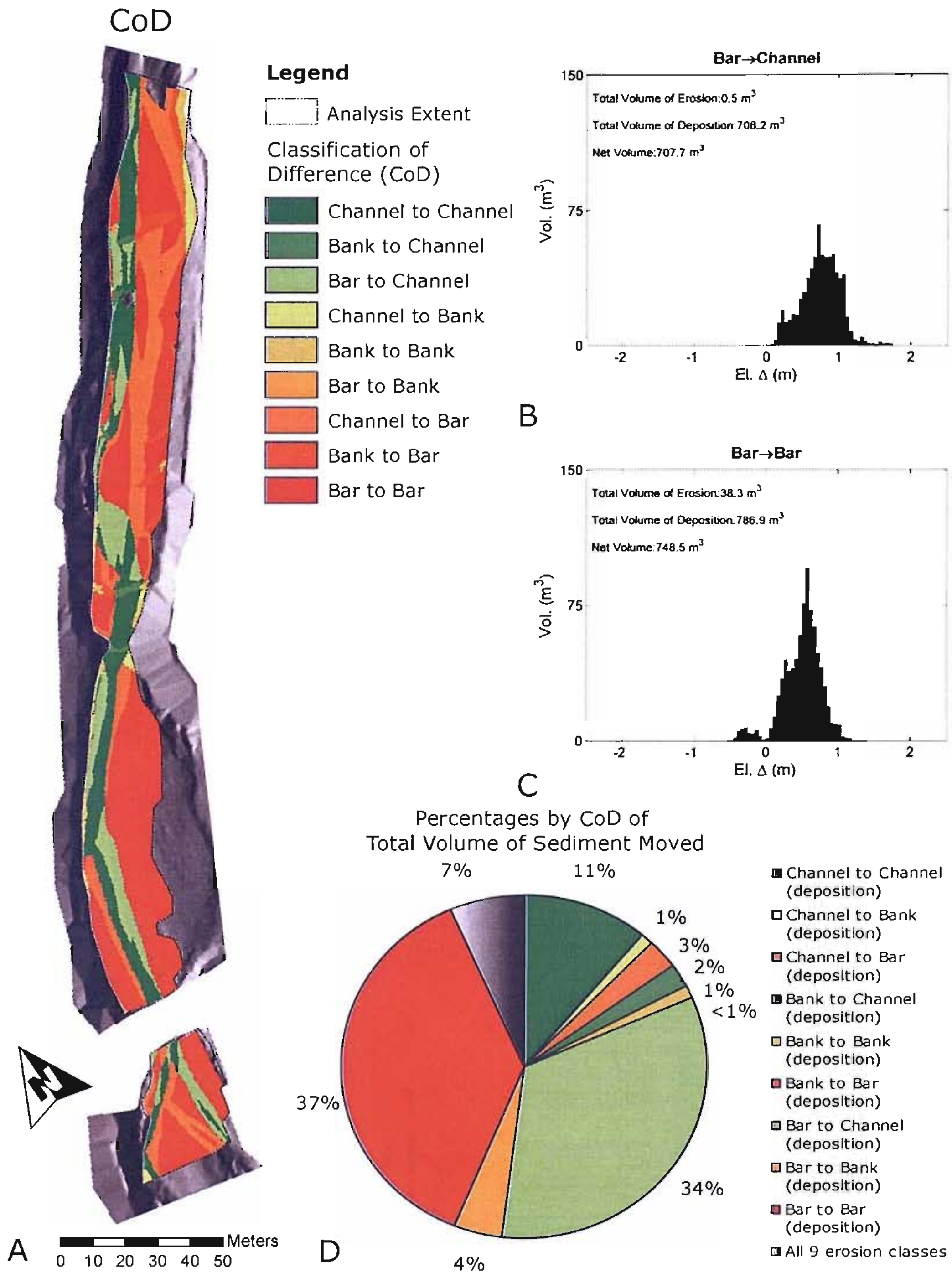


FIGURE 6.14: The use of the CoD categories of change as DoD masks. A) The derived CoD; B) Example of an elevation change distribution for the Bar to Channel CoD mask; C) Example of elevation change distribution for the Bar to Bar CoD mask (see Figure 6.15 for remaining elevation change distributions); D) Pie chart showing the relative percentages of volume of deposition for each CoD mask class and the summed volume of all 9 erosion classes. Flow direction is up the page.

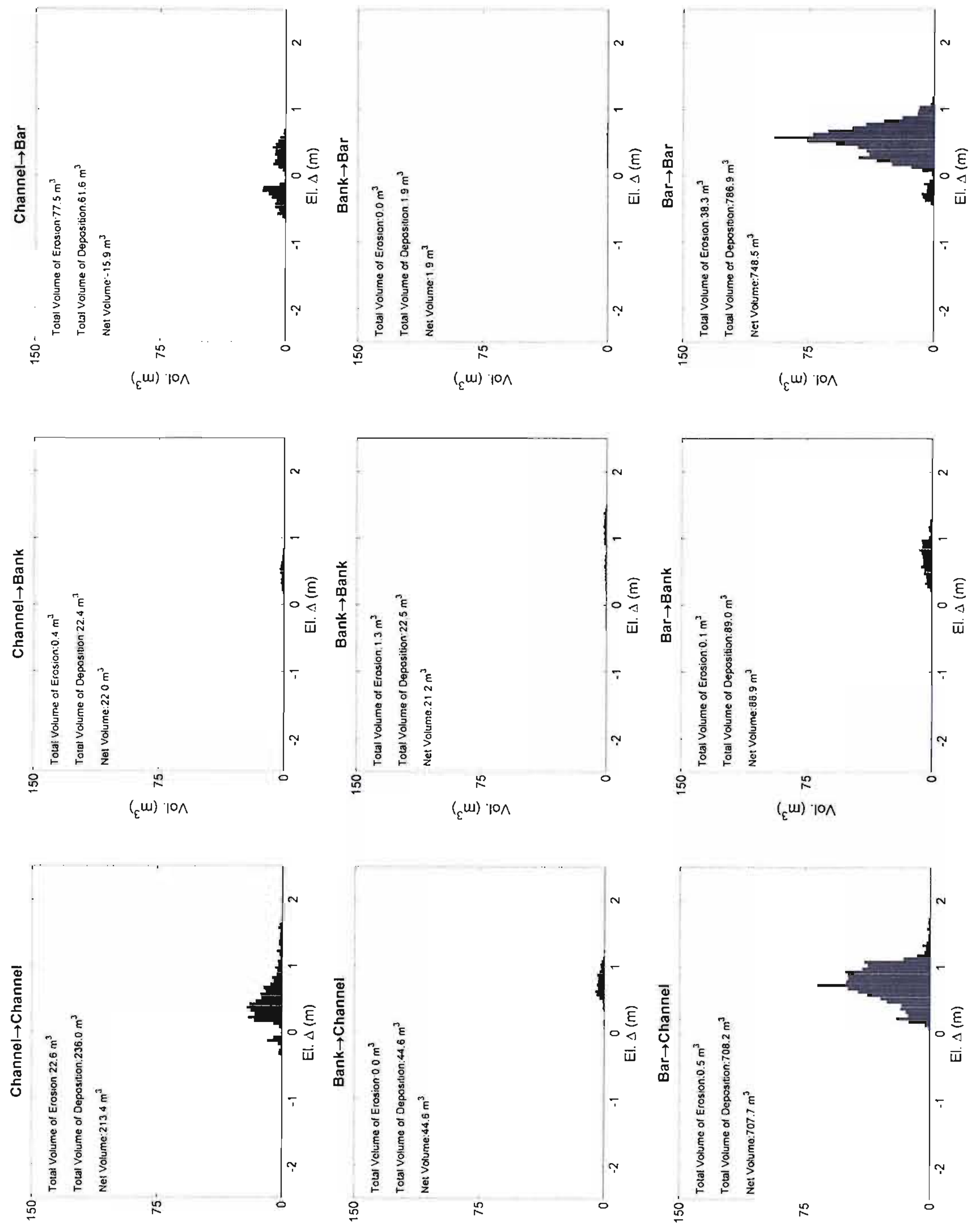


FIGURE 6.15: Elevation change distributions for the nine CoD categories from the CoD in Figure 6.14. The scales between all nine subplots are equal to emphasise the relative magnitude of volumetric change between the classes.

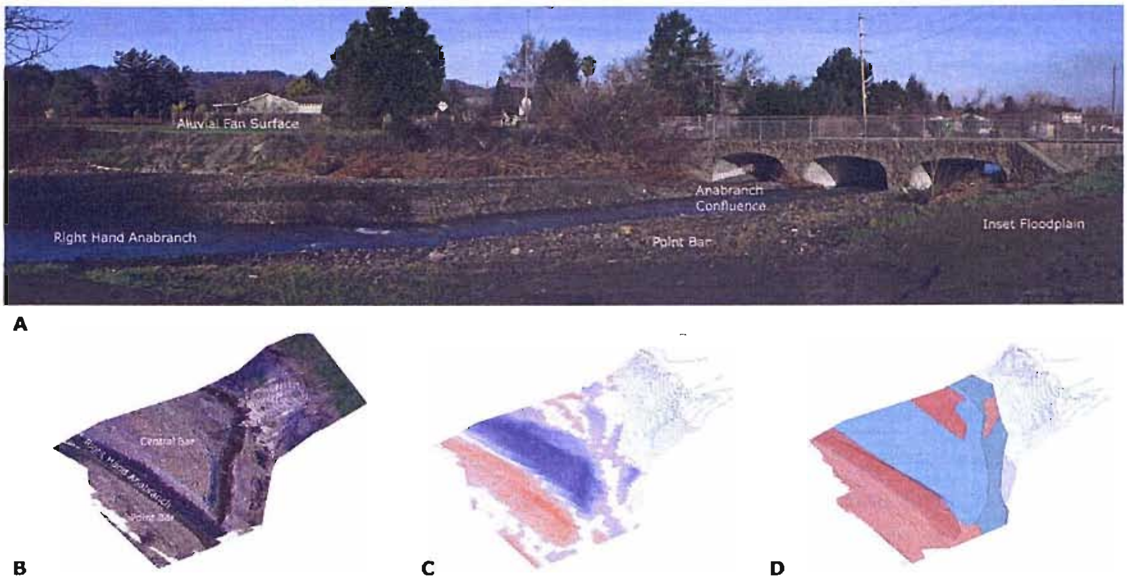


FIGURE 6.16: The components of the geomorphological interpretation of the DoD (example using the central bar upstream of Crane Street Bridge). A mixture of field evidence (A), low altitude aerial photogrammetry (B), interpretation of the magnitude of DoD elevation change in relationship to the morphology (C), are used to segregate the DoD into categories of change (D); see Figure 6.17 for colour legends.

was even more complex as Bar Development could occur from any of the depositional fractions of the three classes (Bar→Bar, Channel→Bar, Bank→Bar).

By contrast, after investigating changes in the field and inspecting a DoD, one could quite reasonably delineate on a DoD map those areas that were experiencing different mechanisms of change (e.g. bank erosion, bar development, channel deepening, channel filling, etc.).[21] This concept of expert-based delineation of categories of DoD change grew out of the above observations. It is difficult to combine this information to make interpretations about the style of change as a uniquely reproducible algorithm like the CoD.[22] Moreover, different experts will produce slightly different classifications based on their perceptions even when using the same classification. However, as the classifications are only to be used as analysis masks that aid in the interpretation of the DoD, their accuracy and repeatability is less important than how they are used to inform the geomorphological interpretation.

An example of some of the components used to aid in this interpretation is shown in Figure 6.17. These include basic field observations (shown here from one perspective in Figure 6.17A), delineations made from repeat aerial photography (shown for post flood flight in Figure 6.17B), comparison of the pre and post morphologies shown on the DEMs in relationship to the DoD (shown in Figure 6.17C).[23] As described in § 6.6.1 for the upstream

[21] See § 5.2.1.3 for background.

[22] Even multi-scalar object-oriented classification software,like Definiens' e•Cognition™, attempt to emulate powerful human cognitive processes such as this geomorphological interpretation by training the software. The utility of such sophisticated software pays off as the volume of datasets to be classified increases. With the relatively small datasets typical in fluvial DoD analyses, a manual classification is probably more economical.

[23] Figures 6.17B,C and D are shown as 3D isometrics with 10 cm contour intervals and a vertically exaggerated

sub-reach, the most obvious change in this sub-reach is the growth of the central bar. The large area of blue in the DoD (Figure 6.17C) shows the bar development. In Figure 6.17D one can see how this was simply delineated as central bar development with light blue (See Figure 6.17 for colour legend). In the right hand anabranch and adjacent lateral bar one can see primarily erosion on the DoD (Figure 6.17C). These areas of erosion were segregated into channel scour (over the anabranch) and bar sculpting (over the lateral bar) in Figure 6.17D. The inference that the degradation over the lateral bar was due to bar sculpting, came from the fact the DoD was showing scour. Field observations during floods (see middle photograph in Figure 6.8) also show that a powerful eddy fence (shear zone) developed at high-stage along this inside bend upstream of the bridge.[24] Interestingly, post-flood there was evidence of fresh deposition of fines on this lateral bar surface, suggesting that an even greater magnitude of erosion took place prior to experiencing some deposition in the recession limb of the storm when the secondary flow cell became less powerful (see bottom photograph in Figure 6.8).[25] By contrast the left hand anabranch shows modest aggradation and was classed as channel filling.

This process of working through the reach morphological unit by morphological unit and drawing on the available evidence to perform the classification was extended throughout the reach. The classification system used here consisted of 10 categories, four of which were inferred erosional mechanisms and four of which were inferred depositional mechanisms. In addition, a 'questionable edge effect' category was defined to delineate areas of the DoD where changes were predicted and not filtered from the Pathway 4 analysis, but for which the field evidence suggested that no changes took place. These are primarily interpolation errors in areas of low point density (potentially calibrating the FIS for low point densities could remove these). Figure 6.17A shows the results of this geomorphological interpretation of the New Year's Eve Flood DoD.

The pie chart in Figure 6.17B shows the the relative percentage of total volumetric change that took place in each of the geomorphological interpretation classes. At 66% of the total volume of change, lateral bar development dominated the other changes with 1388.2 m^3 of the 1995.3 m^3 of deposition. Channel filling was a distant second at 12% of the total volume of change and the central bar development upstream of Crane Street Bridge rounded out the third spot at 8%. The filling of the deep pools downstream of GC3 comprised 5% of the total change, whereas there was a three-way tie at 3% for the questionable changes and the erosional channel scour and bar sculpting classes. Eddy deposition in the wake of boulders and large woody debris accounted for roughly 7.3 m^3 of deposition. No bank erosion was recorded and only negligble eddy scour occured (more deposition was misclassed as eddy scour than actual erosion).

scale to give a better perspective on the morphology.

[24]This is where water was backed up before being funneled into the right hand box culvert on Crane Street Bridge.

[25]There was notable evidence of fine deposition on the floodplain within this high stage secondary flow cell (see right hand AP in Figure 6.6), but this area was not surveyed pre-event and its volumetric contribution could not therefore be calculated from the DoD.

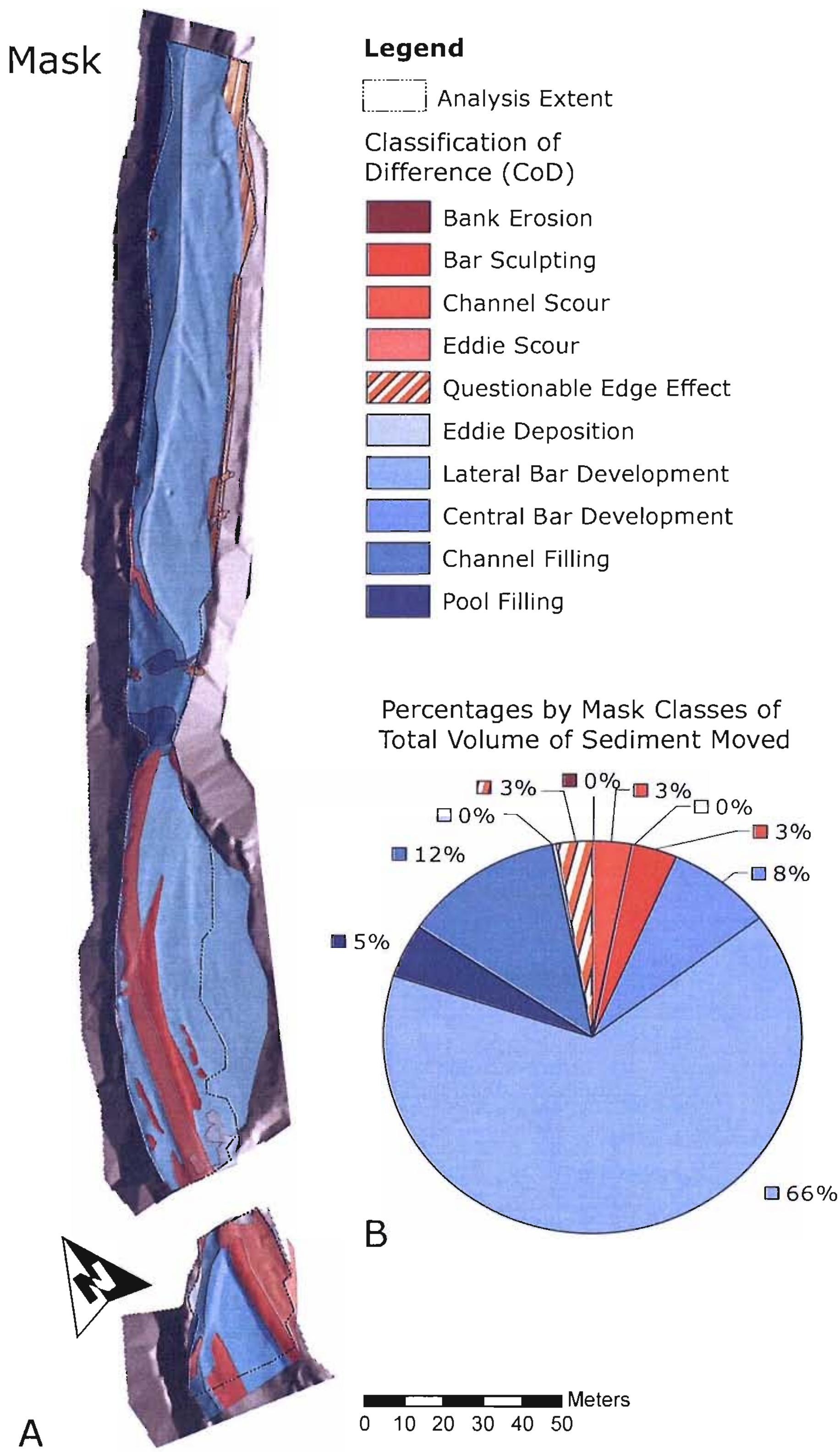


FIGURE 6.17: Segregation of DoD into geomorphological processes. A. The spatial segregation mask. B. A pie-chart showing the relative percentages of different fluvial processes in contributing to the total volume of sediment moved (as recorded by the DoD). Flow direction is up the page.

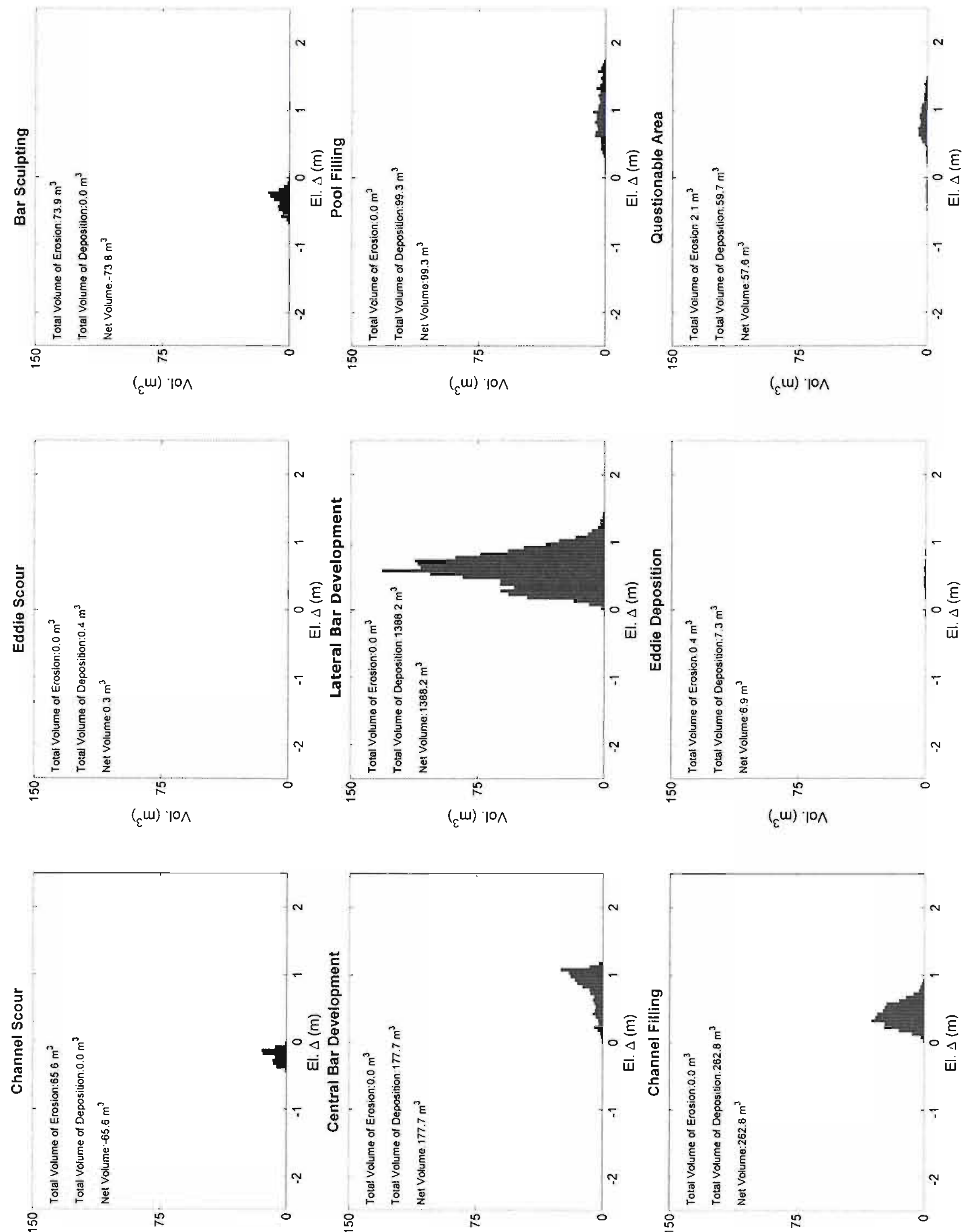


FIGURE 6.18: Elevation change distributions for nine of the ten process classes (bank erosion not shown as entirely negligible in this DoD). The scales between all nine subplots are equal to emphasise the relative magnitude of volumetric change between the classes.

In § 1.3.2 and § 5.1 it was postulated that specific signatures of geomorphological change should be recognisable from more detailed analyses and process inferences of morphological sediment budgets. These signatures were alluded to in § 6.6.1 and § 6.6.2, but can be more explicitly distinguished from ECDs based specifically on geomorphological interpretation masks like those in Figure 6.18. Unlike the ECDs in Figures 6.12 and 6.15, those based on geomorphological interpretation bare either entirely erosional or depositional signatures because they are based on an explicit segregation of the DoD. The only exceptions to this are minor classification errors (e.g. an accidental overlap of a polygon into the opposite class) and the questionable change category, which in principle can include any questionable changes (erosional or depositional).[26] The signatures from the individual classes will be discussed further below.

In wandering or braided rivers, Brasington *et al.* (2000) postulated that channel scour tends to be more concentrated spatially (i.e. in pools) then depositional patterns, which may tend to occur in broader flatter sheets. As such, the channel scour ECD might be expected to be spread out over a range of scour depths with relatively minor peak(s) correlated to the mean depth(s) of the thalweg. The New Year's Eve Flood DoD is probably not the best example for a channel scour ECD (Figure 6.18), as the erosional signal was so subdued relative to the overwhelming depositional signal. None-the-less, the ECD for channel scour does generally fit the conceptual model with subtle peaks at 15-20 cm and 35-40 cm, but channel scour did not exceed 55 cm.

Bar sculpting is the process of trimming bar edges adjacent to active channels and/or skimming across the tops of bars, with the latter generally playing a minor role volumetrically. As such, the ECD for bar sculpting might be expected to exhibit a peak that is related to the average bar height (relative to average bed elevation) and the spread of the distribution toward deeper scour depths will be related to degree of variation in bar height. In Figure 6.18, the ECD peak is between 20 and 25 cm and bar sculpting does not exceed 70 cm of scour. These observations scale reasonably well to the relative relief between the post flood bed and bar tops, where bar sculpting was inferred to have taken place. However, they are slightly downscaled (25% to 50%) to the overall relative relief between bar tops and beds throughout both the pre and post project reaches. This is an indication that bed elevations did not remain constant (in fact they experienced substantial aggradation), and is probably suggestive that where bar-sculpting did take place, it was sculpting of newly created or accentuated bars during the recession leg of the flood.

The central bar development shown in the ECD in Figures 6.18 and 6.19 is essentially the depositional fraction of the sub-reach upstream of Crane Street Bridge (Figure 6.6.1, described in § 6.6.1). However, in addition to the volumetric ECD shown in Figures 6.18 and 6.6.1, an areal ECD is shown in Figure 6.19A. Although both the areal and volumetric ECDs show their largest peaks at fill depths of 1.0 to 1.15 m, the portion of the lower magnitude fill-depth fraction of the ECDs is markedly different in each case. This is highlighted to point

[26]Note in this case due to the dominance of deposition the ECD is overwhelmingly depositional.

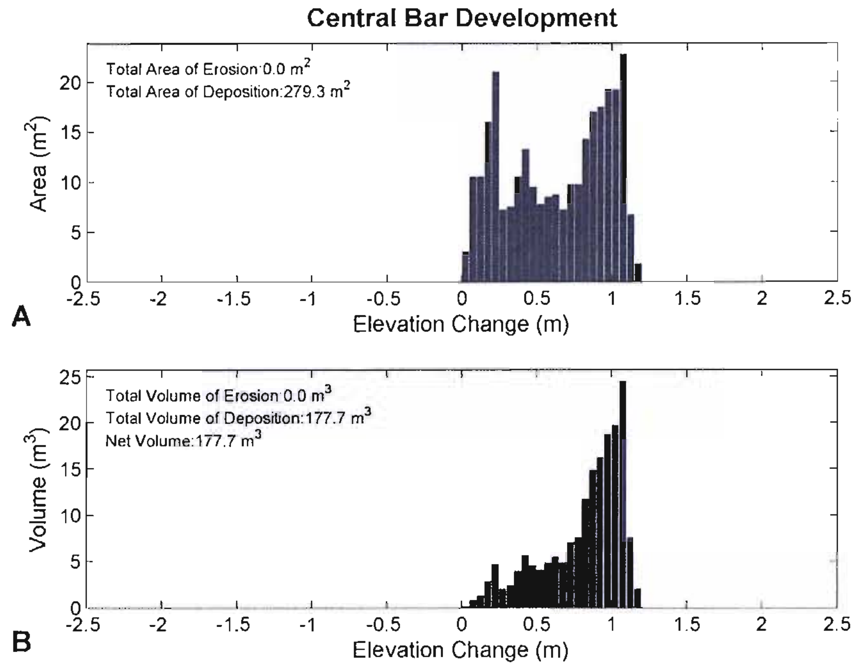


FIGURE 6.19: Example of contrast between areal and volumetric elevation change distributions for Central Bar Development.

out how assessing the relative proportions of geomorphological work done from areal and/or field observations may be misleading (Gaeuman *et al.* 2003, Brewer & Passmore 2002). In the areal ECD, there are prominent peaks at both 0.15 to 0.25 m fill depths and 1.0 to 1.15 m fill depths. However, in the volumetric ECD the lower magnitude fill depths contribute just a fraction of the total of the total volume precisely because they are smaller depth deposits. Thus, when interpreting volumetric ECDs, like the lateral bar development in Figure 6.18, one can identify less prominent peaks at lower fill depths. In terms of surface area, such low magnitude areas of elevation change are likely just as prominent as their higher fill depth counter-parts.

As a distinction was drawn between channel filling and pool filling[27], the channel filling ECD in Figure 6.18 peaks at about 30-35 cm fill depth and fill depths do not exceed 95 cm. By contrast, the pool filling ECD has a broadly distributed ECD that does not start until fill depths of 35 cm and extends up to 1.80 cm with a subtle peak at 0.95 to 1.00 cm. This ECD shape is a reflection of the distribution of pre-existing pool-depths that were erased with a rather flat, smooth-surfaced fill. Superimposing these two ECDs to create a complete channel fill ECD would simply extend the tail of the original channel fill.

6.6.4 Which is Best?

Each of the masks used in this section provide different types of insight into the specific nature of geomorphological changes captured by the DoDs. No single mask type is necessarily better

[27]Pool filling is obviously a subset of channel filling.

than another, but the geomorphological interpretation mask probably produces interpretations that accord most strongly with perceptions of practitioners (because it is nothing more than a formal articulation of those perceptions). It might be argued that the CoD is a more objective classification, but caution must be exercised in its application as the use of too many categories produces so many categories of change that the results become rather confusing. Simple masks like the sub-reach classification certainly have their utility and are an extremely helpful way of focusing the DoD analysis in logical regions as opposed to having to repeat the analysis manually for all such sub-regions. In principle, any mask for which there is some geomorphological basis might be useful for making geomorphological interpretation of the DoDs. In practice, which is most useful will depend on the specific questions the DoD is being used to address. Here, no single geomorphological question was focused on but instead the range of mask types was used to illustrate the types of questions they can help to address.

6.7 Hypothetical Scenario: Impact on Salmonid Embryos

In addition to using DoD masks to aid in geomorphological interpretation, they may have utility in considering the ecological ramifications of geomorphological change. Here, a hypothetical scenario using redd locations observed in 2004 is used to explore the possible ramifications of the New Year's Eve storm event on embryo survival at those locations.

6.7.1 Salmon Spawning in Sulphur Creek

According to Koehler (2003*a*) and Pearce *et al.* (2003), the habitat function of the study reach for Pacific salmonids is solely as a migration corridor for steelhead (*Oncorhynchus mykiss*) making their way upstream to spawning and rearing grounds above the Heath Canyon confluence. Historical observations and records on Sulphur Creek suggest that steelhead are the only salmonids which utitlise Sulphur Creek (Liedy *et al.* 2003). The overall character of the upper Sulphur Creek mainstem and tributaries is consistent with that of typical steelhead streams in the California Coast Range. However, in December of 2004, roughly 40 chinook salmon were observed spawning and 24 redd locations were recorded with a GPS in the formerly gravel mined reach (Wheaton 2005).[28] Six of the 24 redds were recorded within the study reach used for this chapter (Figure 6.20).

The observation of chinook spawning within the reach raise questions about whether this event represents an anomaly, or whether it signals a recovery of salmon in the watershed, or whether such spawning did occur in the past but was never officially recorded? Anecdotal reports from Harold Varozza (p. comm), suggest that some spawning did occasionally take place within this gravel-mined reach back in the 1950s and 1960s. This could have been easily overlooked by the non-systematic and infrequent fish surveys over the years reported by Liedy *et al.* (2003),

[28] Redd surveys performed by author and Napa County Resource Conservation District fisheries biologists Jonathan Koelher and Chad Edwards.

which would have focused more on typical steelhead habitat in upstream reaches. This semi-braided reach is unlikely to have attracted steelhead spawners, but Varozza's observations can not definitively confirm that the fish he observed historically were chinook[29] or the fish he saw were spawning versus just migrating upstream. Given the ephemeral flows of the reach[30], the survival of chinook fry that might have incubated in this reach is dependent on their ability to emerge from gravels and make their way downstream to safe suitable rearing grounds before the last of the spring flows recede and the annual summer drought ensues. Fall-run chinook migrate to their spawning grounds anytime between early October and late December with a peak of activity typically toward late November. In many years, there are not enough early-season storms to restore and maintain flows from the summer drought to this reach during the fall-run (e.g. 2005). By contrast, following some early-season storms in early November 2004 enough flow was produced to create viable spawning habitat conditions in Sulphur Creek during the spawning season. In 2004, Koehler (2005) recorded 62 chinook redds in a 5.8 km section of the Napa River (roughly 1.6 km downstream of Sulphur Creek confluence with Napa River). Koelher (p. comm) postulated that the chinook observed spawning on Sulphur Creek were opportunistic 'Jack and Jills'[31] who were unable to compete with the larger fish in the mainstem of the Napa River for a relatively small amount of acceptable spawning habitat.[32]

6.7.2 Methodology for Hypothetical Scenario

By contrast to 2004, 2005 was notably dry[33] throughout the potential fall run chinook spawning season. As such, there was no recorded or observed chinook spawning activity coincident with the study period for the New Year's Eve Storm. However, it is not difficult to envisage a scenario with a similar sequence of early-season storms to 2004, that was then followed by a large flood event like the New Year's Eve storm during the incubation period for the salmon embryos. It is precisely this hypothetical scenario that is addressed in this section. Using the observed redd locations from 2004 as a mask for the DoD[34] during the incubation period, it is possible to consider how embryo survival would have been impacted by the recorded storm event (Figure 6.20). This sort of analysis is only appropriate where topographic surveys exist before and after a change event (e.g. flood) that coincides with the incubation period for salmon embryos. It is good for inferring the impact of geomorphological changes that might produce scour beyond the burial depth of embryos, or deposition that increases the burial depth of eggs to the point that fry can not emerge and/or inter-gravel flow is no longer ade-

[29]To a casual observer, steelhead do appear similar to chinook.

[30]The reach dries up every summer, except for some of the deepest pools.

[31]'Jack and Jill' refers to 2-3 year old young adult salmon who have returned from the ocean 1-3 years earlier than normal and subsequently have shorter fork-lengths (i.e. smaller fish).

[32]SFBWQB (2002) found spawning habitat availability to be one of the limiting factors for salmon on the mainstem of the Napa River.

[33]Refer back to § 6.3.

[34]Note that there was no appreciable difference in the locations and distribution of channel morphology between December 2004 and December 2005. This means that assuming that what were attractive spawning locations in 2004 would be attractive locations in 2005 under similar flows is reasonable.

quate.[35] However, the morphological method takes no account of the caliber and composition of sediment nor mechanisms like infiltration of fine sediment into interstitial spaces. Thus, using redd surveys as a mask for DoDs derived from the incubation period will likely give a conservative estimate of the potential impact to incubating salmonids.

To infer the potential impact on embryos, the egg burial depths are needed. As this is difficult to measure without disrupting or killing the eggs, they were not measured in 2004. Here the typical range of egg burial depths from the literature are used to make inferences. Evenson (2001, Table 5, pp 44) reported egg burial depths for chinook salmon from the literature ranging from 5 to 53 cm with mean burial depths ranging from 19 to 34 cm. Thus if streambed scour in the vicinity of a redd exceeds the actual egg burial depth, loss of eggs (and highly probably egg mortality) will follow. Egg burial depths can also be used to infer roughly how much deposition might reduce the likelihood of fry being able to emerge from the gravel interstitial pore space. Additionally, if so much deposition occurs that the egg pocket is no longer in the low flow channel (e.g. turns from a channel into an exposed bar), this will greatly reduce the chances of survival as inter-gravel flow rates will likely decrease and fry will have a more difficult pathway to follow for emergence.

The redd locations were recorded as points centred over the tailspill (see Figure 3.3). To convert these point measurements to a mask for the DoD, rough polygons were drawn around the tailspill points oriented streamwise with the flow and of the approximate dimensions (1.5 to 2 m wide and 3 to 5 m long) of typical redds observed and reported in the literature (Merz *et al.* 2006, Chapman 1988, e.g.). These polygons are shown in Figure 6.20 overlaid on the pre-flood and post flood morphologies as well as the DoD. The polygons were then used as six[36] separate masks applied to the DoD as in previous sections.

6.7.3 Hypothetical Results and Interpretation

The results of the DoD mask analysis for each redd is shown in Figure 6.21. Overlaid on each ECD is a colour-coded band showing what impacts are inferred when the ECD intersects this band. For example, Redd 2 is buried by over a metre of deposition, which intersects the dark blue band (indicating high likelihood of impact; see figure caption). This increases the effective burial depth of the egg pocket and is highly likely to inhibit the ability of the fry to emerge successfully from the egg pocket through the gravels. In addition from a comparison between Figure 6.20 A and C, it is apparent that Redd 2 went from being a submerged riffle in close proximity to a pool to an exposed lateral bar well outside the low flow channel. Thus, for fry to emerge from the gravels at this redd, they would either have to navigate a substantial distance (>10 m) laterally through the interstitial pore-space or wait for high flows to submerge the lateral bar and emerge vertically (still a distance of 1.2 to 1.7 m vertically!). As the original burial depth of the egg pocket is still well below the post low-flow channel bed, stranding

[35] Refer back to the end of § 3.2.2 for a review of the vulnerabilities of incubating eggs to geomorphological changes.

[36] Although seven redds are shown, the seventh redd is outside the DoD analysis extent

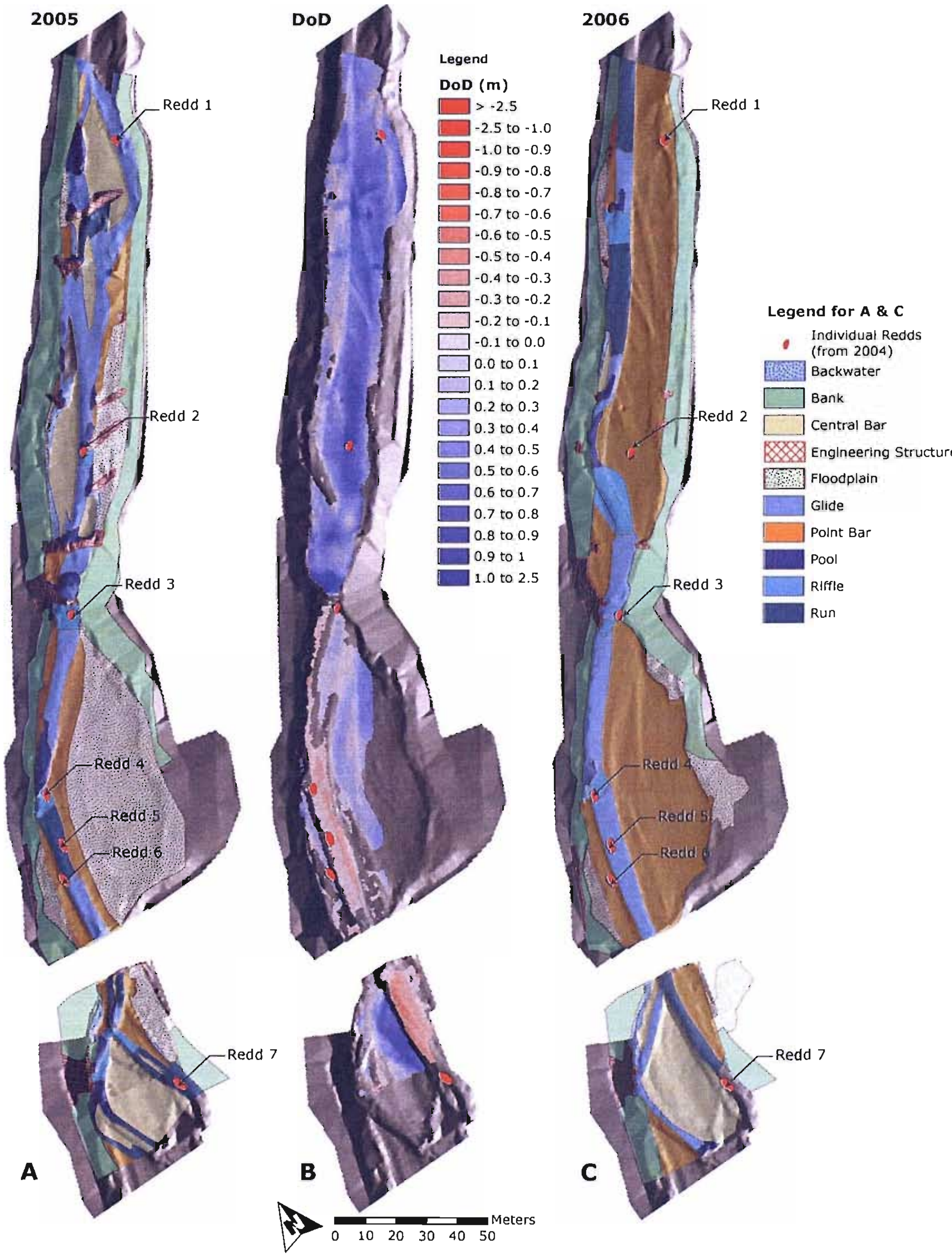


FIGURE 6.20: Locations of 2004 Fall-Run chinook redds in relationship to A) Pre-flood morphology; b) New Year Eve Storm DoD, c) Post-flood morphology.

Redd	DoD Change	Pre-Flood	Post-Flood	Impact
1	10 to 35 cm deposition	Submerged run	Exposed lateral bar	Likely burial inhibiting emergence and/or smothering of redd
2	90 to 120 cm deposition	Submerged riffle in close proximity to pool	Exposed lateral bar	Highly likely burial inhibiting emergence and/or smothering of redd
3	5 to 20 cm deposition	Submerged riffle in close proximity to pool	Submerged glide	Slight potential for burial inhibiting emergence and/or smothering of redd
4	5 to 20 cm scour	Submerged riffle in close proximity to pool	Submerged riffle in close proximity to pool	Slight potential for scour beyond burial depth resulting in egg loss and/or mortality
5	5 to 15 cm scour	Submerged run	Submerged glide	Slight potential for scour beyond burial depth resulting in egg loss and/or mortality
6	20 to 40 cm deposition	Submerged run	Exposed lateral bar on channel margin	Potential burial inhibiting emergence and/or smothering of redd

TABLE 6.3: *Hypothetical* (see text) impacts of New Years Eve Storm on incubating salmonid embryos (using redd locations from 2004 Fall-Run Chinook).

of the redds from inter-gravel water is unlikely, but inter-gravel flow rates may well decrease making it more difficult to maintain oxygenated water and flush metabolic wastes.

A similar approach is undertaken with each of the other five redds. To aid in concisely inter-comparing the hypothetical fates of the six redds, Table 6.3 tabulates the range of elevation changes experienced and the changes in morphology at each redd location. This information is then used to make the interpretations shown in the fifth column of Table 6.3. Consistent with the major depositional signature of this event[37], four of the six redds (1, 2, 3 and 6) were subjected to significant deposition. Ignoring the potential smothering of the redds by infiltration of fines into the gravels or caking by the fine fraction of this deposition might have on embryo survival, the impact of inhibiting emergence is present to varying degrees for each redd. Redd 3 eggs stands the best chance of survival, remaining in the channel. Redd 6 eggs, despite no longer being submerged at the surface, also have reasonable survival chances due to its proximity post flood to the channel margin and relatively low magnitude of deposition. However, redds 2 (described above) and 1 are unlikely to have many successfully emerging fry as they are so far away from the new low flow channel.

Redds 4 and 5 were each subjected to relatively low magnitudes (<20 cm) of channel scour,

[37] Refer back to § 6.6.

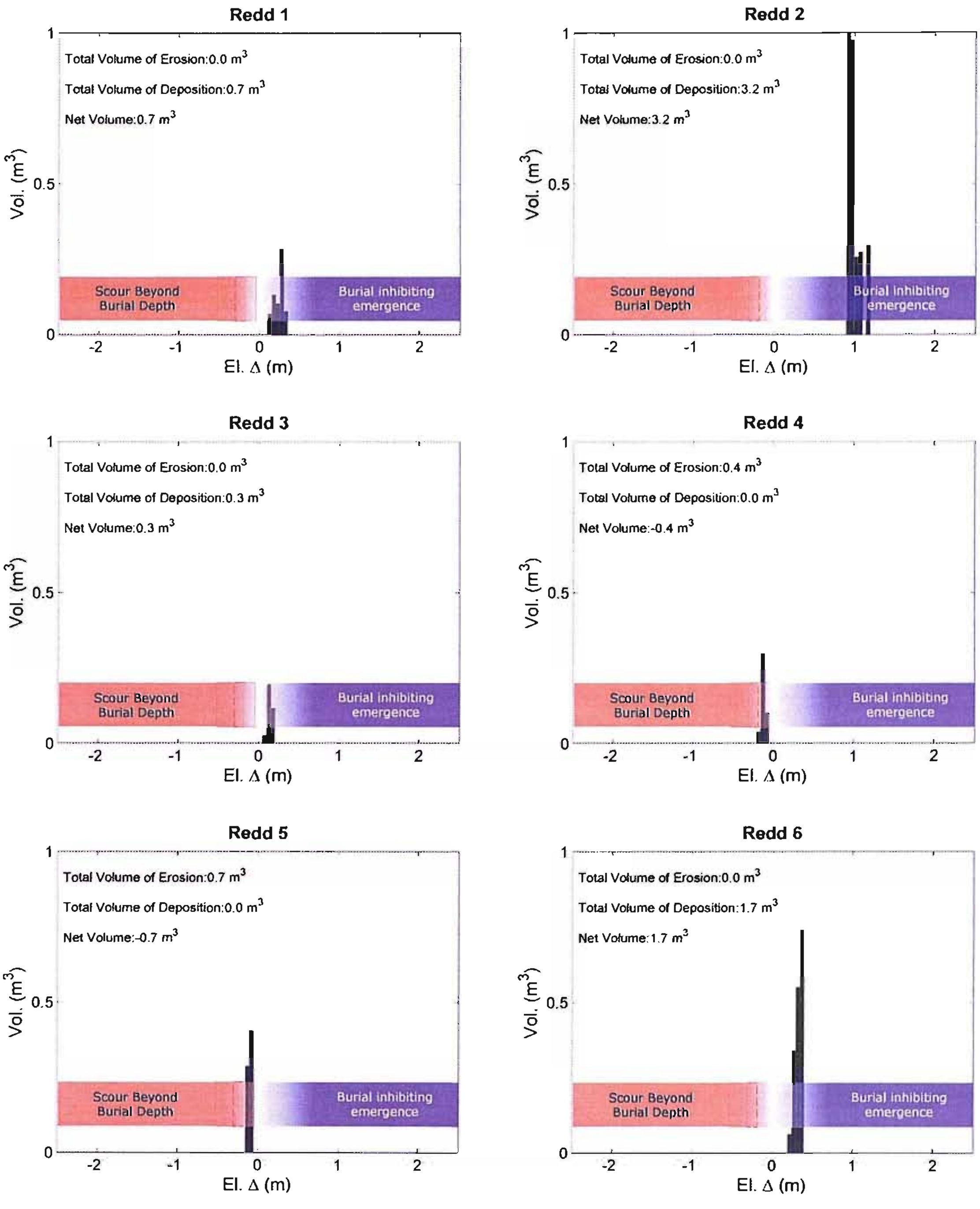


FIGURE 6.21: Volumetric elevation change distributions for each individual redd to assist in interpreting *hypothetical* (see text) ecological significance of DoD recorded geomorphological change. Solid red box indicates the range of possible egg burial depths (5 to 53 cm) and dashed redd box indicates the range of average egg burial depths (19 to 34 cm). The intensity of redd shading represents the likelihood (dark red = high likelihood) of scour resulting in egg loss and/or mortality. The intensity of blue shaded areas represents the likelihood (dark blue = high likelihood) of burial depths increasing due to deposition to the point that emergence from the gravels is highly unlikely (likelihoods based on literature-reported value ranges reported earlier in text).

that makes them somewhat vulnerable to egg loss and mortality. However, as the majority of erosion in these areas was below average egg burial depths, the risk of egg loss and mortality may be greater due to erosion threats from later floods during the incubation period. It is also worth noting that only net scour is recorded by a DoD[38], and this might hide sequences of erosion (in this case potentially below egg burial depths) and subsequent re-deposition. However, assuming such 'negatively biased' events did not occur[39], if the scour that occurred did not exceed egg burial depth it may actually increase the likelihood of survival for the following reasons:

- Decreased distance of travel through gravel interstices for emerging fry
- Increased hyporheic exchange from scour and/or winnowing of fines (increasing oxygenation of water, delivery of nutrients to embryos and flushing of metabolic wastes) resulting in greater growth rates, earlier emergence and better embryo health

Thus, the impact of this storm on the hypothetical embryos from the six redds is quite variable locally, but probably results in an overall increase in egg mortality and embryo survival. What makes the redds as masks useful, is that it provides a mechanism to assess the local impacts at each redd and make a hopefully more meaningful assessment of the overall impact of the storm.

[38]This is the concept of *negatively biased budgets* through local *compensation* of scour and fill (Lindsay & Ashmore 2002, p. 28), and was reviewed briefly in § 3.2.2.

[39]A more reasonable assumption for single-event DoDs then for DoDs reflecting multiple events.

6.8 Sulphur Creek Conclusions

Through application of three different types of masks, a clearer picture of the geomorphological response of Sulphur Creek to the New Year's Eve Flood was acquired. The masks helped explain the composition and nature of the 1995 m^3 of fill and 142 m^3 of cut calculated from the gross DoD of the reach. Specifically, distinctive ECD signatures were exhibited when dividing the reach into subreaches, when using a geomorphological classification of difference to identify categories of change, and when using expert-based geomorphological judgment to divide the reach by the mechanisms of change. Some of the most obvious and pronounced changes, such as the extension of the central bar upstream of Crane Street Bridge and the filling of the pools downstream of GC3, actually only accounted for 8% and 5% respectively of the total volumetric change. These visually distinctive changes paled in significance to the widespread lateral bar development at 66%, which was the primary sink for this large slug of sediment which reset the channel and dramatically simplified the morphology. This relatively simple example from a single event in a small reach, provided an illustration of how geomorphological segregation of the DoD can extend the robustness of qualitative interpetations and test the intial perceptions of the change.

While no salmonid spawning activity took place at the study site resulting in incubating salmon embryos during the New Years Eve Storm, it is possible to consider the hypothetical impact such an event would have by using redd surveys from the previous year. The implications for each redd were explained by using the redd itself as a mask for the DoD. Each redd had locally distinctive mechanisms of change and subsequent impacts, but the overall impact of this event dominated by a slug of deposition would likely have been to decrease the overall chances of survival for this cohort. As this hypothetical result is based on a relatively rare large-magnitude event, it is probably more useful for illustrating the methodological advantages and potentials of using redd surveys as masks for DoDs then for drawing generic conclusions about the impacts of storm events on egg survival.

Chapter 7

Mokelumne River - Long-Term Monitoring of Spawning Habitat Rehabilitation

7.1 Introduction

Monitoring geomorphological changes in response to river restoration interventions through the use of repeat topographic surveying is becoming more common in *long-term*[1] monitoring (Downs & Kondolf 2002, Golet *et al.* 2003). Typically a pre-project survey is performed, with a post-project (or as-built) survey immediately following the construction or intervention. Beyond that, repeat monitoring surveys are often performed on a defined-interval (typically annually initially) or an event-basis. How uncertainties in these surveys are managed to decipher what changes can be taken as meaningful and how one interprets restoration works is a question that requires careful consideration.

Arguably, two factors are and will continue to drive an increase in repeat topographic surveying as part of restoration monitoring. First, improvements in ground-based and aerial surveying technology have made the rapid-acquisition of high density topographic survey data easier to acquire and more affordable.[2] Secondly, the restoration community has been under increasing pressure to be accountable for their often expensive restoration interventions.[3] Restoration monitoring is one way to gather data that can be used to assess whether restoration projects are meeting their objectives and/or whether they are causing unintended consequences or benefits (Downs & Kondolf 2002). However, how does one account for uncertainties in the monitoring process? Monitoring is a key part of any adaptive management program, whereby restoration of complex systems is accepted as uncertain and treated as an iterative process of

[1] Note that *long-term* in a restoration context usually means 3 to 5 years or up to 10 years.

[2] These surveying developments were reviewed in § 3.3.1.1.

[3] See Darby & Sear (2008) and Sear *et al.* (2008) for justification.

learning-by-doing (Clark 2002). In this context, the monitoring helps complete the feedback loop, but it needs to articulate the uncertainties discovered in the process.

Within the restoration literature, there is nearly unanimous consent for monitoring and subsequent reporting and sharing of 'lesson's learnt' with fellow restoration practitioners and scientists (Bernhardt *et al.* 2005, Wheaton *et al.* 2006, Wheaton *et al.* 2008). Although monitoring has been advocated in the restoration literature extensively for some time, and restoration monitoring is increasingly taking place (Wheaton *et al.* 2006), relative to the number of projects there are few examples of published monitoring efforts articulating what the monitoring has revealed (Bernhardt *et al.* 2005, Bash & Ryan 2002). There are even fewer examples of how that information is then used to feedback adaptively to the original and/or future restoration efforts (Sabine *et al.* 2004, Walters 1997). Practitioners have already successfully convinced clients and funding agencies of the importance of restoration efforts (Bernhardt *et al.* 2005). Assuming the subsequent trend of convincing clients and funders of the merits of monitoring also increases, it is argued that practitioners will need some more sophisticated tools for making sensible interpretations from the analysis of monitoring data. In the case of repeat topographic surveying, the surveying technology has developed rather rapidly; but, analysis and interpretation tools addressing what the data can be used to say naturally lags behind.

Even with topographic surveying becoming more affordable, restoration monitoring is generally an expensive endeavour with monitoring costs potentially exceeding the actual costs of the restoration intervention (Downs & Kondolf 2002).[4] Nevertheless, there is growing recognition amongst clients and managers paying for restoration (as opposed to just amongst practitioners and scientists) of the importance of monitoring and the associated 'cost of knowing'. It is speculated that, as the restoration community becomes more accustomed to undertaking monitoring, topographic surveying will play a larger role. The challenge of being able to make sensible interpretations of repeat topographic surveys that robustly account for uncertainties is therefore very topical.

The purpose of this chapter is to demonstrate how the methods developed in Chapter 5 for making geomorphological interpretations from morphological sediment budgets can be used in a PHR context. This is the second of the three stories of geomorphological change. Like Chapter 6, the DoD Uncertainty Analysis techniques developed in Chapter 4 are used to derive thresholded DoDs from the morphological sediment budgeting that can reliably distinguish real changes from noise. Again, this is merely the starting point and the focus is on using various masking techniques proposed in Chapter 5 to make meaningful geomorphological interpretations of the changes captured in the DoD. However, unlike Chapter 6 where the narrative was organised around the different types of masks; here, the narrative is geared to specific questions about PHR. Namely, the questions are divided into those from four separate 'as-built' surveys and those from two periods of monitoring subsequent adjustments and changes to salmonid habitat restoration (SHR)[5] projects. These four SHR projects all come from the

[4]Monitoring costs are thought to typically be around 30% to 50% of total project value (p. comm River Restoraton Centre).

[5]SHR is a sub-class of PHR (see acronym list at front).

Mokelumne River in Northern California and represent an example of typical monitoring associated with reach-scale restoration consisting of pre-project, as-built and repeated post project topographic surveys on an annual basis. The 'as-built' questions addressed are:

- What is the total volume of gravel that was placed? (§ 7.4.1)
- How much gravel was used to produce what types of morphological units or habitat? (§ 7.4.2)
- How much gravel was used to produce what quality of habitat? (§ 7.4.3)

The monitoring questions addressed are:

- What are the geomorphological interpretations of the DoD predicted changes that took place one wet season after construction? (§ 7.5.1)
- What impact did the changes that took place have on habitat quality? (§ 7.5.2)
- What changes took place where salmon spawned? (§ 7.5.3)

First the study site and SHR context (§ 7.2) is described. Then the results of the DoD uncertainty analysis applied to six analysis periods on the Mokelumne are briefly presented (§ 7.3). Then the remainder of the chapter is focused around the specific questions defined above.

7.2 Study Site and SHR Context

The study site on the Mokelumne River is a heavily regulated and modified reach located less than 200 m downstream of a major dam, which is described briefly in § 3.5. A full study site description can be found in Appendix G. Starting in the mid 1990's, East Bay Municipal Utility District began constructing one spawning habitat rehabilitation (SHR)[6] project each year for chinook salmon. The projects each consisted of placing between 600 and 3000 m^3 of clean, triple-washed spawning gravels in the channel with a rubber-tired front loader to create spawning habitat (Figure 1.1). Up until 2000, these projects were constructed on an ad-hoc basis at the direction of a fisheries biologist in the field; from 2001 onwards the projects were constructed from detailed designs developed using the SHIRA (Spawning Habitat Integrated Rehabilitation Approach) framework developed by Wheaton (2003) and Wheaton *et al.* (2004*c*).[7]

The focus of this case study is on the geomorphological monitoring of a 510 m long reach of the Mokelumne located approximately 200 m downstream of Camanche Dam (Figure 7.1). The

[6]Note that SHR is just a subset of the physical habitat restoration (PHR) discussed in Chapter 1, § 1.2.1.
[7]For further details of SHIRA, visit `http://shira.lawr.ucdavis.edu/`.

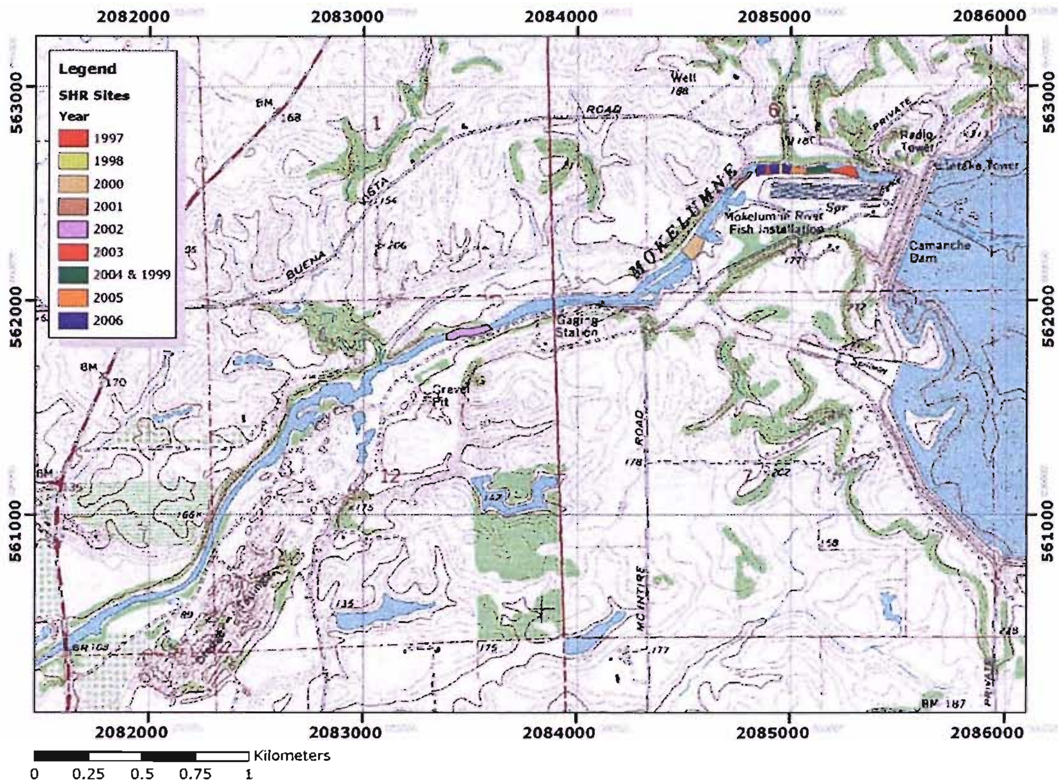


FIGURE 7.1: Spawning Habitat Rehabilitation Site Map for Mokelumne River. The study reach for this chapter includes the 2003, 2004, 2005 and 2006 SHR sites. Flow is from right to left. See Figure G.1 for Location Map.

reach begins upstream at a fish guidance fence, which blocks fish migration upstream and is intended to divert migrating salmon into a fish hatchery.[8] The reach extends virtually due west downstream, until it is diverted left by a prominent Mehrten formation rock outcrop, roughly 150 m downstream of the Murphy Creek confluence. SHR began within this reach in 1997 and 1998, with ad-hoc construction of two small riffles downstream of Murphy Creek. In 1999, a more substantial ad hoc project was constructed between 110 m and 240 m downstream of the fish guidance fence. Detailed pre and post project monitoring and assessment were performed at this site and are reported in Pasternack *et al.* (2004) and Merz & Setka (2004), with other elements reported in Merz *et al.* (2004) and Merz *et al.* (2006). Further downstream, other SHR efforts were also undertaken using SHIRA. By 2003, the focus returned to the 510 m reach described here. As of 2007, five consecutive years of staged SHR projects have been constructed in the reach, all relying on the Elkins *et al.* (2007) design concept of slope creation (Figure 7.2).

The essence of the slope creation design concept is as follows. If plan form is held fixed within pool-riffle morphology reaches, there is a finite amount of elevation head available for redistribution by changing local bed slopes along a longitudinal profile and altering habitat conditions. Wheaton *et al.* (2004*c*, Figure 4) showed that changing the distribution of slopes

[8]See Table G.2 for hatchery take numbers.

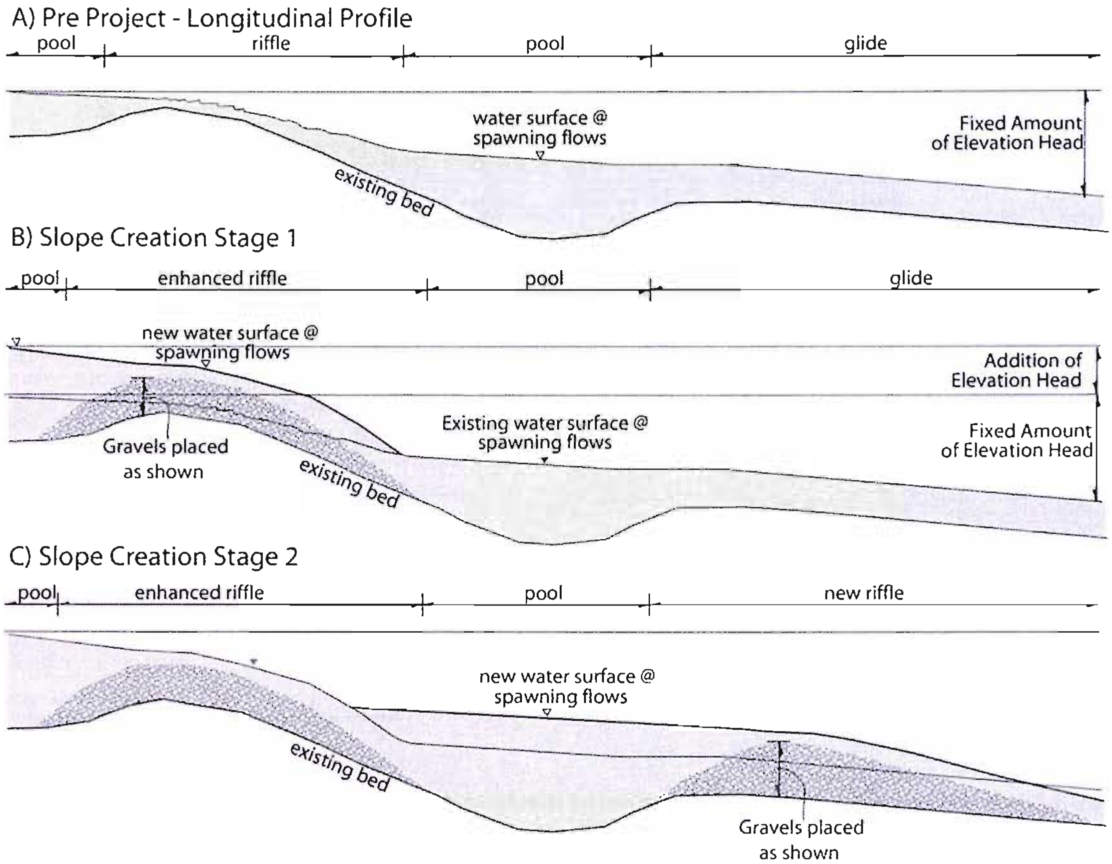


FIGURE 7.2: The slope creation design concept used on the Mokelumne River SHR projects. A fixed amount of elevation head is available for redistribution within the reach, unless the uppermost riffle crest elevation is raised. When this is done, this creates a new amount of elevation head, which can be subsequently redistributed throughout the reach. Figure reproduced from Elkins *et al.* (2007).

can be used to improve physical habitat quality locally, but in reaches where slope is limiting this can be at the expense of habitat quality in the next upstream unit(s) as a backwater effect from placed gravel will lessen the available elevation head for upstream use. In the context of a regulated river, the riffle crest elevation closest to the dam determines the available elevation head for downstream reaches. If this elevation crest can be raised without impacting dam operations, this elevation head can be redistributed in the downstream reaches to improve physical habitat conditions (Elkins *et al.* 2007). Figure 7.2 illustrates this concept for two years, but such a strategy can be implemented over many years.

On the Mokelumne, Elkins *et al.* (2007) envisaged raising the upstream riffle crest by roughly 1 metre. However, the total volume of gravel required to create such a fill was economically and logistically unfeasible within a single year. As such, the uppermost riffle crest was raised by 0.5 metre originally, and then that elevation head was redistributed amongst the entire study reach over the course of four years in 2004, 2005 and 2006. In 2007 (not included in this thesis), EBMUD raised the riffle crest and the entire study reach again by another 0.5 metres. Thus, in five years of SHR, the original slope creation design afforded by raising the

Analysis Period	Older Survey	Newer Survey	Description
TS1	2003 Pre Project	2003 Post Project	As-Built
TS2	2003 Post Project	2004 Pre Project	PPA Adjustment
TS3	2004 Pre Project	2004 Post Project	As-Built
TS4*	2004 Post Project	2004 Post Project	PPA Adjustment
TS5	2004 Post Project	2005 Post Project	As-Built
TS6	2005 Post Project	2006 Pre Project	PPA Adjustment
TS7	2006 Pre Project	2006 Post Project	As-Built

TABLE 7.1: Definition of Mokelumne DoD Analysis Periods. *NOTE: TS4 does not actually exist as the 2005 Pre Project Survey could not be performed prior to construction due to high flows. PPA refers to post project appraisal, in this case appraising the adjustment over roughly one year of the PHR placed gravel.

uppermost riffle crest by 1 metre was realised, bringing the bed up to the point where some degree of floodplain connectivity was restored (p. comm Greg Pasternack).[9]

7.2.1 The Analysis Periods

There are seven potential (six actual) analysis periods[10] (Table 7.1). The study period extended from the Summer of 2003 to the Summer of 2006 and captures the construction of four phases of the SHR project within the study reach. These are referred to as 'As-Built' surveys and they represent geomorphological changes due to the artificial placement of gravel according to SHIRA-guided SHR designs (TS1, TS3, TS5 and TS7). Questions related to the interpretation of these four as-built surveys are addressed in § 7.4.

In addition there are two survey intervals that capture the natural adjustment of the SHR projects due to fluvial processes alone (TS2 and TS6). These are referred to as post project appraisals (PPA)[11] or monitoring surveys and are addressed in § 7.5. The hydrological drivers of this style of change are represented by the hydrograph in Figure 7.3. Two hydrographs are shown in the figure[12] to highlight the highly regulated and artificial nature of the flow regime at the site. TS2, was the tail end of a drought and the study site experienced no competent flows. By contrast, TS4 was a decent water year enabling a controlled pulse flow experiment to be conducted (Merz *et al.* 2006); while TS6 was the biggest flow year in over a decade on the Mokelumne, with the maximum possible dam release of 141.6 cumecs being realised.

Thus, two distinct styles of change on the Mokelumne River are captured in the dataset presented here. One is primarily due to the injection of gravel during the construction process

[9]Note that prior to SHR gravel augmentation starting in 1996, the there was no input of gravel to the reach since the construction of Camanche Dam. On top of this 40 year gravel deficit, the reach was extensively gravel mined prior to that.

[10]Analysis periods are labeled TS# for time step.

[11]In keeping with Downs & Kondolf (2002).

[12]The actual Camanche Dam release in black (experienced by the site), and the Mokelumne Hill gauge upstream of Pardee reservoir.

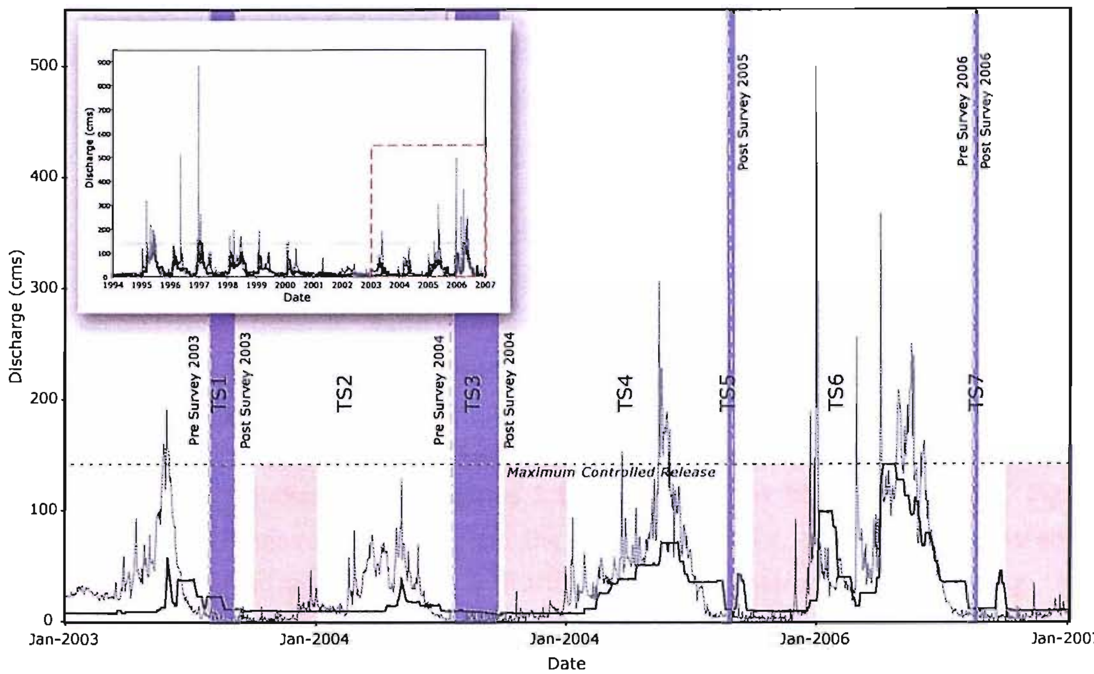


FIGURE 7.3: Hydrographs for Mokelumne River reflecting the four year study period and the preceding decade (inset box) for context. The thick black line represents the flows experienced at the study site with the Camanche Dam release. The gray line represents the hydrograph at the Mokelumne Hill gauge near Highway 49 and upstream of both Camanche and Pardee reservoirs (reasonable proxy for natural flow regime).The seven analysis intervals are labeled as TS1 through TS7 (time step) and are defined by the dates of the topographic surveys. The blue shaded time steps indicate the period when the PHR projects were constructed.The pink shaded areas represent the spawning seasons.

of SHR projects, and the other is the subsequent adjustment of those gravels post-placement due to various processes (Merz *et al.* 2006).

7.3 Application of Morphological Method and DoD Uncertainty Analysis

Seven DEMs were used to apply the morphological method and DoD Uncertainty Analysis (Figure 7.4). These DEMs were all derived at resolutions of 25 cm from the point data used for a 2D hydrodynamic model mesh construction under SHIRA.[13] A pathway 4 DoD analysis was conducted using the DoD Uncertainty software developed in Chapter 4. Figure 7.5 shows all seven DoDs for direct inter-comparison. Their respective ECDs are shown in the right hand column of Figure 7.6 (the left-hand column shows a pathway 3 DoD analysis for comparison). As the spatial extent of the surveys varied from year to year, different DoD analysis extents

[13]The original DEMs and the derived DoDs can be found in Appendix G.4 for all six analysis periods (TS1-TS7). Details on the topographic surveys and methods used to derive the DEMs and DoDs can be found there as well.

were used. For TS1, TS2 and TS3, an analysis extent covering the 2003 and 2004 SHR projects was used. For TS5 and TS6, an analysis extent covering the 2005 SHR project was used. For TS7, an analysis extent covering the 2006 SHR project was used.

7.4 Interpreting As-Built Surveys

In this section three types of masks are used to address three simple questions regarding the effectiveness of construction that arise in the SHR process. In the simplest sense, SHR here is about placing gravel in a river to improve spawning habitat. This is fundamentally a geomorphological change brought about by an anthropogenic process (i.e. a front end loader dumping gravel in the channel; see Figures 1.1 and 7.18). As Merz *et al.* (2006, Figure 1) showed for four other earlier projects on the Mokelumne River, there are many potential sinks for the purchased gravels, which are artifacts of the construction process (e.g. loss in staging). Thus, not all of the purchased gravel is placed in the channel in exactly the configuration suggested by the best intentioned design. As stated in the introduction, the questions requiring further consideration for each of the four SHR projects (TS1, TS3, TS5 and TS7) are:

1. What is the total volume of gravel that was placed? (§ 7.4.1)
2. How much gravel was used to produce what types of morphological units or habitat? (§ 7.4.2)
3. How much gravel was used to produce what quality of habitat? (§ 7.4.3)

Table 7.2 highlights the availability of masks for each timestep. An expert based geomorphological interpretation mask[14], as suggested in § 5.2.1.3, to address the first question; a morphological unit mask is used, as suggested in § 5.2.1.1, is used to address the second question; and a mask based on an estimate of spawning habitat quality derived from a 2D CFD simulation, as suggested in § 5.2.1.4, is used to address the third question. These are presented in order in the next three sub-sections. In the first sub-section, the backgrounds and design goals for each project are also elaborated.

7.4.1 What is the total volume of gravel that was placed?

This question arises from the fact that discrepancies typically exist between the design volume, DoD predicted volumes and actual placed volume of gravel in PHR projects (Merz *et al.* 2006, Sawyer *et al.* Submitted). A related question is whether or not all the DoD predicted changes are due to PHR construction? The answer to this question depends on the extent of the survey and the analysis extent of the DoD. If the survey and analysis extent boundaries were

[14] Similar to that used in § 6.6.3 for Sulphur Creek.

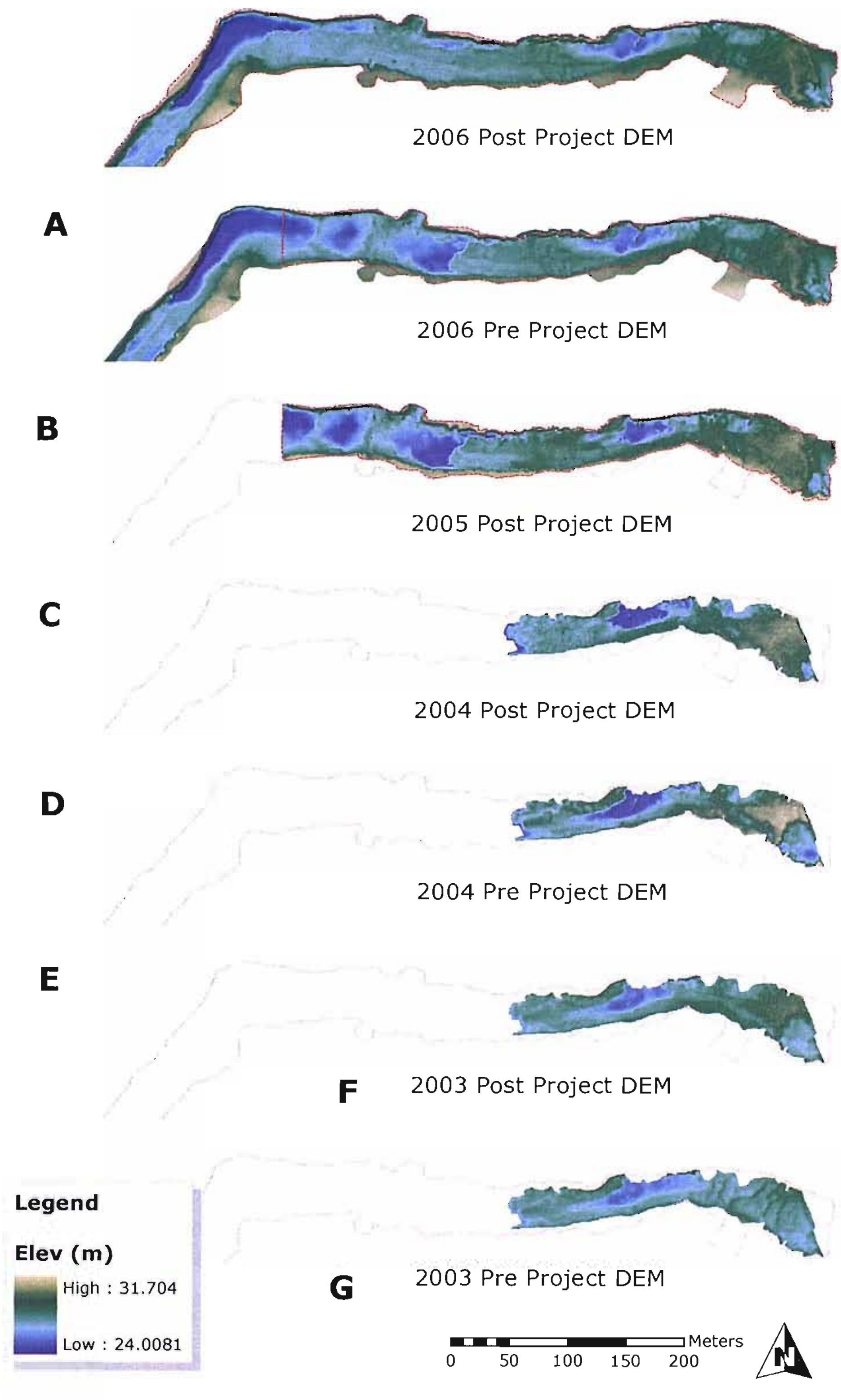


FIGURE 7.4: DEMs used in DoD Analysis. A) 2006 Post Project; B) 2006 Pre Project; C) 2005 Post Project; D) 2004 Post Project; E) 2004 Pre Project; F) 2003 Post Project; and G) 2003 Pre Project. Flow is from right to left.

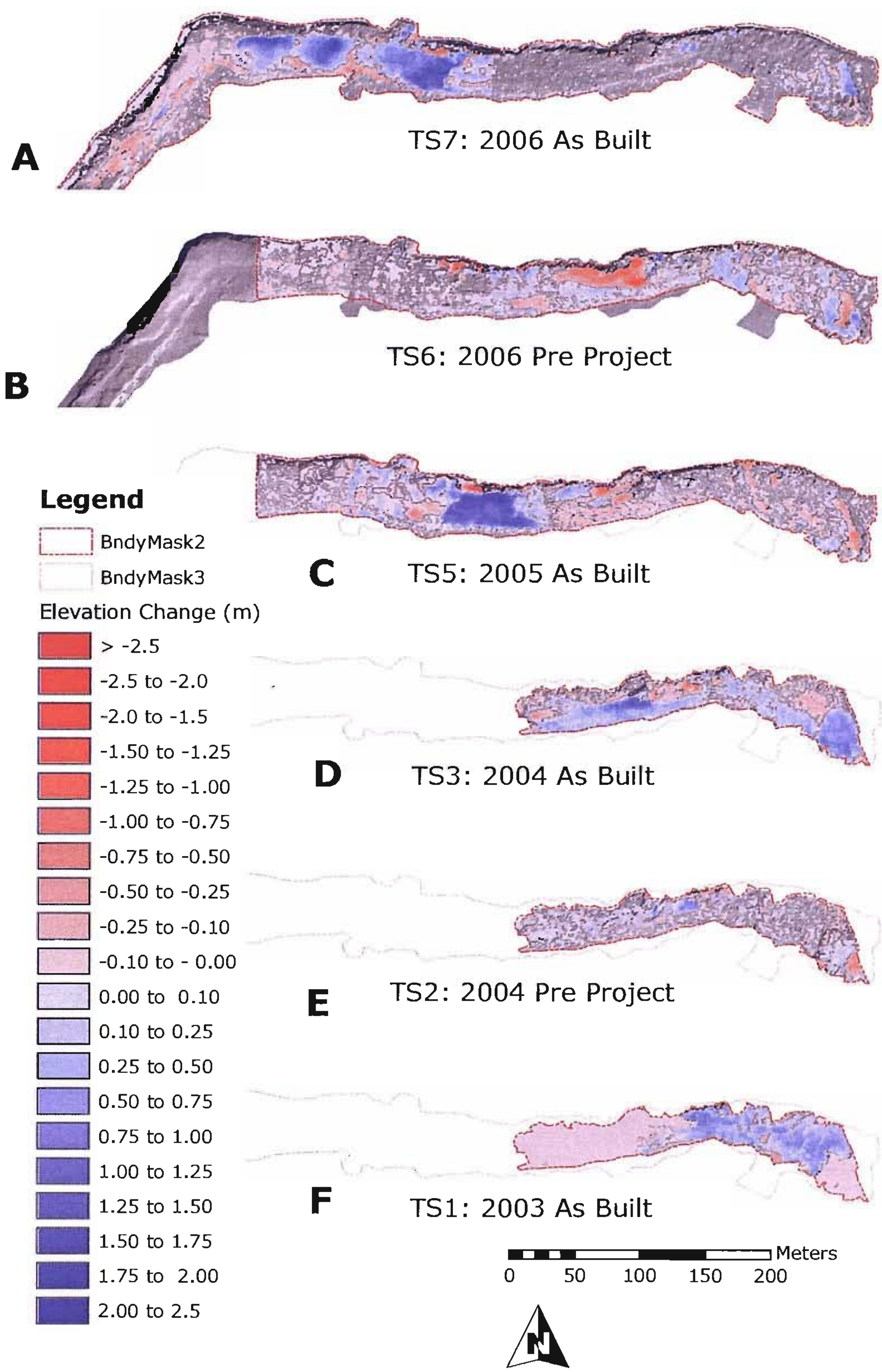


FIGURE 7.5: Thresholded DoDs for the six analysis periods. DoDs were thresholded using a Pathway 4 analysis and 95% confidence interval (see Chapter 4 for explanation). The large contiguous blue areas in TS1, TS3, TS5 and TS7 are the placed gravel fills from the SHR projects. Hillshades derived from the more recent DEM in each time step are shown in the background for context. Flow is from right to left.

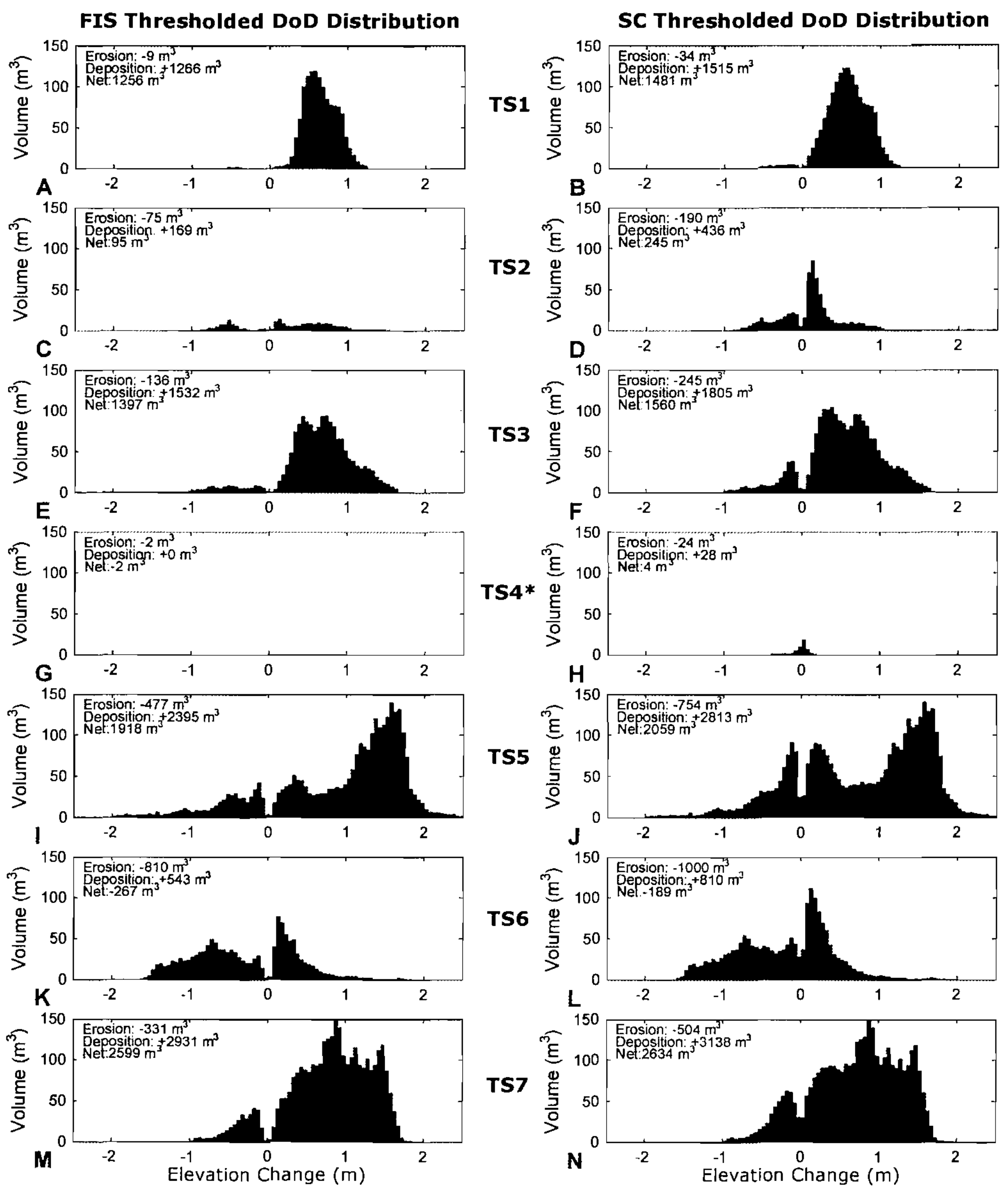


FIGURE 7.6: Elevation change distributions for Pathway 3 (left hand side) and Pathway 4 (right hand side) thresholded DoDs for the seven analysis periods. DoDs were thresholded using a Pathway 4 analysis and 95% confidence interval (see Chapter 4 for explanation). The progression is from most recent (top) to oldest (bottom) down the page: A and B correspond to TS7; C and D to TS6, E and F to TS5, G and H to TS4, I and J to TS3, K and L to TS2; and finally M and N to TS1. *TS4 does not technically exist (see Appendix G.4.4 for explanation).

		Masks Used:		
Time Step	Description	GI	MU	GHSI
TS1	2003 As-Built	✓	✓	NA
TS3	2004 As-Built	✓	✓	✓
TS5	2005 As-Built	✓	✓	✓
TS7	2006 As-Built	✓	✓	✓

TABLE 7.2: Use of four mask types in analysing DoDs from each time step. Where a ✓is shown, the mask type derived from that TS was used. Where NA is shown, data to produce the mask type was not available.

specifically clipped to the boundaries of the project, then if one was confident that all the DoD predicted changes were real, the DoD would be a reliable estimate of the total volume of gravel placed. However, an unthresholded DoD is not necessarily a reliable estimate of the total volume of gravel placed; hence, the need for a DoD uncertainty analysis (i.e. § 7.3). If by contrast the survey and analysis extents extended beyond the SHR gravel placement boundaries, then the DoD has the potential of reflecting changes (real or erroneous) that took place outside the placement area. It may seem reasonable to assume, under conditions of low flows and only a limited time window between the pre-project survey and post-project survey (e.g. TS1, TS3 and TS7), that the only changes that could take place are those from the placement of gravel. However, there are a number of plausible explanations of other changes (e.g. SHR induced erosion, fluvial deposition of project gravels placed in project area but transported hydraulically downstream of project boundaries).

In this section, the best estimate of the total volume of gravel placed during SHR is calculated by accounting for *unreliability uncertainties* in the DoD (i.e. thresholding DoD under pathway 4) and using a mask defined by the actual project placement boundaries in the field to eliminate the possibility of changes outside the placement boundaries being erroneously included. However, to make sure that the other DoD calculated changes should not be included in the total volume of gravel placed, an informed geomorphological interpretation of these changes is necessary. As in § 6.6.3, an expert geomorphological interpretation based on a mix of field evidence, survey notes, and the DEMs and derived surface are used to interpret the DoD. The geomorphological categories in the classification used on the Mokelumne were tailored to the observed changes and included:

- *SHR Placed Gravel*: Areas where gravel was placed with a front-end loader as part of a SHR project (the key category of interest for answering this section's question)
- *Fluvial Deposition*: Areas where natural fluvial deposition occurred.
- *SHR Induced Erosion*: Areas that experienced erosion during construction as a result of altered hydraulics and morphology from SHR construction (not by design or by grading)
- *SHR Grading (cut)*: Areas that were specifically graded with the front end loader as part of SHR construction to achieve design grades.

- *Changes to SHR Placed Gravel*: Changes to areas where gravel was previously placed as part of SHR.
- *Fluvial Erosion*: Areas that experienced natural fluvial erosion.
- *Questionable Change*: Areas where no field evidence for change was present and/or where suspect interpolation errors exist.
- *Placed Boulder*: The footprint of placed boulders (erosion indicates that boulders are sinking, deposition indicates they are either buried or raising).
- *Not Resurveyed*: Areas where both DEMs in a DoD were derived from the same survey data.
- *SHR Placed Pea Gravel*: Areas where pea gravel (as opposed to medium to coarse gravels) were placed as part of the 2005 SHR project

Next the four SHR projects will be worked through in order and a summary presented at the end of this sub-section.

7.4.1.1 TS1: 2003 As Built

The 2003 project was designed by Elkins *et al.* (2007) as part of the four year 'slope creation' design. This project consisted of placing a design volume of 2020 m^3 of gravel at the upstream-most SHR site in the c. 510 m long study reach (Table 7.3). The boundaries of the SHR Placed Gravel extent are delineated with a black polygon in Figure 7.7 (light blue area in A). Applying this mask revealed that only 1500 m^3 of the 2020.4 m^3 design volume was actually placed in the channel (Figure 7.8).[15] Although the SHR Placed Gravel mask accounts for only 43% of the surface area in Figure 7.7A, it accounts for over 99% of the volume of deposition and 96.8% of the total volumetric changes. A very minor extent of erosion (4.9 m^3) was induced by the construction process and minor amount of grading (16.6 m^3) and/or compaction from the front-end loader tracks was recorded.

In Figure 7.7A, roughly 49.7% of the analysis area was not resurveyed following construction (yellow shaded area in Figure 7.7A), but the DoD suggests a very low magnitude of erosion across this entire area. At 6.6 m^3 over such a large area, this volume is essentially negligble. Upon closer inspection of the raw point data used for each DEM, the difference is due to a minor rounding error with different numbers of significant figures (10^{-4} versus 10^{-6} m) being saved in each of the raw point files. In practise, such a rounding error[16] could be easily avoided or corrected by reformatting the raw input point data. However, it is left here to highlight the utility of the masking approach for easily filtering out erroneous data without

[15] See Merz *et al.* (2006, Figure 1) for a discussion of sinks and sources for gravel purchased for SHR projects. It is quite typical for the final placed volume to be significantly less than the design volume.

[16] Refer to § 2.2.1 for difference between uncertainty and an error. This is an error because the true *unchanged* value is actually known.

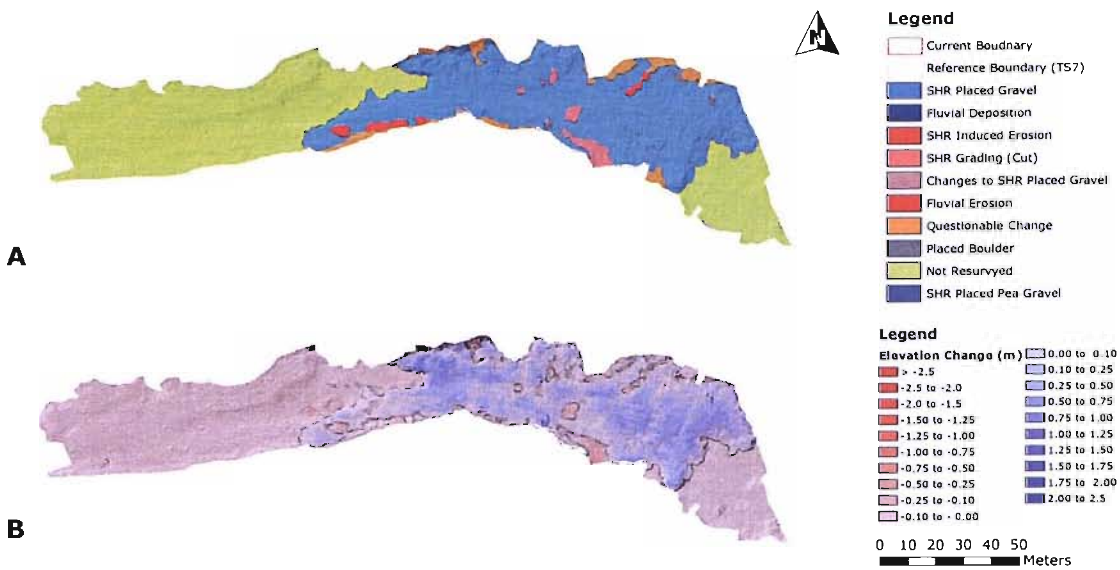


FIGURE 7.7: Geomorphological interpretation mask and DoD associated with the As-Built 2003 Project (TS1). A) Geomorphological Interpretation Mask; B) Pathway 4 DoD. Hillshade from the 2003 Post Project DEM shown in background for context. Flow is from right to left.

having to redo the entire analysis. Intially, such errors might not be obvious, but the DEM uncertainty analysis and simple inspection of the plausibility of the results can highlight such problems. Reassuringly, Figure 7.8 demonstrates that in this case the error represents a neglible proportion (<0.5%) of the total budget from the elevation change distribution in Figure 7.6B.

The geomorphological interpretation of TS1 is useful, but not particularly interesting from a geomorphological perspective because there is virtually no geomorphological change due to fluvial processes. Instead, a new assemblage of geomorphic units has been put together through the artificial placement of spawning gravels. These changes will be discussed in § 7.4.2.

7.4.1.2 TS3: 2004 As Built

As described in Elkins *et al.* (2007), the 2004 project was the second phase in what was initially[17] a two year slope-creation design SHR project. The goal of the project was to redistribute the slope created by the 2003 project upstream to improve the habitat at the next pool-riffle unit downstream (raising the riffle crest by roughly 0.5 metres). As Figure 7.9 indicates, this included roughly equal placement of gravel in both the 2003 and 2004 project. Upon applying the SHR Placed Gravel mask to the DoD, the ECD in the upper left corner of Figure 7.10 shows a dual peaked depositional ECD with a peak at 35-40 cm and a second peak at 65-75 cm of fill. This analysis suggests that the total volume of gravel placed in both the 2003 project area and 2004 project areas in 2004 was 1735.8 m^3.

[17] Under SHIRA adaptive management, this later turned into a five year project (four of which are reported here).

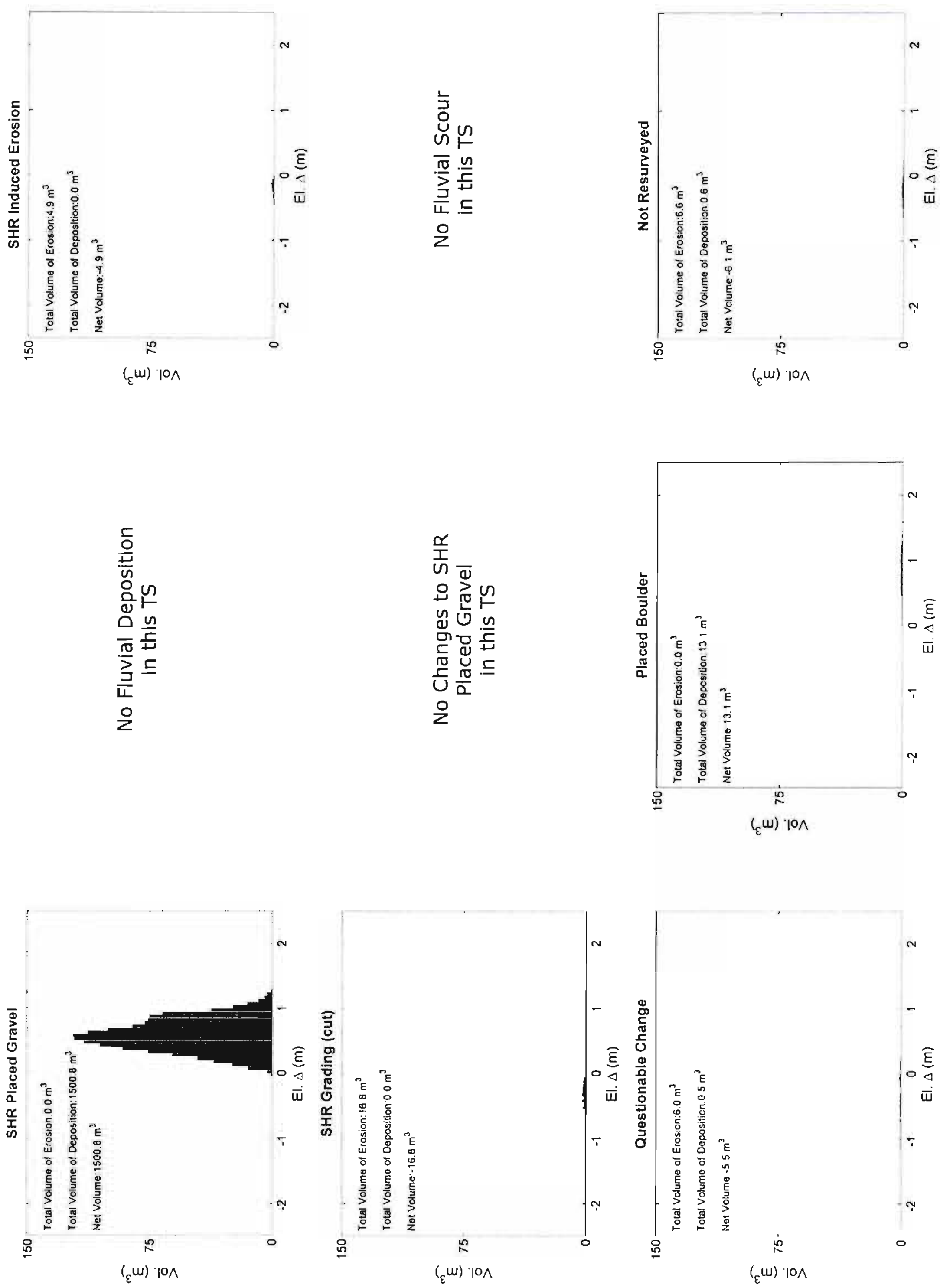


FIGURE 7.8: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2003 Project (TS1).

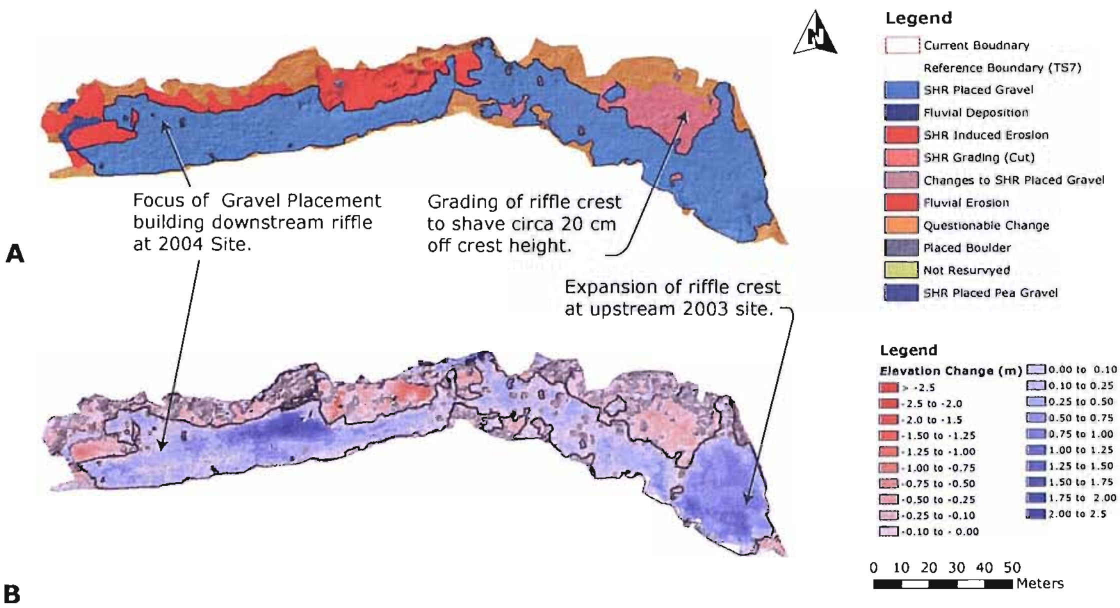


FIGURE 7.9: Geomorphological interpretation mask and DoD associated with the As-Built 2004 Project (TS3). A) Geomorphological Interpretation Mask; B) Pathway 4 DoD. The key map shown in the upper left hand corner indicates the mask between the SHR fill from this project in the 2003 and 2004 project areas. Hillshade from the 2004 Post Project DEM shown in background for context. Flow is from right to left.

A second tier mask was produced to segregate the SHR Placed Gravel area into its 2003 and 2004 components. The resulting ECDs are shown in the centre-left (2003) and bottom-left (2004) in Figure 7.10. These reveal that 52.8% of the total placed gravel was placed in the 2003 site, with the rest in the 2004 site. Additionally, the second ECD peak is primarily the result of the filling of the pool upstream of the 2003 site to expand the riffle, whereas the 2004 ECD contributes more to the first ECD peak.

Modest amounts of secondary processes were also inferred from the DoD and the application of their masks constitute the rest of the ECDs in Figure 7.10. There was roughly an order of magnitude more natural fluvial scour (90.5 m^3) than fluvial deposition (8.3 m^3) and this is likely due to the moderately elevated flows during the gap between the pre-project survey and construction. By contrast, roughly a third less (60.5 m^3) erosion was deemed to be SHR induced (from altered hydraulics associated with construction), but not due to direct modification. A similar amount (58.2 m^3) of cut was recorded and attributed to very shallow grading of the 2003 site riffle crest, to accommodate the extension of the riffle crest upstream and produce hydraulic conditions in accordance with the 2004 design. This was achieved by the front end loader using the backside of its bucket and reversing, skimming a shallow depth of gravel off the crest. Interestingly, the ECD demonstrates this shallow grading nicely with its pronounced peak at 15 to 20 cm of cut and a maximum cut of less than 45 cm. Even smaller amounts of questionable changes around the periphery that were likely due to TIN artifacts along the banks in heavily vegetated areas, were filtered out (total volume of 79.6 m^3; only accounting for 3.8% of the total volume of thresholded DoD recorded changes).

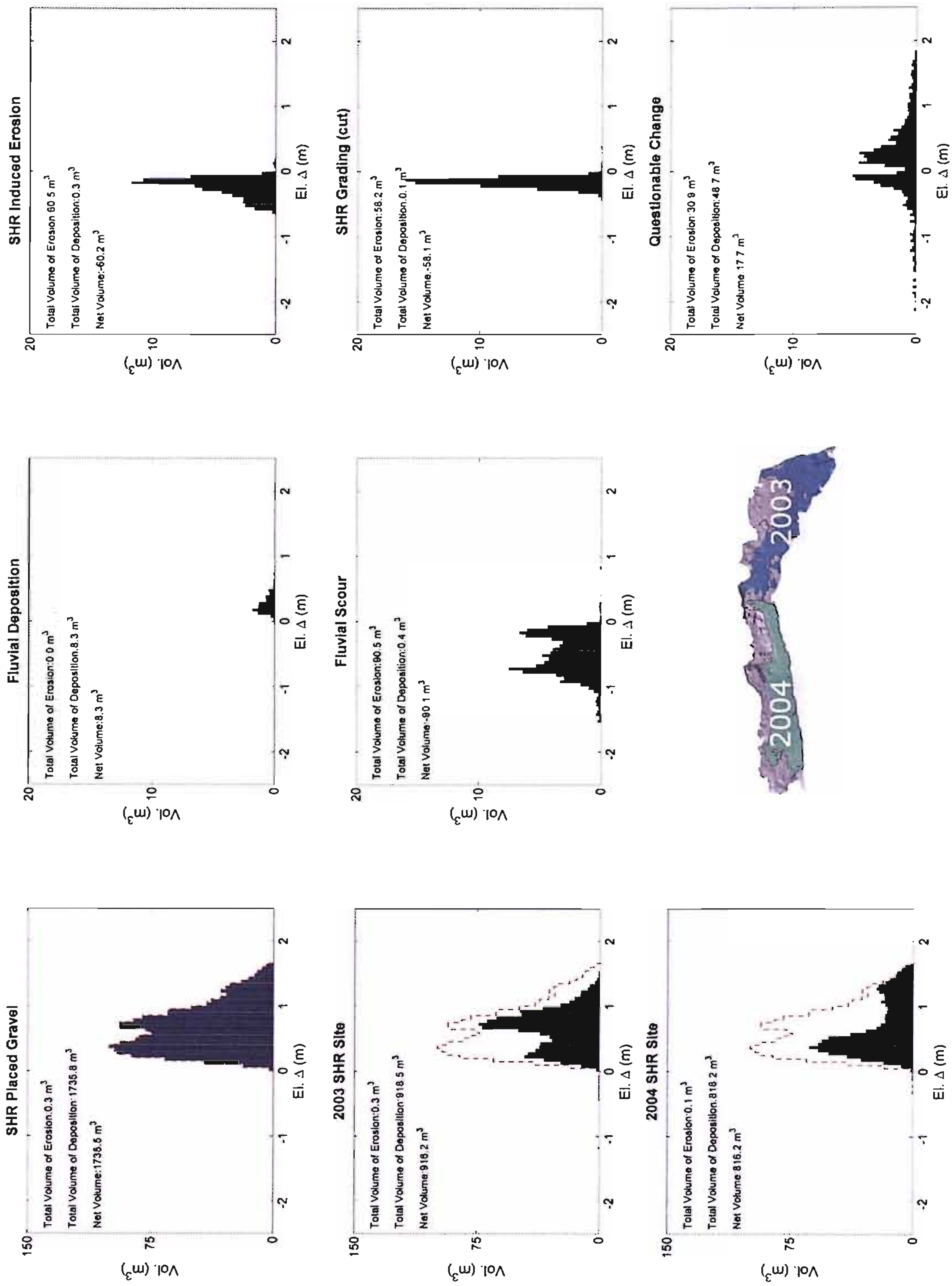


FIGURE 7.10: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2004 Project (TS3). See text for explanation. Note that the vertical scale on the SHR Placed Gravel ECD is different than the other ECDs.

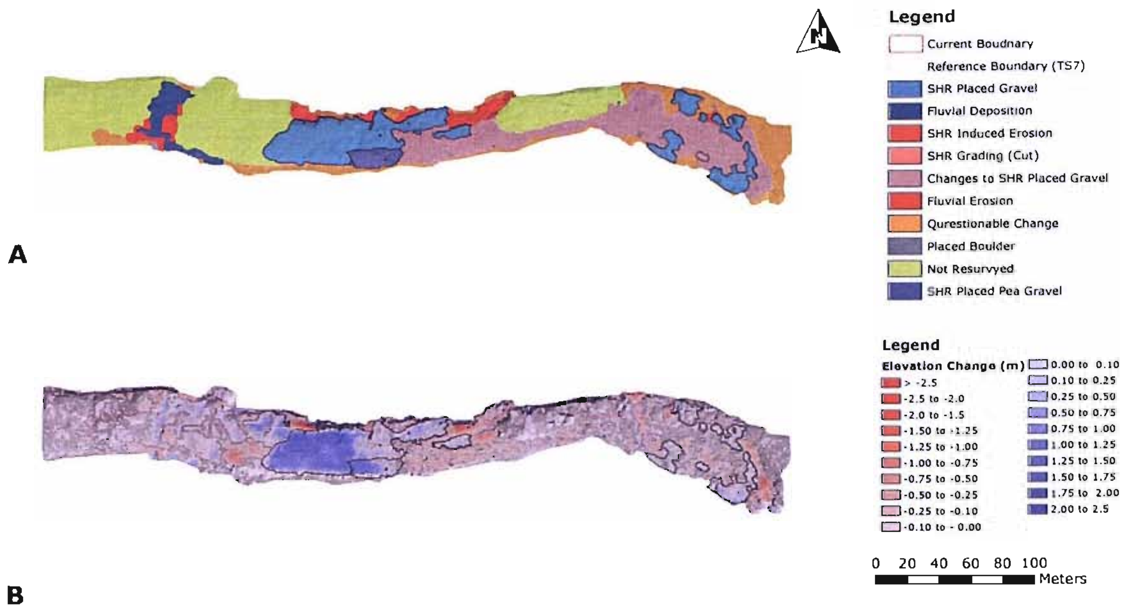


FIGURE 7.11: Geomorphological interpretation mask and DoD associated with the As-Built 2005 Project (TS5). A) Geomorphological Interpretation Mask; B) Pathway 4 DoD. Hillshade from the 2005 Post Project DEM is shown in background for context. The black polygons in both A & B represent areas of SHR placed gravel. Note the small area of pea gravel placement on river left adjacent to the 2004 site. Flow is from right to left.

7.4.1.3 TS5: 2005 As Built

Nine designs were considered under SHIRA for the 2005 site (p. comm Pasternack, 2007). Design objectives included a) increasing the lateral variability, b) filling a former mining hole in the channel, possibly leaving a pool of more appropriate depth,c) increasing flow complexity and habitat heterogeneity, and d) preserving the existing thalweg dictated by channel confinement. No new elevation head was created as part of this project, instead a redistribution of the head created in 2003[18] was relied on. As Figure 7.11 indicates (with black outlined polygons), the vast majority of the SHR placed gravel was in the 2005 project area, but there were small zones of shallow gravel replenishment in both the 2004 and 2003 areas.

Applying the SHR placement boundary mask, the ECD in the upper left corner of Figure 7.12 shows that roughly 2017.9 m^3 of gravel was placed in 2005. Applying site specific (by year) masks to the SHR Placed Gravel Mask, ECDs can be calculated to show the proportion of placed gravel for the 2003, 2004 and 2005 site respectively (Figure 7.13). From this, 1827.6 m^3 (90.3%) was used to create new features in the 2005 site and only 4.8% and 4.9% were used in the 2003 and 2004 sites, respectively. Both the 2003 and 2004 site ECDs show peaks of very shallow fill (around 20-30 cm), reflecting the fact these sites were already built up in previous years and were merely being replenished. By contrast, the 2005 site ECD has a massive pronounced peak at about 1.6 m of fill reflecting the large volume of gravel needed

[18] This head was set by building up the uppermost riffle crest at the top of the reach.

to fill in the deep mining hole.

Returning to the other ECDs in Figure 7.12, there are a variety of DoD calculated changes that were not from placed gravel and which collectively account for over 37% of the total volume of change. Over 32% (12% of total) of these are complete artifacts of TIN construction with low point density or areas that were not actually resurveyed and therefore changes can not be assessed (yellow area in Figure 7.11A; bottom left ECD in Figure 7.13). Another 13.5% (5% of total) of these are areas of questionable change around the margins[19] (orange area in Figure 7.11A; bottom right ECD in Figure 7.13). Thus, roughly 17% of the volumetric budget can be discarded.

The remaining 54.5% (20% of total change) of these non placed gravel changes deserve some mention as they constitute a much larger percentage of the total volume of change than in the other as-built survey timesteps. About 80 m^3 of this is interepted to be SHR induced erosion occuring durring construction. There was no pre project survey that summer due to sustained high flow releases from the dam, the DoD is calculated with respect to the 2004 post project DEM.[20] Accordingly, changes outside the SHR placement areas could have occured at any point over the past year. Thus the majority of these changes are most likely due to natural fluvial processes associated with high flow releases[21] through the spring and summer (see hydrograph in Figure 7.3). The fluvial scour ECD (middle right ECD in Figure 7.13) reflects a mix of shallow scour of the riffle downstream at Murphy Creek and deep scour at the riffle head of the 2004 site reflecting expansion of the pool-exit slope into the riffle. Within the 2003 and 2004 site areas (pink area in Figure 7.11A), a fair amount (352 m^3) of erosion and some minor deposition (29.4 m^3) was recorded (indicated in middle ECD in Figure 7.12).

7.4.1.4 TS7: 2006 As Built

The final and largest of the four SHR projects discussed in this chapter was built in 2006. The 2006 project objectives were: a) to raise the bed elevation in an old mining hole between the 2005 project site and the Murphy Creek confluence to create more suitable pool habitat for native species, b) to continue the effort to redistribute the slope and elevation head created in 2003 further downstream, and c) to increase the amount and quality of spawning habitat. In Figure 7.14 there are three primary focal points for the placement of gravel: 1) the filling of a deep gravel mining hole upstream of Murphy Creek, 2) the extension of two small riffles into one another downstream of Murphy Creek, and 3) the extension of the slope downstream into a lateral bar. The upper left ECD in figure 7.15 shows that 2971.8 m^3 of gravel was placed to accomplish this. Of that, 89.6% was used in building new habitat at the 2006 site, largely consumed by creating the changes described above. Similar to previous years, much

[19] As the lower Mokelumne in this area has artificially stable (due to flow regime) banks heavily armoured with alders, there is virtually no field evidence of bank erosion where most of these questionable areas are shown.

[20] See § G.4.5 for full explanation.

[21] Note the circa 84 cumec flows were the highest flows in the decade leading up to 2005 and were capable of producing limited transport (Pasternack *et al.* 2006).

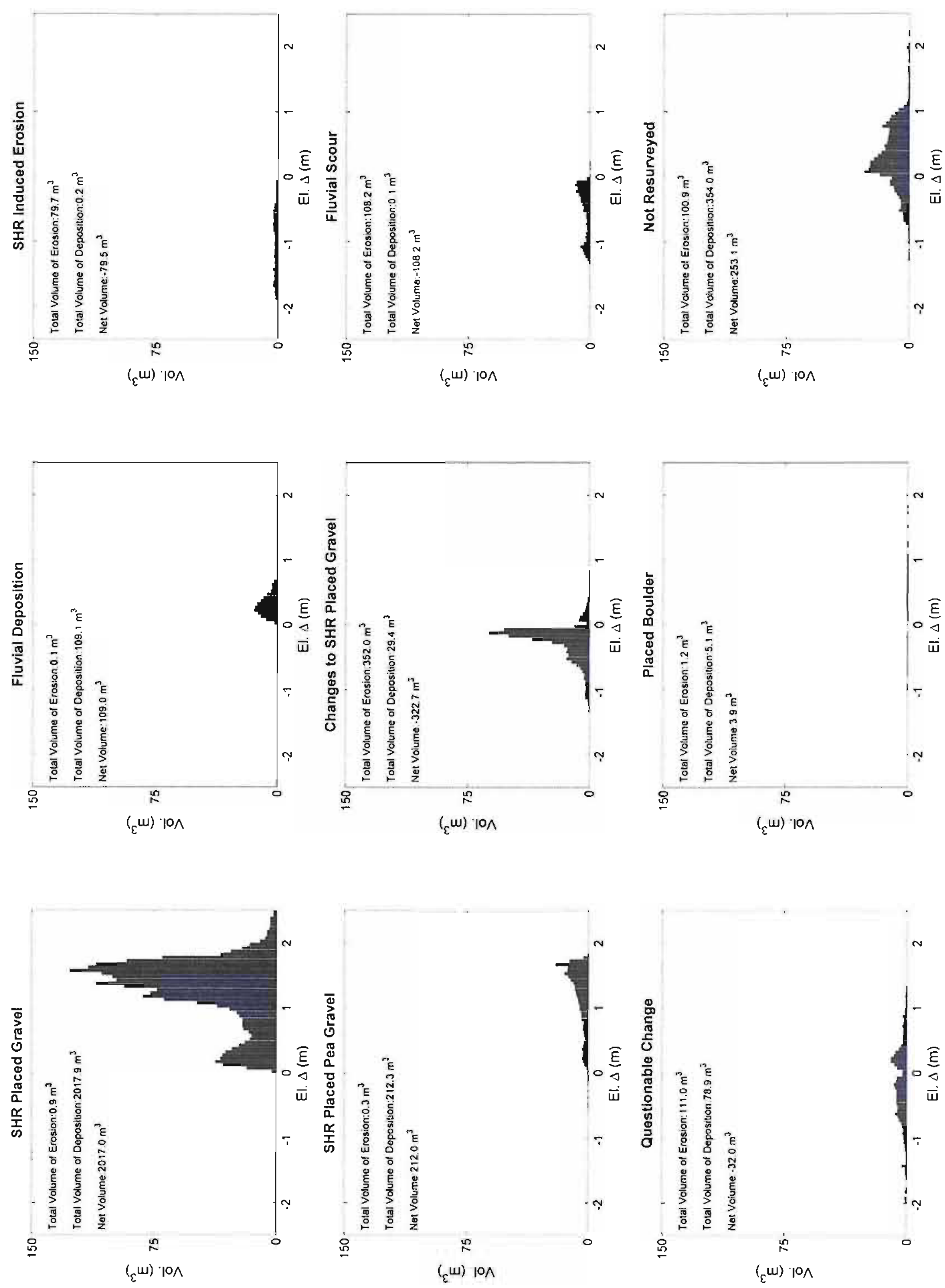


FIGURE 7.12: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2005 Project (TS5).

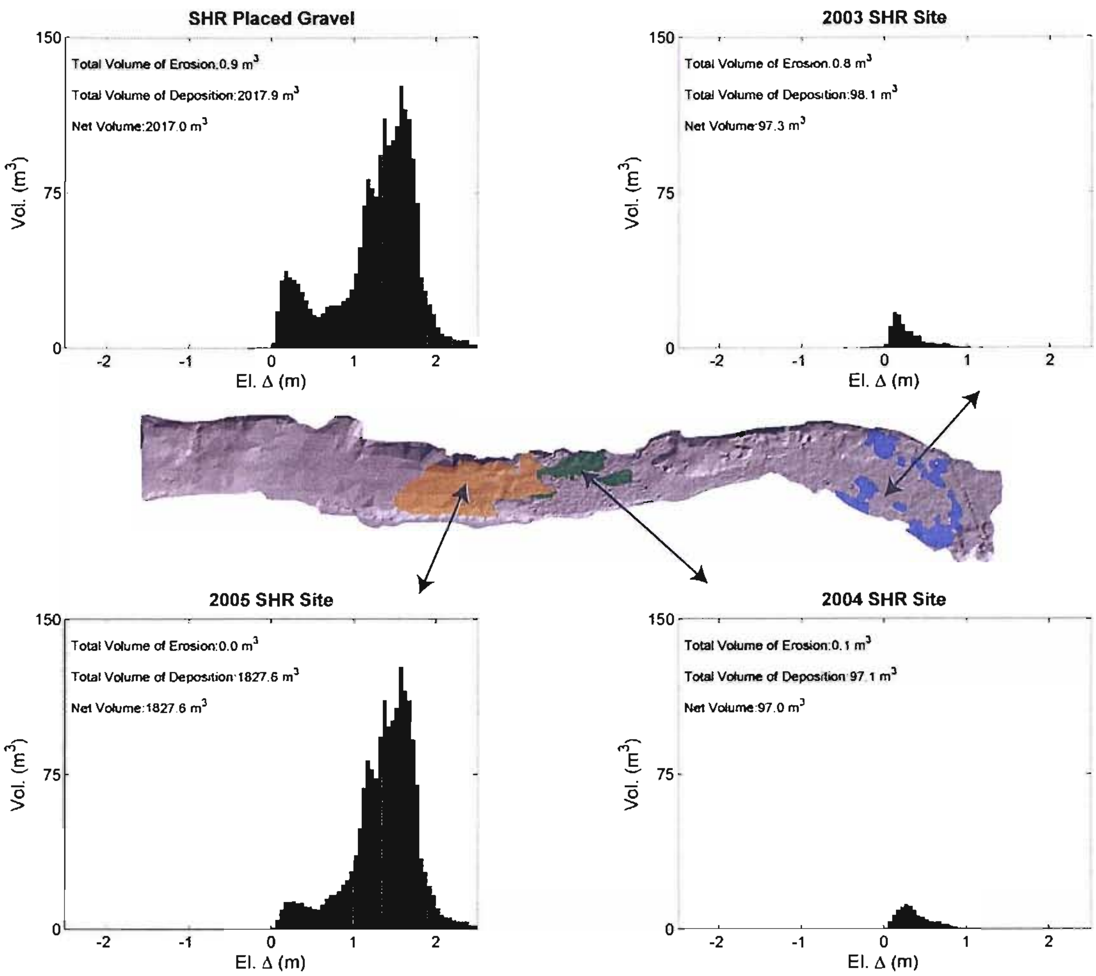


FIGURE 7.13: Application of a site area mask to the 2005 SHR Placed Gravel Mask showing how the overall ECD (upper right) is segregated into placement in the 2003, 2004 and 2005 site areas respectively (corresponding to blue, green and gold areas in centre key map).

more modest percentages at low fill depths (4.3%, 1.3% and 4.8% for 2005, 2004 and 2003 sites respectively) were used to top up the previous sites (Figure 7.16).

Returning to the secondary geomorphological interpretations associated with the classification masks in Figure 7.14A and the remaining ECDs in Figure 7.15, these other calculated changes accounted for 18.4% of the total volumetric changes. Of these, 39% fall under questionable changes in areas where either there was no field evidence of change or in which poor TIN interpolation is producing suspect patterns. These were discarded from consideration. During TS7, there were no appreciable flows but there were coherehent zones of fluvial deposition (176.5 m^3) that roughly balanced with coherent paterns of fluvial scour further upstream on the point bar and the SHR induced erosion around the edge of the sites (141.4 m^3 and 39.6 m^3, respectively) on the point bar downstream of the project. These changes could plausibly be attibuted to altered hydraulics over relatively short durations during construction. The fraction that doesn't balance is largely explained by the SHR induced erosion at the top of the

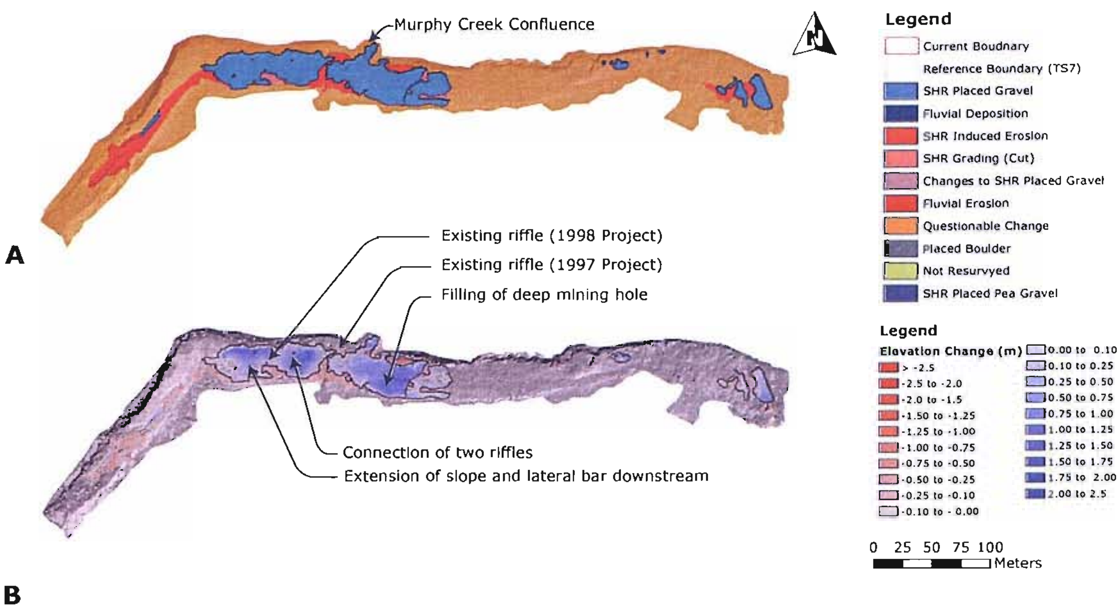


FIGURE 7.14: Geomorphological interpretation mask and DoD associated with the As-Built 2006 Project (TS7). A) Geomorphological Interpretation Mask; B) Pathway 4 DoD. Hillshade from the 2006 Post Project DEM is shown in background for context. Flow is from right to left.

reach in the 2003 site. There is a small volume (37.3 m^3) of SHR-grading that was performed at the riffle crest to match design criteria and produce the desired hydraulic conditions.

7.4.1.5 Overall Observations of Total Volume of Gravel Placed

Figure 7.17 and Table 7.3 show directly the best estimates of the total volume of gravel placed for each project, amounting to a total of 8226.3 m^3. Figure 7.17 shows a gradual increase from year to year in the scope of the projects, with increasing volumes, and a willingness to venture into deeper water. In earlier projects on the Mokelumne, there was more concern about the efficiency of gravel placement, in terms of creating better spawning habitat. For example, it is more economical to convert a glide into a riffle then converting a deep mining pit into a riffle (or even raising a pit to a pool of more *natural* depth). Thus, the broader slope creation design philosophy and staged implementation to redistribute that slope in a manner most effective for geomorphological functioning and provision of suitable spawning habitat came to dominate over short-term economic efficiency of the designs.

Table 7.3 is probably the most direct comparison that can be used to address the secondary question of whether or not all the DoD predicted changes are due to PHR construction.[22] The 'GM Calc' (geomorphological mask calculation) column in Table 7.3 always show a lower value than the total DoD predicted changes. This is typically[23] between 1% and 5% lower than the pathway 4 thresholded value. In the case of the UC Davis calculation (UCD Calc

[22] Question posed in § 7.4.1.

[23] 2005 (TS5) is an anomaly at 28%, due to the lack of a pre-project survey.

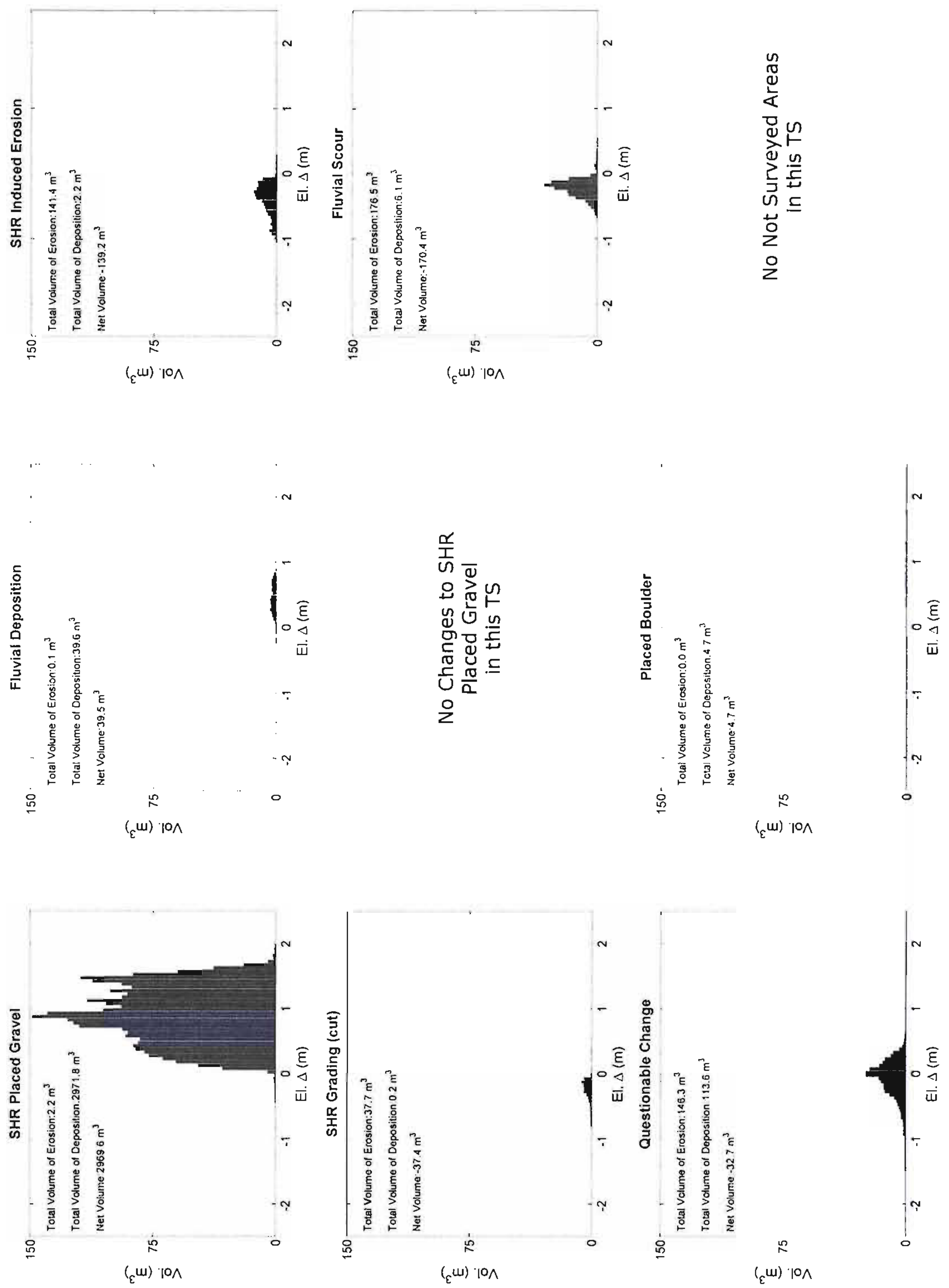


FIGURE 7.15: The elevation change distributions for masks associated with the geomorphological interpretation classification of the As-Built 2006 Project (TS7).

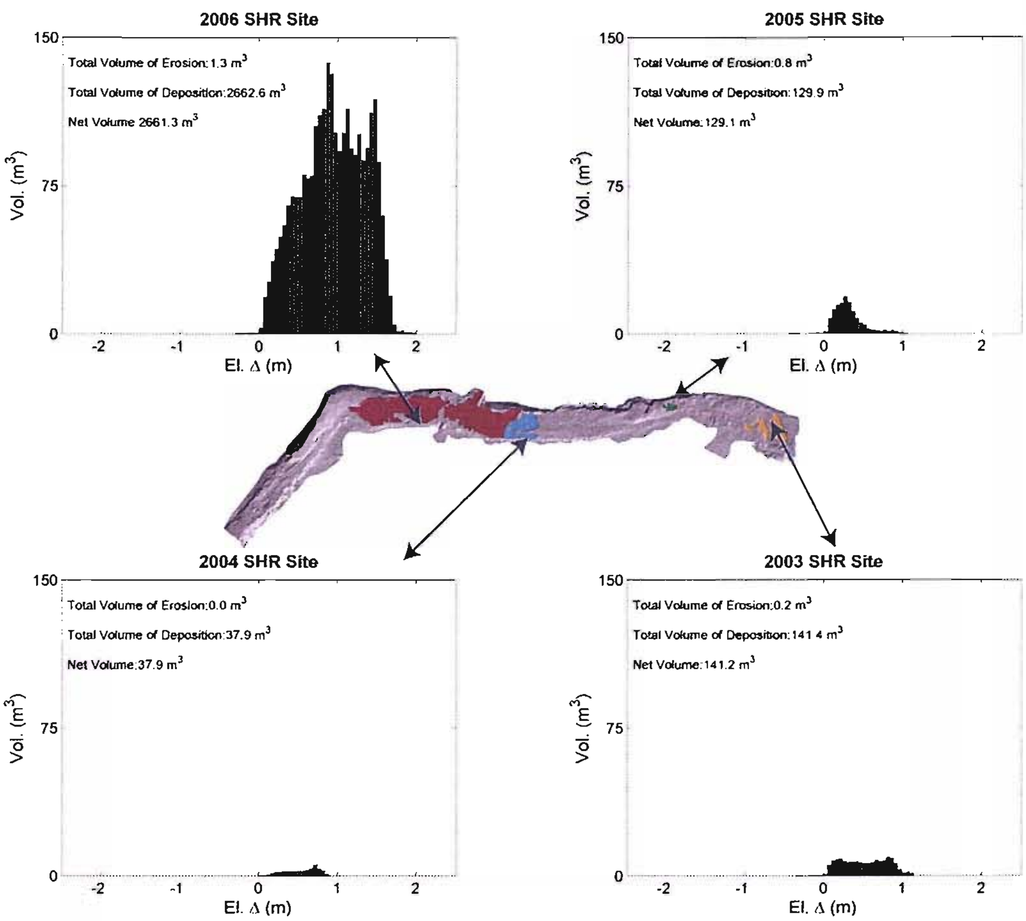


FIGURE 7.16: Application of a site area mask to the 2006 SHR Placed Gravel Mask showing how the overall ECD (upper left ECD in Figure 7.15) is segregated into placement in the 2003, 2004, 2005 and 2006 site areas, respectively (corresponding to gold, green, blue and red areas in centre key map).

- column 3 in Table 7.3), the gross calculation (Gross Calc - column 4 in Table 7.3) and the pathway 4 analysis (PW4 Calc - column 5 in Table 7.3), all three were taken from the total deposition volume recorded in their respective DoDs. The first thing to highlight is the difference between the UC Davis calculation and gross calculation. The gross calculation is the unthresholded DoD[24] The UC Davis calculation is also an unthresholded DoD, but was calculated independently using slightly different survey extents as well as being derived from a different TIN and DEM surfaces. As such there is no consistent relationship between the two. Both the 2003 and 2004 comparisons are within 5% of each other, but the 2005 has a 23% discrepancy. Thus, two independent calculations are of the same approximate magnitude, but it is difficult to assess how reliable either estimate is as an approximation of the actual fill volume from PHR construction.

The pathway 4 analysis (PW4 Calc) of the DoD presented in § 7.3 represents a thresholding of the gross DoD calculation and shows a consistently smaller volume (between 2.6% and 7.3%

[24]A pathway 1 analysis from Chapter 4, which is a straight DoD with no accounting for uncertainty.

	Volume of Placed Gravel (m^3)				
SHR Year	Design	UCD Calc	Gross Calc	PW4 Calc	**GM Calc**
2003 (TS1)	2020.4	1517.0	1556.5	1514.9	**1500.8**
2004 (TS3)	1667.4	2005.0	1924.5	1805.3	**1735.8**
2005 (TS5)	1950.1	2359.0	3042.5	2819.1	**2017.9**
2006 (TS7)	3402.0	NA	3333.6	3138.2	**2971.8**
TOTAL	9039.8	5881.0	9857.1	9277.5	**8226.3**

TABLE 7.3: Comparison of design versus calculated fill volumes for each SHR project. UCD Calc refers to the original calculation from UC Davis (p. comm. Greg Pasternack). Gross Calculated is the total unthresholded fill volume. PW4 Calc is the thresholded fill volume from a Pathway 4 analysis. GM Calc refers to the geomorphological mask is a field-based mask of the actual SHR construction extents with a PW4 Analysis.

than the unthresholded DoD). This estimate of deposition represents the best estimate of the total deposition reliably recorded by the DoD. The sixth column of table 7.3 summarises the use of a geomorphological mask (GM Calc) based on the actual delineated boundaries in the field of the gravel placement extent.

One of the interesting tangential points that arose from these analyses was the presence of a minor, but coherent, erosional signal in the SHR areas. This erosional signal was inferred to be due to a process of SHR induced erosion[25] induced over very short periods (e.g. seconds to hours) during the construction process itself (Figure 7.18). On the longer timescale of hours, during construction exceptionally steep water-surface slopes can be created by temporary morphologies (Figure 7.18B, C, D and E), which in turn dramatically alter hydraulics locally producing temporarily competent flows. Another mechanism, which occurs on the scale of seconds to minutes, are highly accentuated velocities and turbulent bursts associated simply with the rapid displacement of water in the wake of the front end loader navigating the site and when the loader drops its bucket (Figure 7.18F). Anecdotal evidence[26] from the field certainly supports the plausibility of these inferred mechanisms and the spatial patterns of scour observed are also consistent with this (e.g. on the periphery of projects and in the thalwegs of pools where flows are concentrated anyway). In fact, the recording of the mechanisms with an erosional signature in the DoD is almost certainly conservative, with the final grading and placement of gravel compensating for intermediate erosion occurring within the core zones of gravel placement itself.

7.4.2 How Much Gravel was used to Produce what Types of Morphological Units or Habitat?

From the perspective of monitoring PHR and restoration projects, another useful way of segregating the DoD budget for interpretation is in terms of the constructed morphological

[25]Will also be described in § 7.4.2.

[26]See `http://shira.lawr.ucdavis.edu/moke_2004_archive_movie2.htm` for video showing visual evidence of these mechanisms.

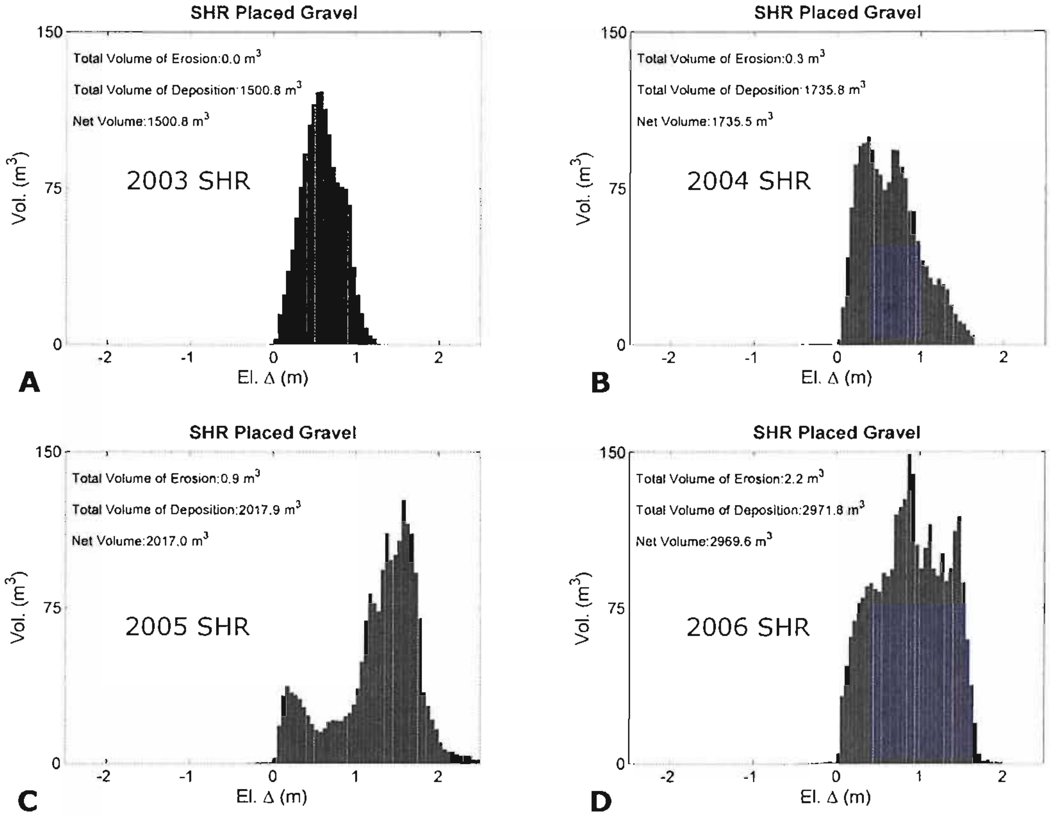


FIGURE 7.17: Comparison of placed gravel ECDs for A) 2003, B) 2004, C) 2005 and D) 2006 SHR Projects, showing a gradual increase from year to year in both the volume of gravel placed and the relative fill depths. Note, all these ECDs were shown in previous sub-sections but are shown here again for easy inter-comparison.

features. Of the 1500 m^3, 1735 m^3, 2017 m^3 and 2971 m^3 of gravel placed in SHR projects in 2003, 2004, 2005 and 2006, respectively (Figure 7.17), it would be helpful to know how much of the gravel was used creating what types of habitat. This could highlight the relative cost of different components of SHR projects. For example, of the total volume of placed gravel in a PHR project, how much was used in building a riffle crest versus building a point bar? For each of the SHR projects, a geomorphic unit classification was performed showing what the final types of habitat were for each area. By using the geomorphological design as a mask, these questions can be answered directly. The geomorphological categories in the classification used on the Mokelumne were tailored to the constructed and existing morphologies and included:

- *Riffle Crest*: The actual constructed crest of the riffle (separated out from the rest of riffle as riffle crest construction can account for greater fill depths and this is the critical component in slope creation)
- *Riffle*: The riffles are one of the primary SHR features
- *Chute*: Shallow notches through bars and riffles for encouraging specific flow patterns
- *Lateral Bar*: Bank-attached bars

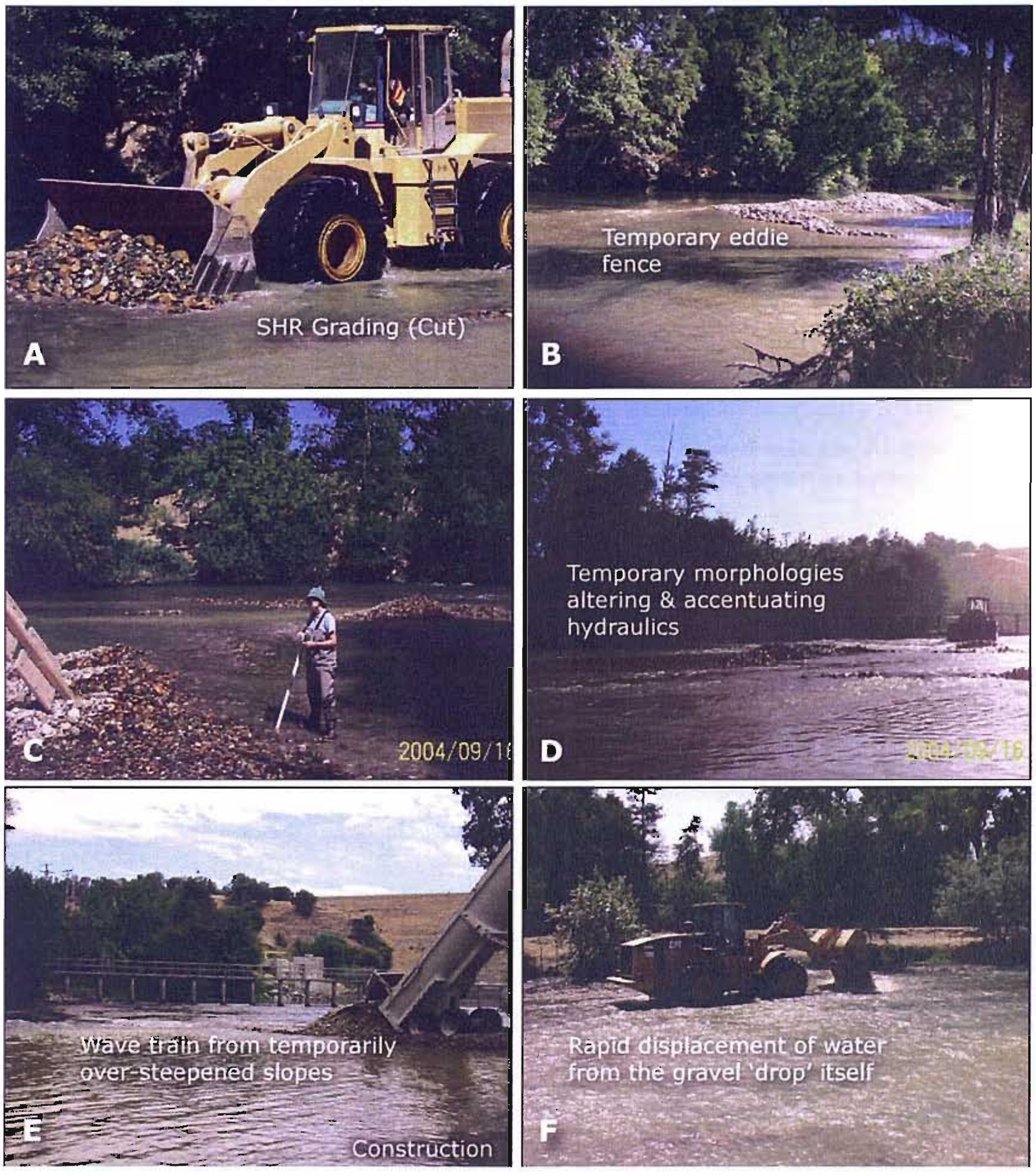


FIGURE 7.18: Examples of altered hydraulics during construction process due to grading (A), temporary staging of gravel producing altered morphologies (B-E) and rapid displacement of water from the gravel 'drop' (F). Photos A-D are from the 2003 project, photo E is from the 2004 project and photo F is from the 2002 project (see Figure 7.1 for site map).

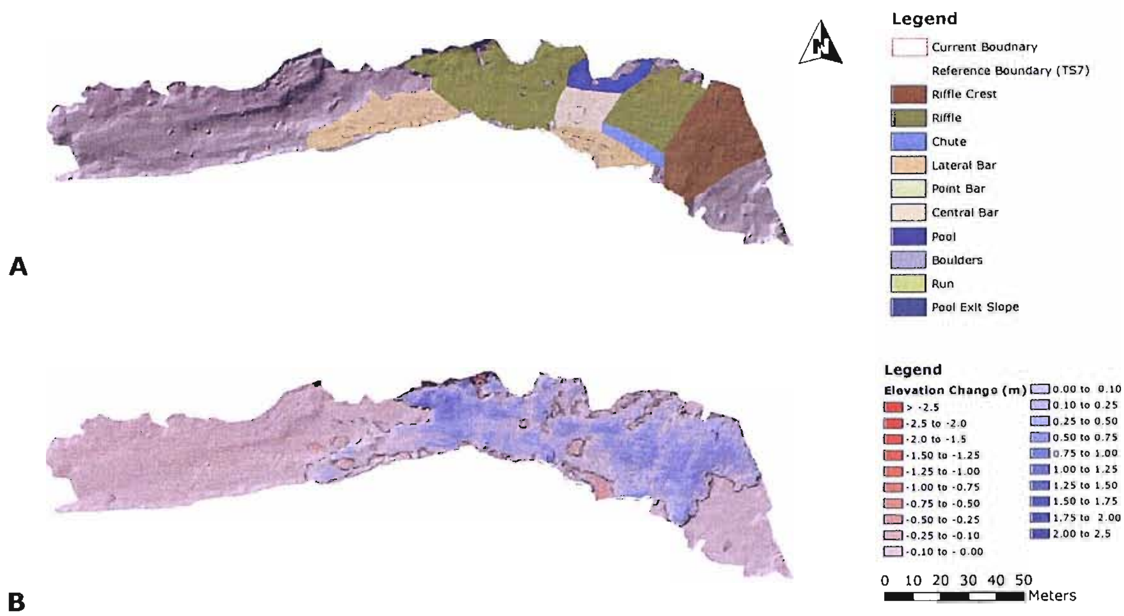


FIGURE 7.19: Morphological unit mask (A) and DoD (B) associated with the As-Built 2003 Project (TS1).Hillshade from 2003 Post Project DEM shown in background for context. Flow is from right to left.

- *Point Bar*: Bank-attached bars on inside bends
- *Central Bar*: Bars built in centre of channel to divide flow and produce habitat heterogeneity
- *Pool*: Pools were primarily created by not filling areas with gravel and accentuating pool shape and maintenance with placement of gravels on pool edges
- *Pool-exit Slope*: Pool exit slopes were specific areas on the transition between pool and riffle that were constructed and represent hot-spots of spawning activity

The results of this geomorphic unit mask segregation of the DoDs are presented and discussed for each of the four SHR projects in the next four subsections.

7.4.2.1 TS1: 2003 As Built

An SHR project is fundamentally designed to create a new assemblage of geomorphic units through the artificial placement of spawning gravels. Thus, in Figure 7.20B, the SHR Placed Gravel area in Figure 7.20A is sub-divided by a classification of the geomorphic units which were created. This allows one to assess how much gravel was used in creating each such feature. For example, from Figure 7.20 roughly 374 m^3 was used building the riffle crest; 826 m^3 building the rest of the large riffle; 41 m^3 building a smooth transition for the chute on river left; 130 m^3 on the lateral bars; and 99 m^3 building the central bar. Additionally, four large boulder clusters were placed for habitat heterogeneity (Elkins *et al.* 2007) equating to roughly 6 m^3 of *deposition*; and 30 m^3 was used building a smoother transition into the pool habitat on river right. Each of these morphologies exhibit distinctive ECDs in Figure 7.20, which are largely a reflection of the underlying pre-project morphology and the amount of fill required to achieve the design morphologies. The only ECD showing a pronounced erosional signature is the lateral bar ECD with roughly 18 m^3 of low magnitude erosion ranging from 0 to 55 cm. This ECD is virtually identical to the SHR grading ECD in Figure 7.8 and is a reflection of very minor grading associated with carving a peripheral chute on river left to prevent excessive scour from the increased elevation head between the 2003 and 2004 project construction (Elkins *et al.* 2007).[27]

7.4.2.2 TS3: 2004 As Built

Figure 7.22A shows the spatial arrangement of geomorphic units following the 2004 project[28] construction in relationship to the TS3 DoD in Figure 7.22B for the SHR Placed Gravel area. Again, the riffle and riffle crest dominates the volumetric consumption of gravel, together comprising 74% of the 1735 m^3 of placed gravel. Interestingly, they also comprise 45% of the more minor 177.3 m^3 of erosion recorded within the SHR project area (largely made up of the SHR Induced Erosion and SHR Grading reported in Figure 7.10). Roughly 52% (92.4 m^3) of the total volume of calculated erosion was recorded in the pool area (particularly in the thalweg), suggesting that altered hydraulics during construction was concentrating high energy flows locally in the pool and promoting erosion. Roughly 178.5 m^3 of gravel deposition was reported on the pool-exit slope downstream of the two pools experiencing scour, and was likely a combination of placed gravel and gravel depositing having been eroded from its own pool upstream. A very minor amount of gravel (35.7 m^3) was used in accentuating and topping up the central bar in the 2003 site upstream. Finally 169.3 m^3 of gravel was used building up existing lateral bars to force pool confinement in both the 2003 and 2004 sites.

7.4.2.3 TS5: 2005 As Built

Figure 7.23 shows the relatively modest spatial extent of the 2005 project, which extended the 2004 project downstream with two new lateral bars and an elevated central thalweg.[29] However, as Figure 7.17 showed, it did this with more gravel as the pre-existing morphology was so deep (a legacy of gravel mining). In contrast to TS1 and TS3, the riffle and riffle crests were not the dominant consumer of gravel in this project, constituting a combined total of only 10% of the placed gravel volume. In contrast, the majority (56% or 1262.5 m^3) was used constructing two large lateral bars, which were logical extensions of the 2004 project. The lateral bar ECDs (centre-left ECD in Figure 7.24) exhibit a strong peak at about 160

[27] See `http://shira.lawr.ucdavis.edu/moke_2003.htm` for further details of the 2003 SHR project and photographs of its construction.

[28] See `http://shira.lawr.ucdavis.edu/moke_2004.htm` for further details of the 2004 SHR project and photographs of its construction.

[29] See also description in § 7.4.1.3.

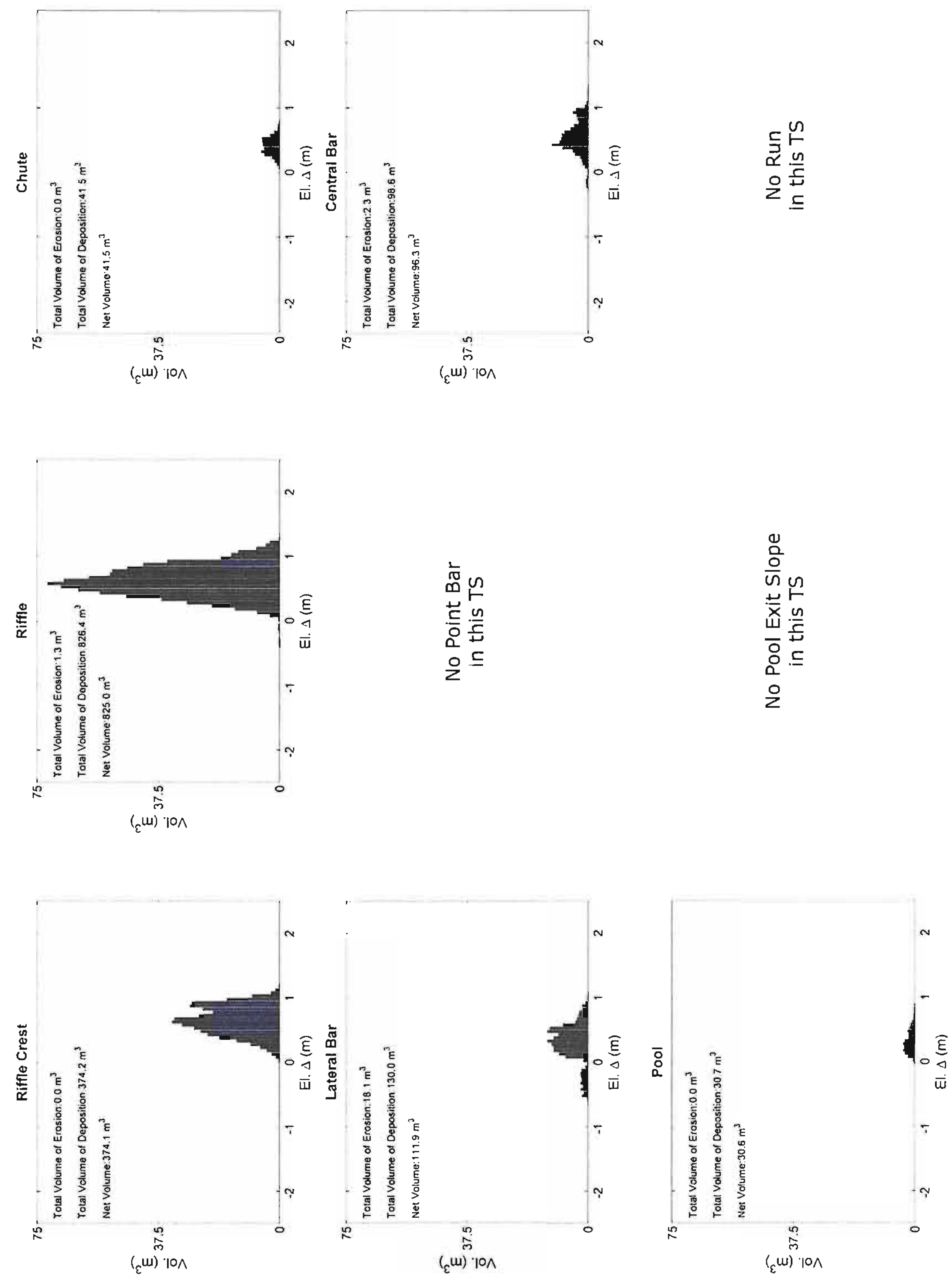


FIGURE 7.20: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2003 Project (TS1).

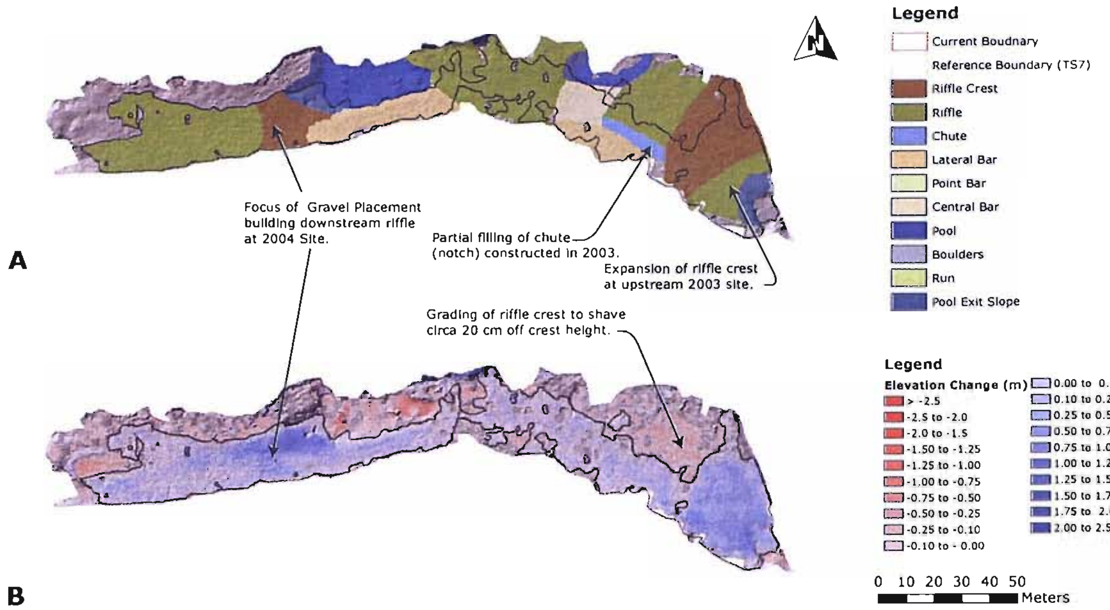


FIGURE 7.21: Morphological unit mask (A) and DoD (B) associated with the As-Built 2004 Project (TS3).Hillshade from 2004 Post Project DEM shown in background for context. Flow is from right to left.

to 175 cm fill depth, reflecting the large volume of gravel needed to bring the bed levels up on the channel margins. The construction of the elevated chute as the new channel thalweg had a similar ECD (top-right ECD in Figure 7.24), reflecting roughly 30% of the total volume of placed gravel. As in previous years, the pool had a minor but primarily erosional ECD signature (bottom-left ECD in Figure 7.24) that in this case could be reflecting both erosion due to construction (as discussed previously) and erosion due to natural fluvial processes over the 2004-2005 season.[30] The pool exit slope again showed a mix of shallow deposition and shallow scour, but only amounted to 3.7% of the total volume of change.

7.4.2.4 TS7: 2006 As Built

As the most ambitious of the four SHR projects in terms of spatial extent and volume of gravel placed, the 2006 project (TS7) represents the most varied mix of morphologies (Figure 7.25). As such, no single morphological unit dominates in terms of gravel consumption, with the riffle, chute, lateral bar and point bar all within 13% of each other at 23%, 15%, 22% and 28% of the total volume of placed gravel (2971.8 m^3), respectively. The riffle and lateral bar ECDs (centre-left and centre top ECDs in Figure 7.26) both exhibit reasonably uniform ECDs over a broad range of fill depths up to roughly 1.8 m. The chute ECD has a more exponentially shaped distribution that grows towards a fill depth peak of about 1.5 m and then drops to nothing by about 1.7 m. The point bar ECD has the most symmetrically shaped ECD, with a peak at approximately 80 to 85 cm.

[30] Recall there was no 2005 pre project survey to difference against.

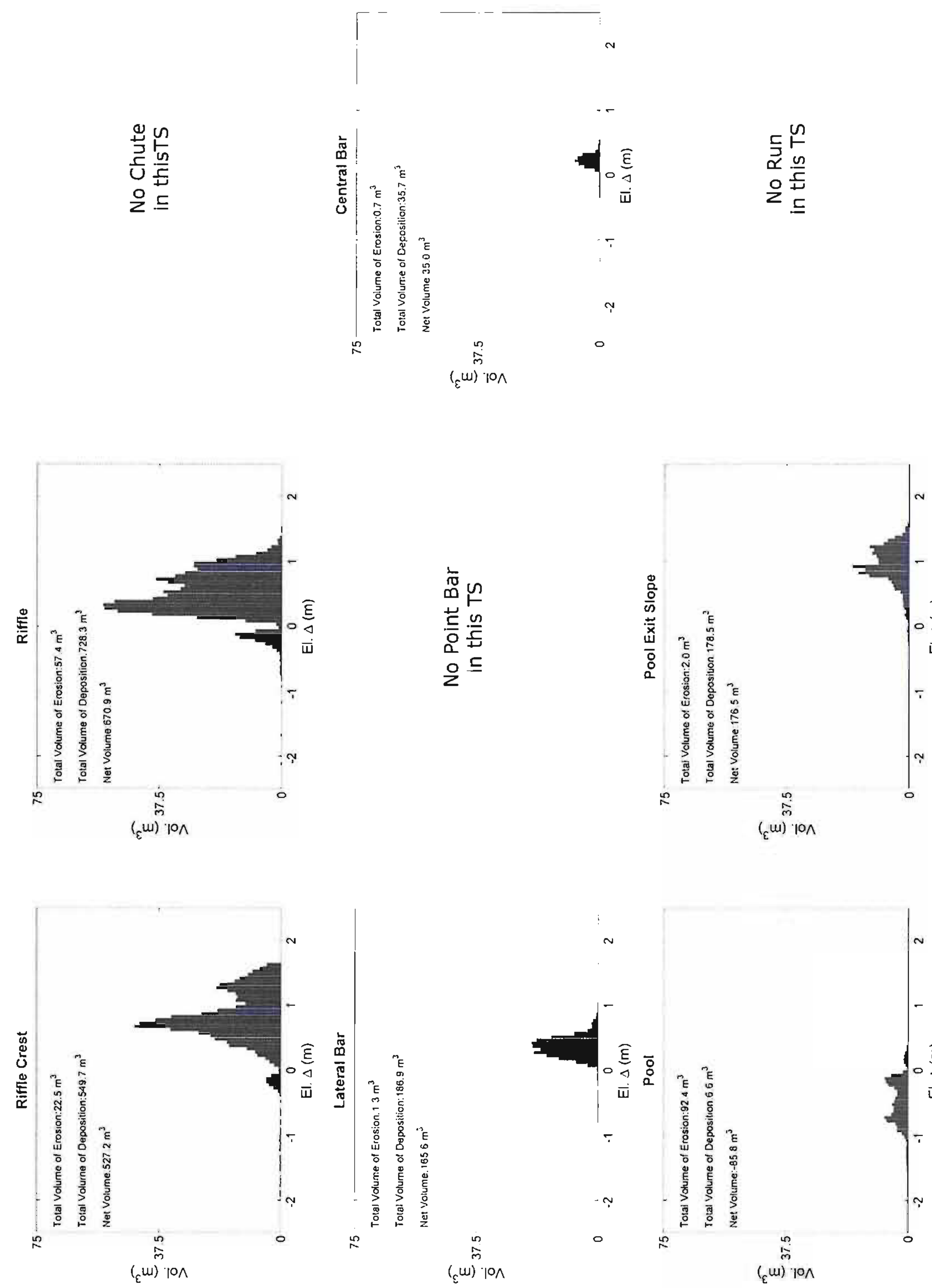


FIGURE 7.22: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2004 Project (TS1).

FIGURE 7.23: Morphological unit mask (A) and DoD (B) associated with the As-Built 2005 Project (TS5).Hillshade from 2005 Post Project DEM shown in background for context. Flow is from right to left.

7.4.2.5 Summary of Gravel Consumption by Geomorphic Units

Using the geomorphic units as masks of the DoD across all four SHR projects, resolves directly the question of how much gravel is consumed by different geomorphic units. Not surprisingly, the morphological units that dominate across all four years are the morphological units known to provide the best spawning habitat. This is by design. Table 7.4 shows a complete summary[31] of the results presented for each project in the preceding subsections. Overall, 41% of the volume placed over the four years was used in constructing riffles (riffles + riffle crests). The next most consumptive units were lateral bars (26%), chutes (14%), and point bars (10%). In addition, the ECDs of all these units show some interesting patterns, which help highlight differences between designs and the pre-project morphologies.

[31] Note that the slight discrepancy between total volumes in Table 7.3 and Table 7.4 is a reflection of slightly different analysis extents, largely because of the inclusion of pool morphologies in this analysis.

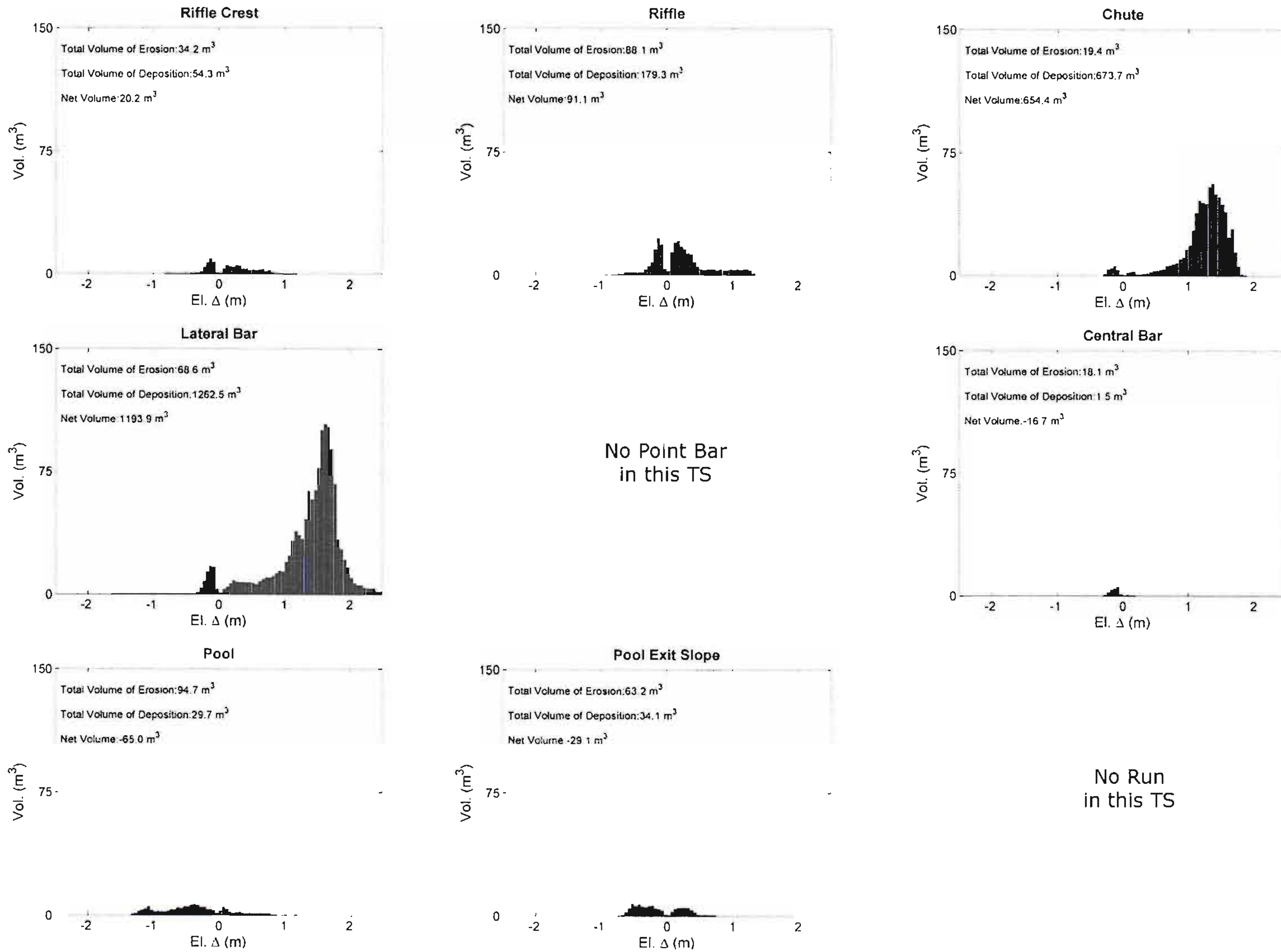


FIGURE 7.24: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2005 Project (TS5).

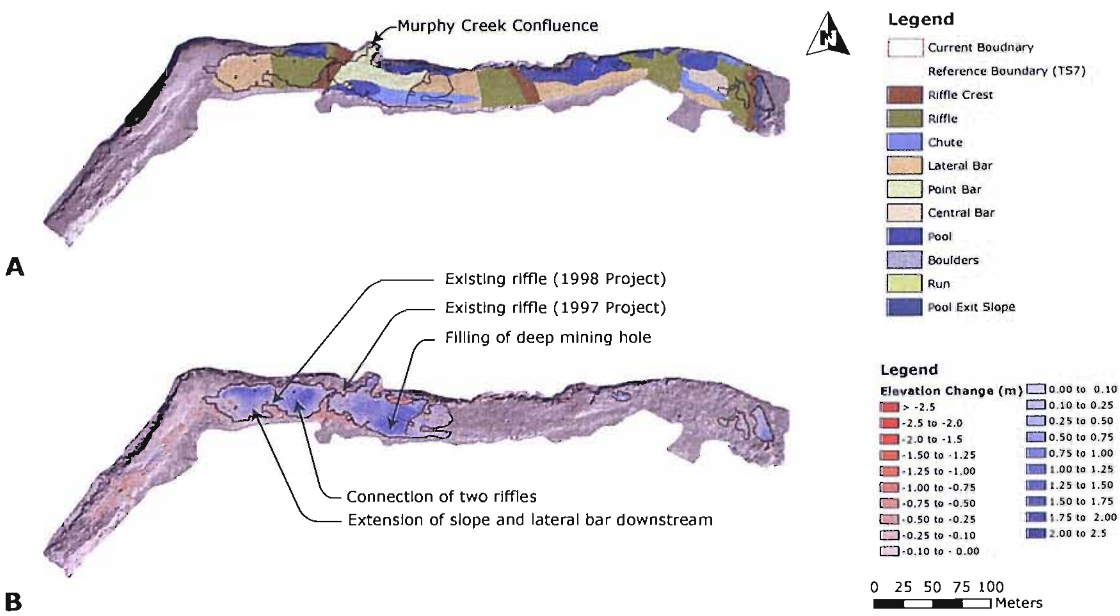


FIGURE 7.25: Morphological unit mask (A) and DoD (B) associated with the As-Built 2006 Project (TS7).Hillshade from 2006 Post Project DEM shown in background for context. Flow is from right to left.

Morphological Unit	Deposition Volume (m^3) by Project Year 2003	2004	2005	2006	Total Volume (m^3)
Riffle Crest	374.2	549.7	54.3	28.9	1007.1
Riffle	826.4	728.3	179.3	667.6	2401.5
Chute	41.5	44.2	673.8	438.2	1197.7
Lateral Bar	130.0	166.9	1262.5	643.9	2203.4
Point Bar	0.0	0.0	0.0	831.2	831.2
Central Bar	98.6	35.7	1.5	4.8	140.6
Pool	30.7	6.6	29.7	212.7	279.6
Boulders	6.2	9.5	4.0	6.2	25.9
Run	0.0	0.0	0.0	0.1	0.1
Pool Exit Slope	0.0	178.5	34.1	45.2	257.8
Total Volume (m^3):	1507.5	1719.5	2239.2	2878.7	8344.9

TABLE 7.4: Segregation of fill volumes for each SHR project by morphological unit masks, to show the relative consumption of gravel in constructing each type of unit.

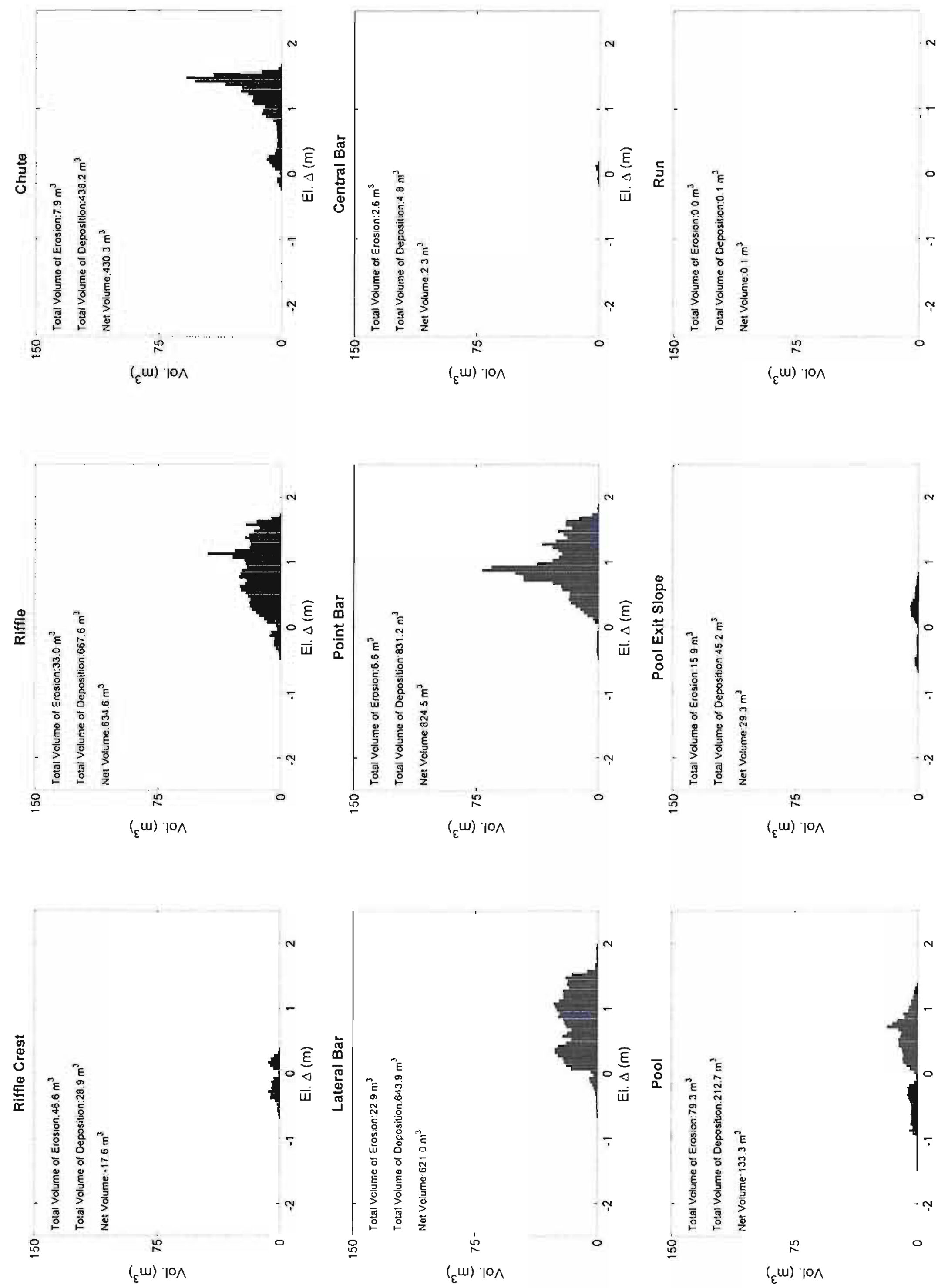


FIGURE 7.26: The elevation change distributions for masks associated with the SHR interpretation classification of the As-Built 2006 Project (TS7).

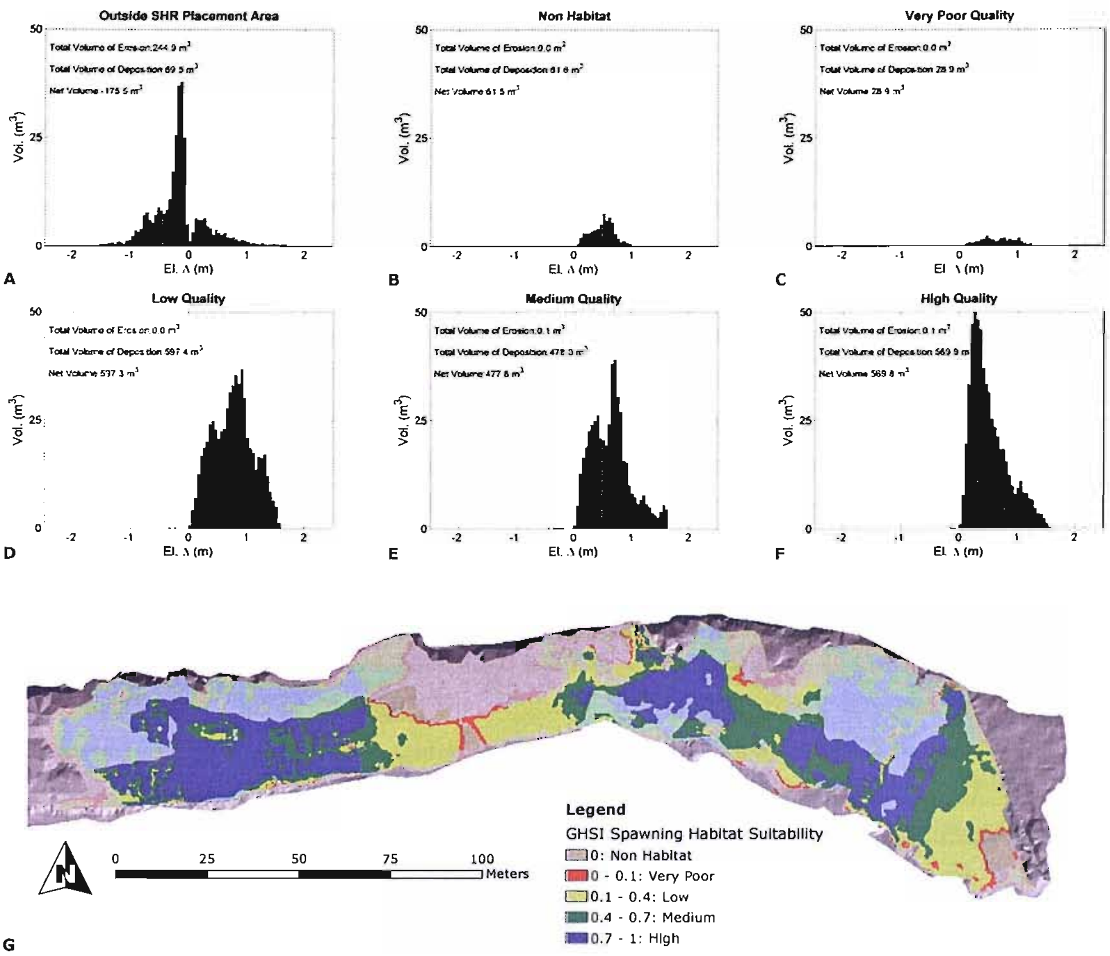


FIGURE 7.27: Elevation change distributions (A-F) corresponding to masks of the DoD from GHSI-predicted spawning habitat suitability classes (G) for TS3 (2004).

7.4.3 How Much Gravel was used to Produce what Quality of Habitat?

To address the question of habitat quality, spawning habitat suitability simulations of the post project conditions are compared to the DoD changes that describe the construction process leading to the as-built condition. This was done to investigate whether there is any correlation between how much gravel was used in relation to the quality of habitat it produces. By using the habitat suitability classes from the habitat suitability simulation as a mask for the DoD, ECDs were derived to address this question directly.

The habitat suitability model used is based off of depth and velocity habitat suitability curves for Fall-Run chinook from the Mokelumne River as reported in Elkins *et al.* (2007, p.6, Figure 5) and Wheaton (2003). Those curves are modelled using high-order polynomial equations to calculate suitability based on velocity and depth separately. The two univariate suitability measures are then combined using a weighted sum (equal weighting of 0.5) to produce a global habitat suitability index (GHSI) that ranges from zero to one, with one being the highest quality (Jorde & Schneider 2004). Habitat quality is calculated on a node-by-node basis using velocity and depth predictions from a 2D hydraulic model simulation at a given flow (Leclerc *et al.* 1995, Crowder & Diplas 2000, Wheaton *et al.* 2004*d*, e.g.). The model simulations were all performed by members of the UC Davis Watershed Hydrology and Geomorphology Lab under SHIRA implementation (Elkins *et al.* 2007, e.g. for 2003 and 2004). For the Mokelumne, with over 14 years of complete redd surveys and seven years of 2D hydraulic model simulations at spawning flows, there is a high degree of confidence in the predictive capability of the GHSI model. That is, the documented occurrence of spawning on the Mokelumne is extremely well correlated to the model predicted high and medium quality habitat suitability classes in the GHSI,[32] with only very rare utilisation of predicted low and poor quality habitat areas, and virtually no utilisation of GHSI-predicted non-habitat (Pasternack *et al.* 2004, Elkins *et al.* 2007, Wheaton *et al.* 2004*d*). Where spawning is tending toward lower quality classes, it has *always* been explainable on the Mokelumne in terms of a close proximity of the redd to habitat heterogeneity elements like shear zone refugia or structural cover (Wheaton *et al.* 2004*e*).

GHSI simulations were only available for the 2004, 2005 and 2006 as-built surveys.[33] The GHSI masks were clipped to match the extent of SHR placed gravel for that year and this is indicated by the non-grayed out area in Figures 7.27G, 7.28G, and 7.29G for 2004, 2005 and 2006 respectively. Between the three Non-Habitat ECDs (Figures 7.27A, 7.28A, and 7.29A), they all show bimodal distributions with a strong peak of low magnitude erosion (c. 15 cm) and a more subdued peak of low magnitude deposition (c. 15 cm). By contrast, all of the other ECDs for all three periods (Figures 7.27B-F, 7.28B-F, and 7.29B-F) show entirely depositional distributions representative of the mask indicating that these are in the SHR placement zone.

In all three periods, the ECDs for the non-habitat and poor quality habitat areas are dwarfed by their low, medium and high quality habitat counter-parts (Figures 7.27B & C versus D, E & F, 7.28B & C versus D, E & F, and 7.29B & C versus D, E & F). This is another way of saying that the projects used most of their gravel making higher quality habitat as opposed to using it on poor quality habitat. This is a good measure of project performance, but hardly surprising given the detailed, hypothesis-testing driven design approach used under SHIRA (Wheaton *et al.* 2004*d*). The iterative design process hones in on a final design that provides the best compromise between providing high quality habitat, optimising the efficiency of gravel used, and a hopefully geomorphologically functional and/or sustainable design.

Table 7.5 summarises these results in terms of volume of gravel placed to create each type of habitat quality. Only 3.4% of the total volume of gravel placed over the three years (2004-2006) was used to create poor quality habitat or non-spawning habitat. Roughly 37.9% was used creating low quality habitat as defined by GHSI.[34] Approximately 38.2% was used creating

[32] Generally between 75% and 90% of redds (Wheaton *et al.* 2004*e*).

[33] GHSI simulations were performed by Elkins *et al.* (2007) for 2003 and 2004, but the data was not located for these analyses.

[34] Note that low quality spawning habitat in hydraulic terms is often made more attractive to spawners by provision of habitat heterogenity elements in close proximity, which provide important shear zone refugia and

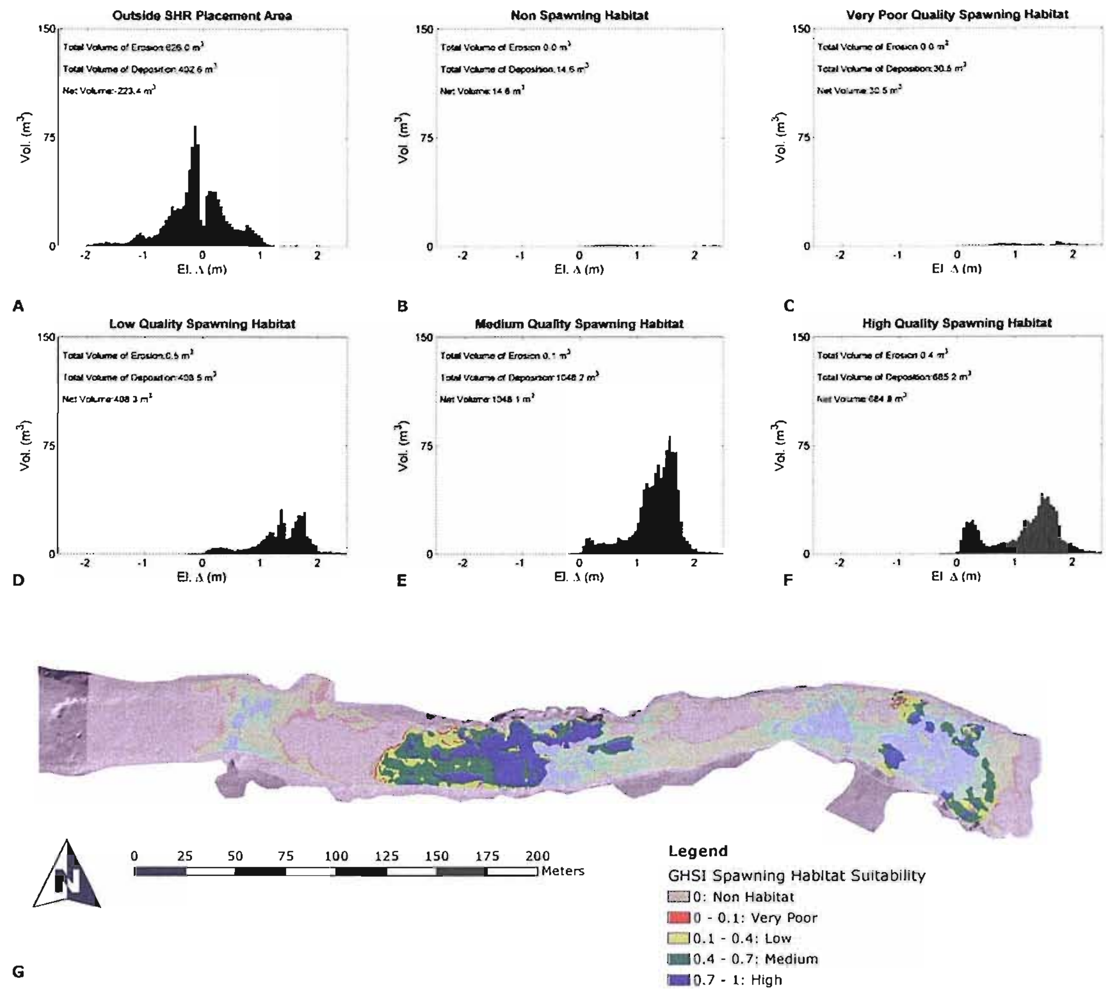


FIGURE 7.28: Elevation change distributions (A-F) corresponding to masks of the DoD from GHSI-predicted spawning habitat suitability classes (G) for TS5 (2005).

Habitat Quality	Volume (m^3) by Project Year			Total Volume (m^3)
	2004	2005	2006	
Outside SHR Placement Area	69.5	402.6	131.2	603.3
Non Habitat	61.6	14.6	32.1	108.4
Very Poor Quality	28.9	30.5	65.9	125.3
Low Quality	597.4	408.8	1607.7	2613.8
Medium Quality	478.0	1048.2	1103.0	2629.2
High Quality	569.9	685.2	158.8	1413.9
Total Volume Placed (m^3)†:	1735.7	2187.3	2967.6	6890.6

TABLE 7.5: Segregation of fill volumes for each SHR project by the quality of spawning habitat (as defined by GHSI) it was used to create, showing the relative consumption of gravel constructing each type of unit. † Note that the total volume is calculated by summing just the portion of recorded deposition in the SHR placement area.

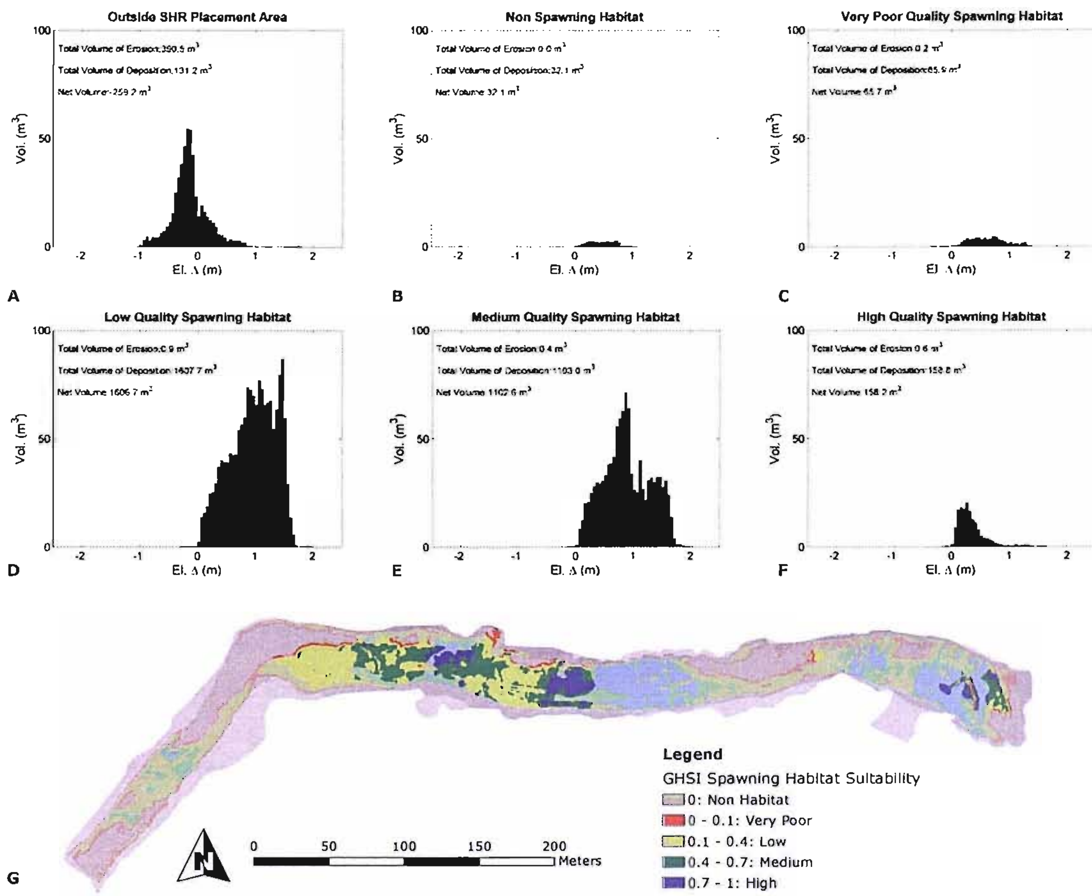


FIGURE 7.29: Elevation change distributions (A-F) corresponding to masks of the DoD from GHSI-predicted spawning habitat suitability classes (G) for TS7 (2006).

		Masks Used:		
Time Step	Description	GI	GHSI	Redds
TS2	2004 Pre Project (1 Year after 2003 Project)	✓	NA	✓
TS6	2006 Pre Project (1 Year after 2005 Project)	✓	CoD	✓

TABLE 7.6: Use of three mask types in analysing DoDs from each time step. Where a ✓is shown, the mask type derived from that TS was used. Where NA is shown, data to produce the mask type was not available. Where CoD is shown, a classification of difference between the two surveys in the time step was used. KEY: GI - Geomorphological Interpretation; GHSI - Global Habitat Suitability Index; Redds - Redd surveys.

medium quality habitat and only 20.5% was used creating the highest quality haibtats.

7.5 Interpreting Monitoring Surveys

In restoration, a common problem is interpreting changes to a restored reach through time (Merz *et al.* 2006, Wohl *et al.* 2005, Gillilan *et al.* 2005). Although there are four years of monitoring data presented here, because the SHR was a multi-year effort it does not represent the response of the system to a single restoration intervention and its subsequent annual adjustment over the following years. This was a five-year project that iteratively improved the same reach of river. As such the monitoring surveys here really only represent the response to the system after a single year. There are only two timesteps (TS2 and TS6), which meet this 'post-project appraisal / monitoring' criteria.[35] For these two annual post project appraisal surveys, the following questions are of interest:

1. What are the geomorphological interpretations of the DoD predicted changes one wet season after construction? (§ 7.5.1)
2. What impact did the changes have on habitat quality? (§ 7.5.2)
3. What changes took place where salmon spawned? (§ 7.5.3)

The same types of masks used in § 7.4 will be used, but in addition redd surveys will be used as a mask to address the third question. Table 7.6 shows the availability of these masks for each time step.

7.5.1 What are the Geomorphological Interpretations?

Perhaps the most common restoration monitoring question is simply to interpret the geomorphological changes that took place to a project and attempt to attribute what mechanisms of

structural cover for both resting and hiding from predation (Wheaton *et al.* 2004*e*). See also, § 7.5.2.

[35]TS4 would have, but does not exist (see § G.4.4).

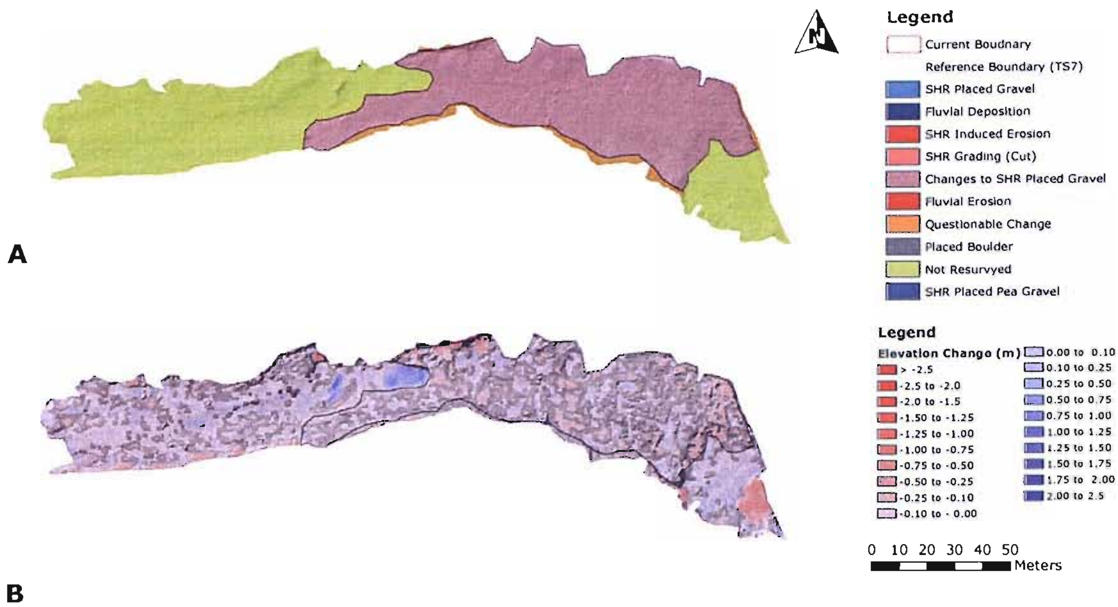


FIGURE 7.30: Masks and DoD associated with the 2004 Pre Project (TS2). A) Geomorphological Interpretation Mask; B) Pathway 4 DoD. Hillshade from the 2004 Pre Project DEM shown in background for context.

change and/or what processes were responsible for these changes. The same classes used for this expert-based geomorphological interpretation which were used in § 7.4.1 will be used here, but some of the categories will not apply (e.g. the SHR gravel placement categories). TS2 and TS6 are a nice contrast here because TS2 represents a drought water-year subjected to a flat-lined flow regime with virtually no competent flows, whereas TS6 represents a very wet water-year in which the maximum controlled dam release from Camanche Reservoir (141.6 cumecs) was realised (see Figure 7.3).

7.5.1.1 TS2: 2003 Post Project to 2004 Pre Project

The year following the 2003 SHR Project placement only produced a peak discharge of 42.7 cumecs (Figure 7.3) and Elkins *et al.* (2007, p. 13) reported no *measurable* differences from the DoDs and predicted 'little to no intermittent or partial sediment transport' from modelling analyses. However, a closer look at the DoD in Figure 7.30C reveals the suggestion of some small magnitude changes and a couple of areas of larger, seemingly coherent, areas of deposition and scour within some of the pools. As the large portion of yellow in Figure 7.30A suggests, these seemingly coherent areas of change actually fall outside the area that was resurveyed and are therefore not real changes.[36] In Figure 7.31, the majority (69%) of volumetric changes in the DoD are shown to be entirely artifacts of TIN interpolation (101.8 m^3 of erroneous erosion and 330.3 m^3 of erroneous deposition).

[36]This is discussed in § G.4.4, whereby the DEM analysis extent was inherited by the CFD modelling domain, and did not necessarily always reflect the true extent of the topographic survey. In other words, areas that did not show evidence of change and were outside the SHR boundaries were not always resurveyed.

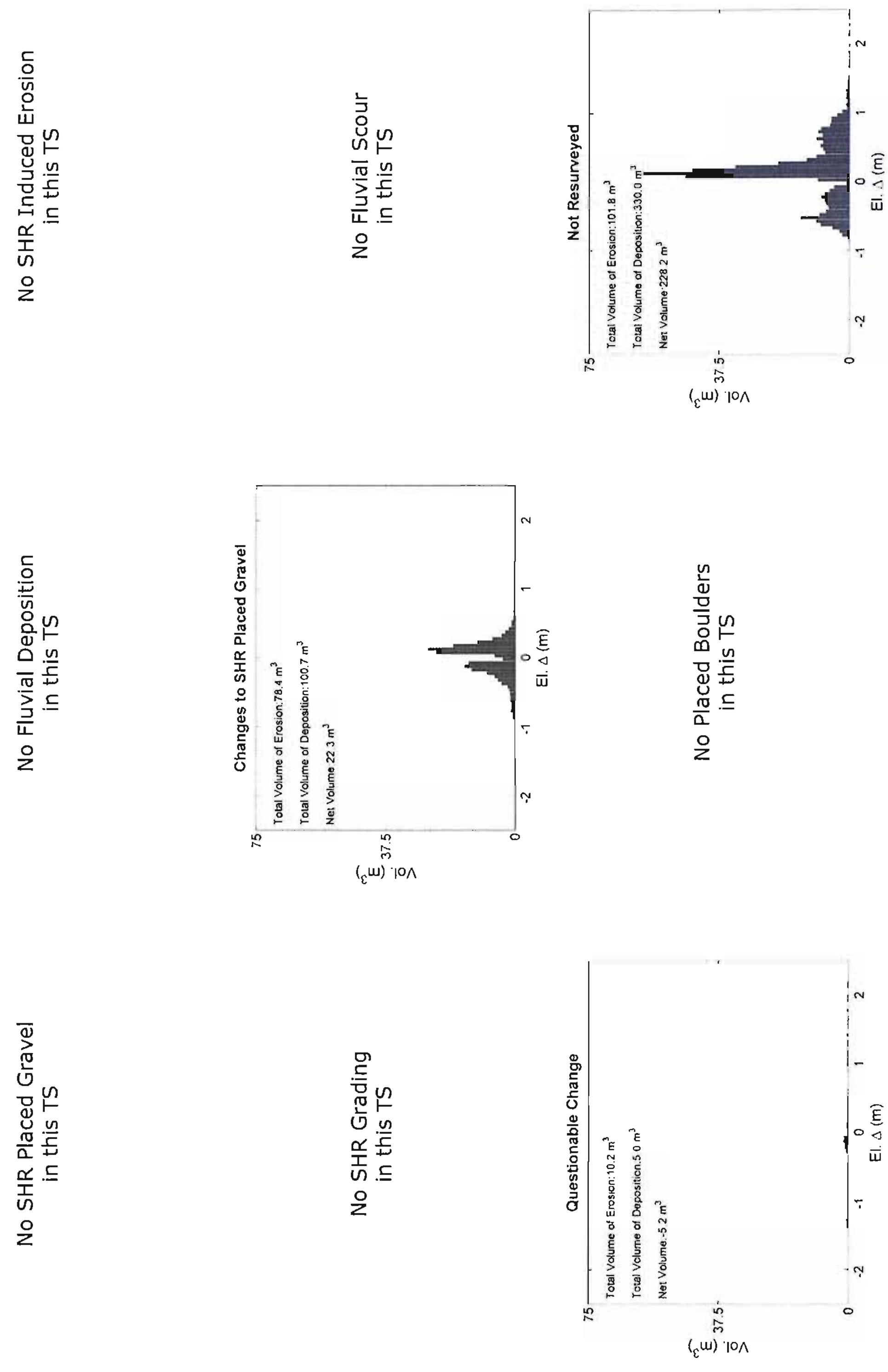


FIGURE 7.31: The elevation change distributions for masks associated with the geomorphological interpretation classification of the 2003 Post Project to 2004 Pre Project (TS2).

However, after this noise is filtered out, roughly 78.4 m^3 of erosion and 100.7 m^3 of deposition are shown to have taken place within the 2003 SHR project area (Figure 7.31). Despite the lack of any significant flow events, these small magnitude changes are certainly plausible. Merz *et al.* (2006, pp. 209-210) postulated that SHR placed gravels exhibit compaction or settling and some degree of gravitational sloughing (particularly around the project periphery where over steepened fill slopes may have resulted). The magnitude of DoD calculated erosion is in keeping with the magnitude of changes Merz *et al.* (2006) estimated theoretically for such mechanisms.

Gottesfeld *et al.* (2004) found that as a result of redd construction, salmonids can play a significant role both in mobilising quantities of bed material locally and, potentially more importantly, in breaking up the armour layer and subsequently lowering entrainment thresholds for subsequent floods. On the Mokelumne Merz *et al.* (2006, pp. 220) measured an average volume of 2.26 m^3 being excavated locally during redd construction.[37] 73 redds were recorded within the 2003 project area in the Fall of 2003.[38] Using the Merz *et al.* (2006) estimate, this would equate to roughly 165 m^3 of potential erosion from redd construction. Thus, the combination of plausible mechanisms of change exceeds the actual measured magnitude of change.[39]

The slight (22.3 m^3) imbalance in favour of net aggradation within the 2003 SHR Project Area raises some questions. Given the lack of competent flows and the nature of the heavily armoured and sediment starved bed in the 200 m between the top of the project and Camanche Dam, it is highly unlikely that a) an upstream source of sediment would be mobilised to provide this net input; or b) that if sediment was mobilised that its step lengths would be long enough to transport it to within the project area. However, the overall magnitudes (c. 75-100 m^3) of material moving are certainly plausible in terms of the settling/compaction and gravitational sloughing mechanisms discussed above. The erosional fraction can be explained by redd construction, settling and/or sloughing mechanisms, and the very short step-lengths material would travel under such mechanisms can explain the depositional fraction. However, even with these mechanisms at work, one would expect a net balance or potentially a slight loss (i.e. net degradation) with losses out of the project area to downstream.[40] Instead the slight aggradational imbalance calculated might be explained in terms of low magnitude elevation changes that fall beneath the minimum level of detection ($_{min}$LoD) threshold and are discarded. This could be exacerbated slightly by a bias in that the $_{min}$LoD is applied equally about zero, which may have a tendency to influence deposition values more than erosion values (Brasington *et al.* 2003).

Although it is difficult with the available data for TS2 to establish accurately what proportion of the changes to the SHR placed gravels are due to which mechanisms, it is relatively straight forward to calculate the magnitude of change in each of the morphological units. This is

[37] Refer back to § 3.2.1 and Figure 3.3 for review of redd construction.

[38] Note, changes produced by the 2003 fall run would correspond to those captured in TS2.

[39] Refer to § 7.5.3 to see how much change was actually measured in areas where redds were found.

[40] Unfortunately, because the deep pool areas downstream of the project were not resurveyed since the 2003 Pre Project, it is not possible for TS2 to infer this on the basis of changes in the downstream pools.

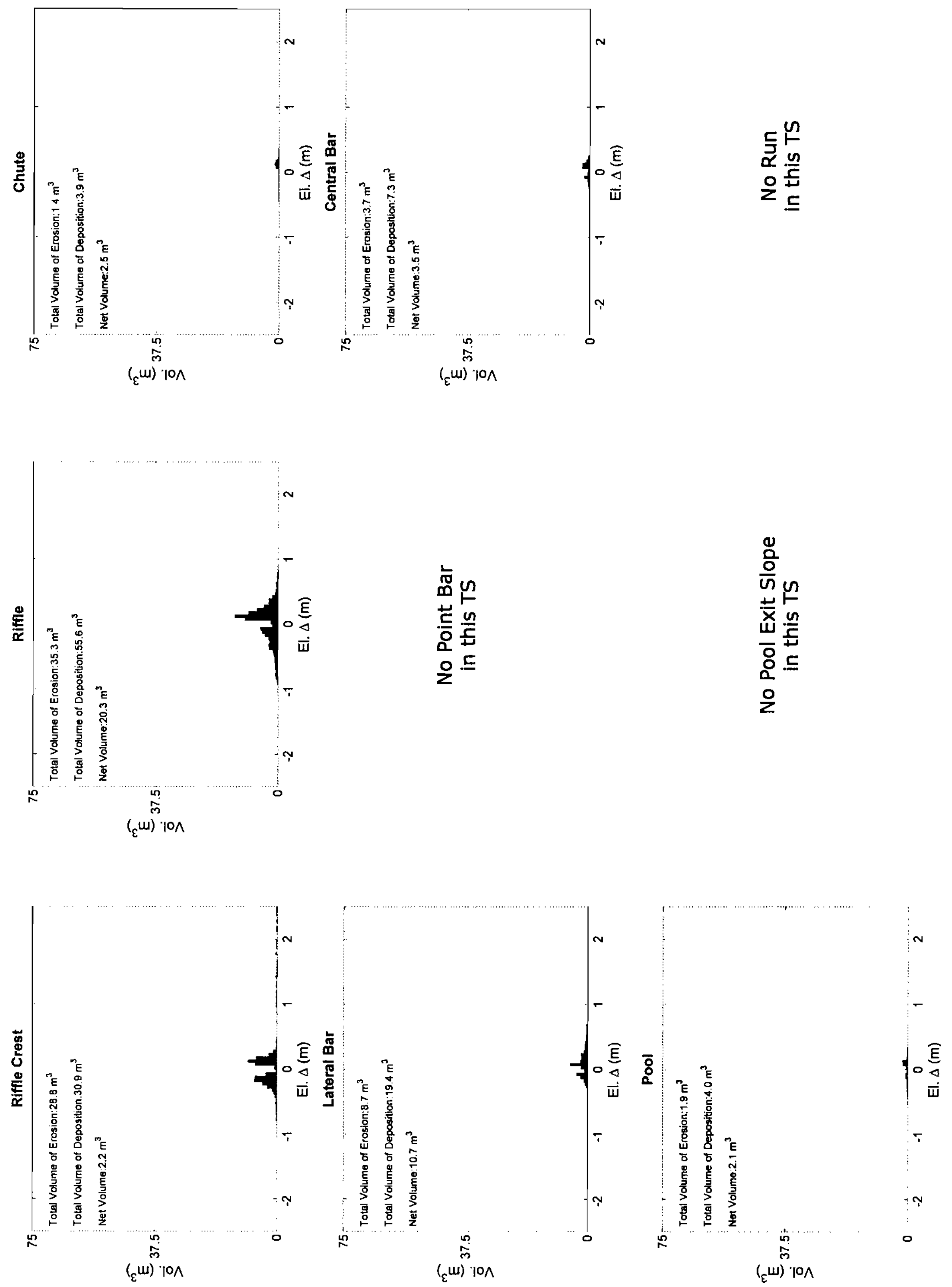


FIGURE 7.32: The elevation change distributions for masks associated with the SHR interpretation classification of the 2004 Pre Project (TS2).

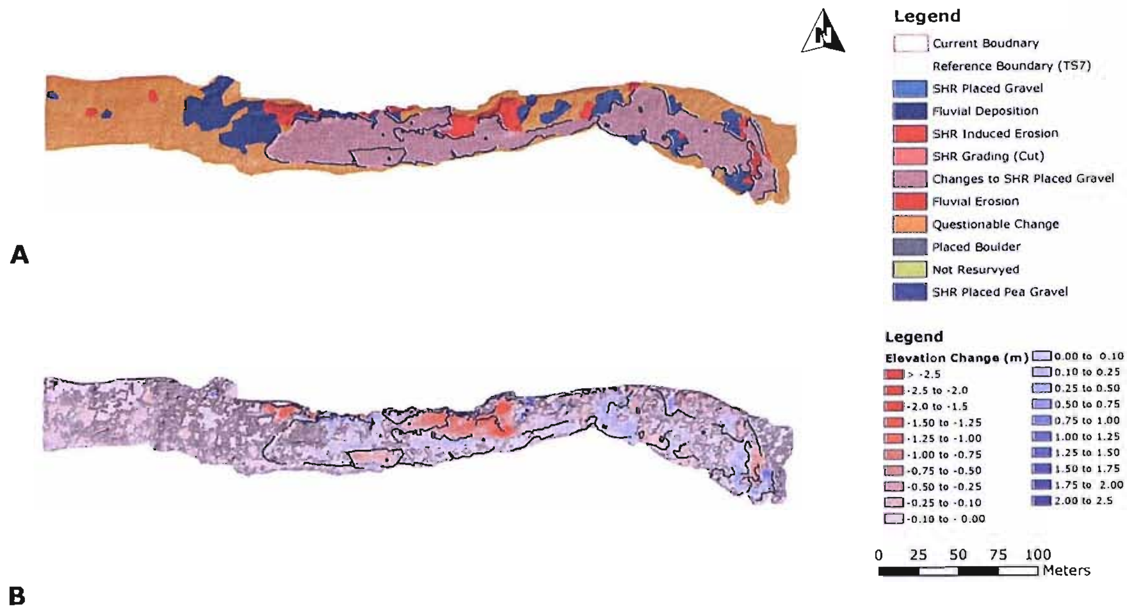


FIGURE 7.33: Masks and DoD associated with the 2004 Pre Project (TS6). A) Geomorphological Interpretation Mask; B) Pathway 4 DoD. Hillshade from the 2006 Pre Project DEM is shown in background for context.

achieved using the same morphological unit classification masks as were originally constructed and delineated in Figure 7.19B. The fate of those constructed morphological units over the course of their first year is explained by the ECDs in Figure 7.32. Roughly 75% of the total volumetric changes are occuring to the constructed riffle or riffle crest.

7.5.1.2 TS6: 2005 Post Project to 2006 Pre Project

The 2005-2006 season (TS6) is the best possible test of the maximum magnitude of event that the study reach is capable of responding to in its current form. Figure 7.1 shows the location of the study site in proximity to Camanche Reservoir. Camanche is only capable of releasing a maximum of 141.6 cumecs as a controlled release, and this is all that can physically be delivered to the study site (barring dam removal or failure). There is a spillway for uncontrolled releases (see again Figure 7.1), but it joins the Mokelumne well downstream of the study site. As shown in Figure 7.3, the 141.6 cumecs release was maintained for over a week as part of the spring snow melt. Although smaller controlled 'pulse flow' releases were released in 2003 and 2005, these 2006 flows were the first real geomorphological test in a high-flow setting of the SHIRA projects.

Figure 7.33A shows the geomorphological interpretation of the observed changes that took place in TS6, in relationship to the DoD (Figure 7.33B). Unlike TS2, the role of natural fluvial erosion and fluvial deposition are playing a larger role. Here the aim is to separate those changes that took place within the SHR project boundary (i.e. to get at the fate of placed gravel) from those changes which took place outside (e.g. fluvial erosion and deposition). The overall ECD of change for this event can be found in Figure 7.6L. This ECD contrasts with all the others in that it shows a much more balanced bimodal distribution, with a prominent erosional fraction. The ECD signature of this water year is characteristic of a natural river: with a high depositional peak of low-magnitude deposition (i.e. broad sheets of deposition) and a more spread out and uniform erosional distribution, reflecting more spatially concentrated areas of erosion but spanning a greater range of scour depths. The magnitude of this 'natural' event pales in significance to the artificial SHR injection events, which are dominated by depositional ECDs (Figure 7.6). However, its 1000 m^3 of erosion and 810 m^3 of deposition are still very significant in the context of the heavily regulated Mokelumne flow regime. The question this subsection wishes to address is what fraction of that overall budget is due to what mechanisms of change?

Figure 7.34 shows the segregation of the budget into five ECDs based on the masks defined in Figure 7.33A. Table 7.7 summarises this information in tabular form and adds the areas. First, the questionable changes are discarded, which account for about 8% of the total volume of change. Outside the SHR area (primarily pools), fluvial scour outpaces fluvial deposition at 25% versus 14% of the total volume of change (i.e. pool maintenance is occuring). It is intersting to note that 47% of the total volume of erosion is taking place outside the SHR placement boundaries (44% inside the SHR boundaries). Within the SHR boundaries, 51% of the total volumetric changes are taking place and here deposition is slightly outpacing erosion (476.0 m^3 versus 445.3 m^3). Figure 7.35 shows the segregation of the TS6 budget by the morphological units defined in TS5 (Figure 7.11A). The ECDs show the phenomenon discussed previously of the riffles and bars generally growing and building, whereas the pools are being scoured out and maintained at high flows. In the context of the SHR, this is quite good because although the habitat is changing the riffles and bars are continuing to build as places of net deposition and the pools are being maintained. This is the first real test of the pool-maintenance design hypotheses proposed in Wheaton *et al.* (2004*d*). Another test is of the Merz *et al.* (2006) observation that boulders were tending to lower themselves through time after placement. Although the placed boulders occupy a negligible fraction of the budget here, they are mentioned in passing as they are almost entirely recording degradation (Table 7.7), which is supportive of the boulder sinking mechanism Merz *et al.* (2006) reported.

7.5.2 What Impact did the Changes that Took Place have on Habitat Quality?

To address this question, the classification of difference technique proposed in § 5.2.1.2 is used. The two classifications employed are the GHSI spawning habitat suitability predictions from the 2005 Post Project to the 2006 Pre Project (Figure 7.36A & B). In each, six categories were considered:

1. Outside 2005 SHR Placement Area
2. Non Spawning Habitat

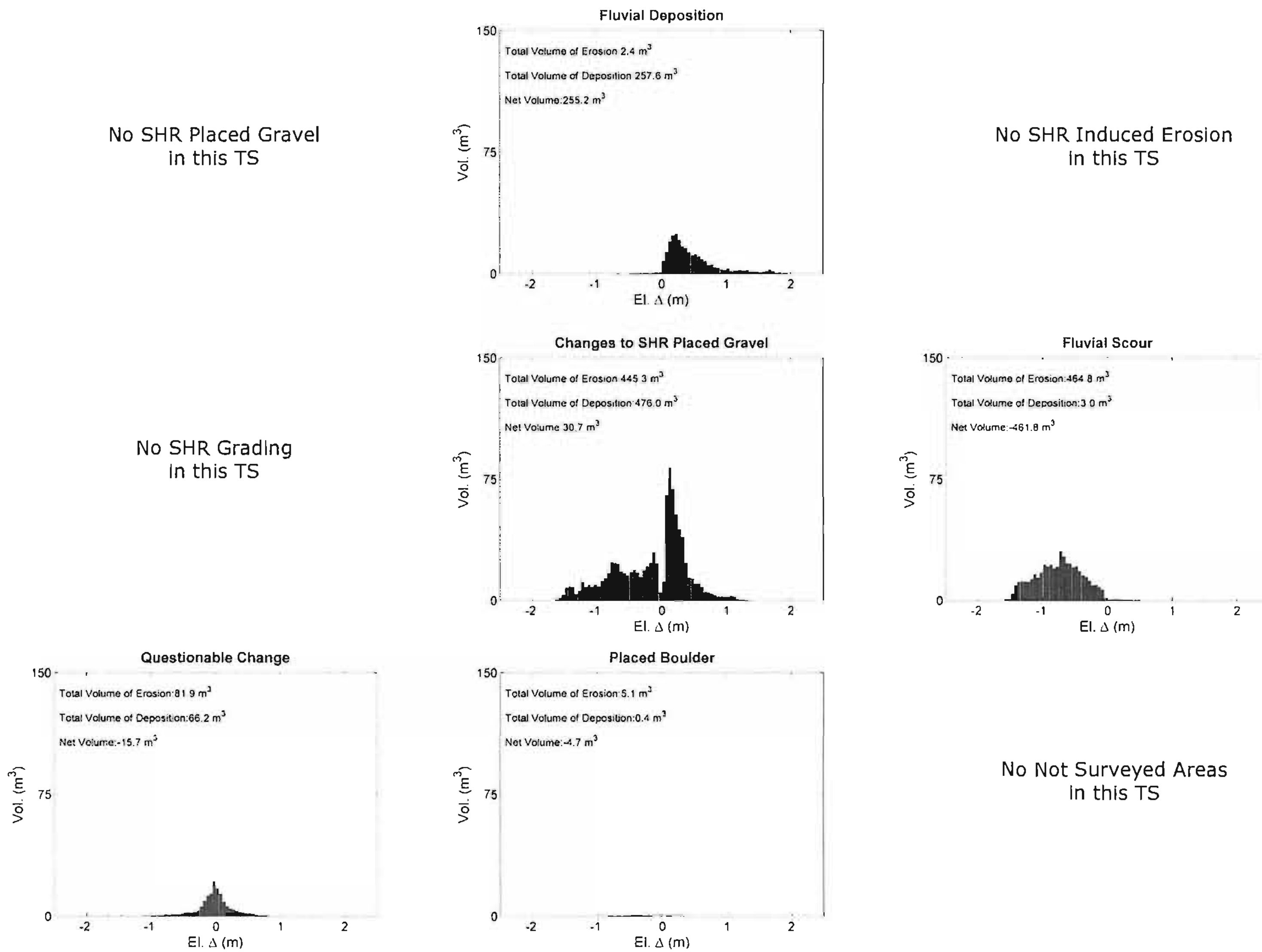


FIGURE 7.34: The elevation change distributions for masks associated with the geomorphological interpretation classification of the 2005 Post Project to 2006 Pre Project (TS6).

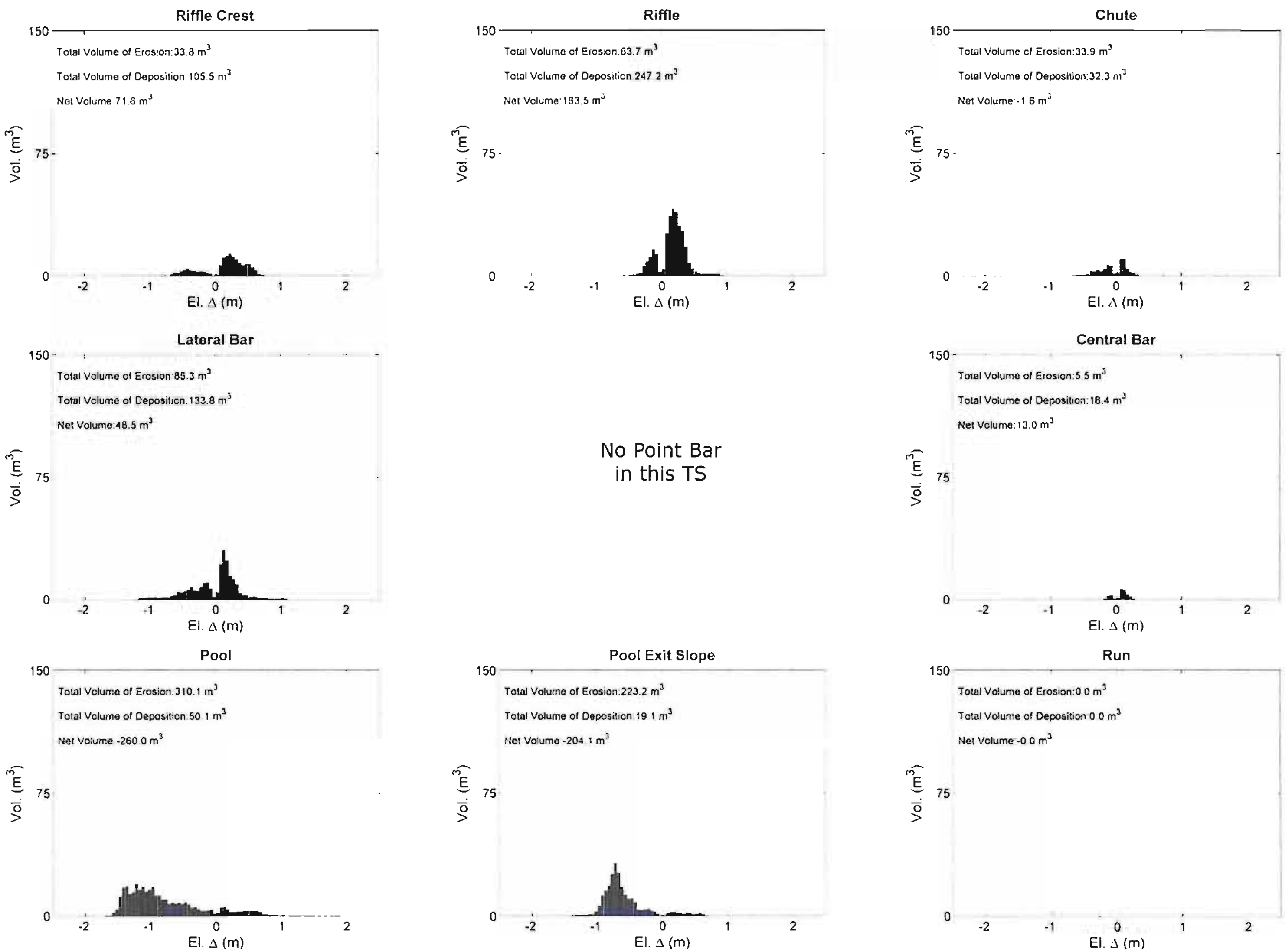


FIGURE 7.35: The elevation change distributions for masks associated with the SHR interpretation classification of the 2006 Pre Project (TS6).

	Erosion Volume (m^3)	Deposition Volume (m^3)	Total Volume (m^3)	Erosion Area (m^2)	Deposition Area (m^2)
Fluvial Deposition	2.4	257.6	260.1	45072.0	1487.8
Changes to SHR Placed Gravel	445.3	476.0	921.4	111393.0	3003.8
Fluvial Scour	464.8	3.0	467.8	21396.0	26.6
Questionable Change	81.9	66.2	148.0	139257.0	1238.3
Placed Boulder	5.1	0.4	5.5	613.0	3.6
TOTAL:	999.5	803.3	1802.8	317731.0	5759.9

TABLE 7.7: Segregation of the TS6 budget by geomorphological interpretation.

3. Very Poor Quality Spawning Habitat
4. Low Quality Spawning Habitat
5. Medium Quality Spawning Habitat
6. High Quality Spawning Habitat

Thus the classification of difference had 36 categories. The six CoD categories for the areas outside the 2005 SHR placement area were discarded so the analysis focused on the project itself. The remaining 32 categories were simplified into three classes whereby habitat quality either remained the same, improved or degraded (Figure 7.36C). This question is only addressed for TS6 because there were negligible geomorphological changes in TS2 and the GHSI mask for the 2003 Post Project (necessary to calculate a difference in TS2) was not available.

Figures 7.37 A, B & C show the primary results of the analysis with three ECDs for the habitat change categories. The top portion of Table 7.8 tabulates the same results. Over 53% of the area in which gravel was placed in 2005 retained the same habitat quality characteristics, as predicted by GHSI. Interestingly, this stable habitat class shows the most balanced ECD (although it is depositionally biased; Figures 7.37A) and only accounts for 19.5% of the total volumetric change to the SHR area. By contrast, the improved and degraded habitat quality class masks account for 34.5% and 46.0% of the total volumetric change, respectively (Figures 7.37 A & B). The improved and degraded classes also make an interesting contrast geomorphically through their ECDs. In general, habitat degradation was associated with erosion and habitat improvement was associated with deposition. Both the stable and improved class ECDs have their most pronounced peak in areas of shallow deposition (10 to 25 cm), with the stable class favouring shallower deposition. The habitat degradation class ECD has its erosional peak at about 75 cm. This is primarily due to the erosion and resculpting of the pool-exit slope[41]. While such a change does result in a reduction in habitat quality by simple hydraulic criteria, pool-exit slopes tend to be hot-spots of spawning activity due

[41] Described in § 7.5.1.2.

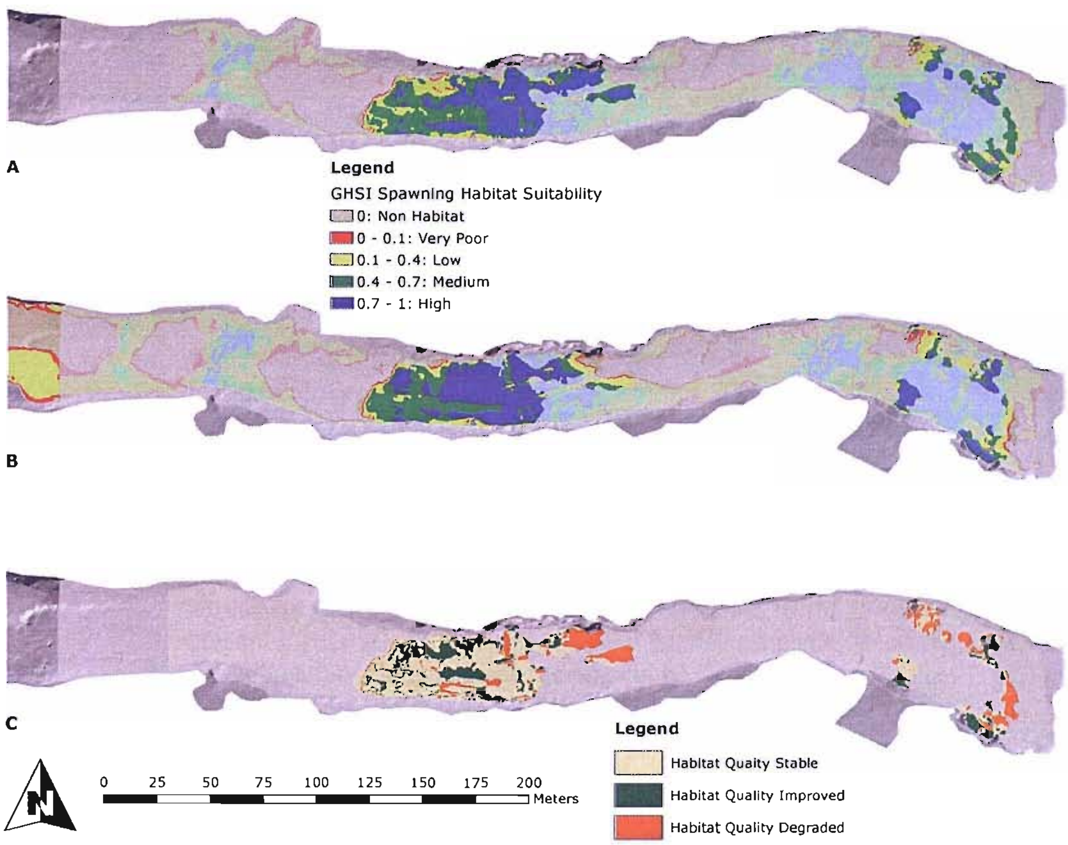


FIGURE 7.36: The derivation of the habitat suitability classification of difference for TS6. Habitat quality was compared on a cell by cell basis from the beginning of the time step (Fall 2005: sub-figure A) to the end of the time step (Summer 2006: sub-figure B) to calculate where habitat quality remained stable, improved or degraded in sub-figure C. The changes in habitat are due to the geomorphological changes which occurred during TS6 (see text and § 7.5.1.2). The grayed out areas reflect those areas outside the SHR placement zone and outside the analysis extent.

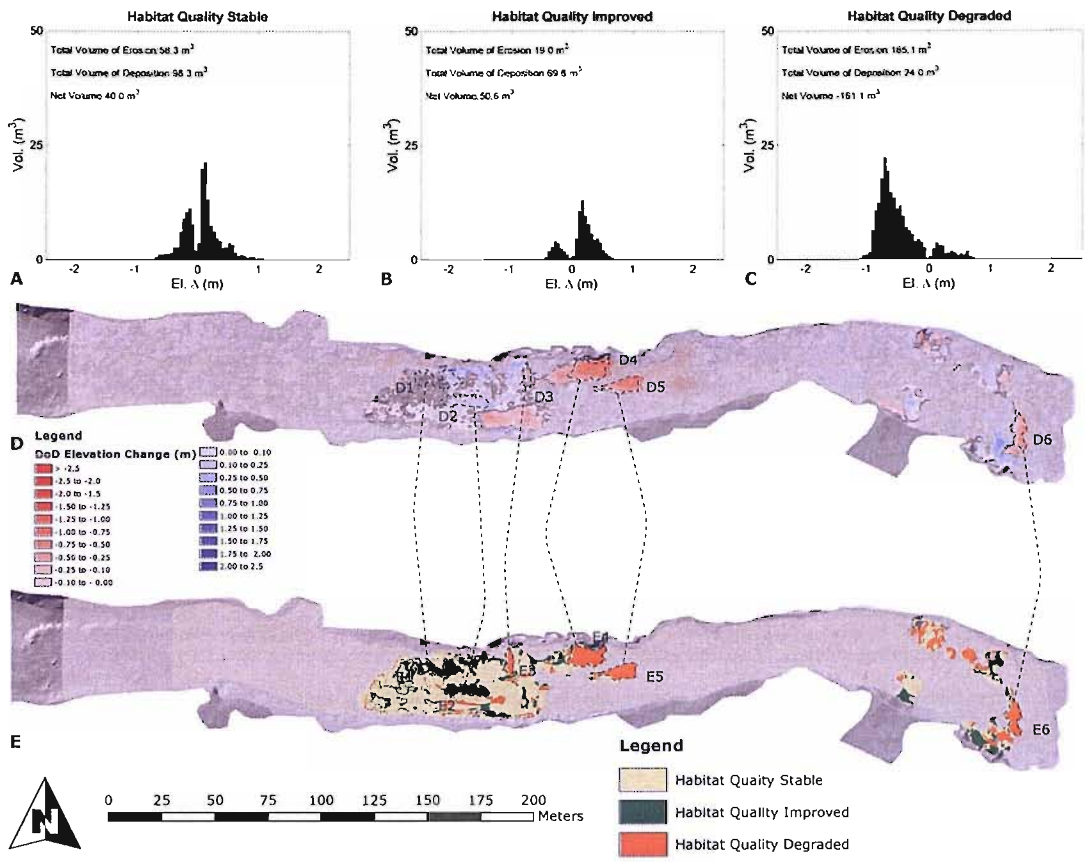


FIGURE 7.37: The elevation change distributions (A-C) from the masks based on the habitat quality classification of difference (E - see also Figure 7.36) derived from the thresholded DoD for TS6 (D). The ECDs correspond to the three different CoD categories: habitat quality stable (beige in E), habitat quality improved (green in E), and habitat quality degraded (orange in E).

to their proximity to deep pool refugia from predation and increased hyporheic downwelling (Geist 2000, Wheaton *et al.* 2004*e*, Geist & Dauble 1998).

To further differentiate these results, the specifics of habitat stability, degradation and improvement CoDs are shown in the bottom three-fourths of Table 7.8. From the fourth column, it is encouraging to note that the highest recorded percentage of the SHR area remained high quality (at 29%). As these percentages of the area are largely a reflection of the distribution of habitat qualities, it can be helpful to normalise the percentages by calculating them with respect to their specific habitat quality class (e.g. very poor, low, medium or high) (column five in Table 7.8). From this, the majority of high quality habitat remained high quality habitat (67%). Additionally, across the habitat quality classses there are consistently higher percentages of habitat improvement than habitat degradation.

Thus, it can be concluded that changes associated with a wet water year and the largest possible flow releases from Camanche Dam actually resulted in a net improvement to constructed habitat quality. Whether this result is transferable through time or just represents a natural initial adjustment following a restoration intervention can not be said. However, it is inter-

	Erosion Volume m^3	Deposition Volume m^3	Percentage of SHR Area %	Percentage of Habitat Class %
Overall				
Habitat Improvement	19.0	69.6	22%	NA
Habitat Degradation	185.1	24.0	25%	NA
Habitat Stable	58.3	98.3	53%	NA
Improvement Details				
Very Poor Quality Improvement	0.4	1.1	0%	30%
Low Quality Improvement	3.6	25.2	6%	44%
Medium Quality Improvement	14.9	42.5	15%	38%
High Quality Improvement	NA	NA	NA	NA
Degradation Details				
Very Poor Quality Degradation	0.5	0.4	0%	20%
Low Quality Degradation	15.4	1.0	2%	14%
Medium Quality Degradation	58.3	10.6	8%	21%
High Quality Degradation	110.9	12.1	14%	33%
Stable Details				
Remained Very Poor Quality	0.9	1.5	0%	50%
Remained Low Quality	6.9	19.3	6%	43%
Remained Medium Quality	17.6	31.1	16%	40%
Remained High Quality	31.9	43.2	29%	67%

TABLE 7.8: Summary of classification of difference between 2005 Post Project and 2006 Pre Project GHSI-predicted habitat suitability for TS6. The percentage of SHR Area is calculated by comparing the area of the said CoD class to the total area within the SHR placement boundary mask. The percentage of habitat class is calculated by comparing the area of the said CoD category (e.g. improved, degraded or remained) to the total area in the quality class (e.g. low, medium or high quality).

esting to note that the patterns of habitat degradation were consistently more closely related with higher magnitude scour (generally above typical egg burial depths); habitat improvement was associated more with shallow deposition; and that habitat stability (not surprisingly) was associated with lower magnitude changes altogether. It is speculated that these correlations as revealed by the ECD masks are probably more generally transferable. It is also encouraging that these geomorphological changes are occurring spatially where they were designed to (i.e. degradation at flow with constrictions and aggradation at flow width expansions) even at the highest possible flows for the Mokelumne (Wheaton *et al.* 2004*d*).

7.5.3 What Changes Took Place where Salmon Spawned?

A related question to the changes in spawning habitat quality is whether or not the types of habitat that attract spawners are prone to particular types of change. Wheaton *et al.* (2004*d*, Figure 8) showed that for spawning flows, the habitat patches that attract spawners are typically not prone to erosion. This is not a surprising result - fish are not going to spawn where erosion is actively taking place as they will not be able to safely bury their eggs. However, following spawning, the occurrence of erosion producing scour beyond the burial depth of eggs is certainly possible if high (competent) flows concur with the incubation period.[42] On the Mokelumne, two factors make such events highly unlikely. First, the Mokelumne is naturally a spring snow-melt dominated river, which typically produce such events later in the spring well after the incubation period. Secondly, the Mokelumne now suffers from a completely regulated flow regime, and dam operations are such that competent flow releases are not made during the incubation period. Thus, in the context of the Mokelumne, this is not so much a question of whether changes to spawning habitat will be detrimental to spawning or incubation success, but rather whether spawners tend to select sites that are likely to change (geomorphologically) or stay the same. There are two possible time steps this question can be asked of (TS2 and TS6).

For the TS2 (2003-2004) season, there were no competent flows to make make major changes to the 2003 SHR project morphology. Of the 807 redds in the 2003 Fall run on the Lower Mokelumne, 72 spawned in the 2003 site following its construction (Table G.1). According to Figure 7.38A, changes where redds took place only amounted to 7 m^3 of erosion and 4 m^3 of deposition. Although this is a far cry from the 2.25 m^3 per redd that Merz *et al.* (2006) estimated, it is not necessarily surprising. The redds covered only 83.2 m^2 of surface area (lots of superimposition) of an area that only received 190 m^3 of erosion and 436 m^3 of fill. In reality, redd construction might have been responsible for moving a much greater volume of sediment locally, but the resolution of the topographic surveys was not fine enough to discriminate redd morphologies. Therefore, the small volumes of erosion and deposition calculated in areas where there were redds should not be expected to resolve differences due to redd construction. Instead, this mask is just picking up a fraction of the small magnitude changes to the 2003 SHR Placed gravel area. These changes were attributed largely to compaction and sloughing mechanisms in § 7.5.1.1. Although the magnitude of change was small in TS2, it can be said that 58% (48.3 m^2) of the redds were found in areas that experienced some erosion and 42% (34.9 m^2) were found in areas that experieced some deposition. None of the erosion was greater than 45 cm, with most peaking below average burial depths for Chinook redds at 15-20 cm.

In contrast to TS2, the TS6 (2005-2006) season produced the maximum controlled release available to the lower Mokelumne River.[43] As described in § 7.5.1.2, a reasonably interesting suite of geomorphological changes due to natural fluvial processes accompanied this event. As such, it is probably a better test of the question posed in this section as to whether or not fish tend to spawn in areas that are more or less prone to either depositional, erosional or stable areas. There were 196 redds found in areas where gravel was placed in 2005 (478 in the study reach and 2157 in the entire LMR - the highest ever recorded; see Table G.1). Of these 196 redds, 45% (600.3 m^2) covered areas that came to experience erosion later in the season and 55% (729.0 m^2) covered areas that came to experience deposition later in the season. Thus,

[42] See also discussion of scour during incubation period in § 6.7.

[43] Uncontrolled releases only occur on a spillway that is positioned to overflow downstream of the entire study reach.

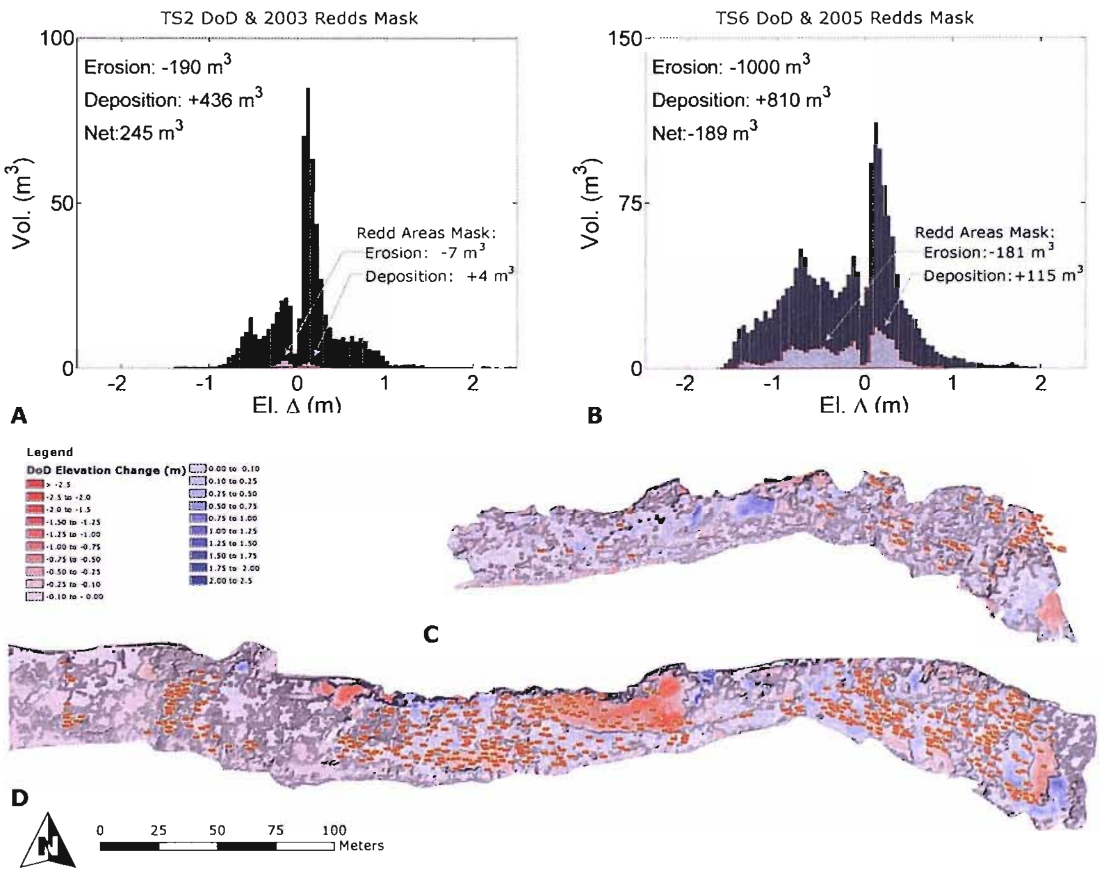


FIGURE 7.38: The use of redd surveys as a DoD Mask. The redd surveys for 2003 (C) and 2005 (D) are shown overlaid on top of the corresponding DoDs for TS2 and TS6 respectively.Using each redd as a mask, the ECDs in A (for TS2) and B (for TS6) show what proportion of the total thresholded DoD ECD reflects subsequent geomorphological changes in areas where redds were observed.

between the two years, there is no consistent preference on the binary test for erosional versus depositional areas.

With the higher density of redds in 2005, the redd mask came to cover a higher percentage of the overall volumetric budget at 18% of the total erosion and 14% of total deposition. The redd ECD in Figure 7.38B also spanned a greater range of erosion and fill depths with up to 1.5 m of erosion and up to 1 m of deposition. In terms of the longer-term significance of these observations (i.e. to the next spawning season), the analysis in the previous section on habitat quality are worth reviewing (§ 7.5.2). Over 54% of the redds were in areas where habitat quality remained the same, only 20% were in areas where habitat quality improved, and 26% were in areas where habitat quality decreased. Thus, 74% of redds were located in areas that would still be suitable habitat in the next spawning season.

In summary, on the basis of this limited dataset, there is inconclusive evidence to support or refute the idea that redds may have a preference for habitat types that are prone to either erosion or deposition versus stability. The technique of using redd surveys as a DoD mask might prove more fruitful as a tool for assessing threats to egg survival during the incubation period if surveys were performed following events during the incubation period. The technique would also be interesting to apply to datasets where topographic surveys were specifically performed at resolutions to resolve the morphology of redds. There, the mask could be used to calculate the net amount of material moved by salmon versus floods, a question considered by Gottesfeld *et al.* (2004) and Hassan *et al.* (2002). In this context, the technique is still insightful for directly answering the question of what changes took place where salmon spawned.

7.6 Conclusions

The purpose of this chapter was to demonstrate how various masking techniques for segregating morphological sediment budgets in conjunction with a DoD uncertainty analysis can be interpretively powerful in a restoration monitoring context. Three questions related to interpreting as-built surveys and three questions related to interpreting monitoring surveys were addressed.

Focusing first on the as-built questions, the main findings as they relate to four consecutive years of construction of spawning habitat rehabilitation (SHR) projects on the Mokelumne River in California are as follows. Using simple construction masks and DoD uncertainty analyses, 8226.3 m^3 of gravel actually placed as part of the four SHR projects was separated from the total of 9277.5 m^3 of deposition calculated in the DoDs after accounting for uncertainty. A further segregation of these areas into the constructed geomorphic units revealed that over 41% of the total volume of gravel placed was in the form of riffles, 26% in lateral bars, 14% in chutes and 10% in point bars. In terms of the quality of spawning habitat these gravel placements helped produce, more gravel was spent creating low and medium quality habitat then high quality habitat. Each of these analyses are useful in terms of a) addressing how well the constructed project matched the design, b) considering whether or not project objectives were met, and c) articulating specifically how the projects were implemented.

Only two years of post-project appraisal annual monitoring surveys were available from the Mokelumne River projects. These represented two end-members of flow-regulation on the lower Mokelumne. The first was a drought year in which the flow regime was flat-lined throughout the year with only a minor 42.7 cumec release associated with spring snow-melt. The second was a large water year in which the maximum possible flow release from Camanche Dam was realised (141.6 cumecs). In the drought year there were essentially negligible geomorphological changes (78.4 m^3 of erosion and 100.7 m^3 of deposition) to the SHR project from the previous year. These changes are thought to be largely due to compaction, settling and gravitational sloughing of the newly placed gravels as well as salmonid redd construction. In the high-flow year, by contrast, fluvial processes both within the SHR placement boundaries and outside it produced over 1000 m^3 of erosion and 810 m^3 of deposition (compared with 2018 m^3 of gravel placed in the reach the year before). Although there was a net loss of material from the project area, most of the reworked gravels remained in the project areas. Of key importance was that during high-flows deposition was taking place in the best spawning habitat areas such as riffles and the large regions of scour were focused in and along pools.

During the high-flow year (Fall 2005 to Summer 2006) net changes in spawning habitat quality (as predicted by a 2D habitat suitability model) were compared against the DoD changes. These revealed that 53% of the reach retained its same habitat quality as a result of the high flows, but that 22% improved and 25% degraded. Only 19.5% of the total volumetric changes took place in areas that retained the same habitat quality, with over 46% of the volumetric changes taking place where habitat quality improved. In general, the areas experiencing habitat degradation were associated with higher magnitude scour and areas experiencing habitat improvement were associated with shallow deposition; whereas areas retaining their habitat quality were generally only subjected to even lower magnitude changes. Redd surveys were used as masks to address whether or not salmon may naturally select redd locations that are prone to erosoion, or deposition or stable areas. The survey data was not dense enough to resolve redd morphologies themselves, so the changes were not reflecting redd construction. As there was only one year of significant fluvial changes, the dataset was not large enough to definitively answer this question. However, in the 2005-2006 water year, over 74% of the 2005 Fall-run redds were located in areas that would still provide suitable spawning habitat the following year.

From a restoration monitoring perspective, the DoD uncertainty analysis and masking tools aid in making much more meaningful and informed interpretations of the topographic monitoring data then previously possible. From a geomorphological perspective, the heavily regulated flow regime of the Mokelumne River provides only rare opportunities to explore significant geomorphological changes post-restoration. However, when such changes did present themselves, the DoD uncertainty analysis and masking tools enabled direct answers to a range of geomorphological and ecohydraulic questions.

Chapter 8

River Feshie - Investigating the Dynamics of a Braided River in the Scottish Highlands

8.1 Introduction

The River Feshie, in the heart of the Scottish Highlands, is an anomaly in the contemporary British Isles landscape. It boasts an unconfined 3 km-long braided reach and active braidplain, set within a longer, actively wandering 8 km reach called Glen Feshie. The Glen itself is a glacial trough, which was deglaciated roughly 13,000 BP (Gilvear *et al.* 2000) and is flanked by impressive fluvio-glacial terraces on the valley sides (Robertson-Rintoul 1986). The river has an abundant supply of fluvial and fluvio-glacial sediments to rework from its own valley floor (Figure 8.1). Combine this with the unregulated and flashy flow-regime of the Feshie (Soulsby *et al.* 2006), its credence as a classic Scottish salmon stream (Gardiner & Mackay 2002, Grant *et al.* 2006), and an upper catchment that drains 'some of the steepest, most mountainous terrain in the United Kingdom' (Soulsby *et al.* 2006) it is no wonder the Feshie has been the subject of so much geomorphological[1], hydrological[2], and geological[3] research for so long. Gilvear *et al.* (2000) called the Feshie 'the best example of a relatively natural highly active gravel-bed river in the UK...' and credited the rich vegetation diversity on its alluvial fan to this dynamism. For these impressive fluvial traits, the Feshie is designated as a Site of Special Scientific Interest by the Joint Nature Conservation Commission under the Wildlife and Countryside Act of 1981 (Werritty & Brazier 1991, Werritty & McEwen 1993).

For five years from the late 1970's, two sub-reaches of this braided[4] reach in the Feshie were

[1] For example, Gilvear *et al.* (2000), Ferguson & Ashworth (1992), Ferguson & Werritty (1983), Rumsby *et al.* (2001), Werritty & Ferguson (1980), Brasington *et al.* (2000), Brasington *et al.* (2003) and Robertson-Rintoul (1986).

[2] For example, Soulsby *et al.* (2006), Rodgers *et al.* (2005), Soulsby *et al.* (2005) and Rodgers *et al.* (2004).

[3] For example, Bremner (1915), Golledge (2004), Brazier & Ballantyne (1989) and Young (1976).

[4] Note that Ferguson & Werritty (1983, p.181) refer to this reach as 'wandering' instead of braided in keeping

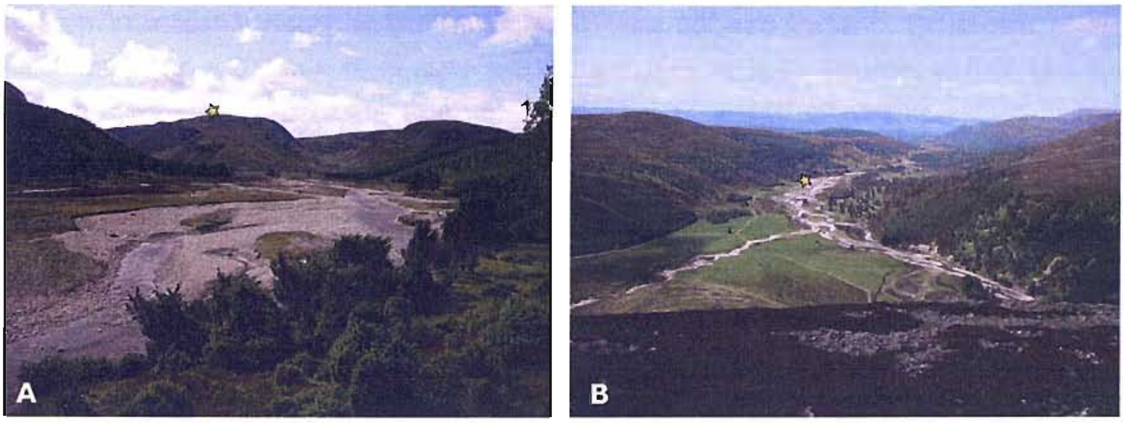


FIGURE 8.1: Context photographs of Glen Feshie. A) View looking South (up valley) at the study reach from Glen Feshie Lodge (star in photo B) B) View looking North (down valley) from on top of the ridge (star in A).

extensively studied by Ferguson & Werritty (1983).[5] They studied two sub-reaches of the Feshie from 1976 to 1981: the 'bridge reach' and the 'tree reach'. The 'tree reach' is a 160 m long, 60 m wide sub-reach in the middle of the 1 km long 300 m wide study reach used here (see Figure 4.1 for their respective locations). Their study was focused on mechanisms of bar development and channel evolution as inferred by tracking channel changes on an annual basis using repeat transect and planform surveys.[6] From their measurements and observations, Ferguson & Werritty (1983, Figure 3) produced a conceptual model of diagonal-bar development, which helped explain some of the observed changes in the Feshie. In the first-stages of their model, bar progradation at high-flows forces bank erosion on the opposite side of the channel at lower and intermediate flows, which feeds the growth of the next diagonal bar downstream. The process is eventually interrupted either by chute dissection of the downstream bar, or avulsion outside the channel from ponded-pool overflow. Such a simple model is an elegant example of how basic quantitative field observations, can be synthesised qualitatively to produce a clearer understanding of the channel kinematics.

At the time, the work of Bluck (1976) and Werrity & Ferguson (1980) were the first known examples of repeat surveys of bar-development and channel changes in a braided reach. As part of those campaigns, Ferguson & Werritty (1983) used instrumental levels to resurvey 60 m transects across the 160 m long reach and mapped planform changes with a tacheometric plane-table and alidade. The surveys were completed annually each summer for five years (1976 to 1981). For the transects, they surveyed elevations every 2 m along nine 60 m parallel transects, spaced 20 m apart (circa 270 points) - an impressive effort given the technology. Just 1.2 km upstream and 20 years later, Brasington *et al.* (2000) and Brasington *et al.* (2003) started undertaking repeat topographic surveying using survey-grade rtkGPS (real time kinematic global positioning system) capturing the three-dimensional geometry of fluvial

with Church & Rood (1983). That distinction is not observed here for simplicity, and the reach is simply termed braided.

[5]Building on work by Werrity & Ferguson (1980) and Werritty (1984).

[6]In other words, this was a classic 1D implementation of the morphological method (see § 3.3.1.2).

surfaces at a spatial resolution probably unimaginable 20 years earlier.[7] Brasington *et al.* (2000) surveyed a 200 m x 80 m reach in 1998 and 1999 at point densities of 0.69 to 1.10 pts/m^2 (circa. 10,000 to 14,000 points). In 2000, a long-term monitoring annual repeat surveying monitoring campaign[8] was resurrected in a roughly 1 km stretch of the Feshie containing the 'tree reach'. The GPS surveys were used to acquire between 30,000 and 50,000 points each year with point spacing varying between a point every 25 cm in areas of topographic complexity to up to every 2.5 m over flat areas of braid-plain (Brasington *et al.* 2004, Wheaton *et al.* 2004*a*, Wheaton *et al.* 2007). The reach can be surveyed in about 25 person-days, and this is typically now accomplished in a week's time with 3-5 rovers deployed simultaneously. Starting in 2006, the reach was also surveyed concurrently with a terrestrial laser scanner, collecting upwards of 1000 points per second, resolving grain-scale morphological features and producing overall point-clouds on the order of 25 to 50 million points (Brasington *et al.* 2007).

There is no question that advances in technology over the past 25 years have enabled an unprecedented expansion in the spatial scope and spatial resolution of data that can be collected and captured (Lane & Chandler 2003). In just these Feshie examples, the GPS pushed the volume of data acquisition up two orders of magnitude, with similar effort; whereas the terrestrial laser scanning has expanded the volume of data a whole five orders of magnitude! Impressive as the this may be, the real question is whether or not the additional data is delivering better mechanistic understanding of how such systems function? One of the premises for pursuing the second objective of this thesis[9] was that, to date, the modern high-resolution surveys have not yet effectively taken advantage of the wealth of data and information locked up in their topographic data sets. There have been very interesting and necessary methodological developments to demonstrate how to apply these new technologies and more robustly identify their inherent uncertainties.[10] However, can the increased spatial resolution and extent that comes from these developments be used to meaningfully extend the type of Ferguson & Werritty (1983) observations and inferences at the bar-scale to analyses across entire reaches? If so, a better understanding of the relative importance of different processes at bringing about observed channel changes might be revealed.

The purpose of this chapter is primarily to describe the dynamics of a braided river (for a four year period) in the Scottish Highlands (the Feshie) and secondarily to demonstrate how the methods developed in Chapter 5 for making geomorphological interpretations from morphological sediment budgets can be used when monitoring a relatively dynamic system exhibiting a broad range of fluvial processes. It is asserted that new tools or techniques[11] are needed to learn how to better exploit these more complicated topographic datasets[12], in

[7]See Figure 4.1 for relative locations of study sites.

[8]See § 4.2 for description of this field campaign.

[9]Of making more meaningful mechanistic geomorphological interpretations of repeat topographic surveys. See § 1.3.2 and § 3.4.

[10]For example, the developments in Chapter 4. See Chapter 3 for a review of these developments.

[11]Such as those proposed here (see Part II).

[12]Such topographic datasets include both those collected by conventional ground-based methods (total station and GPS), as well as terrestrial laser scanning. This chapter focuses exclusively on conventional GPS

a manner that allows a return to the mechanistic explanations of the likes of Ferguson & Werritty (1983). If such a mechanistic understanding can be upscaled from the bar-scale to larger reach-scales, then a clearer understanding of the relative importance of different styles of change and their interdependence on each other may be achieved.

This is the final of the three case studies of geomorphological channel change that comprise Part III. It will also be the most concise for the following reasons:

1. The Feshie study site does not need to be reintroduced as this was already done in § 4.2, justified in § 3.5 and § 5.3, and outlined in more detail in Appendix A.

2. Unlike the previous two chapters, the application of the DoD Uncertainty Analysis techniques from Chapter 4 does not need to be presented, as they were already reported for the Feshie in Chapter 4. Thus, the thresholded DoDs from a pathway 4 analysis presented in Figure 4.29, are the starting point for the analysis here. That is, DoDs that have had a full spatially-variably accounting of uncertainty analysis and application of a spatial coherence filter will be used. These are thresholded at a 95% confidence interval so as to be reasonably confident that real changes are distinguished from the noise.

3. As the method and utility of various masking techniques proposed in Chapter 5 have already now been demonstrated in the previous two chapters, the only mask applied here is an expert-based geomorphological interpretation masking technique.

Thus, this chapter will begin with an overview of the four year study-period from 2003 to 2007 (inclusive) and the primary drivers of change in that time. It will then proceed into the a detailed analysis of the sequence of change for each of those periods. The reader may find it helpful to refer back to § 4.6, which presented the basic sequence of change at a coarse reach scale with different pathways through a DoD uncertainty analysis. This chapter will close with a discussion of how the analyses can be used to address some more specific questions about the evolution of particular bar complexes, confluences and diffluences within the reach.

8.2 Overview and Drivers of Change

Four analysis periods fall out of the five annual surveys reported here. As the intermittently occupied Carnachuin Bridge gauge[13] is no longer rated, flow records for the study reach were not available. Instead, SEPA's Feshie Bridge gauge (some 7 km downstream) is used here as a proxy for the flows and event drivers of change at the site (Figure 8.2). The catchment area of the study site is roughly 47% of that at Feshie Bridge (110 km^2 versus 231 km^2). The mean

data sets as there are five years of record (only two for the terrestrial laser scan data), and even this has not yet been exploited.

[13]This gauge is located on a wooden foot bridge in the Ferguson & Werritty (1983) 'bridge reach'(Figure 4.1). The station was occupied in 1978-1981 by the University of St. Andrews (Ferguson & Werritty 1983); again in 2004 as part of the CHASM project (Soulsby *et al.* 2006), and most recently by the University of Cambridge in 2006 (p. comm Cox). To the knowledge of the author, the section was only rated in 1978-1981.

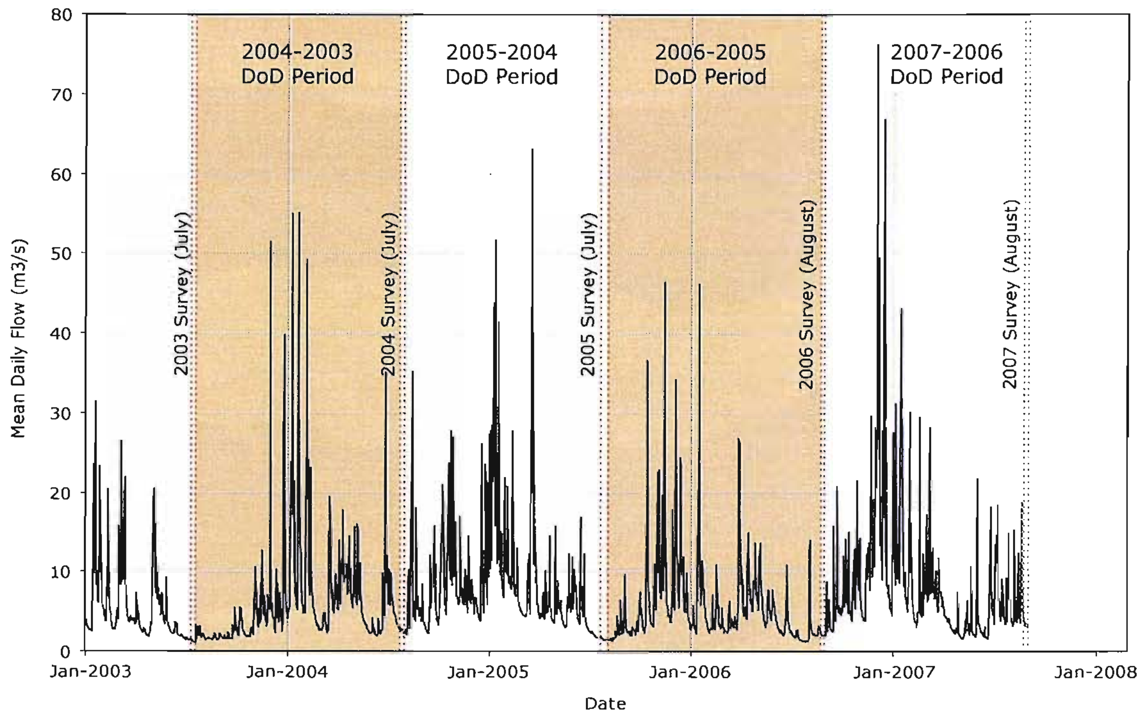


FIGURE 8.2: Hydrograph for Feshie Bridge during study period. The dashed vertical orange lines represent the start and stop dates for the five individual surveys. Data from SEPA.

flow at Feshie Bridge (based on 10 years of data) is 8.01 cumecs (Soulsby *et al.* 2006, Gilvear *et al.* 2000). Thus, the 2003 to 2004 season and 2005 to 2006 season were both less than average years; whereas the 2004 to 2005 season and 2006 to 2007 season were both higher than average years (Table 8.1). Those crude distinctions are actually enough to begin to distinguish the relative magnitude of geomorphological changes observed in both years. As the survey frequncy is only annual, the DoDs are integrating changes from a range of flow events with varying magnitude and frequency. However, some further generalisations can be drawn.

Ferguson & Werritty (1983) estimated 'bankfull' discharges for the study reach to be somewhere in the region of 20 to 30 cumecs. This might notionally correspond to a Feshie Bridge flow of 28 to 42 cumecs (p. comm Cox). A simple flow frequency and peaks-over-threshold analysis for the study period at Feshie Bridge is shown in Table 8.1. The peaks-over-threshold analysis for the range of notional discharges at which braidplain inundation might begin to occur, reveals a greater frequency of inundation in 2004-2005 and 2006-2007. Coupling this with field evidence of inundation, it is quite likely that during the 2005-2006 season the majority of the braidplain was not inundated at all.

The largest two individual events (76.3 and 66.8 cumecs at Feshie Bridge) occurred within two weeks of each other toward the end of 2006. These were two of only three storms over the whole study period to exceed 60 cumecs, with the other big event (63.0 cumecs) occurring

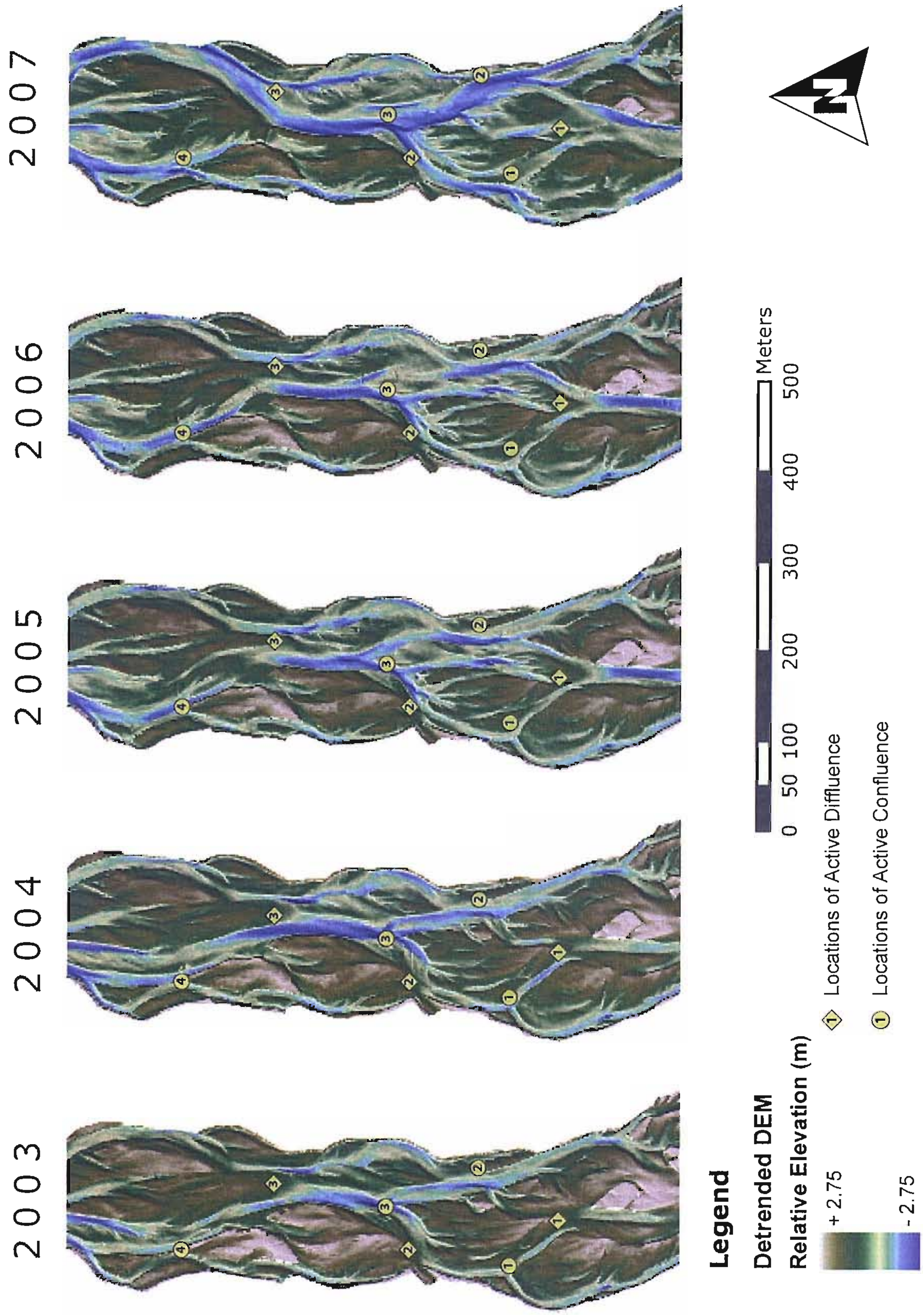


FIGURE 8.3: Detrended DEMs showing relative elevations for the five DEMs from 2003 to 2007. The small yellow diamonds indicate locations of active diffluence zones and the small yellow circles represent locations of active confluence zones that will be referenced throughout the chapter.

Period	2003-2004	2004-2005	2005-2006	2006-2007
Mean Flow	6.41	8.77	5.60	8.44
High flow	55.17	63.01	46.39	76.28
2nd high flow	54.98	51.78	46.09	66.80
3rd high flow	51.52	43.95	36.49	49.48
4th high flow	49.21	41.39	34.20	43.14
5th high flow	39.71	37.48	27.87	33.23
POT (28 cumec)	6	11	5	11
POT (42 cumec)	4	2	0	3
POT (60 cumec)	0	1	0	2
100th percentile	55.17	63.01	46.39	76.28
99th percentile	43.03	38.89	28.18	36.80
95th percentile	17.96	25.57	14.54	26.38
90th percentile	12.29	17.35	10.90	17.00
75th percentile	7.25	10.19	6.39	9.91
50th percentile	4.20	6.25	3.64	5.64

TABLE 8.1: Flow statistics from Feshie Bridge during study period. All flows reported in cumecs. The top half are mean and ranked flows for each water year. POT refers to peaks over threshold analysis, which counted the number of storms in each year over 28, 42 and 60 cumecs. The bottom half shows various percentage quantiles (flow that x% of the time is not exceeded in a given year). Raw 15 minute data from SEPA dating back to 1992; analysis by Cox (p. Comm).

in March of 2005.[14] A notable contrast between these large events is their timing within the season, and the subsequent effectiveness of intermediate storms. The 2006 events were followed by between eleven and three potentially floodplain inundating events (depending on what estimate of bankfull and/or P.o.T. is used). However, it is likely those three to eleven later season floods would have been less effective (geomorphologically) without those early season storms to break up the armour layer and potentially deposit fresh new unarmoured sediments. By contrast the high magnitude event in March 2005 came mid-season and was preceded by a series of intermediate storms, but was not followed by any significant events in the spring snow melt season before the next survey. None of these larger events compare to the three storms exceeding 100 cumecs (notionally >140 cumecs at Feshie Bridge) that Ferguson & Werritty (1983) reported during their five year study period at the site in the 1970s. However, the same patterns that Ferguson & Werritty (1983) observed still persist: a) most of the biggest floods tend to follow prolonged frontal rainfall in the late autumn or early winter; b) the spring-snowmelt peaks are highly diurnal, but generally produce only intermediate size floods; and c) occasional flashy summer floods from convective thunderstorms can rival those in late autumn or early winter.

For an overview of the changes these events brought about, the time series of DEMs used in the DoD analysis for this chapter are shown in Figure 8.3.[15] The DEMs were detrended

[14]Throughout this chapter, these floods exceeding 60 cumecs will be referred to descriptively as 'large' floods. By contrast, those floods in the 28 to 60 cumec range will be referred to as 'intermediate' floods.

[15]See Appendix C and § C.4 for more information on how DEMs were derived and detrended.

	DoD Change			
DoD	Erosion m^3	Deposition m^3	Net m^3	Total m^3
2006-2007	8581.0	6605.3	-1975.7	15,186.3
2005-2006	1857.8	1288.5	-569.3	3146.3
2004-2005	5794.0	4810.8	-983.2	10,604.8
2003-2004	2268.1	1156.1	-1111.9	3424.2
μ:	4625.2	3465.2	-1160.0	8090.4
Total:	18,500.9	13,860.7	-4640.2	32,361.6

TABLE 8.2: Summary of volumetric estimates of erosion, deposition, net change and total volume of change (in m^3) for each analysis period. Calculations from a pathway 4 analysis of DoDs thresholded at a 95% confidence interval. μ refers to the mean for all four periods.

by valley slope to highlight the local relative relief exhibited by the changing morphologies. These DEMs represent the snap-shot observations recorded by the surveys, and the rest of this chapter will focus on the analyses used to interpret the geomorphological changes captured therein.

8.3 Geomorphological Interpretation of DoDs

The top half of Figure 8.4 shows the DEMs (digital elevation models) of difference (DoDs) that are used in this chapter to make geomorphological interpretations. These DoDs were derived from a pathway 4 analysis and thresholded at a 95% confidence interval as discussed in Chapter 4. The corresponding budget that will be used here for segregation in terms of a geomorphological interpretation is shown in Table 8.2. Elevation change distributions (ECDs) are shown in Figure 4.30 (B, D, F & H). Recall from Table 4.11 that thresholding the budget under a pathway 4 analysis resutlted in an average of a 43% reduction of the total volumetric budget. This percentage was significantly smaller for the bigger flood years (2004-2005 and 2006-2007) than the smaller flood years(2003-2004 and 2005-2006). With or without uncertainty thresholding, every individual analysis period suggests that the reach is slightly degradational (by 6% to 32% of total change), and the overall imballance over the entire study period is a net degradation (or loss of sediment from the reach) of 4640.2 m^3. This finding is consistent with a formely glaciated fluvial system that is slowly incising into its aluvial and fluvio-glacial valley fill (Ballantyne & Whittington 1999).

It is also worth noting the excellent correspondence between the magnitude of changes in Table 8.2 with event magnitudes in Table 8.1 by study year. Over the whole study period, an estimated total volumetric change[16] of 32,361.6 m^3 took place but 15,186.3 m^3 of that was in 2006-2007 alone - the year with the two largest floods. On the low-magnitude end as

[16]Note that total volumetric change is not the total volume of material moved, but is simply the sum of DoD recorded deposition and erosion. It is a good proxy for the relative magnitude of geomorphological work done.

well, the quietest flooding period of 2005-2006 also produced the lowest magnitude of total volumetric change. None of these observations are overly surprising, but they are contextually helpful.

As described in § 5.2.1.3, an expert-based geomorphological interpretation is a useful way of segregating the budget based on geomorphological interpretation of the DoD recorded changes. This is a multi-proxy approach that uses a mix of field observations and the DoD itself overlaid by before and after morphological classifications, facies mappings and aerial photographs.[17] The categories of change used are tailored to the known mechanisms of change in the system under study and/or particular questions of interest.

For the Feshie, the categories of change used include four depositional categories, four erosional categories and a questionable change category. The questionable change category is a mask that was used to segregate portions of the reach, which showed the least coherent and/or least reliable changes. Such areas were inferred on the basis of field observations and aerial photographs. These primarily included the tops of terrace surfaces bounding the braidplain on the west side of the study reach, as well as elevated braidplain areas (typically vegetating or vegetated). These were areas where either a) there was no clear evidence of inundation[18] (thus no fluvial mechanism for change); or b) where if there was evidence of minor change (e.g. very localised deposition of fines around vegetation), there was little confidence that such changes would be clearly detectable given the resolution of the survey relative to the roughness and/or presence of vegetation. The erosional categories used were:

- *Channel Carving* - Delineates areas where a new channel has been carved where one did not formerly exist (e.g. avulsions).
- *Channel Deepening* - Delineates areas where an existing channel has experienced erosion and its bed elevation has lowered (e.g. pool scour, confluence scour, incision, headcuts, etc.).
- *Bar Sculpting* - Areas where exposed and/or active bars have experienced erosion. This is typically either in the form of trimming around the edge of a bar margin, or dissection of a chute through a bar surface.
- *Bank Erosion* - Delineates areas where lateral erosion has occurred along a channel margin. Such channel margins are generally distinguished in the Feshie by a relatively steep bank separating a regularly inundated area (e.g. channel or lateral bar) from a less regularly inundated area (e.g. vegetated or vegetating braidplain).

The depositional categories used were:

[17] All used where available. Here aerial photographs were available for April 2005 (Figure B.11), August 2005 (Figure B.12) and August 2007 (Figure B.13).

[18] 'Evidence would include signs of sediment deposition, signs of trash-lines and flood debris, and areas that were topographically unlikely to have been inundated given the flow record for that year and other hydraulic simulations of the reach (Cox *et al.* Submitted, e.g.) not reported here.

- *Channel Filling*- Delineates areas of channel aggradation that may have raised a channel bed or caused a channel to shift laterally, exposing bars and/or riffles in the process. Such a shift differs from abandonment of the channel or avulsion in that the overall course has not dramatically changed. This can include pool-filling and large-flat sheets of in-channel deposition leading to plane bed morphologies.

- *Channel Plugging*- This is a sub-class of channel filling that is reserved to specifically delineate areas where the channel aggradation has led to an avulsion or abandonment of the channel (or chute).

- *Bar Development*- Areas that have experienced deposition resulting in the development of new bars or expansion of existing bars. This can include the development of mid-channel bars (e.g. diagonal, lobate or longitudinal bars) or bank-attached bars (e.g. lateral bars, point bars, riffles).

- *Gravel Sheets* - Delineates areas of overbank deposition (typically of coarse gravels and or cobbles) onto braidplain surfaces. These are differentiated from regular overbank deposition of finer material (typical floodplain deposits) that are often below minimum levels of detection (i.e. would be classed in a 'questionable change' category). Ferguson & Werritty (1983) referred to these deposits as overbank bars and cobble sheets, and noted how they were characterised by at least decimeter-thick deposits burying heather, moss and grass vegetation on the braidplain. Thus, the large caliber of the material is making it detectable with GPS measurements.

The bottom half of Figure 8.4 shows an overview of the geomorphological interpretations using the categories outlined above for each study period in relationship to their DoD. More detailed maps, interpretations and elevation change distributions (ECDs) are reported with each change period in the next four subsections.

8.3.1 2003 to 2004 DoD

From the summer of 2003 to 2004, there were four to six flood events that might have led to partial inundation of the braidplain (§ 8.2). There are a number of small patches of generally low magnitude changes on the braid-plain shown in the DoD in Figure 8.5A. These areas were primarily zones of contiguous erosion or deposition that were recovered from the spatial coherence filter in the pathway 4 analysis. As pointed out in Chapter 4, it is certainly plausible that such changes occurred on the braidplain as a result of overbank deposition and/or minor scour from sheet-flow. However, given the lack of aerial photographs, facies maps and other evidence for 2003-2004, there is not enough information to reliably distinguish such changes from noise, and these overbank areas have been classified as questionable changes accordingly. These areas constitute 83% of the surface area of the surveyed reach (red cross hatched area in Figure 8.5B), but only account for 9% of the total volume of change because of their generally shallow depths (see centre ECD in Figure 8.6). The questionable change ECD is

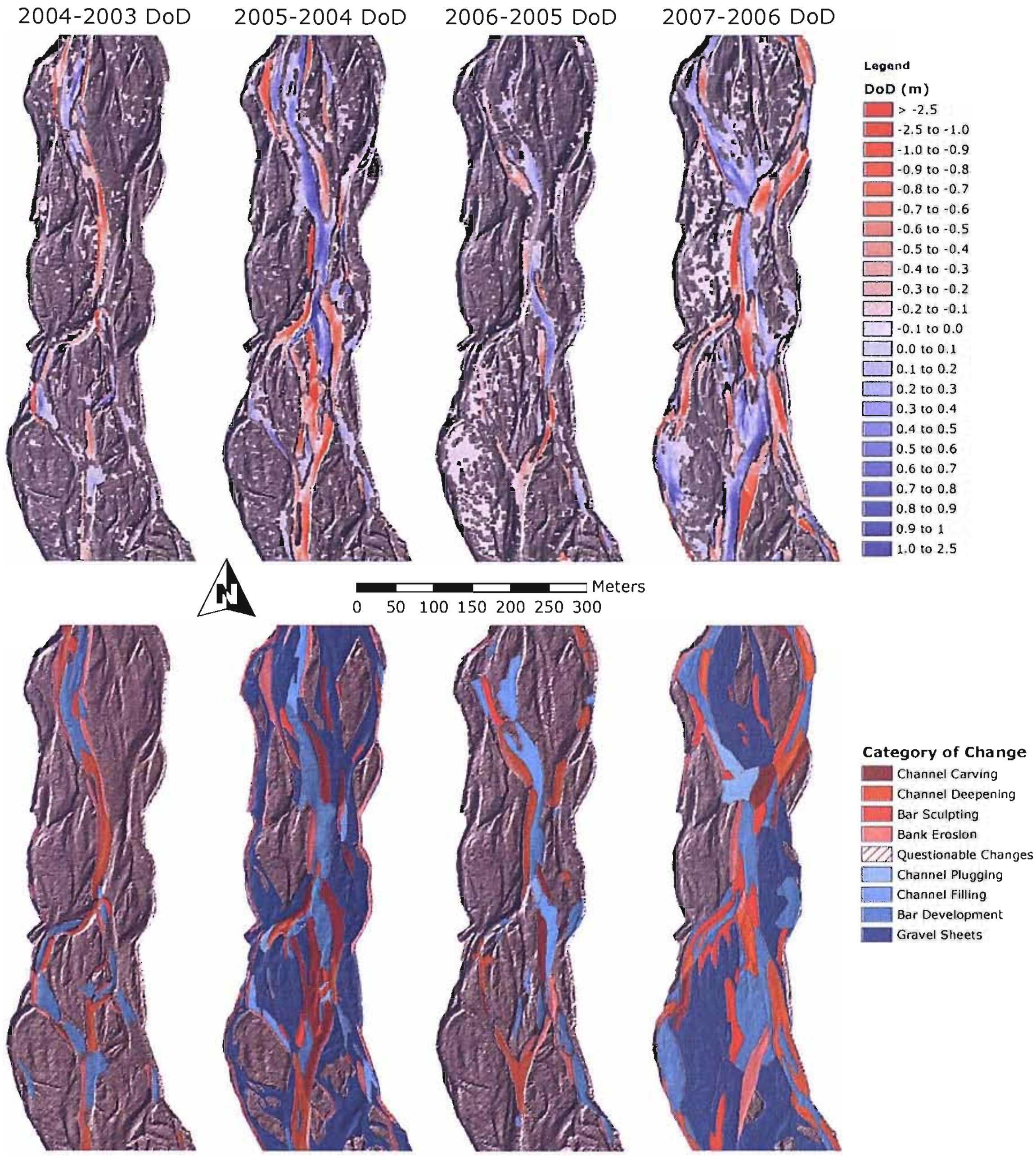


FIGURE 8.4: Overview of geomorphological interpretations (bottom) of all four DoDs (top) on the Feshie over the study period. More detailed views for each individual DoD are provided in the next subsections (§ 8.3.1, § 8.3.2, § 8.3.3 and § 8.3.4), whereas this figure facilitates inter-comparison of the DoDs.

dominated by a peak of 5-10 cm of erosion, but does pick up limited scour up to 75 cm, and has a secondary depositional peak at 5-10 cm that quickly tapers off to maximum fills of up to 45 cm.

The vast majority (91%) of DoD recorded changes are confined to the other 17% of the reach comprising the active channel network. Therein, 64% (59% of the total volume) of the changes were due to erosional mechanisms (Figure 8.5C). In broad terms, the changes were predominatntly confined to the main channel through the reach with some less extensive changes on some of the secondary anabranches. This is typical of what might be expected for a year in which the primary floods rarely or barely got out of bank, and thus concentrated their erosive energy in the channel.

As Figure 8.5C indicates, there were three dominant categories of change: bank erosion (33%), channel deepening (25%), and bar develpoment (31%). Throughout the reach, there are eight coherent zones where bar development appears to be working in concert with bank erosion. That is, the growth of bars is either constricting effective flow width or forcing the flows to be directed outward at banks and causing lateral migration of the channel via bank erosion. The bar development (light blue in Figure 8.5B) appears to be taking place anywhere there is a flow-width expansion and/or change in channel gradient. Of the eight coherent zones, half are associated with mid-channel bar development (primarily diagonal bars) and half are associated with lateral or point bar development. The 1056 m^3 of bar development was associated with fill depths of up to 80 cm, but is generally consistent with much shallower fills over broader areas as indicated by the ECD in Figure 8.6H with a peak at 20 to 30 cm of fill.

The bank erosion occurring on the opposite banks of the bar development is much less areally extensive (accounting for half of the surface area of bar development), but the erosion is generally much deeper than the bar development fills (Figure 8.6D). This depth of scour is more a reflection of the average heights of the adjacent braid-plain and terraces that are being eroded into. Scour depths associated with bank erosion have a broad ECD extending up to 130 cm of cut, but with peaks between 50 and 75 cm. These coupled zones of bar development and bank erosion reflect gross changes from what is likely a more complex sequence of events. Logically, the bar development probably precedes the onset of bank erosion and is likely primarily occurring at high stages and at the beginning of the recession from the flood peak, when flow energy and transport capacity begins to decrease (Dinehart 1992). The new or expanded bar forms confine the effective flow width and force flows away from themselves, hence directing flow at the banks. During the recession limb as stages are dropping, but flow energy is relatively high, these outward directed flows are likely accelerated as flow is concentrated into a narrower and narrower cross section. This process could easily repeat itself with successive intermediate floods and continue to accentuate both bar development and bank erosion. Such a conceptual explanation of these mechanisms of change is quite similar to what Ferguson & Werritty (1983) reported on the Feshie for diagonal bar evolution[19], but here we see similar mechanisms taking place for both mid-channel bars (e.g. diagonal bars)

[19] This was reviewed briefly in the introduction (§ 8.1).

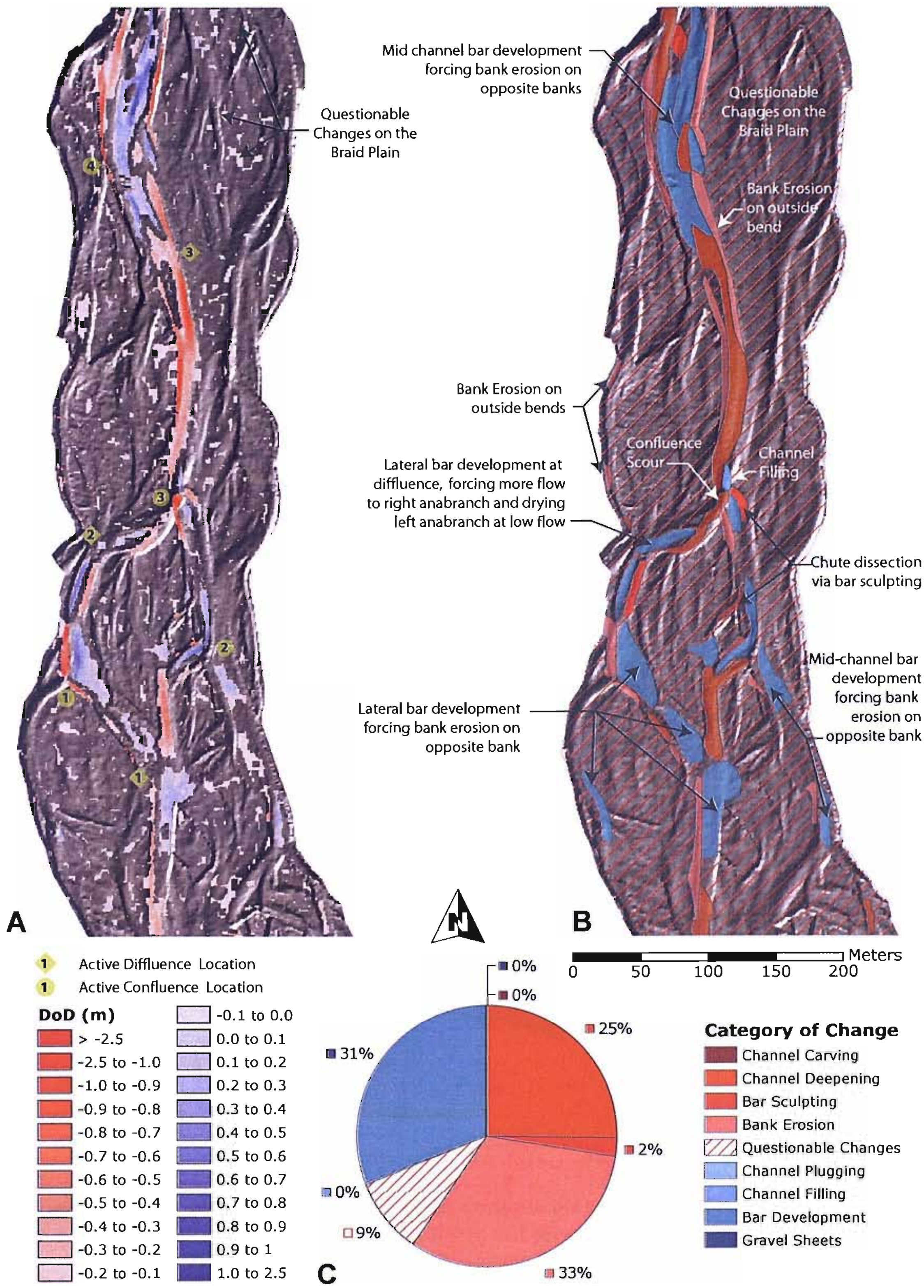


FIGURE 8.5: Map of the 2003 to 2004 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

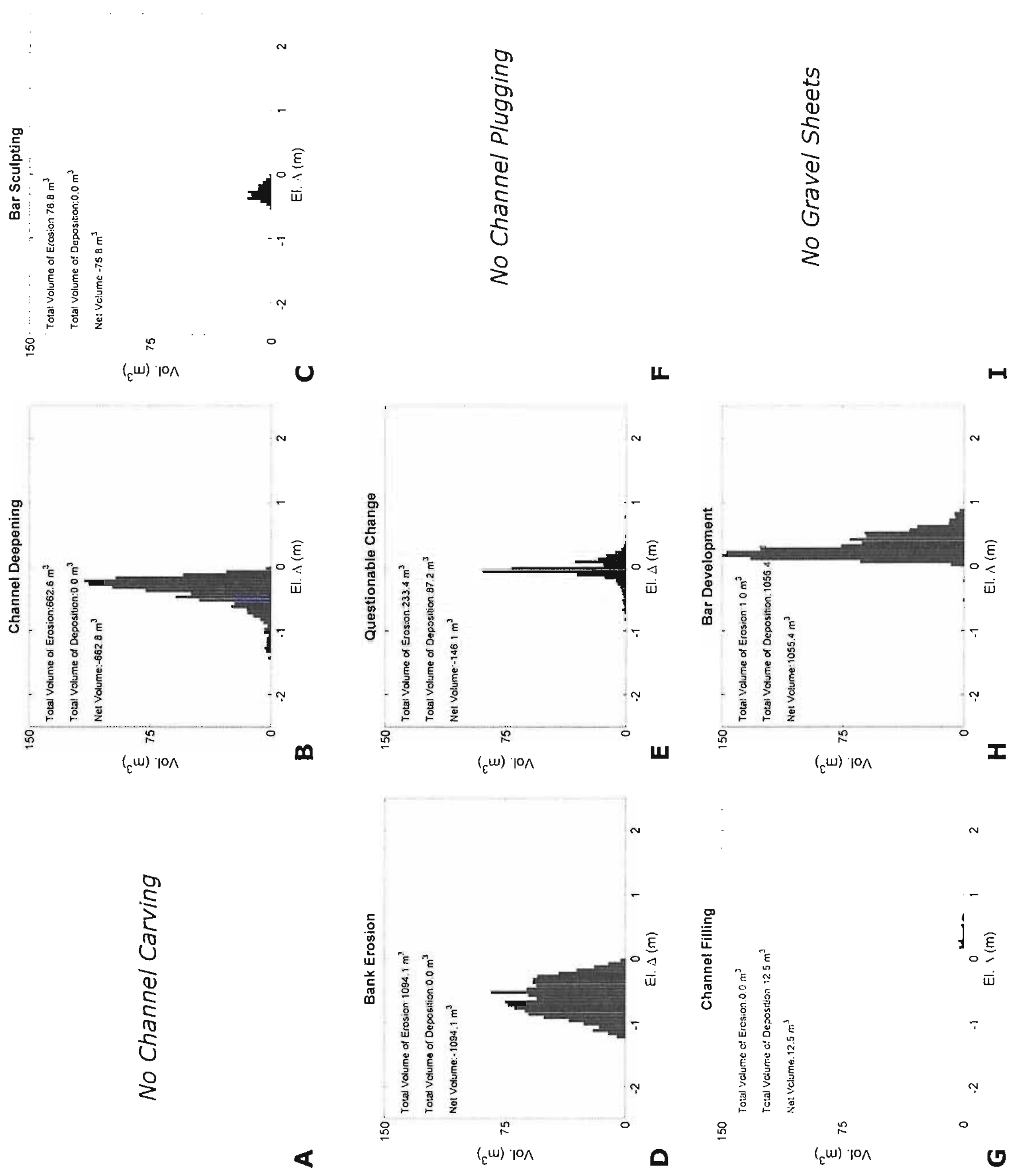


FIGURE 8.6: Elevation change distributions corresponding to the geomorphological interpretation mask of the 2003 to 2004 DoDs shown in Figure 8.5B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

and lateral bars.

Not all of the 1094 m^3 of bank erosion was associated with forcing due to bar development. Particularly between the deep confluence pool at confluence junction 3 and what is labeled as diffluence junction 3 in Figure 8.5A, there is a long coherent sliver of bank erosion on the inside bend adjacent to a large coherent zone of channel deepening. While it is odd to have bank erosion on an inside bend, here this can be explained by the high-stage flow geometry. At high stages the flow coming from the right-hand anabranch at confluence junction 3 is directed straight down valley and across the channel at this inner bank; whereas at low flows it takes a left-hand bend into the confluence pool. The lack of bar development in this zone and wider pattern of shallow channel deepening can also be explained by the high-stage flow geometry. With the high flows for the 2003-2004 season probably never leaving the banks here, the entire flow through the reach was confined to this single channel[20] creating an erosive funneling effect. At 862 m^3, channel deepening comprised 25% of the overall budget. As the ECD in Figure 8.6B shows, most of this was relatively shallow scour (25-30 cm) as described above.

One final, somewhat speculative, observation is that every single bar unit that showed growth appears to be associated with either a sliver of bank erosion or a concentrated zone of channel deepening upstream of it, recalling that the bar deposition is always associated with a flow width expansion. If one moves upstream of each bar unit, a coherent zone of bank erosion, channel deepening or, in some cases, bar-sculpting is always encountered. The volume of sediment derived from these coherent zones of erosion roughly scales to the volume of deposition in the bars, suggesting a crude potential source and morphological control on average step-lengths for transported material (Pyrce & Ashmore 2003, Richard S. Pyrce 2003, Pyrce & Ashmore 2005). It is also interesting that these coherent zones of erosion, either a) always occur before the next flow-width expansion upstream and associated bar; or b) occur coincident with the next zone of bar development and bank erosion (source) on its opposite bank. For example, the largest zone of mid channel bar development (downstream of diffluence 4) is the first depositional zone downstream of the largest area of coherent bank erosion and channel scour described in the previous paragraph. Without detailed tracer-experiments, these ideas can not be verified. It is likely that the bar development is comprised of source material from sources encompassing a wide variety of distances upstream (Sear 2004). None-the-less, the relatively simple observation of apparent correlations is mechanistically plausible.

8.3.2 2004 to 2005 DoD

The first thing to note about the 2004 to 2005 DoD (Figure 8.7A) is the relatively straight scar or band of erosion and deposition that was ripped through the middle of the reach, with little regard for the *normal* main channel path during lower flows. By contrast to the 2003-2004 DoD, in which all the changes paid respect to the initial channel network configuration, here

[20] Elsewhere there are at least 2-4 anabranches two split the flow.

the simplest path was taken. This path departs from the main channel at the first active diffluence (1), extends downstream avoiding the first two confluences, opting instead for the a new path through the braidplain, and reconnects with the main channel at confluence 3, remaining in and significantly widening the main channel the rest of the way through the reach.

As indicated by the large areal extent of 'gravel sheets' (dark blue areas in Figure 8.7B)[21], there was extensive overbank deposition, such that changes were recorded in 75% of the study reach. These gravel sheets themselves accounted for 41% of the area of the reach, but only 7% of the total volumetric change. As the gravel sheet ECD in Figure 8.8H shows, they accounted for 546 m^3 of predominatly low magnitude (decimeter thick) deposition, but occasionally reached fill depths of up to 80 cm. There was also a minor (168 m^3) erosional fraction of primarily low magnitude braidplain scour (peak of 10-15 cm) recovered in the gravel sheet ECD, which reflects erosion[22] across the braidplain at high flows.

The questionable change areas were delineated and inferred as before, but this time only constituted 25% of the reach and less than 1% of the total volume of change. It is certainly plausible that real changes were being recorded from the DoD in these areas, but as the ECD in Figure 8.8E indicates, they amounted to low magnitude changes if they were real (17 m^3 of erosion and 63 m^3 of deposition).

At 32% of the total volume of change, bar development again played a very prominent role volumetrically (3288.5 m^3). The bar development fraction of the 2004-2005 budget alone almost matched the total volume of change in the 2003-2004 season. As the bar development ECD shows (Figure 8.8H), bar development was constituted by greater fill depths this time, with an average fill depth of 50 to 65 cm and fill depths of up to 2.4 meters. Again, bar development appears to take place only where there is a flow width expansion and seems to be associated with forcing bank erosion or channel deepening. However, this appears to be occuring at two scales. In the anabranches that were not part of the high stage swath through the centre of the reach, the process of bar growth forcing bank erosion is taking place at a scale very similar to in 2003-2004. However, up the main high-stage swath through the centre of the reach, the scale of the bar features dwarfs those in the other anabranches. Within this high stage channel, very large diagonal mid-channel bars developed that tend to alternate back and forth spatially between favouring one side of the main channel. For example, the diagonal bar located just downstream of diffluence 1 is favouring the left side of the channel and shedding flow diaganoly from the left towards the right. Moving downstream through the large channel carving zone (discussed below), the next large bar is favouring the right hand side of the channel, and sheds its flow diagnolly from right to left into confluence 3. The process is reset downstream of confluence 3, due to the strong input from the left hand anabranch (low-stage main channel) pushing the bar towards the right. However, the pattern then persists at least

[21]These areas were delineated on the basis of field observations of fresh gravel and cobble deposition and aerial photograph evidence (Figures B.11 and B.12)

[22]Recall that these areas were delineated largely on the basis of exposed gravel, which often implies deposition; but can imply erosion of braid-plain vegetation leaving exposed braidplain sediments.

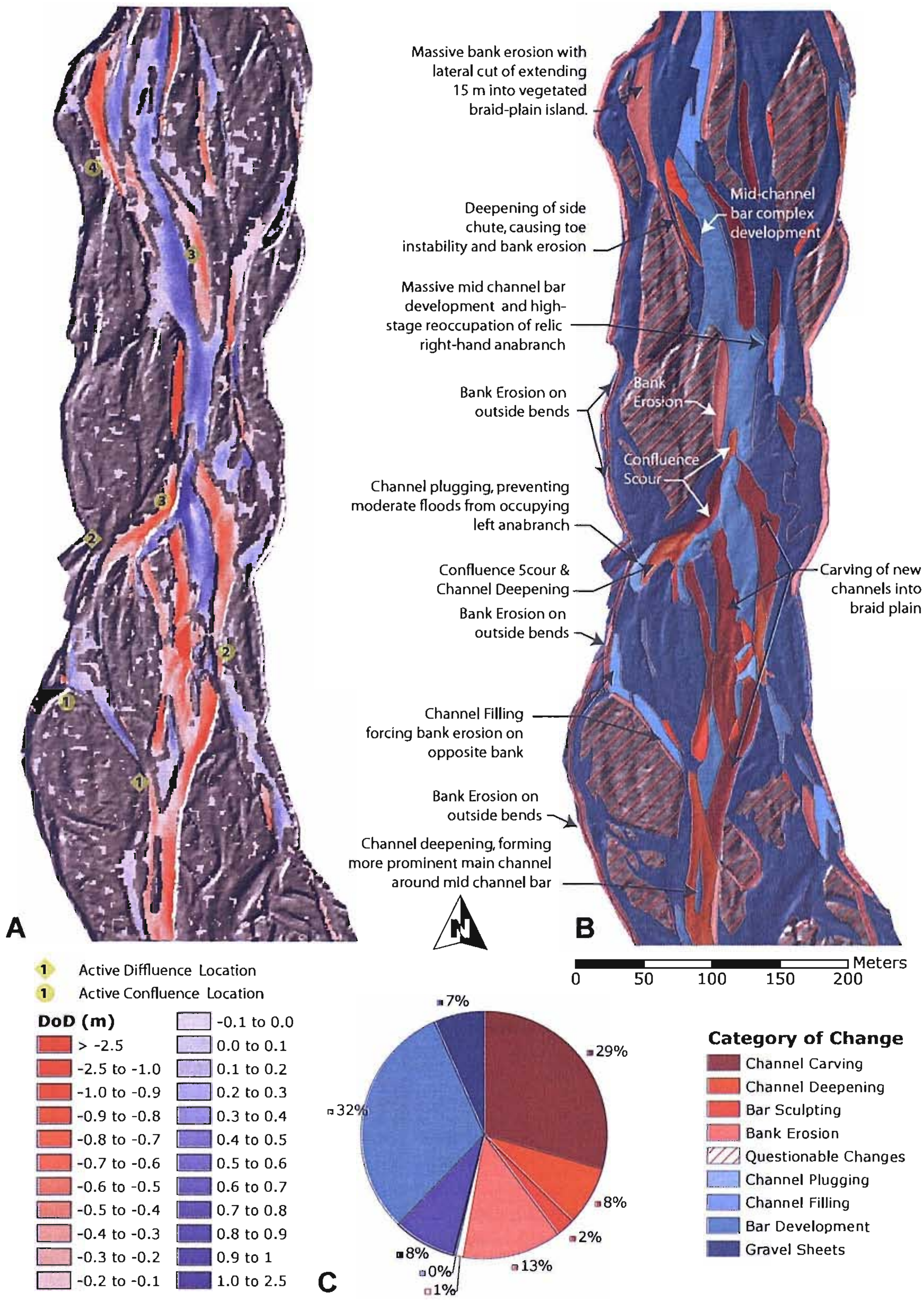


FIGURE 8.7: Map of the 2004 to 2005 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

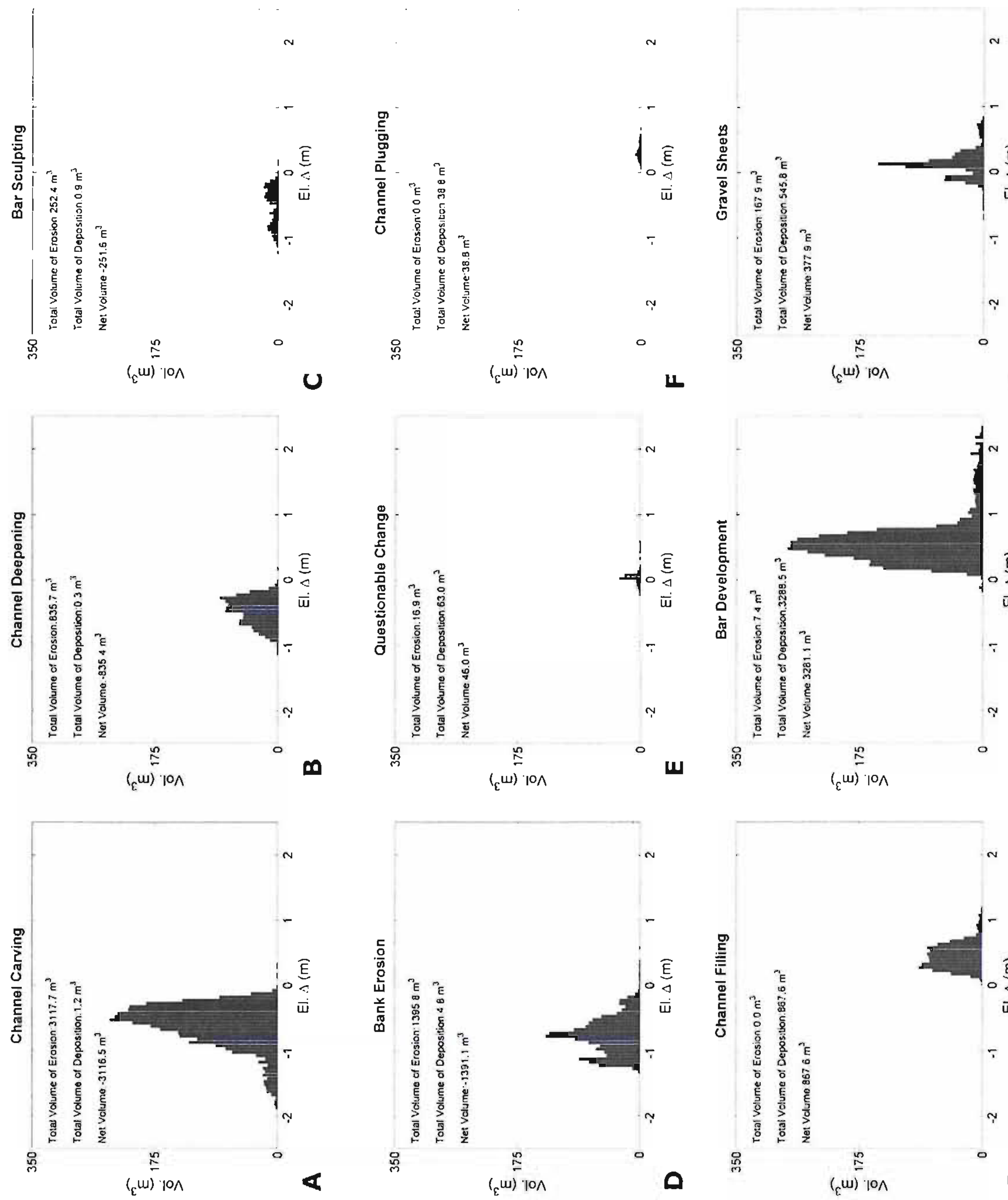


FIGURE 8.8: Elevation change distributions corresponding to the geomorphological interpretation mask of the 2004 to 2005 DoDs shown in Figure 8.7B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

down through diffluence 3 to confluence 4. Thus, the extensive diagonal bar development through the centre of the reach seems to be shunting the high stage flows from side to side, creating swaths of erosion (primairly channel carving and some bank erosion).

Channel carving was the second most dominant category of change at 29% and the most dominant erosional mechanism. The high stage flood ripped 3117.7 m^3 out of the braidplain to accommodate a 30 to 50 m high-stage channel. Most of this channel carving took place between diffluence 1 and confluence 3 via confluence 2. This was most likely in response to the largest flood(s), which found a more direct route staight down the braidplain, preferable to the left-hand anabranch via confluence 1. In terms of reoccupation of relic channels and anabranches, the diagonal bar that developed between confluence 2 and 3 and the channel carving on its right hand side were of key importance. The channel carving did not carve a direct connection to the the relic anabranch down the right hand edge of the reach. However, it did remove a section of the braidplain that acted as a high flow barrier, and allowed the larger (i.e. >20 cumec) floods to reoccupy this relic channel, which was very active through the 1990's, but appeared to be abandoned around 2000.[23] Some additional, small-scale channel carving though this temporarily unoccupied braidplain meant the re-establishement of a viable anbranch down the right-hand side of the reach at low to medium flows (Figure B.11). Flow in this secondary anabranch and the main anabranch both curved toward one another downstream of confluence 3, but never quite met (at low flows), both going their separate ways around the braidplain downstream of diffluence 3. The small bar separating these two anabranches was only about 10 m wide and less than 75 cm in relief (Figure B.11). This is a Site to watch closely in the next two seasons.

8.3.3 2005 to 2006 DoD

The 2005 to 2006 monitoring period showed experienced the lowest number of floods and the lowest peak flow (Table 8.1). It appears unlikely that flows ever got out overbank, instead concentrating their energy in the low-flow channel network as shown in Figure 8.9. As in 2003-2004, there was a return to the majority of the reach (81%) being classified as questionable change, because of the lack of evidence of braid-plain inundation. Moreover, because of the low overall magnitude of changes (3146.3 m^3 of total change; see Table 8.2), the questionable areas were occupying a noteable percentage (15%) of the overall budget (Figure 8.9C). The questionable change ECD (Figure 8.10B) shows the characteristic signature of an error distribution centred around zero but with a shorter tail in deposition then erosion.

Returning to the potential for diffluence 3 to finally connect at low stages[24], recall the precarious small bar separating the right-hand anabranch from the main channel. It appears the diffluence was connected during at least the peak flows during 2004-2005. However, as flow would have been diverging over this bar in an unconfined area of flow expansion, this bar (a lateral bar to the main channel at the time) actually grew. At the same time, the channels

[23] See aerial photographs from 1993 (Figure B.8), 1997 (Figure B.9) and 2000 (Figure B.10) for evidence.
[24] Discussed at end of previous section (§ 8.3.2).

on both sides experienced some degree of channel deepening and as such the relative relief between the right-hand anabranch and main channel grew. In the main channel in particular there was headward incision from the thalweg on the left up through the riffle into the plane-bed reach between confluence 3 and diffluence 3 (Figure 8.9B). These changes and some bank erosion were further encouraged by the plugging of the main channel route, following a more central path downstream of diffluence 3 in 2005.

The greatest magnitude and concentration of bank erosion occurred in 2005-2006 around confluence 2. To start, focus attention upstream at diffluence 1, which experienced some channel deepening extending into both its right-hand and left-hand anabranches. However, with more extensive erosion and a steeper gradient into the right-hand anabranch this anabranch was now diverting more flow. These flows shaved off sediment on the outer flanks of its two chutes before being funneled into confluence 1. This jet of water was now directed at the opposite bank downstream of the confluence, inducing 5-10 m of lateral bank erosion. Upstream of confluence 2 on the right-hand feeder anabranch, a persistent pattern of areally extensive mid-channel bar development, inducing bank erosion on the opposite banks was also recorded (much as described for 2003-2004 in § 8.3.1).

Moving just downstream of confluence 2, the bank erosion on the far bank of confluence 2 appeared to make a more direct path for the flows from the right-hand anabranch. Subsequently this has caused the channel to migrate toward the centre of the reach and the old channel has filled up with sediment. This channel filling upstream of confluence 3, and the channel filling downstream of diffluence 3, constitute the vast majority (85%) of the 694 m^3 in the channel filling ECD in Figure 8.10G. The ECD is very similar to the bar development ECD, with a peak at 25-35 cm and fills not exceeding 70 cm in depth. Here, channel filling comprises 22% of the budget (Figure 8.10C) as compared to the 13% comprised of bar development. Technically one might argue that in these examples the channel plugging is simply a form of bar development (primarily lateral bars in in this case), but the distinction was drawn here because the deposition filled the whole of the existing channel and caused the whole channel to shift. If one did combine these two into one, they would comprise 33% of the total volume of change, and 92% of the total deposition.

There was a very small zone designated as channel plugging, where the prominent chute connecting the channel at confluence 3 was plugged completely and a new chute was carved just downstream (Figure 8.9B). The deposition itself was actually part of a continuous train of deposition that extended from confluence 2 all the way down past diffluence 3. However, it was distinguished within this category of change because of the result it had on the morphology and channel network. Its ECD ranges from 10 to 50 cm with a peak at 35-40 cm, constituting 90 m^3 of fill (Figure 8.10F). The significance of this is that it shifts the location of confluence 3 downstream a further 35 m (Figure 8.13). Thus what was the deepest pool (c. 1.5 m deep) in the reach in 2003 and 2004, had diminished to a shallow pool less than 0.5 m deep in 2006. The left hand feeder anabranch to confluence 3 enters the pool with a relatively steep slope, and the grade break has remained at a relatively stationary position. Although the right hand anabranch also enters with a steep slope, its confluence shifted 20 m downstream from

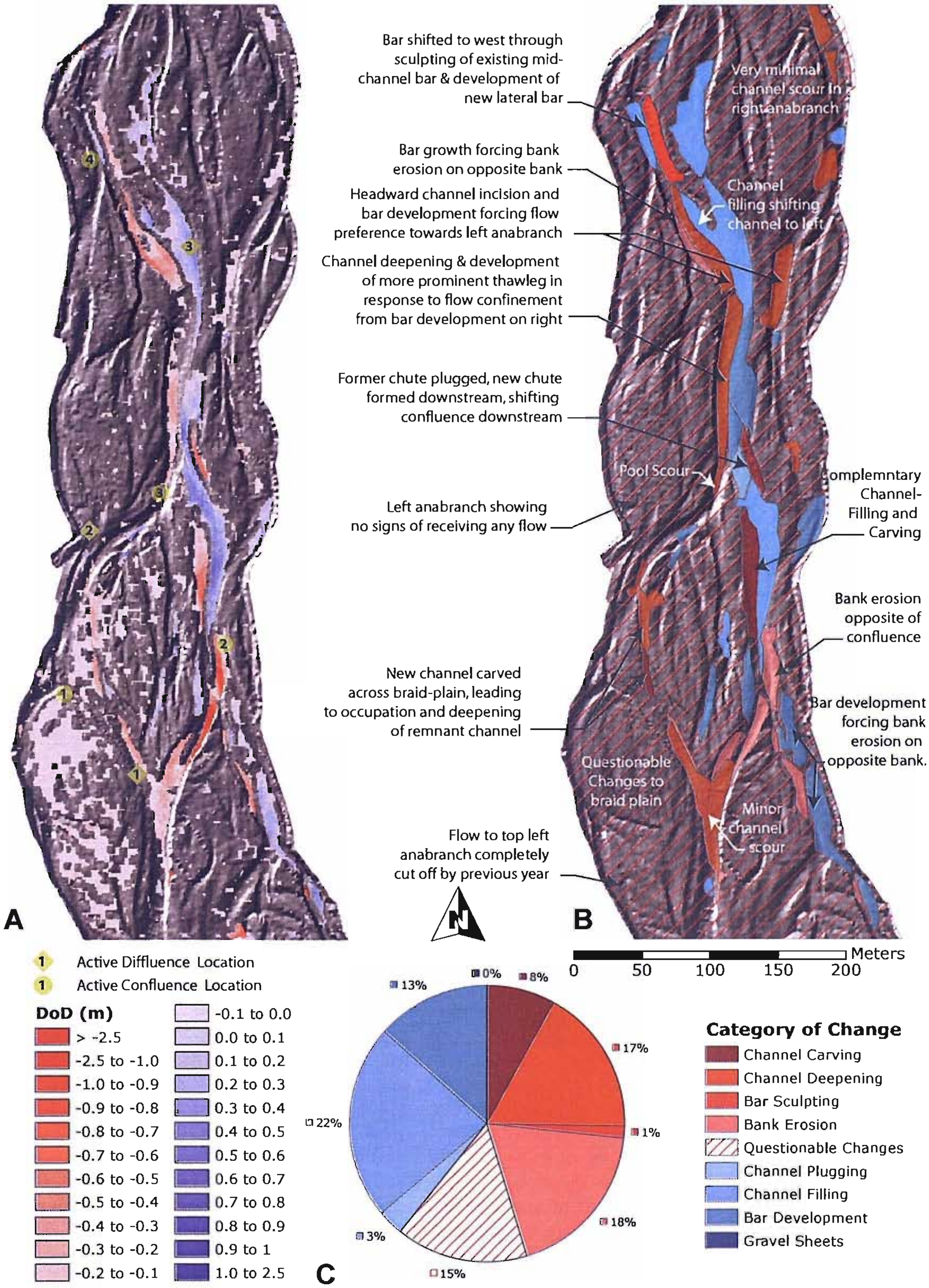


FIGURE 8.9: Map of the 2005 to 2006 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

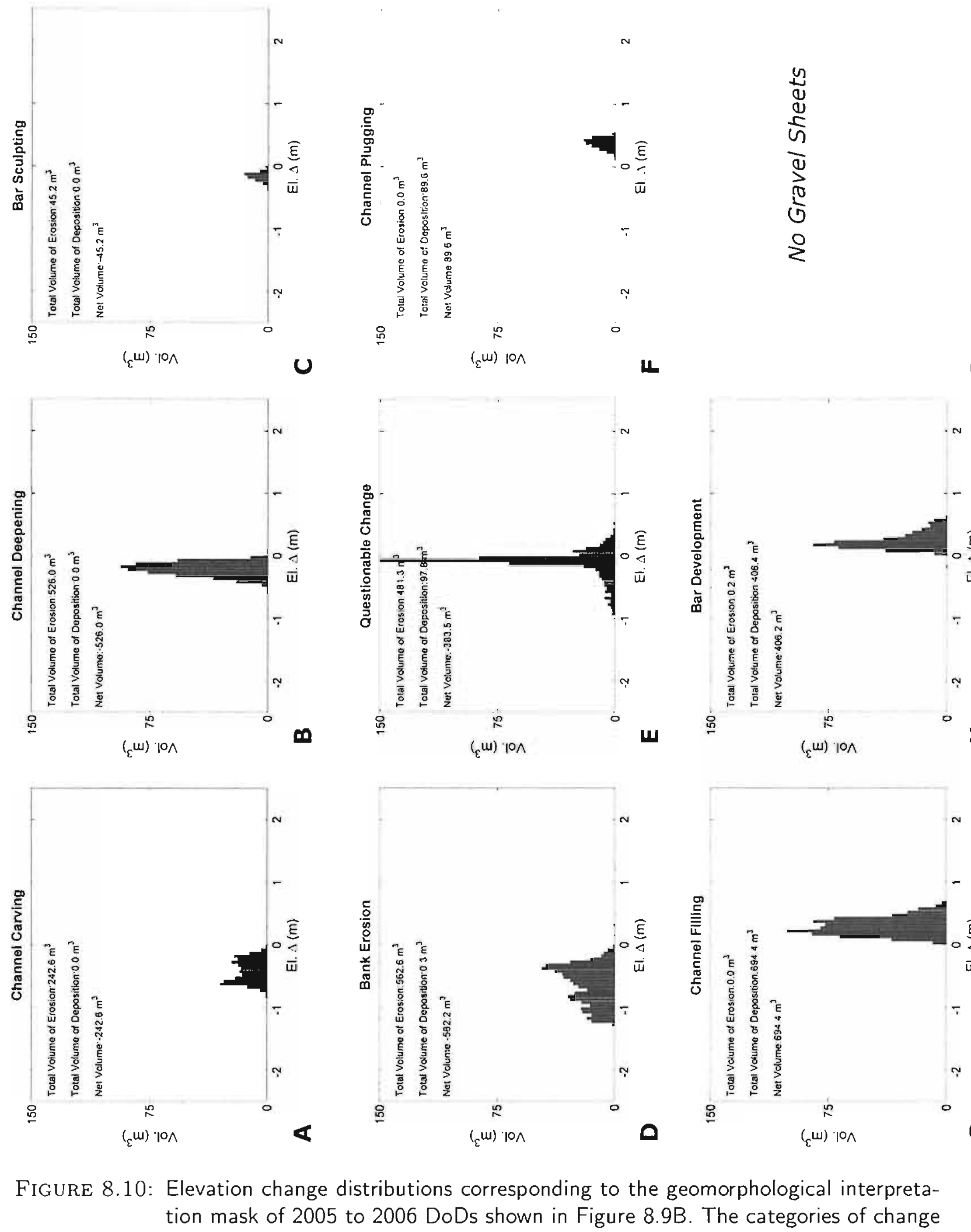


FIGURE 8.10: Elevation change distributions corresponding to the geomorphological interpretation mask of 2005 to 2006 DoDs shown in Figure 8.9B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

2004-2005 and another 35 m from 2005-2006. Thus, the two anabranches are now coming together after the left-hand anabranch has dissipated most of its elevation head. Subsequently the two anabranches are not combining all their energy head into one focal point to create the deep pool of years past.

Thus, the overall story for this low-flow year is very similar to 2003-2004. The bar-development and bank erosion signatures of the ECDs in 2005-2006 (Figures 8.10D and I) are strikingly similar to those in 2003-2004 (Figures 8.6D and I), varying only in their precise magnitudes.[25] The reach is still slightly degradational, but this time channel deepening and carving played more prominent roles. Bank erosion was still the dominant source of erosion.

8.3.4 2006 to 2007 DoD

The 2006-2007 season boasted the largest floods (Table 8.1 & Figure 8.2), the largest volume of change (Table 8.2) and the most dramatic morphological changes (Figure 8.11). This is explained by the occurrence of two early-season floods, within two weeks of each other, that were of greater magnitude than any of the other floods during the study period. Like in 2004-2005, there is a major swath of change located down the middle of the reach, clearly reflecting the impact of the high-stage floods. However, there are three major morphological differences:

1. Roughly half (47% of 837 m^2) of a large stable vegetated island at the top centre of the reach was washed away from a massive swath of bank erosion extending 9 m to 16 m laterally into the island.[26]

2. The drying up of the main channel in the centre top of the reach, and the subsequent splitting of the flow (upstream of study boundary) into the left-hand anabranch (previously dry) and the right-hand anabranch

3. The avulsion at diffluence 3 in which the main channel (on left) was completely plugged at low flows, and the new main channel carved across the bar formerly dividing the right hand anabranch and main channel, to reoccupy the right hand anabranch.

It is likely that one or both of the large early-season floods were responsible for 1, and the main swath of change down the centre of the reach. However, there were roughly 11 intermediate size floods later in the season, at least 1 of which resulted in some floodplain inundation (Table 8.1). These three major morphological differences will be described first, and then the remaining changes will be reported.

The island at the top of the reach that was carved in half, is a remnant of a large vegetated island, which formed sometime after 1964 (Figure B.6), but was well established by 1989 (Figure B.7). The island was substantially trimmed down between 1993 (Figure B.8) to a

[25] Add also to this the channel filling ECD as discussed above.
[26] Compare the 2005 (Figure B.12) and 2007 (Figure B.13) aerial photographs.

shape and size it largely maintained up until 2000 (Figure B.10). During the 2006 to 2007 period, it appears an extensive broad cobble sheet washed in with the high flows upstream of confluence 1 (Figure 8.11B). This sheet spread out across the braidplain to the left and, to a lesser extent, around the island to the right. Deposition in these areas was typical of the 1-2 decimeter thick sheet exhibited in the 2004-2005 season. However, complete burial of what was the main channel resulted in deposition of up to 1 m, but leaving a flat smooth morphology across the surface. These two styles of deposition are exhibited in the bimodal ECD of Figure 8.12*I*. The ECD shows fill depths of up to a 105 cm with a secondary peak at 80 to 85 cm of fill, which is entirely made up of deposition in this channel zone. The rest of the shallow gravel sheet deposition across the braidplain contributes to the primary peak at 20 to 35 cm of fill. This volume of net deposition at this location only makes sense to be associated with high-stage flows, when flow width is extensive enough and the energy grade-line flat enough for the flow to drop its load in a broad sheet like it did.

It appears that this large grave sheet fill, in the main channel, shunted the flow into the western edge of the vegetated island. Even though the surface of the island was vegetated and 'stable', the island fill was comprised almost entirely of easily erodible non-cohesive sediments. The slice through this island is an incredibly linear feature, suggestive of a change in flow direction from straight down the valley (North) to about 20° east of north. The bank erosion extends along this line downstream into the braidplain and does not end until it reaches the left-hand anabranch at confluence 2. The change probably occurred gradually over the course of the flood(s), pivoting around the head of the island, and slicing like the second hand on a clock from 12:00 into the island at 2:00 (Figure 8.11A). With each second, shaving a little more. To drive this second hand on the clock into the island suggests that there was a rather continual supply of sediment from upstream building that gravel sheet faster than it could be evacuated. Such a large supply is probably only possible during a large event and it is likely that when this ceased, the second hand stopped and the rest of the island was spared.

The second major change listed above was the partial abandonment of the main channel in the centre of the reach at the top. In the scar of the bank erosion described above, a thalweg was carved that still received overflows at intermediate floods, and was recharged with groundwater at low flows. However, as the low flow inundation map in Figure 8.13 shows, the flow was predominantly split between anabranches running down the opposite sides of the reach. From the data it is difficult to pinpoint when this occurred, but it is speculated that it was probably in the recession of the second major flood. With the extensive gravel sheet deposition described above, the centre of the reach upstream of confluence 1 was now elevated relative to the anabranches flanking both sides. Thus, these two channels became the preferential paths for flow being split at the confluence upstream of the study reach boundary.

The third major change was the plugging of the high stage diffluence (labeled diffluence 3 in Figure 8.11A) in the bottom third of the reach. There are substantial areas of deposition downstream of the diffluence. These include areas of gravel sheet deposition down the centre swath of braidplain (much the same as in 2004-2005), as well as the familiar patterns of extensive mid-channel bar development inducing bank erosion and or channel scour on opposite

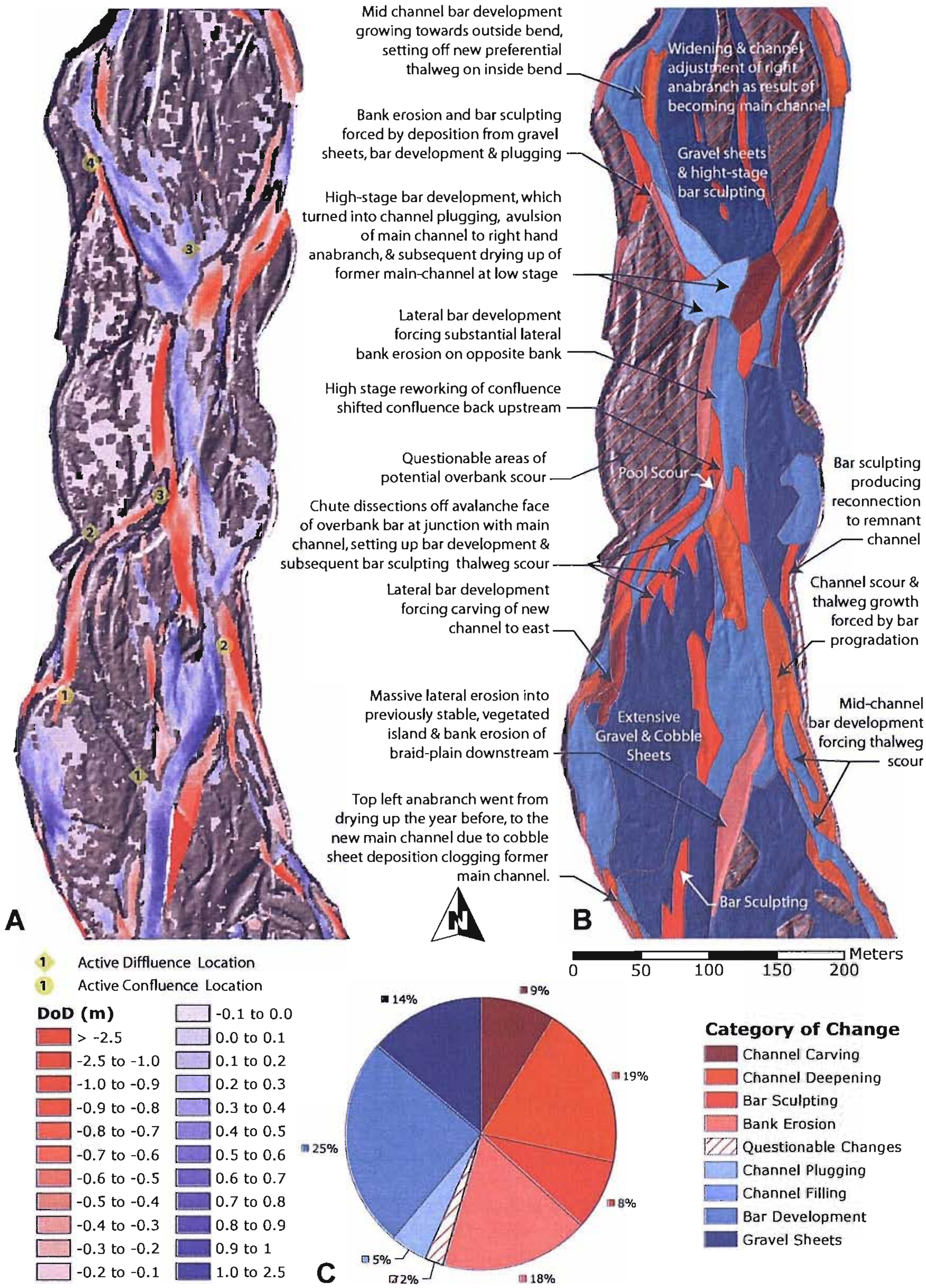


FIGURE 8.11: Map of the 2006 to 2007 DoD (A), its geomorphological interpretation (B), and the relative proportion of each category of change (C). Relative proportions are calculated volumetrically with reference to the total volume of material net change recorded by the DoD (both erosion and deposition). The flow direction is up the page.

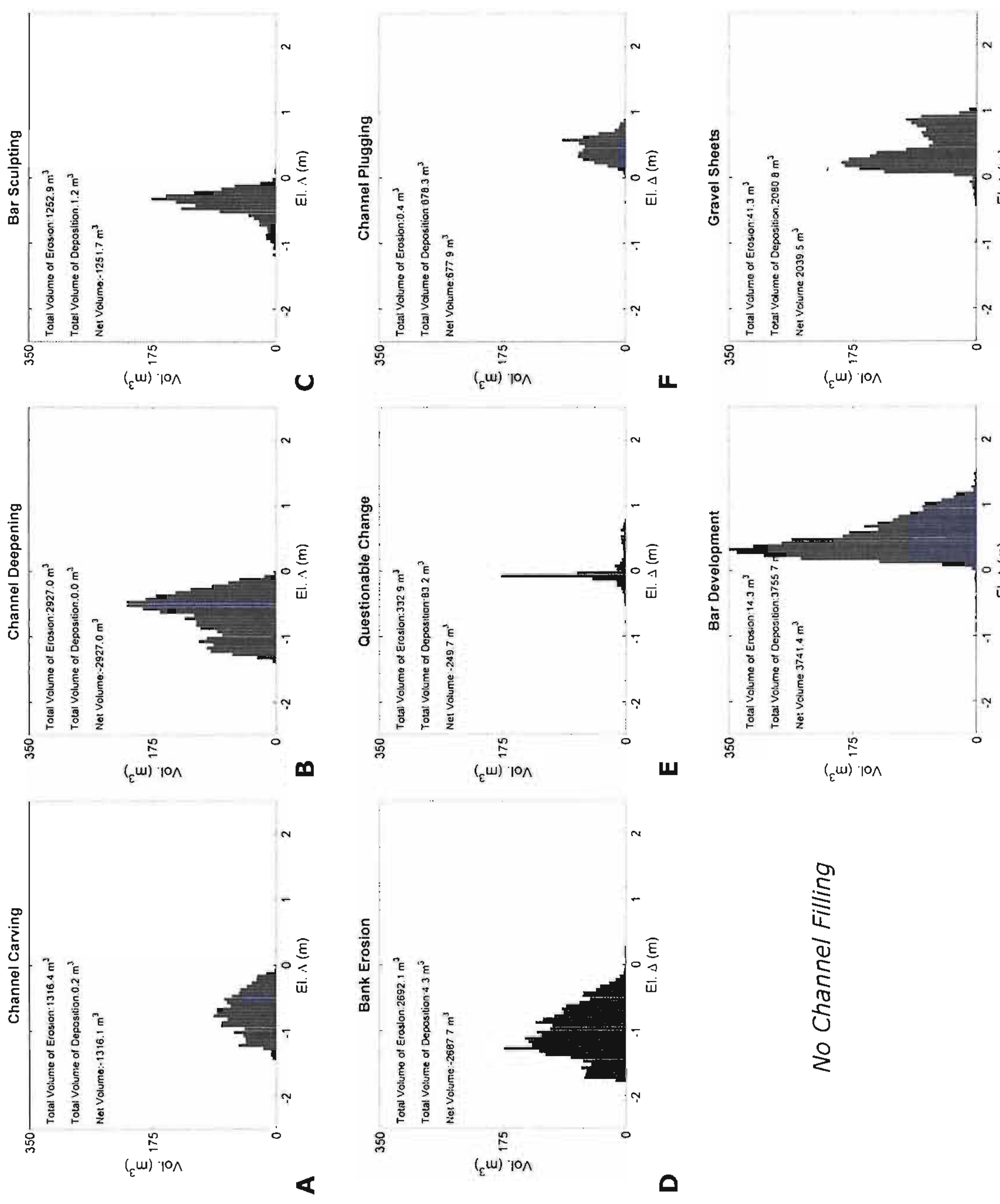


FIGURE 8.12: Elevation change distributions corresponding to the geomorphological interpretation mask of the 2006 to 2007 DoDs shown in Figure 8.11B. The categories of change are A. Channel Carving, B. Channel Deepening, C. Bar Sculpting, D. Bank Erosion, E. Questionable Change, F. Channel Plugging, G. Channel Filling, H. Bar Development, I. Gravel Sheets (see § 8.2 for explanation of categories).

banks. The gravel sheets almost certainly could only have occurred during one or both of the major early season floods. The changes in what was the main channel from the mid 1990s (Figure B.1) could have occurred during intermediate floods, as it appears the plugging only blocks the channel at low flow. The channel plugging ECD (Figure 8.12F) shows a peak of deposition at 60 to 65 cm and deposition up to 90 cm. This magnitude of elevation change is larger than average bar development changes, suggesting they were deposited by the higher magnitude floods. The 678.3 m^3 of channel plugging was essentially mid-channel bar development that, while only constituting 5% of the toal volumetric changes (Figure 8.11C), exerted a fundamental control on switching the main channel over to occupy the right-hand anabranch, whereby intermediate floods could concentrate their energy on shaping that channel.

In terms of the overall picture of change during 2006-2007, the three major changes certainly dominated the picture, but a wide variety of other interesting changes also took place. As Figure 8.11C suggests, the 3756 m^3 of bar development constituted 25% of the overall volumetric changes, with the gravel sheets (2080 m^3) constituting another 14%. As discussed above, the gravel sheets are likely almost entirely due to the two large floods, but the bar development likely involves a complicated mix of changes from both the large and intermediate floods. The bar development ECD in Figure 8.11H has the same characteristic shape we have seen throughout the study period with a shallow fill peak of about 30-35 cm. However, this ECD extends much further into deeper fills with a maximum fill depth of 1.5 m. The portion of the ECD making up those deeper fills are most likely associated with the bigger floods, but this is impossible to segregate out spatially in Figure 8.11 without more evidence from throughout the year.

On the erosional side (54% of total budget), there are a number of interesting changes with the erosional budget being split between channel deepening (35%), bank erosion (33%), channel carving (17%) and bar sculpting (15%; see Figure 8.11C). There is a much greater degree of erosion seen in both the left-hand and right-hand anabranches flanking both sides at the top of the reach. This is one of the reasons that it is speculated that the main mid-channel at the top of the reach was shut off early in the season by the large floods. At the time there may well have been much more extensive deposition in both branches, but the intermediate floods through the rest of the winter and spring would be confined to working primairly within these areas. Starting with the left hand side near confluence 1, bar development against the left hand side (possibly an extension of gravel sheet deposition at high floods later disected) forced the carving of a new channel through the braidplain. There was considerable sculpting of the lateral bar between diffluence 2 and confluence 3 that also appears to have been forced by progradation of gravel sheets into this section of channel from upstream. There was also dissection of some chute features in this vicinity.

Confluence 3 was also substantially rearranged, with the net result being that, having previously moved 50 m downstream, it had now moved 70 m back upstream. What is labeled as pool-scour in Figure 8.11B was actually bank erosion of a triangular wedge-shaped island, which consequently scoured to become a pool.

Similar to 2004-2005, the questionable changes cover 24% of the reach, but only constitute 3% of the total volume of change (15,186 m^3).The questionable change ECD (Figure 8.12E) is biased towards erosion (333 m^3 of erosion verus 83.2 m^3 of deposition), but this is composed primarily of low magnitude elevation changes (5-10 cm). Some of this could reflect inundation and scour across the braidplain, but this can not be established reliably here.

8.4 Discussion

With respect to the preceding results, there are a few broader themes that are helpful to draw attention to. Here, the overall trends observed across all the analyses are discussed to sythesise the sequence of changes observed during 2003 to 2007. In addition, some broader observations about the utility and limitations of the geomorphological interpretation masks are discussed.

8.4.1 Overall Trends on Feshie

After delving into the details of the geomorphological interpretation of the DoD recorded changes from each year, it may be difficult to keep track of the overall trends that emerge from looking at four years of change data. Returning to the drivers of this change (§ 8.2), there were crudely two wetter years with large magnitude floods, and two drier years with limited if any inundation of the braidplain. While Figure 8.4 showed all the DoDs maps and their geomorphological interpretation together as an overview of the different changes from year to year, another, even simpler way is to compare the low-stage inundation maps from year to year (Figure 8.13). The low-stage channels represent the primary channel network and in Figure 8.13 are shown for each year with their water depths at the time of survey and then the previous year's outline in grey as a reference point for changes to the channel network. In both 2004 and 2006, there is minor accentuation of the channel network, and some stage-dependent changes, but the overall networks are largely unchanged. Contrast this to 2005 and 2007, where there are substantial changes to the channel network with whole anabranches being shut off, and other anabranches being reactivated or created.

With this simplistic overview in mind, Table 8.3 provides a summary of the overall trends between different geomorphological categories of change. The table contrasts these different mechanisms of change in both areal terms (as a percentage of total surface area of study reach) and volumetric terms (as a percentage of the total volume of change). Looking first at the areas of questionable change, in areal terms this is essentially the percentage of the reach that probably was not inundated. In the dry years, it is 83% and 81% of the reach, which drops to 25% and 24%, respectively in the wet years. Volumetrically, in the dry years the questionable change areas also comprised a larger perctange of the total volume of change (at 9% in 2003-2004 and 18% in 2004-2005) than in the wet years (at 1% in 2004-2005 and 3% in 2006-2007).

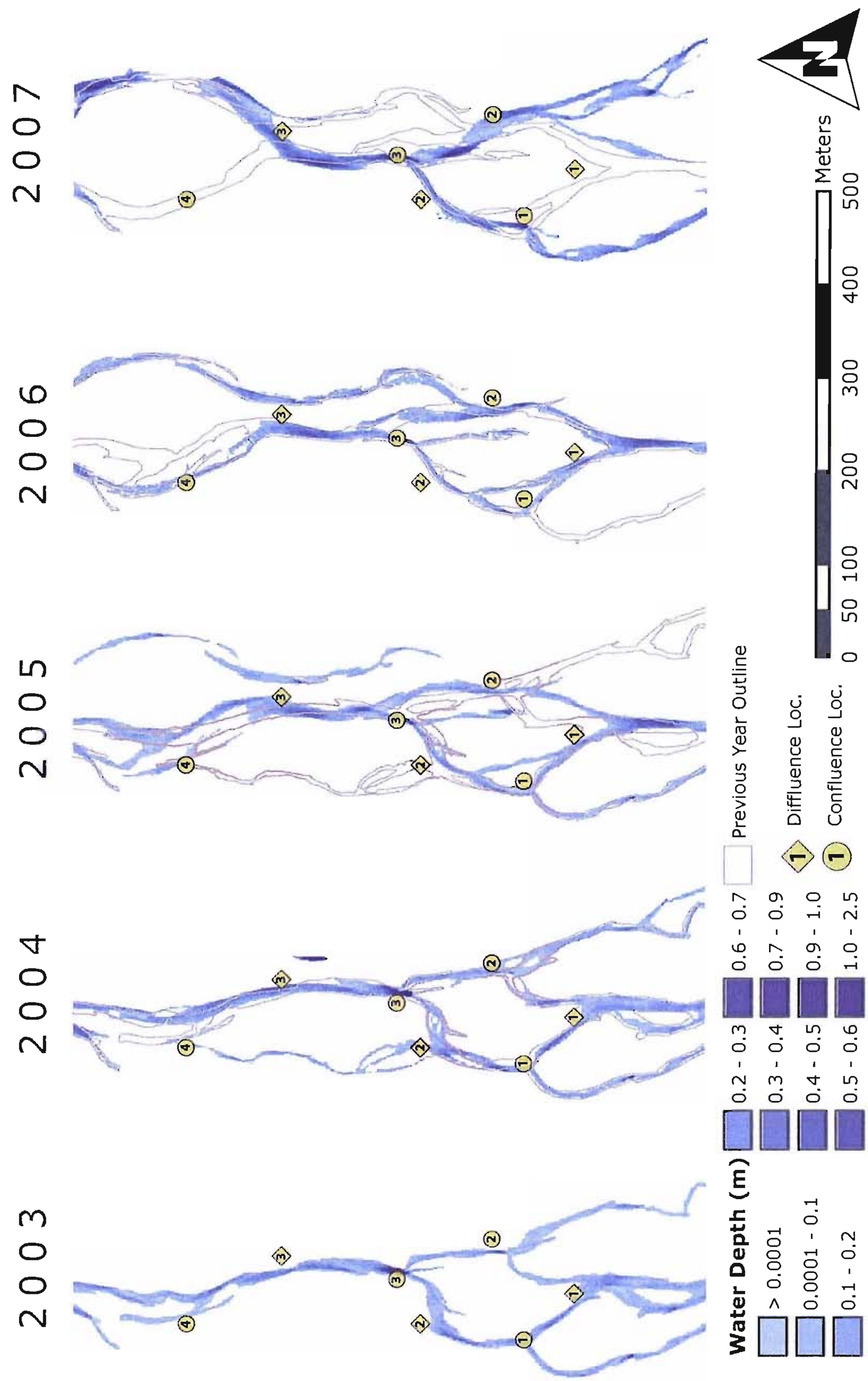


FIGURE 8.13: Maps of low-stage channel network, showing flow depths at time of survey for each year and patterns of change in the primary channel network. For 2004-2007, the previous year's channel network outline is shown in grey for reference.

	2004-2003 % of Total		2005-2004 % of Total		2006-2005 % of Total		2007-2006 % of Total	
	Volume	Area	Volume	Area	Volume	Area	Volume	Area
Channel Carving	0%	0%	29%	8%	8%	1%	9%	3%
Channel Deepening	25%	5%	8%	3%	17%	5%	19%	8%
Bar Sculpting	2%	1%	2%	1%	1%	1%	8%	7%
Bank Erosion	32%	4%	13%	8%	18%	2%	18%	4%
Questionable Change	9%	83%	1%	25%	18%	81%	3%	24%
Channel Plugging	0%	0%	0%	0%	3%	0%	4%	2%
Channel Filling	0%	0%	8%	3%	22%	5%	0%	0%
Bar Development	31%	8%	31%	10%	13%	4%	25%	17%
Gravel Sheets	0%	0%	7%	41%	0%	0%	14%	34%
Summary								
Erosional	59%	9%	53%	20%	44%	9%	54%	22%
Depositional	31%	8%	46%	55%	38%	10%	43%	54%
Questionable	9%	83%	1%	25%	18%	81%	3%	24%

TABLE 8.3: Summary comparison of areal and volumetric percentages by the expert-based geomorphological interpretation categories of change. Percentages are calculated as a percentage of the total DoD thresholded volumetric change and area of change (i.e. deposition + erosion)

Across all the years, the erosional categories of change constituted higher percentages volumetrically than the depositional categories. However, in three of the four years that trend was reversed for the areal percentages and considerably so for the wet years. In 2004-2005, 55% of the reach was depositional with only 20% showing erosion. Similarly in 2006-2007, 54% of the reach was depositional with only 22% showing erosion. This reversal in volumetric versus areal dominance can be explained as an extension of an observation Brasington *et al.* (2003) raised about generic contrasts between fluvial erosion and deposition. As fluvial erosion is more often the result of flow being concentrated in a particular location, it is generally less areally extensive but can produce quite high magnitudes of elevation change. For example, bank erosion may only carve a sliver in plan-form area off the edge of a braidplain, but if that braid plain is 2 m high, this can amount to a substantial volume of material. By contrast, deposition tends to take place where flows are dissipating. Thus, deposition often takes place in broad, areally extensive layers and/or sheets of relatively low magnitude fill depths. With lower magnitude elevation changes, a much greater surface area is required to match the volume of a high magnitude elevation change over a smaller surface area. As such, even though erosion dominates the volumetric budget of the Feshie, it is not surprising to see a greater surface area of the reach covered in deposition. This has important implications for qualitiative interpretations that might be made on the basis of visual evidence alone. As the signature of deposition may cover a broader area, it is very likely that this may give the false impression that deposition is the dominant process.

In terms of dominant mechanisms of change, on the erosional side these vary from year to year. Bank erosion varies between 13% and 32% of the total volume of change, but never covers more than 4% of the surface area of the reach (Table 8.3). Over all four years, bank erosion was the most effective mechanism of erosion with over 5743 m^3 of erosion constituting 31% of the total volume of erosion. Channel deepening ranges between 8% and 25% of the total volume of change and never covers more than 5% of the reach. Over all four years, channel deepening comprised 27% of the total volume of erosion (5151 m^3). Channel carving was quite important in 2004 to 2005, at 29% of the total budget, but was not present at all in 2003 to 2004 and only accounted for 8% to 9% in other years. However, channel carving did account for 467 m^3 of change over the whole study, thus comprising 25% of the total volume of erosion. Overall, bar sculpting was the smallest agent of fluvial erosion, but still amounted to 1627 m^3 (8%) of erosion, with the remaining 8% in the questionable change category.

On the depositional side, bar development is the most prominent depositional mechanism in every year except 2005 to 2006 (the range is 13% to 31% of total volume of change). Over the entire study period, there was over 8507 m^3 of bar development making it not only the most effective depositional mechanism of change (61% of total volume of deposition), but also the most effective mechanism of change overall (at 26% of the total volumetric budget). This deposition was primarily in the form of diagonal bars as described by Ferguson & Werritty (1983), but there was also extensive lateral bar development. Another type of bar develoment, gravel sheets, was only present in the high water years, but would cover 41% and 34% of the reach in 2004-2005 and 2006-2007 respectively (Table 8.3). Due to the generally shallow depth of these fills, they were more modest as a percentage of the total volume in each year at only 7% and 14%. However, at 2625.8 m^3 they still made up a respectable 19% of the overall erosional budget for the entire study period. Channel plugging played only a minor role volumetrically in later years, but played a fundamental role in forcing anastamosis on the reach. Channel filling was very pronounced in 2005-2006 at 22% of the total budget, but over the entire four years, only amounted to 1574 m^3 over the entire four years (11% of total volume of erosion).

What is particularly interesting is that on the surface the reach is dominated by different types of bar development (including gravel sheets), and even volumetrically this is the most dominant agent of change. This may leave even the trained geomorphologist with the impression that the reach is aggradational. After-all, braided rivers are supposed to be zones of deposition where transport supply is exceeded by transport capacity (Knighton 1998). However, the overall story reveals that the reach is consistently degradational and that three main mechanisms of change (bank erosion, channel carving and channel deepening) are accomplishing this change without leaving a large mark on the reach in terms of areal extent. On average, these processes are only shaping 13% of the surface area of the reach!

8.4.2 Why is There Questionable Change?

With up to 83% of the reach being classified as showing questionable changes (Table 8.3), it is fair to ask why such areas were not removed during the DoD uncertainty analysis? Recall from Chapter 4 that the purpose of the DoD uncertainty analysis is to produce the *best* estimate of what DoD changes can reliably be distingusihed from noise. It produces a better estimate than has been yielded from traditional, simple, minimum level of detection techniques ($_{min}$LoD), but it is by no means perfect. It still has the potential to include some changes that are not real, and discard other changes that probably are.

The pathway 4 DoD Uncertainty analysis used here is working in three steps. First, spatially variable uncertainties in the DEM surface representation are approximated on a cell-by-cell basis using a fuzzy inference system. These uncertainty estimates from both DEMs are propagated through into an estimate of DoD uncertainty, which can be represented probabilistically. In a pathway 3 analysis, a confidence interval would be selected to threshold the DoD, discarding changes that have probabilities of being real below the threshold. While this does a better job than spatially uniform uncertainty estimates, it is still prone to discarding large segments of low-magnitude elevation changes that probably are real.

As Figure 8.4 shows, the DoDs are capturing very coherent spatial patterns of change with clear distinctive zones of erosion and deposition. Where these cuts and fills taper down to low magnitude changes (e.g. approaching zero at their boundaries), there are still large areas of changes that are probably real, but might fall below the selected confidence interval. Under a pathway 4 analysis, an attempt is made to recover some of these changes by updating the probability that the change is real (with Bayes Theorem), based on a neighbourhood moving window analysis. For example, cells that are showing erosion, which are entirely surrounded by cells also showing erosion are given a higher probability of being real; whereas a cell showing erosion that is entirely surrounded by cells showing deposition is given a lower probability of being real. This analysis recovers significant areal and volumetric DoD predicted changes, that would otherwise be discarded. However, it may also recover patches of very small magnitude elevation changes that exhibit spatial coherence, but probably are not real. This is a trade off between using an automatic filter (as used here), versus a manual filter.

Returning to this question of why are there still questionable changes after the above analysis, recall this category is being highlighted in the context of a geomorphological *interpretation*. It is thus an opportunity to exercise geomorphological judgment, and manually incorporate evidence that may not have been considered in the DoD uncertainty analysis.[27] It is a manual filter or mask to improve upon the estimate of the pathway 4 DoD uncertainty analysis. The

[27] It should be noted that the rule-based fuzzy inference system is flexible enough that if such additional evidence can be represented via a spatial classification, it can be simply built into the rule system. However, a more complex rule system may not always be necessary or desirable.

classification of a region as showing 'questionable changes' is not necessarily saying that the changes can not be real. It is simply suggesting that this is a region in which there is less confidence that the changes are actually real and it is likely that real changes are mixed in with non-meaningful changes. In this case, there were large areas of the braid plain in which there was no or inconclusive evidence of inundation, and thus no fluvial agent for change. Using the questionable change mask allows these areas to be segregated and interpreted separately.

8.4.3 So What?

This chapter started with an assertion that high resolution topographic datasets from repeat surveys have not been effectively exploited to give insight into geomorphological mechanisms of change. An attempt to demonstrate how this can be rectified was made, with new analyses based on four years of monitoring data from the Feshie. Comparisons were made to analyses undertaken by Ferguson & Werritty (1983) using much simpler surveys based on the surveying technology available at the time. It is thus fair to ask whether or not this new style of analysis reveals anything that the plane table surveys and transects of (Ferguson & Werritty 1983) could not?

While this question is ultimately for the reader or practitioner performing the analysis to judge, some methodological differences and improvements are highlighted in Table 8.4 to help make that judgment. What the table highlights is that more detailed quantitative analysis can be made using the masking techniques identified in Chapter 5 and used in this chapter. In this chapter, these interpretations were made with respect to DoDs which had an uncertainty analysis applied. In principle, the masking techniques can just as easily be applied to a raw DoD with no uncertainty analysis. The, 'Chapter 4's column in Table 8.4 is shown to highlight what sort of geomorphological interpretations are possible with only a standard DoD analysis. This is largely what has been reported in the literature to date (Brasington *et al.* 2000, Fuller *et al.* 2003, Lane *et al.* 2003, e.g.). While the DoD analysis itself captures all the changes, it can only be quantitatively described at the reach scale, and any sub-reach or bar-scale geomorphological interpretations are strictly qualitative.

In terms of the quality of geomorphological interpretations that can be made using DoD masks, versus regular DoDs, versus older transect-based analyses, this is partly down to the geomorphologist casting judgment on the system. The geomorphological interpretation mask is posed as an 'expert-based' system. As such, different experts will have different levels and types of experience as well as potentially conflicting ideas[28] about how a system works. Those differences are for peers to judge. However, it is argued that interpretations and hypotheses that are formed on the basis of change analyses, can be more robustly tested if there is more quantitative data available. For example, a reasonable hypothesis from field observations, DoD measurements and the work of Ferguson & Werritty (1983) might be that central bar development is the most dominant mechanism of geomorphological change on the

[28]These are an example of a structural uncertainty (Figure 2.2).

	Ferguson & Werritty (1983)	Chapter 4	This Chapter
Morphological Method:	1D (repeat transects/planform)	2.5D (repeat topography)	2.5D (repeat topography)
Uncertainty Analysis:	None (estimated at +/− 10 cm based on roughness)	Pathway 4 (spatially variable and spatial coherence analysis)	Pathway 4 (spatially variable and spatial coherence analysis) + use of questionable change mask
Scale of Geomorphological Interpretation:	Bar-scale, quantitative in one dimension, qualitative other wise	Crude reach-scale, qualitative description of specifics	Detailed, bar-scale interpretations, quantitative
Spatial Extent Used:	1-3 bar complexes (180 m subreach)	1 km reach	1 km reach
Spatial Resolution of Data Used:	2 m transect spacing; 20 m between transects	1 m resolution DEM used, resolving between 2.5 and 20 cm (μ 7 cm) resolution in vertical	1 m resolution DEM used, resolving between 2.5 and 20 cm (μ 7 cm) resolution in vertical
Spatial Resolution of Geomorphological Interpretation	Bar scale	Reach Scale	Bar Scale
Quantification of elevation change	Only in 1D (along transects)	Fully spatially distributed; but integrated across reach	Fully spatially distributed and possible segregate down to resolution of raster
Elevation change distributions	Only for transects; not spatially integrated over whole study areas	Spatially integrated across entire reach, but not resolved locally	Spatially integrated across any area (mask) user defines
Sediment budgeting (storage terms only)	Either aerial (i.e. just at cross-sections), or major spatial interpolation and assumptions required	Volumetric, across entire reach	Volumetric, can be resolved down to individual bar units; here, resolved by categories of change
Sampling Frequency Used	Annually	Annually	Annually
Sampling Frequency Possible	Event-scale (down to hourly or daily for limited spatial extents; less laborious)	Event-scale (weekly for spatial extent used here, and presuming no other events occur in between; Daily or hourly possible for smaller spatial extents)	Event-scale (weekly for spatial extent used here, and presuming no other events occur in between; Daily or hourly possible for smaller spatial extents)

TABLE 8.4: Comparison of geomorphological interpretation techniques used in Ferguson & Werritty (1983) study, Chapter 4 and this Chapter.

Feshie. Masking the DoDs provides a direct test of this simple hypothesis. Indeed, central bar development was, volumetrically, one of the most dominant mechanisms of change.

The masking technique provides a simple way to segregate DoDs spatially and quantitatively. While this is a helpful methodological development, the real significance is that it affords the geomorphologist more confidence in making statements about channel development and response. Specifically, this method quantitatively unlocks spatially explicit information about the magnitude of geomorphological change in accordance with the geomorphologist's interpretation of the reach. Instead of qualitatively and/or graphically highlighting, which areas of the DoD pertain to what inferred mechanisms of change, this technique allows the explicit quantification of such spatial units. The areal dominance of some styles of change may create false impressions about the relative importance of different mechanisms of change. Pre-conceptions about the relative magnitude and importance of such processes can be tested. In the case of the Feshie, the relatively modest areal signature of erosional processes like bank erosion, channel carving and channel deepening was consistently out-pacing all of the depositional processes combined.

8.5 Conclusion

A simple new technique presented in Chapter 5 for segregating a DEM of difference (DoD) to make more meaningful geomorphological interpretations in a fluvial morphological sediment budgeting context was applied to a four year time series. The technique relied on the definition of spatial masks, which classify the DoD recorded changes based on an expert-derived geomorphological interpretation. In principle, any and/or multiple classifications that are helpful for making a geomorphological interpretation can be used. The utility comes in that the mask allows the morphological budget to be segregated in areal and volumetric terms on the basis of the classification.

This technique was applied to four years of high resolution topographic surveys from a dynamic, braided reach of the River Feshie in Scotland. The Feshie is an interesting case study partly because of the range of fluvial processes it exhibits over annual time-scales, but also because the same reach was the subject of a similar monitoring study by Ferguson & Werritty (1983), which tracked channel changes and bar development using more traditional transect and planform surveys. Here, a similar channel change monitoring effort was undertaken with survey-grade rtkGPS to produce high resolution topographic surveys. The Ferguson & Werritty (1983) study focused primarily at the bar-scale and involved tracking the development of several diagonal bars, presenting a mechanistic conceptual model for their formation and evolution. The analysis here, was able to confirm the general applicability of this conceptual model over a much larger spatial extent.

This case study also highlighted the relative significance of a fuller range of mechanisms of fluvial change in each year across the entire study site. These included eight depositional mechanisms, eight erosional mechanisms and a questionable change category to highlight suspect areas of the DoD. It was shown that the reach was consistently experiencing overall degradation, with bank erosion being the most effective mechanism of erosion, but with channel carving and channel deepening also playing very prominent roles. Bar development was the single most-effective mechanism of volumetric change and also the most areally extensive. In years with floods exceeding 60 cumecs, deposition covered well over half of the reach with erosion only impacting less than 20% of the reach. In years with floods from only 20 to 60 cumecs, deposition still out-flanked erosion areally but these changes were confined to just the active channel network instead of extending across the braid plain. In both cases, the areal extent of deposition and the volumetric dominance of bar development creates an impression that the reach is aggradational. However, the more aerially efficient erosional mechanisms are actually outcompeting the deposition. This is consistent with the longer-term context of late Holocene incision through a fluvio-glacial valley fill.

Part IV

Synthesis

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

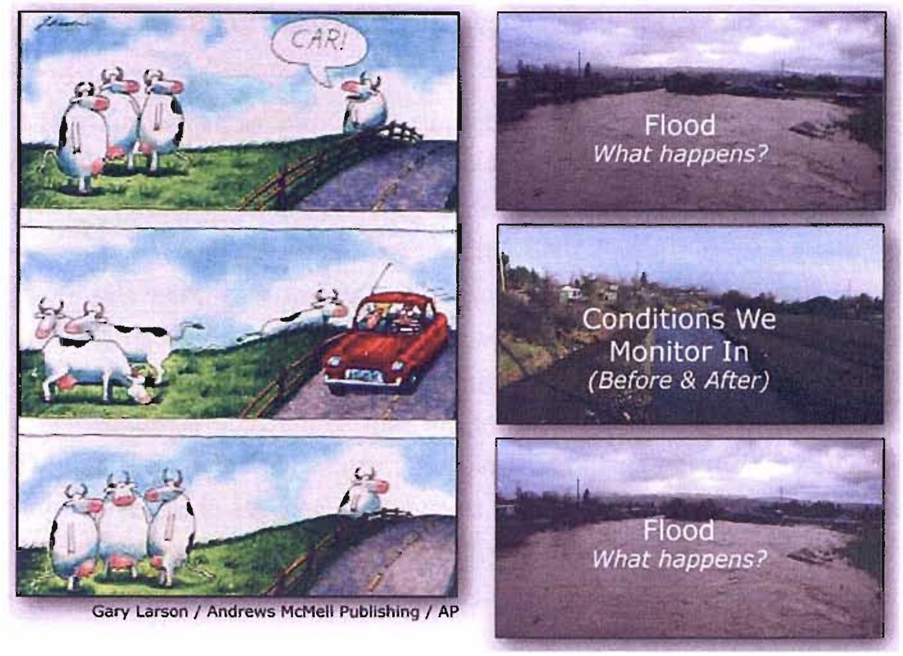


FIGURE 9.1: An illustration of Gary Parker's rivers in flood analogy to the popular Far Side Cartoon. As direct observations of river beds during big floods are rarely ever actually made, we can only infer from observations before and after the flood the behaviour of river beds. Similarly, Parker argued 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.

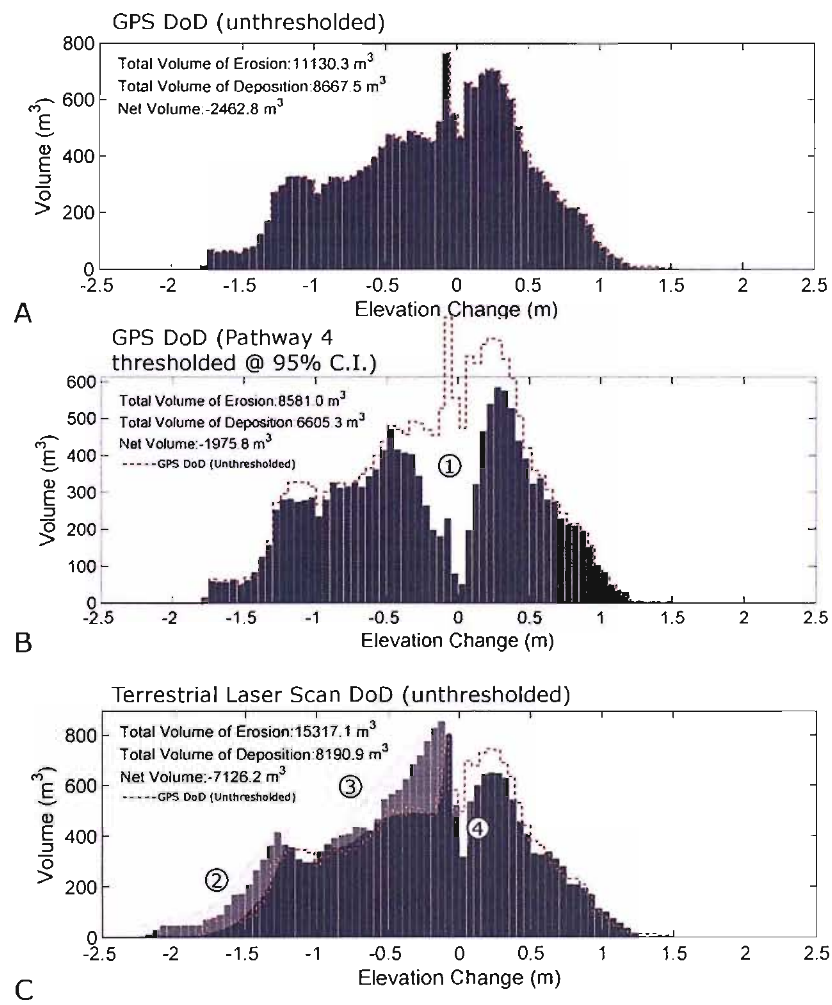


FIGURE 9.2: A comparison of DoD elevation change distributions derived from a GPS survey and a concurrent terrestrial laser scan survey on the Feshie from 2007 to 2006. A) The unthresholded DoD from GPS surveys with no accounting for uncertainty. B) The DoD from GPS surveys with a pathway 4 uncertainty 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.

Part V

Appendices and Bibliography

Appendices

Appendix A

River Feshie Catchment and Acknowledgments

A.1 Purpose

The purpose of this appendix is to provide a slightly more detailed catchment site description then was provided in § 3.5, § 4.2 and § 8.2. This catchment description (§ A.2) is a direct excerpt from Soulsby *et al.* (2006). Some maps of the study site are also provided. Finally, acknowledgments to the individuals and organisations who supported the work on the Feshie through collaboration, field work, providing data and/or analyses, and financial assistance is provided here.

A.2 Feshie Catchment Description

From the rich literature on the Feshie, one of the most concise and informative physiographic overviews of the Feshie catchment was written by Soulsby *et al.* (2006) and is quoted below. A catchment map is shown in Figure A.1

> 'The river Feshie drains an area of 231 km^2 on the western side of the Cairngorms, Scotland. The catchment covers some of the steepest, most mountainous terrain in the UK, with an altitudinal range between 230 and 1262 m, and a mean elevation of 617 m. The highest parts of the catchment are associated with granite batholiths in the northeast and south (Fig. 1c). These were intruded into the Moinian schists, which underlie most of the catchment and were metamorphosized in the Grampian Orogeny (Brown & Clapperton 2002). In places, the schists contain dykes of felsite and diorite.
>
> 'The topography of the catchment reflects the geology and the glacial history, which resulted in a river capture of the Upper Feshiea 32.3 km^2 subcatchment,

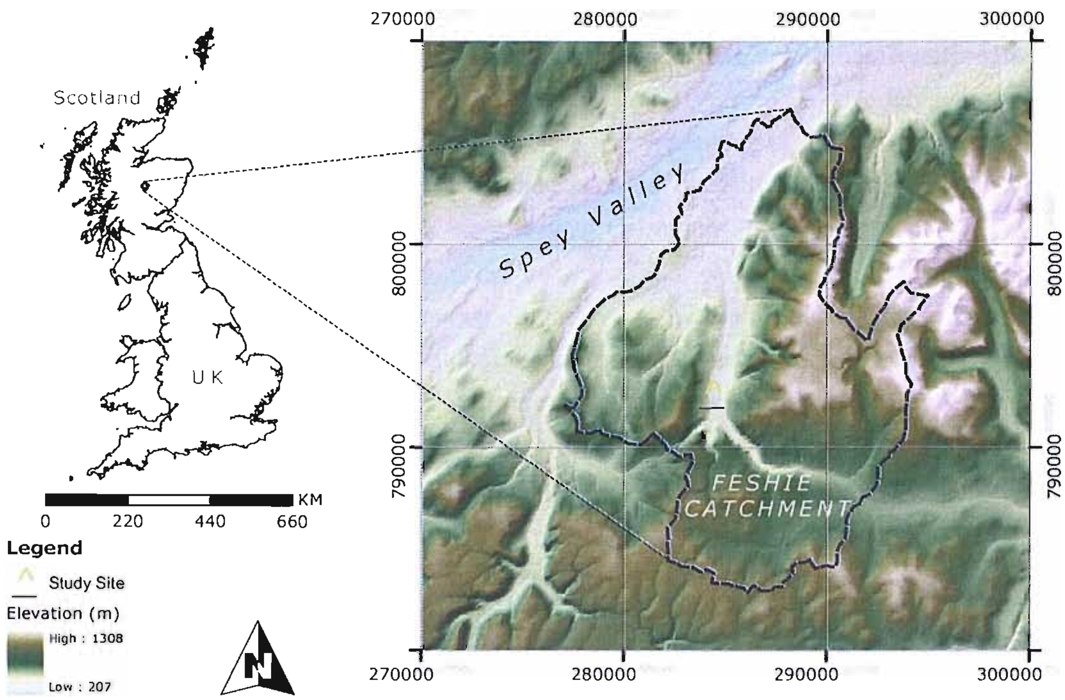


FIGURE A.1: Location Map of River Feshie Study Site.

which formerly drained in to the Dee catchment, but was diverted by glacial deposits (Werritty & McEwen 1993). Thus, the Upper Feshie undergoes an 180° turn, just upstream of its confluence with the Eidart, a second 29.9 km^2 headwater subcatchment (Fig. 1a). These headwaters drain catchments of contrasting character (Table 1). The Upper Feshie drains a lower subcatchment (mean altitude 686 m), which mainly comprises a flattish basin, dominated (65% cover) by peat soils over 1 m deep which have formed on low permeability drifts (Fig. 1b). The Eidart (mean altitude 865 m) drains part of the Cairngorm granite above altitudes of 900 m and flows south through a steep, incised, glaciated valley. The dominant soils (59.5% cover) are shallow (~0.5 m) alpine soils or bedrock, though peat also covers 28% of the subcatchment.

'Downstream of the Upper Feshie-Eidart confluence, the river flows west through the glaciated trough of Glen Feshie. Just upstream of the Lorgaidh, a south bank tributary, alluvial deposits (in places over 10 m deep) become more extensive, as the Feshie flows north through a braided section, which is some 4 km in length (Rodgers *et al.* 2004). Downstream of this, the valley widens out, and extensive alluvial and fluvio-glacial terrace deposits cover the valley floor down to the catchment outfall at Feshie Bridge (Werritty & Ferguson 1980). A large west bank tributary, the Allt Chomraig, enters the mainstem of the Feshie, whilst five smaller east bank tributaries, including the Allt a Mharcaidh experimental catchment, drain the main area of granite, and enter the river between the braids and the Feshie Bridge (Soulsby *et al.* 2001). The Chomraig is low-lying (mean altitude 490

m) and like the lower Feshie, has extensive peat soils (35% of the area) covering the upper subcatchment. However, in its lower catchment it also has widespread cover (10% of the area) of alluvial soils. Sub-alpine soils (often overlying deep, freely draining periglacial material) and more freely draining podzols predominate in the east bank tributaries of the Feshie, such as the Allt a Mharcaidh (mean altitude 699 m), which drain the main area of Cairngorm granite.

... paragraph omitted ...

'Land use in the Feshie is mainly characterised by alpine heath at higher altitudes above ca. 800 m, heather (*Calluna*) moorland covers the steeper slopes, with boreal blanket bog vegetation covering the flatter peat-dominated areas. Forest cover is restricted to some small areas of native woodlands of Scots pine (*Pinus sylvestris*) in the lower catchment and some small areas of commercial forest. Almost the entire catchment lies within the Cairngorms National Park, so conservation is a major land management priority. However, Glen Feshie Estate, which owns much of the land, is managed as a working highland estate, with Red Deer (Cervus cervus) shooting and Atlantic Salmon (*Salmo salar*) fishing being important objectives. Mean annual precipitation is estimated for the catchment at 1300 mm which is mainly derived from prevailing westerly weather systems. Snow can account for as much as 30% of annual precipitation inputs (Soulsby et al., 1997). The mean flow at Feshie Bridge is 8.01 cumecs, with the long term (10 year) Q_{95} at 1.71 cumecs and the Q_{10} 16.28 cumecs. Mean monthly temperatures at 575 m in the catchment vary between 1.2 °C in February and 10.3 °C in July.'

A.3 River Feshie Study Acknowledgments

Field work at the River Feshie has been part of an extensive long-term monitoring effort initiated by Dr. James Brasington in 1998 and later reported in (Brasington *et al.* 2000) and (Brasington *et al.* 2003). I began working with James on the Feshie in 2004. This research on the River Feshie has led to a collaboration of a variety of researchers from the United Kingdom. Indirect support from their respective institutions is acknowledged and appreciated. The primary research team has consisted of:

- Principle Investigator: James Brasington (Centre for Catchment and Coastal Research, Institute of Geography and Earth Science, Aberystwyth University; formerly Department of Geography, University of Cambridge)
- Clare Cox (University of Cambridge)
- Dr. Rebecca Hodges (University of Glasgow; formerly University of Cambridge)
- Richard Williams (JBI Ltd.)

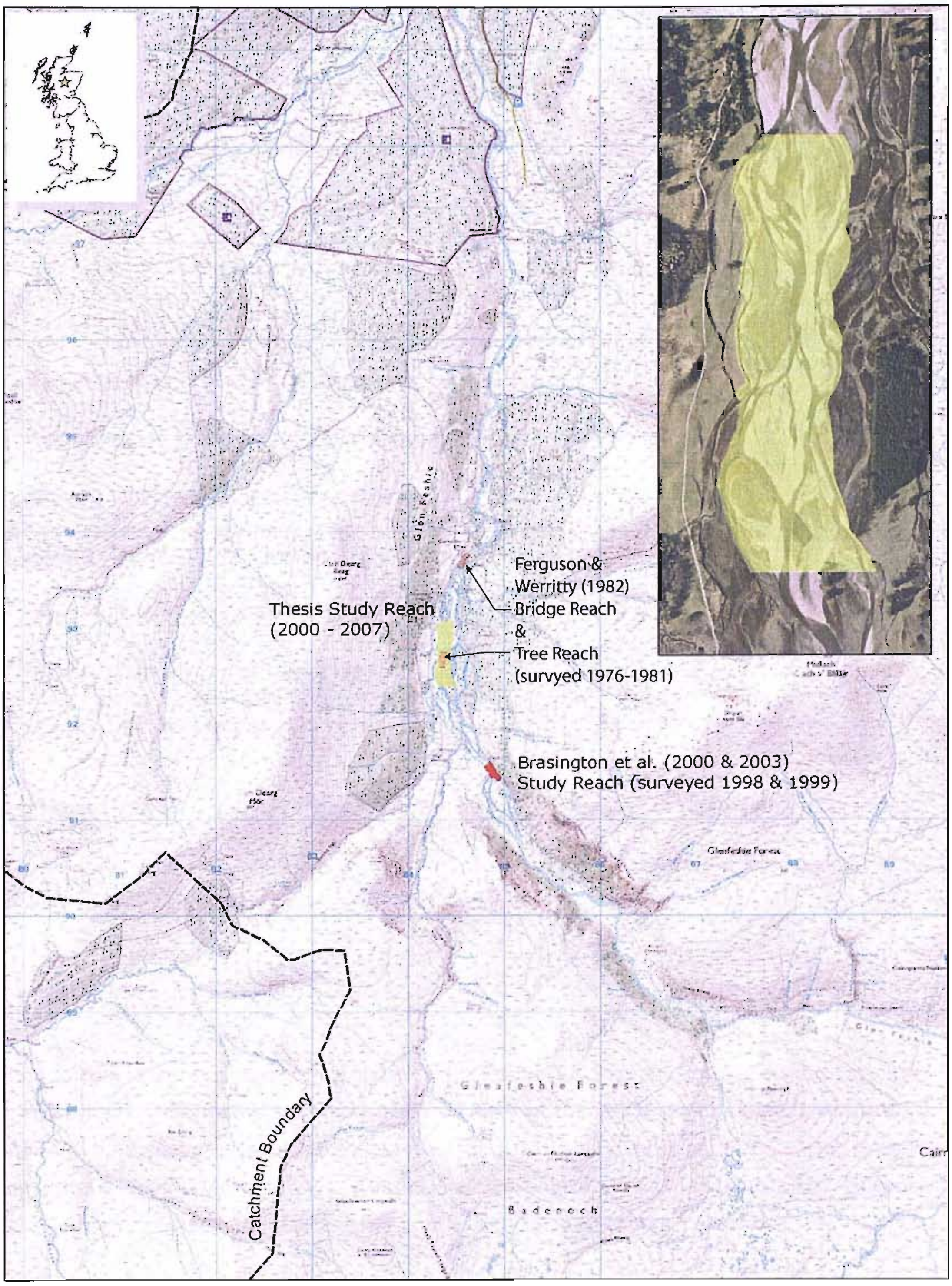


FIGURE A.2: Vicinity Map for River Feshie Study Site. The thesis study site is depicted in yellow on both the Ordinance Survey 1:25,000 map (background hillshade derived from NextMap 5m DTM data flown in 2005) and the aerial photograph from 2005.

A variety of individuals in addition to the primary collaborators have offered their time and expertise during numerous field work campaigns on the Feshie. Below is a non-exhaustive list, but all those who have helped are sincerely thanked:

- Dr. Paul Brewer (CCCR, Aberystwyth University)
- Dr. Barbara Rumsby (University of Hull)
- Clare Black (University of Cambridge)
- Clare Hartley (University of Cambridge)
- Dr. Damiá Vericat (CCCR, Aberystwyth University)
- Catherine Swain (CCCR, Aberystwyth University)
- Kirsti Proctor (Aberystwyth University)
- Richard Williams (J.B.A. Consultants)
- Adrian (University of Cambridge)
- Chris Rolf (University of Cambridge)
- Mathew (University of Cambridge)
- Booker (my mongrel dog)

My apologies to those who I have failed to mention here. Your support is certainly appreciated.

Please refer back to the Acknowledgments at the front of the thesis for acknowledgments pertaining to the thesis as a whole.

A.3.1 Funding

Funding for the long-term monitoring on the River Feshie has primarily been pieced together by staff, equipment and travel-grant resources from each of the collaborator's parent institutions as opposed to a single large research grant. NERC PhD studentships and College support through the University of Cambridge (under Dr. Brasington) for collaborators Dr. Rebecca Hodges (currently University of Glasgow) and Clare Cox are notable exceptions.

- The University of Southampton's School of Geography and the Centre for Ecology and Hydrology (a PhD Studentship for author)
- A Horton Hydrology Research Grant from the Hydrology Section of the American Geophysical Union (travel funds)
- Aberystwyth University Research Fund (travel funds)

- Centre for Catchment and Coastal Research seed-corn funds (staff and equipment)
- Department of Geography, University of Cambridge (staff, travel and equipment)

Appendix B

Feshie Aerial Photography

B.1 Purpose

The purpose of this appendix is to provide the reader with historical aerial photographs of the Feshie Study site used in Chapter 4 and Chapter 8. The aerial photos provide some historical context for how the five year study period reported in this chapter, compares with changes experienced over the previous 60 years. A very simple locational probability analysis is also shown, to highlight the dynamism of the reach and the correspondence between zones that are currently active or inactive within the reach to historical zones of activity or inactivity.

B.2 Locational Probability Analysis

A total of eight aerial photos of the study reach were available at irregular intervals over the past 60 years (Table B.1). The photographs are shown in Figure B.1 and full page versions can be found in § B.3.

As shown in Figure B.2, the images were each classified by Brasington and Cox (2006, p. comm) into six categories:

1. Water (standing or running)
2. Exposed gravel (unvegetated)
3. Annual vegetation
4. Grasses
5. Moss
6. Mix of Heather and Moss

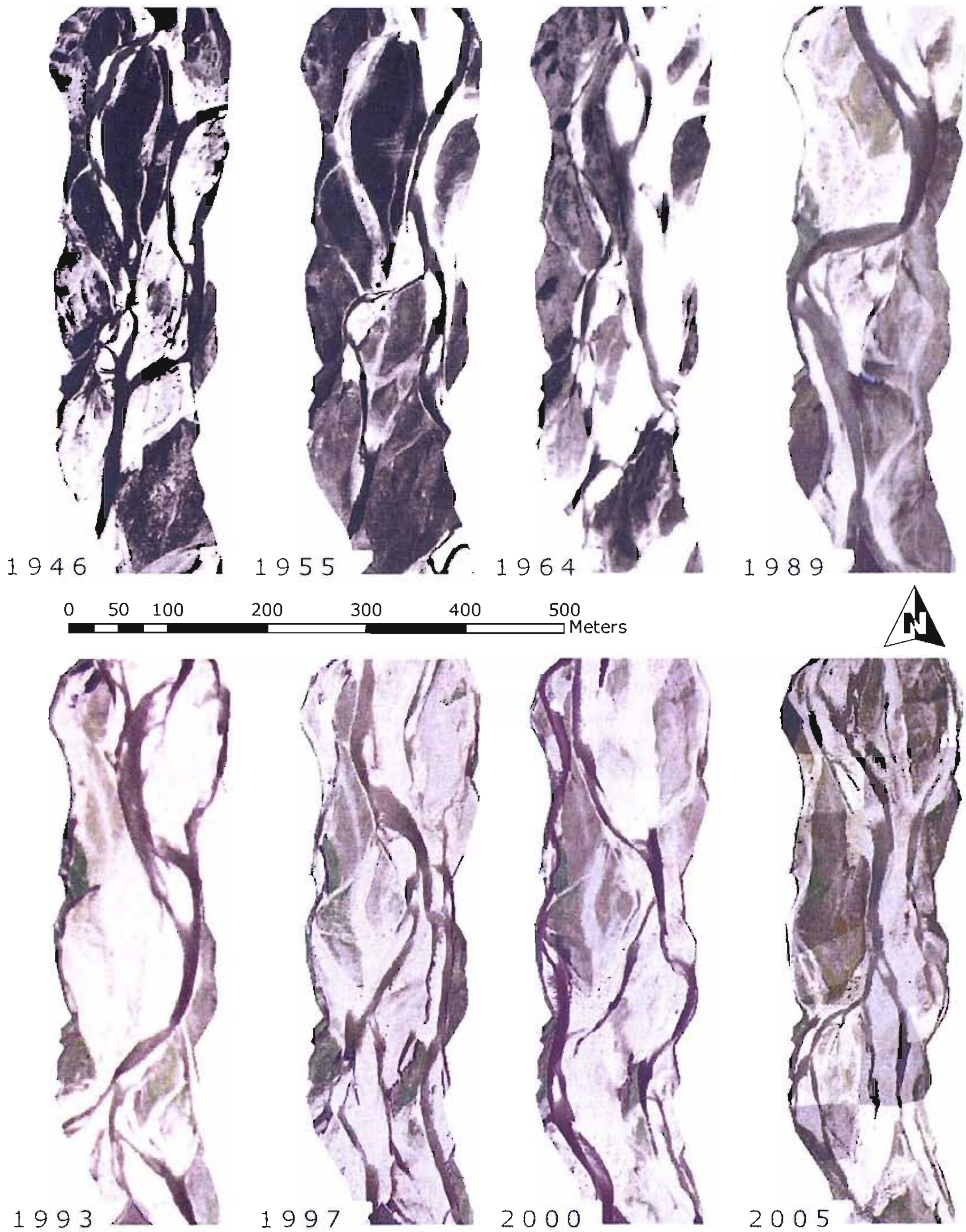


FIGURE B.1: Comparison of all aerial photography of study reach. The photographs have been clipped to the same analysis extent used throughout the thesis (Full images are viewable in §B.3

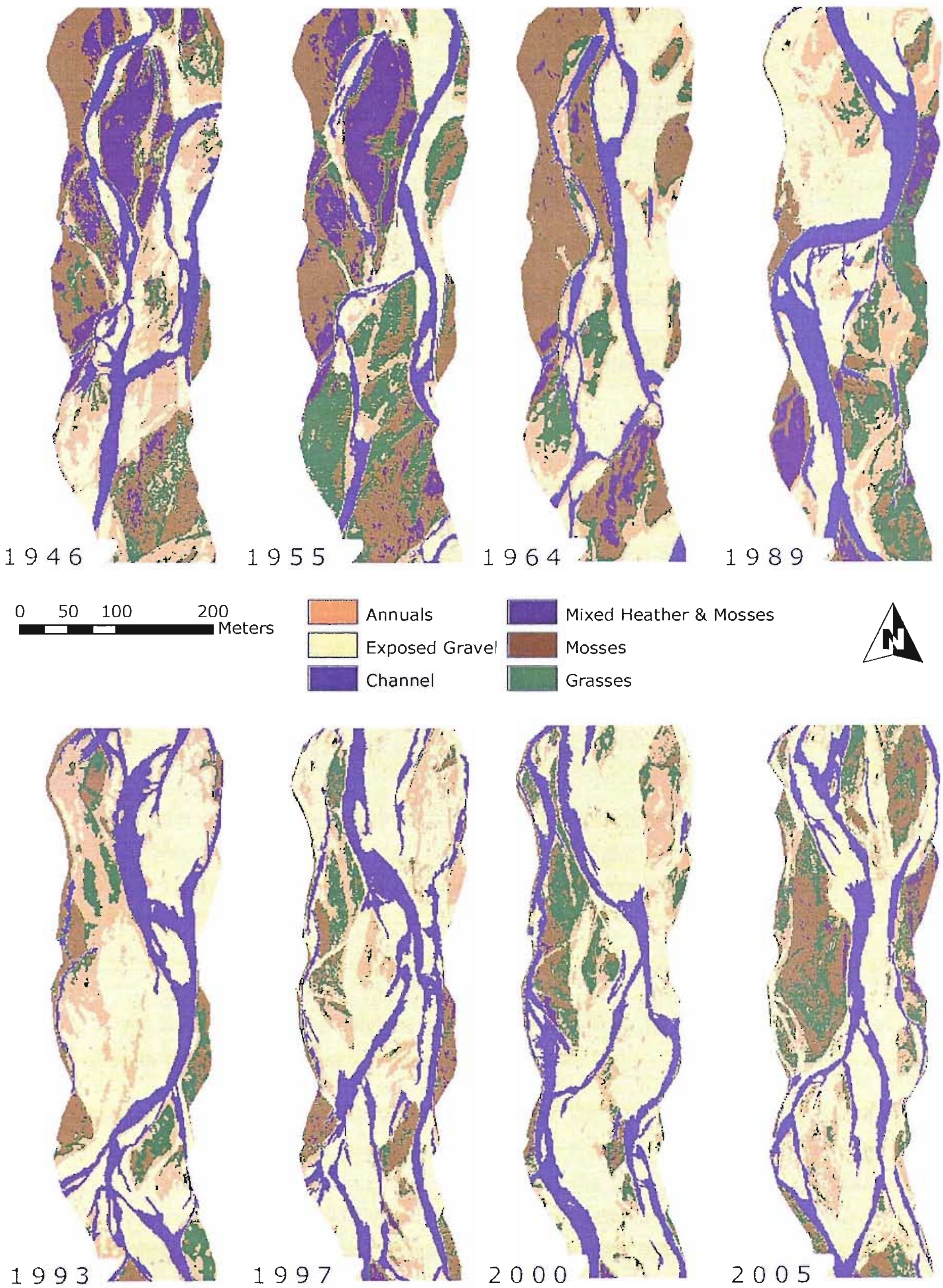


FIGURE B.2: Vegetation classification of aerial photographs. Analysis from Brasington and Cox (p.comm).

Year of Photo	Time Gap (yrs)	Type
1946	-	Black & White
1955	9	Black & White
1964	9	Black & White
1989	25	Colour
1993	4	Colour
1997	4	Colour
2000	3	Colour
2005 April	5	Colour†
2005 July	5	Colour†
2007	5	Colour†

TABLE B.1: Aerial Photo Availability. All photos were 30 cm resolution. † The 2005 July and 2007 photos were a mosaic from a ground-based kite/blimp survey. See photo captions in § B.3 for sources of photography.

Notice that the above ordering is also indicative of floodplain age for this successional floodplain vegetation community. For the purposes of this thesis, I prepared a simple locational probability analysis of the vegetation classes for the 59 year period for which aerial photography was available, following the procedure outlined in Graf (2000). Briefly, the probability p that each class existed as one of the six given categories was calculated independently for each category on a cell by cell basis using:

$$p = (W_1F_1) + (W_2F_2) + \ldots (W_nF_n) \tag{B.1}$$

where n is an index corresponding to the n^{th} photo, F_n is a boolean feature occurrence for each cell (0 if false; 1 if true) in that year, and W_n is the weight given to each photo, such that $\sum(W_n) = 1$ and is calculated as a time-weighted percentage using:

$$W_n = t_n/m \tag{B.2}$$

where t_n is the time between the previous photo and the current photo and m is the total number of years between the oldest and most recent photos.

This simple analysis was used to ask the question: over the past 60 years, what was the likelihood that a particular location existed as each of the six classes? The calculated locational probabilities for each class are shown in Figure B.3. From the channel locational probability analysis, the darkest areas (highest likelihood) correspond primarily to confluence and diffluence zones, with fairly persistent secondary channels on the right and left hand margins, as well as a main channel through the middle of the bottom half of the reach. The exposed gravel shows how much activity and turn-over the braid plain has been subjected to with the most widespread areas of high probability of any of the calculations. The exposed gravel shows notably shows a large light-shaded area on the lower left half of the braid plain that is explained

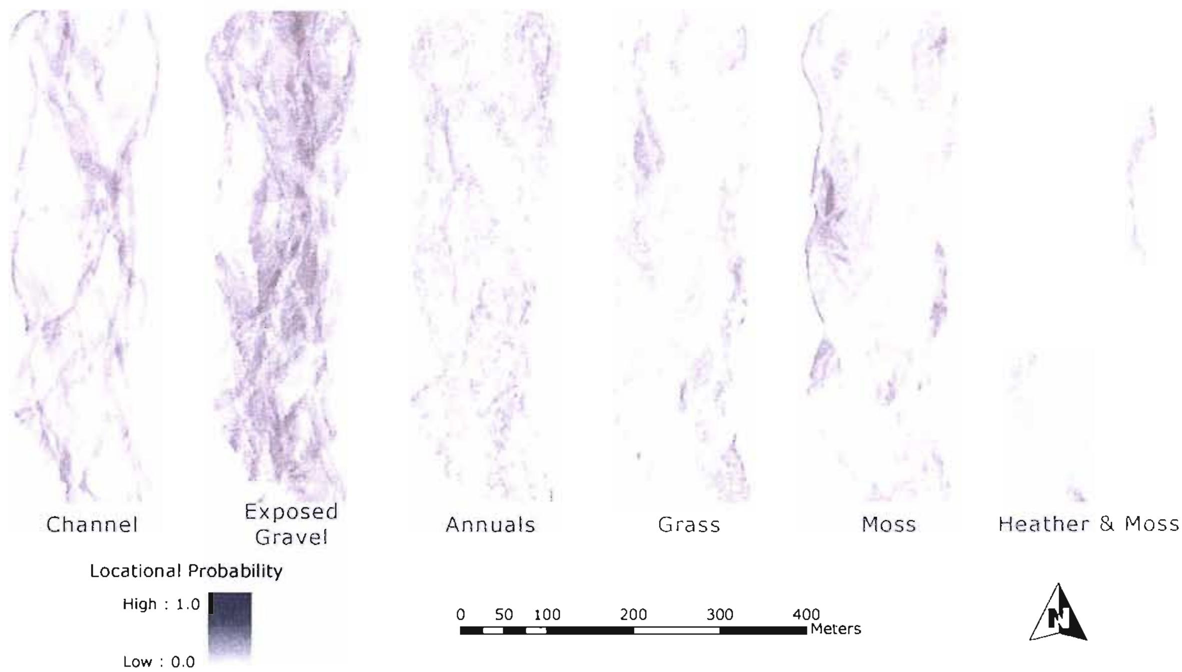


FIGURE B.3: Locational probability analysis of aerial photos (Based on classification presented in Figure B.2).

by the persistence of grass, moss, and heather as indicated by the high locational probabilities shown for these categories in that same area.

B.3 Aerial Photographs

This section shows full-page figures of the aerial photographs used in this thesis for reference.

FIGURE B.4: Black and white aerial photography of study reach from 1946. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

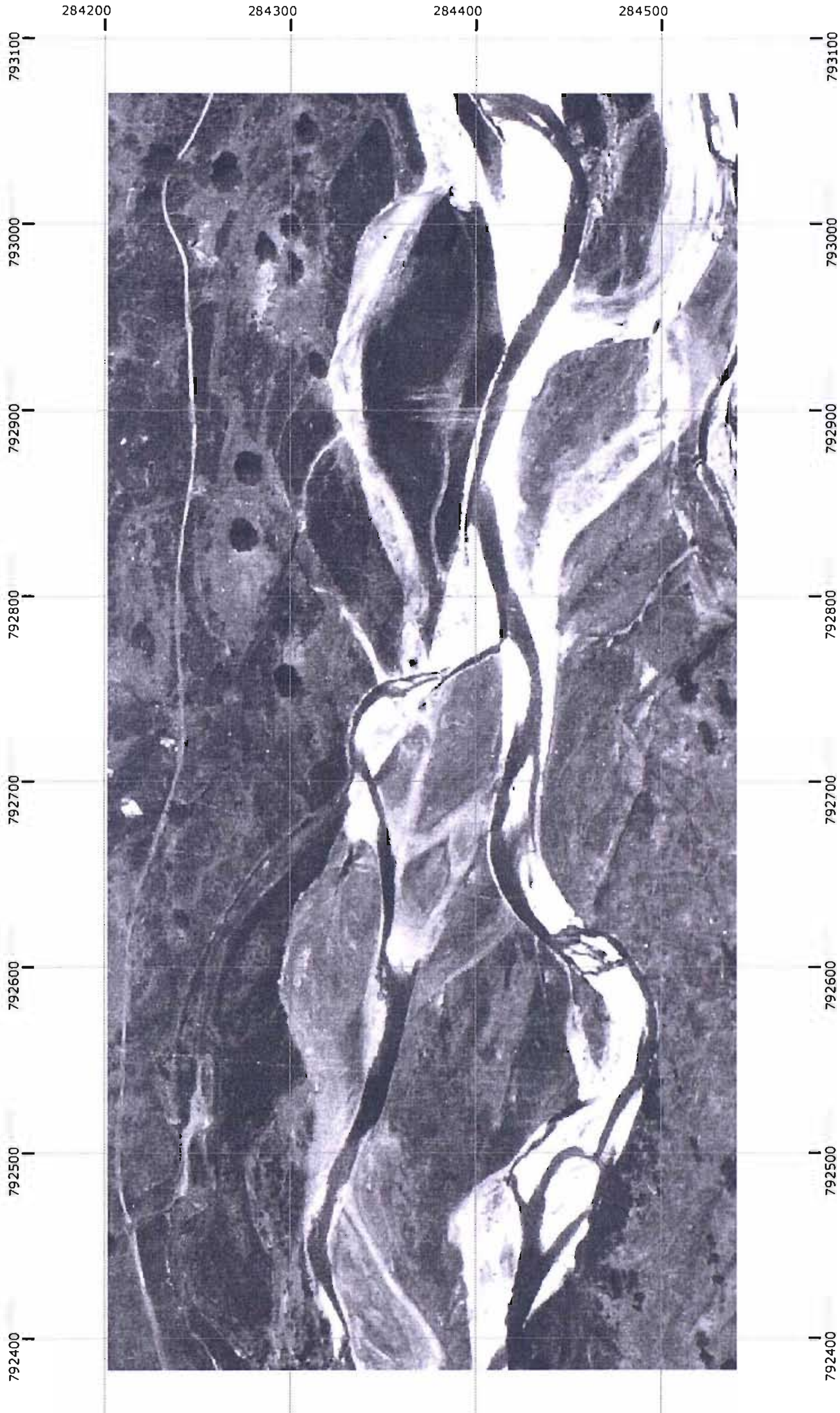


FIGURE B.5: Black and white aerial photography of study reach from 1955. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

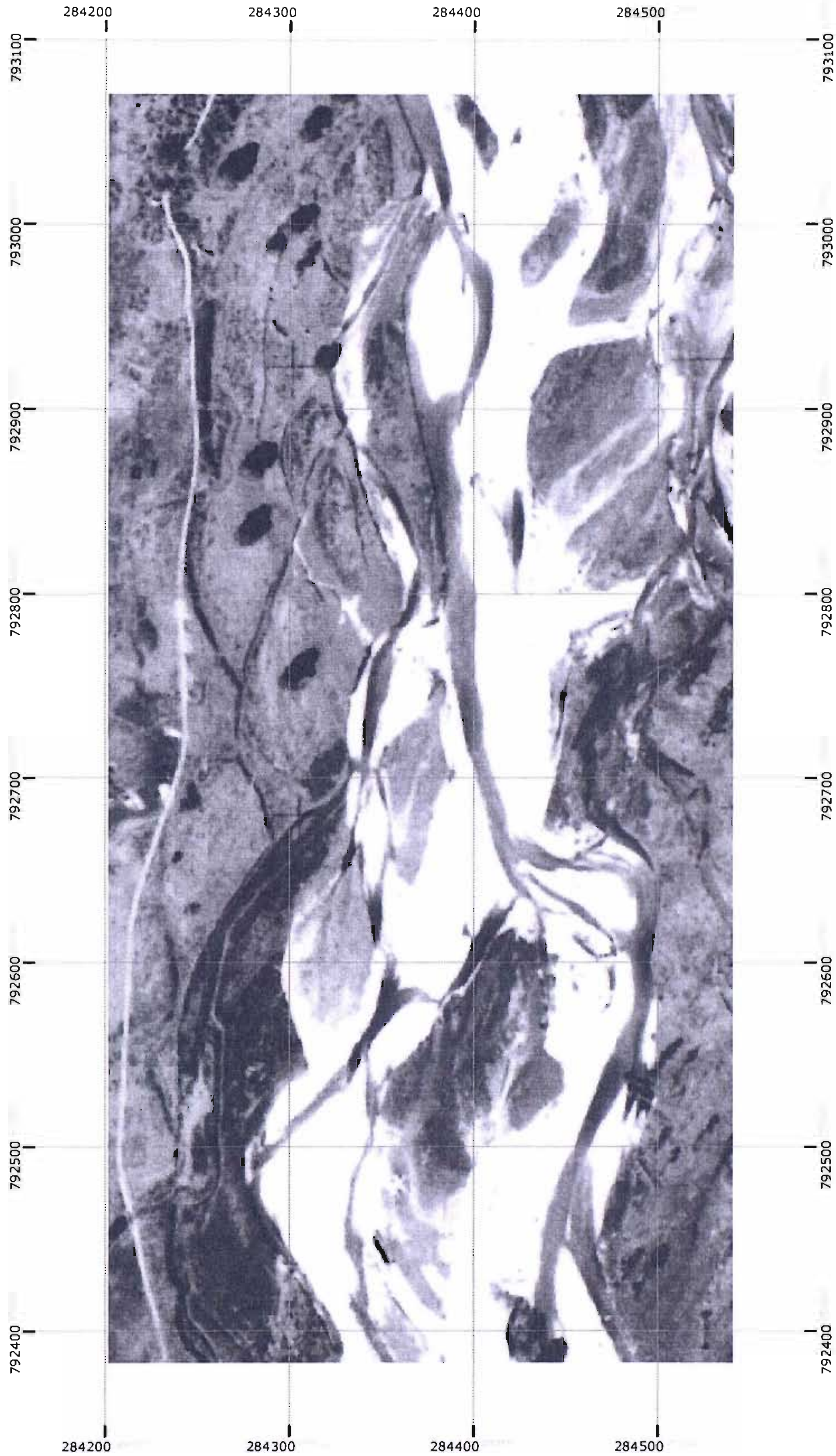


FIGURE B.6: Black and white aerial photography of study reach from 1964. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

FIGURE B.7: Colour aerial photography of study reach from 1989. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

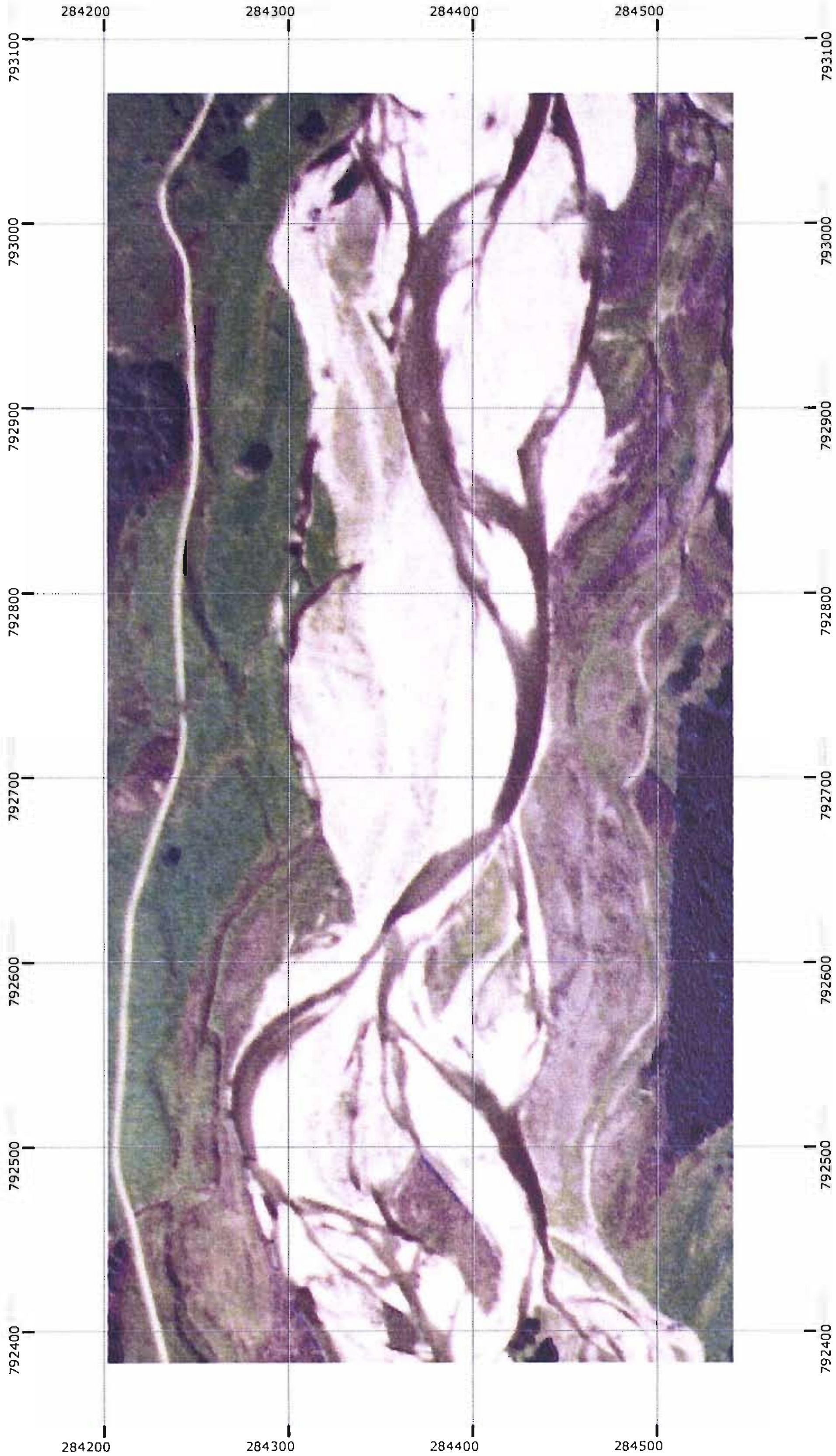


FIGURE B.8: Colour aerial photography of study reach from 1993. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

FIGURE B.9: Colour aerial photography of study reach from 1997. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

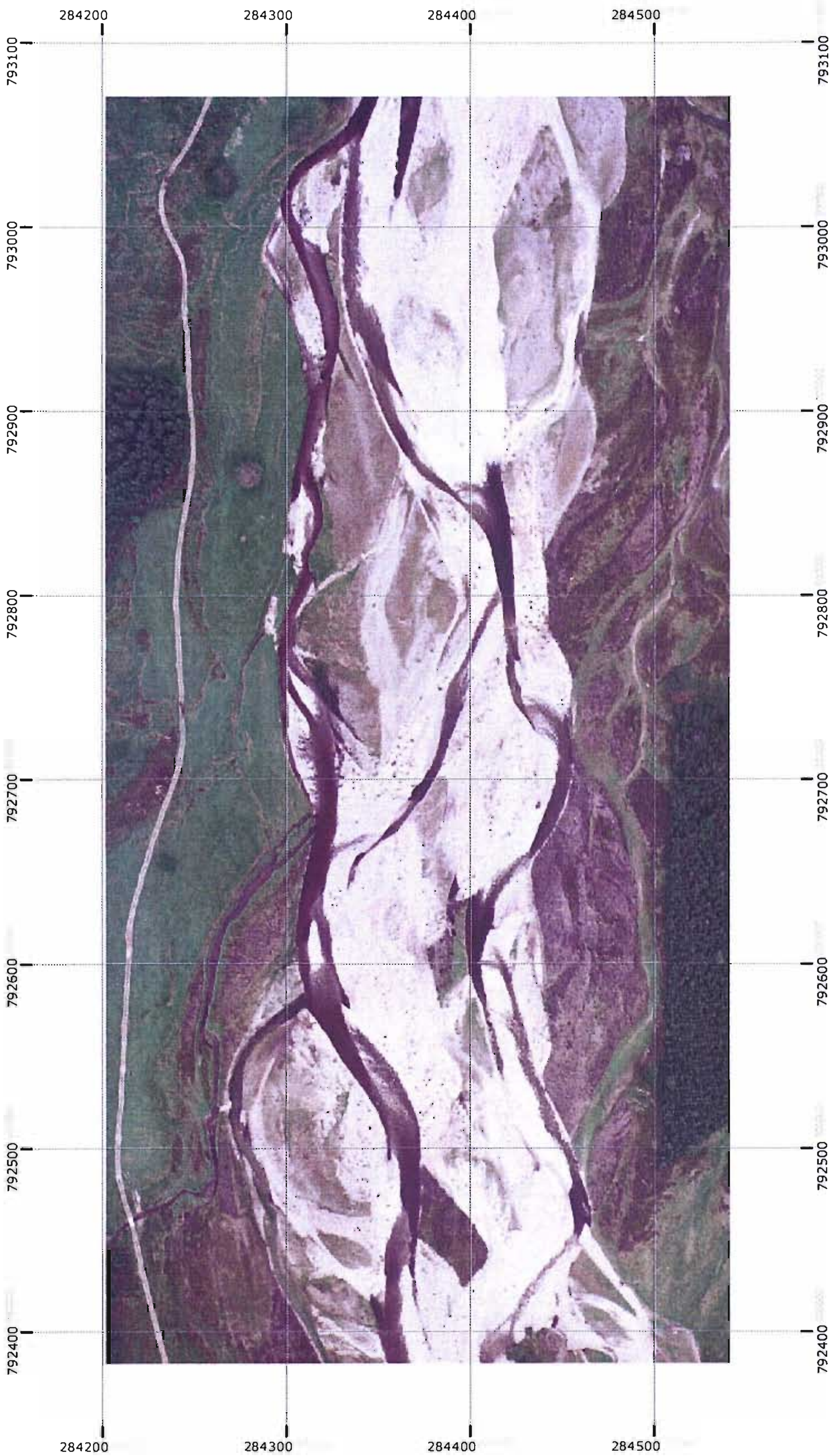


FIGURE B.10: Colour aerial photography of study reach from 2000. Photography acquired from the Royal Commission on the Ancient and Historical Monuments of Scotland's AirPhotoFinder™.

FIGURE B.11: Colour aerial photography of study reach from April, 2005. Notice the extensive areas of exposed fresh gravel deposits (primarily gravel and cobble sheets described in § 8.3.2. Photography acquired from the GetMap AirPhotoFinder™.

FIGURE B.12: Colour aerial photography of study reach from August, 2005 blimp survey. Photography acquired and processed by collaborators Brasington and Cox (p. comm) and ortho-rectified in ArcGIS with reference to an elaborate ground control network.

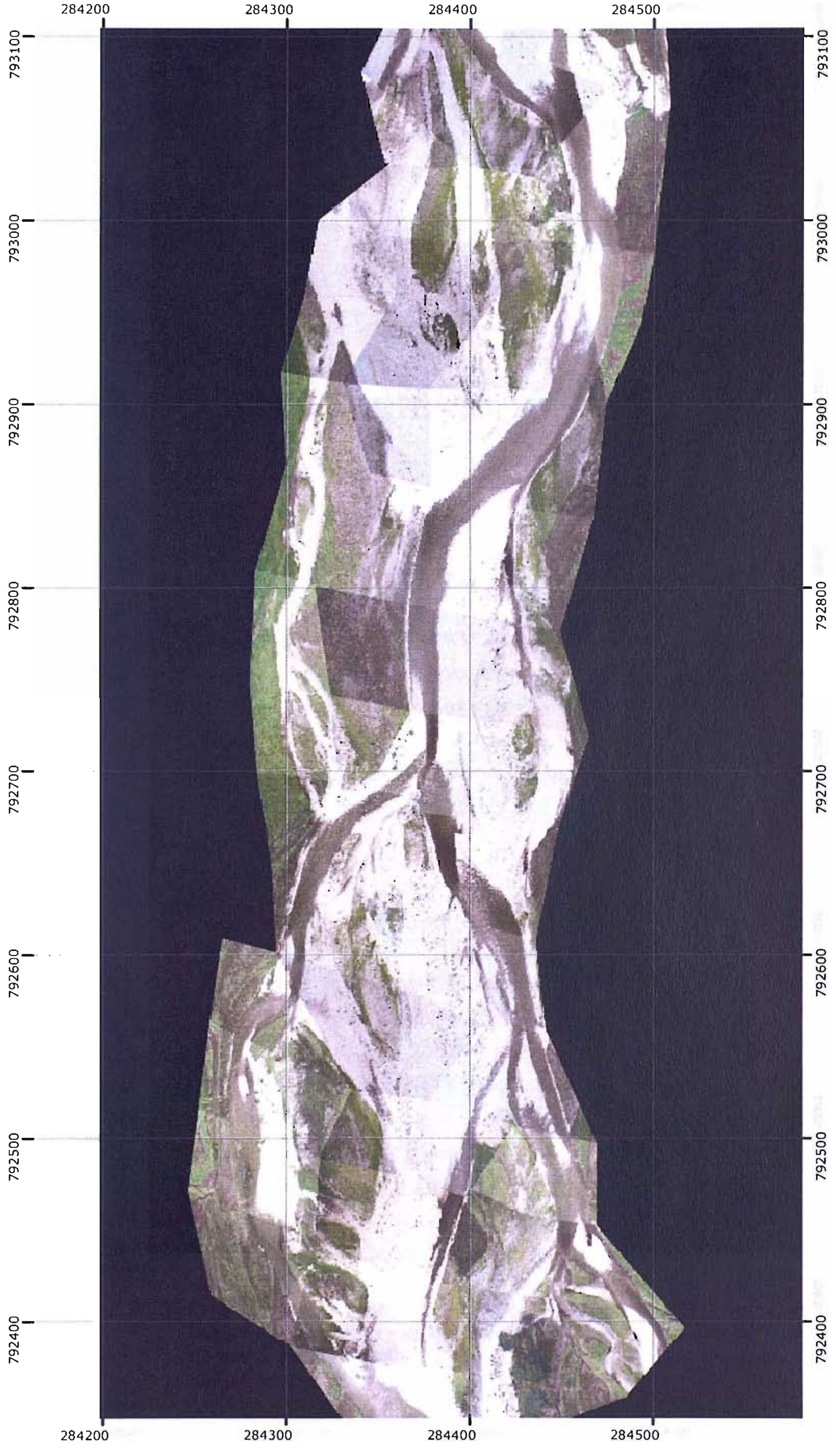


FIGURE B.13: Colour aerial photography of study reach from August, 2007 blimp survey. Photography acquired by collaborators Brasington, Vericat and Cox (p. comm) and the author and was ortho-rectified in ArcGIS with reference to an elaborate ground control network.

Appendix C

Feshie Digital Elevation Models and Morphometric Analyses

C.1 Purpose

The purpose of this appendix is to provide the reader with information and figures relating to the topographic data collected at the study site (see Figure 4.1). In this appendix, the reader will find summary statistics and figures showing the raw survey data (§ C.2), a description of how the DEMs were constructed and figures of all available DEMs (§ C.3), a description of how the detrended DEMs were constructed and corresponding figures (§ C.4), and a section showing morphometric analyses derived from the DEMs (e.g. Slope analyses: § C.5).

C.2 Survey Data

A total of 248,266 ground-based survey points were acquired and used for DEM construction between 2003 and 2007. Of these, 2622 points in 2007 were collected using a Leica TCRP 1205 robotic total station.[1] The remaining 245,644 points were collected with differential GPS rovers[2] running in real-time kinematic (RTK) mode communicating to a base station occupying a known control point on a local grid coordinate system that approximates the Ordnance Survey's British National Grid (Figure C.1). The average point density (pt ρ) was on the order of 0.3 points/m^2, with a crudely 2-3 meter grid sampling scheme adopted across the entire reach, but with infilling feature-stratified infilling of grade breaks in areas of greater topographic complexity to capture bar-scale morphological features (Brasington *et al.* 2000, Valle & Pasternack 2005). In general, this results in high point density in areas

[1] The total station was used in 2007 to speed up the survey as the instrument was available and was used to augment the four GPS rovers running concurrently.

[2] Primarily Leica System 1200 GPS receivers were used. However, in 2006 and 2007, to speed data collection up (by using more available rovers concurrently) two Trimble R8s (GNSS enabled) were also used (with a separate R8 base).

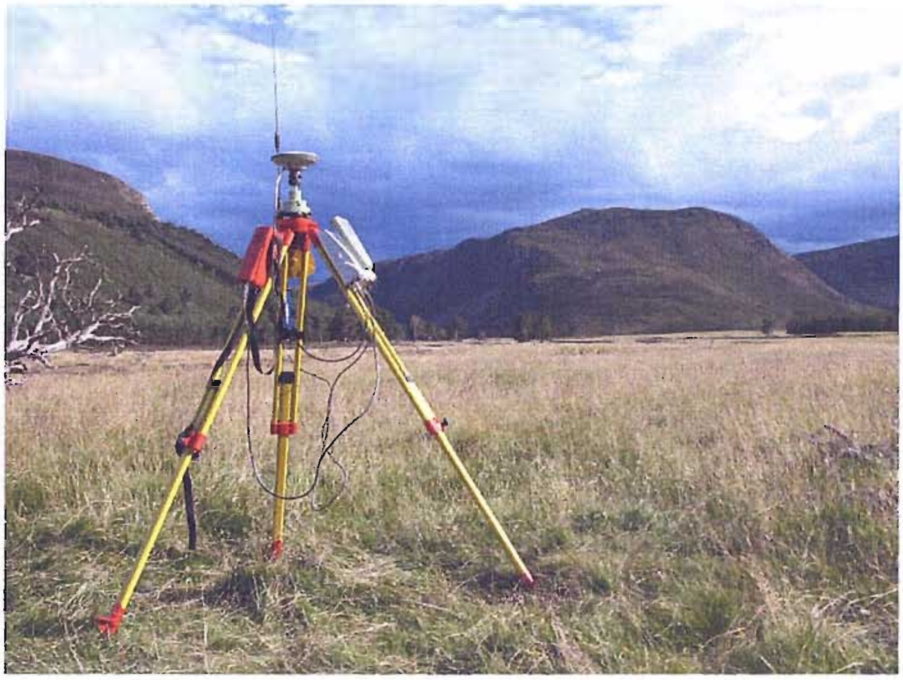


FIGURE C.1: Photograph of rtkGPS Base Station setup used on Feshie.

of topographic complexity and low point density in topographically simple areas. Summary statistics are shown in Table C.1, whereas Figure C.2 depicts the sampling strategy from the point clouds and shows the spatial variability in point density.

Point density, when combined with slope, was recognised in Chapter 4 to be one of the factors exerting a strong control on DEM elevation uncertainty $\delta(z)$. As long as the raw survey points are available, point density can be easily calculated in most GIS packages. As such, point density was used in the FIS developed in § 4.4.1. The point densities used for inputs to the FIS and depicted in Figure C.2 were calculated using the point density toolbox command in ArcGIS's Spatial Analyst with a 5 x 5 rectangular moving window.

	Points Surveyed		Global pt ρ		Moving Window pt ρ (pts/m^2)		
Survey	Total	Analysis Clip	Total	Analysis Clip	Mean	Max	σ
2003	51080	33811	0.51	0.29	0.40	4.56	0.32
2004	48145	32675	0.38	0.28	0.37	2.52	0.28
2005	35536	23258	0.26	0.20	0.26	2.92	0.21
2006	37861	23258	0.26	0.20	0.29	4.11	0.17
2007	34266	27592	0.24	0.24	0.24	2.64	0.17
Average	41378	28119	0.33	0.24	0.31	3.35	0.23

TABLE C.1: Survey point density statistics. The total number of points surveyed are reported in the second column, whereas those used for analyses (intersection of all survey areas) are reported in the third column. Statistics for point density (pt ρ) are based on a global calculation (column 4 and 5) and a 5 x 5 moving window average are reported in the columns 6 through 8.

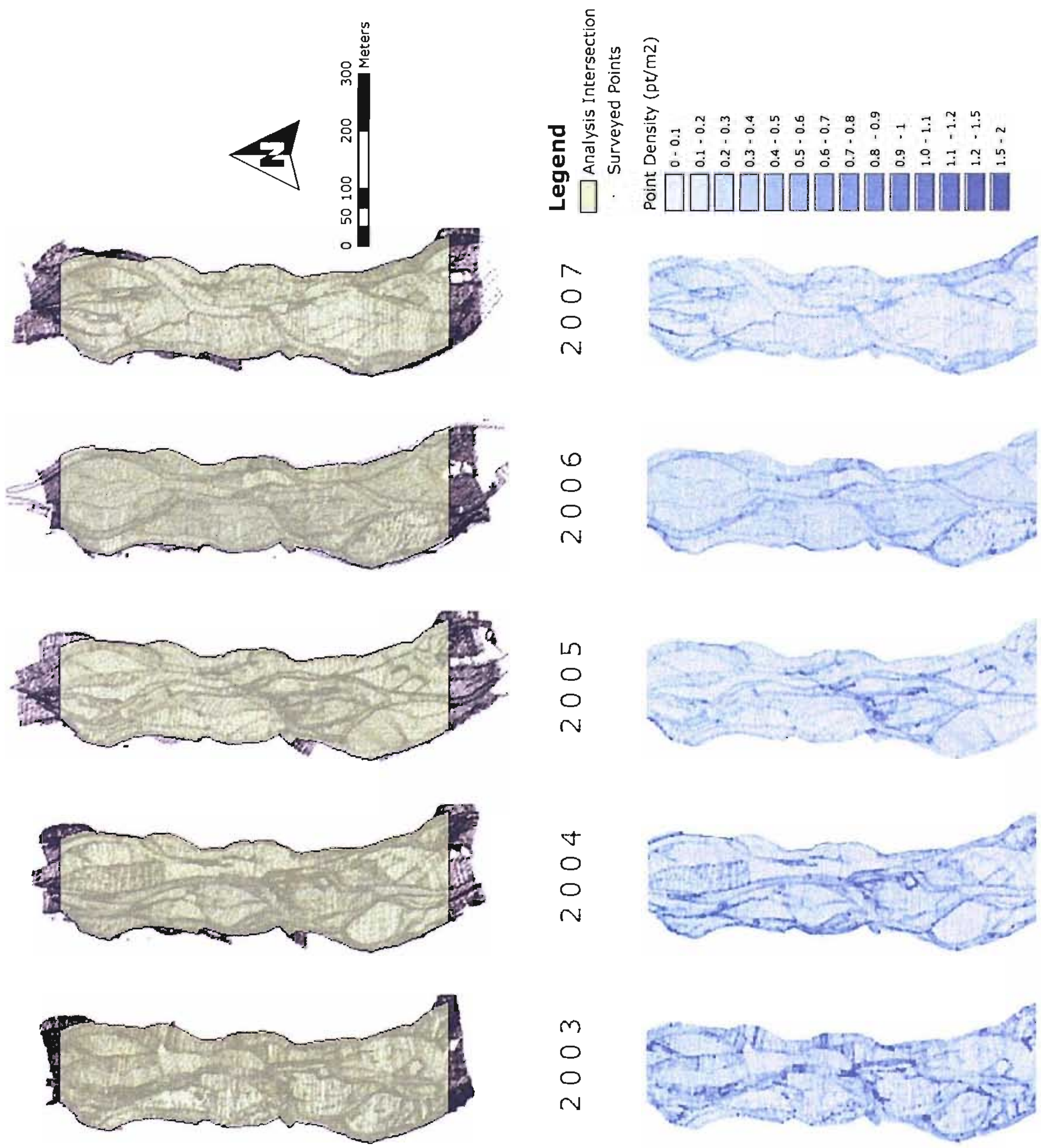


FIGURE C.2: Survey points (top) and point density (bottom) for each survey. See also Table C.1.

C.3 Digital Elevation Models

This section shows full-page figures of the digital elevation models (DEMs) used in this thesis for reference. Throughout the thesis, a one meter resolution DEM was used for analysis. The one meter resolution was deemed to be the best compromise between computational efficiency, minimal information loss, and adequate resolution to resolve geomorphic unit features at a scale relevant to physical habitat for fish. The DEMs were constructed in ESRI's ArcGIS 3D Analyst by a) producing a triangular irregular network (TIN) between survey points[3]; b) then converting the TIN to a raster.[4] The detrended DEMs are found in Figures C.3 (2000), C.4 (2002), C.5 (2003), C.6 (2004), C.7 (2005), C.8 (2006), and C.9 (2007).

C.4 Detrended Digital Elevation Models

Here full-page figures of the detrended digital elevation models used in this thesis (e.g. Figure 4.2)can be found. The DEMs were detrended by valley slope to more clearly delineate local morphology without the influence of the overall valley slope. These detrended DEMs were used for the attempt at roughness extraction (§ E) as well as morphological unit delineation (Chapter 5). A simple Matlab script[5] was written to produce the detrended DEMs in which elevation values were adjusted on a cell-by-cell basis based on their valley position relative to the centre of the study reach. Elevation was subtracted from those cells upstream of the centre and added from those cells downstream of the centre. The magnitude of elevation subtracted or added was determined by multiplying the valley slope by the distance from the centre. The valley slope used for all seven DEMs was 0.009. This slope was determined empirically by averaging three measures of valley slope from each DEM and then averaging them all. Table C.2 shows the data used to determine this average valley slope as well as the influence of the detrending process on total DEM relief. On average, the detrending process lowered the elevation relief by 4.2 meters (roughly halved). The detrended DEMs are found in Figures C.10 (2000), C.11 (2002), C.12 (2003), C.13 (2004), C.14 (2005), C.15 (2006), and C.16 (2007).

C.5 Slope Analysis

Slope was recognised in Chapter 4 to be one of the factors exerting a strong control on DEM elevation uncertainty $\delta(z)$. A slope analysis can be readily calculated from any TIN or DEM

[3]Survey points were filtered to remove those of low 3D point quality and any anomalies or busts.

[4]The TIN to Raster conversion uses a linear interpolation scheme whereby an elevation for each raster cell is assigned by evaluating which triangular plane the centre of the cell occupies in 2D space and linearly interpolating the elevation on the triangular plane.

[5]The script is available for download on both the Author's website (`http://www.joewheaton.org.uk/Research/software.asp`) and Matlab File Exchange (`http://www.mathworks.com/matlabcentral/fileexchange/`).

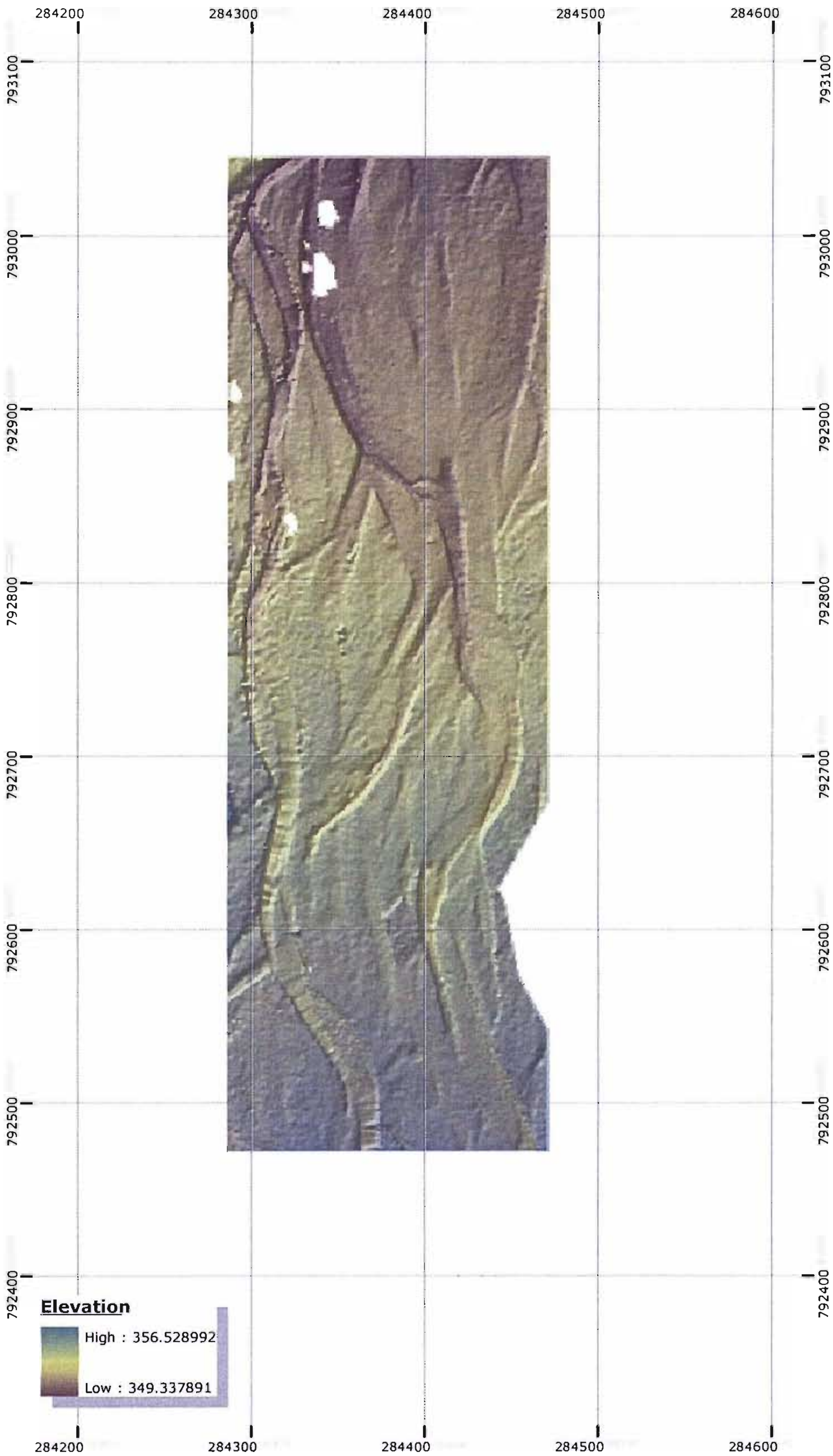


FIGURE C.3: 1 meter resolution DEM derived from 2000 aerial photogrammetry survey.

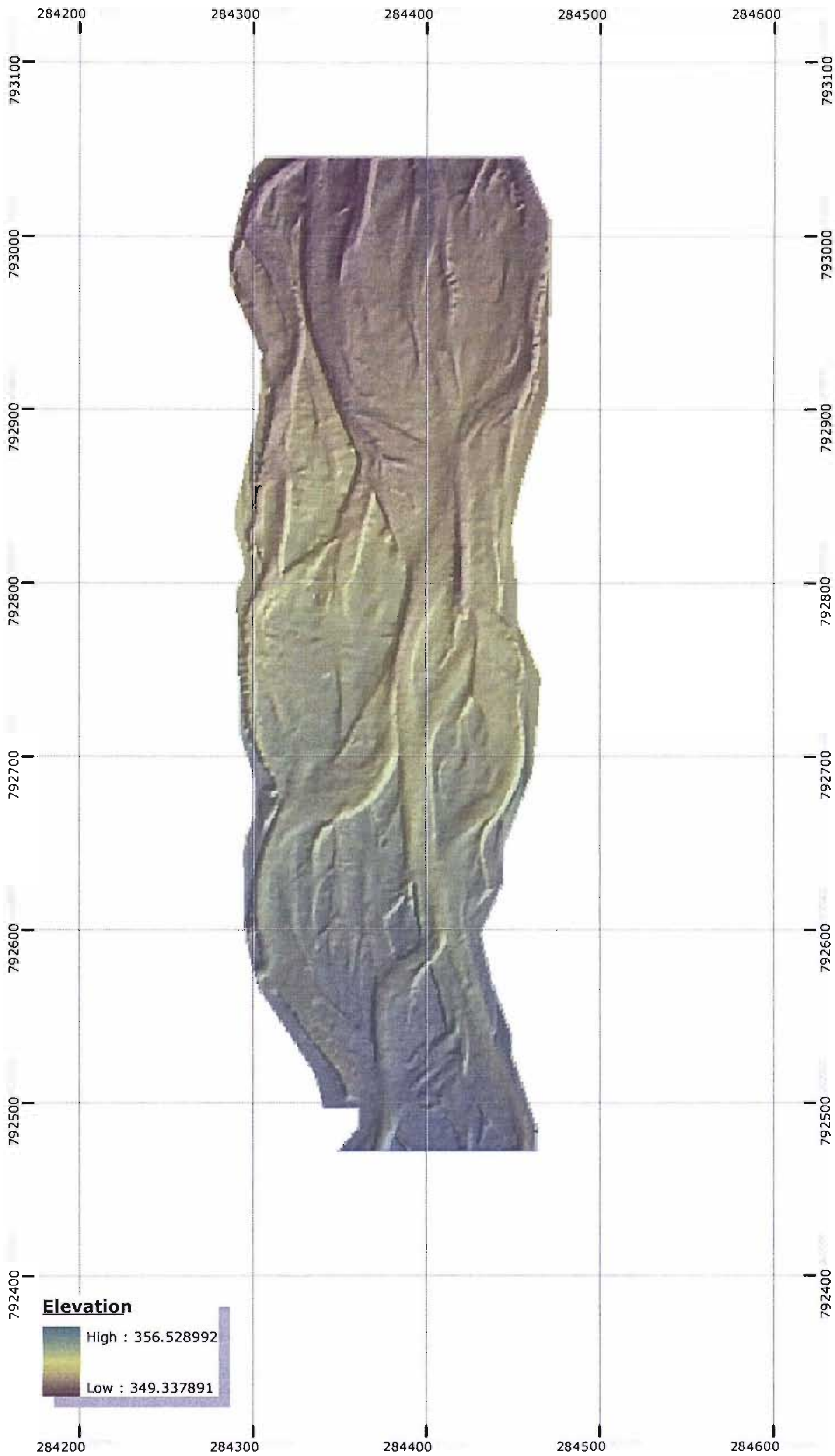


FIGURE C.4: 1 meter resolution DEM derived from 2002 GPS survey.

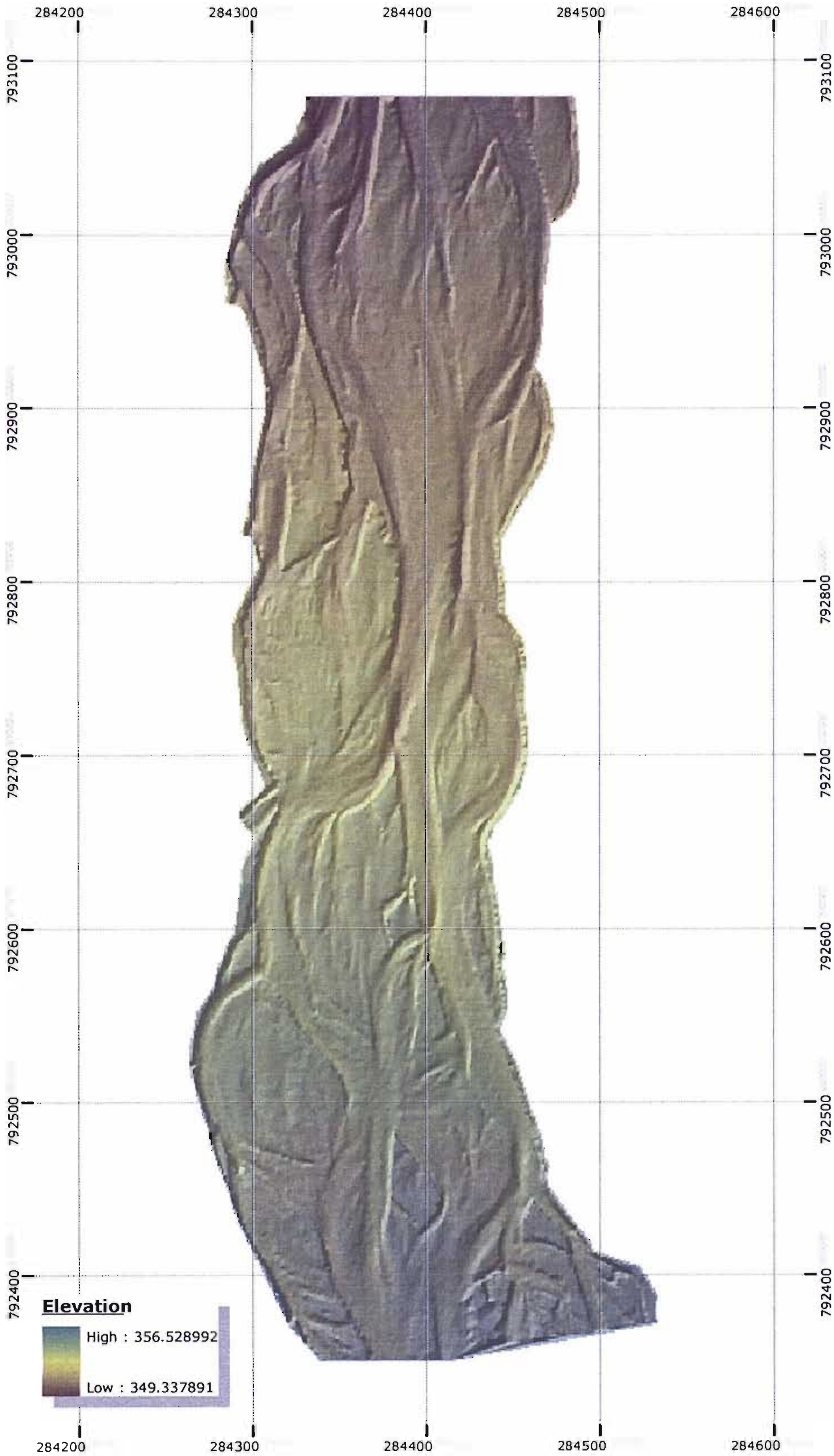


FIGURE C.5: 1 meter resolution DEM derived from 2003 GPS survey.

FIGURE C.6: 1 meter resolution DEM derived from 2004 GPS survey.

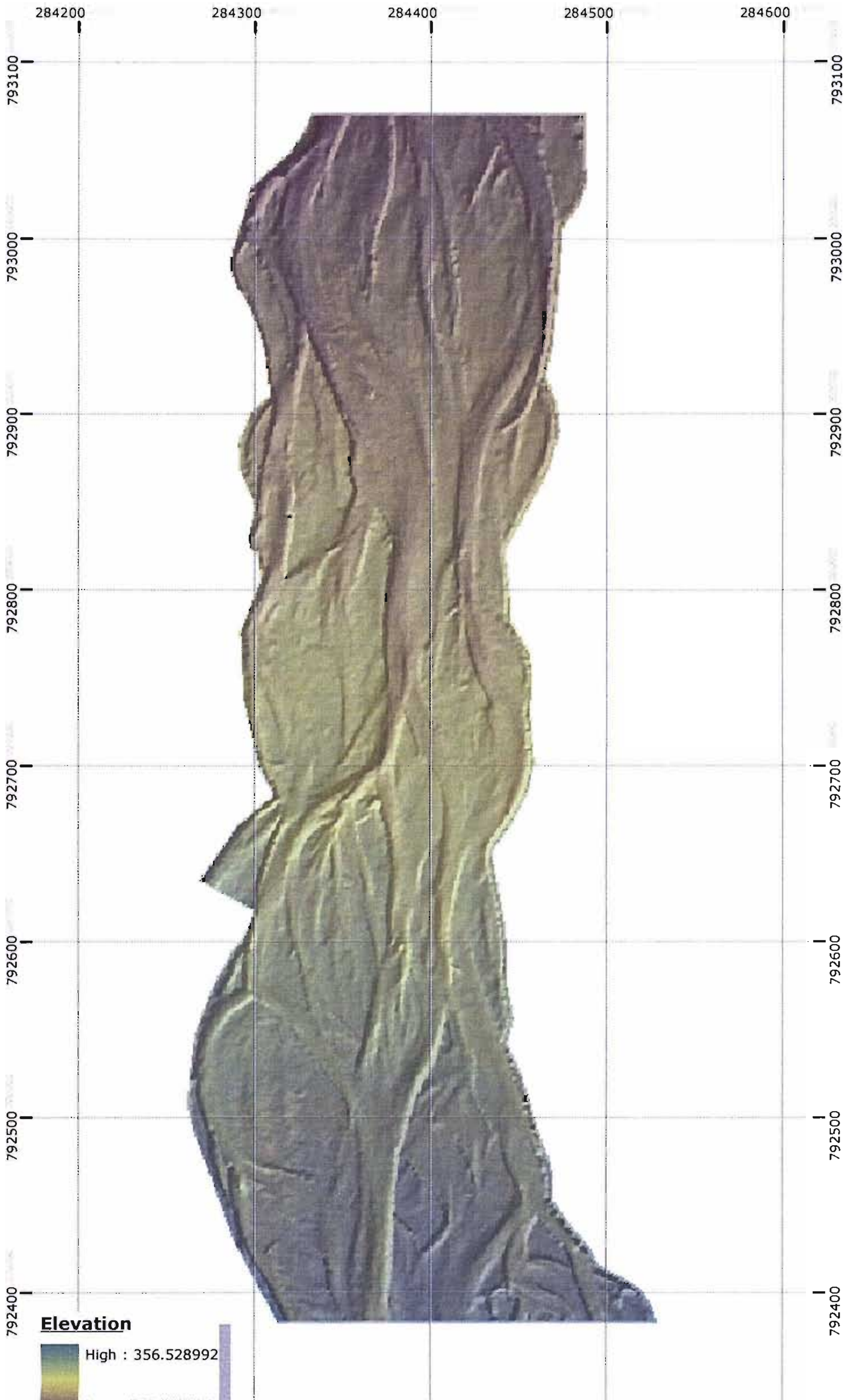


FIGURE C.7: 1 meter resolution DEM derived from 2005 GPS survey.

FIGURE C.8: 1 meter resolution DEM derived from 2006 GPS survey.

FIGURE C.9: 1 meter resolution DEM derived from 2007 GPS and total station survey.

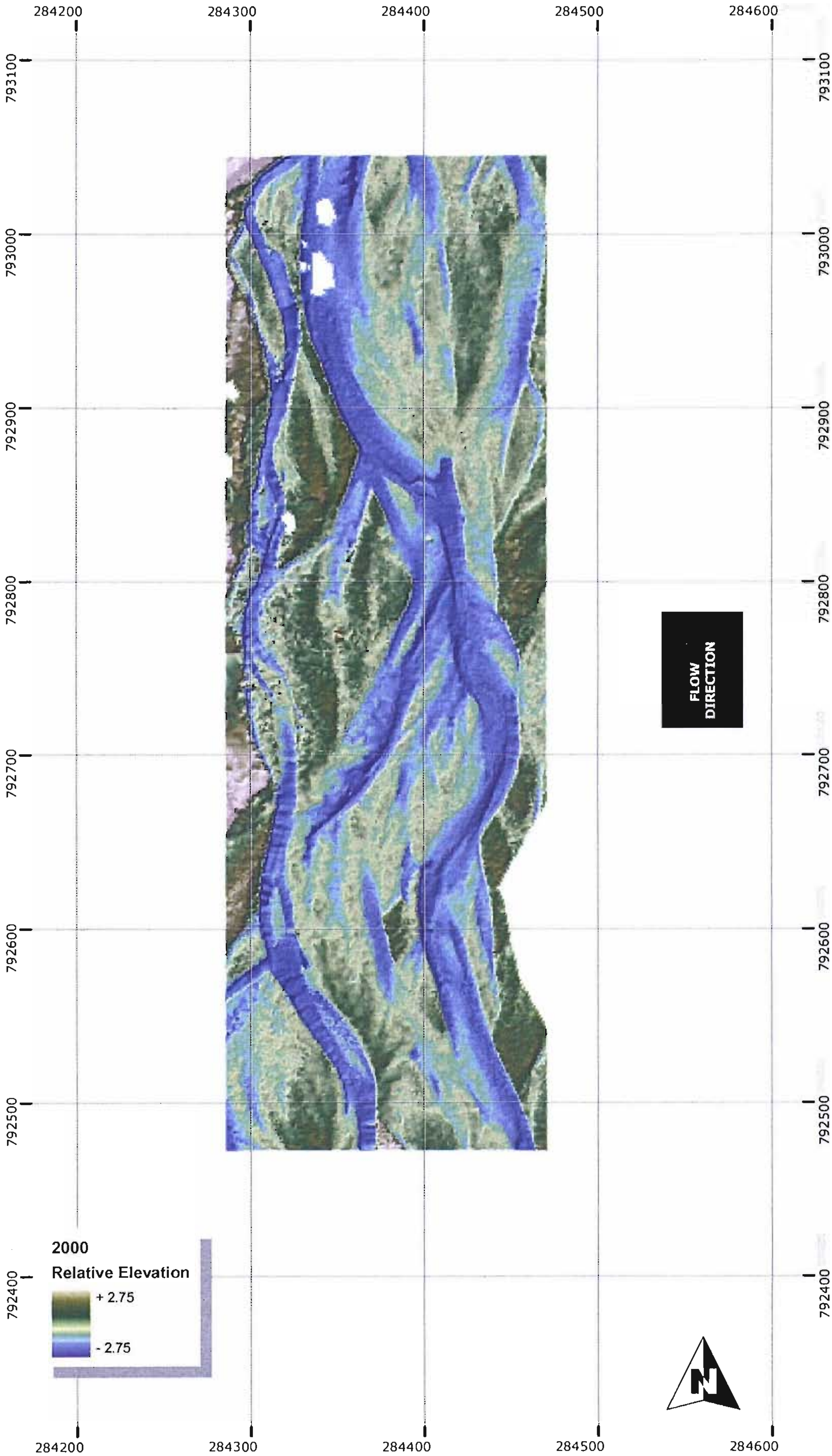


FIGURE C.10: 1 meter resolution detrended DEM derived from 2000 aerial photogrammetry survey.

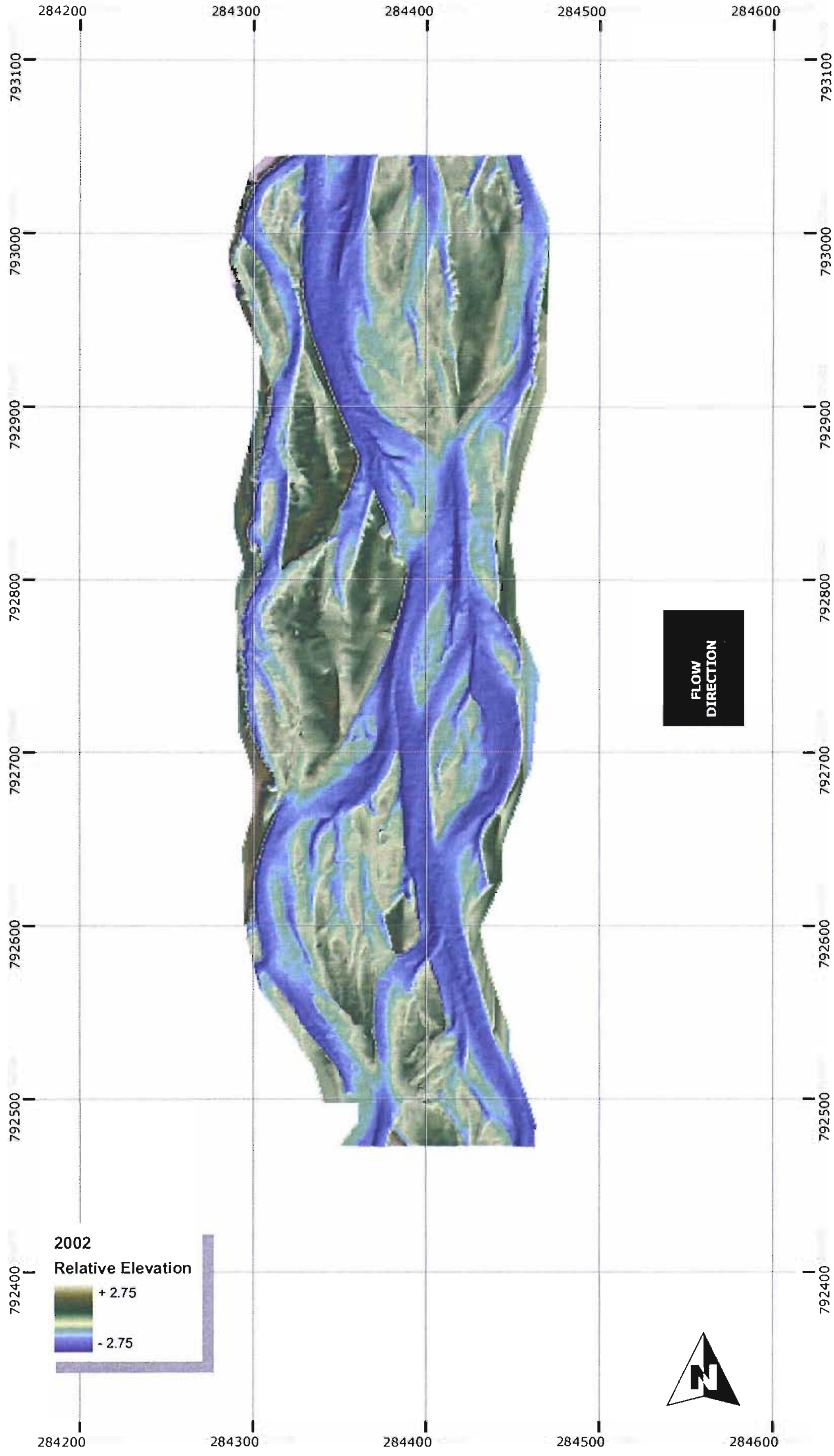


FIGURE C.11: 1 meter resolution detrended DEM derived from 2002 GPS survey.

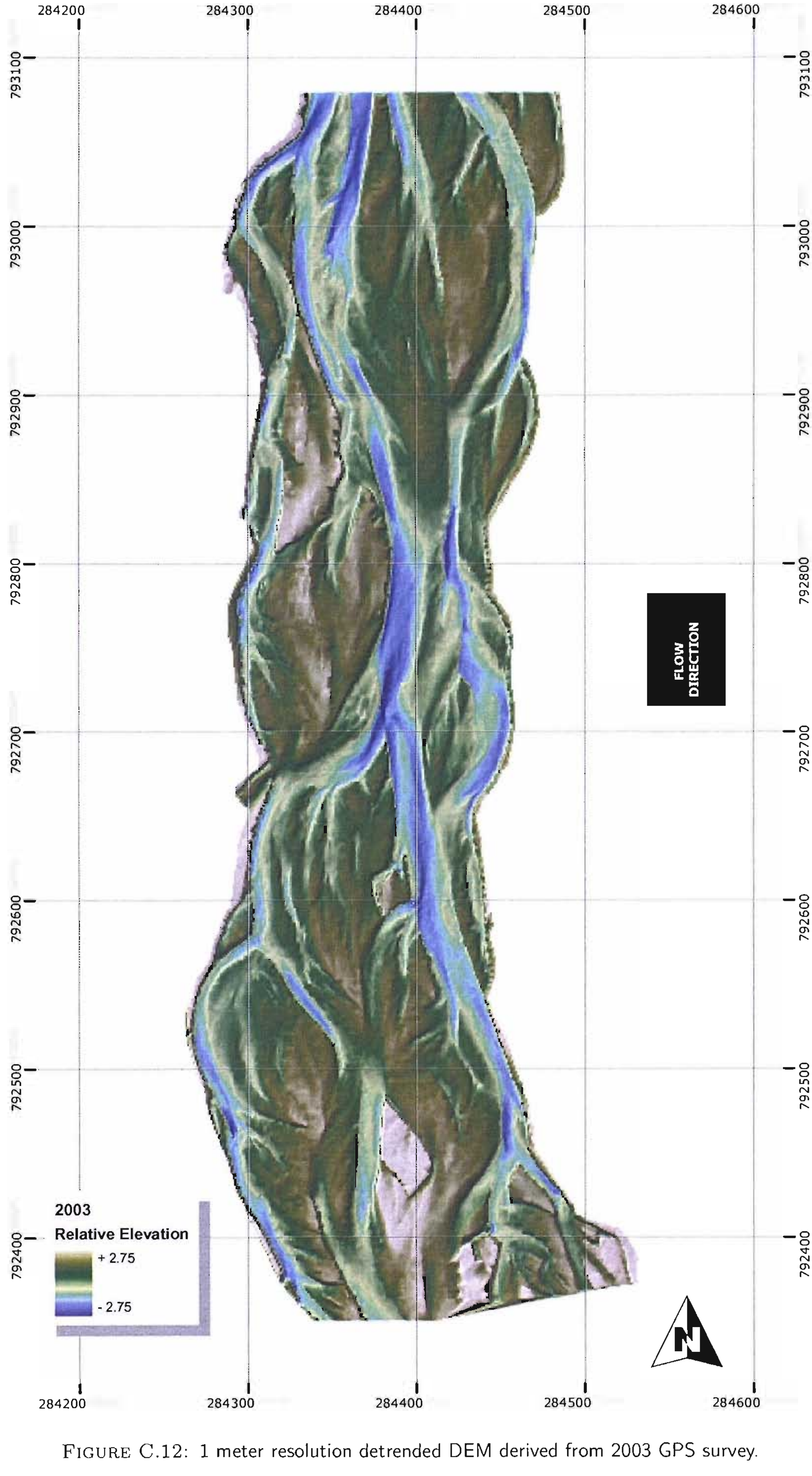


FIGURE C.12: 1 meter resolution detrended DEM derived from 2003 GPS survey.

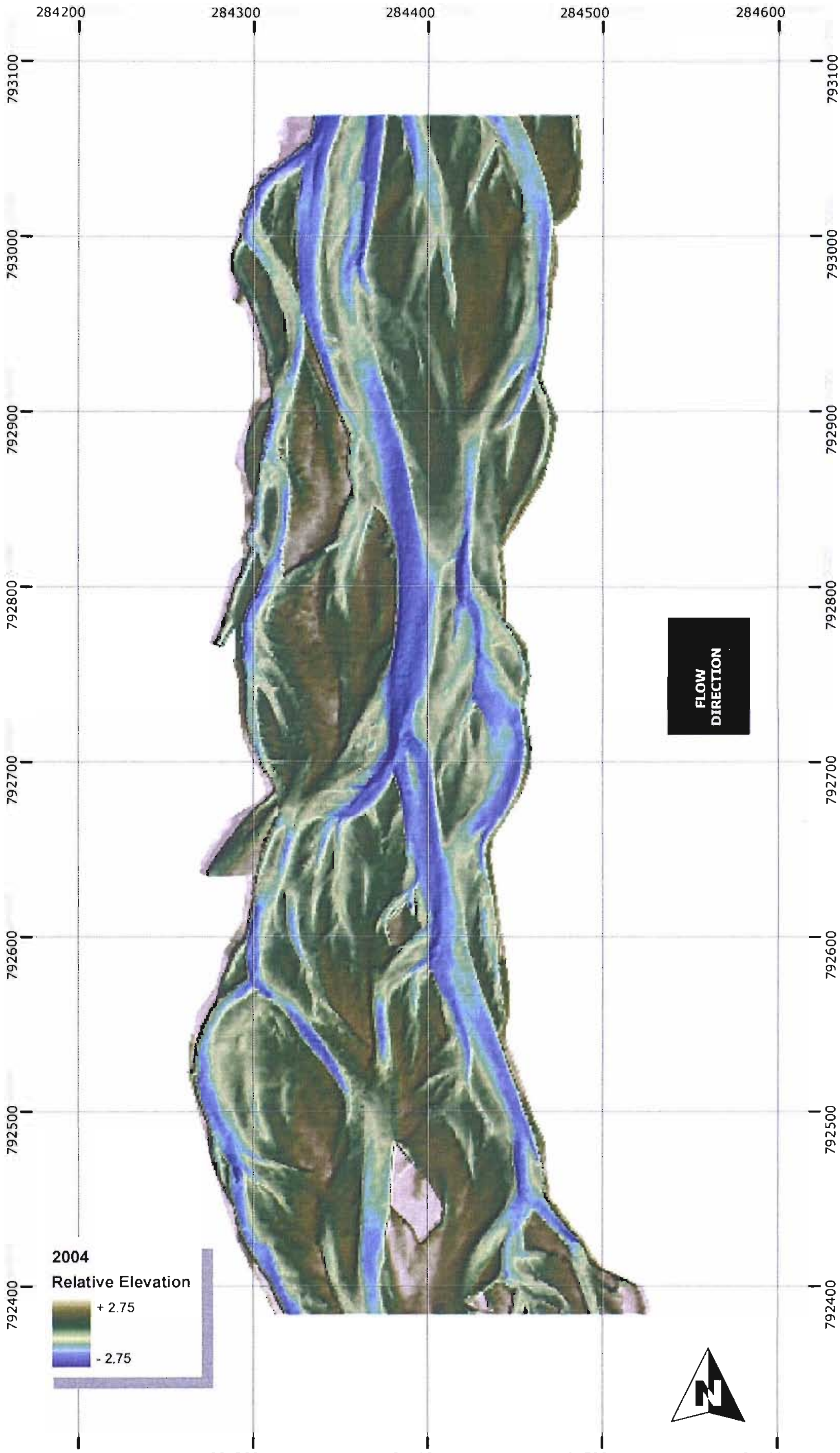


FIGURE C.13: 1 meter resolution detrended DEM derived from 2004 GPS survey.

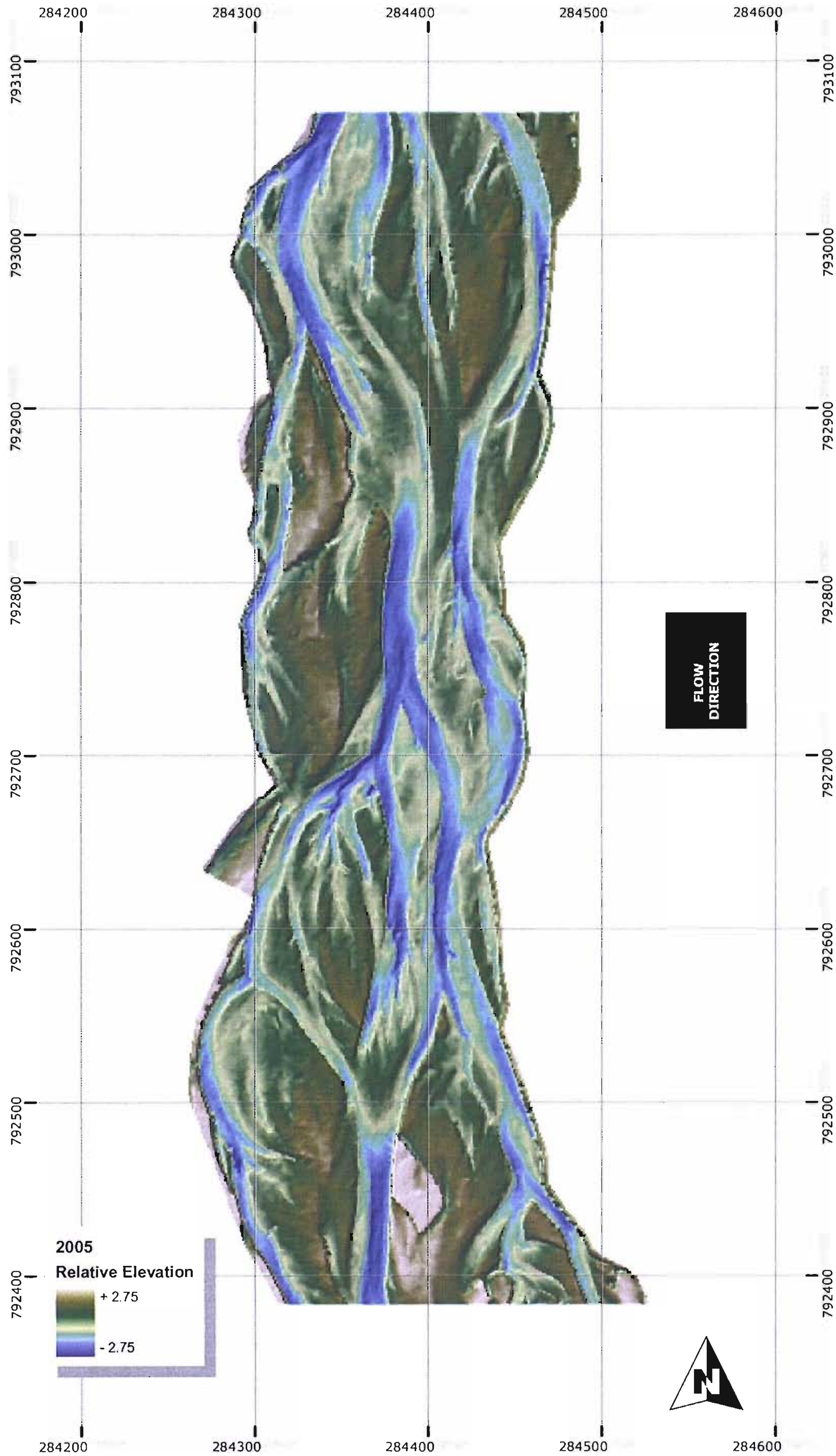


FIGURE C.14: 1 meter resolution detrended DEM derived from 2005 GPS survey.

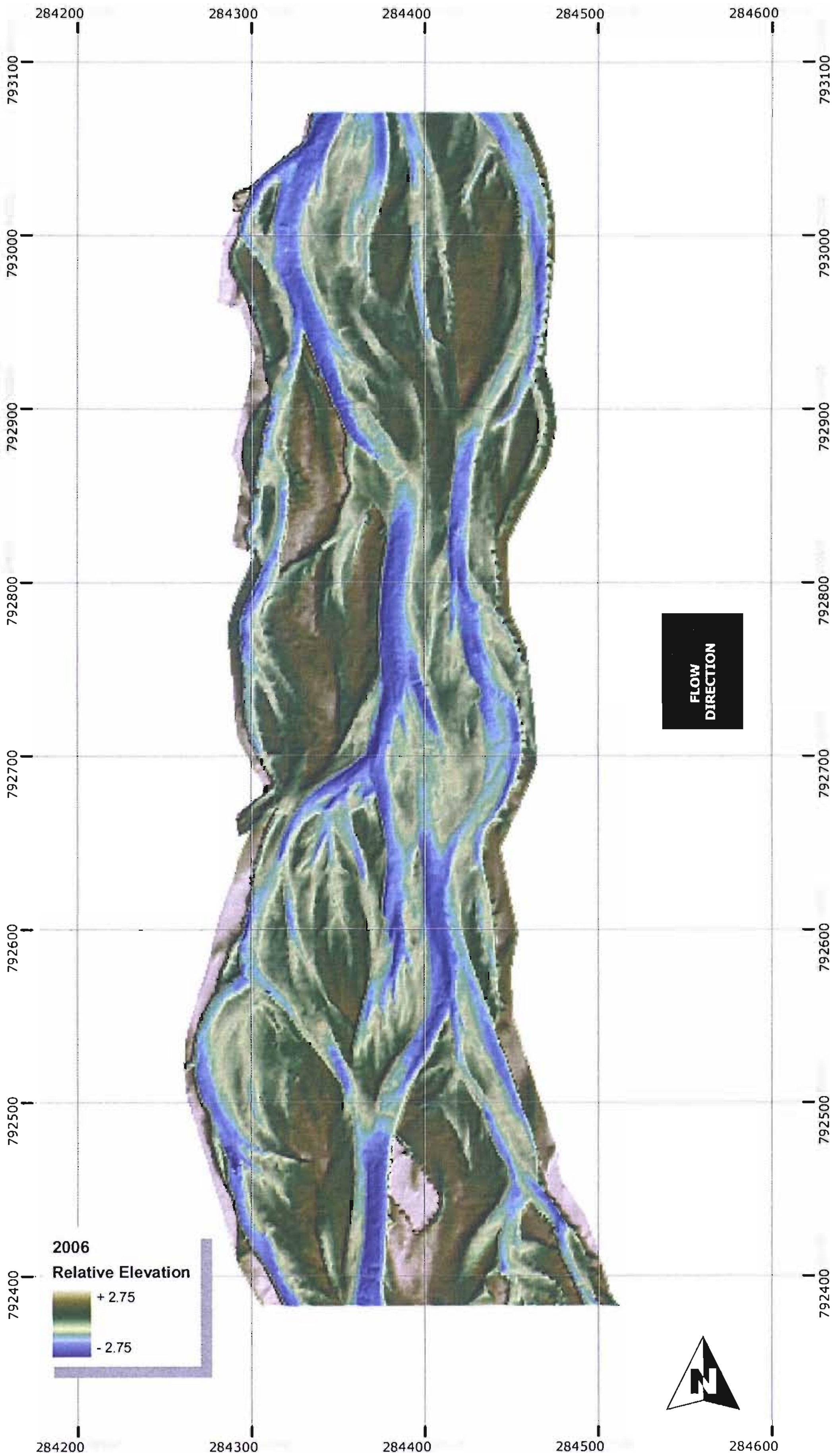


FIGURE C.15: 1 meter resolution detrended DEM derived from 2006 GPS survey.

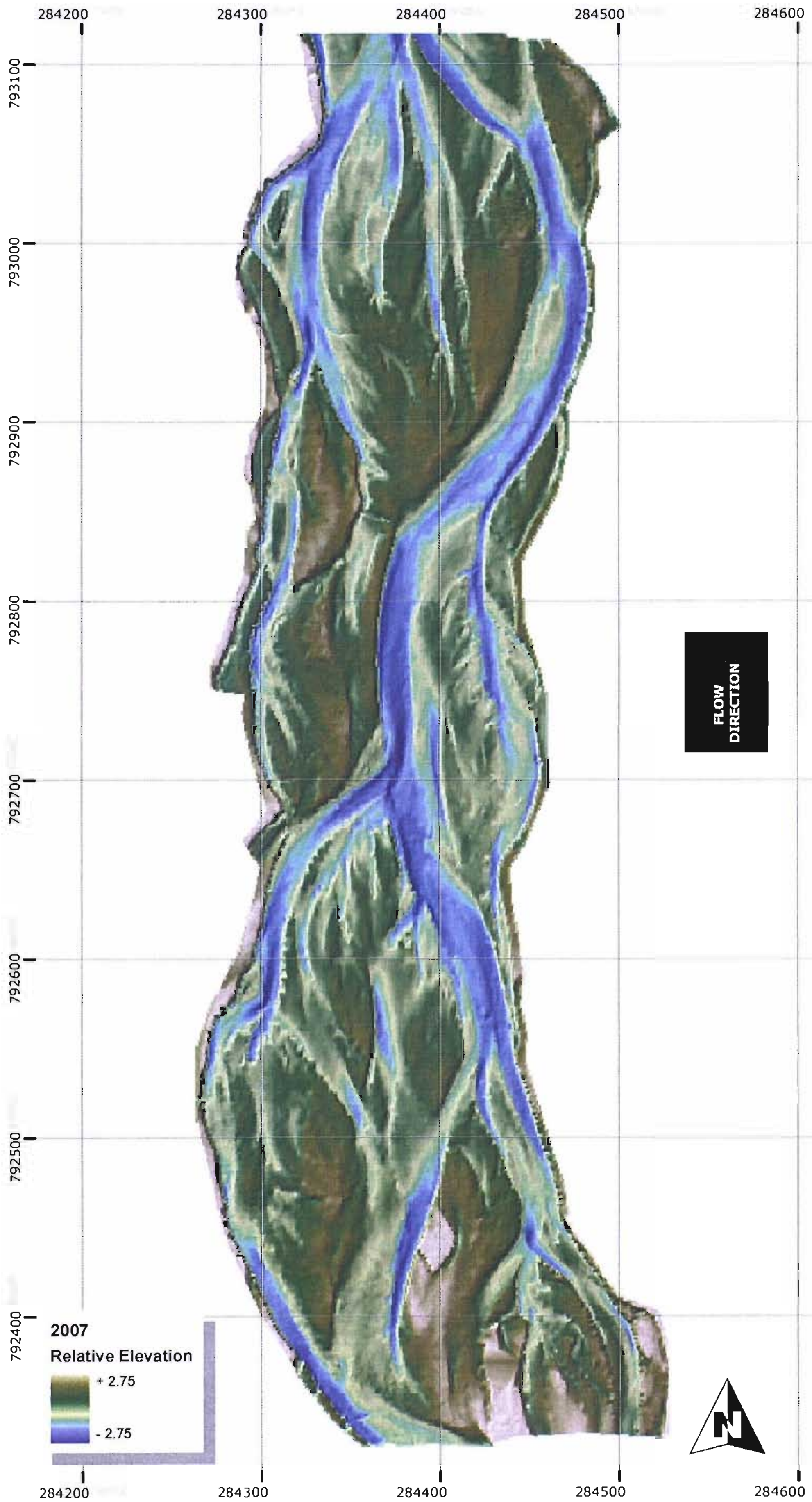


FIGURE C.16: 1 meter resolution detrended DEM derived from 2007 GPS and total station survey.

Survey	Valley Slope (n =3)		Elevation Relief	
	Mean	Std. Dev.	Original	Detrended
2000	0.0094	0.0010	8.46	5.46
2002	0.0093	0.0005	7.19	2.99
2003	0.0088	0.0007	8.38	3.45
2004	0.0091	0.0005	8.30	5.15
2005	0.0090	0.0011	8.12	3.50
2006	0.0099	0.0008	8.26	2.96
Average	0.0093	0.0007	8.12	3.92
NextMap	0.0096	0.0003	NA	NA

TABLE C.2: Valley slope and elevation relief. Three valley slopes were measured from each DEM to produce the statistics shown in the second and third column. Note the independent comparison with the 5 meter resolution NextMap DTM data from a radar survey. For the purposes of detrending the DEMs, the valley slope was taken to be 0.009.

in a wide range of GIS applications. As such, percent slope was used in the FIS developed in § 4.4.1. Here slope was calculated using ArcGIS's 3D Analyst, which uses an algorithm that calculates the slope from the centre cell to all eight of its surrounding neighbours and then assigns a slope value based on the maximum (i.e steepest downhill descent).Figure C.17 shows the slope analyses used in this study.

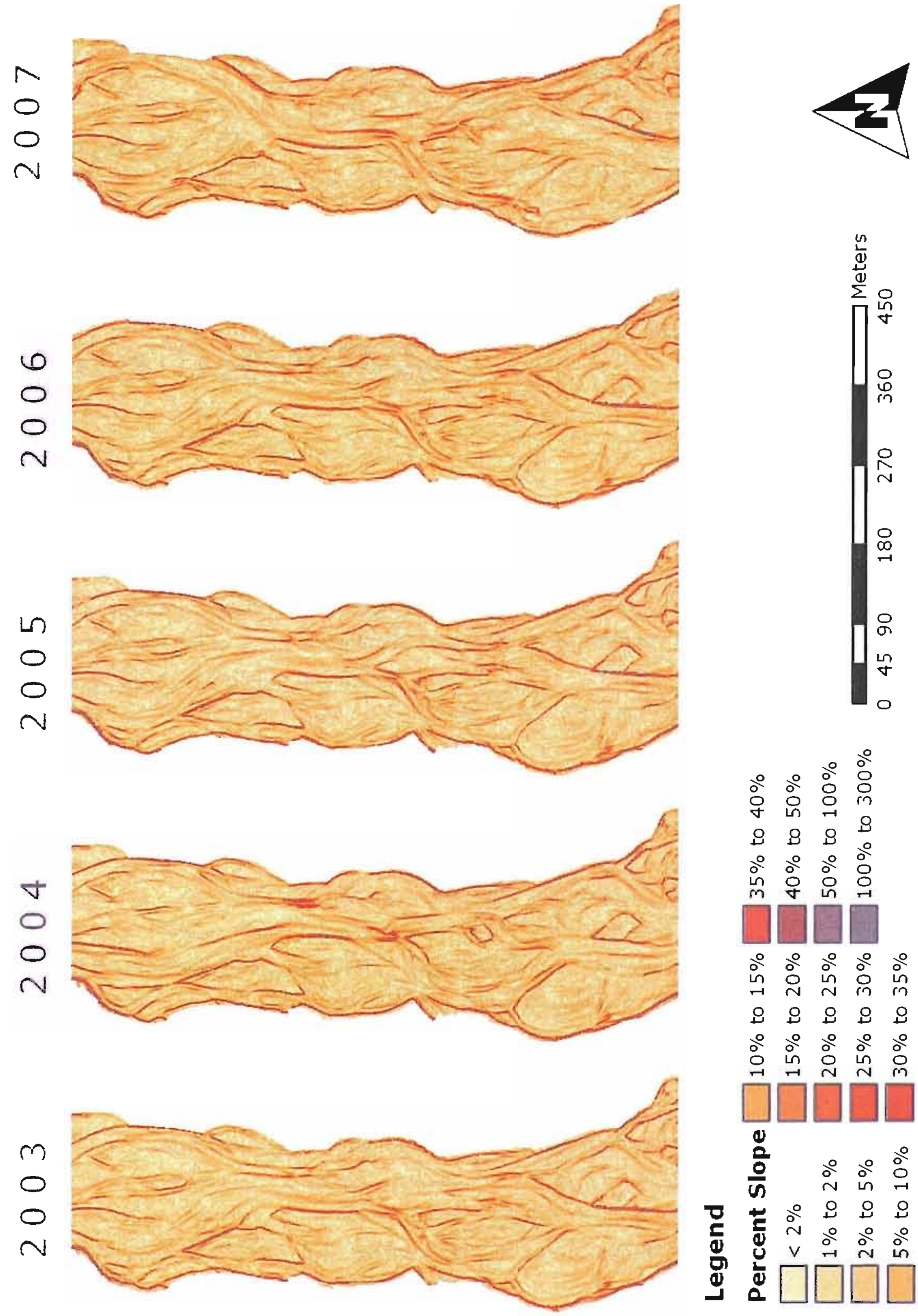


FIGURE C.17: Slope analyses of each survey .

Appendix D

Experiment Assessing Influence of Tilted Detail Pole

D.1 Purpose

The purpose of this appendix is to report the method and results of a set of simple experiments that were conducted to assess the influence of on DEM uncertainty of a surveyor inadvertently tilting a detail pole during a topographic survey.

D.2 Background

Whereas historically the limiting factor controlling the acquisition time of individual topographic survey points with GPS or total station was the technology, now rtk-GPS and auto-tracking total stations can acquire accurate fixes in a fraction of a second. Thus, now the time it takes the operator to physically move between one point and the next and accurately position the pole approximately plumb is the primary control on acquisition time (at best 2 to 3 seconds). While an accurate solution for the GPS antennae or total station prism centre may be easy to acquire rapidly, the topographic point (determined by assuming the pole is vertical and subtracting the rod height) accuracy is only as true as the detail pole was held plumb (e.g. Figure D.1). As the figure shows, the highest elevation value it is possible to attain is only when the pole is perfectly plumb. Thus, this component of elevation uncertainty ($\delta(z)$) can only systematically introduce negative errors. When working in a rapid topographic survey acquisition mode (e.g. 2-6 seconds between shots), it is very easy and quite common for the detail pole to be tilted slightly off vertical.

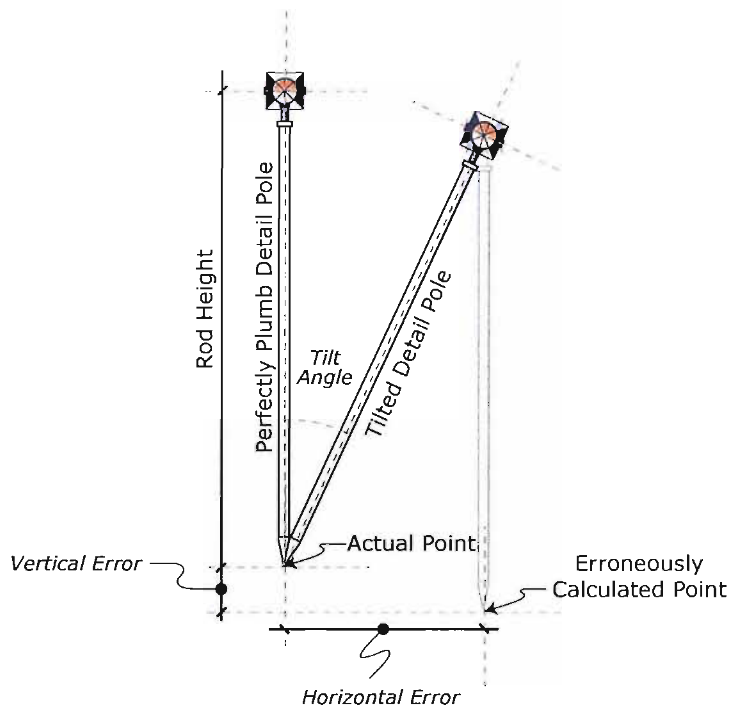


FIGURE D.1: Illustration of horizontal and vertical position errors due to a tilted detail pole.

D.3 Methods

A simple experiment to assess the influence of a titled detail pole on topographic point accuracy was conducted. The experiment consisted of four parts:

1. independently determine 'true' coordinates of a control point;
2. determine the variation in point accuracy when the operator attempts to hold the detail pole perfectly plumb without the assistance of a bipod or tripod;
3. determine the variation in point accuracy when the operator makes little attempt to hold the detail pole perfectly plumb ($\leq 5°$ off vertical; thought to emulate actual survey conditions) ;
4. determine the variation in point accuracy when the operator records an exceptionally sloppy shot, (with detail pole between 5° to 15° of vertical; used as an end-member)

For part 1, the coordinates of a control point were determined by averaging 41 independent reoccupation control measurements (15 epoch observation time, average of 10 observations per epoch) of the point (Table D.1). For the remaining steps, roughly 25 regular topographic points were recorded. In between observations, the detail pole was removed completely from the point and the operator then reoccupied the point. However, the low standard deviation between measurements (even on parts 3 and 4; see Table D.1) and the strong bias in the

Stat:	Easting	Northing	Elevation	3D Point Quality
CP1 - Independent Establishment of Point (n = 44)				
Mean	792950.020	284285.473	352.753	0.015
CP1 - Plumb ($\angle \cong 0°$; n = 25)				
Range	0.018	0.018	0.017	0.004
Std Dev	0.004	0.004	0.005	0.001
Error	0.007	0.005	0.002	
CP1 - Slight Slant ($\angle \leq 5°$; n= 25)				
Range	0.030	0.126	0.024	0.004
Std Dev	0.008	0.040	0.007	0.001
Error	0.017	0.109	0.010	
CP1 - Major Slant ($\angle 5°$ to $15°$; n = 25)				
Range	0.041	0.142	0.031	0.004
Std Dev	0.009	0.030	0.007	0.001
Error	0.002	0.540	0.073	

TABLE D.1: Influence of a titled detail pole on x-y-z coordinate accuracy.

easting are a reflection that the operator was still returning to roughly the same tilt position that happened to be oriented in an east-west axis for each reoccupation. A Leica System 1200 GPS was used operating in RTK mode.

D.4 Results

Table D.1 shows summary statistics of the experiment. When the operator was attempting to hold the pole perfectly plumb, the horizontal error was on the order of 5 to 7 mm and the vertical error was on the order of 2 mm. When the operator was a little less careful (as they would during the course of a regular topographic survey), horizontal error increased to between 1 and 10 centimeters and vertical error increased to about 1 cm. When the detail pole was blatantly held at an angle off vertical, horizontal errors grew up to circa 50 cm, whereas vertical errors grew to circa 7 cm.

D.5 Discussion

It is noted that GPS 3D Point Quality remained extremely consistent throughout the experiments. This is partly due to the short time window over which the experiment was conducted in which satellite geometry did not change appreciably. Moreover, this is a reflection of how steady the operator held the pole during the acquisition of individual points, which again did not vary appreciably between points. This also highlights that 3D point quality is not a good discriminator of points that may have been collected with the detail pole tilted. Of course, if the tilt angle is known (which in practise it is not), the horizontal and vertical errors shown

Tilt ∠	Horiz. ϵ_{XY} (m)	Vert. ϵ_z (m)
0°	0.000	0.000
0° 30'	0.017	0.000
1°	0.035	0.001
2°	0.070	0.002
3°	0.105	0.005
4°	0.139	0.010
5°	0.174	0.015
6°	0.208	0.022
7°	0.242	0.030
8°	0.276	0.039
9°	0.309	0.049
10°	0.342	0.060
15°	0.500	0.134
20°	0.643	0.234
25°	0.766	0.357
30°	0.866	0.500
45°	1.000	1.000

TABLE D.2: Influence of a tilt angle of a detail pole on x-y-z coordinate accuracy for a 2 m rod height.

in Figure D.1 can be calculated directly with simple trigonometry given a specific rod height. This is illustrated in Table D.2 over a range of tilt angles.

While this simple experiment provides some empirical evidence as to the magnitude of influence of a non-plumb survey pole on point accuracy, it does not give a direct indication of the role of this error in DEM surface representation and ultimately elevation uncertainty. In terms of the contribution of the horizontal error components, this experiment suggests that under normal topographic surveying conditions (i.e. plumb to slight slant) the horizontal errors tend to be a fraction of the typical resolutions that DEMs for DEM-differencing are modelled at. Particularly with 1 m resolution DEMs, as used in this chapter, a positional error on the order of 1 to 10 cm is going to place a negligible role in elevation uncertainty in relationship to other components. The vertical errors under normal topographic surveying conditions (on the order of 5-10 mm) are less than the magnitude of surface grain-roughness for a gravel bed river. Thus, given that most of the time the tip is not placed in voids between grains when surveying gravel bed surfaces,[1] the systematic error introduced by a tilted pole will result in a slightly lower elevation value, but one that is still well within the range of sufrace grain roughness. In comparison to other error components that contribute to overall surface representation uncertainty (see § 4.3.1), the influence of a tilted detail pole on elevation uncertainty ($\delta(z)$) will probably vary between 5% and 50% of the total mangnitude $\delta(z)$. However, in the context of monitoring gravel beds like the Feshie, the influence of tilt can

[1]Elevations sampled in voids represents the lower range of true elevation values due to surface grain roughness. See Table 4.5 and Figure 4.5 A and B, which suggest that 84% of the time the detail pole tip is placed on the 'tops' of grains as opposed to in the voids between grains.

probably be considered negligble.[2]

[2]Beds comprised primarily of fines will obviously be different.

Appendix E

Roughness Extraction

E.1 Summary and Purpose

The purpose of this appendix is to report the method and findings of a set of analyses attempted to try to extract roughness patterns from DEMs. The intention was to used spatially variable roughness maps as one of the inputs into the Fuzzy Inference System (FIS) used for quantifying DEM surface representation uncertainty in Chapter 4. A facies map well calibrated to field measurements, spatially distributed profilemeter measurements, image classification techniques, or more sophisticated roughness retrievals from higher resolution terrestrial laser scanner data (Vericat *et al.* 2007, Brasington *et al.* 2007, e.g.) would all be suitable alternatives to use. However, recall from § 3.3, that the aim of the DoD uncertainty analysis (of which the roughness extraction is just one component) was to develop a tractable method of quantifying surface representation uncertainty from raw topographic survey data alone (i.e. point cloud).

The analyses reported here were not able to produce consistent, coherent or reliable estimates of surface roughness. The fundamental reason is that the resolution of the topographic data collected is too coarse to resolve surface roughness due to grain size. They were therefore not used in the FIS Rule system in Chapter 4. However, the results may be helpful to readers considering similar analyses and are therefore provided here.

E.2 Background

Surface roughness is one of the primary components of surface representation uncertainty. In some instances, the roughness height can be of a similar magnitude to that of the elevation change being detected from a DoD (e.g. depositional gravel sheets); thus complicating the distinction between what changes are real and what changes are just a reflection of surface roughness. Given that surface roughness varies spatially, its influence on surface representation uncertainty will also vary spatially. As such, if coherent spatial estimates of surface roughness can be derived, it would be prudent to include such estimates in the estimation of surface representation uncertainty. In the absence of a tractable method highlighting spatial patterns of roughness, a more conservative isotropic estimate of roughness may suffice (e.g. based on a D_{84} or D_{90} for the reach).

Surface roughness in the fluvial environment is primarily a function of three factors: 1) composition, 2) organisation and 3) relative protrusion (above a mean surface) of the material that comprises the surface. The materials that typically comprise fluvial surfaces are sediments (alluvium), vegetation, detritus and other forms of organic and inorganic matter.

Various methods exist for producing spatially distributed estimates (i.e. a map[1]) of surface roughness. All methods involve some form of spatial averaging. This may be based on a field interpretation (e.g. facies map classification) or on a computational spatial model between point values (e.g. Kriging, TIN, Nearest Neighbour, etc.). On a cell by cell basis, roughness maps can either be classified into various discrete categories or a continuous measure of roughness height Lane (2005).

E.3 Roughness Extraction Methods Explored

Three approaches to retrieving roughness from topographic elevation data were explored based on a local neighbourhood analysis of surveyed points using: 1) the standard deviation of elevation; 2) the range of elevation; and 3) the difference of elevations between surfaces derived directly from TINs of the actual elevations, versus a surface derived from the mean elevation of points locally. In all three approaches one variant was attempted that modelled the roughness estimates spatially so as to preserve the exact roughness estimates where they were estimated; whereas a second variant attempted to smooth the spatial model through some combination of low-pass filtering and Kriging modelling. Both variants involved interpolation and spatial averaging, but the first variant seemed to produce more reasonable patterns. The steps eventually decided upon in each of the above three methods were as follows (Using ArcGIS 9.2):

1. Filter point cloud of raw survey data for areas of high slopes ($>$ 10 percent) using a slope analysis of a one meter resolution TIN-Derived DEM of the original survey data.[2] This was done so that local statistics on elevation captured primarily a local roughness signal instead of a macro-morphology roughness signal.

2. A discontinuous raster representing a roughness signal was produced using 'Neighbourhood Point Statistics' (in ArcGIS's Spatial Analyst). The desired local statistic (e.g.

[1]For the purposes of the input requirements for Chapter 4,the map can originate as a vector (polygon), but ultimately needs to be a raster of either roughness values or classes.

[2]The original survey data was already filtered to remove erroneous points and those failing to meet minimum precision tolerances.

mean, range, standard deviation) of the elevation values for the filtered points was calculated in a 3x3 rectangular moving windows.[3]

3. In the case of the mean elevation statistic, this 1 m resolution raster was subtracted from the actual DEM and the absolute value taken to give an estimate of roughness. In the case of the standard deviation and range, these statistics were preserved as an estimate of roughness.

4. The 'Extract Values to Points' feature was used to extract the estimated roughness values at the same locations as the original filtered survey points (step 1)

5. The new point cloud was filtered to remove values with zero roughness height or no data.

6. To produce a continuous surface between points with estimates of roughness height, a natural neighbour interpolation scheme was used to produce a roughness raster

7. The final roughness surface was clipped by the original extent of the survey data.

The roughness analyses were conducted for all GPS surveys (2002, 2003, 2004, 2005, 2006), but not for the 2000 photogrammetric DEM as original point data was not available to perform neighbourhood points statistics. The patterns from the results shown in Figure E.1 are largely incoherent, and the magnitudes did not show a reliable relationship to grain size distributions from 17 pebble counts in 2006 and 3 bulk surface samples in 2004.

Ideally, the selection of an appropriate roughness extraction method would be based on a direct comparison of derived roughness values with field measurements of roughness height. However, 'direct' measurements of roughness height are rarely available. Profilemeters can give estimates of roughness height along a transect, but statistics and spatial averaging along a profile will differ from similar statistics calculated in 2D space. Although not entirely correct, surface roughness is sometimes equated to grain roughness alone and in such cases grain size might be a proxy for surface roughness. Such a simplification is convenient in that numerous methods exist for measuring grain size distributions in the field. These include pebble counts, bulk sampling, ... etc. (Bunte & Abt 2001). However, even if alluvium dominates the surface composition, the relationship between grain size and surface roughness is certainly not simple or unique.

[3]Various window sizes and shapes were experimented with. Point density was high enough to enable small local window.

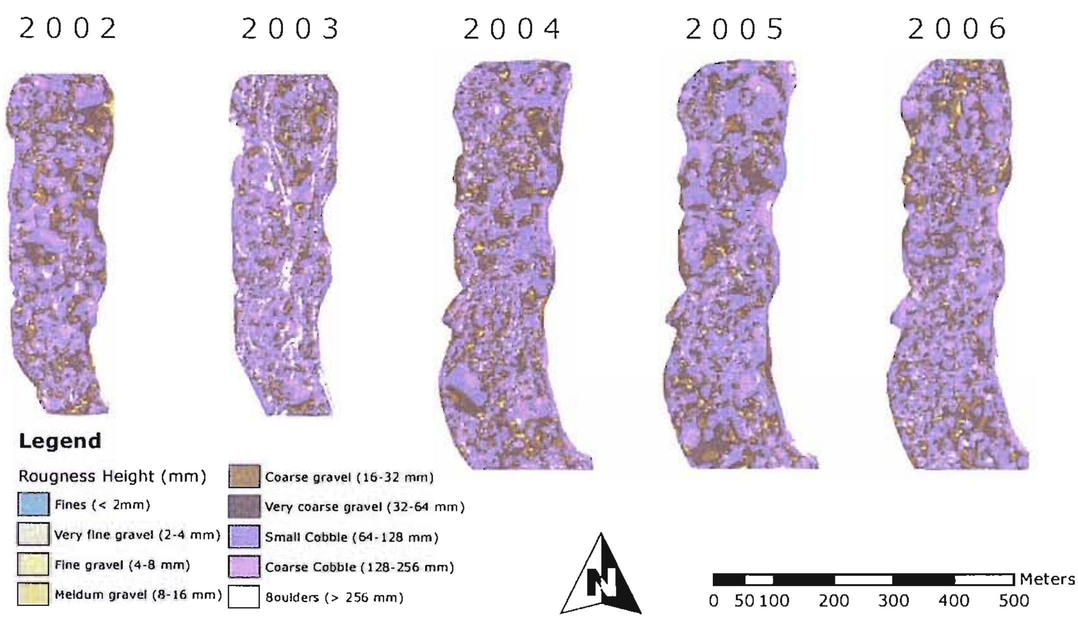


FIGURE E.1: Roughness surfaces derived from a moving window analysis of elevation range (see text for description). Note the roughness heights are classified using ϕ classes; the descriptive labels shown in the legend correspond to Wentworth scale grain size descriptions, but may differ considerably from actual grain sizes.

Appendix F

Sulphur Creek Aerial Photos and Acknowledgments

The purpose of this appendix is to provide the reader with some aerial photos from the Sulphur Creek study site, which augment the descriptions found in § 3.5 and § 6.2. Additionally, acknowledgments for the support received to work in Sulphur Creek are provided (§ F.2).

F.1 Contextual Historical Aerial Photographs

This section shows a time series of historical aerial photographs of the study site and vicinity from 1942, 1953, 1958, 1965, 1982, 1993 and 2003. The photos show a systematic decrease in active channel width[1] from 1942 up to 1982 (post Crane Street Bridge).The decrease in channel width appears to be a gradual encroachment associated with gravel mining activity; whereby banks were established along access roads and armoured with left over concrete and rip rap from construction jobs by the quarry operators, Harold Smith and Sons (p. comm Varozzas).

[1]As delineated by exposed gravel.

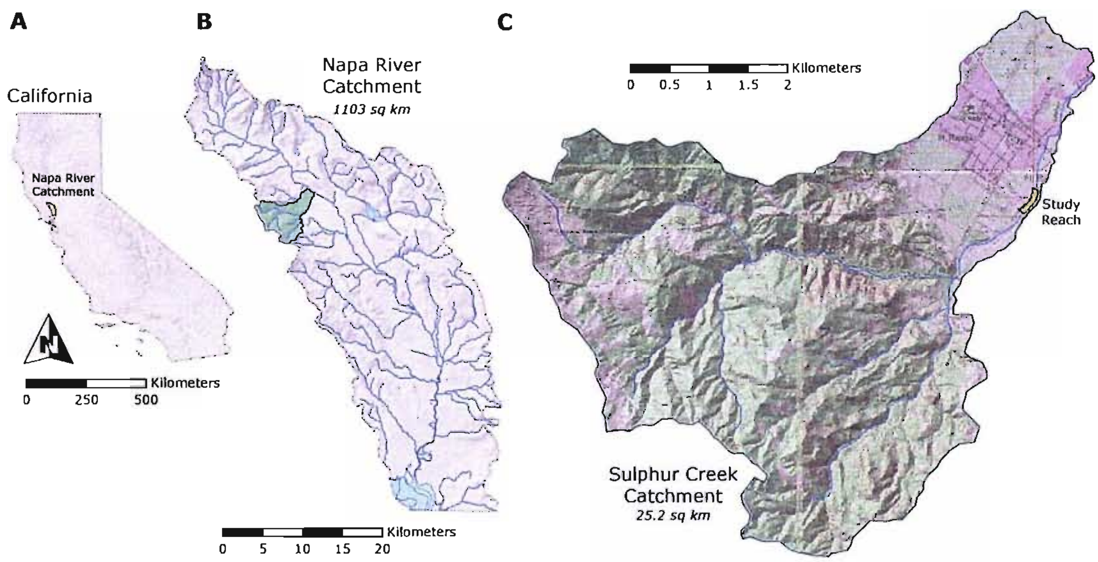


FIGURE F.1: Location and vicinity maps for Sulphur Creek study site. A) Location of Napa River Catchment within California. B) Location of Sulphur Creek Catchment within Napa River Catchment. C) Location of study site within Sulphur Creek Catchment (7.5 Minute Series USGS Map and 2003 NCALM LiDAR derived hillshade shown for context).

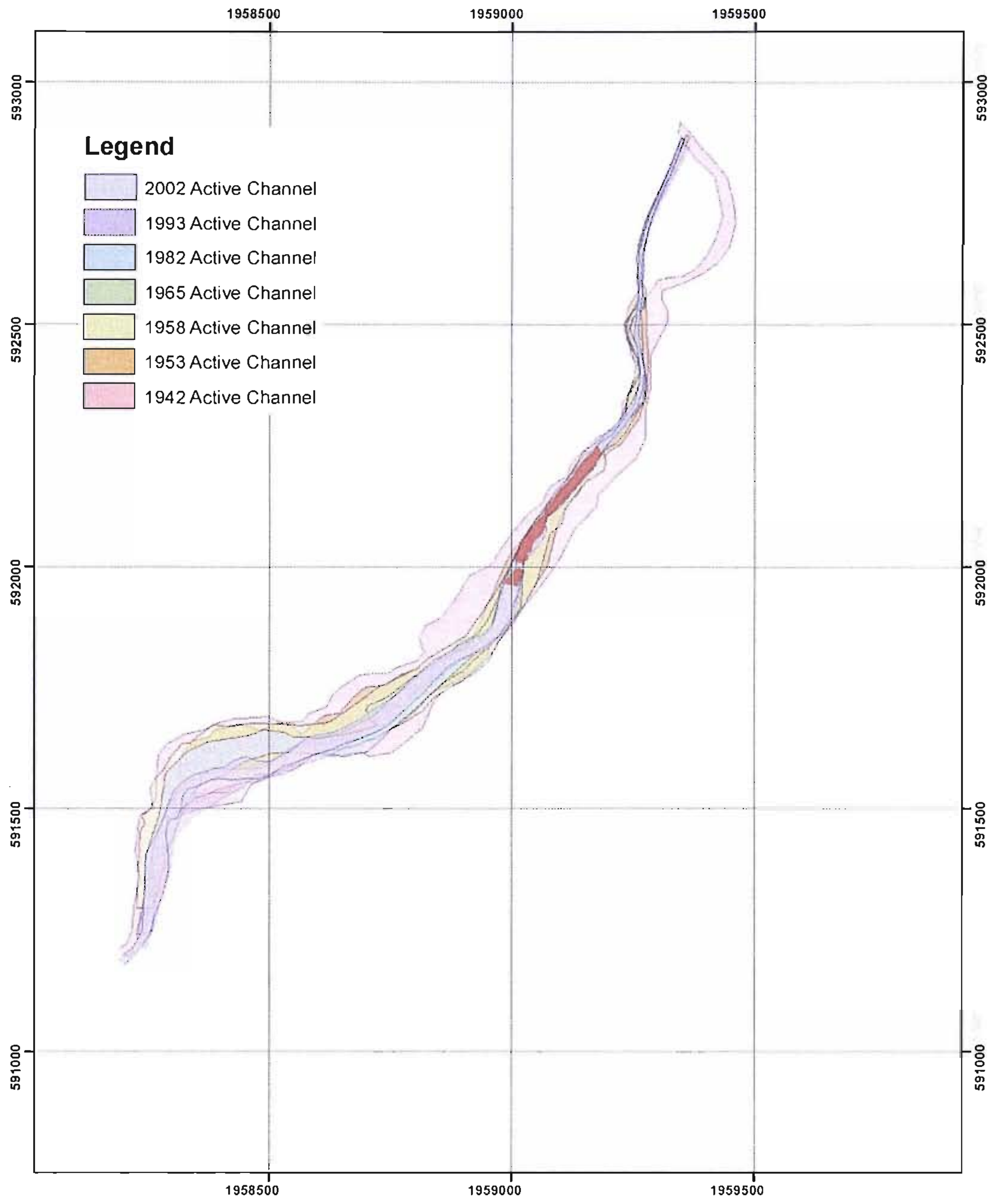


FIGURE F.2: Changes in active channel width (exposed gravel) through time from historical aerial photographs.

FIGURE F.3: Georeferenced black and white aerial photograph of Sulphur Creek in 1942. The study site is shown in transparent red. Source: Grossinger *et al.* (2003, p.32).

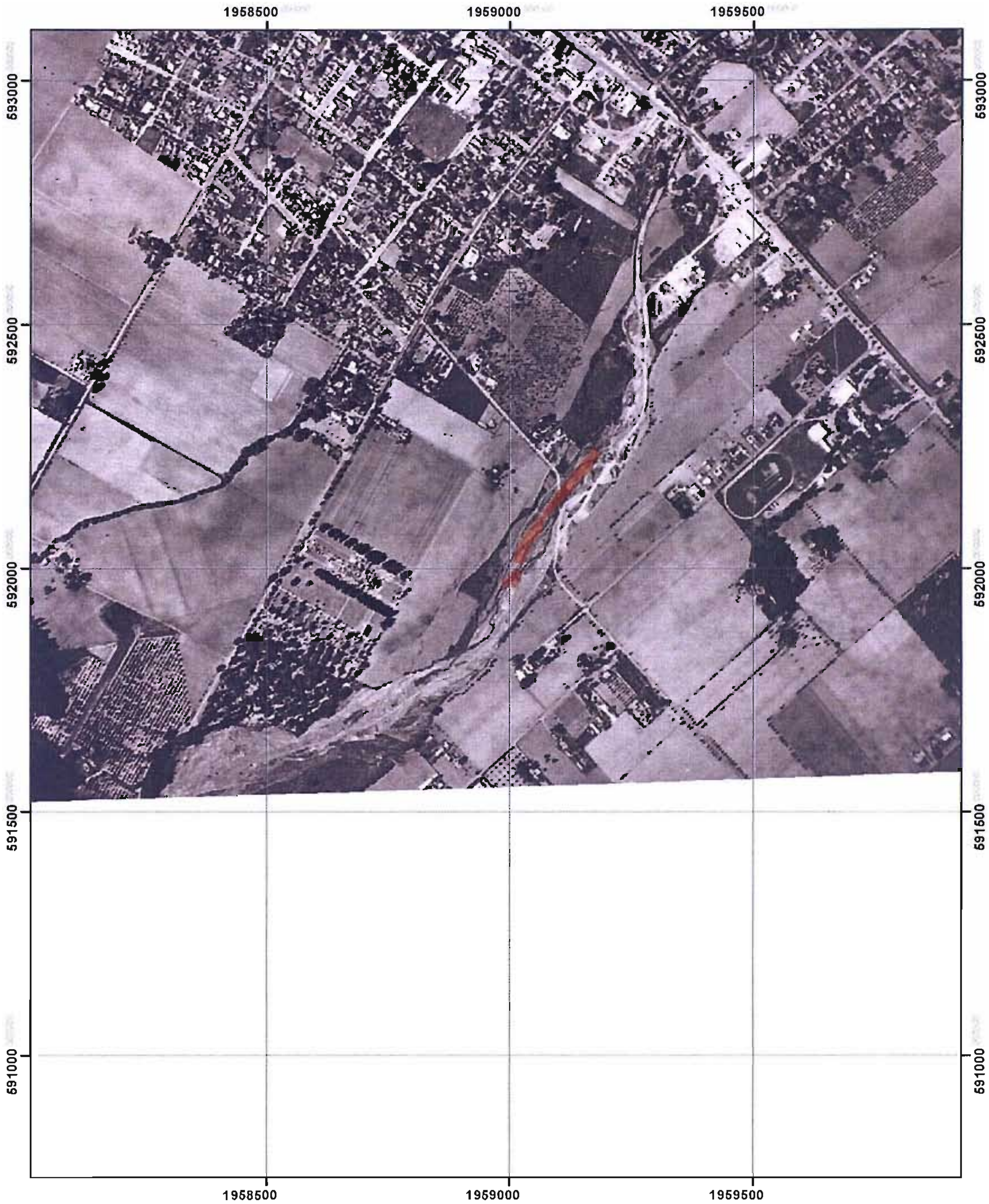


FIGURE F.4: Georeferenced black and white aerial photograph of Sulphur Creek in 1953. The study site is shown in transparent red. Source: (p.comm. Jonathan Goldman, City of Saint Helena).

FIGURE F.5: Georeferenced black and white aerial photograph of Sulphur Creek in 1958. The study site is shown in transparent red. Source: (p.comm. Jonathan Goldman, City of Saint Helena).

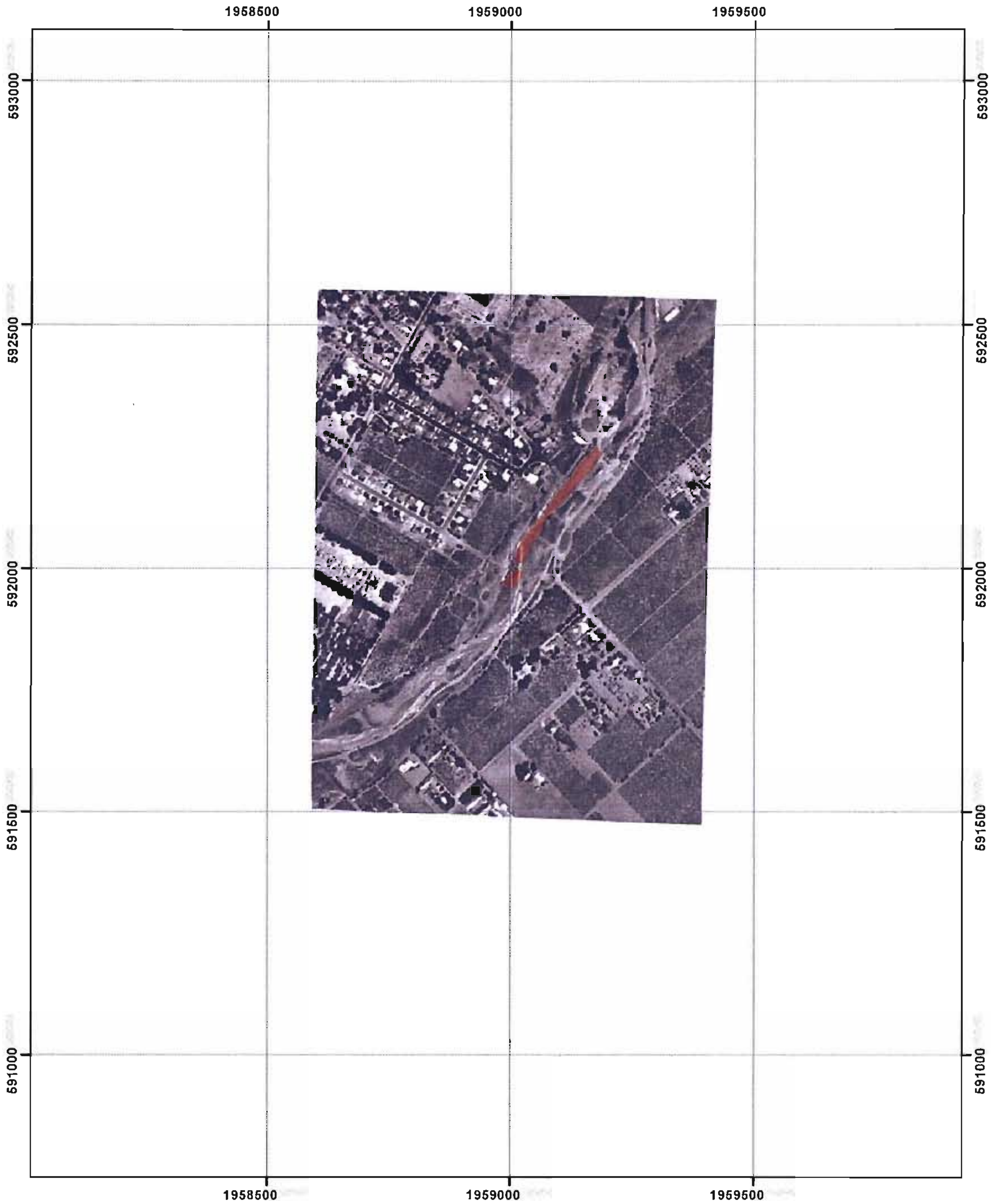


FIGURE F.6: Georeferenced black and white aerial photograph of Sulphur Creek in 1965. The study site is shown in transparent red. Source: (p.comm. Jonathan Goldman, City of Saint Helena).

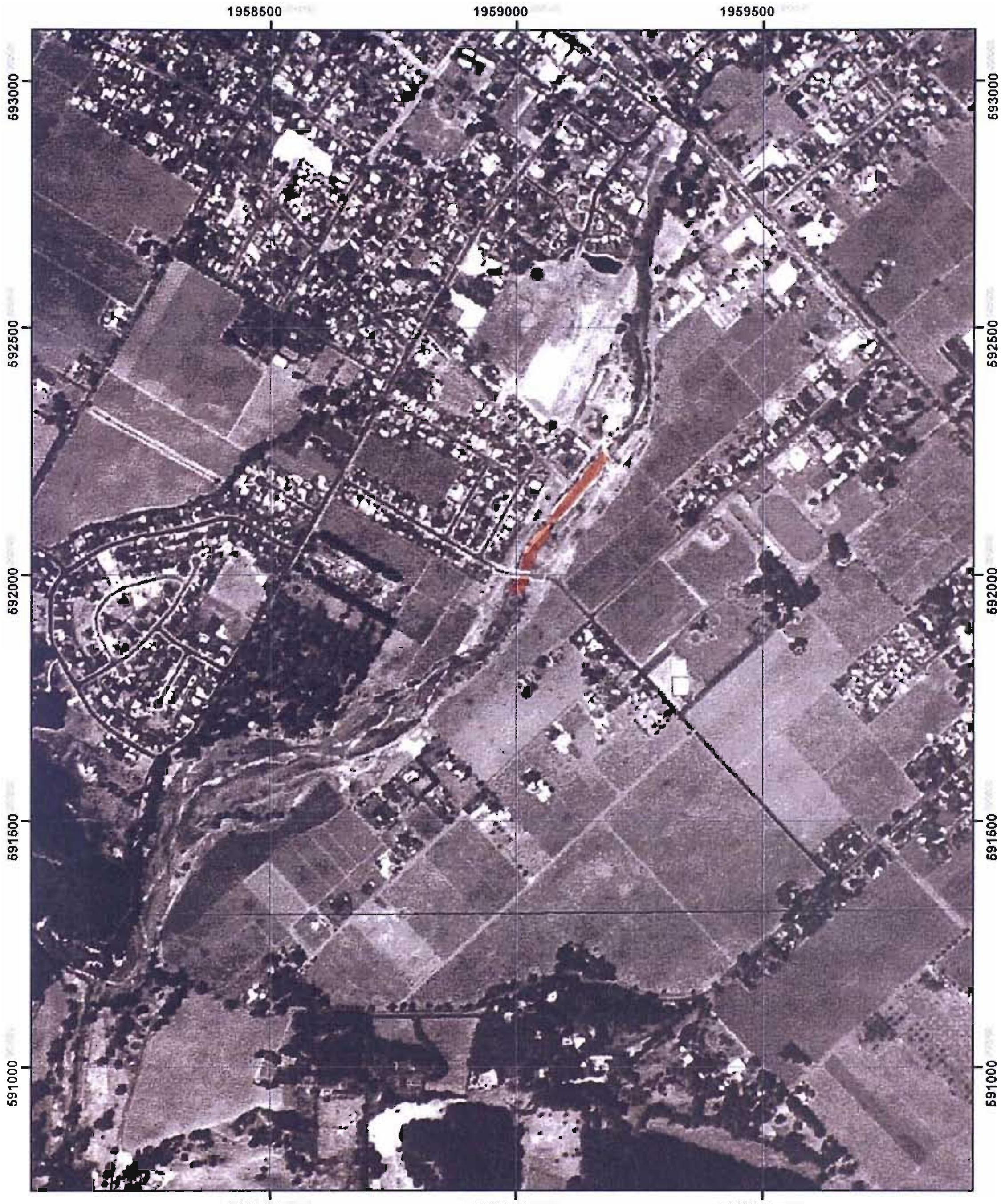


FIGURE F.7: Georeferenced black and white aerial photograph of Sulphur Creek in 1982. The study site is shown in transparent red. Source: (p.comm. Jonathan Goldman, City of Saint Helena).

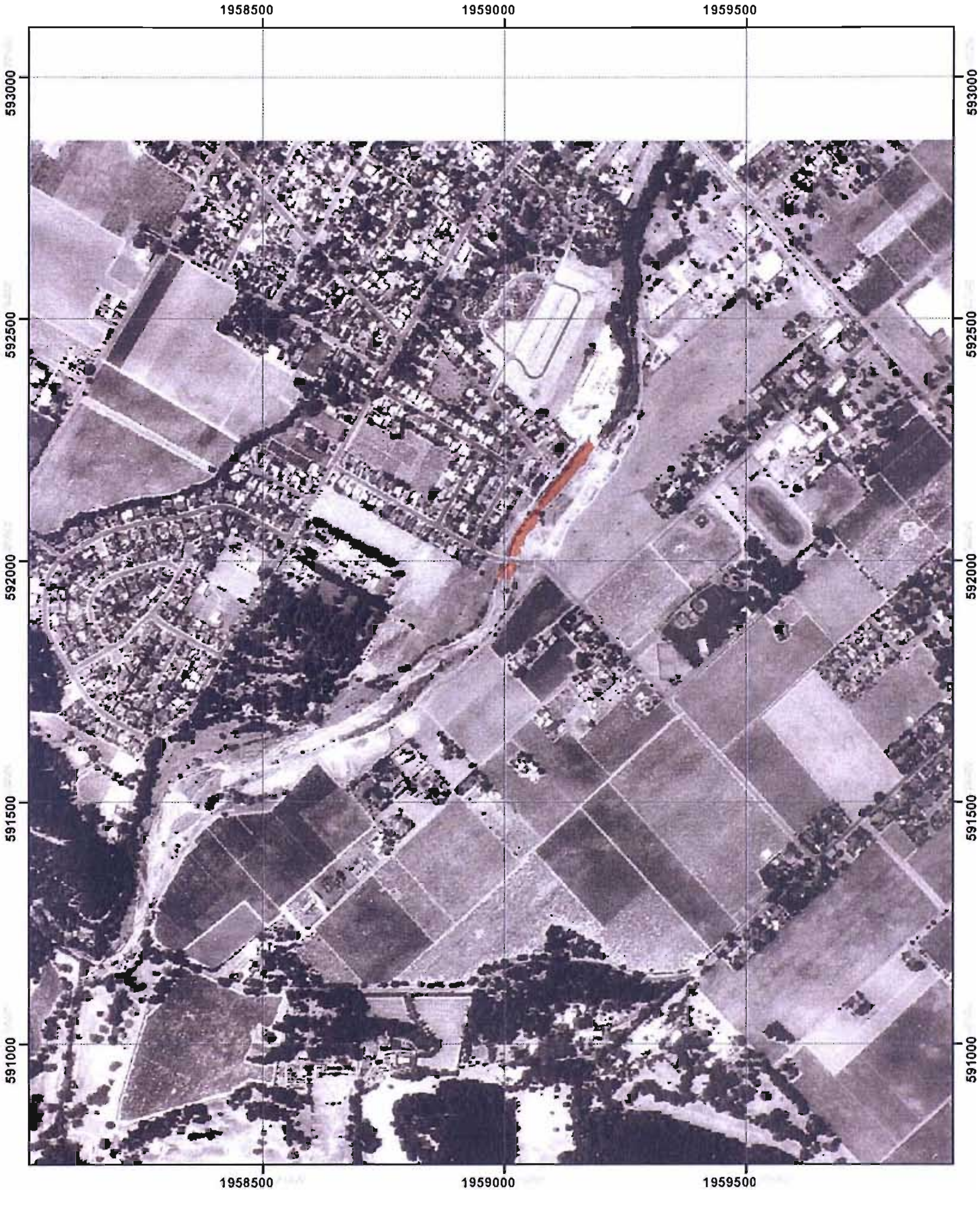


FIGURE F.8: Georeferenced black and white aerial photograph of Sulphur Creek in 1993. The study site is shown in transparent red. Source: (p.comm. Jonathan Goldman, City of Saint Helena).

FIGURE F.9: Georeferenced colour aerial photograph of Sulphur Creek in 2002. The study site is shown in transparent red. Source: (Napa County GIS: `http://gis.napa.ca.gov/gisdata.asp`).

F.2 Sulphur Creek Study Acknowledgments

Field work in Sulphur Creek has been part of a much larger catchment wide research project than the single New Year's Eve event at the small study site reported in this thesis. However, the focused work at this study site would not have been possible without the support of the numerous organisations and individuals listed below who were instrumental in facilitating the larger research effort. The research on Sulphur Creek has led to a collaboration of a variety of researchers from the United Kingdom. Indirect support from their respective institutions is acknowledged and appreciated.

- Principle Investigator: Joseph Wheaton (Centre for Catchment and Coastal Research, Institute of Geography and Earth Science, Aberystwyth University)
- Dr. James Brasington (Centre for Catchment and Coastal Research, Institute of Geography and Earth Science, Aberystwyth University)
- Dr. Steve Darby (School of Geography, University of Southampton)
- Professor David Sear (School of Geography, University of Southampton)

A variety of individuals have offered their time and expertise during three field work campaigns in Sulphur Creek. Below is a non-exhaustive list, but all those who have helped are sincerely thanked:

- Dr. James Brasington (Aberystwyth University)
- Dr. Steve Darby (University of Southampton) and Dr. Natasha Darby
- Duncan Hornby (Geodata Institute)
- Duncan Kitts (University of Southampton)
- Leica Geosystems (provided complementary loan of survey equipment)
- Wayne Leong (Saint Helena Community Forum)
- Julian Leyland (University of Southampton)
- Dr. Jim Milne (University of Southampton)
- Dr. Greg Pasternack and Aaron (University of California, Davis)
- Anne Reilley
- Professor David Sear (University of Southampton)
- Mike and Kelly Wheaton

Without the cooperation and active support of a variety of interested local land owners, citizens and organizations, the research in Sulphur Creek would not be possible. In particular, I thank all those land owners in Sulphur Creek who have signed access agreements and allowed us to conduct field work on your property. In addition, the following individuals and organizations have been particularly generous with their time, support and local knowledge:

- Acorn Soupe Particularly Sandra Leonard Perry and Jeff Mathy
- Jerry Brousseau (Vineyard Valley Mobile Home Park)
- Joseph and Al Butala
- All staff at the Napa County Resource Conservation District
- Members of staff and city council at City of St. Helena
- Phill Blake of Natural Resource Conservation Service
- David Garden
- Christopher Howell, Ashlee and Graham of Cain Vineyard and Winery
- Babe Learned
- The St. Helena Community Forum- Wayne and Cathy Leong, Sandra Ericson and Kelly Wheaton
- All members of the Sulphur Creek Watershed Task Force
- Jack and Harold Varozza (Harold Smith and Sons)
- Don & Lidia McGrath, Wayne & Cathy Leong, Rich Auger & Mary Radu, and Mike & Kelly Wheaton (Generously provided lodging for the researchers)

A variety of professionals, researchers, experts and agency personnel, who have worked in Sulphur Creek, have shared their knowledge and time. These include:

- Drew Aspergen (Napa Valley Vineayrd Engineering)
- Rob Bell (Albion Surveys Donated time, survey equipment and old surveys.)
- Dino Bellugi (U.C. Berkeley / N.C.A.L.M)
- Keith Bowen (U.C. Davis Provided flight reconnasiance with his plane)
- Bob Broadhurst and Don Ristau (Phoenix Geotechnical)
- Jonathan Goldman and Meghan Maloney (City of St. Helena)
- Pat Kowta (Napa County GIS Department)

- Julie Haas (formerly P.W.A. and Associates)
- Eric Larsen (UC Davis)
- Anna Maria Martinez (Napa County Public Works)
- Jonathan Koehler & Entire Staff (Napa County Resource Conservation District)
- Entire Staff (Napa County Natural Resource Conservation Service)
- Pacific Watershed Associates
- Sarah Pearce (San Francisco Estuary Institute)
- Jay Kinberger (US Army Corps of Engineers)
- Victoria E. Langenheim, Robert McLaughlin and Russel Graymer (U.S. Geological Survey)
- Robert A. Leidy (Wetlands Regulatory Office, U.S. Environmental Protection Agency)
- Michael Napolitano (San Francisco Regional Water Quality Control Board)
- Ric Reinhardt (MBK Engineers)
- Peng Wang (University of California, Santa Barbara)

My apologies to those who I have failed to mention here. Your support is certainly appreciated. Please refer back to the Acknowledgments at the front of the thesis for acknowledgments pertaining to the thesis as a whole.

F.2.1 Funding

Funding for the research in Sulphur Creek was generously provided by:

- The University of Southampton's School of Geography and the Centre for Ecology and Hydrology (a PhD Studentship)
- A Horton Hydrology Research Grant from the Hydrology Section of the American Geophysical Union
- A travel grant from the Saint Helena Community Forum

Appendix G

Mokelumne River Study Site

The purpose of this appendix is to provide the reader with further background and context on the Mokelumne River Study Site than the minimal descriptions in § 3.5, § 5.3 and § 7.2. First, the Catchment is described (§ G.1). Then the extensive flow regulation of the Mokelumne is discussed (§ G.2). Next, the Lower Mokelumne River is described (§ G.3) as this is the setting for the study site, which was described previously in § 7.2. Finally, the topographic surveys and the DoD analysis used in Chapter 7 are described in § G.4. Much of the text for the first four sections of this appendix was adapted directly from Wheaton (2003, Appendix 1, pp. 106-121).

G.1 The Mokelumne River Catchment

The Mokelumne River of central California drains a 1700 km^2 (1497 km^2 upstream of Pardee Reservoir) catchment (Figure G.1). The headwaters of the Mokelumne originate in the Mokelumne Wilderness of the Sierra Nevada Mountains south of Lake Tahoe and north of Yosemite. The Mokelumne River flows generally west out of the Sierras and falls from 3050 m alpine peaks down to near sea level at its confluence with the San Joaquin River. Over its roughly 1139 km (707 mi) course it passes through a wide range of ecosystems, micro-climates and contrasting lithologies. Precipitation in the mountainous eastern part of the basin takes the form primarily of snow, of which it receives nearly 1195 mm annually. In contrast, the central region of the watershed in the foothills receives 510 mm of precipitation annually, nearly all of which is rain. Precipitation in the lower Mokelumne basin ranges from 254 - 635 mm.

G.2 Development of Mokelumne River Water Resources

The Mokelumne River has been used for water supply and hydropower since the late 1800's. Pacific Gas and Electric developed the basin above Pardee Reservoir for hydropower, main-

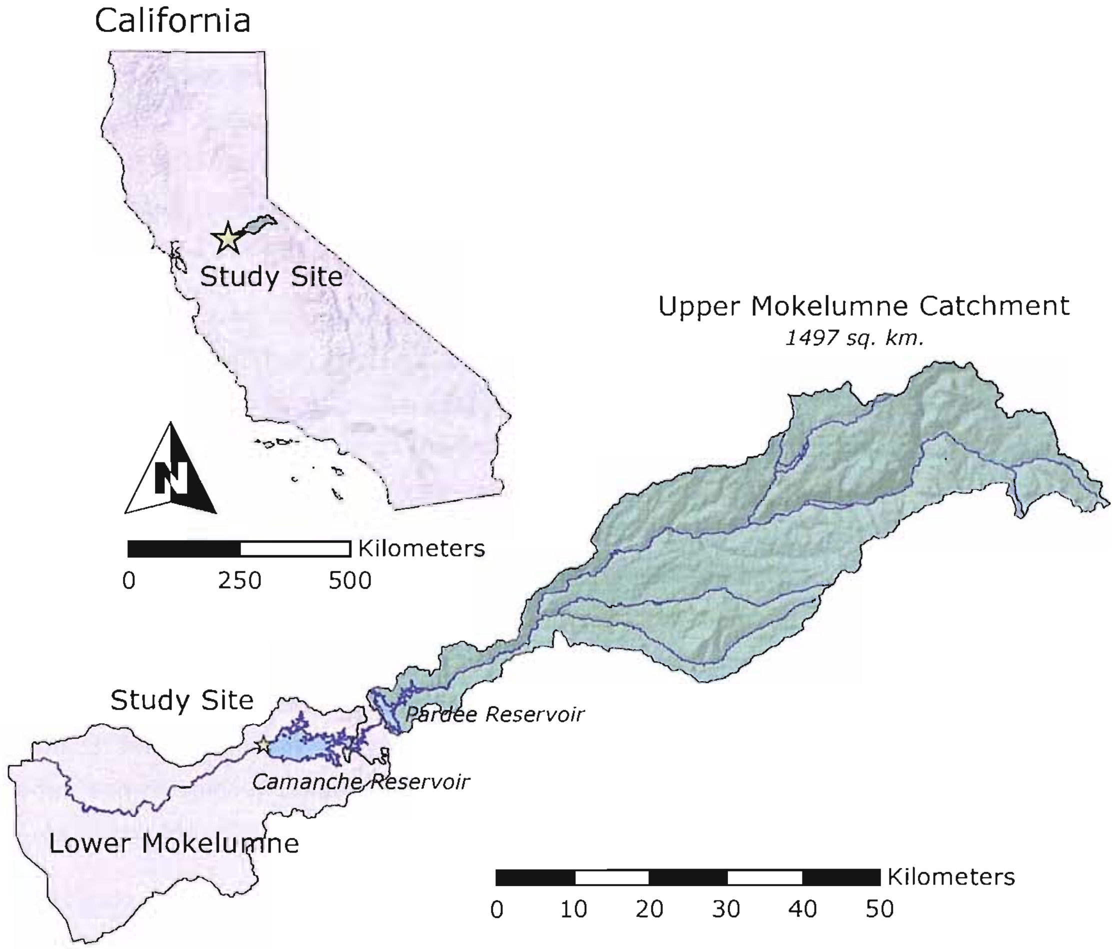


FIGURE G.1: Location maps for Mokelumne River study site. A) Location of Mokelumne River Catchment and Study Site within California. B) Location of study site in Mokelumne River Catchment.

taining seven reservoirs in the region, while East Bay Municipal Utility District (EBMUD) developed the lower Mokelumne (Figure G.1) to provide 'clean' Sierra Mountain' water to the thirsty customers in the East Bay metropolitan area. EBMUD serves 1.2 million people east of San Francisco Bay, including those in Oakland and Berkeley. EBMUD completed Pardee Dam and the Mokelumne Aqueduct from Pardee to the East Bay in 1929. Downstream, Camanche Reservoir was completed in 1963. All of the water EBMUD uses is diverted out of the smaller Pardee Reservoir directly upstream of Camanche Reservoir. However, EBMUD is required to provide provide flood control for communities like Lodi further downstream along the Mokelumne. Prior to the construction of Camanche Dam, this meant that operators at Pardee dam had to leave a certain percentage of Pardee reservoir empty to accommodate big spring floods. This was precisely at the time when dam operators would rather be keeping the reservoir water supply topped up to get them through the long summer. Thus, Camanche was built in the 1960's essentially to give EBMUD the freedom to manage Pardee strictly for water supply, and use Camanche to provide the obligatory flood control.

Camanche Dam is an anomaly amongst the major dams up and down the California Sierra foothills, which collectively impound every single major tributary to the Sacramento and San Joaquin Rivers.[1] The reason the Cosumnes is odd is that it is positioned much further downstream on the very fringe of the foothills than any of the other major dams. Whereas upstream dams can be smaller, only having to plug a gap in a deep gorge or narrow canyon, the topography here is much more subdued and the relative relief much less dramatic. Thus, to achieve an equivalent reservoir capacity, the dams themselves have to be much, much larger. Whereas Pardee Dam consists of a 0.38 km concrete arch dam and a 0.25 km concrete dam, Camanche Dam has more than 5.8 km of earth dam embankment, much of it over 35 m high. The majority of the fill for Camanche dams came from gravels in the Mokelumne itself (p. comm. J. Merz). Camanche impounds over 15 km of the Mokelumne River but is impassible for fish and completely isolates the upper basin from the lower basin. Pardee impounds over 12 km of the Mokelumne.

To mitigate fishery losses caused by Camanche Dam, EBMUD built a hatchery below it that is operated by the California Department of Fish and Game. Declines in the fishery during the 1976-77 and 1987-92 droughts led stakeholders to focus on improving aquatic habitat for fish, specifically for chinook salmon and steelhead trout. Collaborative restoration efforts involving channel modifications as well as changes to the flow regime began in 1992.

G.2.1 Flow Regime below Camanche Dam

Hydrologic analysis of pre- (1904–1963) and post- (1964–1999) dam annual peak flows below Camanche Dam (USGS Station ID 11323500) show the impact of the structure. Prior to the dam, annual peak flows exceeded 200 cumecs for 21 out of 57 water years. Since Camanche Dam was built, annual peak flows have never even reached 200 cumecs. As alluded to above,

[1]Except the Cosumnes River, which is technically a tributary to the Mokelumne.

the overflow spillway bypasses the first 1.2 km of the Mokelumne River below Camanche Dam. The maximum release from the penstocks of Camanche Reservoir is roughly 141 cumecs (5000 cfs). Additional contributions from Murphy Creek have not been determined yet, but vary seasonally with peaks on the order of 14 to 28 cumecs. Therefore, the maximum flow through the project reach is on the order of 155 to 170 cumecs. Mean monthly discharge shows that the pre-dam annual hydrograph was typical of a snowmelt river in Northern California, with highest average discharges occurring inMay to June, following the peak in monthly average precipitation. The post-dam hydrograph shows a significant reduction in the late spring and early summer snowmelt flows below the dam. With a flood frequency analysis using a Log Pearson III distribution, Wheaton (2003, Table A1) showed a dramatic reduction in discharge for all recurrence intervals after the dam was built. Q_2, Q_5, Q_{10}, and Q_{100} decreased by 67%, 59%, 73%, and 75% respectively. For example, the discharge with a 1.5-year recurrence interval, prior to Camanche Dam was 120 cumecs; now this flow has a recurrence interval of roughly 5-10 years. Today, the discharge with a 1.5-year recurrence interval has dropped to an estimated 40 cumecs. Now, flow releases below Camanche Dam generally follow a step hydrograph due to the controlled nature of the releases, with low flows just above the minimum 4.25 cumecs (150 cfs) as agreed upon in the Joint Settlement Agreement (FERC 1998).

A simple comparison of the mean daily discharge releases below Camanche Dam for the past five years illustrates the stepped nature of the regulated flow regime that exists today on the lower Mokelumne River. Figure 7.3 shows the hydrographs for the lower Mokelumne that span a range of water year types from a very wet year in 2006 to a rather dry year in 2001. The unregulated flow regime loosely represented by the Mokelumne Hill Hydrograph in figure 7.3 exhibits several features that are typical of Sierra rivers draining into the Central Valley. Namely, notice the sequence of large pulses early in the year from large storm events. The rising limbs of these storm hydrographs climb rapidly to peak discharges that exceed the later peaks of the spring pulses and then subside relatively quickly. The higher discharges beginning in April and continuing through July reflect the gradual release of the melting snow pack until it is virtually depleted in July. The peaks of these snow pack releases may correspond to late season storms or periods when the temperatures rose melting pulses of snow in the upper Mokelumne basin. After the snow pack is depleted, the Mokelumne reverts to a baseflow dominated flow regime until the following winter. Notice that flows through the spawning season for fall run chinook salmon are essentially flat-lined around 5 cumecs. For further information, refer to Wheaton (2003, Appendix 1), Wang & Pasternack (2001) and Pasternack *et al.* (2004).

G.3 Lower Mokelumne River

The lower Mokelumne River begins below Camanche Dam where the elevation is roughly 28 m above sea level and extends westward down to the Sacramento-San Joaquin Delta roughly 72 km downstream. Average channel gradients range from 0.10 percent in the upper 8 km below Camanche, to 0.02 percent near the Mokelumne's confluence with the Cosumnes River.

Channel widths in the lower Mokelumne River range from 19-43 m with a mean of 30 m (CDFG, 1991). The river tends to be wider in the first 10 km (6 mi) below Camanche Dam and, generally, narrower downstream to the tidal reach. Much of the narrowing of the channel downstream can be attributed to the flood control levees built to protect homes and farmland on the historical floodplains of the river which have encouraged the river to incise as opposed to migrate laterally. There are approximately 65 km of levees constructed on the lower Mokelumne between Camanche Dam and the Cosumnes River confluence (CDFG 1991).

The lower Mokelumne River flows through a mix of alluvial fan deposits (composed of the Valdez-Columbia and Hanford-Greenfield soil associations) in the upper reaches below Camanche, and its own floodplain further downstream (Envirosphere 1988). Both the Valdez-Columbia and Hanford-Greenfield and soil associations are sandy-loams with good to poor drainage characteristics (SCS 1967). Tailings from gravel mines are apparent along the upper third of the lower Mokelumne. Prominent rock outcrops associated with the Mehrten Formation are found along the river. The Mehrten formation consists of Andesitic conglomerates, sandstone, and breccia near Camanche Dam and mostly alluvium, levee and channel deposits (sand and mud) downstream into the Delta. The alluvium is mostly Pleistocene and stems from volcanic, granitic, sedimentary, and metamorphic rock sources. The surface geology of the area consists of one geologic belt, the Victor alluvial plain that extends westward from near Camanche Dam. Deposits in the Victor alluvial plain consist of the unconsolidated sands, silts, and gravels of the Victor formation and recent alluvium. These sediments exhibit a relatively high permeability. The Victor alluvial plain comprises most of the heavily cultivated and irrigated land in the area. Channel substrates in the lower Mokelumne range from large gravels and cobbles in the upper 9.6 km below Camanche to sand, mud, sandstone and highly compacted alluvium further downstream.

Riparian vegetation is found along both banks of the lower Mokelumne corridor (CDFG 1991). Overstory species are tall and include cottonwoods (*Populus fremontii*), valley oaks (*Quercus lobata*), and black walnuts (*Juglans hindsii*) in a mixed stand. Box elder (Acer negundo var. Californicum), willow (*Salix sp.*), alder (*Alnus rhombifolia*) and Oregon ash (*Fraxinus latifolia*) are present in a second canopy layer. Grape (*Vitus californica*) and blackberry vines (*Rubus sp.*) drape the overstory. Groundcover species included horsetails (*Equisetum laveigatum*), nightshade (*Solanum sp.*), and lamb's quarters (*Chenopodium album*).

Pardee and Camanche Dams have altered channel form and riparian vegetation of the lower Mokelumne River. The Mokelumne Fish Hatchery was built over the historic river channel immediately downstream of Camanche Reservoir. A new channel was constructed parallel to the hatchery before connecting to the historic channel roughly 670 m downstream of Camanche Dam. Beyond that alteration, most changes are primarily due to an altered flow regime (in which peaks have been greatly reduced), instream gravel mining and levee construction. Geomorphically, the altered flow regime stabilized formerly active river deposits and permitted encroachment of vegetation into the active channel. Such changes are documented in historical sources, notably aerial photos. The active channel is now roughly half its former width in areas, as evidenced by distinctive bands of alders along the bank of the lower flow channel

Monitoring Year	Project Year						LMR all
	2001	2002	2003	2004	2005	2006	
1994	0	43	104	0	0	13	777
1995	0	83	131	1	0	36	906
1996	0	67	132	0	0	40	928
1997	22	94	188	0	0	69	1321
1998	18	70	183	0	0	59	1088
1999	3	36	99	1	0	20	615
2000	1	55	169	29	0	45	987
2001	7†	49	81	5	0	25	843
2002	5	58†	60	2	0	5	848
2003	4	41	73†	6	0	11	807
2004	4	34	96	65†	0	24	829
2005	19	125	233	176	69†	66	2157
2006	0	47	123	62	25	28†	755

TABLE G.1: Lower Mokelumne River redd surveys from 1994 to 2006. The † symbol indicates a year of SHR intervention at that project site. Project sites are named by the year they were constructed. Data collected by EBMUD staff (p. comm J. Merz) and compiled by UC Davis Watershed Hydrology and Geomorphology Lab staff (p. comm G. Pasternack).

(FERC 1998). In an aerial photo analysis spanning 30 years, Fetherston (1994) concluded that reservoir-induced modifications in the magnitude and frequency of scouring flows permitted seedlings to mature within and adjacent to the active channel. Riparian vegetation encroachment in the form of bands of single-aged Alder trees now line previously unvegetated banks and river deposits. Together with collaborators, EBMUD has conducted spawning gravel replenishment below Camanche Dam since 1990. FERC (1998) encouraged gravel rehabilitation as a non-flow alternative for improving fish habitat below the dam, citing lack of gravel recruitment and plugging of bed pores with fines. The Mokelumne River Spawning Habitat Improvement Project is a joint agency effort, whose primary objectives are to provide additional salmonid spawning gravels within the preferred size range and improve inter-gravel water quality (Smith 2001). Since 1998, project sites have been monitored for inter-gravel permeability, dissolved oxygen content, mean water temperature, macrobiotic diversity, and redd counts (Merz & Setka 2004, Merz *et al.* 2004). Some sites will be monitored through 2009. Redd counts by SHR site and for the total LMR are summarised in Table G.1.

G.4 Topographic Surveys and DoD Analysis

The vast majority of topographic surveying was conducted using ground-based total stations (primarily Leica TPS1200 series), and a minimal amount of boat-based echo-sounding was used in pools to deep to wade or swim and/or at high flows. In later surveys (2005 and 2006), a reflectorless total station was available and was used to capture all bank shots. Some of the survey data dates back to 1999 and in many of the surveys, portions of the points used for

Year	Salmon Escapement	Hatchery Take	Whole River Spawners	Whole River Redds	site Redds	% of Redds
2002	10752	7929	2833	848	62	7
2003	10266	8117	2149	807	79	10
2004	11416	10355	1061	829	161	19
2005	16140	5734	10406	2157	478	22
2006	5861	4138	1723	755	238	32

TABLE G.2: Comparison of salmon escapement (total salmon run), hatchery take (fish the LMR hatchery take), the number of fish left for potential spawning, the actual number of fish that spawned and those that spawned at a SHIRA SHR site. Data collected by EBMUD staff (p. comm J. Merz) and compiled by UC Davis Watershed Hydrology and Geomorphology Lab staff (p. comm G. Pasternack).

the DEM did not actually come from that particular survey. These tended to be either:

- in areas where changes were assumed not to have taken place
- in areas that were not the focus of SHR activities or the study, but still needed to be included for completeness in the hydraulic modelling
- deep pool areas that were too difficult to survey by hand and not central to the performance of the model or design of the SHR project

The primary purpose of doing the topographic surveys was to support the hydrodynamic modelling efforts required under SHIRA (Wheaton *et al.* 2004*c*), with the secondary benefit being the long-term monitoring of topographic changes to the projects (Merz *et al.* 2006, e.g.). It is important to highlight that the raw point datasets used here were not all directly from the raw surveys, but rather represented processed point clouds that were developed iteratively to include topographic representation for use in mesh construction to drive 2D hydrodynamic model simulations (Pasternack *et al.* 2006, Pasternack *et al.* 2004, Elkins *et al.* 2007, Wheaton *et al.* 2004*d*, e.g.) for pre, design and post project modelling analyses associated with SHIRA implementation each year. The process was typically undertaken in AutoCAD by UC Davis staff including QA/QC procedures. The 4 iterative stages of DEM development used were interpolation, visualization, editing, and augmentation following French & Clifford (2000). From these, the original filtered and augmented points were combined to produce a final data set.

As point densities were generally quite high (>1 pt./ m^2) in the SHR areas, the data were sufficiently high resolution to support deriving a 25 cm resolution DEM from the TINs. Point densities were derived from the point clouds and slope analyses were derived from the DEM also at 25 cm resolutions for use in the fuzzy inference system of the DoD analysis. For the DoD analysis (summary reported in § 7.3), a pathway 4 analysis as described in § 4.6.3 was used. Both the intermediate non-thresholded pathway 1 analysis and pathway 3 analysis based only on the fuzzy inference system are reported here for each timestep to allow inter-comparison.

The fuzzy rule system for both was again a two rule system like that reported in § 4.4.1.2, but the input membership functions were calibrated slightly to account for exceptionally high point densities associated with the reflectorless total station. Both the pathway 3 and 4 analyses were thresholded at a 95% confidence interval.

The next seven subsections show the DEMs used at each timestep and their respective DoDs under pathway 1, 3 and 4 analyses for each. Where additional explanation is warranted, there is text.

G.4.1 TS1 DEMs and DoD

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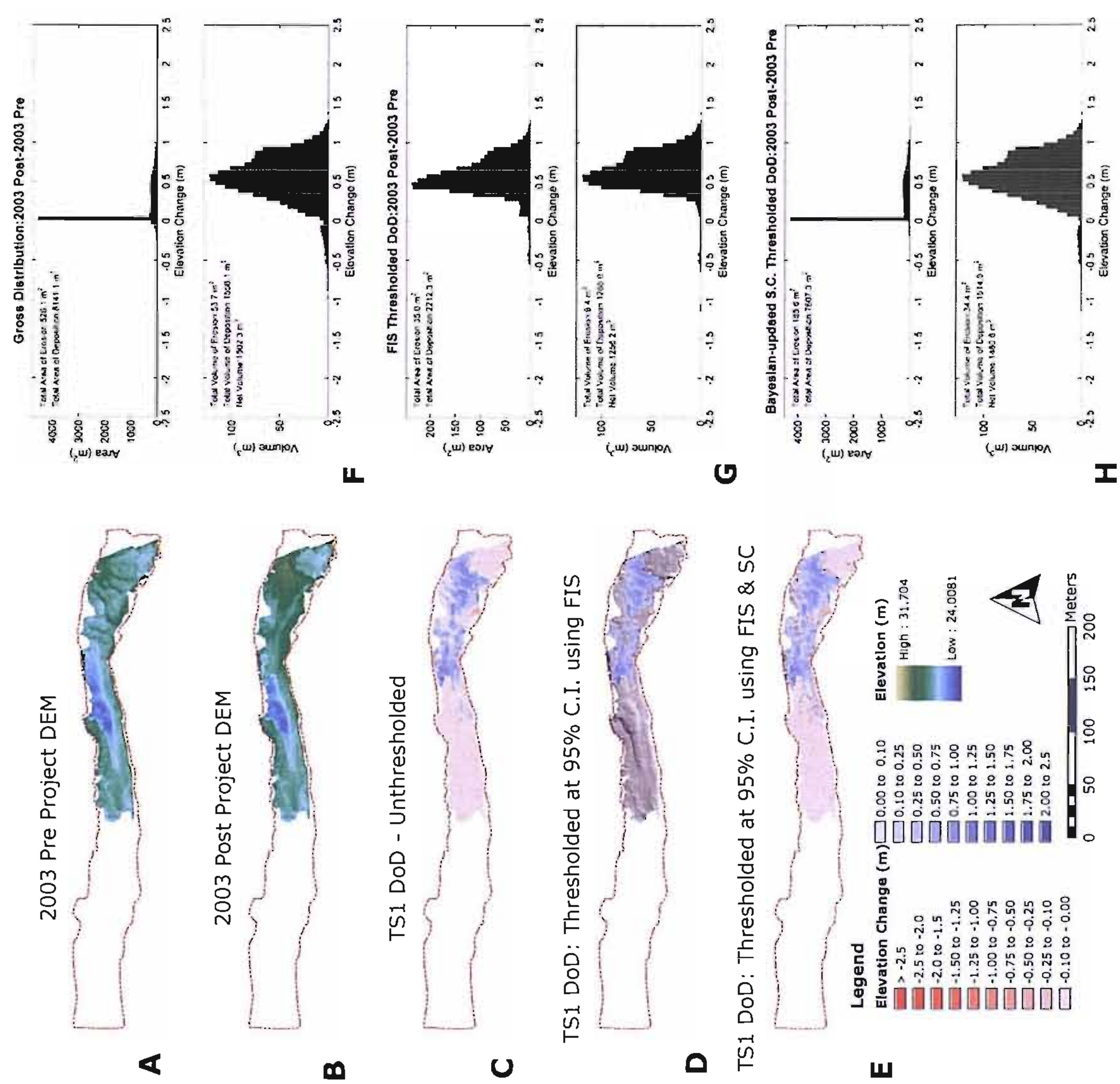

Figure G.2: Pathway 4 DoD Analysis for TS1 (Time Step 1). A. Pre 2003 SHR-Project DEM. B. Post 2003 SHR-Project DEM. C. Unthresholded DoD. D. FIS (Pathway 3) Thresholded DoD (DoDs in D & E were thresholded using a Pathway 4 analysis and 95% confidence interval; see Chapter 4 for explanation). E. FIS & SC thresholded DoD. F through H: Elevation Change Distributions for C, D and E respectively.

G.4.2 TS2 DEMs and DoD

The rest of this page is intentionally left blank. See next page for DEMs and DoDs for TS2 (Figure G.3).

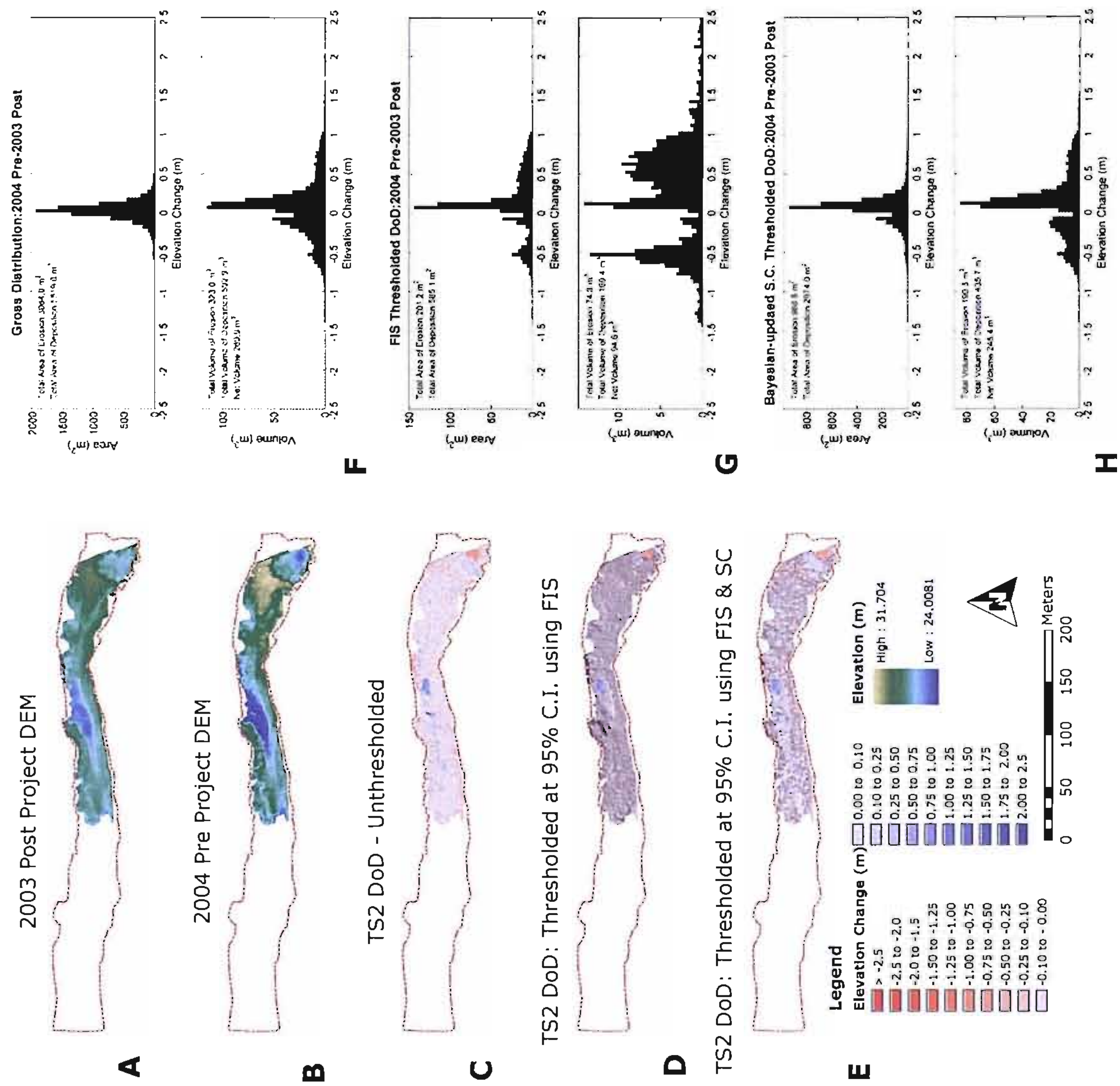

FIGURE G.3: Pathway 4 DoD Analysis for TS2 (Time Step 2). A. Post 2003 SHR-Project DEM. B. Pre 2004 SHR-Project DEM. C. Unthresholded DoD. D. FIS (Pathway 3) Thresholded DoD (DoDs in D & E were thresholded using a Pathway 4 analysis and 95% confidence interval; see Chapter 4 for explanation). E. FIS & SC thresholded DoD. F through H: Elevation Change Distributions for C, D and E respectively.

G.4.3 TS3 DEMs and DoD

The rest of this page is intentionally left blank. See next page for DEMs and DoDs for TS3 (Figure G.4).

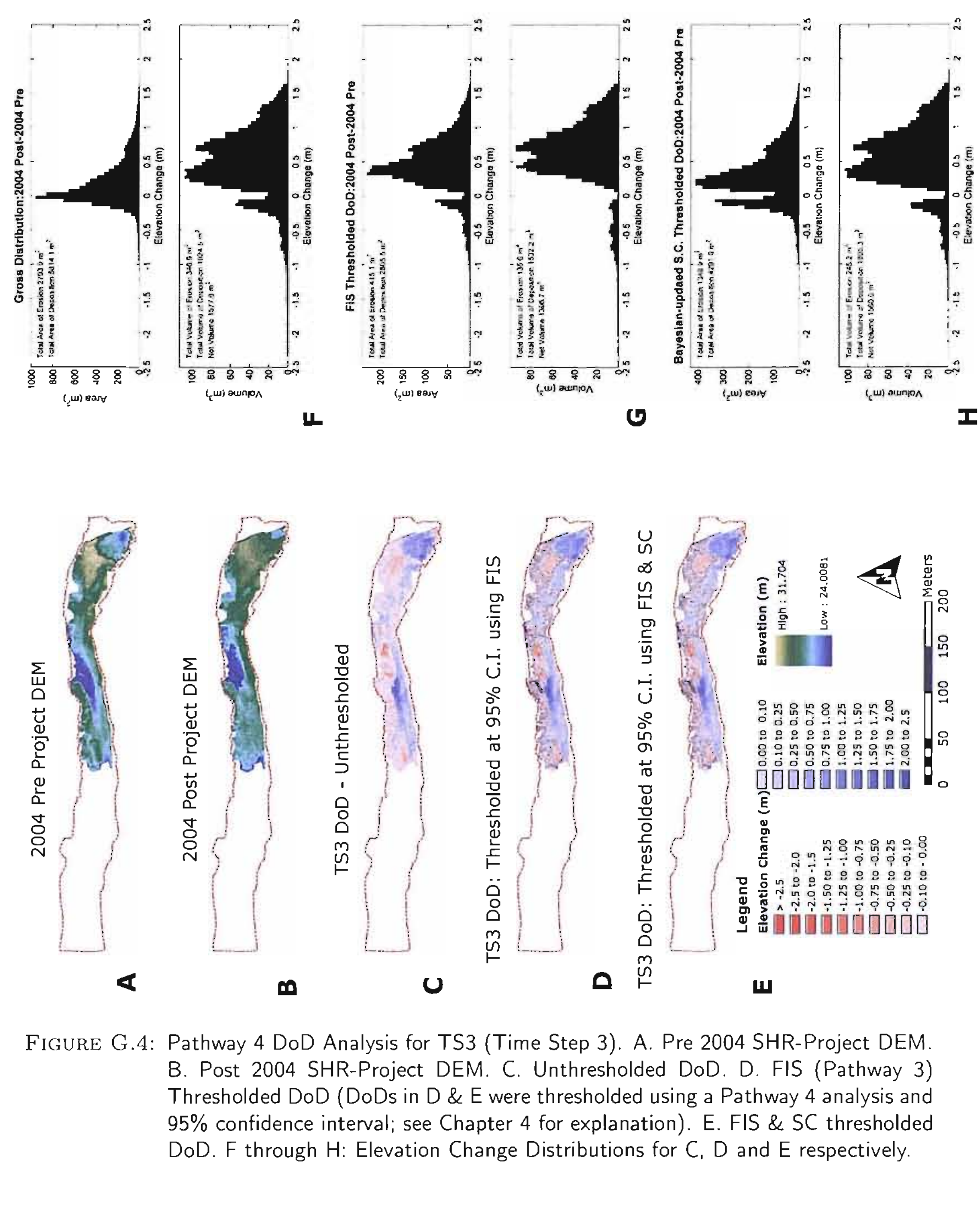

FIGURE G.4: Pathway 4 DoD Analysis for TS3 (Time Step 3). A. Pre 2004 SHR-Project DEM. B. Post 2004 SHR-Project DEM. C. Unthresholded DoD. D. FIS (Pathway 3) Thresholded DoD (DoDs in D & E were thresholded using a Pathway 4 analysis and 95% confidence interval; see Chapter 4 for explanation). E. FIS & SC thresholded DoD. F through H: Elevation Change Distributions for C, D and E respectively.

G.4.4 TS4 DEMs and DoD

Even though there is technically no TS4 due to the lack of a pre project 2005 survey (see § G.4.4), a DoD distribution is shown in Figure 7.6G and H for TS4. This is intentional to illustrate an important tangential point about the magnitude of DEM interpolation error. The datasets used in these analyses were originally cleaned and filtered for mesh boundary construction for use in two dimensional hydraulic model construction by Elkins *et al.* (2007) and others (p. Comm. G. Pasternack, 2007). For each PHR project, a pre project set of model runs was performed and, a series of design runs were performed comparing different design scenarios and a post project as-built model run was performed as part of the SHIRA methodology (Wheaton *et al.* 2004*c*). No pre project dataset was available for the 2005, because Accordingly, the post project topographic survey from 2004 was used along with point augmentation (Wheaton *et al.* 2004*c*, French & Clifford 2000) to create the pre project model mesh. During the initial phase of DoD analysis, the fact that TS4 was exactly a comparison of the same two data sets was not immediately obvious.[2] However, during quality control checks and more detailed inspection of the raw data and DoD analysis results it was discovered that TS4 was not reflecting real changes. This thus raises the question what are the changes shown in the elevation change distributions in Figure 7.6G and H referring to? Fortunately, they are extremely small magnitude changes relative to the magnitude of actual measured changes. They come about as a result of slight differences in the TIN-based interpolation between the two surveys because of a different order and number of points. Particularly in areas of low point density (e.g. deep pools), these slight differences in the TIN geometry lead to slightly different DEMs. Reassuringly, these artifacts are almost entirely filtered out under a pathway 3 analysis (Figure 7.6G), leaving only two cubic meters of erroneously predicted cut. However, some of the erroneous changes are recovered under pathway 4 because they exhibit spatial coherence[3]

[2]This was partly because the point numbering was different, partly due to presence of some 'additional'augmented points, and partially because the DoD revealed potentially believable small magnitude changes.

[3]See § 4.4.2.

G.4.5 TS5 DEMs and DoD

Due to continuous high flow releases of 42-85 cumecs from February through August 2005, it was not possible to re-survey the channel before construction. The reach from the base of the dam to Murphy Creek was surveyed in September 2004 after gravel placement, so that recent data was coupled with 1999 survey of the mouth of Murphy Creek and 2001 data of the riffle downstream of Murphy Creek to produce a pre-project bathymetric map. EBMUD conducted a supplemental boat-based survey of the primary 2005 placement zone using differential GPS and a depth sounder, with bed elevations adjusted according to water surface slope, as surveyed using a total station.

The rest of this page is intentionally left blank. See next page for DEMs and DoDs for TS5 (Figure G.5).

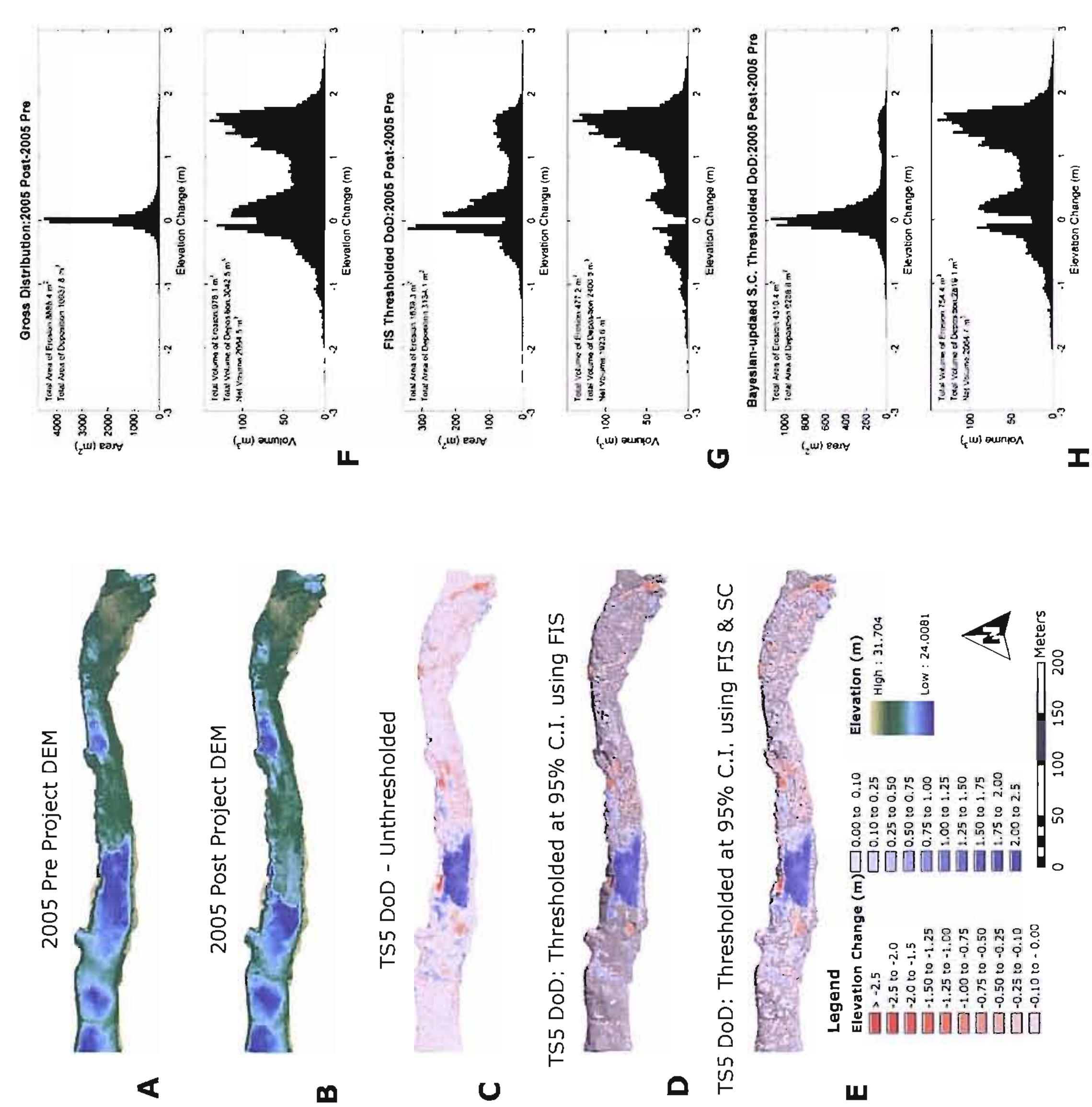

FIGURE G.5: Pathway 4 DoD Analysis for TS5 (Time Step 5). A. Pre 2005 SHR-Project DEM. B. Post 2005 SHR-Project DEM. C. Unthresholded DoD. D. FIS (Pathway 3) Thresholded DoD (DoDs in D & E were thresholded using a Pathway 4 analysis and 95% confidence interval; see Chapter 4 for explanation). E. FIS & SC thresholded DoD. F through H: Elevation Change Distributions for C, D and E respectively.

G.4.6 TS6 DEMs and DoD

The rest of this page is intentionally left blank. See next page for DEMs and DoDs for TS6 (Figure G.6).

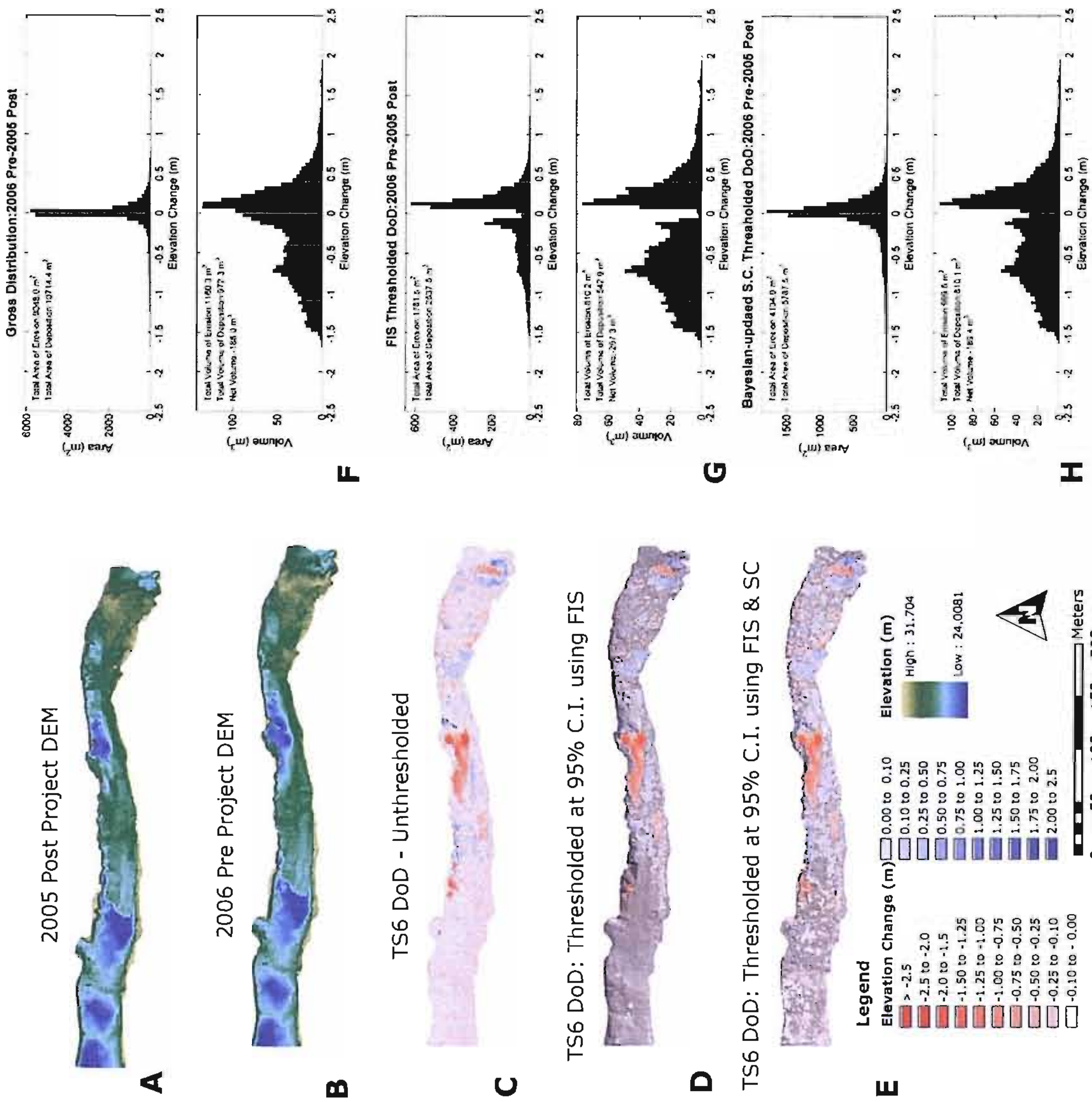

FIGURE G.6: Pathway 4 DoD Analysis for TS6 (Time Step 6). A. Post 2005 SHR-Project DEM. B. Pre 2006 SHR-Project DEM. C. Unthresholded DoD. D. FIS (Pathway 3) Thresholded DoD (DoDs in D & E were thresholded using a Pathway 4 analysis and 95% confidence interval; see Chapter 4 for explanation). E. FIS & SC thresholded DoD. F through H: Elevation Change Distributions for C, D and E respectively.

G.4.7 TS7 DEMs and DoD

The rest of this page is intentionally left blank. See next page for DEMs and DoDs for TS7 (Figure G.7).

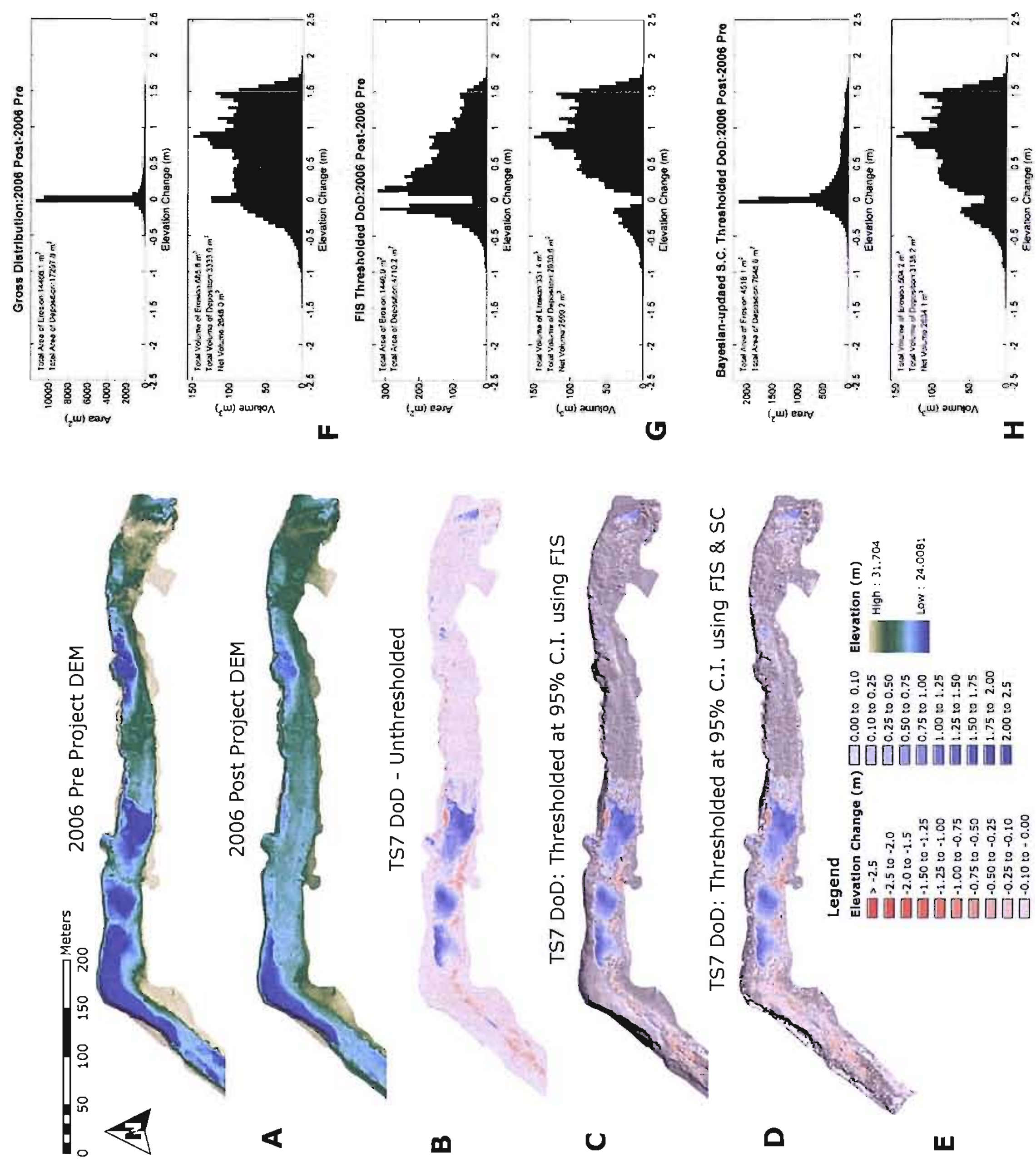

FIGURE G.7: Pathway 4 DoD Analysis for TS7 (Time Step 7). A. Pre 2006 SHR-Project DEM. B. Post 2006 SHR-Project DEM. C. Unthresholded DoD. D. FIS (Pathway 3) Thresholded DoD (DoDs in D & E were thresholded using a Pathway 4 analysis and 95% confidence interval; see Chapter 4 for explanation). E. FIS & SC thresholded DoD. F through H: Elevation Change Distributions for C, D and E respectively.

G.5 Mokelumne River Study Acknowledgments

The research on the Mokelumne River has primarily grown out of a collaboration between researchers at the University of California at Davis and East Bay Municipal Utility District (who own and operate Camanche and Pardee Reservoirs). Indirect support from their respective institutions is acknowledged and appreciated. Since Dr. Gregory. B Pasternack, Dr. Joe Merz and I first developed SHIRA, Eve Elkins and Rocko Brown have completed their Masters at UC Davis extending and improving elements of SHIRA on the Mokelumne and Trinity Rivers. Currently, Ann Senter and Marisa Escobar are working on PhDs extending various aspects of SHIRA on the Mokelumne. I am grateful to these and the many undergraduates and research assistants as part of Dr. Pasternack's Watershed Hydrology and Geomorphology Lab who collected the topographic field data and performed the 2D model runs used in Chapter 7.

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