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Full Citation:

Wheaton JM. 2008. Uncertainty in Morphological Sediment Budgeting of Rivers. Unpublished PhD Thesis, University of Southampton, Southampton, 412 pp.

Note About Resolution

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.

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[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.

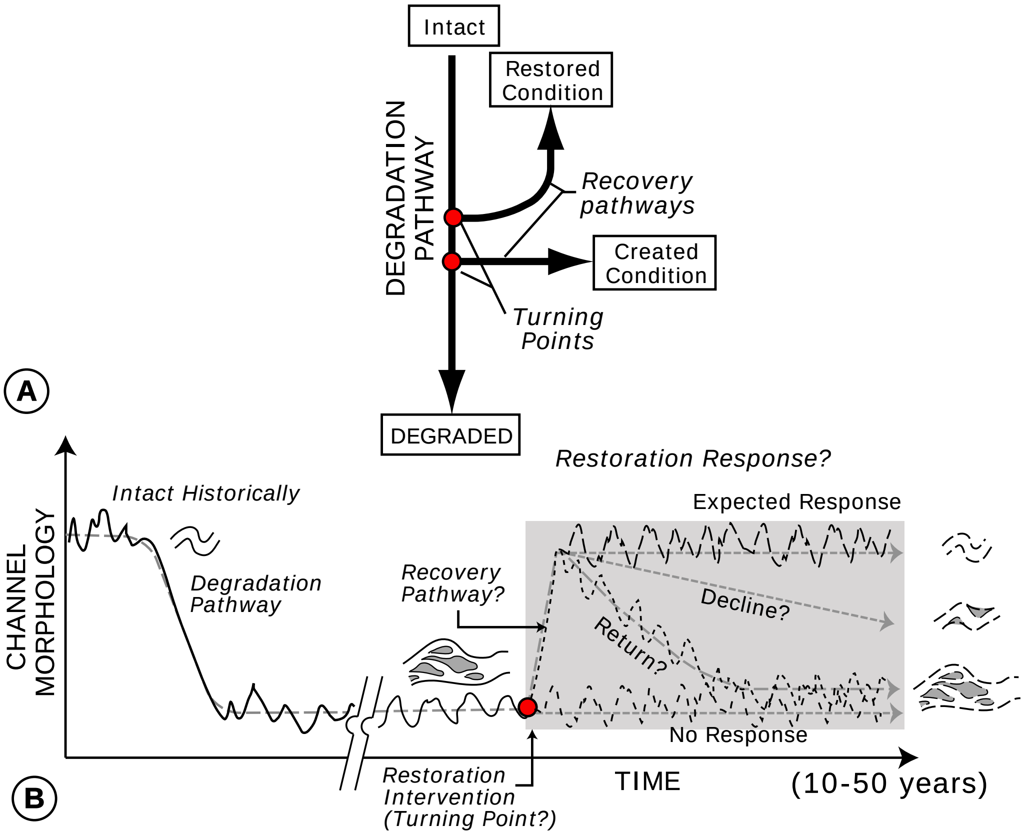

Figure 1.2: A simplified illustration of uncertainty in channel morphology response to a restoration intervention (B) in relation to a recovery diagram (A). In (A), recovery from a degradation pathway is possible through a recovery pathway to either a former condition or a created condition. In (B), 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

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[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

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[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.

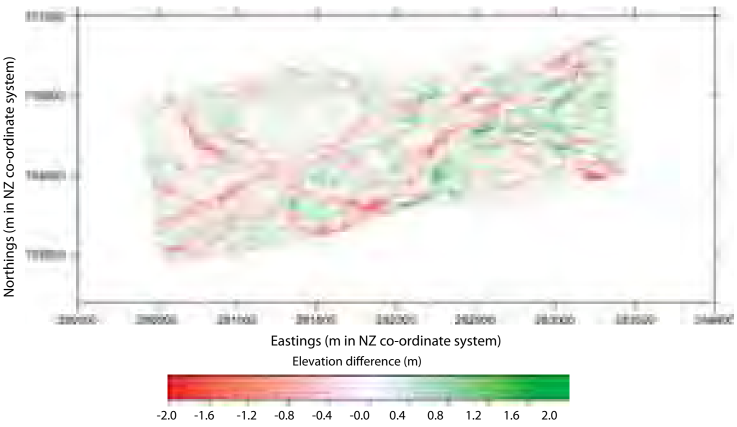

FIGURE 1.3: An example of a DoD from the Waimakariri River, South Island, New Zealand. Figure reproduced from Lane *et al.* (2003).

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

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[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.

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[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]

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[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.

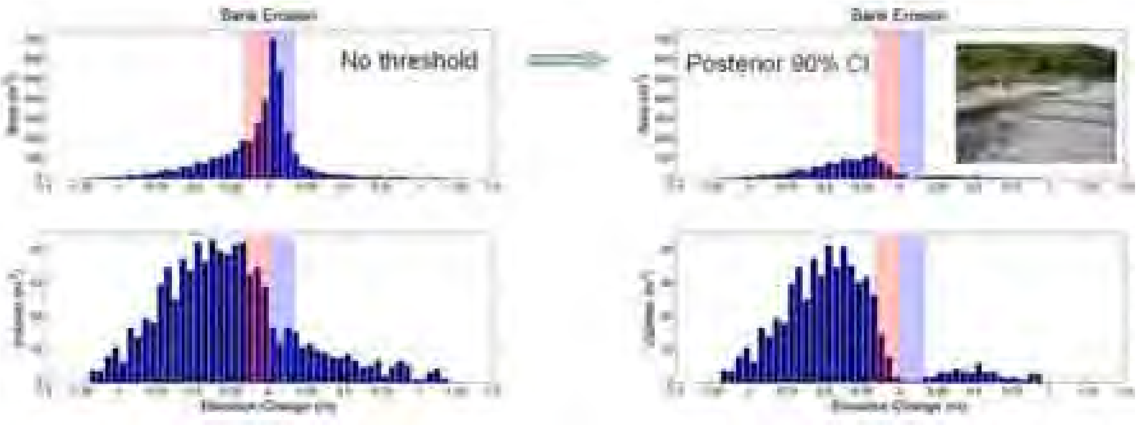

FIGURE 1.4: An example of an elevation change distribution for bank erosion derived from a DoD, with (LHS) and without (RHS) an uncertainty analysis applied. The top distributions are by area subjected to erosion, the bottom distributions are by volume. The light blue and red bands represent the portion 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.