

UNIVERSITY OF SOUTHAMPTON

The Significance of Ecohydraulic and Geomorphic Uncertainties in River Restoration

by

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Contents

Table of Contents	1
List of Figures	3
List of Tables	5
1 Scope of Uncertainties in River Restoration- Literature Review	1
1.1 Introduction:	1
1.2 River Restoration is Booming... For Now	2
1.2.1 Will River Restoration Efforts Make a Difference?	4
1.2.2 Is the River Restoration Community Ignoring Uncertainty?	5
1.3 Understanding the Scope of Uncertainty in an Environmental Management Context	6
1.3.1 A Lexicon of Uncertainty	7
1.3.2 An Existing Typology for Uncertainty	11
1.3.3 How do Knowledge and Uncertainty Relate?	14
1.4 Existing Uncertainty Tools within Environmental Management	14
1.4.1 Decision Support	16
1.4.2 Adaptive Management	18
1.4.3 Precautionary principle	20
1.5 Scientific Tools for Communicating Uncertainty in Observations and Models	21
1.5.1 Metrics of Uncertainty as Expressions of Societal Values	21
1.5.2 Communicating Uncertainty in Observations	22
1.5.2.1 Measurement Uncertainty	22
1.5.2.2 Statistical and Probabilistic Methods	23
1.5.2.3 Fuzzy Set Theory	23
1.5.3 Communicating Uncertainty in Environmental Models	25
1.5.3.1 Probabilistic Uncertainty Representation in Models	27
1.5.3.2 Bayesian Frameworks	28
1.5.3.3 Monte Carlo Models	29
1.5.3.4 Fuzzy Models	29
1.6 Revisiting River Restoration and Uncertainty	32
1.6.1 Diverse Activities Give Rise to Diverse Approaches	32
1.6.2 Motives for Restoration	32
1.6.3 Notions that Drive Restoration	34
1.6.4 Approaches to Restoration	36
1.7 Philosophical Treatments of Uncertainty	39
1.7.1 Ignore Uncertainty	39

1.7.2	Eliminate Uncertainty	41
1.7.3	Reduce Uncertainty	42
1.7.4	Cope with Uncertainty	43
1.7.5	Embrace Uncertainty	43
1.8	Conclusion: Embrace Uncertainty	45
2	Thesis Aims and Objectives	48
2.1	Research Opportunities	48
2.2	Aim and Objectives of Thesis	50
2.2.1	Objective 1: Bridge the Scale Gap	53
2.2.2	Objective 2: Quantifying Geomorphic Uncertainties	54
2.2.3	Objective 3: Demonstrate Significance With Case Study	56
2.2.4	What is not Addressed and Why	57
2.3	Thesis Organization	59
3	PhD Study Plan	62
3.1	Overall Study Plan and Timing	62
3.2	Description of Phases	63
3.2.1	Accomplishments of First Year	63
3.2.2	Wrap up Background Research	64
3.2.3	Feasibility study on Sulphur Creek	64
3.2.4	Model and code development	64
3.2.5	Implementation with Case Study(s)	65
3.2.6	Synthesis and Completion of Thesis	65
3.2.7	Submit, Revisions and Publications.	65
	Bibliography	66

List of Figures

1.1	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.	11
1.2	Typology for sources and degree of uncertainty. Adapted from Van Asselt's (2000) proposed typology for uncertainties in integrated assessment. . . .	12
1.3	Some potential relationships between knowledge and uncertainty through time. Contrary to the argument of the positivist, no unique inverse relationship between uncertainty and knowledge exists. See Section ref{TYPOLOGYSEC	15
1.4	Adaptive Management in River Restoration. From	19
1.5	Crisp versus fuzzy, representations of a temperature classification. Adapted from Klir and Yuan (1995).	24
1.6	Five Philosophical Attitudes Towards Uncertainty. The Venn diagram is meant to illustrate the overlap between contemporary attitudes towards uncertainty. Note that ignoring uncertainty, shares no overlap with contemporary attitudes towards uncertainty.	40
1.7	Reduce Uncertainty Strategy. The positivist/reductionist view of dealing with individual sources of uncertainty.	42
1.8	Cope With Uncertainty Strategy. The reductionist view of coping with individual sources of uncertainty. The end result of this strategy is always to cope with uncertainty. In terms of river management and restoration applications, applying the precautionary principle allows decisions to be made in the face of uncertainty and adaptive management allows iterative improvement.	44
1.9	Embrace Uncertainty Strategy. Framework for embracing uncertainty in decision making process. This framework relies on the	46
2.1	Premise of Reducible Ignorance in Embracing Uncertainty Framework Context. The limited knowledge within the restoration community about uncertainties is highlighted here as <i>reducible ignorance</i> , which could be reduced through further research and education. The grayed out areas are the linkages to the rest of the 'embracing uncertainty' framework (see Figure 1.9).	50
2.2	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 1.9).	52

2.3 Portions of ‘Embracing Uncertainty’ Framework Not Covered in Detail in This Thesis. The grayed out areas of the figure are those areas covered in this thesis. The highlighted areas are numbered and explained briefly in the text. Refer to Figure 1.9 for original. 58

2.4 Organization of thesis around ‘embracing uncertainty’. The color-shaded areas represent research questions and activities specifically covered in this thesis. The non-shaded areas represent the linkages of this research to existing or future components within an ‘embracing uncertainty’ in river restoration decision making process. 60

List of Tables

1.1	Comparison of the scale that river restoration projects are ‘identified and planned at’ versus ‘designed and constructed at.’ Results from an International River Restoration Survey	7
1.2	Potential synonyms of the noun ‘Uncertainty’ and the adjective ‘Uncertain.’	8
1.3	Probabilistic Uncertainty. From	10
1.4	Sources of uncertainty in an environmental management decision process structure. Adapted from	17
1.5	Influence of Uncertainties due to Limited Knowledge on Modelling. Adapted from	26
1.6	Results of some selected ISI Web of Science Searches for ‘Fuzzy’ Literature in Applications Related to River Restoration and comparison with fuzzy applications in engineering and articles in general.	30
1.7	Overlapping motives for river restoration.	33
1.8	Common notions that drive motives and guide river restoration efforts. . .	35
3.1	Thesis Phases and Their Approximate Timing	63

Chapter 1

Scope of Uncertainties in River Restoration- Literature Review

‘Any attempt to fully represent a complex issue and its numerous interlinkages with other issues in a quantitative modeling framework is doomed to failure. Nevertheless...’ - Rotmans & Van Asselt (2001).

1.1 Introduction:

Throughout the world river restoration is undertaken as a response to the exploitation and subsequent deterioration of the riverine environment (Sear 1994, Kondolf 1995b, Brookes & Shields 1996). The science and practice of river restoration are both still very much in their adolescence (Palmer et al. 1997). Yet, both have been graced with funding and support from a diverse range of interest groups, various governmental bodies, agencies and river managers alike (Sear & Darby In Review). The premise of this research is that if funding and resources are expected to be continually allocated to river restoration, it will have to be shown that river restoration is ‘working’ (see preface, Wissmar and Bisson, 2003a). However, definitions of success are subjective and vulnerable to uncertainties in the river restoration process, societal values, the fluvial system and ecosystem response to restoration management activities. Paradoxically, the uncertainties influencing river restoration projects are rarely recognised or quantified, much less reported to stakeholders or the public (Walters 1997).

The topic of uncertainties in river restoration is riddled with complexity and confusion. Indeed, uncertainty manifests itself in river restoration in many ways. As such, it is imperative to first present the rich topic of uncertainty in a broader, more generic context. With this foundation, it becomes clear how the more specific aim and objectives of this thesis fit into the diverse activities of the river restoration community. Thus, this chapter’s purpose is to unravel some ambiguities surrounding uncertainty in river restoration.

The narrative for this chapter will unfold as follows. River restoration is booming today throughout the world as demonstrated by the diverse range of restoration activities and support for them. As cautioned above, potentially significant uncertainties are rarely recognised, much less explicitly dealt with. It is speculated that these uncertainties could potentially undermine restoration efforts and eventually erode support for restoration activities altogether. This remains speculation because the restoration community has yet to demonstrate either the presumed insignificance or significance of uncertainty. Instead, the river restoration community has for the most part ignored uncertainty. The form of uncertainties faced in specific applications of river restoration are similar to those encountered in more general environmental management problems. Hence, some nomenclature and a typology for uncertainty are presented in an environmental management context to delineate the scope of uncertainty. Then existing uncertainty tools in environmental management and the sciences are reviewed, highlighting the sparse examples of explicit recognition of uncertainty in restoration where appropriate. With the broad scope of uncertainty as well as the potential and/or shortcomings of existing techniques for communicating and dealing with uncertainty already employed in environmental management evident, the chapter then returns specifically to river restoration. The tremendous diversity of river restoration in the context of uncertainties arising from restoration motives, notions and approaches are considered. It is then argued that a basic strategy for dealing with uncertainty is needed by the river restoration community that allows both the community and individual investigators or 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 provide these aims is one of embracing uncertainty. The suggestion is that uncertain modified and natural systems are best managed adaptively.

1.2 River Restoration is Booming... For Now

The rapid rise and international popularity of river restoration is both encouraging and worrisome (Kondolf 1996). Although sparse examples dating back to the 1930s exist¹, river restoration has primarily been brought up on the coat tails of an environmental awareness movement that grew out of the late 1970s (Sear 1994). The movement is an

¹The USDA Forest Service started undertaking 'stream improvement' in the 1930s with the intent of increasing salmonid production (Everset & Sedell 1984).

expression of an environmental ethic that desires more natural conditions associated with rivers (Graf 1996). It is encouraging that so much enthusiasm exists to restore rivers. Yet, it is interesting to note the societal choices between some mix of reactive restoration efforts in response to damage already done, as opposed to pro-active conservation actions to prevent further damage (Boon 1998).

The international popularity of river restoration can be illustrated in a variety of ways. Ideally, an inventory of all existing projects throughout the world would make this point obvious. Unfortunately, only a few partial national-level databases exist. Among the more comprehensive are those maintained by the River Restoration Centre (RRC)², and the US Environmental Protection Agency's (EPA) River Corridor and Wetland Restoration Database³. Numerous individual case studies of restoration are reported in both the peer-reviewed and grey literature. For example, the proceedings of a single Conference on River Restoration, held during 2000 in The Netherlands, highlights river restoration activities in 21 countries (Nijland & Cals 2000). In Denmark alone, 1068 restoration projects had been completed by Danish regional authorities by 1998 (Hansen & Iversen 1998). In the United States, Malakoff (2004) reported that by 2004 more than \$US10 Billion has been spent on more than 30,000 projects. The International River Restoration Survey⁴ launched by Wheaton, Sear, Darby & Milne (2004) also highlights some the rich international popularity of restoration activities. As of April, 2004 over 500 respondents from 34 different countries on every inhabited continent in the world participated. Among these, 46% were practitioners practicing in 16 different counties spread across Asia, Australia, Europe, the Middle East and North America. Surveyed practitioners were primarily from the United States (51%), and the United Kingdom (29%). Survey participation was sparse in South America, Asia and Africa, probably reflecting a combination of less activity and poor survey dissemination in those regions.

The popularity of river restoration is apparent in international, national, regional and local public policy that actively promotes, requires and in some cases funds river restoration efforts. This reflects an environmental ethos that has infiltrated into public policy in many of the developed nations of the world (Cairns 2002). However, its effectiveness is constrained by limited funds and scope to deal with closely related landuse issues and other socio-political goals. Internationally, the European Community Water Framework Directive (WFD, 2000) is arguably one of the most progressive examples of specific policy calling for river restoration (Jungwirth et al. 2002). Although the details of implementing river restoration projects under the WFD are left to individual member states, the WFD provides an overarching framework and mandates unparalleled in their explicit calls for the restoration of habitat across international boundaries. Under the WFD, every European Member river basin district shall have a river basin management plan outlining

²RRC Database includes over 750 projects within the United Kingdom: <http://www.therrc.co.uk>.

³USEPA River Corridor and Wetland Restoration Database includes over 600 projects throughout the United States: <http://yosemite.epa.gov/water/restorat.nsf/rpd-2a.htm>.

⁴Complete real-time results, background information and forthcoming interpretations are available on the web: http://www.geog.soton.ac.uk/users/WheatonJ/RestorationSurvey_Cover.asp.

specific objectives relating to water quantity, quality and ecological health. These objectives are required to be achieved or restoration actions underway to meet them by 2015. Numerous national level policies and directives exist throughout the world as well. In the United States, congress has passed the Wilderness Act (1964), Wild and Scenic Rivers Act (1968), Endangered Species Act (1973) and Clean Water Act (1977), which provide a confusing array of federal and state agencies with regulatory powers and funding mechanisms to require, encourage and/or initiate restoration activities. In Canada, Annable (1999) asserted that the broad sweeping requirements of the Federal Fisheries Act (DFO 1986) requiring no net loss in quality or diversity of habitat have subsequently promoted extensive river restoration activities. In Denmark, the Watercourse Act of 1982 has supported large scale river restoration efforts under visions of ecologically acceptable maintenance (Jungwirth et al. 2002). In the Netherlands, river restoration has been supported through the Nature Policy Plan, which seeks to promote ecological sustainability through restoring and maintaining connectivity of high quality habitats (Jungwirth et al. 2002). Since 1997 in Australia, the Natural Heritage Trust, a major federal government initiative, provided over \$90 million to Rivercare projects, including river rehabilitation (Brierley & Fryirs 2000).

1.2.1 Will River Restoration Efforts Make a Difference?

Despite river restoration's popularity in the developed nations of the world, the global decline of the physical and ecological integrity of rivers is difficult to overstate (Vitousek et al. 1997, Jungwirth et al. 2002). It is tempting to conclude that society has already learned the lessons from our exploitation and degradation of riverine landscapes and restoration will provide recovery from those impacts. In reality, most restoration efforts still pale in significance to actively expanding anthropogenic impacts on riverine landscapes (Tockner & Stanford 2002). Even in parts of the world where numerous river restoration efforts are underway (i.e. Europe, North America and Australia), wetlands are actively being drained and filled, rivers are still diverted and regulated, urban sprawl is encroaching into floodplains and headwaters at an alarming rate while we continue to permanently alter basin hydrology and fragment habitats (Moss 2004a, Collins et al. 2000, Mount 1995). These problems pose even larger threats in the developing nations of the world (Marmulla 2001). Over 250 new major dams become operational worldwide annually and 75 are planned for the Amazon Basin alone (Robinson et al. 2002).

Tockner & Stanford (2002) warned that the next few decades will bare witness to dramatic extinctions of aquatic and riparian species and related ecosystem services if urgent attention is not given first to preservation of floodplains and the riverine environment and second to their restoration. Although this forecast is highly uncertain and somewhat speculative, it is certainly plausible. It seems logical that preservation should be easier to achieve than restoration (Frissell et al. 1993), but there seems to be excessive confidence in our ability to restore (Rutherford et al. In Review), sometimes reducing restoration

to a mitigation measure justifying planned impacts or maintaining the status quo. Both conservation and restoration are based on the transformation of uncertain science and uncertain notions of naturalness, ecosystem integrity and physical integrity into societal goals (Graf 2001). Additionally, the good intentions of restoration projects may lead to unintended, but often foreseeable consequences. For example, undesirable ecosystem impacts can arise from dam removal projects that were intended to restore natural flow regimes (Bednarek 2001, Doyle & Harbor 2003). In summary, even if society is willing to make difficult socio-political decisions to support preservation and restoration of rivers, nothing guarantees that the desired outcomes will follow.

1.2.2 Is the River Restoration Community Ignoring Uncertainty?

Uncertainty is frequently misunderstood by the general public (Riebeek 2002), and presumably the majority of the restoration community, as something negative and undesirable (Newson & Clark In Review). A widespread misconception that science embodies certain knowledge persists in the reports of the mainstream media and views of the general public (Riebeek 2002, Clark 2002). Such misconceptions fuel expectations that science-based approaches to river restoration will yield certain and positive outcomes. Ironically, people confront uncertainties everyday without hostility and choose to routinely make decisions about the future (Pollack 2003). Similarly, river managers must make decisions about the future of rivers without absolute knowledge of their consequences (Clark 2002). Whether these decisions are made in the face of uncertainty or ignorance to it, they represent forms of dealing with uncertainty.

Given the dynamicism of rivers, it seems a statement of the obvious that the outcomes of restoration projects are uncertain. However, the restoration community seems hesitant to admit that the goals and science that restoration are founded upon are uncertain as well (Rutherford et al. In Review). Aside from indirect references to uncertainty in adaptive management programs, the river management community has largely brushed uncertainties aside (Clark 2002, Wissmar & Bisson 2003c). It is unclear whether this is a conscious or passive decision. Either way, individual decisions to ignore uncertainty can be plausibly attributed to one or more of the following:

- ignorance of uncertainty and or its significance
- the hope that uncertainty is insignificant
- an acknowledgement of uncertainty, but not knowing how to deal with
- being misinformed about uncertainty, leading to the assumption that it is insignificant
- being knowledgeable about uncertainty, but having established its insignificance

Newson & Clark (In Review) attributed the river manager's current treatment of uncertainty to a 'risk-adverse' management culture that views uncertainty as a risk, and prefers to entrench itself in 'rituals of verification' aimed at minimising liability (Moss 2004b, Power 1999). Presumably, because public perception about river restoration is generally positive, the restoration community has escaped real scrutiny over its relaxed treatment of uncertainty. However, in light of escalating restoration price-tags (Kondolf 2000a), it is unlikely that restoration will avoid political scrutiny indefinitely.

Restoration science and the restoration literature are not much further along than practitioners and decision makers. Wissmar & Bisson (2003b) asserted that 'a better understanding of variability and uncertainty is critical to the successful implementation of restoration programs for aquatic and riparian systems.' Yet, buried within a rich literature on restoration are only occasional passing mentions of uncertainty (Brookes & Shields 1996) and a handful of explicit treatments (Wissmar & Bisson 2003c, Johnson & Rinaldi 1997, Johnson & Rinaldi 1998, Johnson & Brown 2001). Like other treatments of uncertainty in the scientific literature, the emphasis typically narrows in on a specific type of uncertainty that might be reasonably articulated within a specified page limit. In order to unravel the confusion about and significance of uncertainty, a more holistic treatment of uncertainty is necessary (Van Asselt 2000, Newson & Clark In Review). Restoration is established as one important component of environmental management. It would be a shame to lose what public support already exists for restoration if political scrutiny recasts unrealistic expectations of river restoration as a 'failure' of restoration, as opposed to the inadequate consideration of uncertainty they truly stem from.

1.3 Understanding the Scope of Uncertainty in an Environmental Management Context

Increasingly, river restoration is moving away from piecemeal, one-off local projects to more strategically planned projects (Moss 2004b). Although this has not as yet resulted in a fundamental shift from projects implemented at reach and sub-reach scales to those implemented over entire catchments, it is starting to result in a shift towards planning individual projects in a catchment context or as part of larger staged schemes (Table 1.1). With this shift, river restoration really becomes a targeted activity of integrated river basin management (Downs et al. 1991, Loucks 2003), which is itself a specific application of environmental management. If we now shift our attention to the scope of uncertainty in a more generic environmental management context, the prognosis is not as bleak as within the narrower river restoration context. Explicit recognition of uncertainty and techniques for dealing with uncertainty (e.g. adaptive management, precautionary principle) are scattered throughout environmental management. Specifically, applications aimed at investigating climate change scenarios in long-term policy analysis (Lempert et al. 2003) and integrated assessment modelling (Rotmans & Van Asselt 2001) have moved beyond sim-

Activity/Scale		Catchment	Landscape	Reach	Sub-Reach
Project Planning and Site Identification		31%	23%	35%	10%
	Design and Construction	13%	13%	52%	23%

TABLE 1.1: Comparison of the scale that river restoration projects are ‘identified and planned at’ versus ‘designed and constructed at.’ Results from an International River Restoration Survey (Wheaton, Sear, Darby & Milne 2004, Wheaton, Sear & Darby 2004).

ply recognising uncertainty exists and are beginning to assess its significance and make recommendations in explicit recognition of deep uncertainty. Hence, this section steps back from river restoration to draw from the broader expertise on uncertainty first in general terms, and then as found in environmental management.

1.3.1 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 1.2). 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 (e.g. 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.

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 1.2: Potential synonyms of the noun ‘Uncertainty’ and the adjective ‘Uncertain.’

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.

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 may also 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 can potentially 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 phenomena of divergence. In a modelling context, Beven (1996a,b) suggests 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. 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

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 1.3: Probabilistic Uncertainty. From Pollack (2003).

various possible outcomes based either on mathematical calculations or the history of previous occurrences.’

Newson & Clark (In Review) 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 (In Review) described uncertainty and the related concepts of risk⁵ and ignorance in terms of knowledge of impacts and probabilities. Table 1.3 describes uncertainty measures in terms of probabilistic notions.

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 we consider a condition of irreducible ignorance as one extreme of uncertainty, it is difficult at best to estimate the degree of something we do not even know exists. Within this broad view of uncertainty, uncertainty might be considered along a continuum that reflects our ability to quantify it (Figure 1.1. 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.

⁵See risk definition on page 10.

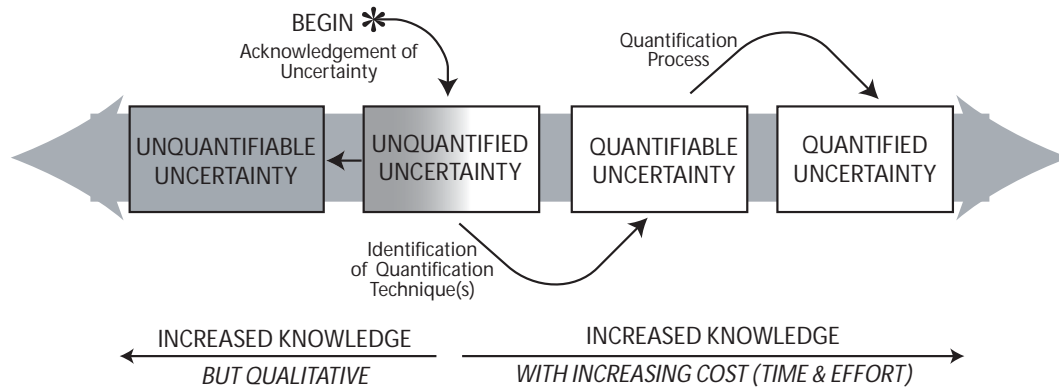


FIGURE 1.1: The Quantifiable Continuum of Uncertainty. Notice that once uncertainties are acknowledged as unquantified uncertainties, increased knowledge about the uncertainties will determine their position on the continuum.

In summary, when someone mentions uncertainty casually, it is difficult to discern whether they are referring 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.

1.3.2 An Existing Typology for Uncertainty

Since uncertainty is so hard to define, classification of uncertainty is often used (van Asselt & Rotmans 2002). The utility of any typology or classification system is ultimately dependent on its application (Kondolf 1995b, Lewin 2001). Rotmans & Van Asselt (2001) astutely pointed out, ‘there is not one overall typology that satisfactorily covers all sorts of uncertainties, but that there are many possible typologies’. In the context of this 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 other typologies in the literature because of its generic and holistic consideration of uncertainty. The typology arose out of Integrated Assessment modelling, 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 1.2). van Asselt & Rotmans (2002) provided the following helpful distinctions and references to similar terminology:

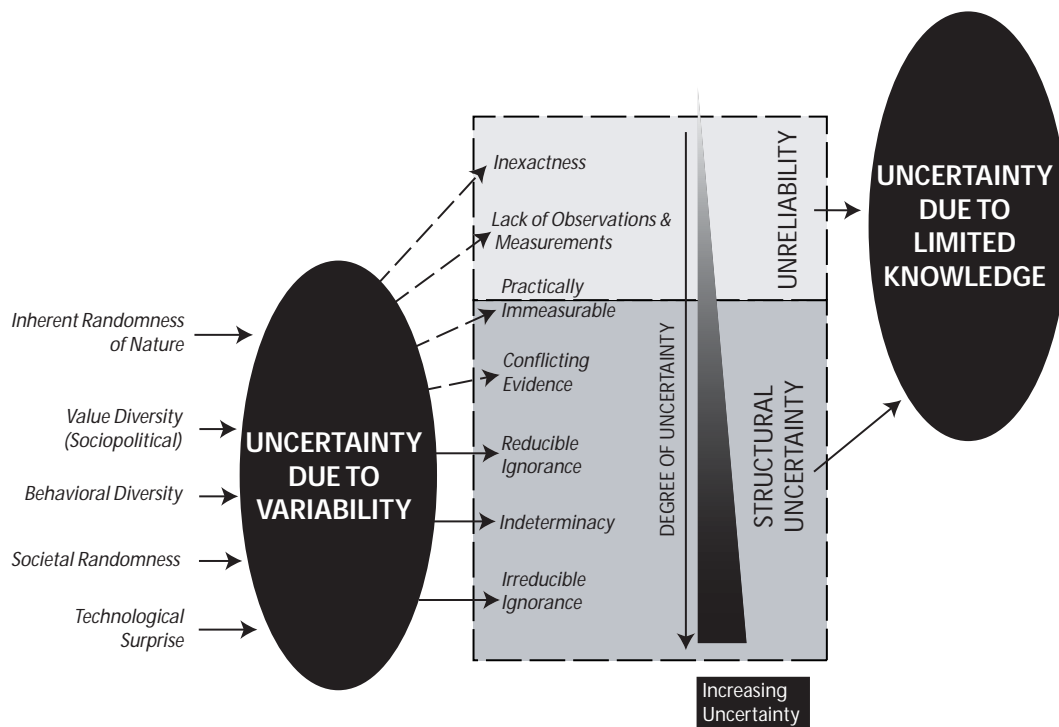


FIGURE 1.2: Typology for sources and degree of uncertainty. Adapted from Van Asselt's (2000) proposed typology for uncertainties in integrated assessment.

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) 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 management of inherently variable natural and managed systems. Knowledge about natural change and variability in ecosystems, fluvial systems and hydrologic systems is incomplete and hence contributes to uncertainty due to limited knowledge in, for example, river basin management and river restoration (Wissmar

& Bisson 2003a). Five distinct subclasses of uncertainty due to variability are proposed: inherent natural randomness, value diversity (socio-political), behavioural diversity, societal randomness, 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 (2003c). Value diversity, behavioural 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 end of the continuum 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 practise, it is recognised that the semantics of uncertainty will always be interpreted differently in different professional contexts (Newson & Clark In Review). However, within the context of this thesis the Van Asselt (2000) typology and associated meanings will be used consistently.

1.3.3 How do 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). 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.’ So, which is it? 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 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 1.3 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, we can proceed into reviews of existing tools within environmental management (see Section 1.4) and science (see Section 1.5) to communicate these uncertainties. 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).

1.4 Existing Uncertainty Tools within Environmental Management

Uncertainties in decision-making, policy-making and management stem from both scientific sources (see section 1.5) and socio-political sources (Alario & Brun 2001, Rotmans

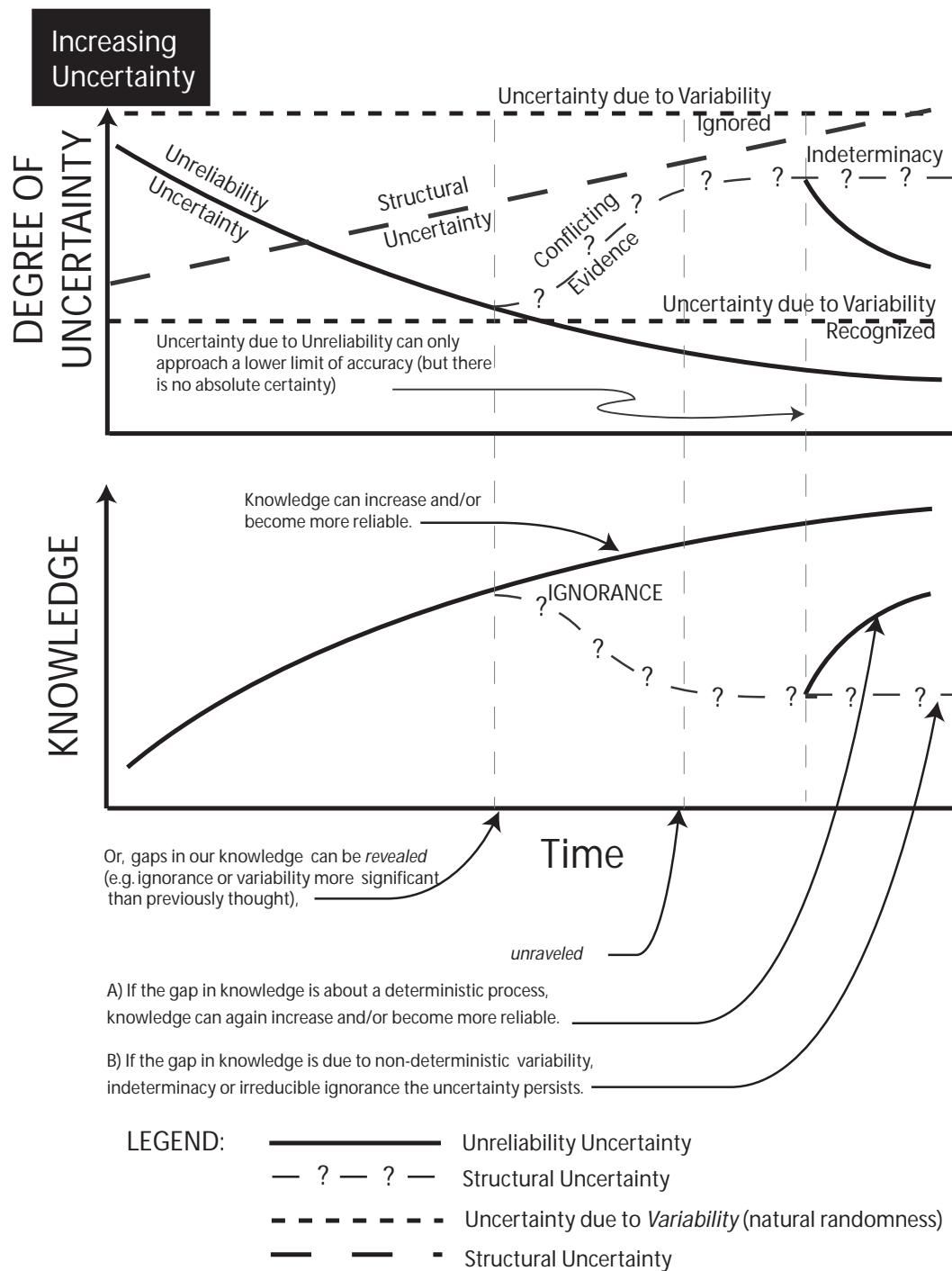


FIGURE 1.3: Some potential relationships between knowledge and uncertainty through time. Contrary to the argument of the positivist, no unique inverse relationship between uncertainty and knowledge exists. See Section ref{TYPOLGYSEC and Figure 1.2 for definitions of uncertainty types.

& Van Asselt 2001). Anderson et al. (2003) divided environmental management decision strategies into three situational components:

- ‘the decision problem itself- for example, information gaps, need for accurate information, effort required to get that information, possibility of reassessing the decision in the future’
- ‘the internal social context- for example, the decision makers’ expertise, analytical resources, accountability, social relationships and communication networks;’
- ‘the external social context- for example, societal values and goals, accountability and group membership of stakeholders, geography and time frame’

The ‘decision problem’ itself represents uncertainty sources primarily from limited knowledge and specifically unreliability uncertainties. Both the ‘internal’ and ‘external social contexts’ are primarily influenced by uncertainty due to variability (e.g. socio-political value diversity, behavioral diversity and societal randomness). Anderson et al. (2003) argued that some of the largest uncertainties in restoring rivers and catchments arise not from technical or scientific challenges, but from trying to answer the question, ‘What does society want from the ecosystem in question?’ Decision-makers may succumb to pressures from constituents and time-constraints to make judgements before adequate evidence or consideration of uncertainty is considered (Anderson 1998). However, decision-makers have always implicitly dealt with uncertainties, and Anderson et al. (2003) argued that humans are quite well adapted to making decisions about complex problems with incomplete information. The purpose of this section is to explore some of the more explicit techniques emerging for coping with uncertainty in what Anderson et al. (2003) called the ‘decision toolbox’ for environmental management. The term ‘toolbox’ hints at the growing recognition that pluralistic approaches to complex problems should provide a range of suitable tools and solutions as opposed to a single optimal one (Lempert et al. 2003, Rotmans & Van Asselt 2001).

The uncertainties encountered in the situational components described above are typically part of a decision process. Chapman & Ward (2002) outlined an environmental management decision process and the sources of uncertainties encountered during each stage (Table 1.4). Decision support systems, adaptive management, the precautionary principle are the uncertainty tools considered below, which map onto specific stages within this decision process.

1.4.1 Decision Support

Decision Support Systems (DSS) have grown out of the expectation that managers should make ‘holistic decisions that are consistent, transparent and accountable’ about highly uncertain and complex problems (Clark 2002). Or more cynically, decision support allows scientists to contribute to the decision-making process without having to actually make the decision or take liability for it. Most decision support systems are computational

Stage in Decision Process	Uncertainty About
Monitor the environment and current operations within the organisation	Completeness, veracity and accuracy of information received, meaning of information, interpretation of implications
Recognise an issue	Significance of issue, urgency, need for action
Scope the Decision	Appropriate frame of reference, scope of relevant organisation activities, who is involved, who should be involved, extent of separation from other decision issues
Determine the performance criteria	Relevant performance criteria, whose criteria, appropriate metrics, appropriate priorities and trade offs between different criteria
Identify alternative courses of action [†]	Nature of alternatives available (scope, timing, logistics involved), what is possible, level of detail required, time available to identify alternatives
Predict the outcomes of courses of action [†]	Consequences, nature of influencing factors, size of influencing factors, effects and interactions between influencing factors (variability and timing), nature and significance of assumptions made
Choose a course of action [*]	How to weigh and compare predicted outcomes
Implement the chosen alternative [*]	How alternatives will work in practice
Monitor and review performance [‡]	What to monitor, how often to monitor, when to take further action

TABLE 1.4: Sources of uncertainty in an environmental management decision process structure. Adapted from Chapman & Ward (2002). [†] Most decision support systems only provide input at these levels. ^{*} The precautionary principle is implemented here. [‡] Adaptive management starts here and feeds back through the process as necessary.

systems that allow comparison of an ensemble of decision scenarios, usually by integrating multi-disciplinary evidence and expertise and then reporting outcomes in terms of consistent metrics (Addin & Jensen 2004). Multi-Criteria Decision Analysis, a specific type of DSS, attempts to reconcile ‘imprecise goals in terms of more precise but often conflicting performance indicators’ (Levy et al. 2000). Clark & Richards (2002) cautioned that decision support tools can not make decisions for river managers, only inform their decisions.

Decision support systems have started to find their way into public policy and environmental management arenas (Levy et al. 2000, Adriaenssens et al. 2003, Reynolds et al. 2000, Lempert et al. 2003), but have only been sparsely applied to river restoration (Clark & Richards 2002). The few noteworthy exceptions tend to be academic case studies and pilot projects (e.g. Zsufa 2000; ISAB 2003). For example, Pieterse et al. (2002) built a GIS-based, integrated DSS to hypothetically guide the development of restoration programs in the River Dommel catchment on the border between the Netherlands and Belgium. They conclude that site-specific solutions throughout the catchment emerge from DSS as opposed to a single restoration strategy. In one of the few papers to offer specific techniques to deal with uncertainty in river restoration design, Johnson & Brown (2001) discussed how decision trees, fault-tree analysis and Failure Modes and Effects

Analysis (FMEA) might be used to account for the risks of project failure associated with uncertainty. The FMEA, for example, involves a systematic mapping of potential component failures within a hierarchical system and assess the effects of the associated failures on the overall function of the system. An application of FMEA to Bentley Creek Watershed in Pennsylvania by Johnson & Brown (2001) revealed the highest risk components (calculated as the product of consequence, occurrence and detection ratings) were associated with rapid channel widening and sediment deposition due to the change in cross section geometry. This led them to conclude that the most effort should be invested in developing a cross section design capable of conveying the sediment and water load without causing bank erosion. Thus, the FMEA as a DSS will tend to encourage low-risk restoration designs, which may not necessarily provide the most optimal design for project aims. However, it transparently documents the uncertainties and the decision process, while providing a means of reconciling potentially conflicting restoration goals with other constraints.

For sustainable river management in England and Wales, Clark & Richards (2002) have proposed a prototype DSS they call SURCoMES that relies on expert knowledge represented in fuzzy logic⁶ to assess the status of river banks and potential management responses. SURCoMES is an explicit attempt to cope with uncertainties arising between science, philosophy, management and logic. However, the prototype is only for the relatively simple example of river bank management and it has yet to be implemented in actual management decisions. As decision support systems become more sophisticated and common, they will likely find their way into river restoration management more frequently. However, if the results of the DSS are too technical, they may risk being misinterpreted or simply not being useful to decision makers lacking specialised training (Anderson et al. 2003).

1.4.2 Adaptive Management

Both the environmental management and river restoration literature generally support the model of adaptive management (Clark 2002, FISRWG 1998). Walters (1997) described adaptive management as ‘a structured process of learning by doing’ (see Figure 1.4). Modeling is often used to integrate interdisciplinary experience and scientific information for: a) problem clarification, b) policy screening and c) identification of knowledge gaps (Clark 2002). The key to adaptive management and its suitability to managing rivers is that its priorities are focused on ‘adjusting to changing circumstances’ and uncertainties, ‘rather than attempting to hold the system in its existing state’ (Clark 2002).

Despite the enthusiastic advocacy of adaptive management, Walters (1997) astutely highlighted four reasons why there has been relatively poor success in implementing adaptive management policies in restoration practice and river basin management: ‘1) over-reliance and faith in modelling to provide “best use” policies; 2) effective experiments are

⁶See section 1.5.2.3 for review of fuzzy logic tools.

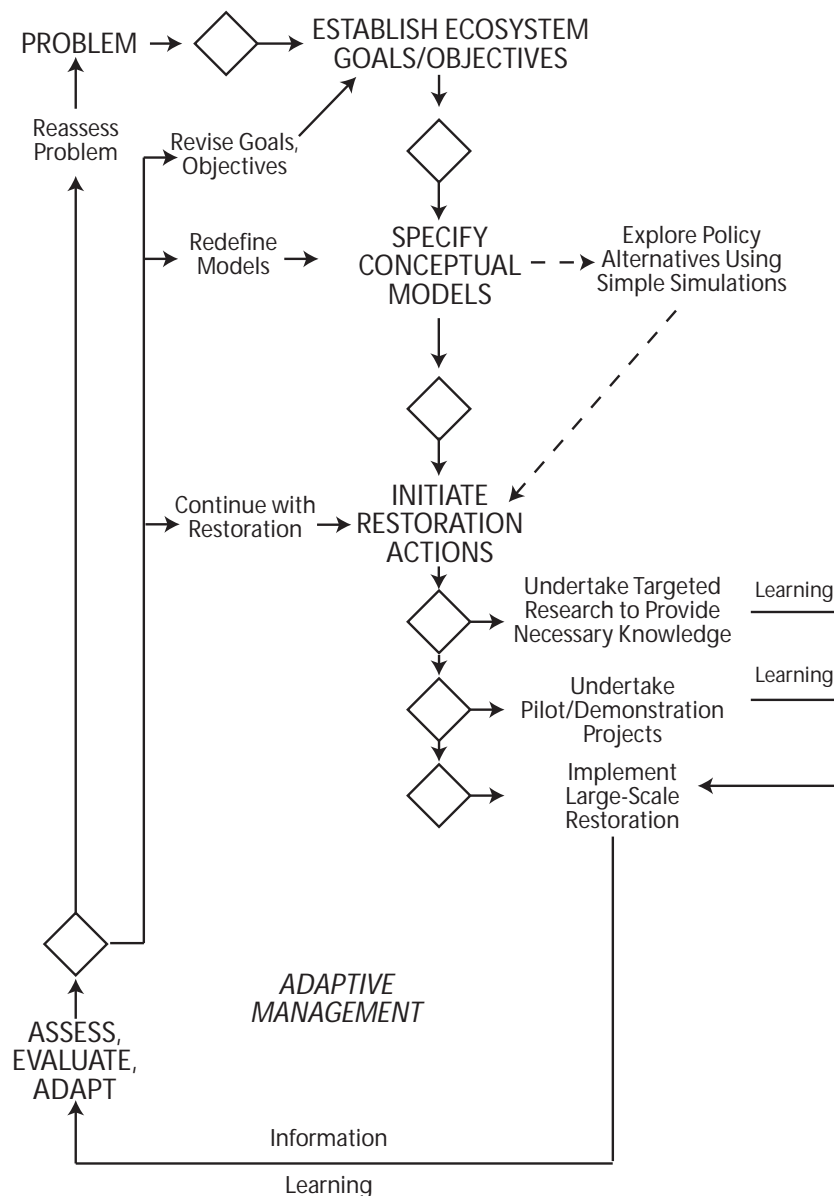


FIGURE 1.4: Adaptive Management in River Restoration. From Kondolf (2000b).

too expensive; 3) strong institutional opposition to experimental policies and breaking status-quo; and 4) deep environmental value conflicts within management.’ Clark (2002) considered these barriers as remnants of the current and historic prevailing management mind set of *predictive management*. Clark describes predictive management as focused on predicting future states and arranging management interactions to achieve desired outcomes; resulting in over-design, factors of safety and fail-safe approaches. So although the adaptive management framework is conceptually appealing, the barriers to its full adoption and success seem to be closely linked to misconceptions of uncertainty and adherence to expectation of static end goals.

1.4.3 Precautionary principle

The precautionary principle is a direct acknowledgement of scientific uncertainty and advocates decisions that act to avoid serious or irreversible potential harm. deFur & Kaszuba (2002) said that the core characteristic of the precautionary principle is ‘acting in the face of uncertainty’ even when cause-effects may not be completely established scientifically. The notion is that, even though we do not know everything we want to know⁷, we know enough to make an informed decision that perhaps errors on the side of caution. This is a stark contrast to special interests who use uncertainty as a call for inaction, typically because of concerns in implementation costs or reductions in short-term profits (deFur & Kaszuba 2002). deFur & Kaszuba (2002) outlined four basic elements of the precautionary principle:

1. ‘There is a threat of harm, either credible or known’
2. ‘The situation presents a lack of scientific certainty or evidence’
3. ‘Cause and effect relationships are not yet proven’
4. ‘There is a necessity or duty to act’

Thus uncertainties are accepted and adaptive management in the future will allow for mid-course corrections (Clark 2002).

The European Environment Agency (2001) compiled a group of historical case studies between 1896 and 2000 that illustrate opportunities where we as a society were given the opportunity to act with precaution, chose not to, and are now paying for the consequences. They use it to make the case that the precautionary principle should be a fundamental tenant of public policy. In as early as the 1970s, the precautionary principle found its way into European public policy (deFur & Kaszuba 2002). More recently, the Water Framework Directive (2000) explicitly promotes the precautionary principle:

‘As set out in Article 174 of the Treaty, the Community policy on the environment is to contribute to pursuit of the objectives of preserving, protecting and improving the quality of the environment, in prudent and rational utilisation of natural resources, and to be based on the precautionary principle and on the principles that preventive action should be taken, environmental damage should, as a priority, be rectified at source and that the polluter should pay.’

In the United States by contrast, the precautionary principle has failed to yet penetrate public policy at the federal level (deFur & Kaszuba 2002). This has not necessarily deterred the popularity of restoration projects in the United States⁸. However, it could

⁷This is an example of a structural uncertainty due to conflicting evidence, see page 13.

⁸See section 1.2 for examples of popularity of restoration projects in the U.S.

be argued that the absence of the precautionary principle in important landuse and environmental resource policies has impeded the overall effectiveness of conservation and restoration efforts.

1.5 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 river basin management, 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 treatment⁹.

1.5.1 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 we express uncertainty in the units or terms based on our 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. As scientists we may communicate to our peers or restoration practitioners technically using metrics of uncertainty that are convenient and/or conventional. However, if we are communicating uncertainty to decision makers, stakeholders and the general public, it is imperative that we express these with metrics that are easily understood and directly related to the societal goals driving the restoration. For example, Rutherford et al. (In Review) expressed their uncertainty in specifying flushing flows that would turn over a gravel bed to maintain habitat quality in

⁹In so far as they apply to the restoration of degraded river systems.

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.

1.5.2 Communicating Uncertainty in Observations

1.5.2.1 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 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 1.3.1 and guidelines for standard statistical techniques are readily available (e.g. 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 are frequently 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 is not to suggest 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 tradeoffs in measurement errors and formulae 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.

1.5.2.2 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 1.3). In general, if the PDF representation is good, accounting for uncertainty is straight forward. The problem, of course, is that complex natural processes and populations are not always necessarily well represented by PDFs.

1.5.2.3 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: $A = \{1, 2, 3\}$

The members of set A are simply 1, 2 and 3, whereas 4 or any other number is clearly not a member. 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 such 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 1.5). 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

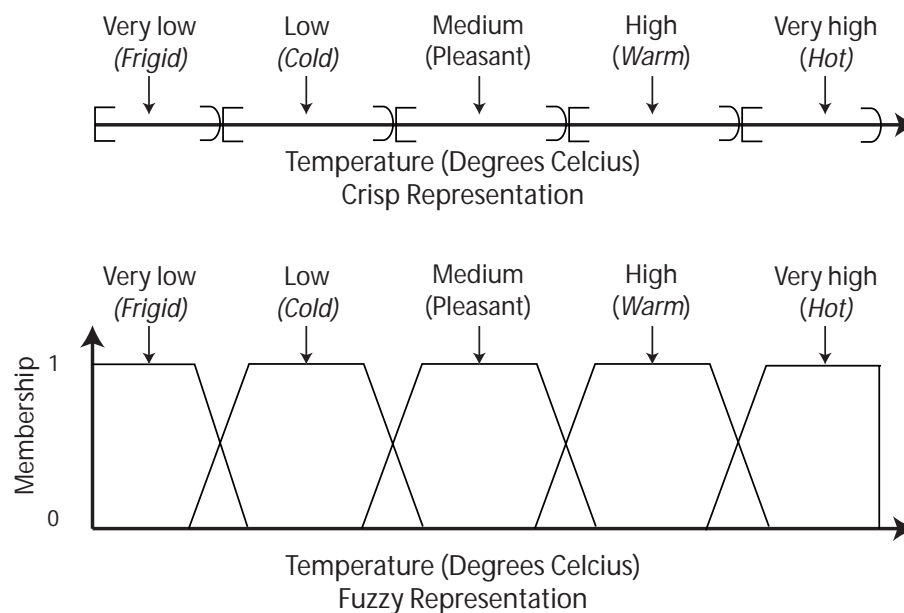


FIGURE 1.5: Crisp versus fuzzy, representations of a temperature classification. Adapted from Klir and Yuan (1995).

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 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 definition¹⁰ 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/m², whereas for a degree of belief $\alpha = 1$, the

¹⁰2703 reported over 16 bankfull definitions exist.

excess shear stress was $\tau_e = 4.2 \text{ N/m}^2$. In other words, the fuzzy representation reports its highest degree of belief as 4.2 N/m^2 , but perfectly 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 assumptions required of probabilistic or statistical representations of uncertainty.

1.5.3 Communicating Uncertainty in Environmental Models

Uncertainty in modelling 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), and are covered in later subsections. First, an overview of the sources of uncertainty in environmental models is provided.

Cao & Carling (2002a) 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 towards a position where rapid impact-modelling 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), hydrologic 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), equilibrium channel morphology models (Sear & Darby In Review) and consideration of parametric uncertainty (McIntyre et al. 2002). In a benchmark review of *structural uncertainties* in mathematical modelling of alluvial rivers, Cao and Carling (2003a & b) attribute the uncertainties in river modelling 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. (In Review) pointed out that the hydrologic, geomorphic 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.’

Type of Uncertainty	Influence on Modelling	Class of Influence
Inexactness	uncertainty in input data	technical uncertainties
Lack of Observations or Measurements	uncertain equations	methodological uncertainties
Practically Immeasurable	model structural uncertainty	methodological uncertainties
Conflicting Evidence	parameter uncertainties	technical uncertainties
Reducible Ignorance	uncertain levels of confidence	epistemological uncertainties
Indeterminacy	uncertainty about model validity	epistemological uncertainties
Irreducible Ignorance	uncertainty about appropriateness of model to address question	epistemological

TABLE 1.5: Influence of Uncertainties due to Limited Knowledge on Modelling. Adapted from van Asselt & Rotmans (2002).

In their review of Integrated Assessment Models (including atmospheric models) Rotmans & Van Asselt (2001) considered how unreliability uncertainty and structural uncertainty¹¹ influence modelling (Table 1.5). 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). Modelling 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 way as a DSS helps inform decisions, rather than making them.

Klir & Yuan (1995) pointed out that maximising model usefulness is a function of three inter-related 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 additional pa-

¹¹Recall, unreliability and structural uncertainties are types of uncertainty due to limited knowledge; see Figure 1.2, page 12.

rameters), cease to provide more valuable predictions?

1.5.3.1 Probabilistic Uncertainty Representation in Models

The majority of environmental models used in river restoration (hydrologic, hydraulic, ecohydraulic, etc.) are spatially distributed and prone to structural uncertainty in spatial averaging. In physically-based hydrologic models, for example, hydrologists are challenged with the daunting task of representing dynamic non-linear hydrologic processes in highly heterogeneous catchments through some up-scaled form of the conservation equations (Singh & Woolhiser 2002). Beven (1996b) 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 uncertainties¹², 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 hydrologic processes, the up-scaling process actually produces ordinary differential equations (as opposed to partial), hence permitting a deterministic solution. The point of this example is that, sophisticated stochastic and probabilistic techniques exist for dealing with uncertainty. However, their practicality in the context of river restoration practice is questionable as most practitioners are unlikely to understand or adopt such techniques.

Levy et al. (2000) suggested that probability models of uncertainty are frequently inappropriate to deal with uncertainty of 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

¹²Structural uncertainties here are referring to the structure of the model (i.e. which processes are represented with which equations).

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.’

Hence, under certain circumstances probabilistic representation of parameter uncertainties (technical uncertainties) may be useful in environmental management. However, due to the narrow range of problems they are appropriate for, additional techniques are needed to address the range of problems of uncertainty in river systems.

1.5.3.2 Bayesian Frameworks

Bayesian frameworks are mentioned briefly here as a subclass of the probabilistic methods discussed above. Essentially 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 for an environmental model, classical Bayesian inference is used to estimate probability distributions from *a priori* information of physically reasonable values for unknown model parameters (Balakrishnan et al. 2003). Although this approach is practical in computationally efficient environmental models, it is often cumbersome in a growing class of computationally intensive models (e.g. Numerical 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 environmental management, engineering and medicine (Addin & Jensen 2004). Varis (1997) suggested that Bayesian analysis can be extended from parameter space to the hypothesis space in decision theory by any of three dominant approaches: decision trees, influence diagrams and belief networks. Addin & Jensen (2004) provided an excellent overview of how to develop Bayesian belief networks for environmental management decision support. 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. Since the actual probabilities are

not known a subjective probability might be estimated using Bayesian inference (Bergerud & Reed 1998). 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).

1.5.3.3 Monte Carlo Models

In environmental models, Monte Carlo simulations can be used to incorporate uncertainty. In essence, a random number generator is often used to produce model parameter values within a pre-specified range (presumably only plausible parameter values). The model is then run repeatedly (typically 10^2 s to 10^5 s of times) under the scenarios defined by these randomly created parameters. Hence, the uncertainty in parameter estimates can be represented by a sensitivity analysis of the parameter influences on model results. A prime example is the GLUE (General Likelihood Uncertainty Estimation) framework developed by Beven & Binley (1992) originally for hydrologic rainfall-runoff models. The GLUE framework has been applied to hydrologic, 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 equifinality¹³ of different model structures (Beven 1996a, 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 (1996b) advocated instead disaggregating the information to reveal that multiple reasonable model structures exist, which are rather elegantly explained by our uncertainties.

1.5.3.4 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 are for ecological applications, four for environmental applications and seven for earthquake studies; whereas sixty-one references addressed uncertainty measures specifically. Several article searches under ISI Web of Science¹⁴ were performed to see if more recent article contributions might have since bridged this apparent gap (Table 1.6). Although these searches are by no means exhaustive and the results have not been exhaustively compared; they highlight a rich body of literature and well developed multidisciplinary theory to deal specifically with uncertainty dating back to the 1960s. Although fuzzy ap-

¹³See section 1.3.1, Page 1.3.1 for description of equifinality (i.e. the same result for different reasons).

¹⁴Web of science can be accessed at <http://wok.mimas.ac.uk/>.

Search Terms	Number of Matches	Comments
'fuzzy AND geomorphology'	8	Only one fluvial geomorphology
'fuzzy AND rivers'	7	All in Decision Support, GIS and Remote Sensing
'fuzzy AND watershed'	20	Primarily GIS and Remote Sensing
'fuzzy AND river management'	3	Including Clayton (2002) and Clark & Richards (2002) referenced elsewhere in this paper.
'fuzzy AND river restoration'	0	Search failed to produce the only two papers we know of on fuzzy applications to river restoration: (Johnson & Heil 1996, Schneider & Jorde 2003).
'fuzzy AND engineering'	702	
'fuzzy'	22,607	

TABLE 1.6: Results of some selected ISI Web of Science Searches for 'Fuzzy' Literature in Applications Related to River Restoration and comparison with fuzzy applications in engineering and articles in general.

plications in GIS and environmental sciences are starting to grow, they seem to be under utilized in river restoration.

A promising example of fuzzy modelling in river restoration has emerged in an eco-hydraulic 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).

In an interesting review of uncertainties 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. That is Petterman & Peters (1998) made the reasonable argument that in the appar-

ent absence of any other tools, such tools for coping with uncertainty have great 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 has yet to be adequately explored in river restoration.

1.6 Revisiting River Restoration and Uncertainty

1.6.1 Diverse Activities Give Rise to Diverse Approaches

It is difficult to generalise about the importance of uncertainty simply because restoration activities and the restoration community itself are so diverse. Among the more obvious examples of this diversity arise out of the varied physiographic regions in which restoration is practiced. The stakeholders who initiate river restoration projects include private individuals, non-governmental organisations (NGOs), governmental organisations and various collaborative combinations of the above. In addition to stakeholders, the restoration community is comprised of practitioners (who carry out the projects), decision makers (who craft and implement policy influencing restoration) and scientists (who investigate and make recommendations about restoration). No attempt is made here to list ‘all’ the uncertainties encountered throughout the restoration process as the daunting list would never be comprehensive, and is entirely perspective and project specific. For example, there is little consensus over the meaning of the term ‘river restoration’ (Sear 1994, Stockwell 2000, NAP 2002, Newson 2002). At least 30 different authors have proposed similar definitions and a number of arguably more appropriate alternatives, including rehabilitation, enhancement, improvement, creation, recovery, stabilisation, and reclamation. There is no reason to believe that any further attempts to clarify the meaning of ‘restoration’ in the literature will have any real influence. Similar to Shields, Cooper, Knight & Moore (2003), I use ‘river restoration’ loosely in this thesis as a catch-all term for a variety of management responses and activities used to address perceived problems with rivers (Kondolf 1996). Given the diversity of the restoration community, it is no wonder we are uncertain about seemingly basic definitions. Below, three other basic topics are briefly explored, which further illustrate the diversity and corresponding uncertainty in river restoration: motives for restoration, notions that drive restoration and approaches to restoration.

1.6.2 Motives for Restoration

Once river restoration projects gain momentum, it is easy to lose sight of why the projects were originally envisioned (Rutherford et al. In Review). Here, the motives for restoration are considered to represent more generalised aims than formalised and specific restoration objectives and activities (i.e. the ‘why’ instead of the ‘what’). Table 1.7 refers to nine common types of motives for river restoration (still others exist). Considerable overlap exists between many of the motives. For example, floodplain reconnection can be a type of flood control. Habitat restoration and water quality restoration are sometimes considered forms of ecosystem restoration¹⁵. In another example, water quality restoration could be viewed as sediment management or to others as aesthetic or recreational restoration.

¹⁵Yet there is considerable criticism of the narrow focus on restoration of habitat for fish as opposed to more holistic ecosystem restoration efforts (Brookes et al. 1996).

Motive:	Considerations or Common Activities:
Ecosystem Restoration	Aims to restore sustainable ecosystem communities in addition to viable individual populations. Sometimes incorporates concepts of indicator or keystone species to permit focus on those species whose needs are similar to and reflect the needs of a broader group of species (Willson & Halupka 1995).
Habitat Restoration	Undertaken when habitat quality and/or availability is identified as a factor limiting productivity (Everest & Sedell 1984). Can be intended to benefit entire ecosystems or limited to specific species and even specific lifestages (e.g. spawning or rearing for fish).
Flood Control	Increasingly flood control projects are intended to dually function as restoration projects (Brookes & Shields 1996).
Floodplain Reconnection	Physical reconnection (e.g. levee removal, raise channel bed or lower adjacent floodplain surface) and/or flow regime adjustments to induce regular inundation of the floodplain (e.g. modified dam operations, pulse flows or dam removal).
Property and Infrastructure Protection	Most commonly in response to fluvial erosion and/or mass failures of river banks but also includes scour around bridge piers. Intended to protect property, roads and structural improvements that have encroached into the floodplain beyond or dangerously close to these eroding banks (Kondolf 1996).
Sediment Management	Sediment management deals with perceived imbalances in fluvial sediment fluxes (e.g. excessive aggradation or fine sediment loads.) Typical activities include catchment erosion control, gravel traps and channel re-alignment, re-grading, re-sectioning, dredging, de-silting and shoal removal (Sear et al. 2003).
Water Quality	In developed nations, point-sources of pollution (e.g. sewage and industrial discharges) have largely been harnessed; whereas non-point sources (e.g. urban and agricultural runoff) remain major problems. (USEPA 1989). Particularly in urban and large lowland rivers, water quality motives for restoration are paramount (Ellis 1996??, Herricks 1996).
Aesthetic and Recreation	Although not central themes in scientific restoration literature, may be crucial to achieving stakeholder support (Pfadenhauer 2001) and have been undertaken throughout the world (Brookes & Sear 1996).

TABLE 1.7: Overlapping motives for river restoration.

Thus, a hierarchical organisation of restoration motives would be highly subjective and dependent on individual values and perspectives. This in itself is not necessarily problematic. However, it represents a form of communication uncertainty arising out of value diversity which is often taken for granted.

Once the motives (why to do it) for restoration are established, restoration aims fall into place, but more specific objectives (what and how to do it) require careful consideration. Many have argued that uncertainty in assessing restoration success arise from inadequate, vague and unclear restoration objectives (Jungwirth et al. 2002, Kondolf 1995a). Motives may serve well as aims (not necessarily to be achieved by an individual project); but they are insufficient to act as detailed project objectives, which in principle should be achievable. Using restoration motives carelessly as objectives produces unrealistic expectations. For example, in a recent request for proposals to fund community-based river restora-

tion projects by American Rivers and the National Oceanic and Atmospheric Association applicants were asked to demonstrate that their project:

‘1) will successfully restore anadromous fish habitat, access to existing anadromous fish habitat, or natural riverine functions; 2) is the correct approach, based on ecological, social, economic, and engineering considerations; 3) will minimise any identifiable short- or long-term negative impacts to the river system as a result of the project; 4) has had community involvement in project decision making and may have community involvement in the implementation; and 5) will have the potential for public outreach and education’

The problem with requiring an applicant to make such bold statements about individual projects is that it asserts a level of confidence in restoration simply not warranted by current science or practise and creates expectations¹⁶ restoration is unlikely to achieve (Rutherford et al. In Review). Subtly rewording such requirements to account for uncertainty could help recast river restoration to the public in a more modest tone commensurate with our abilities and uncertainties. Interestingly, these objectives are consistent with Clark’s (2000) synopsis of *Predictive Management* as the current model in river management¹⁷.

1.6.3 Notions that Drive Restoration

Underlying our motives for river restoration and the eventual specific techniques we try to use to achieve them are some very basic, yet highly uncertain notions. Since these basic notions are rarely questioned, it is important to highlight how they introduce uncertainty. Notions are also known as ‘Lietbilds’ - or target visions - and have gained widespread acceptance in the restoration literature (Kern 1992, Hughes 1995, Jungwirth et al. 2002). Notions, such as those in Table 1.8, that drive restoration strategies are frequently based on societal values and beliefs or on popular, but my no means certain, scientific paradigms (Rhoads et al. 1999, Davis & Slobodkin 2004, McDonald et al. In Press). For example, the fate of 81,000 hectares of forest land allocated for ecosystem restoration around the city of Chicago, Illinois has pitted two ‘environmental’ groups against each other based on their contrasting notions of ‘what is natural’. The divergent environmental views are essentially split between preservationists, who wish to preserve the forest land planted in the 1800s, and restorationists, who want to restore the pre-settlement (1830s) prairie and savanna (Alario & Brun 2001).

Falkenmark & Folke (2002) argued that sustainable catchment management must be based on ethical principles. They suggest that management based on scientific principles alone is primarily concerned with ‘doing the thing right’; whereas notions that drive restoration

¹⁶This is fundamentally a communication uncertainty resulting from socio-political value diversity; see Figure 1.2, page 12.

¹⁷See Section 1.4 on adaptive management alternatives, page 19.

Notion:	Example(s) of Notion
What is Natural?	
Nature is in Equilibrium	‘the equilibrium between sediment supply and available transport capacity.’- (Soar & Thorne 2001); ‘landforms can be considered as either a stage in a cycle of erosion or as a system in dynamic equilibrium.’ - (Schumm & Lichty 1965)
Nature is in flux	‘Restored ecosystems are those in which the rates and types of disturbance do not exceed the capacity of the system to respond to them.’- (Hruby 2003).
Nature Constant	‘confidence on global stability; there are no limitations to development’ - (Levy et al. 2000).
Nature Balanced	‘the environment is forgiving of most shocks, but large perturbations can knock ecological variables into new regions of the landscape.’ - (Levy et al. 2000).
Nature Ephemeral	‘the environment can not safely tolerate human modifications’ - (Levy et al. 2000).
Nature Resilient	‘ecosystems are adaptive, evolutionary, and self organising... ecological systems often thrive under conditions of high variability’ - (Levy et al. 2000).
Physical Integrity	
Physical Integrity	‘Physical Integrity for rivers refers to a set of active fluvial processes and landforms wherein channel, floodplains, sediments, and overall spatial configuration maintain a dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values. Rivers possess physical integrity when their processes and forms maintain active connections with each other in the present hydrologic regime.’- (Graf 2001)
Alluvial River Attributes	Several commonly known concepts that govern how alluvial channels work have been compiled into a set of ‘attributes’ for alluvial river integrity (Trush et al. 2000).
Ecological Integrity	
Ecological Integrity	‘maintenance of all internal and external processes and attributes interacting with the environment in such a way that the biotic community corresponds to the natural state of the type-specific aquatic habitat, according to the principles of self-regulation, resilience and resistance.’- (Angermeier & Karr 1994)
High Biodiversity = Ecological Integrity	Natural systems foster biodiversity and artificial systems are homogenized and dominated by invasive species (Ward et al. 2002, Lister 1998).
Morphological Diversity = Biological Diversity	Newson (2002) did not dispute the abundance of evidence supporting the linkages between channel dynamics and biodiversity, but criticises the lack of direct collaboration between geomorphologists and ecologists to substantiate the links in river management: ‘the mantra “morphological diversity = biodiversity” currently remains an act of faith.’
What is Sustainable?	
Sustainability	According to Cairns (2003), the notion of sustainability is based on ‘the assumption that humankind has the right to alter the planet so that human life can inhabit Earth indefinitely.’
Geomorphic Sustainability	‘sustainability encompasses the notion of self-regulation of spontaneous functions (e.g. sediment deposition, colonisation and succession of vegetation) with minimal intervention and no adverse impact on the future aquatic environment whilst maintaining the functions of the channel demanded by society (flood control, navigation etc.).’- (Sear 1996)

TABLE 1.8: Common notions that drive motives and guide river restoration efforts.

strategies are actually driven by ‘doing the right thing.’ It is a presumption that good ethical practice generally translates into good biological practice (Pister 2001). Hence notions are vague ideas, perhaps based on scientific knowledge, but primarily supported by ethical beliefs and societal values. The restoration literature is rarely explicit in distinguishing the notions it advocates from the science used to support it.

Phillip Williams (p. comm.) asserts that ‘rigour’ in restoration planning should start with development of an explicit conceptual model transparently describing our notions of how the river system functions¹⁸. Such a conceptual model should identify both the historical context and the present day limitations (i.e. uncertainties). Wheaton, Pasternack & Merz (2004a) argued that numerous conceptual models in the scientific literature already exist and can be borrowed or modified to formulate a site or basin specific conceptual model as the basis for restoration. Yet, Rutherford et al. (In Review) described three levels in restoration from which epistemological uncertainties emerge: ‘1) the validity of the conceptual model’; 2) ‘whether the proposed intervention results in the planned geomorphic change’; and 3) ‘whether the change is sustainable.’ Rutherford et al. (In Review) then cautioned that the validity of the conceptual model is the source of the ‘most uncertainty.’ Returning to Phillip William’s concept of rigour in planning, he argues restoration objectives should then be based on an understanding of how the conceptual model interacts and responds to various societal motives (NRC 1992). Based on the specific objectives, a measurable set of indicators and target levels can be selected (Smeets & Weterings 1999, Doyle et al. 2000, Levy et al. 2000, Merkle & Kaupenjohann 2000). Finally, a comparison of predicted indicator responses to restoration intervention versus inaction should be used to decide whether restoration is appropriate. Although available science may be used to inform the steps leading up to this decision, the interpretations and decision whether or not to proceed with restoration is ultimately a political one (Alario & Brun 2001).

1.6.4 Approaches to Restoration

The propagation of uncertainties in motives and notions ultimately influences the selection of an approach to restoration. Generally, river restoration projects consist of three components: 1) planning, 2) implementation and 3) evaluation. The diversity of approaches available to implement these components reflect the varied types of restoration projects and settings they are used in. Approaches are generally thorough outlines and guides to restoration whereas strategies provide key considerations and tactics. A plethora of restoration approaches and strategies have been formalised in both the peer-reviewed and grey literature (Wheaton, Pasternack & Merz 2004a). Examples range from generalised approaches for stream restoration (e.g. NRC, 1992; FISRWG, 1998; Koehn et al., 2001;

¹⁸In principle, the process of ‘rigour’ in restoration planning still follows the generic environmental management decision process of Table 1.4, page 17. In essence what Phillip Williams, a seasoned practitioner, describes is an informal DSS (see section 1.4.1, page 16).

Jungwirth et al., 2002; RRC, 2002) to more specific strategies incorporating: fluvial geomorphology (e.g. Sear, 1994; Brookes and Sear, 1996; Gilvear, 1999; Kondolf, 2000a), ecosystem theory (e.g. Stanford et al., 1996; Richards et al., 2002), hydraulic engineering (e.g. Shields, 1996) and detailed design procedures (e.g. Miller et al., 2001; Shields et al., 2003b; Wheaton et al., 2004b). Most of the approaches have parallels in structure and ideology (Wheaton, Pasternack & Merz 2004a).

Popular labels used to describe restoration approaches include holistic, science-based, integrated and multi-disciplinary (e.g. Hildn, 2000; Jungwirth et al., 2002; Wissmar and Bisson, 2003a). Since most approaches purport or aim to be all of these (Wheaton, Pasternack & Merz 2004a), and the converse of each is perceived as negative, there is little value in discriminating approaches on these grounds. However, the components (i.e. planning, implementation and monitoring) of most approaches can be differentiated using three descriptive metrics that are frequently employed in the restoration literature: 1) the scale of restoration; 2) form-based versus process-based; and 3) active versus passive. These descriptive metrics can provide insight into the types of uncertainties encountered and expectations placed on restoration projects during planning, implementation and monitoring.

Over the past ten years, approaches in the literature almost unanimously call for catchment scale planning in restoration¹⁹. However, confusion arises over whether this means: A) Restore the entire catchment; B) Use watershed assessments to nest reach scale restoration in a catchment context (Brookes & Shields 1996, Bohn & Kershner 2002, Walker et al. 2002) or C) Undertake a range of management and restoration activities across various spatial scales but nested within a catchment context (Frissell et al. 1993, Roni et al. 2002). Ecosystem degradation has often taken place over many decades or centuries and extends across landscape, catchment and regional scales (Palmer et al. 1997). Restoring an entire catchment is rarely financially, politically or physically possible over short time scales commensurate with most restoration activities (Brookes & Shields 1996). Even those who call for ecological restoration of the entire catchment (e.g. Frissell et al., 1993), actually advocate achieving this through a range of targeted activities at various spatial and temporal scales. Restoration of entire catchments include planning restrictions, preventive and conservation-minded landuse policies, erosion control, improved agricultural management practices, road removal and re-vegetation; most of which implicitly occur over time scales longer than that of an individual restoration project.

Most of the restoration literature also points towards consensus that a 'process-based' approach is superior to a 'form-based' one (Wheaton, Pasternack & Merz 2004a). Much of the form versus process debate simplifies down to the difficulty and/or appropriateness in selecting an analogue or reference condition. The frequently referenced 'Lietbilds' or target visions (Kern 1992), and the popular Rosgen approach to restoration (Malakoff 2004, Rosgen 1996) both rely heavily on analogues. McDonald et al. (In Press) referred to

¹⁹See also Table 1.1, page 7.

analogues or reference conditions as ‘templates.’ Jungwirth et al. (2002) suggested that at least three methods for selecting analogue or reference conditions exist:

1. Select an existing reference site with ‘desirable’ conditions (location substitution?).
2. Select a historical reference condition for the site of interest on the basis of historical analysis (time for space substitution?).
3. Create a reference condition on the basis of theoretical models (either conceptual or mathematical).

In referring to these analogue conditions, does one then mimic the desired form or the desired process? This seems to be the point of departure for opinions within the restoration literature. Some will argue that any mimicking of reference conditions is a form-based approach (McDonald et al. In Press). Still others suggest that so-long as ample consideration of sustaining processes and desired functions is made, the use of analogue conditions can be process-based (Palmer et al. 1997, Wheaton, Pasternack & Merz 2004a). Although the exact interpretations are themselves uncertain and will continue to spur debate over semantics, most concur that consideration of sustaining processes is fundamental (Wheaton, Sear, Darby & Milne 2004).

Fundamental methodological disagreements arise in the restoration literature with respect to passive versus active approaches to river restoration (Wissmar & Beschta 1998, Edmonds et al. 2003). I refer to active approaches as those which involve direct structural modification to the river, its floodplain or infrastructure therein (e.g. channel realignment, levee removal, instream habitat structures). By contrast, passive approaches are those that ‘rely on the river to do the work’ (e.g. flow augmentation, landuse change, managing non-point sources of pollution, buffer-strips) (Wissmar & Beschta 1998). Using a ‘process-based’ approach can make intuitive sense for passive approaches to restoration. For example, providing flow releases from a reservoir to mimic a natural hydrograph and encourage mobilization and reorganization of sediments, may restore the processes that ‘allow the river to do the work’ (Stanford et al. 1996, Trush et al. 2000). However, active approaches are considered favourable when natural or passive recovery may take an unacceptably long time (Montgomery & Bolton 2003). The choice of a passive versus active approach will depend very much on the specific social, political, economic and environmental context of individual river basins (Wissmar et al. 2003), as well as the extent to which initial conditions matter. Wheaton, Pasternack & Merz (2004b) suggested that in some spawning habitat rehabilitation contexts, it may be appropriate to employ passive approaches like gravel augmentation in conjunction with active approaches like spawning bed enhancement to kickstart recovery. Ultimately, all these choices are fueled by an uncertain conceptual understanding of the system²⁰ and logical ideas about how best to proceed with restoration. Rutherford et al. (In Review) suggested the amount of uncertainty decision-makers need to accept down to how much time and money is available to spend

²⁰See uncertainty in conceptual models, page 17.

trying to reduce it. Given these inherent uncertainties, adaptive management is well suited to allow practitioners and decision-makers to make a decision in the face of uncertainty, and adjust that decision as time and new challenges unfold (Clark 2002, Lister 1998).

1.7 Philosophical Treatments of Uncertainty

So is all this uncertainty bad? By this point, it should be clear that uncertainty in river restoration is a ubiquitous fact of life (Graf et al. In Review). 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 In Review). 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 1.2, one 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 implications; 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 1.6.

Each of these philosophies is reviewed in the remaining subsections and linked to current attitudes within different segments of the river restoration community.

1.7.1 Ignore Uncertainty

I have already argued that the current restoration community has tended to passively ignore uncertainty²¹ and proposed possible explanations as to why this may be the case. For example, managers, policy- and decision-makers are fearful of admitting uncertainties, as the public might see their uncertainty as a sign of weakness (Levy et al. 2000, Clark 2002). Graf et al. (In Review) proposed that:

‘the researcher has two essential options: either ignore the uncertainty and hope that it is not debilitating, or accept the uncertainty and use it a feature of the research’

However prevalent the first option may be in the restoration community, the premise of this thesis is that it is unethical to assume that the uncertainty is insignificant. There

²¹See Section 1.2.2.

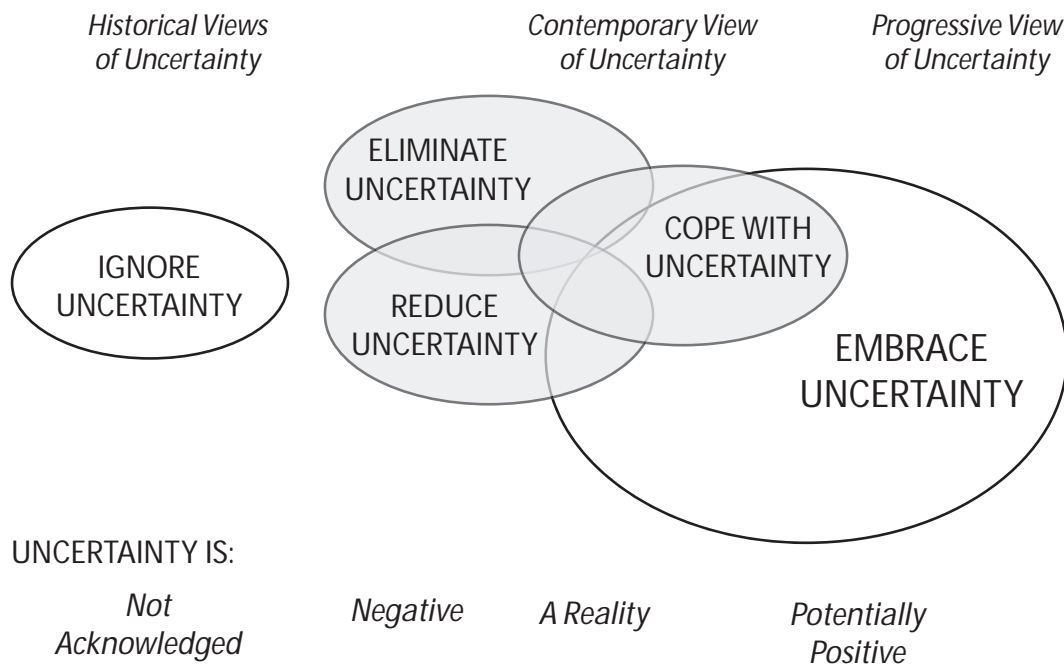


FIGURE 1.6: Five Philosophical Attitudes Towards Uncertainty. The Venn diagram is meant to illustrate the overlap between contemporary attitudes towards uncertainty. Note that ignoring uncertainty, shares no overlap with contemporary attitudes towards uncertainty.

is an increasing recognition in environmental management that the ethical and social dimensions are the primary drivers, with scientific and technical dimensions playing a secondary role (Falkenmark & Folke 2002, Lister 1998)²². Thus, an emerging challenge the restoration community is faced with is combining these dimensions to ‘do the right thing right.’

Now that public support exists for river restoration, so too does the expectation²³ that the problems river restoration addresses are well understood. As was demonstrated in Section 1.6, the problems *are* reasonably well understood, but there are numerous uncertainties in the details. Aside from basic, and potentially reducible, communication uncertainties we simply do not know the significance of the vast majority of uncertainties associated with restoration. Admittedly, specific examples of uncertainties in restoration may indeed be insignificant. However, to assume insignificance on both ethical and technical grounds without establishing it first could backfire on the restoration community and cost them their jobs. The more problematic expectation is that restoration ‘will work.’ What exactly is meant by ‘will work?’

²²Recall the the development of notions in Section 1.8, and the distinction of Falkenmark & Folke (2002) between technical concerns (e.g. ‘doing the thing right’) and ethical concerns (e.g. ‘doing the right thing’).

²³See Section 1.3.1 for relationship between expectation and uncertainty

1.7.2 Eliminate Uncertainty

The positivist view of the world has fueled much of the scientific progress through the 19th and 20th centuries on the notion that uncertainty is bad, absolute knowledge is good, and we must strive to eliminate uncertainty (Klir & Yuan 1995, Priddy 1999, van Asselt & Rotmans 2002). This fosters an unnecessarily narrow view of uncertainty as subsumed entirely within the realm of science. van Asselt & Rotmans (2002) argued this view grew out of the ‘Enlightenment Period’ or ‘Age of Reason’ of the 17th and 18th centuries where science was to be ‘the provider of certainty.’ Further to this endeavour, many scientists assumed that unique causal laws exist for all natural phenomena and ignored the possibilities of indeterminacy and equifinality (Wilson 2001). Many physical scientists still subscribe to a ‘positivist’ view (Harman 1998), implicitly associating uncertainty with an inability to quantify the environment, rather than acknowledging a limited understanding about the environment itself (Klir & Yuan 1995).

Whether specific types of uncertainty can be eliminated depends on one’s interpretation of semantics. There is no doubt that under the holistic view of uncertainty advocated in this chapter²⁴ uncertainty cannot be completely eliminated. Pollack (2003) suggested that ‘uncertainty is always with us and can never be fully eliminated’. However the suggestion of some authors (e.g. Knight, 1921) is that some types of uncertainty can be transformed into related concepts (e.g. error, expectation, reliability, risk) with the help of mathematical constructs and knowledge gained from historical inference. Through this transformation, uncertainty of a specific type (i.e. uncertainty for which a valid basis for classification exists) in a sense might be ‘eliminated.’ Such a transformation represents an improved understanding of uncertainty, but does not truly ‘eliminate’ it.

With technological progress has come the expectation of greater predictive power. Priddy (1999) suggested, ‘the strictest standard of truth in science is that of predictability.’ Although intuitively no one expects prediction to be completely free of uncertainty, the notion that uncertainty can be eliminated is latent in the mainstream media (Riebeek 2002). Pollack (2003) argues that scientists are accustomed to dealing with uncertainty explicitly, but the general public’s familiarity with uncertainty is implicit and often confused. Hence, decision-makers’ perceptions that admission of uncertainties to the public are a sign of weakness may promote an attitude of eliminating uncertainty (Clark 2002). Jamieson (1996) suggested that particularly with respect to decisions about increased environmental protections, the ‘rhetorical role of uncertainty claims’ are frequently used to suggest no action should be taken until uncertainty is eliminated. Hence, it is concluded that attempts to eliminate uncertainty are misleading and founded on ignorance of the principles of uncertainty.

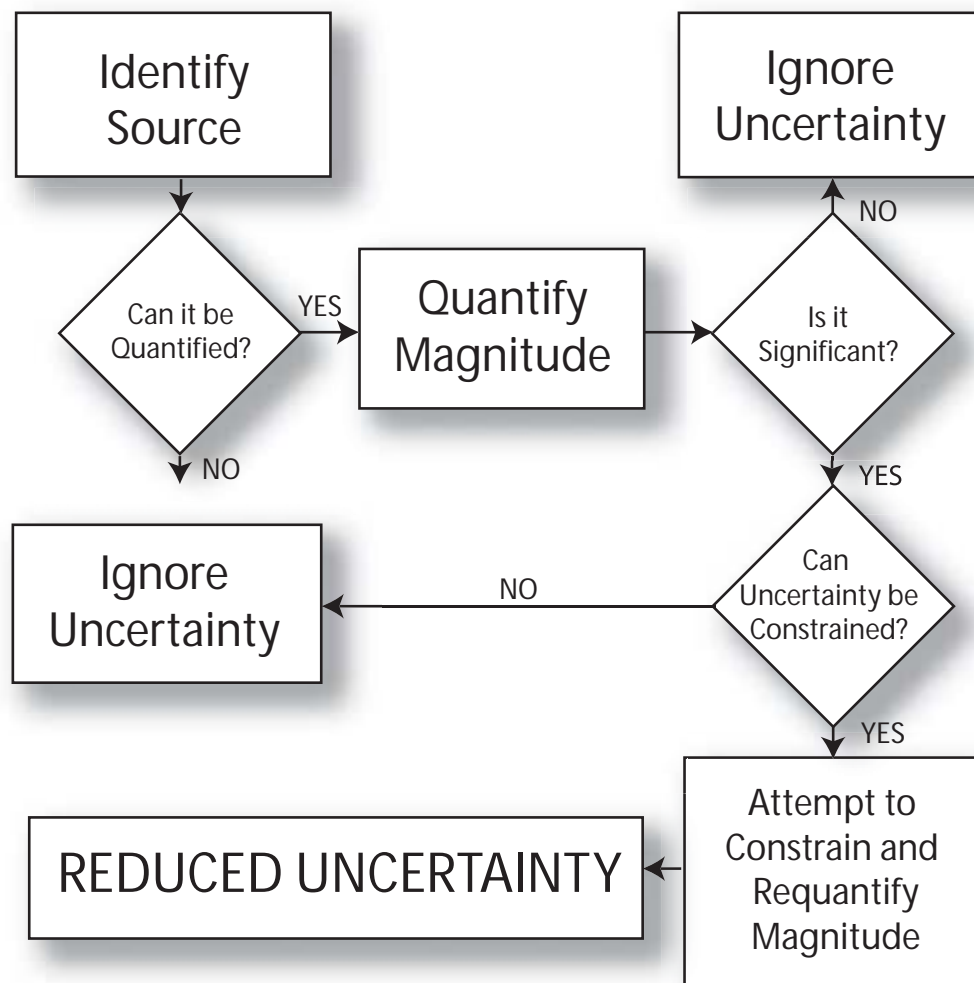


FIGURE 1.7: Reduce Uncertainty Strategy. The positivist/reductionist view of dealing with individual sources of uncertainty.

1.7.3 Reduce Uncertainty

A more pragmatic view of uncertainty seeks to reduce, rather than eliminate, those specific elements that are perceived as problematic (positivist view). Such an approach views uncertainty as a negative fact of life that should be reduced or avoided wherever possible (Klir & Yuan 1995). Figure 1.7 represents this approach to uncertainty diagrammatically. Notice that with regards to reducing uncertainty, the key questions are in order: can it be quantified, is it significant and can it be constrained? So long as the answer is ‘yes’ to all these questions, uncertainty might be reduced. However, if the opposite is true, uncertainty is simply ignored. Jamieson (1996) described this notion as follows:

‘uncertainty is treated as a fixed quantity of which there is more or less. When uncertainty is involved, science is the agent whose job it is to reduce it. On this

²⁴See Sections 1.3.1 & 1.3.2 for holistic view of uncertainty.

view, when uncertainty has been reduced sufficiently (whatever that means), research findings should be communicated. The social world is reduced to a passive public waiting for scientists to deliver their findings.’

Nonetheless, this view is persistent in much of the physical sciences literature (e.g. Samuels et al., 2003). If we are to move beyond uncertainty as an ambiguous buzzword that will forever plague scientists and decision-makers, a broader view of uncertainty as information is appropriate (Newson & Clark In Review).

1.7.4 Cope with Uncertainty

Coping or living with uncertainty represents a more proactive, and arguably progressive, view of dealing with uncertainty than either elimination or reduction. Figure 1.8 shows that this approach explicitly recognises that, regardless of the significance of uncertainty and our ability/inability to quantify or constrain it, we are always forced to cope with it. Even if the uncertainty is insignificant and coped with by ignoring it, this is a significant improvement over ignorance to uncertainty. Especially within the hydrologic and atmospheric modelling literature, uncertainty is actively recognised and specific methods to cope with it are continually being proposed (e.g. Beven, 1996a; Beven, 1996b; Werritty, 2002; Osidele et al., 2003).

1.7.5 Embrace Uncertainty

Despite the apparent advantages of efforts to cope with or reduce uncertainty over eliminating it, all the preceding philosophies still fundamentally view uncertainty as a negative thing. Several authors have departed from a purely negative view of uncertainty towards a more progressive view of embracing uncertainty (Newson & Clark In Review, ?). 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 modelling 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)²⁵, decision makers are faced with what Lempert et al. (2003) referred to

²⁵Which are precisely the time scales that the restoration literature has been suggesting the restoration community needs to move towards (see Section 1.1).

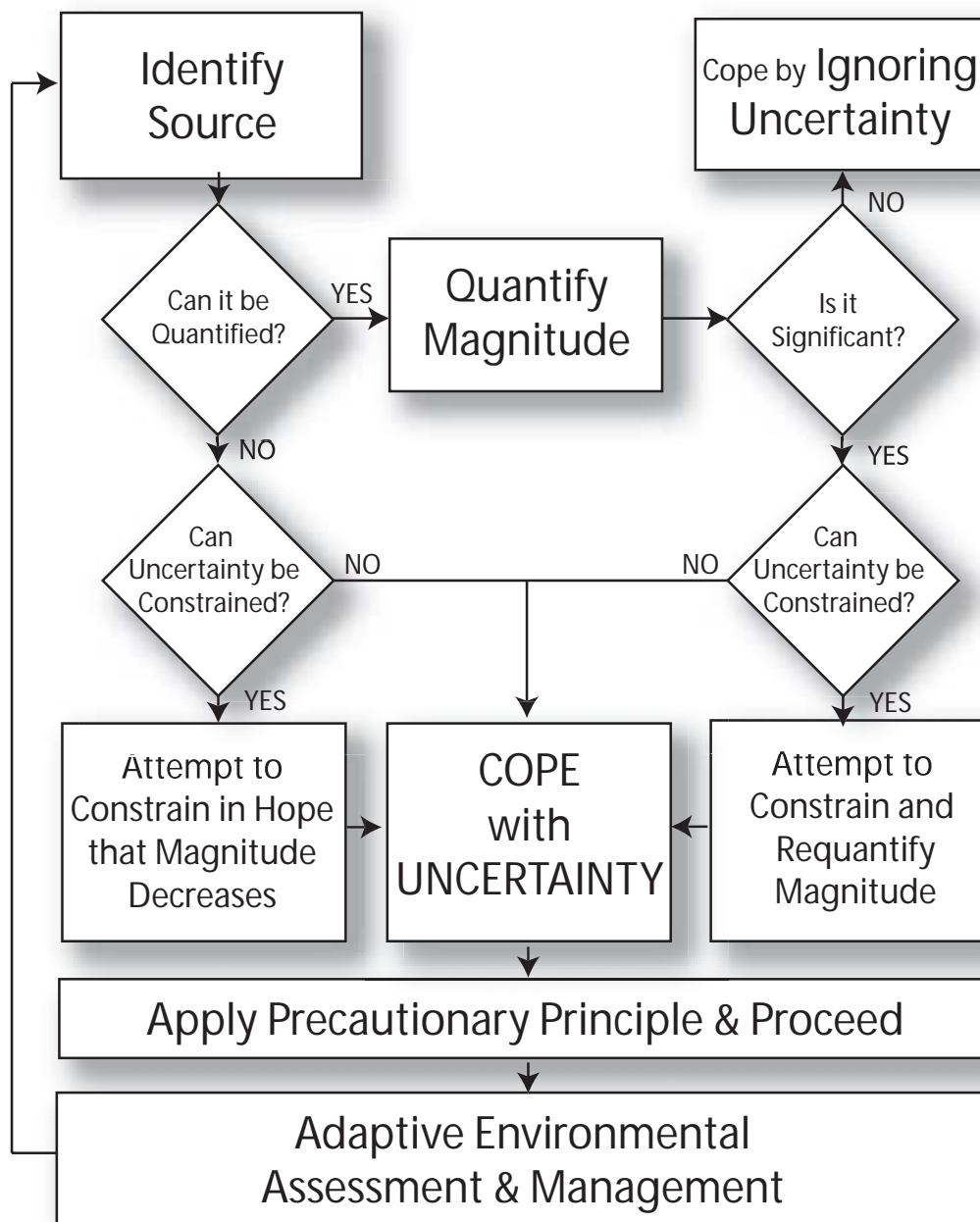


FIGURE 1.8: Cope With Uncertainty Strategy. The reductionist view of coping with individual sources of uncertainty. The end result of this strategy is always to cope with uncertainty. In terms of river management and restoration applications, applying the precautionary principle allows decisions to be made in the face of uncertainty and adaptive management allows iterative improvement.

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. I have argued throughout this chapter 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. In Review).

In Figure 1.9, I attempt to synthesise the notions of embracing uncertainty in the context of the Van Asselt (2000) typology. 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 diverse²⁶ 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 Newson & Clark (In Review), 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

1.8 Conclusion: Embrace Uncertainty

In this chapter a very broad, and potentially overwhelming, picture of uncertainty in river restoration and environmental management has been painted. This was done to unravel the ambiguities around uncertainty in restoration and recast them as useful pieces of information. A typology for discriminating uncertainty was reviewed that allows one

²⁶See Section 1.6 for demonstration of this variability specifically in river restoration.

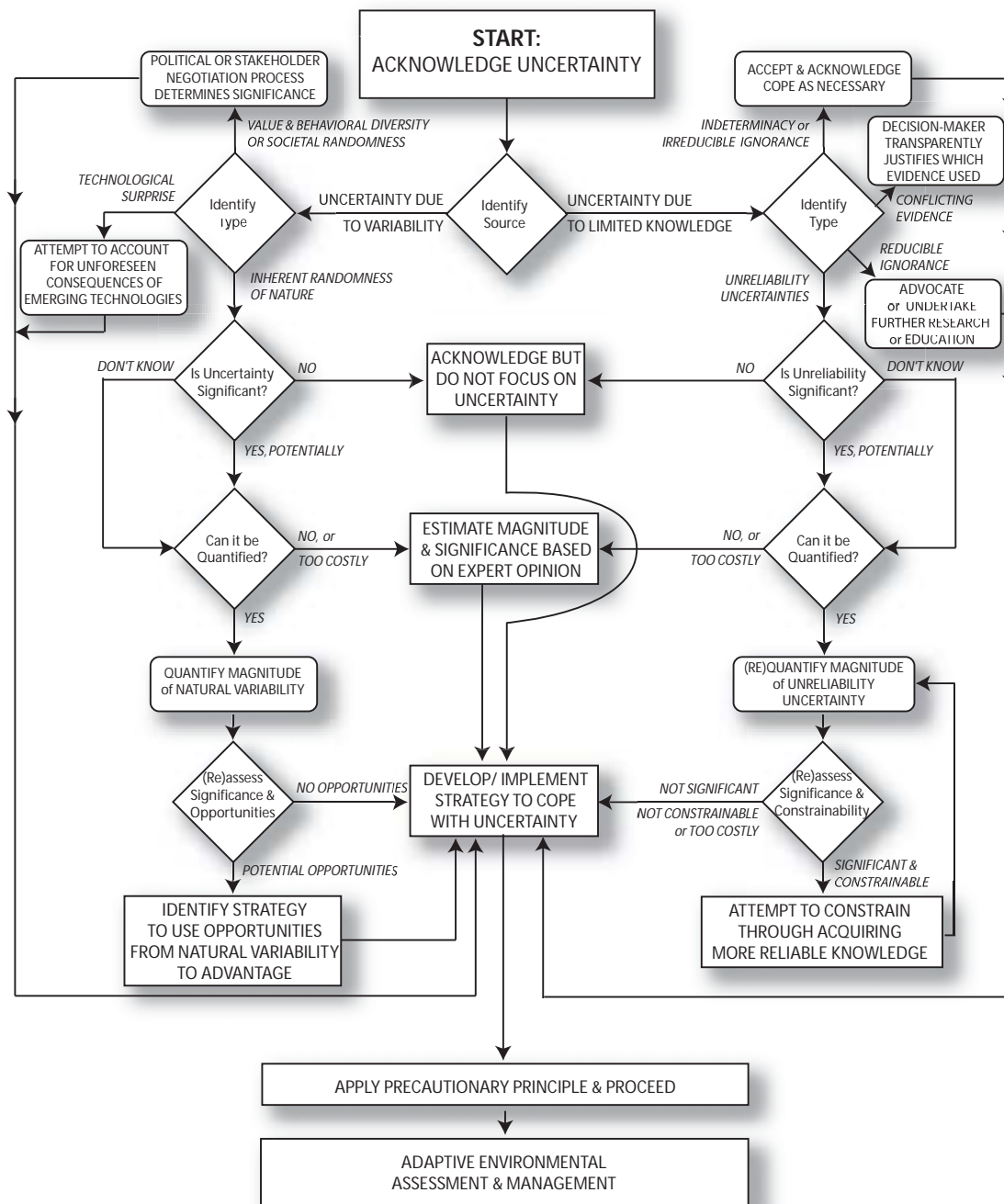


FIGURE 1.9: Embrace Uncertainty Strategy. Framework for embracing uncertainty in decision making process. This framework relies on the Van Asselt (2000) typology of uncertainty.

to separate uncertainties that can lead to unforeseen and undesirable consequences from uncertainties that lead to potentially welcome surprises. Many of the uncertainties surrounding restoration motives, notions and approaches described are most seriously manifested as communication uncertainties. That is, instead of being expressed simply as uncertainties due to limited knowledge, they are ignored and miscommunicated through the restoration process in a manner that prevents transparent decision making under public and political scrutiny. The consequences of this could be a loss of support for river restoration altogether, which combined with failed conservation efforts could be a devastating blow for riverine ecosystems. The significance of the plethora of other uncertainties alluded to is largely situation-specific and, to date, unexplored.

This is a critical point to distinguish between the types of uncertainty traditional scientific research may be able to better understand and possibly address, from those which are the result of a decision making process. The two are clearly intermingled and the latter may be studied successfully in social science, policy-analysis and decision support contexts (e.g. Moss 2004, Clark and Richards 2002). Five philosophical strategies for dealing with uncertainty ranging from the status quo of *ignoring uncertainty* to the advocated *embracing uncertainty* were reviewed. Traditional scientific research 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, from the suggestions and examples in the more general environmental management literature, I conclude that *embracing uncertainty* could also help transcend the scientific research and decision making boundaries in river restoration. Thus, when I focus in on a specific restoration motive in a specific setting, the (Van Asselt 2000) typology and *embracing uncertainty* framework will allow the exploration of the significance of scientific uncertainties with explicit links to the more general challenges faced in river restoration and environmental management.

Chapter 2

Thesis Aims and Objectives

2.1 Research Opportunities

From the intermingled reviews of restoration science, restoration practice and restoration policy undertaken in chapter one, uncertainties were demonstrated to be ubiquitous in river restoration. It is acknowledged that perhaps the largest uncertainties arise from vague policy-directives and limited funding; both stemming from the inherently uncertain political process (Wheaton et al. In Review). Uncertainty in scientific knowledge and research are frequently used to defend the status-quo (Clark 2002), and can act to exacerbate political uncertainties. Although the omnipresence of uncertainties in river restoration or any decision-making, management, design and or construction process is easy to demonstrate, the significance of uncertainty is something that has hardly been explored.

A logical way to deal with uncertainties in river restoration would be to develop and adopt new approaches and strategies to deal with uncertainty. Indeed the restoration literature is already rich with a plethora of restoration approaches geared towards specific restoration motives (Wheaton, Pasternack & Merz 2004a)¹, yet few are tooled to address uncertainty explicitly. Adaptive management and the precautionary principle do exactly this, and actually could dovetail nicely with many restoration approaches already proposed². Thus, specific tools for dealing with uncertainty could be employed modularly within new and existing approaches as they are developed. Although further approaches for specific restoration motives may be warranted, they are not necessary to deal generally with uncertainties in river restoration. From a policy research perspective, there are interesting opportunities to explore the lag-times between science, policy and practice as well as the communication barriers between scientists, policy-makers, practitioners and the public. From a more fundamental perspective, perhaps proposing ways to deal with

¹See section 1.6.4 for summary of types of river restoration approaches.

²See section 3.2.1 for review of adaptive management and precautionary principle.

uncertainty in river restoration presupposes that the uncertainties are indeed significant. Are they?

Recall my claims that the omnipresence of uncertainties in restoration are easy to demonstrate and that the restoration community has largely ignored uncertainty³. If these claims are both true, does this suggest that uncertainty is therefore insignificant with respect to restoration outcomes? In other words, has the collective wisdom of the river restoration community consciously chosen to ignore uncertainty because it has already concluded that its influence on restoration outcomes is negligible? After a review of the scholarly literature on river restoration (Chapter One), over a dozen key-informant interviews and analysis of over 500 responses to an International River Restoration Survey (Wheaton, Sear, Darby & Milne 2004, Wheaton et al. In Prep, Wheaton, Sear & Darby 2004), there is no clear evidence that a) the relative significance or insignificance of numerous uncertainties in restoration has been established; or b) that the decision to ignore uncertainty has been a conscious one. This does not necessarily suggest that every individual in the restoration community is ignorant to uncertainty or ignorant to different ways of dealing with it. However, it supports the notion that the restoration community should at a minimum explore the implications of continuing to ignore uncertainty. For clarity, the corollary premise is that simply ignoring uncertainty without considering its potential significance could a) minimally, foster unrealistic expectations; or b) lead to the emergence of unforeseen consequences worse than the status quo; or c) in the worse instances lead to complete failure of restoration efforts; and d) a longer term lack of support for restoration.

Different segments of the restoration community may seek to explore the significance or insignificance of specific types and sources of uncertainty in different ways. For example, policy-scientists may investigate the ramifications of failing to transparently communicate scientific uncertainties that restoration and conservation policy is based on to the public. Practitioners may be interested in how uncertainties in their underlying assumptions could influence eventual project outcomes⁴. Stakeholders may consider how uncertainties in the motives for river restoration could produce unforeseen consequences or benefits⁵. Physical and biological scientists may consider how uncertainties in theories and the tools we produce based on those theories (e.g. conceptual and mathematical models) might change the outcomes of restoration for better or worse. Most likely, such studies would reveal specific as opposed to general conclusions about the significance/insignificance of uncertainty. That is, the significance of the uncertainty is likely to be highly context-specific and based on historical and spatial contingencies (Phillips 2001, Phillips 2003). Thus, a wide array of potential research opportunities into specific aspects of the significance of uncertainty to river restoration exist.

The purpose of this chapter is to justify the aim and objectives of the thesis and explain the rationale behind the thesis organization. Given the richness, diversity and complicated

³See section 1.2.2 for evidence that restoration community is ignoring uncertainty.

⁴Underlying assumptions are considered notions and reviewed in section 1.8.

⁵The motives that drive river restoration are reviewed in section 1.7

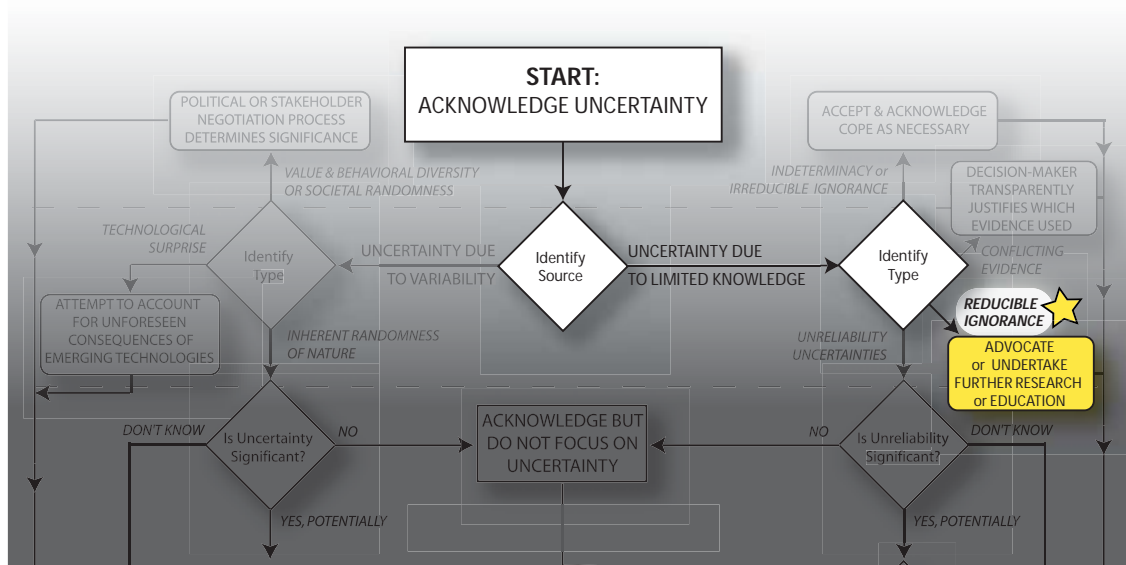


FIGURE 2.1: Premise of Reducible Ignorance in Embracing Uncertainty Framework Context. The limited knowledge within the restoration community about uncertainties is highlighted here as *reducible ignorance*, which could be reduced through further research and education. The grayed out areas are the linkages to the rest of the ‘embracing uncertainty’ framework (see Figure 1.9).

nature of uncertainties in river restoration, it is helpful to keep track of any specific research into this area within a broader conceptual framework for uncertainty. In Chapter One, I concluded that the most reasonable philosophical framework to do this within was the ‘embracing uncertainties’ framework (see Figure 1.9). I organized the framework around the Van Asselt (2000) typology of uncertainty, thereby explicitly segregating how different sources of uncertainty are to be handled in different ways. Throughout this chapter, I will use this framework to contextualize the types of uncertainties addressed. For example, the primary research need that has emerged out of Chapter One is the need to establish the significance or insignificance of uncertainties in river restoration. In Figure 2.1 this need is illustrated as an uncertainty due to limited knowledge that I consider to be *reducible ignorance*. The framework suggests that this is an uncertainty that could be reduced simply by acquiring more knowledge about uncertainties in general. Thus, the framework itself provides a justification for this research.

2.2 Aim and Objectives of Thesis

With a framework for understanding uncertainty in place and a broad overview of river restoration and environmental management complete, two decisions have to be made to study the significance of uncertainties in river restoration. First, a decision regarding what restoration perspective(s) to view the significance of these uncertainties through is necessary. From section 1.7, it is clear that restoration is done for a broad variety of

motives. In-channel habitat restoration for fish will be focused on due to its widespread popularity in practice (Brookes et al. 1996, Kondolf 2000b, Wheaton, Sear, Darby & Milne 2004), the importance of fish to society (Lackey 1997, Ormerod 2003), the ecological relevance of fish as keystone and indicator species (Willson & Halupka 1995) and the fundamental role of hydrologic, hydraulic and geomorphic processes in shaping physical habitat for fish (Montgomery & Bolton 2003). Furthermore, using in-channel habitat as a thematic exemplar allows me to build off of my previous research on spawning habitat for salmonids (Wheaton 2003). The growing field of ecohydraulics is the dominant perspective from which in-channel fish habitat is usually studied. Numerical hydrodynamic models of varying degrees of sophistication (1D, 2D and 3D) are used to drive fish habitat suitability models and quantify the availability of habitat (Hardy 1998). However, it is through field-based observations that fish utilization and ultimately habitat preferences are typically determined (Knapp & Vredenburg 1996). Owing primarily to logistical constraints, the ecohydraulic perspective is often focused between the reach and patch spatial scales (Poff 2004).

Second, a decision about which types of uncertainties to focus attention on must be made⁶. The primary uncertainties of interest in this thesis are those associated with geomorphic changes. These physical changes to the fluvial landscape are an expression of the system dynamics and disturbances, and in turn exert a fundamental control on ecosystem health (Ward et al. 2002, Stanford et al. 1996). A rich body of literature in this field that Poff (2004) called ‘hydroecology’ has produced numerous conceptual models emphasizing the importance of hydrogeomorphic dynamics and disturbances to maintaining biodiverse and self-sustaining riverine ecosystems (Montgomery & Bolton 2003, Ward & Tockner 2001, Levy et al. 2000). Hydroecology tends to emphasize larger spatial and temporal scales than ecohydraulics (Clifford et al. In Review). From a strictly geomorphic perspective, a solid conceptual foundation exists towards understanding geomorphic changes across these scales (Downs & Gregory 1993, Church 2002). However, a host of spatial and historical contingencies, representing *uncertainties due to natural variability* (Star 1 in Figure 2.2), complicate the application of these conceptual models to individual rivers. Methods to quantify these geomorphic changes directly are fundamentally limited by *unreliability uncertainties*⁷ associated with field observations (Kirkby 1996). Numerical models that attempt to predict geomorphic changes are even more uncertain owing in part to the *inherent natural variability*⁸ 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 geomorphic changes to expect in the context of river restoration is strongly contingent on both *uncertainties due to variability* and *limited knowledge*.

⁶See later section 2.2.4 for a more detailed explanation of the uncertainties not included in the thesis aims and objectives.

⁷Namely, *inexactness, lack of observations and practically immeasurable* types of uncertainties (Star 2 in Figure 2.2).

⁸See Star 1 in Figure 2.2.

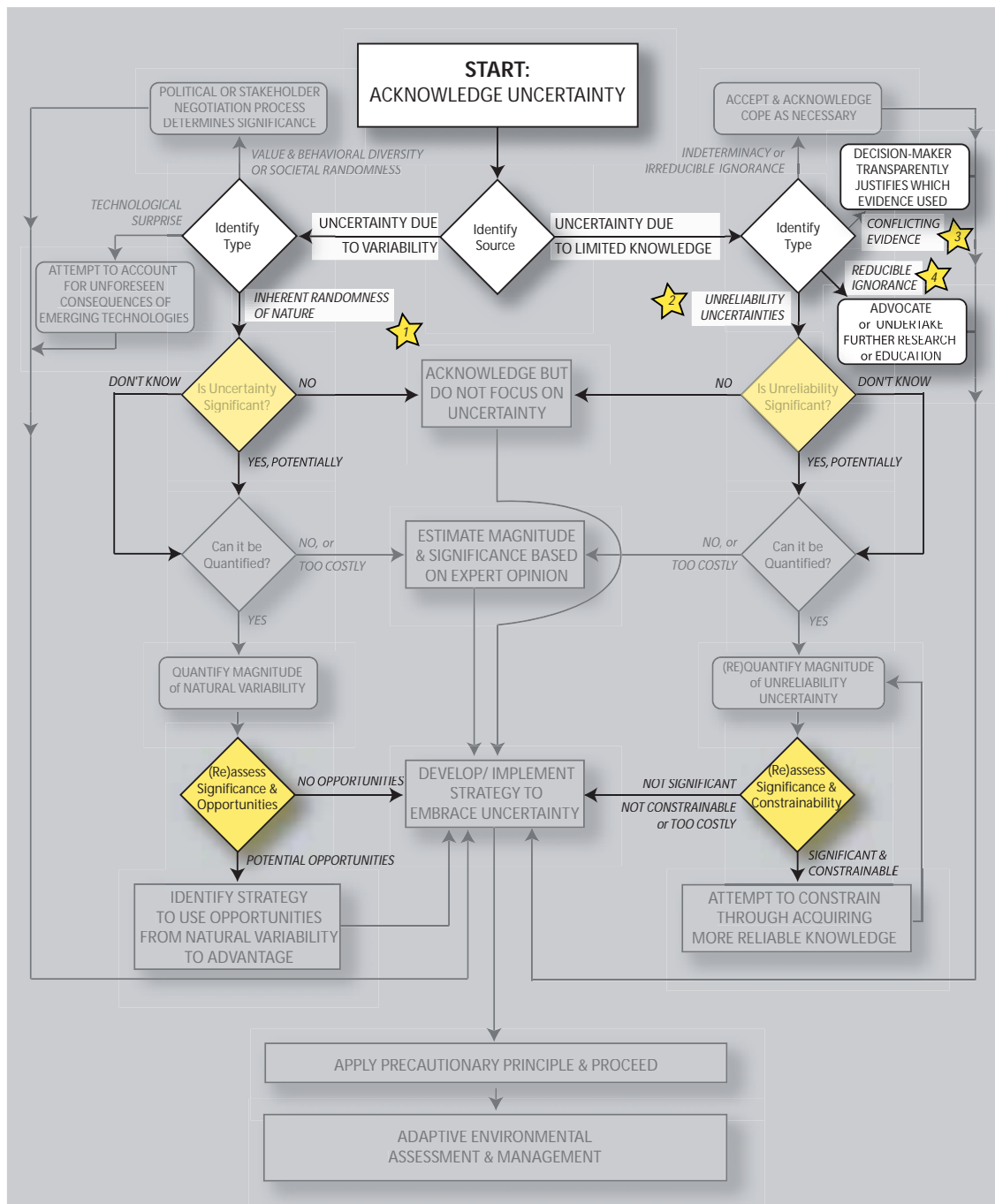


FIGURE 2.2: Aim and Uncertainties Addressed in this Thesis. The aim of assessing the significance of uncertainty is highlighted in yellow within the ‘embracing uncertainty’ framework. The types of uncertainties addressed are labeled with numbered stars one through four, and referenced in the text. The rest of the framework is grayed out (see Figure 1.9).

The aim of this thesis is to demonstrate the significance or insignificance of uncertainty about geomorphic change and its influence on fish habitat restoration. Thus, this is not a question of trying to predict geomorphic changes with certainty. It is instead a question of trying to identify a range of plausible geomorphic changes under various circumstances, and then assessing what impact or benefit those changes could bring to fish in terms of habitat. Three objectives of this thesis are intended to support the above aim in terms of topical research interests and contemporary restoration community challenges:

1. Attempt to bridge the emerging scale gap in river restoration.
2. Identify techniques for quantifying geomorphic uncertainties.
3. Using (a) case study(s), demonstrate the actual significance or insignificance of geomorphic uncertainties in terms of fish habitat metrics.

The specific types of uncertainties addressed within this aim are highlighted with stars in Figure 2.2. The primary question of the significance of those uncertainties is highlighted with yellow in the ‘embracing uncertainty’ framework (Figure 2.2). The following subsections describe the objectives and how they will be explored in more detail, as well as highlighting the uncertainties not included in the aim or objectives.

2.2.1 Objective 1: Bridge the Scale Gap

As mentioned in section 1.6.4, the river restoration community is trying to move towards more holistic, longer term, catchment scale restoration (Moss 2004b). This is in contrast to restoration practice which has tended to be focused at the reach-scale and can rarely conjure up support for monitoring efforts that last in excess of five years (Wheaton, Sear, Darby & Milne 2004). Hence, a scale gap exists. To a certain extent, the debate between passive restoration (facilitating longer term recovery) versus active restoration intervention (for immediate results) illustrates at least a temporal scale gap as well⁹. Interestingly, the ecohydraulic and hydroecology disciplines also map out on different ends of the spatial scale spectrum (Clifford et al. In Review, Poff 2004). That is ecohydraulics is well suited to analyzing physical habitat at the scale a fish experiences it across reach scales and over short (10^0 to 10^1 years) time scales; whereas hydroecology tends to look at much coarser spatial scales across a catchment with longer term (10^1 to 10^2 years) hydrologic records. One might question which end of the spatial-temporal spectrum is most appropriate for restoration of fish habitat. Actually, there exists a hierarchical interaction of processes across these scales (Roni et al. 2002), which make ecohydraulic versus hydroecology analyses and active versus passive restoration approaches highly complementary with one another (Wheaton, Pasternack & Merz 2004b). Poff (2004) describes the need

⁹See section 1.6.4 for further discussion.

to transcend the gap between ecohydrology and hydroecology not to establish the better of the two, but to recognize the importance of each.

Conceptually, the argument to bridge the scale gap is very pleasing. However, practically speaking there are some logical reasons why this has not already happened. Bigger picture, large-scale studies (hydroecology) tend to require simplifications and generalizations that support more qualitative analyses. Such techniques are essential for looking at whole systems or populations, but do not have adequate resolution to resolve finer scale phenomena. Contrast this with more quantitative, reductionist approaches of ecohydraulics (the merger of biologists and engineers), in which computational limitations and the resolution of field data collection limit the upscaling of these approaches. Interestingly, although ecohydraulics is quite interested in the substrates and morphologies of rivers, to date geomorphic dynamics (changes) are usually ignored. The emphasis is on establishing relationships between fish utilization or preference and measureable physical variables (velocities, depths and substrate). Where dynamics are modeled explicitly, it is usually only the hydrodynamics (i.e. using a hydrograph instead of constant discharge) under a fixed-bed (non changing) assumption. This is not so much a criticism of the ecohydraulic approach, but rather a constraint of the modelling tools they typically employ.

So, how does one tease more resolution out of the coarse-scale conceptual information while upscaling the more detailed fine-scale calculations? In this thesis, an attempt to transcend the scale gap will be made by using a cellular automaton (CA) class of model capable of working at the catchment scale but at a fine spatial resolution similar to that used in ecohydraulic studies. Most numerical models used in ecohydraulics work by solving a system of governing partial differential equations iteratively. That is, a guess is made about the model solution and this guess is calculated in each computational node or cell to see that the system of equations is solved correctly. This process is repeated until an approximate solution is converged upon. The CA model gets around the computational demands and limitations of numerical codes by using simpler equations or rules that are solved deterministically at each grid cell and influence only their neighboring cells directly. My intention is to acquire a solution from the CA model at the catchment scale that is 'good enough' to drive a finescale ecohydraulic fish habitat suitability model.

2.2.2 Objective 2: Quantifying Geomorphic Uncertainties

To quantify uncertainties about geomorphic change it is essential to first look at metrics of geomorphic change. The change can be signalled through a variety of morphometric and hydraulic geometry metrics (Knighton 1998). However, to calculate the change directly between two points in time a simple difference of the topographic surface before and after (known as DEM differencing or the morphometric approach), will be required (Brasington et al. 2000, Lane & Chandler 2003).

Next, before quantifying uncertainties about geomorphic changes, the controls and causes

of geomorphic changes need to be considered. This can be done conceptually at first, but ultimately it would be desirable to predictively model these changes based on a physically-based understanding of the processes. The landscape evolution model CAESAR allows us to do just this (Coulthard 1999, Coulthard et al. 1998)¹⁰. Unlike most landscape evolution models, CAESAR is capable of modeling entire catchments with fine grid resolutions (10^0 to 10^1 meters), small time steps that vary according to the rate of geomorphological change (10^{-3} to 10^2 seconds), and over long time periods (10^1 to 10^3 years). This is made possible through some creative routing and computational algorithms in the rule-based cellular automaton model that simply are not possible in numerical computational fluid dynamic (CFD) models (Coulthard 1999).

With a means of measuring geomorphic changes from either observations or simulations, and a process-based understanding of the mechanisms for those changes, we can begin to consider the uncertainties in each. Beginning with our observations, a host of uncertainties exist, primarily due to *unreliability uncertainties* in our measurements and *structural uncertainties* in the surface representation with a digital elevation model (DEM). The fluvial and slope processes that rework sediments and result in observed geomorphic changes are themselves inherently variable and contribute to uncertainty due to variability. Any computational model we might employ to assess or predict such geomorphic changes will be subject to a host of *structural uncertainties* in its formulation and *unreliability uncertainties* in their parameterization¹¹. Additionally, ecohydraulic uncertainties manifest themselves in habitat suitability models both from those propagated by the geomorphic model and in terms of fish habitat preferences and ecological functions provided by local-scale hydraulics.

Although this thesis will systematically consider each of the abovementioned uncertainties, a more fundamental uncertainty about geomorphic change will be the main focus of this thesis. That fundamental uncertainty is simply that we do not know what geomorphic changes to expect¹². That is, there is an underlying uncertainty due to variability in geomorphic changes that we have a limited understanding of. Yet, if we recognize the magnitude of our uncertainty in measuring and predicting geomorphic changes, we actually have a powerful way of constraining the bounds of this more fundamental uncertainty of what to expect. Thus, a suite of model simulation scenarios will be used to develop an understanding of what we might expect in response to various restoration, land use and/or climate change scenarios. Although this approach bears some resemblance to a classical sensitivity analysis, it differs in that the interest is not as much in the specific model response to parametric uncertainty. Instead of treating the model simulations as absolute predictions, they are viewed as plausible system responses. More importantly, those responses can be deconstructed to highlight the specific historical and spatial contingencies that produced them. Thus, we take a *reducible ignorance* uncertainty (Star 4

¹⁰See Chapter Four for full description of the CAESAR model and explanation for why this model was selected over other geomorphic models.

¹¹See Table 1.5 and section 1.5 for a review of sources of model uncertainties.

¹²The source of this fundamental uncertainty is limited knowledge and the type is *reducible ignorance*

in Figure 2.2) and transform it into primarily an *unreliability uncertainty* (Star 2 in Figure 2.2) in our model information. The advantage is that this transformed information is of a form that its uncertainty can be quantified, and its content is more informative.

2.2.3 Objective 3: Demonstrate Significance With Case Study

Whatever method is used to explore the significance or insignificance of uncertainties in river restoration, it should be acknowledged that significance itself is a value-laden concept. Just as different investigators may look at uncertainty in different ways, what is significant to one group may be totally insignificant to another. To avoid the societal and political value-laden dimensions, the consistent metrics by which we will compare significance will be influence on fish habitat.

Specific policy, restoration, climate change and landuse alternatives will be used as scenarios to set the initial conditions for model simulations of potential geomorphic responses to restoration. The model simulations are in no way intended to support a 'predictive management'¹³ framework, but are instead intended to explore the significance of a range of plausible outcomes given specific restoration choices (Lempert et al. 2003). Although the range of plausible outcomes then represent our limited knowledge (uncertainty) about the potential fluvial and ecological responses to restoration activities, they again transform our uncertainty from one of *reducible ignorance* (with high degree) to one of uncertainty about the inherent variability of nature. The latter is not an uncertainty we try to reduce, but instead try to understand. Therein, the significance of geomorphic changes may be highly contingent on the timing, duration and magnitude of those changes in relationship to the lifecycle of a fish.

A specific case study to assess significance in is necessary for a variety of reasons. First, to insure the said techniques do work and provide an illustrative example is helpful. More fundamentally though, the significance of uncertainties in geomorphic change can not be stated in a general way. That is, there will always be historical and spatial contingencies unique to a particular scenario in a particular river basin that determine significance. Therefore, any study catchment that exhibits the following characteristics will be suitable:

- Is or was capable of supporting fish.
- Some degree of degradation and a potential for fish habitat restoration.
- Is or could be subject to geomorphic changes.
- Has, or would be feasible to acquire, necessary data to run proposed numerical models.

¹³See (Clark 2002) and Section 1.4 for description of predictive management.

Beyond these rather generic criteria, the selection of a study catchment is largely a matter of logistical convenience. For a first study site, the Sulphur Creek Watershed, a tributary to the Napa River and part of the San Francisco Bay Watershed in California, was selected. In addition it would be desirable to make a trans-Atlantic comparison and contrast. Thus, a second study site was selected within the United Kingdom.

2.2.4 What is not Addressed and Why

There are several aspects of the ‘embrace uncertainty’ framework, which will not be within the scope of this thesis. In Figure 2.3 these are numbered one through seven and the rationale is briefly explained below. Although these areas are not covered explicitly, they are not simply ignored either. The linkages between these topics and those covered explicitly is critical for understanding the overall scope of uncertainty. The linkages explain how uncertainty topics covered by restoration science relate to restoration practice and policy as well as other complimentary research areas.

Two sources of uncertainty due to limited knowledge will not be addressed (Star 1 in Figure 2.3). These are *indeterminacy* and *irreducible ignorance*. As highlighted in section 1.3.2, there is little utility in trying to study structural uncertainties that ‘we will never know’ or ‘we cannot know’ (van Asselt & Rotmans 2002). It is important to recognize they exist, and to consider how they might influence restoration, but they simply must be coped with.

Three sources of uncertainty due to variability will not be covered (Stars 2 and 3 in Figure 2.3). First, *technological surprise* will not be emphasized simply to limit scope. However, *technological surprises* could provide quite devastating long-term consequences or equally important benefits and breakthroughs. For example, imagine a long-term restoration scheme intended to improve out-migration of smolts past a series of major hydroelectric dams (e.g. Columbia River, USA). Perhaps, the restoration scheme invested all its efforts in fish-guidance fences and structures to encourage avoiding the turbines. A potential *technological surprise* could be the emergence of new turbines capable of passing fish with greatly reduced direct and indirect mortality (Cada et al. 2004). Second, *societal randomness* and *value and behavioral diversity* will not be covered in detail as they are beyond the expertise of a physical scientist. However, it is fully acknowledged that this is perhaps one of the largest sources of uncertainty and could be an exciting frontier for future research by political, economic and social scientists. Although outside the scope of this particular thesis, collaboration across discipline boundaries will be critical to working towards a holistic understanding of uncertainties in river restoration.

Finally, four areas within the ‘embracing uncertainty’ framework that pertain to decision making and strategic planning will not be emphasized (Numbers 4-7 in Figure 2.3). The first of these relates to when decision makers have established that uncertainty is insignificant (Number 4). In this thesis, I am instead postulating that ‘we do not know’ if the

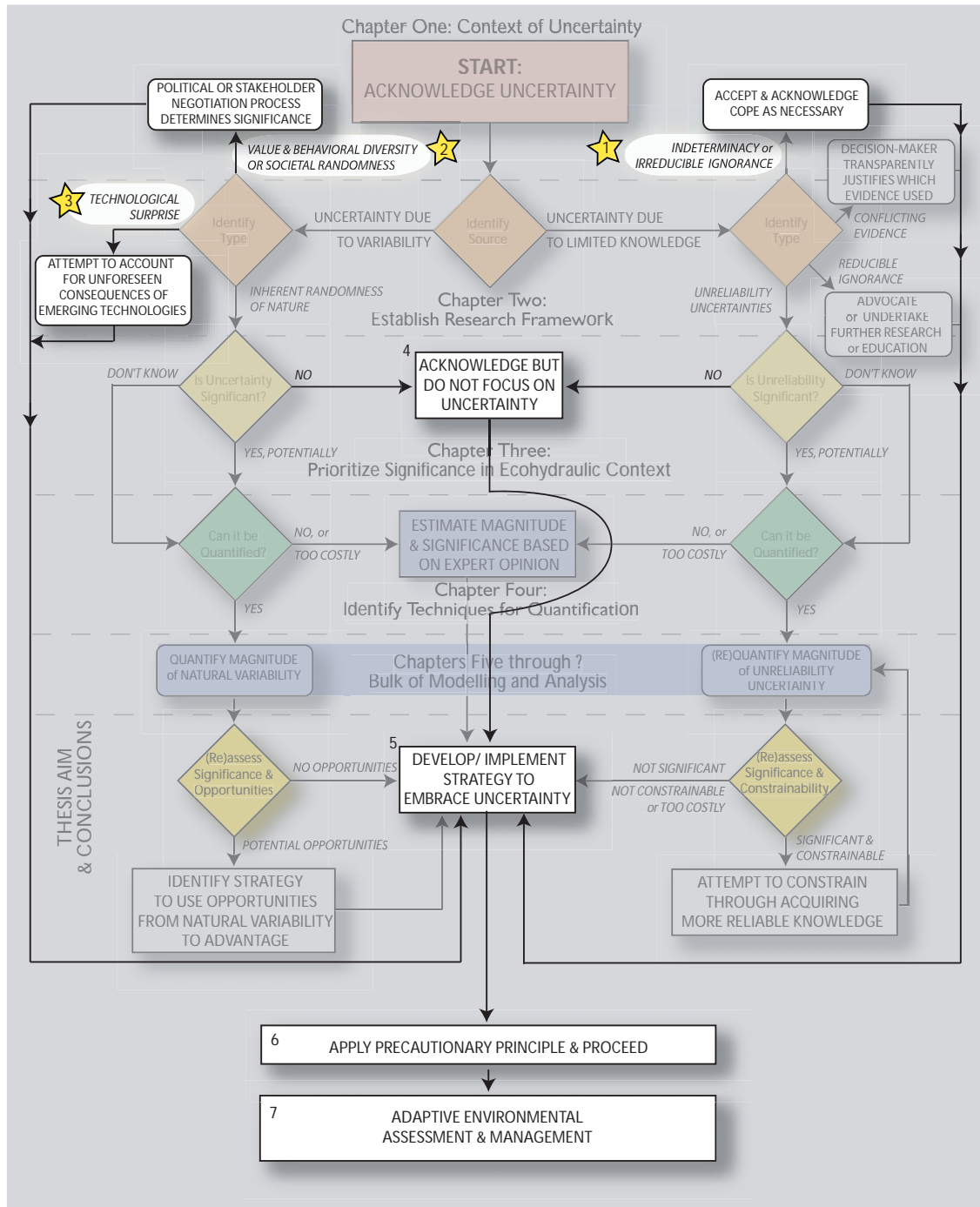


FIGURE 2.3: Portions of 'Embracing Uncertainty' Framework Not Covered in Detail in This Thesis. The grayed out areas of the figure are those areas covered in this thesis. The highlighted areas are numbered and explained briefly in the text. Refer to Figure 1.9 for original.

uncertainties are significant. Number 5 relates to specific judgements decision makers must make to develop and implement a strategy for embracing uncertainty. The entire framework funnels and converges on this point, and in that sense the thesis provides some general guidelines for supporting the strategy development. However, the process itself is not included explicitly within the thesis largely because every individual restoration scheme will have different criteria, which will dictate what the appropriate course of action is here. After which, it is simply a matter of applying the precautionary principle to proceed with restoration activities (Number 6)¹⁴ and then using adaptive management (Number 7)¹⁵ to feed back iteratively into the framework as necessary.

2.3 Thesis Organization

This section outlines briefly the organization of the thesis¹⁶. The first four chapters of the thesis layout the background, purpose and methods to be used in this thesis. Chapter One established the scope of uncertainty in river restoration and a framework for contextualizing uncertainty. This chapter (Chapter Two) serves three purposes: a) summarise research opportunities; b) state aim and objectives; and c) outline the organization of the thesis. Chapter Three provides a more specific literature review of the the ecohydraulic, hydroecology and geomorphic literature of specific relevance to the thesis aim and objectives. Chapter Three is primarily concerned with explaining how this thesis attempts to bridge the emerging scale gap in river restoration (i.e. Objective One). Chapter Four then details the methods and rationale for their selection. In particular, the theoretical background of CAESAR (the landscape evolution model used), CASiMiR (the fish habitat suitability model used) and the corresponding uncertainty analyses will be provided. All modifications to these codes and development of other analysis tools will be described here as well. Thus, Chapter Four fulfills the second objective of identifying techniques to quantify geomorphic uncertainties. Chapters One through Four will provide a thorough context and robust set of tools that should be transferable to a wide variety of specific case studies.

The next two to four chapters will depart from the general and theoretical foundation provided above, and focus on illustration of the said techniques in one or two case studies (timing and logistics will dictate how many). These two to four chapters will be organized by study site with the a methodological description of scenario development preceding the results and discussion in each case. As the magnitude of modelling scenarios would make for a very cumbersome and lengthy reporting of the results, only the primary results will be reported and discussed in detail. However, as all the scenarios may be of potential interest to someone in the future, they will be reported in a consistent format in appendices

¹⁴The precautionary principle is reviewed briefly in section 1.4.3 of Chapter One.

¹⁵Adaptive Management is reviewed briefly in section 1.4 of Chapter One.

¹⁶NOTE: This is an approximate outline based on the current plan, and will likely change after the upgrade from Mphil to PhD.

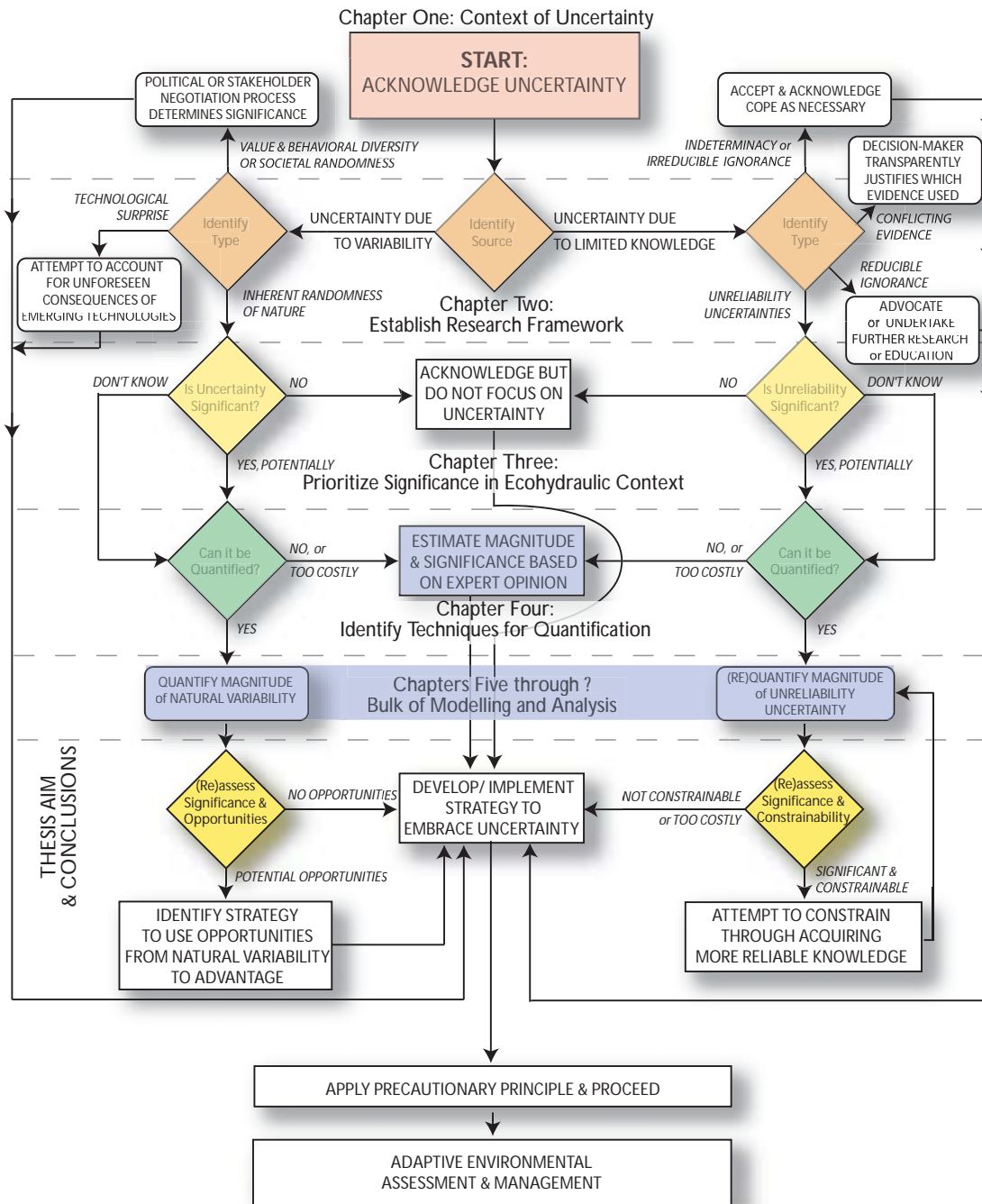


FIGURE 2.4: Organization of thesis around 'embracing uncertainty'. The color-shaded areas represent research questions and activities specifically covered in this thesis. The non-shaded areas represent the linkages of this research to existing or future components within an 'embracing uncertainty' in river restoration decision making process.

to the thesis.

The final chapter will provide a concise synthesis of the main findings of the case studies, highlighting those elements with applicability to the wider restoration community. Then, a brief retrospective assessment of the weaknesses and strengths of the tools used in this thesis will be reported. And finally, a critical assessment of the contribution of this thesis to the restoration community as compared to the applied science community will be summarized with an aim of highlighting future research needs. Figure 2.4 maps the organization of all these thesis chapters onto the ‘embracing uncertainty’ framework.

Chapter 3

PhD Study Plan

NOTE: This study plan is included as a chapter *only* in the Upgrade from Mphil to PhD Document and will not be part of the final thesis. It is intended to provide the assessor and advisors with logistical plans and information to assess whether the scope of research outlined in Chapter Two is indeed feasible.

3.1 Overall Study Plan and Timing

To achieve the aim and objectives laid out in Chapter Two, I have divided the remaining two years into six discrete phases:

1. Wrap up background research
2. Feasibility study on Sulphur Creek
3. Model and code development
4. Implementation with Case Study(s)
5. Synthesis and Completion of Thesis
6. Submit, Revisions and Publications.

A brief synopsis of each is given in the next section. The timing is provided in Table 3.1

Just as I have argued that adaptive management is an important way to account for uncertainties in river restoration, it will be an important way to progress through this PhD. These phases have lots of built in slop to allow for mid-course corrections or unforeseen tangents.

Phase	Duration	Approximate Completion Date
Wrap up background research	2-3 weeks	15 October, 2004
Feasibility study on Sulphur Creek	2-3 months	January, 2005
Model and code development	4-6 months	June, 2005
Implementation with Case Study(s)	6-8 months	February 2006
Synthesis and Completion of Thesis	3-4 months	June 2006
Submit, Revisions and Publications	2-4 months	Submit May or June 2006; Revisions and Publications by September 2006

TABLE 3.1: Thesis Phases and Their Approximate Timing

3.2 Description of Phases

3.2.1 Accomplishments of First Year

Given the vague and general nature of the PhD topic, most of the first year was spent doing background research to better understand the scope of uncertainty in river restoration and to inform a decision as to which areas to focus on. The primary accomplishments are listed below:

- Completed extensive literature review and research outline.
- Completed revisions and had first two peer-reviewed journal articles published (related to both PhD and former Masters Research).
- Launched and conducted a web-based International River Restoration Survey to acquire background information (over 500 respondents from 34 nations). Presented results at conference and preparing a journal article currently.
- Presented papers of on ongoing research at two conferences (one published in conference proceedings; second in preparation for special issue of ESPL).
- Conducted twelve key informant interviews with leading river restoration scientists, policy makers and practitioners in the UK and US to help inform research.
- Forged research collaboration with James Brasington at University of Cambridge to explore significance of DEM Uncertainties in sediment budgeting (presenting results at AGU).
- Completed draft chapter for an edited volume on ‘Uncertainties in River Restoration.’
- Met with developers of CAESAR and CASiMiR models being used in PhD to learn models and explore fertility of making additions and modifications to the source codes.

3.2.2 Wrap up Background Research

There are three manuscripts related to the background research described in the previous subsection, which need to be completed. They include:

- An article on Restoration Survey Results for submission to Area (first author)
- An article on uncertainty in notions of natural for river restoration for submission to a special issue of ESPL (first author)
- An article on uncertainty in restoration design on the River Cherwell for re-submission to ESPL (third author; only contributing new introduction)

Each of these should be ready for submittal shortly.

3.2.3 Feasibility study on Sulphur Creek

Prior to developing a range of model scenarios for the case study(s) and making modifications/additions to the model source codes, a feasibility study will be carried out using the Sulphur Creek study catchment. The purpose of the feasibility study is to become familiar with the time involved and limitations of both the CAESAR and CASiMiR models. Some time will be spent working with the outputs of the models to produce algorithms for analyzing the results in terms of consistent metrics. Included in this will be further exploration into the use of fuzzy set theory for quantifying the uncertainties of interest. The outputs of the preliminary models will be reported to the Sulphur Creek Watershed Stewardship Group in December and input for restoration scenarios will be sought at that point. Also in December, field work will be conducted to acquire necessary validation and verification data for the models. Coming out of this phase, a matrix of model scenarios and relevant restoration questions will be produced and a better idea of how long each might take should follow. Concurrently, Chapter Three of thesis will be written during this phase ¹.

3.2.4 Model and code development

In their present form, CAESAR and CASiMiR used in conjunction with each other will permit the investigation of a number of topical restoration, landuse and/or climate change scenarios. However, with some modifications to the source codes, the influence of a range of other important factors could be incorporated and further scenarios explored. For example, we have conceptually discussed modifying the CAESAR code to incorporate a large wood debris (LWD) model. The LWD model would potentially account for recruitment, movement and storage of LWD (particularly as debris dams) and geomorphic feedbacks.

¹Refer to section 2.3 for description of Chapter Three.

CASiMiR could be modified to include the LWD in its habitat suitability criteria, thus simulating the importance of LWD dynamics for fish habitat. Other more simple modifications to the respective codes will be made to simply put the outputs in more convenient forms for analyses. The lessons learnt in the feasibility phase will dictate to what extent these code modifications are necessary. Help has been offered by the respective developers of the CAESAR and CASiMiR models already. During this phase, the methods will be written up in Chapter Four of the Thesis.

3.2.5 Implementation with Case Study(s)

At a minimum, the Sulphur Creek Case Study will be analyzed during this phase. As most of the time will be spent running models, it may be necessary to use multiple department computers, or purchase some inexpensive computers to carry out model simulations. The results of the feasibility study and the availability of computational resources will determine how many scenarios can be explored and whether a second and/or third case study catchment will be included. While models are running on other computers, I can be using my own computer to carry out analyses and write in the results and discussion chapters.

3.2.6 Synthesis and Completion of Thesis

By February of 2006, I will stop running additional model scenarios. The first part of this period will be for wrapping up the results and discussion chapters, and the models will only be used to revisit details of previous simulations for clarification or correction purposes. Next, a brief follow up on the literature that will have emerged between now and then will be conducted to a) see where the research fits into the most recent developments, and b) help contextualize a synthesis chapter. The synthesis chapter and whatever outstanding revisions for other chapters will also be made at this time. The goal will be to submit by May to June of 2006. Given, the inclusion of time for writing during the other phases, it is hoped that this is realistic.

3.2.7 Submit, Revisions and Publications.

If the above phases proceed according to schedule, this would leave the summer to make whatever revisions the External and Internal Examiners determine are necessary. During this phase, I hope to complete transforming results from the thesis into journal manuscripts. If appropriate, it would be desirable to prepare and submit such journal manuscripts during earlier phases, in order to have the feedback from the peer review process prior to the viva. It is difficult to assess whether this will be feasible or appropriate now, but if possible it will be a priority. If any of the earlier phases take much longer than anticipated, allowing a four month period at the end will hopefully accommodate any extra time needed.

Bibliography

- Addin, O. M. & Jensen, F. V. (2004). Bayesian belief networks in environmental decision support systems, *Technical report*, Centre for Ecology and Hydrology.
- Adriaenssens, V., Baets, B. D., Goethals, P. L. & Pauw, N. D. (2003). Fuzzy rule-based models for decision support in ecosystem management, *Science of the Total Environment* ?(?): ?
- Alario, M. & Brun, M. (2001). Uncertainty and controversy in the science and ethics of environmental policy making, *Theory and Science* **2**(1): Available on the web: <http://theoryandscience.icaap.org/content/vol002.001/02alariobrun.html>.
- Allison, R. J. & Thomas, D. (1993). 1. the sensitivity of landscapes, in D. Thomas & R. Allison (eds), *Landscape sensitivity: British Geomorphological Research Group symposia series*, John Wiley and Sons Ltd, Chichester, U.K., pp. 1–5.
- Anderson, J. L. (1998). Chapter 6: Errors of inference, in V. Sit & B. Taylor (eds), *Statistical Methods for Adaptive Management Studies*, Vol. Land Management Handbook No. 42, B.C. Ministry of Forests, Victoria, B.C., pp. 69–87.
- Anderson, J. L., Hilborn, R., Lackey, R. T. & Ludwig, D. (2003). 9. watershed restoration-adaptive decision making in the face of uncertainty, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 185–201.
- Angermeier, P. & Karr, J. (1994). Biological integrity versus biological diversity as policy directives: protecting biotic resources, *Bioscience* **44**: 690–697.
- Annable, W. K. (1999). On the design of natural channels: Decisions, direction and design, *The Second International Conference on Natural Channel Systems*, Niagara Falls, Ontario, Canada, p. 29.
- Ayyub, B. & Gupta, M. (eds) (1994). *Uncertainty Modelling and Analysis: Theory and Applications*, Elsevier Science, The Netherlands.
- Balakrishnan, S., Roy, A., Ierapetritou, M. G., Flach, G. P. & Georgopolous, P. G. (2003). Uncertainty reduction and characterization for complex environmental fate

- and transport models: An empirical bayesian framework incorporating the stochastic response surface method, *Water Resources Research* **39**(12): 1350.
- Bandemer, H. & Gottwald, S. (1995). *Fuzzy Sets, Fuzzy Logic, Fuzzy Methods: with Applications*, John Wiley and Sons Ltd., Chichester, U.K.
- Bednarek, A. T. (2001). Undamming rivers: A review of the ecological impacts of dam removal, *Environmental Management* **27**(6): 803–814.
- Bergerud, W. A. & Reed, William, J. (1998). Bayesian statistical methods, in V. Sit & B. Taylor (eds), *Statistical Methods for Adaptive Management Studies*, Vol. Land Management Handbook No. 42, Research Branch, B.C. Ministry of Forests, Victoria, B.C., pp. 89–104.
- Beven, K. (1996a). Equifinality and uncertainty in geomorphological modelling, in B. L. Rhoads & C. E. Thorn (eds), *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*, John Wiley and Sons Ltd., Chichester, U.K., pp. 289–314.
- Beven, K. (1996b). The limits of splitting: Hydrology, *The Science of the Total Environment* **183**: 89–97.
- Beven, K. & Binley, A. M. (1992). The future of distributed models: model calibration and uncertainty prediction, *Hydrological Processes* **6**: 279–298.
- Binley, A. M., Beven, K. J., Calver, A. & Watts, L. G. (1991). Changing responses in hydrology - assessing the uncertainty in physically based model predictions, *Water Resources Research* **27**(6): 1253–1261.
- Bohn, B. A. & Kershner, J. L. (2002). Establishing aquatic restoration priorities using a watershed approach, *Journal of Environmental Management* **64**(4): 355–363.
- Boon, P. J. (1998). River restoration in five dimensions, *Aquatic Conservation-Marine and Freshwater Ecosystems* **8**(1): 257–264.
- Brasington, J., Langham, J. & Rumsby, B. (2003). Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport, *Geomorphology* **53**(3-4): 299–316.
- Brasington, J., Rumsby, B. T. & Mcvey, R. A. (2000). Monitoring and modelling morphological change in a braided gravel-bed river using high resolution gps-based survey, *Earth Surface Processes and Landforms* **25**(9): 973–990.
- Brazier, R. E., Beven, K. J., Anthony, S. G. & Rowan, J. S. (2001). Implications of model uncertainty for the mapping of hillslope- scale soil erosion predictions, *Earth Surface Processes and Landforms* **26**(12): 1333–1352.

- Brazier, R. E., Beven, K. J., Freer, J. & Rowan, J. S. (2000). Equifinality and uncertainty in physically based soil erosion models: Application of the glue methodology to wepp-the water erosion prediction project-for sites in the uk and usa, *Earth Surface Processes and Landforms* **25**(8): 825–845.
- Brierley, G. J. & Fryirs, K. (2000). River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in bega catchment, new south wales, australia, *Environmental Management* **25**(6): 661–679.
- Brookes, A., Downs, P. & Skinner, K. (1998). Uncertainty in the engineering of wildlife habitats, *Journal of the Chartered Institution of Water and Environmental Management* **12**(1): 25–29.
- Brookes, A., Knight, S. S. & Shields, F. D. (1996). 4. habitat enhancement, in A. Brookes & F. D. Shields (eds), *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley and Sons Ltd., Chichester, UK, pp. 103–126.
- Brookes, A. & Sear, D. (1996). 3. geomorphological principles for restoring channels, in A. Brookes & F. D. Shields (eds), *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley and Sons Ltd., Chichester, UK, pp. 75–101.
- Brookes, A. & Shields, F. D. (1996). *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley and Sons Ltd., Chichester, UK.
- Brown, T., LeMay, H. E. & Bursten, B. (1994). *Chemistry: The Central Science*, Vol. Sixth Edition, Prentice Hall, Englewood Cliffs, NJ.
- Brunsdon, D. (1993). 2. barriers to geomorphological change, in D. Thomas & R. Allison (eds), *Landscape sensitivity: British Geomorphological Research Group symposia series*, John Wiley and Sons Ltd, Chichester, U.K., pp. 7–12.
- Cada, G., Sale, M., Carlson, T., Sotiropoulos, F. & Smith, B. (2004). Characterizing turbulence and its biological effects at hydroelectric power plants, in D. Garcia & P. V. Martinez (eds), *Fifth International Symposium on Ecohydraulics: Aquatic Habitats: Analysis and Restoration*, Vol. 1, IAHR-AIRH, Madrid, Spain.
- Cairns, J. (2002). *Goals and Conditions for a Sustainable World*, Vol. Book 1. Available at www.esep.de/journals/esep/esepbooks/CairnsEsepBook.pdf, ESEP.
- Cairns, J. (2003). Numeracy and sustainability, *Ethics in Science and Environmental Politics* **2003**: 83–91.
- Cao, Z. & Carling, P. A. (2002a). Mathematical modelling of alluvial rivers: reality and myth. part 2: Special issues, *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering* **154**(4): 297–307.
- Cao, Z. & Carling, P. A. (2002b). Mathematical modelling of alluvial rivers: reality and myth. part i: General review, *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering* **154**(3): 207–219.

- Cardwell, H. & Ellis, H. (1996). Model uncertainty and model aggregation in environmental management, *Applied Mathematical Modelling* **20**(2): 121–134.
- Chapman, C. & Ward, S. (2002). *Managing Project Risk and Uncertainty: A Constructively Simple Approach to Decision Making*, John Wiley and Sons Ltd, Chichester, U.K.
- Church, M. (2002). Geomorphic thresholds in riverine landscapes, *Freshwater Biology* **47**(4): 541–557.
- Clark, M. J. (2002). Dealing with uncertainty: adaptive approaches to sustainable river management, *Aquatic Conservation-Marine and Freshwater Ecosystems* **12**: 347–363.
- Clark, M. J. & Richards, K. J. (2002). Supporting complex decisions for sustainable river management in england and wales, *Aquatic Conservation-Marine and Freshwater Ecosystems* **12**: 471–483.
- Clayton, S. R. (2002). *Quantitative Evaluation of Physical and Biological Responses to Stream Restoration*, Ph.d. dissertation, University of Idaho.
- Clifford, N. J., Acreman, M. C. & Booker, D. J. (In Review). Chapter seven: Hydrological and hydraulic aspects of restoration uncertainty for ecological purposes, in S. E. Darby & D. Sear (eds), *Uncertainties in River Restoration*, John Wiley and Sons Ltd, Chichester, U.K.
- Collins, J. P., Kinzig, A., Grimm, N. B., Fagan, W. F., Hope, D., Wu, J. & Borer, E. T. (2000). A new urban ecology: Modeling human communities as integral parts of ecosystems poses special problems for the development and testing of ecological theory, *American Scientist* **88**: 416–425.
- Coulthard, T. (1999). *Modelling Upland Catchment Response to Holocene Environmental Change*, Unpublished phd thesis, University of Leeds.
- Coulthard, T., Kirkby, M. J. & Macklin, M. G. (1998). Non-linearity and spatial resolution in a cellular automaton model of a small upland basin, *Hydrology and Earth System Sciences* **2**(2-3): 257–264.
- Darby, S. E. & Thorne, C. R. (1996). Modelling the sensitivity of channel adjustments in destabilized sand-bed rivers, *Earth Surface Processes and Landforms* **21**(12): 1109–1125.
- Davis, M. A. & Slobodkin, L. (2004). The science and values of restoration ecology, *Restoration Ecology* **12**(1): 1–3.
- deFur, P. L. & Kaszuba, M. (2002). Implementing the precautionary principle, *The Science of The Total Environment* **288**(1-2): 155–165.
- DFO (1986). The department of fisheries and oceans policy for the management of fish habitat., *Technical report*, Department of Fisheries and Oceans, Canada.

- Downs, P. W. & Gregory, K. J. (1993). 3. the sensitivity of river channels in the landscape system, in D. Tomas & R. J. Allison (eds), *Landscape Sensitivity*, John Wiley and Sons Ltd., Chichester, U.K., pp. 15–30.
- Downs, P. W., Gregory, K. J. & Brookes, A. (1991). How integrated is river basin management, *Environmental Management* **15**(3): 299–309.
- Doyle, M. W., Boyd, K. F. & Skidmore, P. B. (1999). River restoration channel design: Back to the basics of dominant discharge, *Second International Conference on Natural Channel Systems*, Niagra Falls, Canada.
- Doyle, M. W. & Harbor, J. (2003). Toward policies and decision-making for dam removal, *Environmental Management* **31**(4): 453–465.
- Doyle, M. W., Harbor, J. M., Rich, C. F. & Spacie, A. (2000). Examining the effects of urbanization on streams using indicators of geomorphic stability, *Physical Geography* **21**(2): 155–181.
- Edmonds, R., Francis, R., Mantua, N. & Petersen, D. (2003). 2. sources of climate variability in river ecosystems, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 11–37.
- EEA (2001). Late lessons from early warnings: the precautionary principle 18962000, *Technical Report Environmental issue report No 22*, European Environment Agency.
- Ellis, J. B. (1996??). Urban watercourses: Ecological sustainability and restoration, *Technical report*, Natural Environmental Research Council.
- Ellison, S., Rosslein, M. & Williams, A. (eds) (2000). *Quantifying Uncertainty in Analytical Measurement*, Vol. Guide number 4, second edition edn, Eurachem/CITAC, Teddington, UK.
- Everest, F. H. & Sedell, J. R. (1984). Evaluating effectiveness of stream enhancement projects, in T. J. Hassler (ed.), *Pacific Northwest Stream Habitat Management Workshop: American Fisheries Society*, AFS, Humoldt State Universtiy, CA, pp. 156–164.
- Everset, F. H. & Sedell, J. R. (1984). Evaluating effectiveness of stream enhancement projects, in T. J. Hassler (ed.), *Pacific Northwest Stream Habitat Management Workshop*, American Fisheries Society, Arcata, CA, pp. 246–256.
- Falkenmark, M. & Folke, C. (2002). The ethics of socio-ecohydrological catchment management, *Hydrology and Earth System Sciences* **6**(1): 1–9.
- FISRWG (1998). Stream corridor restoration: Principles, processes, and practices., *Technical Report GPO Item No. 0120-A*, Federal Interagency Stream Restoration Working Group.

- Frissell, C. A., Liss, W. J. & Bayles, D. (1993). An integrated, biophysical strategy for ecological restoration of large watersheds, *Changing Roles in Water Resources Management and Policy: American Water Resources Association* **29**(3).
- Gilvear, D. J. (1999). Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework, *Geomorphology* **31**(1-4): 229–245.
- Graf, W. L. (1996). Geomorphology and policy for restoration of impounded american rivers: What is 'natural?', in B. L. Rhoads & C. E. Thorn (eds), *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*, John Wiley and Sons Ltd., Chichester, U.K., pp. 221–254.
- Graf, W. L. (2001). Damage control: Dams and the physical integrity of america's rivers, *Annals of the Association of American Geographers* **91**: 1–27.
- Graf, W. L., Diamond, M. & Kronvang, B. (In Review). Chapter three: The nature and significance of uncertainty in river restoration, in S. E. Darby & D. Sear (eds), *Uncertainties in River Restoration*, John Wiley and Sons Ltd, Chichester, U.K.
- Hankin, B. G., Hardy, R., Kettle, H. & Beven, K. J. (2001). Using cfd in a glue framework to model the flow and dispersion characteristics of a natural fluvial dead zone, *Earth Surface Processes and Landforms* **26**(6): 667–687.
- Hansen, H. O. & Iversen, T. M. (1998). The european centre for river restoration (ecrr), in H. O. Hansen & B. L. Madsen (eds), *River Restoration '96 - Proceedings - Session Lectures*, ECRR, Denmark, pp. 73–79.
- Hardy, T. (1998). The future of habitat modelling and instream flow assessment techniques, *Regulated Rivers: Research and Management* **14**: 405–420.
- Harman, W. (1998). *Global Mind Change: The Promise of the 21st Century*, Vol. Second Edition, Berrett-Koehler Publishers, Inc., San Francisco, CA.
- Helton, J. C. (1994). Treatment of uncertainty in performance assessments for complex systems, *Risk Analysis* **14**(4): 483–511.
- Henrion, M. & Fischhoff, B. (1986). Assessing uncertainty in physical constants, *Annual Journal of Physics* **54**(9): 791–797.
- Herricks, E. E. (1996). 7. water quality issues in river channel restoration, in A. Brookes & F. D. Shields (eds), *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley and Sons Ltd., Chichester, UK, pp. 75–101.
- Herschy, R. W. (2002). The uncertainty in a current meter measurement, *Flow Measurement and Instrumentation* **13**: 281–284.
- Hildn, M. (2000). The role of integrating concepts in watershed rehabilitation, *Ecosystem Health* **6**(1): 39–50.

- Holling, C. (1978). *Adaptive Environmental Assessment and Management*, J. Wiley Sons Ltd., Chichester, U.K.
- Horssen, P. v., Pebesma, E. & Schot, P. (2002). Uncertainties in spatially aggregated predictions from a logistic regression model, *Ecological Modelling* **154**: 93–101.
- Hruby, T. (2003). Where is the ecology in wetland restoration?, *Society of Ecological Restoration Northwest and Society Wetland Scientists Joint Regional Conference*, SERNW, Portland, OR, p. Abstract.
- Hughes, R. M. (1995). Defining acceptable biological status by comparing with reference conditions, in W. Davis & R. Simon (eds), *Biological Assessment and Decision Making*, Lewis Publishers, Boca Raton, FL, pp. 31–47.
- ISAB (2003). 10. decision support models as tools for developing management strategies: Examples from the columbia river basin, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 233–242.
- ISO (1995). Guide to the expression of uncertainty in measurement, *Technical report*, International Standards Organization.
- Jamieson, D. (1996). Scientific uncertainty: how do we know when to communicate research findings to the public?, *The Science of the Total Environment* **184**: 103–107.
- Johnson, P. A. & Brown, E. R. (2001). Incorporating uncertainty in the design of stream channel modifications, *Journal of the American Water Resources Association* **37**(5): 1225–1236.
- Johnson, P. A. & Heil, T. M. (1996). Uncertainty in estimating bankfull conditions, *Water Resources Bulletin* **32**(6): 1283–1291.
- Johnson, P. A. & Rinaldi, M. (1997). Uncertainty in the design of stream channel restorations, in F. M. H. Jr. & A. Alsaffar (eds), *Water for a Changing Global Community: The 27th Congress of the International Association for Hydraulic Research*, ASCE Press, San Francisco, CA, pp. 451–457.
- Johnson, P. A. & Rinaldi, M. (1998). 22. uncertainty in stream channel restoration, in B. M. Ayyub (ed.), *Uncertainty Modeling and Analysis in Civil Engineering*, CRC Press, London, pp. 425–437.
- Jungwirth, M., Muhar, S. & Schmutz, S. (2002). Re-establishing and assessing ecological integrity in riverine landscapes, *Freshwater Biology* **47**(4): 867–887.
- Kahneman, D. & Tversky, A. (1982). *Variants of Uncertainty*, Uncertainty, Cambridge University Press, Cambridge, UK.

- Kavvas, M. L. (1999). On the coarse-graining of hydrologic processes with increasing scales, *Journal of Hydrology* **217**(3-4): 191–202.
- Kavvas, M. L. (2003). Nonlinear hydrologic processes: Conservation equations for determining their means and probability distributions, *Journal of Hydrologic Engineering* **8**(2): 44–53.
- Kerle, F., Zollner, F., Schneider, M., Bohmer, J., Kappus, B. & Baptist, M. J. (2002). Modelling of long-term fish habitat changes in restored secondary floodplain channels of the river rhine, *Conference Proceedings of the Fourth EcoHydraulics Symposium*, IAHS, Cape Town, South Africa.
- Kern, K. (1992). Rehabilitation of streams in south-west germany, in P. J. Boon, P. Calow & G. Petts (eds), *River Conservation and Management*, John Wiley Sons Ltd., Chichester, U.K., pp. 321–336.
- Kirkby, M. J. (1996). A role for theoretical models in geomorphology?, in B. L. Rhoads & C. E. Thorn (eds), *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*, John Wiley and Sons Ltd., Chichester, U.K., pp. 257–272.
- Klir, G. & Yuan, B. (1995). *Fuzzy Sets and Fuzzy Logic: Theory and Applications*, Prentice Hall, Upper Saddle River, New Jersey.
- Knapp, R. A. & Vredenburg, V. T. (1996). A field comparison of the substrate composition of california golden trout redds sampled with two devices, *North American Journal of Fisheries Management* **16**: 674–681.
- Knight, F. (1921). *Risk, Uncertainty and Profit*, Houghton Mifflin, New York.
- Knighton, D. (1998). *Fluvial forms and processes : a new perspective*, rev. and update edn, Arnold, London ; New York.
- Koehn, J., Brierley, G., Cant, B. & Lucas, A. (2001). River restoration framework, *Technical report*, The National Rivers Consortium: Land and Water Australia.
- Kondolf, G. M. (1995a). 5 elements for effective evaluation of stream restoration, *Restoration Ecology* **3**(2): 133–136.
- Kondolf, G. M. (1995b). Geomorphological stream channel classification in aquatic habitat restoration - uses and limitations, *Aquatic Conservation-Marine and Freshwater Ecosystems* **5**(2): 127–141.
- Kondolf, G. M. (1996). A cross section of stream channel restoration, *Journal of Soil and Water Conservation* **51**(2): 119–125.
- Kondolf, G. M. (2000a). Historical changes to the san francisco bay-delta watershed: Implications for ecosystem restoration, in H. Nijland & M. Cals (eds), *River Restoration in Europe: Practical Applications-Conference on River Restoration: Proceedings*, ECRR, Wageningen, The Netherlands, pp. 327–338.

- Kondolf, G. M. (2000b). Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals, *Restoration Ecology* **8**(1): 48–56.
- Koopmans, T. C. (1957). Three essays on the state of economic science, *Technical report*.
- Lackey, R. T. (1997). Restoration of pacific salmon : the role of science and scientists, in S. Sommarstrom (ed.), *Proceedings of the Sixth Biennial Watershed Management Conference*, Vol. Water Resources Center Report No. 92, Davis, CA, pp. 35–40.
- Lane, S. N. & Chandler, J. H. (2003). Editorial: The generation of high quality topographic data for hydrology and geomorphology: New data sources, new applications and new problems, *Earth Surface Processes and Landforms* **28**(3): 229–230.
- Lemons, J. & Victor, R. (In Review). Chapter two: Scientific uncertainty with special reference to river restoration, in S. E. Darby & D. Sear (eds), *Uncertainties in River Restoration*, John Wiley and Sons Ltd, Chichester, U.K.
- Lempert, R. J., Popper, S. W. & Bankes, S. C. (2003). Shaping the next one hundred years: New methods for quantitative, long-term policy analysis, *Technical report*, The Rand Pardee Center.
- Leopold, L. B. & Maddock, T. (1953). The hydraulic geometry of stream channels and some physiographic implications, *Technical Report Geological Survey Professional Paper 252*, United States Geological Survey.
- Levy, J. K., Hipel, K. W. & Kilgour, D. M. (2000). Using environmental indicators to quantify the robustness of policy alternatives to uncertainty*1, *Ecological Modelling* **130**(1-3): 79–86.
- Lewin, J. (2001). 2. alluvial systematics, in D. Maddy, M. G. Macklin & J. C. Woodard (eds), *River Basin Sediment Systems: Archives of Environmental Change*, A.A. Balkema Publishers, Steenwijk, The Netherlands, pp. 19–41.
- Lister, N.-M. E. (1998). A systems approach to biodiversity conservation planning, *Environmental Monitoring and Assessment* **49**: 123–155.
- Loucks, D. P. (2003). Managing americas rivers: Whos doing it?, *International Journal of River Basin Management* **1**(1): 21–31.
- Malakoff, D. (2004). The river doctor: Profile dave rosen, *Science* **305**(13 August): 937–939.
- Marmulla, G. (ed.) (2001). *Dams, fish and fisheries. Opportunities, challenges and conflict resolution*, Vol. Technical Paper no. 419, FAO Fisheries Department, Rome, Italy.
- McDonald, A., Lane, S., Chalk, E. & Haycock, N. E. (In Press). Rivers of dreams: on the gulf between theoretical and practical aspedcts of an upland river restoration, *Transactions of the Institute of British Geographers* .

- McIntyre, N., Wheater, H. & Lees, M. (2002). Estimation and propagation of parametric uncertainty in environmental models, *Journal of Hydroinformatics* **4**(3): 177–198.
- Merkle, A. & Kaupenjohann, M. (2000). Derivation of ecosystemic effect indicators – method, *Ecological Modelling* **130**(1-3): 39–46.
- Merriam-Webster (1994). *Merriam Webster's Collegiate Dictionary*, tenth edition edn, Merriam-Wester, Inc., Springfield, Massachusetts, U.S.A.
- Miller, D. E., Skidmore, P. B. & White, D. J. (2001). Channel design, *White paper*, Inter-Fluve, Inc. - Prepared for Washington Department of Fish and Wildlife.
- Montgomery, D. R. & Bolton, S. (2003). 3. hydrogeomorphic variability and river restoration, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 39–80.
- Moss, T. (2004a). The governance of land use in river basins: prospects for overcoming problems of institutional interplay with the eu water framework directive, *Land Use Policy* **21**: 85–94.
- Moss, T. (2004b). Institutional drivers and constraints of floodplain restoration: a comparative review of projects and policy contexts in england, france and germany, *The River Restoration Centre Annual Network Conference 2004: The Need for a Catchment Scale Approach to River Restoration*, RRC, Durham, UK.
- Mount, J. (1995). *California Rivers and Streams: The conflict between Fluvial Process and Land Use*, University of California Press, Berkeley, CA.
- NAP (2002). *Riparian Areas: Functions and Strategies for Management*, National Academy Press, Washington D.C.
- Natke, H. G. & Ben-Haim, Y. (eds) (1996). *Uncertainty: A Discussion from Various Points of View*, Akademie Verlag, Berlin, Germany.
- Newson, M. & Clark, M. J. (In Review). Chapter sixteen: The sustainable management of restored rivers, in S. E. Darby & D. Sear (eds), *Uncertainties in River Restoration*, John Wiley and Sons Ltd, Chichester, U.K.
- Newson, M. D. (2002). Geomorphological concepts and tools for sustainable river ecosystem management, *Aquatic Conservation-Marine and Freshwater Ecosystems* **12**(4): 365–379.
- Nijland, H. & Cals, M. (eds) (2000). *River Restoration in Europe: Practical Applications*, Conference on River Restoration: Proceedings, ECRR, Wageningen, The Netherlands.
- NRC (1992). *Restoration of aquatic ecosystems: science, technology, and public policy*, National Academy Press, Washington DC.

- Openshaw, S. (1996). Fuzzy logic as a new scientific paradigm for doing geography, *Environment and Planning A* **28**(5): 761–768.
- Ormerod, S. J. (2003). Current issues with fish and fisheries: editor's overview and introduction, *J Appl Ecology* **40**(2): 204–213.
- Osidele, O. O., Zeng, W. & Beck, M. B. (2003). Coping with uncertainty: A case study in sediment transport and nutrient load analysis, *Journal of Water Resources Planning and Management-Asce* **129**(4): 345–355.
- Palmer, M. A., Ambrose, R. F. & Poff, N. L. (1997). Ecological theory and community restoration ecology, *Restoration Ecology* **5**(4): 291–300.
- Petterman, R. M. & Peters, C. N. (1998). Decision analysis: Taking uncertainties into account in forest resource management, in V. Sit & B. Taylor (eds), *Statistical Methods for Adaptive Management Studies*, Vol. Land Management Handbook No. 42, Research Branch, B.C. Ministry of Forests, Victoria, B.C., pp. 89–104.
- Pfadenhauer, J. (2001). Some remarks on the socio-cultural background of restoration ecology, *Restoration Ecology* **9**(2): 220–229.
- Phillips, J. D. (2001). Contingency and generalization in pedology, as exemplified by texture-contrast soils, *Geoderma* **102**(3-4): 347–370.
- Phillips, J. D. (2003). Sources of nonlinearity and complexity in geomorphic systems, *Progress in Physical Geography* **27**(1): 1–23.
- Pieterse, N., Verkroost, A., Wassen, M., Venterink, H. O. & Kwakernaak, C. (2002). A decision support system for restoration planning of stream valley ecosystems, *Landscape Ecology* **17**(Suppl. 1): 69–81.
- Pister, E. P. (2001). Wilderness fish stocking: History and perspective, *Ecosystems* **4**: 279–286.
- Poff, N. L. (2004). Natural flow regime as paradigm for river restoration – a hydroecological context for ecohydraulics?, in D. Garcia & P. V. Martinez (eds), *Fifth International Symposium on Ecohydraulics: Aquatic Habitats: Analysis and Restoration*, Vol. 1, IAHR-AIRH, Madrid, Spain.
- Pollack, H. N. (2003). *Uncertain Science... Uncertain World*, Cambridge University Press, Cambridge, UK.
- Power, M. (1999). *The Audit Society: Rituals of Verification*, Oxford University Press, Oxford, England.
- Priddy, R. (1999). *Science Limited*, Available on the web: <http://home.no.net/rrpriddy/indexlim.html>, Oslo, Norway.

- Reckhow, K. (2003). On the need for uncertainty assessment in tmdl modeling and implementation, *Journal of Water Resources Planning and Management-Asce* **129**(4): 245–246.
- Reynolds, K. M., Jensen, M., Andreasen, J. & Goodman, I. (2000). Knowledge-based assessment of watershed condition, *Computers and Electronics in Agriculture* **27**(1-3): 315–333.
- Rhoads, B. L., Wilson, D., Urban, M. & Herricks, E. E. (1999). Interaction between scientists and nonscientists in community-based watershed management: Emergence of the concept of stream naturalization, *Environmental Management* **24**(3): 297–308.
- Richards, K., Brasington, J. & Hughes, F. (2002). Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy, *Freshwater Biology* **47**(4): 559–579.
- Riebeek, H. (2002). The perception of scientific uncertainty in science news writing.
- Robinson, C. T., Tockner, K. & Ward, J. V. (2002). The fauna of dynamic riverine landscapes, *Freshwater Biology* **47**(4): 661–677.
- Roni, P., Beechie, T., Bilbly, R., Leonetti, F., Pollock, M. & Pess, G. R. (2002). A review of stream restoration and a hierarchal strategy for prioritizing restoration in pacific northwest watersheds, *North American Journal of Fisheries Management* **22**: 1–20.
- Rosgen, D. (1996). *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, CO.
- Rotmans, J. & Van Asselt, M. (2001). Uncertainty management in integrated assessment modeling: Towards a pluralistic approach, *Environmental Monitoring and Assessment* **69**(2): 101 – 130.
- Routledge, R. D. (1998). Chapter 5: Measurements and estimates, in V. Sit & B. Taylor (eds), *Statistical Methods for Adaptive Management Studies*, Vol. Land Management Handbook No. 42, B.C. Ministry of Forests, Victoria, B.C., pp. 55–68.
- RRC (2000). An evaluation of uk river restoration appraisal procedures -results from a national survey, *Technical report*, The River Restoration Centre.
- Rutherford, I., Montgomery, D. R. & Hobbs, R. (In Review). Chapter five: Uncertainty in designing restored river channels, in S. E. Darby & D. Sear (eds), *Uncertainties in River Restoration*, John Wiley and Sons Ltd, Chichester, U.K.
- Samuels, P., Bramley, M. & Evans, E. (2003). Reducing uncertainty in conveyance estimation, *Technical report*, HR Walingford.
- Schneider, M. & Jorde, K. (2003). Fuzzy-rule based models for the evaluation of fish habitat quality and instream flow assessment, *Proc. International IFIM Users Workshop*, Fort Collins, CO, p. 22.

- Schulz, K. & Huwe, B. (1999). Uncertainty and sensitivity analysis of water transport modelling in a layered soil profile using fuzzy set theory, *Journal of Hydroinformatics* **1**(2): 127–138.
- Schumm, S. A. (1991). *To Interpret the Earth: Ten ways to be wrong*, Cambridge University Press, Cambridge, UK.
- Schumm, S. & Lichty, R. (1965). Time, space and causality in geomorphology, *American Journal of Science* **263**(February): 110–119.
- Sear, D. (1996). 6. the sediment system and channel stability, in A. Brookes & F. D. Shields (eds), *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley and Sons Ltd., Chichester, UK, pp. 149–177.
- Sear, D. A. (1994). River restoration and geomorphology, *Aquatic Conservation-Marine and Freshwater Ecosystems* **4**(2): 169–177.
- Sear, D. A. & Darby, S. E. (In Review). Uncertain geomorphology and river restoration, *Earth surface Processes and Landforms?* ?(?): ?
- Sear, D., Newson, C. L. & Thorne, C. R. (2003). Guidebook of applied fluvial geomorphology, *Technical Report R and D Technical Report FD1914*, DEFRA: Flood Management Division.
- Shields, F. D. (1996). 2. hydraulic and hydrologic stability, in A. Brookes & F. D. Shields (eds), *River Channel Restoration: Guiding Principles for Sustainable Projects*, John Wiley and Sons Ltd., Chichester, UK, pp. 103–126.
- Shields, F. D., Cooper, C. M., Knight, S. S. & Moore, M. (2003). Stream corridor restoration research: a long and winding road, *Ecological Engineering* **20**: 441–454.
- Shields, F. D., Copeland, R. R., Klingeman, P. C., Doyle, M. W. & Simon, A. (2003). Design for stream restoration, *Journal of Hydraulic Engineering-Asce* **129**(8): 575–584.
- Singh, V. P. & Woolhiser, D. A. (2002). Mathematical modeling of watershed hydrology, *Journal of Hydrologic Engineering* **7**(4): 270–292.
- Sit, V. & Taylor, B. (eds) (1998). *Statistical Methods for Adaptive Management Studies*, Vol. Land Management Handbook No. 42, Research Branch, B.C. Ministry of Forests, Victoria, B.C.
- Smeets, E. & Weterings, R. (1999). Environmental indicators: Typology and overview, *Technical Report Technical Report No 25*, European Environment Agency.
- Soar, P. J. & Thorne, C. R. (2001). Channel restoration design for meandering rivers, *Technical Report ERDC/CHL CR-01-1*, U.S. Army Corps of Engineers, Engineer Research and Development Center.

- Stanford, J. A., Ward, J., Liss, W. J. ., Frissell, C. A., Williams, R. N., Lichatowich, J. A. & Coutant, C. C. (1996). A general protocol for restoration of regulated rivers, *Regulated Rivers: Research and Management* **12**: 391–413.
- Stockwell, B. R. (2000). *The Mary River and tributaries rehabilitation plan: a review of river processes, fluvial geomorphology and ecological concepts and their application to a river rehabilitation plan for a major South-East Queensland catchment*, Masters dissertation, University of New England.
- Taylor, B. N. & Kuyatt, C. E. (1994). Guidelines for evaluating and expressing the uncertainty of nist measurement results, *Technical Report NIST Technical Note 1297*, United States Department of Commerce: National Institute of Standards and Technology.
- Tockner, K. & Stanford, J. A. (2002). Riverine flood plains: present state and future trends, *Environmental Conservation* **29**(3): 308–330.
- Trochim, W. M. (2000). *The Research Methods Knowledge Base, 2nd Edition*, Atomic Dog Publishing, Cincinnati, OH.
- Trush, W. J., McBain, S. M. & Leopold, L. B. (2000). Attributes of an alluvial river and their relation to water policy and management, *Proceedings of the National Academy of Sciences of the United States of America* **97**(22): 11858–11863.
- USEPA (1989). Nonpoint sources: agenda for the future, *Technical Report WH-556*, U.S. Environmental Protection Agency: Office of Water.
- Van Asselt, M. (2000). *Perspectives on uncertainty and risk: The PRIMA approach to decision support*, Ph.d.-thesis, Kluwer Academics Publishers.
- van Asselt, M. B. A. & Rotmans, J. (2002). Uncertainty in integrated assessment modelling - from positivism to pluralism, *Climatic Change* **54**(1-2): 75–105.
- van Witteloostuijn, A. (1987). *Uncertainty in Psychology: A Look beyond the Non-Differentiated Approach*, PhD thesis, Maastricht University.
- Varis, O. (1997). Bayesian decision analysis for environmental and resource management, *Environmental Modeling and Software* **12**(2-3): 177–185.
- Vitousek, P., Mooney, H., Lubchenco, J. & Melillo, J. (1997). Human domination of earth's ecosystems, *Science* **277**: 494–499.
- von Schomberg, R. (ed.) (1993). *Controversies and Political Decision Making*, Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Walker, J., Diamond, M. & Naura, M. (2002). The development of physical quality objectives for rivers in england and wales, *Aquatic Conservation-Marine and Freshwater Ecosystems* **12**(4): 381–390.

- Walters, C. (1997). Challenges in adaptive management of riparian and coastal ecosystems, *Conservation Ecology [online]* **1**(2): 1. Available from the Internet. URL: <http://www.consecol.org/vol1/iss2/art1>.
- Ward, J. V. & Tockner, K. (2001). Biodiversity: towards a unifying theme for river ecology, *Freshwater Biology* **46**: 807–819.
- Ward, J. V., Tockner, K., Arscott, D. B. & Claret, C. (2002). Riverine landscape diversity, *Freshwater Biology* **47**(4): 517–539.
- Ward, T. (1998). Chapter 6: Risk and uncertainty in environmental policy evaluation, in M. H. I. Dore & T. D. Mount (eds), *Global Environmental Economics: Equity and the Limits of Markets*, Blackwell Publishers, UK, pp. 116–135.
- Werritty, A. (2002). Living with uncertainty: climate change, river flows and water resource management in scotland, *The Science of The Total Environment* **294**(1-3): 29–40.
- Wheaton, J. M. (2003). *Spawning Habitat Rehabilitation*, M.s. thesis, University of California at Davis.
- Wheaton, J. M., Darby, S. E. & Sear, D. (In Review). Chapter three: Scope of uncertainty in river restoration, in S. E. Darby & D. Sear (eds), *Uncertainties in River Restoration*, John Wiley and Sons Ltd, Chichester, U.K.
- Wheaton, J. M., Milne, J. A., Darby, S. E. & Sear, D. (In Prep). Does scientific conjecture accurately describe restoration practice? insight from an international river restoration survey, *Area* .
- Wheaton, J. M., Pasternack, G. B. & Merz, J. E. (2004a). Spawning habitat rehabilitation - i. conceptual approach and methods, *International Journal of River Basin Management* **2**(1): 3–20.
- Wheaton, J. M., Pasternack, G. B. & Merz, J. E. (2004b). Spawning habitat rehabilitation - ii. using hypothesis testing and development in design, mokelumne river, california, u.s.a., *International Journal of River Basin Management* **2**(1): 21–37.
- Wheaton, J., Sear, D. & Darby, S. E. (2004). Preliminary results of an international river restoration survey, *River Restoration Centre Annual Network Conference*, Durham, UK, p. Poster.
- Wheaton, J., Sear, D., Darby, S. & Milne, J. (2004). The international river restoration survey. internet url: http://www.geog.soton.ac.uk/users/WheatonJ/RestorationSurvey_Cover.asp.
- Wilcock, P. R. (2001). Toward a practical method for estimating sediment-transport rates in gravel-bed rivers, *Earth Surface Processes and Landforms* **26**: 1395–1408.

- Willson, M. F. & Halupka, K. C. (1995). Anadromous fish as keystone species in vertebrate communities, *Conservation Biology* **9**(3): 489–497.
- Wilson, D. W. (2001). *On the Problem of Indeterminacy in Fluvial Geomorphology*, Ph.d. thesis, University of Southapton.
- Wissmar, R. C. & Beschta, R. L. (1998). Restoration and management of riparian ecosystems: a catchment perspective, *Freshwater Biology* **40**: 571–585.
- Wissmar, R. C. & Bisson, P. A. (2003a). 1. strategies for restoring river ecosystems: Sources of variability and uncertainty, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 3–7.
- Wissmar, R. C. & Bisson, P. A. (2003b). 11. strategies for restoring rivers: Problems and opportunities, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 245–262.
- Wissmar, R. C. & Bisson, P. A. (eds) (2003c). *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland.
- Wissmar, R. C., Braatne, J., Beschta, R. & Rood, S. B. (2003). 5. variability of riparian ecosystems: Implications for restoration, in R. C. Wissmar, P. A. Bisson & M. Duke (eds), *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, 1st edn, American Fisheries Society, Bethesda, Maryland, pp. 107–127.
- Wohl, E. E. (1998). Uncertainty in flood estimates associated with roughness coefficient, *Journal of Hydraulic Engineering-Asce* **124**(2): 219–223.
- Zadeh, L. A. (1965). Fuzzy sets, *Information and Control* **8**(3): 338–353.
- Zadeh, L. A. (1996). Fuzzy logic = computing with words, *IEEE Transactions on Fuzzy Systems* **4**(2): 103–111.
- Zak, S. K. & Beven, K. J. (1999). Equifinality, sensitivity and predictive uncertainty in the estimation of critical loads, *The Science of the Total Environment* **236**: 191–214.
- Zapert, R., Gaertner, P. & Filar, J. (1998). Uncertainty propagation within an integrated model of climate change, *Energy Economics* **20**: 571–598.
- Zsuffa, I. (2000). *Multi-criteria decision support for revitalization of river floodplains*, Doctoral dissertation, Wageningen University.