



3 The Scope of Uncertainties in River Restoration

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3.1 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 *et al.*, 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 (Malakoff, 2004; Sear and Darby, In Review). One of the premises of this book 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). 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 established in Chapters One and Two. Lemons and Victor (This Volume) illustrated how deep the value-laden dimensions of uncertainties lie not just in decision making, but in scientific research as well. Graf *et al* (This Volume) expanded on these uncertainties in river restoration research, citing uncertainties from theories, the research itself, communication and biases among investigators. Graf *et al* (This Volume) concluded that the research can either ‘ignore the

uncertainty and hope that it is not debilitating for the project at hand, or accept the uncertainty and use it as a feature of the research.’ In this chapter we present the rich topic of uncertainty in a broader, more generic context. This foundation is intended to help the reader separate the sources and types of uncertainties that the various authors in this book present, and meanwhile unravel some ambiguities surrounding uncertainty in river restoration.

The narrative for this chapter will unfold as follows. As cautioned in earlier chapters, potentially significant uncertainties are rarely recognised, much less explicitly dealt with in the increasingly popular science and practice of river restoration. First, we will outline a lexicon and typology for uncertainty to explicitly show what we mean by ‘uncertainty.’ The form of uncertainties faced in specific applications of river restoration are similar to those encountered in more general environmental management problems. Hence, environmental management is used as a context to delineate the scope of uncertainty in river restoration. 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.

3.1.1 The Status-Quo in River Restoration

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; Graf, 1996). It is encouraging that so much enthusiasm exists to restore rivers. Yet, it is interesting to note the societal choice between reactive restoration efforts in response to damage already done, as opposed to proactive conservation action to prevent further damage (Boon, 1998). The international popularity of river restoration is evident in the restoration literature (e.g. restoration in 21 different countries reported in Nijland and Cals, 2000), restoration databases (e.g. RRC, EPA)², and an International River Restoration Survey³ launched by Wheaton *et al.* (2004c) with respondents from 34 different countries. In Denmark alone, 1068 restoration projects had been completed by Danish regional authorities by 1998 (Hansen and Iversen, 1998); whereas in the United States, Malakoff (2004) reported that by 2004 more than \$US10 Billion has been spent on more than 30,000 projects. 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 (Jungwirth *et al.*, 2002). However, their effectiveness is constrained by limited funds and scope to deal with closely related landuse issues and other socio-political goals (Tockner and Stanford, 2002).

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

² RRC Database includes over 750 projects within the United Kingdom: <http://www.therrc.co.uk>; the USEPA River Corridor and Wetland Restoration Database includes over 600 projects throughout the United States: <http://yosemite.epa.gov/water/restorat.nsf/rpd-2a.htm>.

³ Complete real-time results, background information and forthcoming interpretations are available on the web: http://www.geog.soton.ac.uk/users/WheatonJ/RestorationSurvey_Cover.asp.

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). From restoration's popularity, 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 and 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 (Mount, 1995; Collins *et al.*, 2000; Moss, 2004). 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). 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.*, This Volume), 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; Lemons and Victor, This Volume). Additionally, the good intentions of restoration projects may lead to unintended, but often foreseeable consequences. 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.

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.*, This Volume). Aside from indirect references to uncertainty in adaptive management programs, the river management community has largely brushed uncertainties aside (Clark, 2002; Wissmar and Bisson, 2003a). 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 (This Volume) 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 (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, 2000b), it is unlikely that restoration will avoid political scrutiny indefinitely. Uncertainty is frequently misunderstood by the general public (Riebeek, 2002), and presumably the majority of the restoration community, as something negative and undesirable (Newson and Clark, This Volume). A widespread misconception that science embodies certain knowledge persists in the reports of the mainstream media and views of the general public (Clark, 2002; Riebeek, 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).

Restoration science and the restoration literature are not much further along than practitioners and decision makers. Wissmar & Bisson (2003c) 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 and Shields, 1996) and a handful of explicit treatments (Johnson and Rinaldi, 1997; Johnson and Rinaldi, 1998; Johnson and Brown, 2001; Johnson *et al.*, 2002; Wissmar and Bisson, 2003a). 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 uncertainty, a more holistic treatment of uncertainty is necessary (Van Asselt, 2000; Newson and Clark, This Volume). 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.

3.2 What do We Mean by Uncertainty?

3.2.1 A Lexicon of Uncertainty

In the simplest sense, uncertainty can be a lack of sureness about something or someone (Merriam-Webster, 1994). However, uncertainty can be more than simply a lack of knowledge. It persists even in areas where knowledge is quite extensive; and knowledge does not necessarily equate to truth or certainty (van Asselt and Rotmans, 2002). There are at least 24 potential synonyms for the noun uncertainty and 27 synonyms for the adjective uncertain (Table 1). There are a number of concepts related to and influenced by uncertainty, but which differ from uncertainty itself. A non-exhaustive selection of these concepts are considered briefly below.

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.

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; 1996b) 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 from accuracy, 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 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 and 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 of total uncertainty (complete irreducible ignorance) and absolute certainty. Probabilistic uncertainty is an example of a quantification of uncertainty, yet not all

uncertainty is quantifiable. To quantify uncertainty it is necessary to estimate the degree of our limited knowledge. Yet, 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 also be considered along a continuum that reflects our ability to quantify it (Figure 1).

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 abovementioned concepts that are influenced by uncertainty. Moreover, the lexicon provided here contains concepts that 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 unravelled and an attempt to understand it is made.

3.2.2 A Typology for Uncertainty

Since uncertainty is so hard to define, classification of uncertainty is often used (van Asselt and 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. 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 was first introduced in detail in Van Asselt (2000) and concisely reviewed in Rotmans & Van Asselt (2001) and van Asselt & Rotmans (2002).

At the highest level, two sources of uncertainty exist: uncertainty due to variability and uncertainty due to limited knowledge (Figure 2). van Asselt & Rotmans (2002) provided the following helpful distinctions and references to similar terminology:

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 and Ben-Haim, 1996), “stochastic uncertainty” (Helton, 1994), “primary uncertainty” (Koopmans, 1957), “external uncertainty” (Kahneman and Tversky, 1982) or “random uncertainty” (Henrion and 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” (Helton, 1994; Natke and Ben-Haim, 1996), “incompleteness of the information” (von Schomberg, 1993), “informative uncertainty” (van Witteloostuijn, 1987; Bandemer and Gottwald, 1995; Natke and Ben-Haim, 1996), “secondary uncertainty” (Koopmans, 1957) or “internal uncertainty” (Kahneman and 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 (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’. The natural variability of river systems should be a fundamental consideration in integrated river basin management and restoration and was reviewed thoroughly in Wissmar & Bisson (2003a). 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 and 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 and Clark, In Review). However, within the context of this chapter, the Van Asselt (2000) typology and associated meanings will be used consistently.

3.2.3 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 and 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 and 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 ‘normal science is predicated on the belief that knowledge and information reduce uncertainty.’ He then pointed out that Zadeh’s principle of incompatibility suggests the exact opposite is true for complex systems. Figure 3 illustrates a few examples of potential relationships between knowledge and uncertainty using the nomenclature of the Van Asslet typology.

Now that the basic terminology of uncertainty is established, we can proceed into reviews of existing tools within environmental management (see Section 3.3) and science (see Section 3.4) 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).

3.3 Existing Uncertainty Tools within Environmental Management

Uncertainties in decision-making, policy-making and management stem from both scientific sources (see Section 3.4) and socio-political sources (Alario and Brun, 2001; Rotmans and 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, behavioural 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; Lemons and Victor, This Volume). However, decision-makers have always implicitly dealt with uncertainties, and humans are quite well adapted to making decisions about complex problems with incomplete information (Anderson *et al.*, 2003; Pollack, 2003). 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 (Rotmans and Van Asselt, 2001; Lempert *et al.*, 2003).

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 2). Decision support systems, adaptive management, the precautionary principle are the uncertainty tools considered below, which map onto specific stages within this decision process.

3.3.1 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). Most decision support systems are computational 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 and Jensen, 2004). 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; Reynolds *et al.*, 2000; Adriaenssens *et al.*, 2003; Lempert *et al.*, 2003), but have only been sparsely applied to river restoration (Clark and Richards, 2002). The few noteworthy exceptions tend to be academic case studies and pilot projects (e.g. Zsuffa, 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 and 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 and 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 logic⁴ 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

⁴ See section 3.4.3.4 for review of fuzzy logic tools.

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).

3.3.2 Adaptive Management

Both the environmental management and river restoration literature generally support the model of adaptive management (FISRWG, 1998; Clark, 2002). Walters (1997) described adaptive management as ‘a structured process of learning by doing’ (see Figure 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 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.

3.3.3 *Precautionary principle*

The precautionary principle is a direct acknowledgement of scientific uncertainty, which 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 know⁵, 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 and Kaszuba, 2002). deFur & Kaszuba (2002) outlined four basic elements of the precautionary principle:

- ‘There is a threat of harm, either credible or known’
- ‘The situation presents a lack of scientific certainty or evidence’
- ‘Cause and effect relationships are not yet proven’
- ‘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 and Kaszuba, 2002). More recently, the Water Framework Directive (2000) explicitly promotes the precautionary principle:

⁵ This is an example of a structural uncertainty due to conflicting evidence, see page ___.

‘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 and Kaszuba, 2002).

3.4 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, most of these treatments are limited to certain classes of problems and types of uncertainty (Klir and 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.

3.4.1 Communicating Uncertainty in Observations

3.4.1.1 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 and 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 3.2.1 and guidelines for standard statistical techniques are readily available (e.g. Routledge, 1998). 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. If any of these assumptions are violated, ‘standard statistical analyses may not work properly.’ These assumptions are frequently violated but the techniques 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 & Smart (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.

3.4.1.2 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. 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.

3.4.1.3 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 and 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 and 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 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 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 and Heil, 1996; Schulz and 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. To acknowledge and quantify the implications of these uncertainties, Johnson & Heil (1996)

represented each of these values as fuzzy numbers and performed subsequent calculations with fuzzy mathematical operations.

3.4.2 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 and Gupta, 1994), and are covered in later subsections. First, an overview of the sources of uncertainty in environmental models is provided. Cao & Carling (2002b) 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 and 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 and Thorne, 1996), equilibrium channel morphology models (Sear and 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 & Carling (2002a; 2002b) attribute the structural 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.* (This Volume) 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.’

In their review of Integrated Assessment Models (including atmospheric models) Rotmans & Van Asselt (2001) considered how unreliability uncertainty and structural uncertainty⁶ influence modelling (Table 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 parameters), cease to provide more valuable predictions?

⁶ Recall, unreliability and structural uncertainties are types of uncertainty due to limited knowledge; see Figure 2.

3.4.2.1 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 and Woolhiser, 2002). Beven (1996a) 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 uncertainties⁷, 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

⁷ Structural uncertainties here are referring to the structure of the model (i.e. which processes are represented with which equations).

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 (Bergerud and Reed, 1998) made the same warnings, and add significance tests, P-values and the frequentist paradigm to the statistical toolkit they claim is inadequate in ecosystem management. Klir & Yuan (1995) contrasted statistical methods with traditional analytical methods (e.g. calculus) to map out the two extremes of problems that analytical and statistical techniques can address:

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

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.

3.4.2.2 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 and 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. 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 might be used to account for the risks of project failure associated with uncertainty. 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 and Reed, 1998). Among the shortcomings of Bayesian frameworks are the assumptions that the causality within a system is known (Addin and 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).

3.4.2.3 Monte Carlo Models

In environmental models, Monte Carlo simulations can be used to incorporate uncertainty. In essence, a random number generator is 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 equifinality (i.e. the same result for different reasons) of different model structures (Beven, 1996b; Hankin *et al.*, 2001). Within this context, equifinality is used to reject the notion of an 'optimal' model (Binley *et al.*, 1991; Zak and Beven, 1999; Brazier *et al.*, 2000; Brazier *et al.*, 2001). Beven (1996a) advocated instead disaggregating the information to reveal that multiple reasonable model structures exist, which are rather elegantly explained by our uncertainties.

3.4.2.4 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 and 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 Science revealed that more recent article contributions might have not since bridged this apparent gap. 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.

A promising example of fuzzy modelling in river restoration has emerged in an ecohydraulic habitat suitability model similar to PHABSIM, which was developed using fuzzy logic as an alternative or augmentation to traditional habitat suitability curves (Schneider and 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 and 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 apparent 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 and 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 and Gottwald, 1995; Klir and Yuan, 1995; Openshaw, 1996; 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.

3.5 Revisiting River Restoration and Uncertainty

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; Lemons and Victor, This Volume). 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 *et al.* (2003), we use ‘river restoration’ loosely in this book 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 due to historical, spatial and value-laden contingencies and their corresponding uncertainty in river restoration motives, notions and approaches.

3.5.1 *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.*, This Volume). 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’). Nine common types of motives for river restoration (still others exist) are listed below:

- Ecosystem Restoration
- Habitat Restoration
- Flood Control/Defence
- Floodplain Reconnection
- Property and Infrastructure Protection (bank stability)
- Sediment Management
- Water Quality
- Aesthetic and Recreational

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 restoration. In another example, water quality restoration could be viewed as sediment management or to others as aesthetic or recreational 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 (Kondolf, 1995a; Jungwirth *et al.*, 2002; Skinner *et al.*, This Volume). 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 restoration 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...’

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 expectations⁸ restoration is unlikely to achieve (Rutherford *et al.*, This Volume). 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

⁸ This is fundamentally a communication uncertainty resulting from socio-political value diversity; see Figure 1.

and uncertainties. Interestingly, these objectives are consistent with Clark's (2002) critical synopsis of Predictive Management as the current model in river management.

3.5.2 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 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 and 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 savannah (Alario and 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 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 functions⁹. Such a conceptual model should identify both the historical context and the present day limitations (i.e. uncertainties). Wheaton *et al.* (Wheaton *et al.*, 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. (This Volume) 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. (This Volume) 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 and Weterings, 1999; Doyle *et al.*, 2000; Levy *et al.*, 2000; Merkle and 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 (Lemons and Victor, This Volume), the interpretations and decision whether or not to proceed with restoration is ultimately a political one (Alario and Brun, 2001).

3.5.3 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

⁹ In principle, the process of 'rigour' in restoration planning still follows the generic environmental management decision process of Table 4. In essence what Phillip Williams, a seasoned practitioner, describes is an informal DSS.

implement these components rather appropriately reflects the varied types (motives) of restoration projects and physiographic settings they are applied in. Thus, historical and spatial contingencies are contributing to uncertainties due to *natural variability* (Phillips, 2001). Approaches are thorough outlines and guides to restoration whereas strategies provide only key considerations and tactics. A plethora of restoration approaches and strategies have been formalised in both the peer-reviewed and grey literature (Wheaton *et al.*, 2004a). Examples range from generalised approaches for stream restoration (e.g. NRC, 1992; FISRWG, 1998; Koehn *et al.*, 2001; 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 (Miller *et al.*, 2001; Shields *et al.*, 2003; Wheaton *et al.*, 2004b). Most of the approaches have parallels in structure and ideology (Wheaton *et al.*, 2004a).

Popular labels used to describe restoration approaches include holistic, science-based, integrated and multi-disciplinary (Hildén, 2000; Jungwirth *et al.*, 2002; Wissmar and Bisson, 2003b). Since most approaches purport or aim to be all of these (Wheaton *et al.*, 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 restoration¹⁰. 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 (e.g. Brookes and Shields, 1996; Bohn and 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 (e.g. 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 and 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 includes 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 *et al.*, 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 (Rosgen, 1996; Malakoff, 2004) both rely heavily on analogues. McDonald *et al.* (In Press) referred to analogues or reference conditions as ‘templates.’ Jungwirth *et al.* (2002) suggested that at least three methods for selecting analogue or reference conditions exist:

¹⁰ See also Table 1.

- Select an existing reference site with ‘desirable’ conditions (location substitution?).
- Select a historical reference condition for the site of interest on the basis of historical analysis (time for space substitution?).
- 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 *et al.*, 2004a). Although the exact interpretations are themselves uncertain and will continue to spur debate over semantics (*conflicting evidence* uncertainties), most concur that consideration of sustaining processes is fundamental (Wheaton *et al.*, 2004c).

Fundamental methodological disagreements arise in the restoration literature with respect to passive versus active approaches to river restoration (Wissmar and 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 and 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 and Bolton, 2003). The choice of a passive versus active approach will depend

very much on the specific social, political, economic and environmental contingencies of individual river basins (Wissmar *et al.*, 2003), as well as the extent to which initial conditions matter (Phillips, 2002). Wheaton *et al.* (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 kick-start recovery. Ultimately, all these choices are fuelled by an uncertain conceptual understanding of the system 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 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 (Lister, 1998; Clark, 2002).

3.6 A Way Forward?

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.*, This Volume). 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 and Victor, This Volume). As already mentioned, humans are quite comfortable with the uncertainties of life in an intuitive and non-explicit sense (Anderson *et al.*, 2003; Pollack, 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 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 6. Each of these philosophies is reviewed in the remaining subsections and linked to current attitudes within different segments of the river restoration community.

3.6.1 Ignore Uncertainty

I have already argued that the current restoration community has tended to passively ignore uncertainty 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). Now that public support exists for river restoration, so too does the expectation¹¹ that the problems river restoration addresses are well understood. As was demonstrated in Section 3.6, 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.

3.6.2 Eliminate Uncertainty

The positivist view of the world has fuelled 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 and Yuan, 1995; Priddy, 1999; van Asselt and 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

¹¹ See Section 3.3.1 for relationship between expectation and uncertainty.

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 and 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 chapter 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.

3.6.3 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 and Yuan, 1995). Figure 6 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. 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 and Clark, This Volume).

3.6.4 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. 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).

3.6.5 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 (Johnson and Brown, 2001; Newson and Clark, This Volume). 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 and Richards, 2002; Pollack, 2003). Especially in long-term policy analysis (next 20-100 years)²¹, decision makers are faced with what Lempert et al. (2003) referred to as ‘deep uncertainty’. Johnson and 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. We 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 and Bolton, 2003; Clifford *et al.*, This Volume).

In Figure 7, the notions of embracing uncertainty are synthesized 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 diverse¹² 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. van Asselt and Rotmans, 2002; Lempert *et al.*, 2003).

The embracing uncertainty framework proposed here embraces this 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 (This Volume), 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

3.7 Conclusion

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 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

¹² See Section 3.5 for demonstration of this variability specifically in river restoration.

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.

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. We argue that it is unethical to assume that the uncertainty is insignificant. There 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 (Lister, 1998; Falkenmark and Folke, 2002)¹³. Thus, an emerging challenge the restoration community is faced with is combining these dimensions to ‘do the right thing right.’ 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, we conclude that embracing uncertainty could also help transcend the scientific research and decision making boundaries in river restoration.

¹³ Recall 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’).

References in Figures

(Chapman and Ward, 2002)

(van Asselt and Rotmans, 2002)

(Van Asselt, 2000)

(Kondolf, 2000a)

(Schumm and Lichty, 1965)

(Hruby, 2003)

(Trush *et al.*, 2000; Newson, 2002; Ward *et al.*, 2002; Cairns, 2003)

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Table Captions

Table 1: Potential synonyms of the noun ‘Uncertainty’ and the adjective ‘Uncertain.’

Table 2: 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.

Table 3: Influence of Uncertainties due to Limited Knowledge on Modelling. Adapted from van Asselt & Rotmans (2002).

Table 4: Common notions that drive motives and guide river restoration efforts.

Figure Captions

Figure 1: The Quantifiable Continuum of Uncertainty. Notice that once uncertainties are acknowledge as unquantified uncertainties, increased knowledge about the uncertainties will determine their position on the continuum.

Figure 2: Typology for sources and degree of uncertainty. Adapted from Van Asselt’s (2000) proposed typology for uncertainties in integrated assessment.

Figure 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 and Figure 1.1 for definitions of uncertainty types.

Figure 4: Adaptive Management in River Restoration. From Kondolf (2000b).

Figure 5: Crisp versus fuzzy, representations of a temperature classification. Adapted from Klir and Yuan (1995).

Figure 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.

Figure 7: Embrace Uncertainty Strategy. Framework for embracing uncertainty in decision making process. This framework relies on the Van Asselt (2000) typology of uncertainty.

Table 1

Synonyms of Uncertainty	Synonyms of Uncertain
Ambiguity	Ambiguous
Indeterminacy	Causeless
Capriciousness	Capricious
Chance	Probabilistic
–	Deferred
Danger	Dangerous
Disbelief	Disbelieving
Equivocation	Equivocal
Doubt	Doubtful
–	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: Potential synonyms of the noun ‘Uncertainty’ and the adjective ‘Uncertain.’

Table 2

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 organization 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 2: 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.

Table 3

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 uncertainties

Table 3: Influence of Uncertainties due to Limited Knowledge on Modelling. Adapted from van Asselt & Rotmans (2002).

Table 4

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 Nature Balanced	'confidence on global stability; there are no limitations to development' -(Levy et al. 2000). '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 Nature Resilient	'the environment can not safely tolerate human modifications' -(Levy et al. 2000). '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 Morphological Diversity = Biological Diversity	Natural systems foster biodiversity and artificial systems are homogenized and dominated by invasive species (Ward et al. 2002, Lister 1998). 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 4: Common notions that drive motives and guide river restoration efforts.

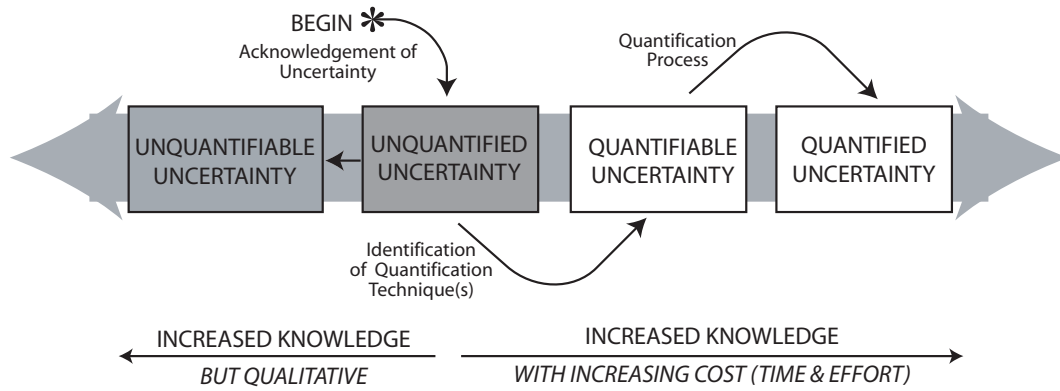


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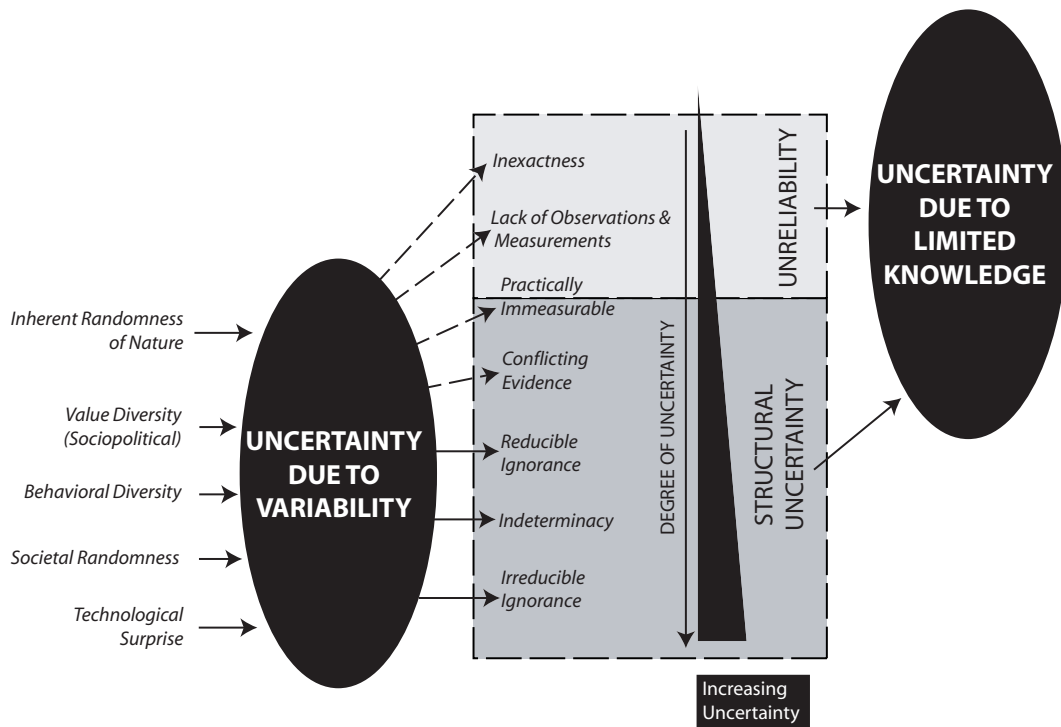


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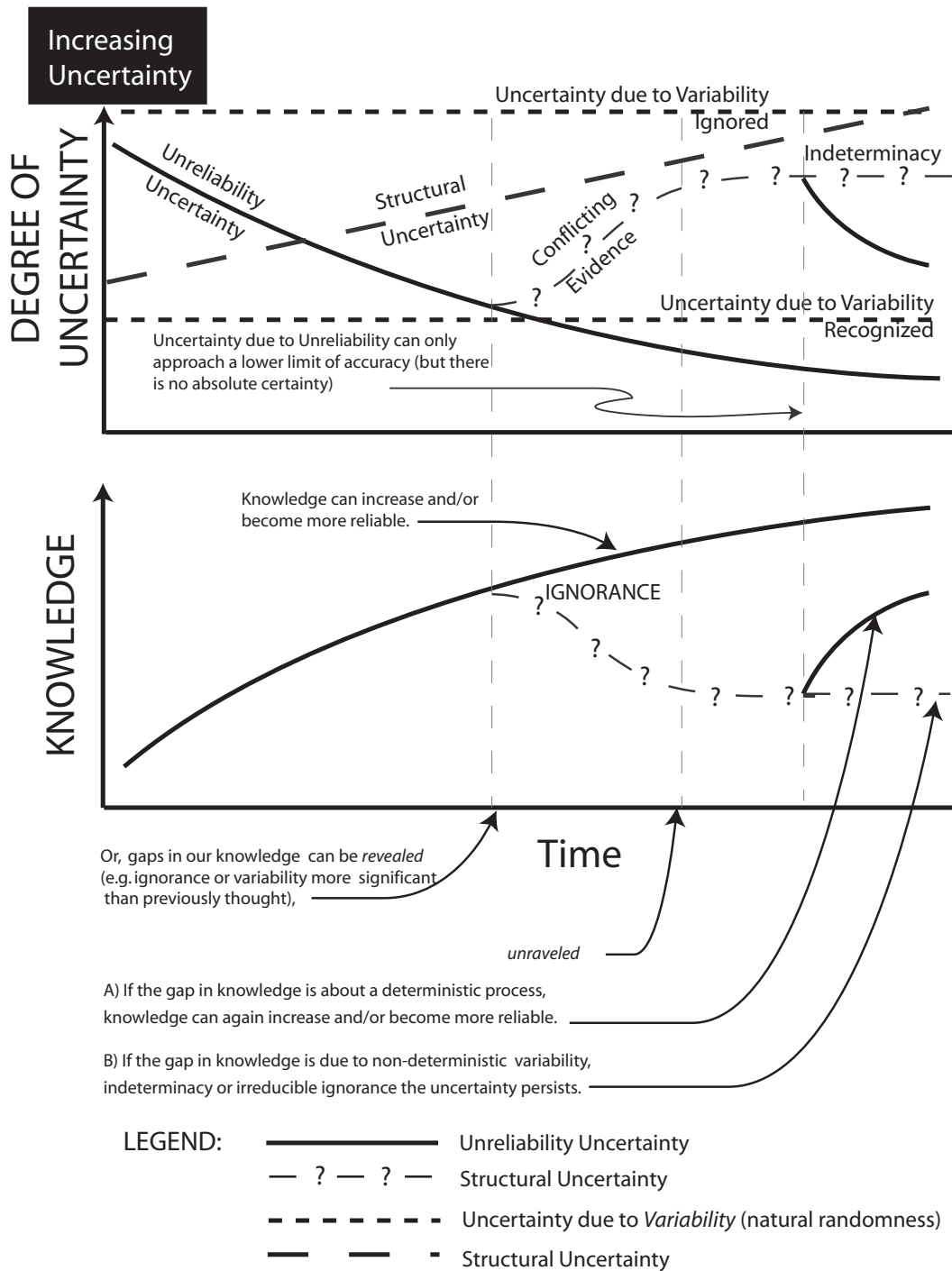


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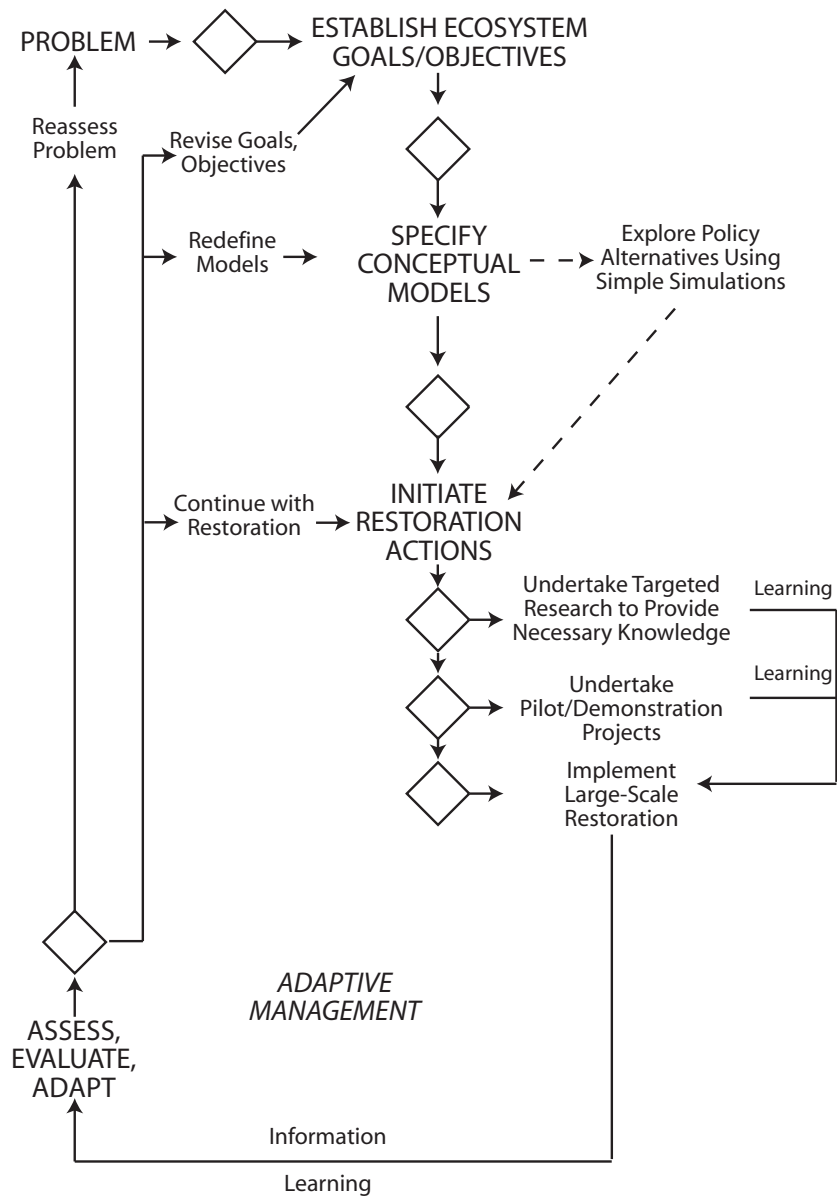


Figure 4: Adaptive Management in River Restoration. From Kondolf (2000b).

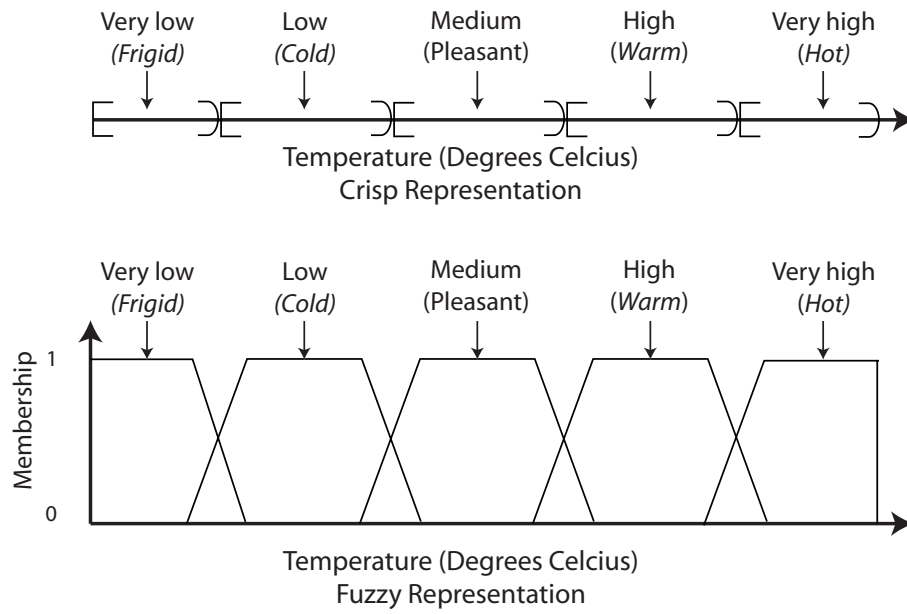


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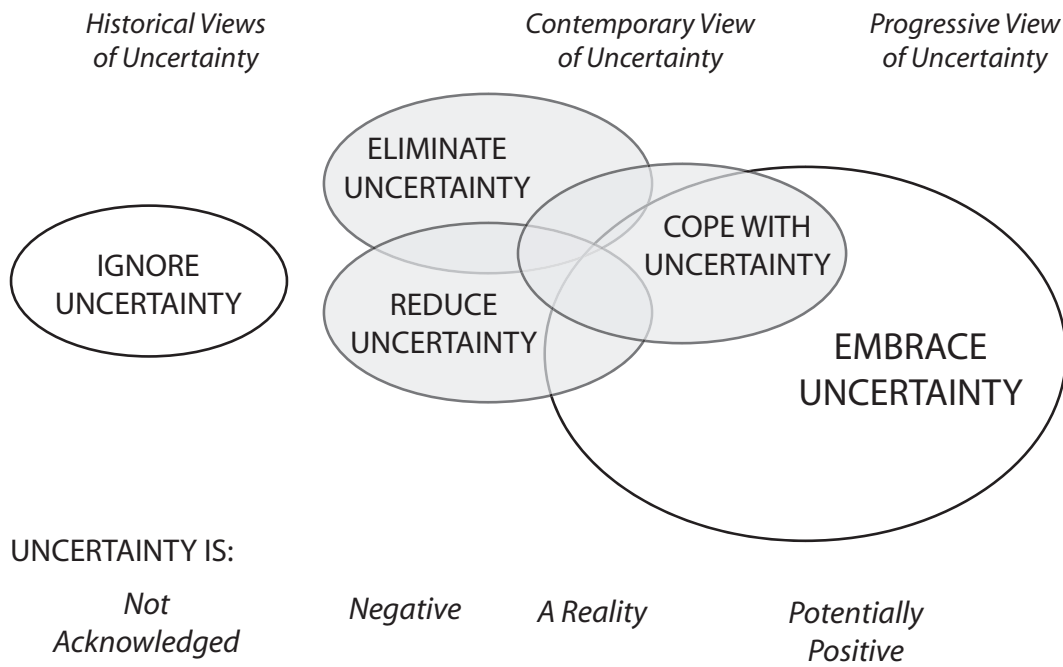


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