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# Adaptive management frameworks for natural resource management at the landscape scale: implications and applications for sediment resources

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**Abstract**
*Purpose* The management of natural resources over large spatial scales is inherently complex due to numerous biophysical and socioeconomic factors and the uncertainty associated with environmental systems and human behavior. Numerous approaches have been put forward to facilitate the decision-making process, including adaptive management (AM) which was developed in the 1960s and 1970s as an alternative to more rigid management frameworks. In recent years, it has been utilized for the management of water and river basin resources, particularly in North America. Its use for sediment resources is less well developed. This paper presents a review of the AM approach, including its characteristics, steps, and barriers to implementation. It also gives some recent examples where the AM approach has been used for sediment quantity and quality issues. Finally, it considers the potential of the AM approach for sediment resource management given Water Framework Directive and other legislative requirements.
*Conclusions, recommendations, and perspectives* It is felt that while the AM approach offers many advantages, there are some institutional barriers to its wider uptake amongst those involved with the management of sediment resources. Some recommendations for implementation and for future research are presented.

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## 1 Introduction

While the concept of adaptive management (AM) has a history of several decades for the management of natural resources, it is only recently that it has been linked to sediment management. Several publications have put forward various conceptual and strategic frameworks for sediment management (e.g., Apitz and White 2003; Apitz et al. 2007; White and Apitz 2008), including those that specifically encompass the concept of AM (Owens et al. 2008; Slob and Gerrits 2008). Recently, Apitz (2008) has requested that there needs to be more discussion on the role of AM within sediment management. The aim of the paper is to contribute to this discussion by presenting some information on the development and characteristics of AM, and how it may be used for managing sediment resources.

## 2 Developmental history and definitions

There is reasonable agreement that the theory of AM was developed in British Columbia, Canada by C. S. Holling and colleagues at the University of British Columbia's Institute for Resource Ecology in the late 1960s (Smith 2008). It was originally called adaptive environmental assessment and management (AEAM; Holling 1978). Since this time, the concept of AM has been applied to a variety of different natural resources including forestry, fisheries, and wildlife conservation (Walters and Hilborn 1976;

Johnson and Williams 1999; AME 2003) and, more recently, to water resources and river basin management (Walters et al. 1992; Medema et al. 2008). A useful review of AM applications and case studies is presented in Linkov et al. (2006). In the case of river basins, the AM approach shares some common ground with integrated water resources management (Medema et al. 2008) and systems analysis (Bruen 2008).

Adaptive management was partly developed due to the limitations, and often failings, of other management approaches, which tended to be fairly rigid in design and implementation. Table 1 gives descriptions of four "traditional" approaches to resource management as identified by Johnson (1999). These "traditional" approaches tended to work best in relatively small and simple systems, but were less successful in large, ecologically complex situations with a high degree of uncertainty. This was because, in the case of the latter, there are usually numerous different components which interact both directly and indirectly, and because they are socially complex systems with multiple user groups who often have conflicting goals that involve multiple components of the system (Johnson 1999).

As Apitz (2008) correctly identifies, while the overarching concept of AM is fairly simple—that management should follow flexible rather than rigid guidelines—a precise definition is more elusive. Consequently, there are many different definitions of AM. One such definition, as put forward by the British Columbia Ministry of Forests and Range (BCMFR), is:

> "Adaptive management is a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form—active adaptive management—employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed." (BCMFR 2008).

Another operational definition is that developed by the U.S. National Research Council (NRC 2004) and is advocated by the U.S. Department of the Interior Adaptive Management Working Group:

> "Adaptive management [is a decision process that] promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a trial and error process, but rather emphasizes learning while doing. Adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions amongst stakeholders." (Williams et al. 2007).

Other definitions are listed in Table 2. While there are many different definitions, there are some common themes, usually represented by key words or phrases such as "uncertainty", "learning", "experimentation", "alternative hypotheses," and "operational approaches." We could also add to this list "change", "flux", "balance", "stakeholders", "sustainable", "cyclic," and "iterative," amongst others. Most, if not all, of these definitions are valid and

**Table 1** Examples of traditional approaches to natural resource management (adapted from Johnson 1999)

| Approach | Description |
|---|---|
| Political/social | The main concerns are public and political response to a decision. This approach sometimes dictates a specific course of action to appease a powerful interest or to keep options open for the future. However, a decision to do nothing or to delay an action until more data are available is often a political/social decision |
| Conventional wisdom | A historical method or rule-of-thumb approach that has been applied to similar situations in the past is used. Managers typically rely on historical knowledge of the situation and the resource involved and assume that the response to management will be similar to that experienced previously |
| Best current data | Current data collected through new or existing sampling is used to inform management decisions. Managers analyze these data using the latest technology, assess their management options, and then choose the best option to implement. The approach is appealing because it uses the best available knowledge and techniques |
| Monitor and modify | A policy decision is typically made using conventional wisdom or best-current-data methods, and then the policy is implemented along with a monitoring plan. Monitoring data are used to evaluate and periodically modify the policy relative to a specific goal. The purpose of periodic modifications is to "hone" the management policy and maintain the system in an optimal state |

**Table 2** Some definitions and operational descriptions of adaptive management (AM; modified from Farr (2000), BCMFR (2008), and references listed below)

| Definition | Source |
|---|---|
| AM is an integrated, multidisciplinary, and systematic approach to improving management and accommodating change by learning from the outcomes of management policies and practices | Holling (1978) |
| AM is an innovative technique that uses scientific information to help formulate management strategies in order to learn from programs so that subsequent improvements can be made in formulating both successful policy and improved management programs | Halbert (1993) |
| AM involves constructing a range of alternative response models (hypotheses) based on existing data, calculating the long-term value of knowing which is correct, and then weighing this long-term value against any short-term costs incurred in finding out which is correct. Active AM involves deliberately perturbing the system to discriminate between alternative models (hypotheses) | Taylor et al. (1997) |
| AM is a structured process of learning by doing that involves more than simply better ecological monitoring and response to unexpected management impacts. It should begin with a concerted effort to integrate existing interdisciplinary experience and scientific information into dynamic models that attempt to make predictions about the impacts of alternative policies | Walters (1997) |
| AM is a systematic process for continually improving management policies and practices by learning from their operational outcomes | Nyberg (1998) |
| AM is an approach to managing complex natural systems that builds on learning—based on common sense, experience, experimenting, and monitoring—by adjusting practices based on what was learned | Bormann et al. (1999) |
| AM is a systematic process for addressing the uncertainties of resource management policies by implementing the policies experimentally and documenting the results | MacDonald et al. (1999) |
| Typically, AM management begins by bringing together interested parties (stakeholders) in workshops to discuss the management problem and the available data and then to develop computer models that express participants' collective understanding of how the system operates. The models are used to assess the significance of data gaps and uncertainties and to predict the effects of alternative management actions. The stakeholders develop a management plan that will help to meet management goals and also generate new information to reduce critical gaps and uncertainties. The management plan is then implemented along with a monitoring plan. As monitoring proceeds new data are analyzed and management plans are revised as we improve our understanding of how the system works | Johnson (1999) |
| AM describes an iterative process designed to improve the rate of learning about the management of a complex system. The process incorporates an explicit acknowledgement of uncertainties and knowledge gaps about the response of the system to management actions. Reducing these uncertainties (i.e., learning) becomes one objective of management | Farr (2000) |
| AM is a structured method for "learning by doing" that includes established clear goals, defining practices to achieve those goals, implementing those practices, monitoring the outcome of those practices, assessing how those practices are succeeding relative to the goals, and adjusting management response to the assessments | Kremswater et al. (2002) |
| AM treats actions and policies as experiments that yield learning (it mimics the scientific method: specifies hypotheses, highlights uncertainties, structures actions to expose hypotheses to field tests, processes and evaluates results, and adjusts subsequent actions in light of those results), and embraces risk and uncertainty as opportunities for building understanding that might ultimately reduce their occurrence | Stankey et al. (2003) |
| AM is "learning by doing" with the addition of an explicit, deliberate, and formal dimension to framing questions and problems, undertaking experimentation and testing, critically processing results, and reassessing the policy context that originally triggered investigation in light of the newly acquired knowledge. The concept of learning is central to AM | Stankey et al. (2005) |
| AM is a formal process for continually improving management practices by learning from the outcomes of operational and experimental approaches. Four elements of this definition are key to its utility. First, it is adaptive and intended to be self-improving. Second, it is a well-designed formal approach that connects the power of science to the practicality of management. Third, it is an ongoing process for continually improved management, so the design must connect directly to the actions it is intended to improve. Fourth, although experimental approaches can be incorporated into adaptive management effectively, operational approaches and scales are emphasized to permit direct connection to the efforts of managers | Bunnell et al. (2007) |
| AM is a process to cope with uncertainty in understanding centered on a learning model where natural resource management actions are taken not only to manage, but also explicitly to learn about the processes governing the system | Medema et al. (2008) |
| AM is a planned and systematic processes for continuously improving environmental management practices by learning about their outcomes. AM provides flexibility to identify and implement new mitigation measures or to modify existing ones during the life of the project | CEAA (2009) |

useful. While the quest for a single definition of AM that is suitable for all users is probably unrealistic, what is clear is that the approach does need some formal guidelines for each specific operational program. In other words, people dealing with the management of a particular resource, such as a river basin or forest or sediment issue, need to agree on the reason why they have selected AM as an approach and agree on some rules by which they intend to use it. Otherwise, there will be confusion and confrontation.

## 3 Characteristics of adaptive management

There are several characteristics that shape what AM is. Farr (2000) states that the AM approach has the following key attributes:

- Decision makers, scientists, and other stakeholders work together and seek to enhance the understanding of the system they manage.
- Identification of: indicators, actions, and processes.
- Explicit predictions of outcomes and potential management actions on a suite of indicators, using simulation models or other projection tools. Exploration of trade-offs among alternative approaches.
- Identification of key uncertainties and knowledge gaps.
- Active AM typically involves (management) experiments implemented at an operational scale, designed to test hypotheses or qualitative relationships between management actions and changes in indicators.
- Monitoring of indicators.
- Evaluation of observed and predicted changes, diagnosis of reasons for differences, and assessment whether newly acquired knowledge justifies modification of management plans.

Similarly, according to BCMFR (2008), some of the characteristics of AM are:

- Learning to reduce key uncertainties. There is explicit acknowledgement of uncertainties and knowledge gaps about the response of the system to management actions. Reducing these uncertainties (i.e., learning) becomes one objective of management.
- Using what is learned to change policy and practice. Put a process in place to make certain that what is learned informs decisions (i.e., closing the loop). It is essential to have a good idea at the project design stage of what policies and practices may change and what institutional mechanisms are in place to support that change.
- Focus is on improving management. AM integrates the worlds of science and management, ensuring applied science is well directed to key uncertainties, and scientific advances are transferred to managers (i.e., this is where the learning is applied).
- Often called experimental management. AM is about thoughtfully applying management activities as experiments to see which are most effective in achieving desired goals.
- It is formal, structured, and systematic. AM is a deliberate process, not an ad hoc or simply reactionary one. Flexibility in the approach, however, is important to allow for the creativity that is crucial in dealing with uncertainty and change.

## 4 Types of adaptive management

There are several different types of AM that merit consideration. Walters (1986) proposed passive and active forms of AM (Fig. 1). With passive AM, due to the presence of uncertainty, managers implement the alternative they think is “best” (with respect to meeting management objectives), and then monitor to see if they were correct, making adjustments if desired objectives are not met. With active AM, due to the presence of uncertainty, managers implement more than one alternative as concurrent experiments to see which will best meet management objectives. It is characterized by actively probing the system in order to distinguish between competing hypotheses (where the different hypotheses suggest different optimal actions). The key is that there are alternatives that can be compared more confidently (BCMFR 2008; Smith 2008).

According to Smith (2008), active AM is the preferred approach to use when there is a high level of uncertainty about how effective the management actions will be in meeting the management goals and objectives when learning quickly is more important. Passive AM is a practical, lower cost choice and can be used when there is less uncertainty about the management option or when the institutional structure prevents management experimentation.

In addition to passive and active AM, workers have also introduced other types of AM, which are often specific to the resource issue being addressed. Thus, there is also evolutionary adaptive management (Walters 1986; AME 2003) “in which management policies and practices evolve in response to past performance and changing priorities. This trial and error approach to learning about management ecosystems is highly inefficient.” Adaptive co-management (ACM) is when the iterative learning of AM is combined with the linkages of collaborative management. The emerging concept of ACM is a collaborative approach to AM that engages governments, proponents, and planning participants explicitly in defining issues, developing management plans, and monitoring outcomes (Ruitenbeek and Cartier 2001).

One of the advantages of having several types of AM approach is that it increases the likelihood that the AM approach can be applied to complex natural resources like sediment, where management interventions are often scale-specific. It may be, therefore, that passive AM is more appropriate for small, site-specific interventions, such as sediment dredging, where the number of potential management options is low and where the uncertainty of the success of a management option is also low. At larger spatial scales, such as the river basin, active AM may be a better approach because the system is inherently more complex, and the outcomes of management interventions are uncertain. In this situation, it may be possible to

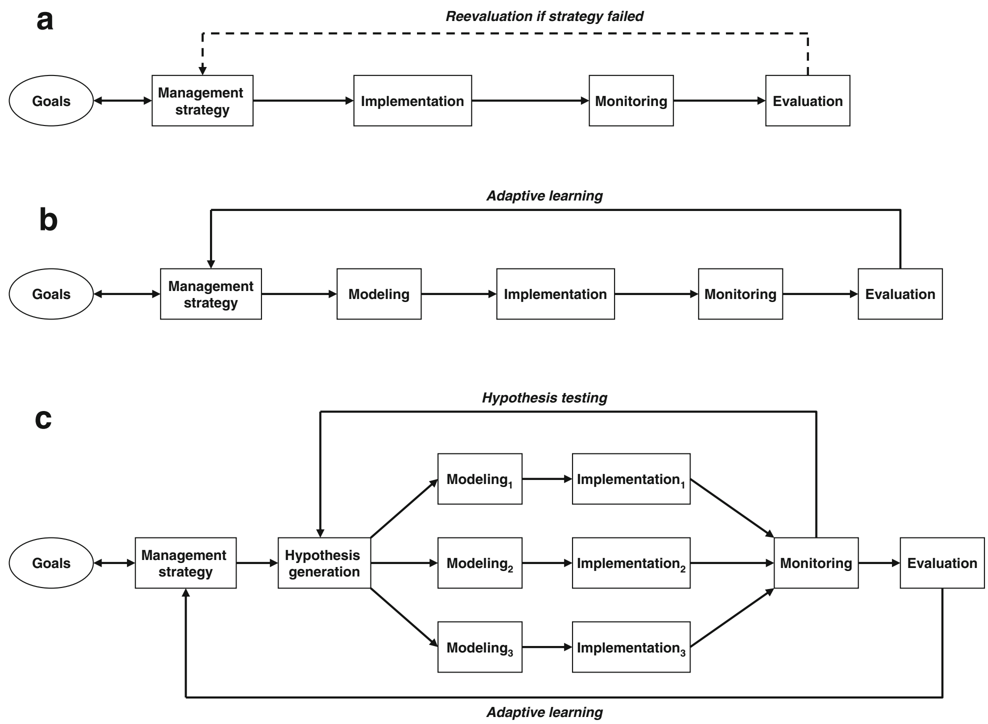


**Fig. 1** Types of approaches to management of natural resources. **a** Traditional management. **b** Passive adaptive management. **c** Active adaptive management (from Linkov et al. (2006) reproduced with the permission of Elsevier)

implement contrasting "experimental" treatments (e.g., land use change, land management, river use management) in different parts of the basin (e.g., subcatchments) in order to see how successful each treatment is in achieving the objective. In some instances, it may be possible to incorporate both passive and active AM approaches. Again, the selection may be one dictated by scale and level of uncertainty with passive AM (e.g., capping of contaminated sediment) nested within a larger scale active AM approach concerned with establishing optimal habitat conditions within a river basin.

## 5 Is adaptive management appropriate?

Given the information presented above on definitions and types of AM, it is useful to consider if AM is a suitable approach for a given situation. Goodman and Sojda (2008) state that AM is most effective when situations have the following characteristics:

- The stakes are high: mistakes can be expensive, but rewards from determining optimum management would also be high.
- There is consensus about management goals and how to recognize success. It must also be possible to objectively monitor progress toward reaching objectives.
- A spectrum of plausible management choices exists, and there is strong probability that at least some will work.
- Uncertainty in the system is considerable, complicating any attempt to make clear management choices by informal methods. And, there is a reasonable promise that uncertainty would significantly reduce (i.e., major decisions would be more straightforward) with well-designed experiments.

In a similar way, Smith (2008) suggests that a series of questions can help managers and other stakeholders decide if AM is a suitable approach:

- Is there support (institutional, stakeholder, and partner) to implement AM?
- Is there sufficient uncertainty regarding what management actions will best achieve the desired outcomes?
- Is a management experiment the best way to reduce this uncertainty (e.g., can you use retrospective analyses on data previously collected for some other purpose)?
- Can there be "safe failures" (i.e., failures, or unexpected outcomes different from those desired, are acceptable or reversible)?
- Is the response time short enough to learn something in the near future? (You can have short- and long-term objectives and indicators).
- Is sufficient monitoring feasible (i.e., measuring enough indicators long enough to account for natural variability and confounding factors)?
- Can you design a powerful enough management experiment to discern the effects of different management actions?

Williams et al. (2007) also present another useful set of criteria for deciding whether the AM approach is suitable for a particular resource management issue. In addition, Williams et al. (2007) also identify broad situations where the AM approach should not be employed if one or more of the following limitations apply:

- Decision making occurs only once.
- Monitoring cannot provide useful information for decision making.
- There are irresolvable conflicts in defining explicit and measureable management objectives or alternatives.
- Decisions that affect resource systems and outcomes cannot be made.
- Risks associated with learning-based decision making are too high.

When such limitations are encountered, Williams et al. (2007) suggest that decision makers should question whether AM is suitable and should consider other management approaches.

Inevitably, this raises the question as to whether AM is appropriate for sediment management. Potentially, the answer is yes. Sediment is a natural resource that is complex, and where the outcome of any single management action is uncertain. An iterative process which involves experimentation with management solutions and learning from this process would appear to be an appropriate way to proceed. However, there are some aspects of managing sediment resources that could limit the potential of the AM approach. For instance, there may not be: “consensus about management goals.” While not particular to sediment management, conflict over management goals or policy objectives is often more frequent or extreme with managing sediment. In consequence, it may not be possible to define “explicit and measureable management objectives or alternatives.” The case of Oslo harbor, Norway, is a good example here, where the perceptions of stakeholders and the lack of communication between the various stakeholders have resulted in confrontation and disagreement over management goals. A similar example is the management of sediment in the lower Fraser River in British Columbia, Canada. Here, sediment management goals differ radically between First Nations (aboriginals) concerned with erosion and flooding, and environmentalists concerned with habitat preservation (Globe and Mail 2008).

Another important concern is that, although sediment management at the site-specific scale (e.g., maintenance dredging, capping, reservoir management) has a relatively long history, at the river basin and landscape scales, typically, sediment does not merit its own management, but is instead incorporated within other resource management programs (e.g., habitats, water, estuaries). Thus the true potential and appropriateness of the AM approach at these larger spatial scales has yet to be evaluated. It may be that, at present, there is not the institutional structure in place for this to happen. Some other concerns over the appropriateness of the AM approach for sediment management are discussed in the sections below.

## 6 Steps in adaptive management

There are several procedural approaches to AM. Figure 2 shows the series of steps to be followed as recommended by the British Columbia Ministry of Forests and Range (Nyberg 1998; Sit and Taylor 1998; BCMFR 2008; Smith 2008) and the U.S. Department of the Interior (Williams et al. 2007), which are:

Step 1: Assess and define the problem

- Design scope of management problem
- Define measureable management objectives
- Identify key indicators for each objective
- Explore effects of alternative actions on indicators
- Make explicit forecasts about responses of indicators to management actions
- Identify and assess key gaps in understanding

Step 2: Design the management plan

- Design a management plan that will provide reliable feedback and fill gaps in understanding
- Evaluate management options/alternative designs and choose one to implement
- Design monitoring protocol
- Plan data management and analysis

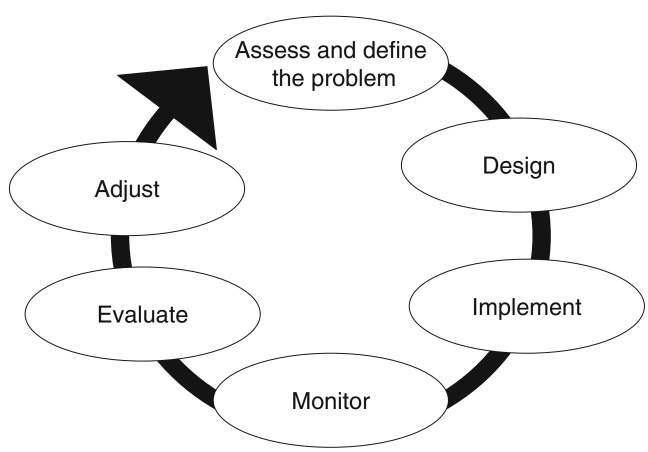


**Fig. 2** Suggested steps in the AM process (from Williams et al. 2007, BCMFR 2008, Smith 2008). Multiple iterations of this loop may occur in the overall decision-making process

- State how management actions or objectives will be adjusted
- Set up system to communicate results and information

Step 3: Implementation

- Follow the plan
- Monitor implementation and document any deviations from the plan

Step 4: Monitor

- Monitor for implementation, effectiveness, validation, and surprises
- Follow the monitoring protocol designed in Step 2

Step 5: Evaluation of results

- Compare actual outcomes to forecasts made in Step 1
- Document results and communicate them to others facing similar management issues

Step 6: Adjustment/revision of hypotheses and management

- Identify where uncertainties have been reduced and where they remain unresolved
- Adjust the model used to forecast outcomes, so that it reflects the hypothesis supported by the results
- Adjust management actions and re-evaluate objectives as necessary
- Make new predictions, design new management experiments, test new options, and repeat cycle as necessary.

There are other variations on this six-step AM cycle. For example, Pohl-Wostl (2007) suggests the following five-stage approach:

- Policy assessment
- Goal setting
- Policy formulation
- Policy implementation
- Monitoring and evaluation

Williams et al. (2007) developed a modified version which consists of nine steps within a two-phase AM process: (1) a set-up phase and (2) an iterative phase (Fig. 3). In the set-up phase, key structural elements are put in place, which are then used in an iterative phase of learning and decision making. Williams et al. (2007) also identify that this two-phase AM approach must be integrated with all appropriate legislation.

In the context of sediment resource management, relevant legislation is more nebulous. This may represent one of the main stumbling blocks for the uptake of the AM approach for sediment management; in that without clear and unequivocal legislation for sediment, it is difficult to agree on policy objectives. Regulations for sediment tend to fall into many sectors, including regulations for air, water, soil, and waste (for a review of legislation relevant to sediment management see Casper (2008)). At large spatial scales, such as river basin or landscape scales, where all of these regulative and legislative sectors are likely to apply, it may be difficult to agree on common legislation for sediment. At small spatial scales, such as river reach and specific areas for dredging, it may be easier to agree on what legislation is appropriate and relevant. This issue is particular relevant where sediment management is multinational. However, in the European Union (EU) at least, there is hope that the EU Water Framework Directive (WFD) may develop common ground for managing water and sediment resources, and this is discussed further later.

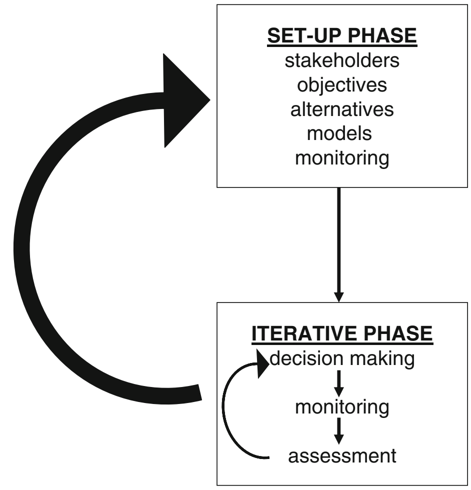


**Fig. 3** Two-phase learning in adaptive management. Technical learning involves an iterative sequence of decision making, monitoring, and assessment. Process and institutional learning involves periodic reconsideration of the adaptive management set-up elements (from Williams et al. 2007)

## 7 Types of uncertainty

Given the importance of uncertainty within the AM approach, it seems appropriate to consider the types of uncertainty that might exist in management of natural resources. Williams et al. (2007) identify four types of uncertainty:

- Environmental variation: the most prevalent source of uncertainty, and is largely uncontrollable and possibly unrecognized. It often has a strong influence on natural resource systems, through such factors as random variation in climate.
- Partial observability: uncertainty about a resources status. For example, the uncertainty that arise from resource monitoring.

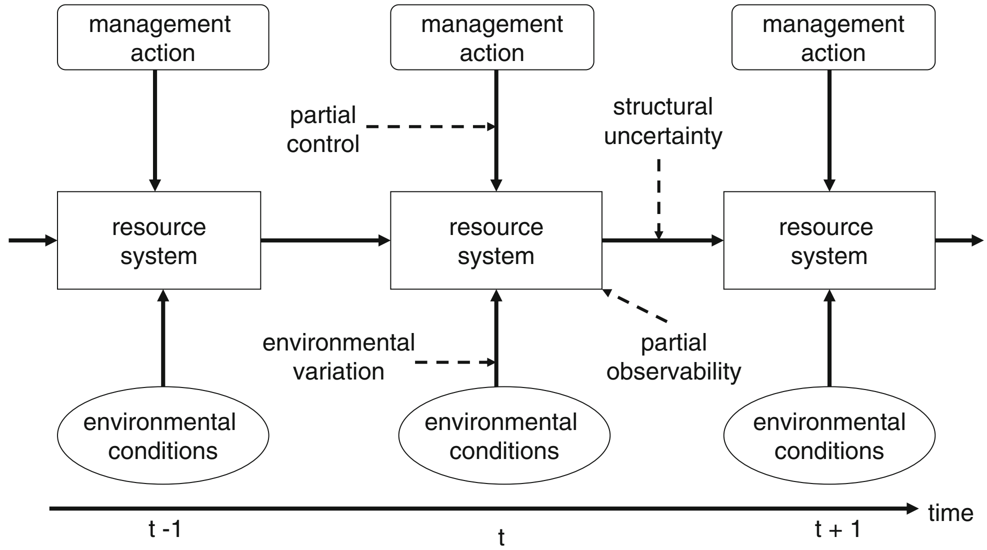


**Fig. 4** Uncertainty sources in natural resource management. Partial control limits the influence of management decisions. Environmental variation affects resource system status and dynamics. Partial observation limits the recognition of system status. Structural uncertainty limits the ability to characterize the system change (from Williams et al. 2007)

- Partial controllability: this expresses the difference between the actions targeted by decision makers, and the actions that are actually implemented. This uncertainty typically arises when indirect means are used to implement a targeted action, and it leads to the possible misrepresentation of management interventions and thus, to an inadequate accounting of their influence on resource behavior.
- Structural or process uncertainty: this concerns a lack of understanding about the structure of biological, ecological, hydrological, and geomorphological relations that drive resource dynamics.

Figure 4 illustrates these four types of uncertainty. In terms of sediment management, much of our present uncertainty is of "structural or process uncertainty" due an incomplete understanding of how environmental systems function. While we may have a good understanding of some components of the system, such as sediment transport and fluxes associated with river flow, our understanding of relations between sediment and biological components of the system is much less complete. For example, we are only recently understanding how in-stream biological processes influence sediment fluxes and sediment storage on channel beds and the impacts these have on water and fisheries resources (e.g., Hassan et al. 2008; Rex and Petticrew 2008). This inevitably leads to issues of "partial observability" in that we may not be measuring all of the parameters required to make a complete assessment of the sediment resource in question. Measurement of sediment chemical quality provides one measure of assessment but typically we do not measure all (i.e., physical, chemical, and biological) relevant parameters at a sufficient resolution to get a complete picture of sediment quality.

In a similar way, we have an incomplete understanding of "environmental variation" due to global environmental change (including climate change). Recent work is demonstrating the complex linkages between global and regional climate and flows of water in rivers. In some situations, river flows are increasing in response to climate change, while in others flows are decreasing. While broad synoptic patterns are becoming clearer, predicting smaller-scale (in time and space) fluctuations in water and sediment fluxes is more elusive (e.g., Moore et al. 2009).

## 8 Tools for adaptive management

One of the common themes in the literature is the role of experimentation in the AM process. For many, it is one of the pillars of the AM approach. Logically, this leads to experimental design and analysis of data. The latter also features in the monitoring aspect of AM. Consequently, there are a variety of tools available for scientists and resources managers. These include remote sensing and geographic information systems, numerical modeling, and statistical techniques (see Sit and Taylor 1998, Van der Perk et al. 2008). There are also socioeconomic tools that can be used to help make decisions, such as cost–benefit analysis (CBA), societal CBA (e.g., Slob et al. 2008a), and multi-criteria decision support systems (e.g., Linkov et al. 2006; Bruen 2008). Carpenter et al. (1999) provide a good example of the use of simple models linking nonlinear ecosystem dynamics with social and economic variables to explore and illustrate management options associated with lake eutrophication.

While most scientists will be familiar with many of the tools available to them, often resource managers are less so.

As Nyberg (1998) states "Scientists can play an important role in adaptive management (Walters 1986), but it is local resource professionals who must become the "adaptive managers" if the promise of the concept is to be realized…" There exists, therefore, an important need for scientists and managers to share experience and expertise. In this respect, scientists have a moral obligation to help develop tools that are user-friendly. Many of the decision support systems currently being developed, often specifically aimed at enforcement agencies and resource managers, are trying to address this need.

To date, it is probably true to say that many of the tools that have been utilized, especially modeling, have mainly addressed the physical and ecological processes and aspects of resource management, and there is a need for tools that consider social and economic aspects.

## 9 Barriers to adaptive management

Inevitable with all new approaches, there are barriers to their uptake and implementation. In many cases, such barriers cause delays in the implementation of the management plans and, in some extreme cases, may cause plans to fail. In this respect, AM is no different and indeed may be subject to more barriers than more traditional approaches (see Table 1). Identifying likely barriers and developing procedures to deal with such barriers, often in the form of alternatives, helps to ensure that the implementation process (i.e., steps 1 to 6 as described above) runs relatively smoothly.

The type and extent of barriers that arise are specific to the type of AM being implemented, the resource being addressed, and the scale and complexity of the management issue. The inherent flexibility of the AM approach means that there is scope to address such barriers within the procedure. BCMFR (2008) identify some of the likely barriers to AM implementation and possible solutions to these:

Additional costs

- Identify designs and monitoring schemes that offer best trade-off between cost and effectiveness
- Compare potential costs of AM compared to traditional approaches
- Consider using volunteers
- Develop cheaper measurement and monitoring techniques
- Identify cost-sharing partnerships

Problems associated with designing and conducting large experiments

- Consider alternative methods and designs which while less ideal may still prove valid
- Draw on other sources of knowledge to help interpret results (e.g., retrospective studies, local knowledge)

Reluctance to experiment with high value, threatened ecosystems

- Passive approaches may be less risky than active approaches in some circumstances
- Test risky actions in test plots first
- Design contingency plans
- Monitor indicators that are sensitive or respond quickly to change
- Recognize that the risk of managing in continued ignorance is also high

Maintaining long-term continuity of staff and funding

- Ensure good documentation and accessibility of information
- Document and communicate interim results and knowledge gains
- Generate local support and sense of ownership
- Have ongoing and overlapping staff training
- Design plans to accommodate possible gaps in funding

Regulatory and institutional inflexibility and inertia

- Get commitments at outset
- Ensure good on-going communication between those who make decisions and those who implement them and evaluate them
- Delegate decision-making authority to those as close to the ground as possible
- Get agreement at outset on how potential results will change objectives or practices
- Sense of ownership in the project will enhance willingness to change on the basis of results

Pressure to alter plans or poor understanding of how to implement plans

- Involve operations staff or contractors responsible for implementing plans in the assessment and design phases
- Anticipate potential pressures that may arise to alter plans and agree on response

Fear of making mistakes and trying new solutions

- Build public trust through education, public involvement with the process
- Reward learning and innovations in performance evaluations

Unclear, inconsistent definition of AM and how it should be carried out

- Reinforce and repeat the definition throughout the process
- Correct misinterpretations as they arise

These and additional barriers are also described by Walters (1997), Lee (1999), Williams et al. (2007), and Medema et al. (2008). While this list is not exhaustive, it nevertheless helps to illustrate the type of problems that can be encountered. The reader is directed to Gerrits and Edelenbos (2004) and Slob et al. (2008b) for discussion on some of the other risks and pitfalls specifically associated with stakeholder engagement and participation within the water and sediment resources management process. For example, a particular problem for sediment is the lack of a "common language" between the various interested parties, which in turn has impacts on communication. In addition, in the case of multinational situations, both water and sediment resources are likely to be unevenly distributed such that establishing common policy objectives may be difficult. However, these barriers and limitations apply to most approaches/frameworks for resource management, and the AM approach may help to overcome these through ongoing discussion and interaction between parties, and though the iterative way in which the AM approach proceeds.

## 10 Deciding if adapted management has been successful?

Williams et al. (2007) state that "in general, the implementation of adaptive management is defined as successful if progress is made toward achieving management goals through a learning-based (adaptive) decision process." They suggest that there are four criteria that can used to assess whether AM has been successful (Fig. 5). The AM approach can be regarded as successful only if all four assessment criteria are met over the timeframe of the project.

## 11 Examples of adaptive management frameworks for water and sediment resources

Scientists and managers concerned with the management of water and sediment resources are increasingly looking to develop conceptual approaches that can be effectively utilized for more holistic and integrated management. In Europe, many of these initiatives are being driven by policy measures which envisage management at large spatial scales, such as the river basin and wider landscape, and include the EU WFD and the Soil Framework Directive. In other situations, AM is explicitly described by operational policy statements as part of broader environmental assessment, such as the Canadian Environmental Assessment Act (CEAA 2009), which encompasses sediment management as part of management of the wider environment.

On the basis of the above discussion, it seems reasonably clear that AM offers considerable potential as an approach for the effective management of water and sediment resources at river basin and landscape scales. This is because, at these spatial scales, water and sediment systems are physically (Owens 2005; Nilsson and Renöfält 2008; Taylor et al. 2008) and socially (Slob et al. 2008a; Slob and Gerrits 2008) complex, and because there are usually numerous management options. Under such situations, AM "tries to understand the potential trade-offs among stakeholder interests under different management plans and tries to generate innovative approaches and "win-win" situations whenever possible" (Johnson 1999).

It is probably true to say that the AM approach has not been widely accepted by the sediment resources community. In part, this stems from the fact that the approach can

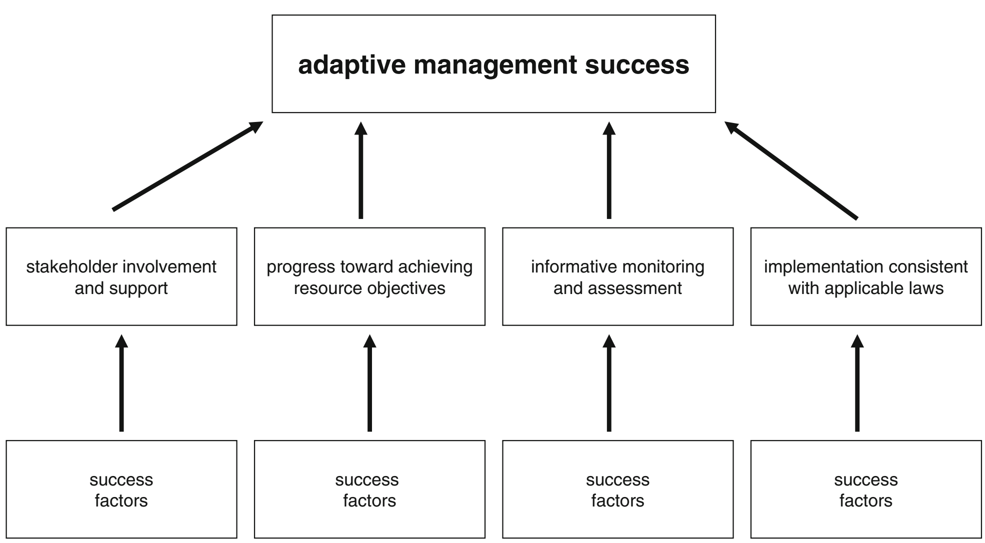


**Fig. 5** Adaptive management success model. Success factors for each of the four criterion are addressed by a series of questions that help practitioners increase the likelihood of success (from Williams et al. 2007)

appear ambiguous and perhaps irrelevant. While partly true, there has been some discussion in the literature (e.g., Apitz 2008) suggesting that it may be time to consider the AM approach in more detail. Some examples where the AM approach is being used for sediment management are described below. The examples consider sediment management in terms of both sediment quantity (e.g., Glen Canyon Dam) and sediment quality (e.g., NRC initiatives) and range in scale from site- to basin-scale. These examples both help to illustrate the potential of the approach and the range of scales at which it can be used.

### 11.1 The Glen Canyon Dam Adaptive Management Program

Perhaps the best example to date of AM being used for the management of river basin resources is the Glen Canyon Dam Adaptive Management Program (GCDAMP) in the USA. This AM program was initiated in the mid to late 1990s, and since this time has used the AM approach to learn about how management operations of the dam influence downstream water resources and ecological habitats in the Colorado River, which drains a basin of ca 642,000 $km^2$ (Lovich and Melis 2007). The dam was finished in 1963, creating Lake Powell, and reduced the supply of sand at the upstream boundary of Grand Canyon National Park by about 80–90% (Lovich and Melis 2007). In response to this reduction in sand supply and due to changes in the natural flow characteristics of the river due to dam operations, sandbars downstream of the dam have eroded and continue to do so under normal dam operations: there is a "continuous fine-sediment deficit" (Lovich and Melis 2007). The sandbars represent an important part of the riverine landscape and are important aquatic habitats. In addition, the downstream net removal of fine sediment is eroding and exposing important artifacts and cultural structures. The GCDAMP has undertaken a series of experiments over the last 10 years or so, including a series of high-flow experiments in 1996, 2004, and 2008, designed to provide greater understanding of high-flow releases on water and sediment fluxes and, in particular, on downstream sand redistribution and storage in sandbars (Topping et al. 2006). Importantly, these and other experiments have transformed the understanding of sediment dynamics downstream of the dam. According to Lovich and Melis (2005):

> "The [original Environmental Impact Study] assumption that sand would accumulate on the bed of the river over multiple years has been transformed through learning and adaptive management experimentation. Recent research suggests that future management of sediment should involve high-flow releases immediately following inputs of sand and finer sediment from tributaries below the dam. While such release may be controversial … … recent studies also suggest that the duration of flows may need to be only a fraction of what was originally suggested… … which could reduce the financial impacts and controversy associated with such management options."

A review by Lovich and Melis (2007) compared predictions made at the start of the AM program with the present situation. In many cases, predictions of how the river system would respond due to the construction of the dam and an operational program of modified low-fluctuating flows have not turned out as expected, such as the sediment dynamics described above. This highlights the uncertainties associated with managing a large and complex river basin. Importantly, Lovich and Melis (2007) identify that this is not a failure of the AM approach but rather presents opportunities for learning and adjustment.

### 11.2 NRC initiatives for contaminated sediment

There are several recent initiatives in the contaminated sediment community where AM is being considered as a viable option for decision making. Many of these initiatives have been undertaken by the U.S. National Research Council (e.g., NRC 1997, 2001, 2003, 2004, 2007) as part of a risk-based process. In general, the initiatives follow many of the aspects of the AM approach described above, such as stakeholder participation, systematic and structured assessment for implementing options, and monitoring the success of the overall process. Following on from these NRC initiatives, Linkov et al. (2006) describe how a coupled AM and multiple criteria decision analysis approach could be used to assist with contaminated sediment management issues in New York/New Jersey Harbor, USA.

Given the primary concern with contaminated sediments (e.g., from polychlorinated biphenyls (PCBs)) and sites (e.g., dredging at Superfund Megasites), then emphasis has been on site-specific assessment and remediation, and less attention has been given to the use of the AM approach for integrated water and sediment resource management at the river basin and landscape scales.

### 11.3 Transboundary water (and sediment?) management

Not all water or sediment resource issues lend themselves to the AM approach. A good example to illustrate this point is the assessment of AM for water management in transboundary river basins. Raadgever et al. (2008) used a series of 18 factors grouped according to five main nonoperational criteria—actor networks, legal framework, policy, infor-

**Table 3** Qualitative scores on nonoperational criteria for adaptive management for the Orange (southern Africa) and Rhine (central Europe) transboundary river basins

| Criteria | Factors | Orange basin (948,000km$^2$) | Rhine basin (198,000km$^2$) |
|---|---|---|---|
| Actor networks | Cross-sectoral cooperation | − | 0 |
| | Cooperation between administrative levels | 0 | 0 |
| | Cooperation across administrative boundaries | 0 | + |
| | Broad stakeholder participation | 0 | + |
| | Average | 0 | 0/+ |
| Legal frameworks | Appropriate legal frameworks | − | + |
| | Adaptable legislation | 0 | 0 |
| | Average | −/0 | 0/+ |
| Policy | Long time horizon | 0 | + |
| | Flexible measures, keeping options open | 0 | + |
| | Experimentation | 0 | 0 |
| | Full consideration of possible measures | 0 | + |
| | Actual implementation of policies | − | + |
| | Average | 0 | + |
| Information management | Joint/participative information production | 0 | + |
| | Interdisciplinarity | NE | 0 |
| | Elicitation of mental models/critical self-reflection about assumptions | NE | NE |
| | Explicit consideration about uncertainty | 0 | 0 |
| | Broad communication | NE | + |
| | Use of information | − | 0 |
| | Average | −/0 | 0/+ |
| Financing | Appropriate financing system | − | + |

The more positive the scoring, the more suitable AM is for this river basin (adapted from Raadgever et al. 2008)

− low, *0* average, + high, *NE* not enough information

mation management, and financing—to assess the (hypothetical) suitability of AM for several contrasting transboundary river basins throughout the world. Not surprisingly, AM was assessed to be unsuitable for some river basins. Table 3 presents two contrasting river basins, the Rhine and the Orange. Based on the scores shown in Table 3, AM is likely to be a suitable management approach for water resources in the Rhine River basin. In part, this stems from initiatives such as the International Commission for the Protection of the Rhine and the WFD. It is, therefore, likely that the AM approach may also be suitable for other river basins with similar actor/stakeholder, legal, policy, information, and financing structures. Given the relation between sediment resources and water resources, then it is not unrealistic to assume that the same implications identified above for the suitability of AM for water resources management could be transferred to sediment management at the river basin scale. However, considerable work is required to substantiate this statement.

### 11.4 A draft adaptive management framework for sediment resources

One of the few sediment management frameworks recently put forward which implicitly includes an adaptive structure is described in Owens et al. (2008) and is illustrated in Fig. 6. While not strictly an AM framework, it shares many of the characteristics of AM, such as:

- It is flexible (i.e., the stages in Fig. 6 do not need to be followed in a set order) and adaptable (i.e., to climate and land use change)
- It explicitly identifies uncertainty, with learning and understanding as the key processes to dealing with uncertainty
- It has a cyclic nature unlike many other frameworks which are more linear in design
- Monitoring is systematic and required at several levels
- Stakeholders are involved at all stages and undergo continuous learning (i.e., adaptive co-management)

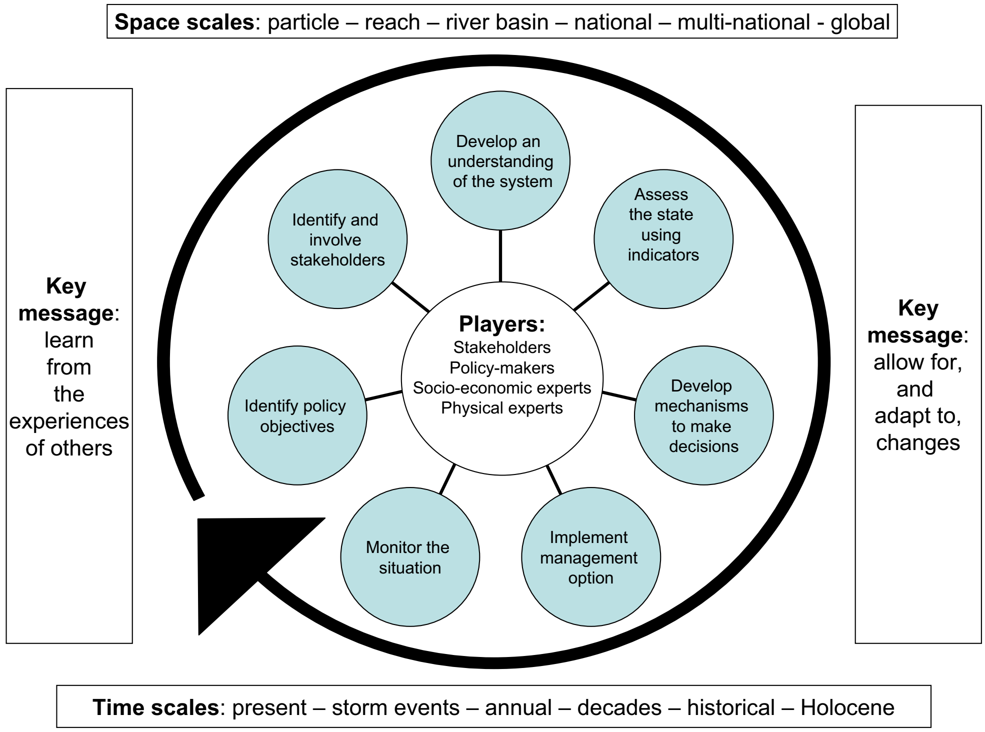


**Fig. 6** Adaptive framework showing the stages (*outside circles*) and players (*inner circle*) required for sediment management at the river basin scale. It may be possible to enter and leave at any stage, and there is no set order to the stages. The management framework does require an appreciation and assessment of the space and time scales involved with both the various stages and players that are relevant to the particular policy objectives. See Owens et al. (2008) for further explanation (reproduced with the permission of Elsevier)

- The underlying structure is one of assessment–design–implementation–evaluation

In this respect, Fig. 6 represents a hybrid adaptive management framework, as it does not meet all of the criteria and characteristics of AM as identified above. This begs the question: can the framework identified in Fig. 6 be implemented for managing sediment resources within river basins? In theory, yes: it has most of the key components that most proponents of the AM approach feel are required. What it perhaps lacks is the detail. At present, it is largely a conceptual diagram illustrating a series of steps to be followed within a framework that encourages learning and adaptation. While there is documentation to help support its implementation (i.e., Owens et al. 2008), there needs to be comprehensive training in the rationale of the framework and its effective implementation in the real world. Abstract theory needs to be turned into real-world usefulness. In this respect, several organizations involved with resource management (such as BCMFR, NRC) have developed useful supporting documentation and organized workshops. This aspect of implementation is as important as the steps identified in the conceptual diagram (see Fig. 6).

Furthermore, one of the main obstacles associated with the successful implementation of the AM approach for sediment management relates to the general perception of sediment. There is less of an issue for water resources management, as there is more consensus on what water is and what its key services and functions are. However, for many, sediment is still regarded as something that is negative: a waste or contaminated product. Few regard sediment as an important natural resource which provides important services and functions within aquatic systems (Owens 2008). Because of this, there are still perceptual, institutional, and regulatory barriers which limit the uptake of AM approaches which require a certain degree of understanding and common ground amongst the "players" (see Fig. 6: stakeholders, policy-makers, socioeconomic experts, physical experts). For example, Casper (2008) describes that "across Europe, with the exception of the management of dredged material, there are few specific legislative requirements for sediment, and the level of consideration afforded to sediment management is primarily left to the discretion of individual countries." This means that the AM approach, such as that illustrated in Fig. 6, is probably best suited for local, site-specific management issues such as those associated with sediment quality where there exists more common ground between the players and where there is some appropriate legislation. Thus, while the AM approach offers great potential for basin-, landscape-, and multinational-scale sediment management, there are still too many institutional and regulatory barriers for full implementation. In Europe, policy measures like the WFD may help to reduce these barriers, at least for water management. For sediment, however, while the WFD may help to break down some barriers, the fairly rigid approach to sediment assessment though quality standards may introduce new barriers.

## 12 Perspectives

Adaptive management clearly has an important role to play in the management of natural resources, particularly those that are physically and socially complex and which occur over large spatial "landscape" scales. Water and sediment resources fall within this category, with the river basin likely to be the most appropriate management unit and scale for numerous reasons (Owens 2005). The timescales and costs of implementing AM are such that this approach may not be easily applied by resource managers and agencies, which may instead prefer the more traditional approaches which are usually quicker and cheaper to implement. In addition, management frameworks such as AM are often developed by academic scientists, meaning that the community developing the framework is unlikely to be the community implementing the framework (i.e., resource managers), which may lead to a mismatch between development and practice (Medema et al. 2008). Thus, while the AM approach may seem conceptually elegant, its adoption and implementation for managing sediment resources may be considerably more difficult. It risks, therefore, being yet another "buzzword" (Lee 1999) in the literature on natural resources and ecosystem management.

However, there are aspects of AM that suggest that it does indeed have potential for the management of water and sediment resources. For example, the iterative approach—which includes the gathering of information and knowledge, the exchange and development of ideas and goals, and the continued dialog with stakeholders and policy developers—lends itself well to the implementation of the WFD, which requires public/stakeholder participation and which has a structure of updating river basin management plans on a regular basis (typically every 6 years). In addition, due to the flexible and iterative elements of the AM approach, it may well be one of the only approaches presently available that is able to deal with natural resource management under conditions of uncertain global environmental change.

The concept of AM should be considered as a viable option early in the decision-making process. If we can at least consider the spirit and philosophy of AM during the decision-making and management processes, then there is hope for suitable and acceptable management solutions. According to Lee (1999):

> "…there is reason to think that this (adaptive) mode of learning is important, possibly essential, in the search for a durable and sustainable relationship between humans and the natural world."

However, despite some 30 years of development, the AM approach has yet to be fully implemented within the water and sediment resource management sectors. Below are some suggested research and implementation needs that may help:

- There is a need for assessment and monitoring tools that are able to couple the physical and ecological aspects with the social and economic aspects of water and sediment management. To date, many of the tools available (e.g., sediment flux monitoring and modeling and societal cost–benefit analysis) have been used in relative isolation. Monitoring of developments and evaluation of management outcomes, in particular, require further development.
- There is a need to develop institutional mechanisms that enable sediment resources to be managed in a multinational, transboundary way and that provide the level of flexibility needed to ensure sustainable long-term solutions are reached.
- There is a need for public education on the important functions and roles that sediment plays within river basins, and also, why there is a need to manage sediment. While the AM approach provides the framework for decision making, the largest obstacle to successful implementation is still likely to be public and managerial ignorance associated with what sediment actually is (i.e., it is not necessarily contaminated and/or a waste product), and why it needs to be managed at the appropriate (i.e., river basin, landscape) scale. Initiatives such as the European Sediment Network, SedNet (Brils 2002, 2005) are trying to do this at several levels (e.g., port authorities, policy-makers), but there is still a long way to go.

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## References

AME (2003) Adaptive Management. Adaptive Management Experiment (AME). University of Alberta, Edmonton, Canada. http://www.ameteam.ca

Apitz SE (2008) Editorial: adaptive management principles and sediment management. J Soils Sediments 8:359–362

Apitz SE, White S (2003) A conceptual framework for river-basin-scale sediment management. J Soils Sediments 3:132–138

Apitz S, Carlon C, Oen A, White S (2007) Strategic frameworks for managing sediment risk at the basin and site-specific scale. In: Heise S (ed) Sustainable management of sediment resources: sediment risk management and communication. Elsevier, Amsterdam, pp 77–106

BCMFR (2008) Adaptive Management. British Columbia Ministry of Forests and Range. Victoria, British Columbia, Canada. http://www.for.gov.bc.ca/amhome (last accessed 2/12/2008)

Bormann BT, Martin JR, Wagner FH, Wood G, Alegria J, Cunningham PG, Brookes MH, Friesema P, Berg J, Henshaw J (1999) Adaptive management. In: Johnson NC, Malk AJ, Sexton W, Szaro R (eds) Ecological stewardship: a common reference for ecosystem management. Elsevier, Amsterdam, pp 505–534

Brils J (2002) The SedNet mission. J Soils Sediments 2:2–3

Brils J (2005) 2005, a transition year for SedNet. J Soils Sediments 5:70

Bruen M (2008) Systems analysis—a new paradigm and decision support tools for the Water Framework Directive. Hydrol Earth Syst Sci 12:739–749

Bunnell FL, Dunsworth BG, Kremswater L, Huggard D, Beese WJ, Sandford JS (2007) Forestry and biodiversity—learning how to sustain biodiversity in managed forests. UBC Press, Vancouver

CEAA (2009) Operational policy statement: adaptive management measures under the Canadian environmental assessment act. Canadian Environmental Assessment Agency, Ottawa, Ontario

Carpenter S, Brock W, Hanson P (1999) Ecological and social dynamics in simple models of ecosystem management. Conserv Ecol 3(2):4. URL: http://www.consecol.org/vol3/iss2/art4/

Casper ST (2008) Regulatory frameworks for sediment management. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 55–81

Farr D (2000) Defining adaptive management. Document for Adaptive Management Experiment (AME). University of Alberta, Edmonton. http://www.ameteam.ca

Gerrits L, Edelenbos J (2004) Management of sediments through stakeholder involvement. J Soils Sediments 4:239–246

Globe and Mail (2008) The battle for a riverbed. Globe and Mail, British Columbia, pp 1–3

Goodman D, Sojda RS (2008) Applying advanced technologies for adaptive management and decision support in natural resources. http:www/esg.montana.edu/esg/adaptive_mgmt_1.html (last accessed 2/12/2008)

Halbert CL (1993) How adaptive is adaptive management? Implementing adaptive management in Washington State and British Columbia. Rev Fish Biol Fisher 1:261–283

Hassan MA, Gottesfeld AS, Montgomery DR, Tunnicliffe JF, Clarke GKC, Wynn G, Jones-Cox H, Poirier R, MacIssac E, Herunter H, MacDonald SJ (2008) Salmon-derived bed load transport and bed morphology in mountain streams. Geophys Res Lett 35: L04405. doi:10.1029/2007GL032997

Holling CS (ed) (1978) Adaptive environmental assessment and management. Wiley, London

Johnson BL (1999) The role of adaptive management as an operational approach for resource management agencies. Conserv Ecol 3(2):8. URL:http://www.consecol.org/vol3/iss2/art8/

Johnson F, Williams K (1999) Protocol and practice in the adaptive management of waterfowl harvests. Conserv Ecol 3(1):8. URL: http://www.consecol.org/vol3/iss1/art8/

Kremswater L, Perry J, Dunsworth G (2002) Forest Project technical project summary: adaptive management program. Update of Report 1. Weyerhaeuser Enhanced Forest Management Pilot Project. Forest Renewal B.C. (FRBC). Nanaimo, British Columbia

Lee KN (1999) Appraising adaptive management. Conserv Ecol 3 (2):3. URL: http://www.consecol.org/vol3/iss2/art3/

Linkov I, Satterstrom FK, Kiker G, Batchelor C, Bridges T, Ferguson E (2006) From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. Environ Internat 32:1072–1093

Lovich JE, Melis TS (2005) Lessons from 10 years of adaptive management in Grand Canyon. In: Gloss SP, Lovich JE, Melis TS (eds) The state of the Colorado River System in Grand Canyon, USGS Circular 1282, pp 207–220

Lovich JE, Melis TS (2007) The state of the Colorado River ecosystem in Grand Canyon: lessons from 10 years of adaptive ecosystem management. Int J River Basin Manag 5:207–221

MacDonald GB, Fraser J, Gray P (eds) (1999) Adaptive management forum: linking management and science to achieve ecological sustainability. Ontario Ministry of Natural Resources, Peterborough, Ontario

Medema W, McIntosh BS, Jeffrey PJ (2008) From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector. Ecol Soc 13(2):29. URL: http://www.ecologyandsociety.org/vol13/iss2/art29/

Moore RD, Fleming SW, Menounos B, Wheate R, Fountain A, Stahl K, Holm K, Jakob M (2009) Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. Hydrol Processes 23:42–61

Nilsson C, Renöfält BM (2008) Linking flow regime and water quality in rivers: a challenge to adaptive catchment management. Ecol Soc 13(2):18. URL: http://www.ecologyandsociety.org/vol13/iss2/art18/

NRC (1997) Contaminated sediments in ports and waterways—cleanup strategies and technologies. National Research Council, The National Academies Press, Washington DC

NRC (2001) A risk-management strategy for PCB-contaminated sediments. National Research Council, The National Academies Press, Washington DC

NRC (2003) Bioavailability of contaminants in soils and sediments—processes, tools and applications. National Research Council, The National Academies Press, Washington DC

NRC (2004) Adaptive management for water resources planning. National Research Council, The National Academies Press, Washington DC

NRC (2007) Sediment dredging at Superfund megasites—assessing the effectiveness. Committee on sediment dredging at Superfund megasites. National Research Council, The National Academies Press, Washington DC

Nyberg JB (1998) Statistics and the practice of adaptive management. In: Sit V, Taylor B (eds) Statistical methods for adaptive management studies. British Columbia Ministry of Forests, Research Branch, Victoria, British Columbia, Handbook 42, pp 1–7

Owens PN (2005) Conceptual models and budgets for sediment management at the river basin scale. J Soils Sediments 5:201–212

Owens PN (2008) Sediment behaviour, functions and management in river basins. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 1–29

Owens PN, Slob AFL, Liska I, Brils J (2008) Towards sustainable sediment management at the river basin scale. In: Owens PN (ed) sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 217–259

Pohl-Wostl C (2007) Requirements for adaptive water management. In: Pohl-Wostl C, Kabat P, Moltgen J (eds) Adaptive and integrated water management: coping with complexity and uncertainty. Springer, Berlin, pp 1–22

Raadgever GT, Mostert E, Kranz N, Interwies E, Timmerman JG (2008) Assessing management regimes in transboundary river basins: do they support adaptive management? Ecol Soc 13 (1):14. URL: http://www.ecologyandsociety.org/vol13/iss1/art14/

Rex JF, Petticrew EL (2008) Delivery of marine-derived nutrients to streambeds by Pacific salmon. Nature Geoscience 1:840–843

Ruitenbeek J, Cartier C (2001) The invisible wand: adaptive co-management as an emerging strategy in complex bio-economic systems. Occassional Paper 34. Centre for International Forestry Research, Bago, Indonesia

Sit V, Taylor B (eds) (1998) Statistical methods for adaptive management studies. British Columbia Ministry of Forests, Research Branch, Victoria, British Columbia, Canada, Handbook 42

Slob A, Gerrits L (2008) The dynamics of sedimentary systems and the whimsicality of policy processes. J Soils Sediments 7:277–284

Slob AFL, Ellen GJ, Gerrits L (2008a) Sediment management and stakeholder involvement. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 199–216

Slob AFL, Eenhoorn J, Ellen GJ, Gomez CM, Kind J, van der Vlies J (2008b) Costs and benefits of sediment management. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 175–197

Smith A (2008) Defining adaptive management in the BC Ministry of Forests and Range. Link 10:12–15

Stankey GH, Clark RN, Bormann BT (2005) Adaptive management of natural resources: theory, concepts and management institutions. U.S. Forest Service Pacific Northwest Forest Station Report PNW-GTR-654, Portland, Oregon

Stankey GH, Bormann BT, Ryan C, Schindler B, Sturtevant V, Clark RN, Philpot C (2003) Adaptive management of the northwest forest plan: rhetoric and reality. J Forestry 101:40–46

Taylor B, Kremsatar L, Ellis R (1997) Adaptive management of forests of British Columbia. British Columbia Ministry of Forests, Forest Practices Branch, Victoria

Taylor KG, Owens PN, Batalla RJ, Garcia C (2008) Sediment and contaminant sources and transfers in river basins. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 83–135

Topping DJ, Rubin DM, Schmidt JC, Hazel JE Jnr, Melis TS, Wright SA, Kaplinski M, Draut AE, Breedlove MJ (2006) Comparison of sediment-transport and bar-response results from the 1996 and 2004 controlled-flood experiments on the Colorado River in Grand Canyon. In: Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, NV, pp 1–8

Van der Perk M, Blake WH, Eisma M (2008) Decision support tools for sediment management. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 137–173

Walters CJ (1986) Adaptive management of renewable resources. McGraw-Hill, New York

Walters CJ (1997) Challenges in adaptive management of riparian and coastal ecosystems. Conserv Ecol 1(2):1. URL: http://www.consecol.org/vol1/iss2/art1/

Walters CJ, Hilborn R (1976) Adaptive control of fishing systems. J Fisheries Res Board Canada 33:145–159

Walters CJ, Gunderson L, Holling CS (1992) Experimental policies for water management of the Everglades. Ecological Applic 2:189–202

White SM, Apitz SE (2008) Conceptual and strategic frameworks for sediment management at the river basin scale. In: Owens PN (ed) Sustainable management of sediment resources: sediment management at the river basin scale. Elsevier, Amsterdam, pp 31–53

Williams BK, Szaro RC, Shapiro CD (2007) Adaptive management. United States Department of the Interior Technical Guide, Adaptive Management Working Group, Washington DC