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Adaptive monitoring based on ecosystem services

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ABSTRACT

Monitoring consists of repetitive data collection to determine trends in parameters monitored. Unfortunately, too often monitoring consists of "fishing expeditions" where data collection is justified after the fact rather than being based on *a priori* technically defensible and testable hypotheses. Monitoring conducted following legal (e.g., regulatory) stipulations is not always useful. Ideally, monitoring should be conducted to determine the current status of the parameters monitored, their temporal and spatial trends (to assist in predicting future status), and the possible need for management actions. The most effective and productive scientific monitoring is adaptive, and is based on assessment endpoints that comprise ecosystem services, in other words, the benefits of Nature to human beings.

1. Introduction

The US National Research Council (USNRC, 2007) reviewed monitoring conducted at US Superfund Megasites – where monitoring would have been expected to be extensive and comprehensive. They wanted to use this information to answer the question as to whether dredging alone was capable of long-term risk reduction at these very large contaminated sites. To their surprise, they could not answer this question because the monitoring conducted had been inadequate – it was generally an "add-on" activity, not an essential part of the management remedies at these sites.

Lindermayer and Likes (2009) have argued that the three major problems hindering monitoring effectiveness are: the wrong drivers (e.g., politics rather than good science); poor initial design; and, lack of clarity regarding goals and components. They suggest that the solution lies in what they term "adaptive monitoring" linked to protection of ecosystem services. I agree and herein provide further support to their suggestion by considering, in turn: stressors of potential concern (SOPCs); adaptive monitoring; ecosystem services; and, adaptive monitoring of SOPCs based on ecosystem services.

2. Stressors of potential concern

SOPCs can be biological (e.g., invasive species), physical (e.g., habitat change) or chemical (e.g., contaminant inputs). Effective monitoring begins by determining SOPCs and their potential effects (Table 1).

Physical habitat changes are not necessarily negative, neither are invasive species which can be desirable (e.g., rainbow trout – MacCrimmon, 1971) and can increase diversity (Karatayev et al., 2009). Similarly, chemical contamination does not necessarily indicate pollution. Contamination is simply a substance present where it should not be or above background levels. Pollution is contamination that results in adverse biological effects. All pollutants are contaminants, but not all contaminants are pollutants (cf Paracelsus – *Omnia sunt venena, nihil est sine veneno. Sola dosis facit venenum*). For example, the environmental fate and behavior of metal (e.g., lead, cadmium, copper, zinc), metalloid (e.g., arsenic), and non-metal (e.g., selenium) contaminants is dependent on abiotic factors (e.g., pH, hardness, alkalinity and organic matter), which influence their toxicity and mobility by altering their speciation, or physical-chemical forms, in aquatic systems (USNRC, 2003; USEPA, 2007; Chapman, 2008).

Tolerance can ameliorate contaminant toxicity. Tolerance comprises the ability of exposed organisms to acclimate or adapt to concentrations of contaminants as those concentrations slowly increase. Acclimation is an energetic process that may not have a net benefit to the organism; however, genetic adaptation may not require energy and thus may provide a net benefit to the organism (Chapman, 2008). Where resident populations are tolerant to existing contamination, laboratory testing with naïve (i.e., non-tolerant) laboratory species will not be environmentally relevant (USEPA, 2007; CCME, 2007).

Interactions between different stressors can result in increased or reduced risks to aquatic ecosystems. For example, Norwood et al. (2003) reviewed existing literature regarding the frequency of occurrence of less than additive (antagonistic), more than additive (synergistic), and additive responses in toxicity tests with metal mixtures. They found that all three possibilities occurred with about equal frequency, and interaction responses were dependent on both the actual mixture combinations (metals and ratios) and the exposed biota. Interactions between other stressors likely also encompass all three possibilities.

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Table 1
Potential effects of some physical and chemical stressors in aquatic environments. Note that this table is illustrative and far from comprehensive (e.g., it does not include pesticides, pharmaceuticals and personal care products or other emerging contaminants such as nanoparticles).

Stressor	Effects	Biota at risk	Comments
Biological			
Invasive species	Change or loss of diversity, change in community composition	All biota	Irreversible changes
Physical			
Habitat change	Change or loss of rearing, breeding, feeding habitat	Primarily those with limited mobility and/or a restricted home range	Reversible
Chemical			
Metals and metalloids	Acute and chronic toxicity dependant primarily on aqueous concentration and water quality conditions	Those that may be exposed to a sufficient dose/concentration in a bioavailable form to be toxic (USNRC, 2003)	Biomagnification only occurs for the organic forms of Hg or Se; inorganic metals do not biomagnify, but they can be toxic; chronic toxicity is more common than acute toxicity (USEPA, 2007; Chapman, 2008)
Selenium – a non-metal	Acute toxicity of the inorganic form is rare; chronic toxicity occurs via dietary uptake of the organic form	Egg-laying vertebrates (Chapman et al., 2010)	
Biomagnifying organics (e.g., PCBs; 2,3,7,8-TCDD; methyl mercury)	Acute toxicity only at very high concentrations; toxicity at low concentrations via dietary uptake more common	Higher trophic level biota including humans	Higher trophic levels are more affected than lower trophic levels
Non-biomagnifying organics (e.g., PAH, phthalate esters)	Acute and chronic toxicity dependant primarily on aqueous concentrations and water quality conditions	Those that may be exposed to a sufficient dose/concentration to be toxic	Physical effects also possible (e.g., smothering by oil slicks; digestive blockages from plastics)
Total dissolved solids	Acute and chronic toxicity	Those that may be exposed at a sufficient concentration to be toxic	Reversible
Nutrients	Enhanced primary production	All biota	Indirect effects can include reduced dissolved oxygen and loss of biodiversity

PCB = polychlorinated biphenyl.
PAH = polynuclear aromatic hydrocarbon.
2,3,7,8-TCDD = 2,3,7,8-tetrachlorodibenzo-p-dioxin, the most potent chemical of the dioxin family of chemicals.

Both acute and chronic effects are possible including different modes of toxic action. For instance, selenium can be acutely toxic at very high concentrations in water similar to other chemical contaminants; however, it has an unusual mode of chronic toxicity. It can cause reproductive failures and abnormalities in egg-laying vertebrates via dietary uptake. The primary manifestation of this chronic toxicity will be an absence of young year-classes in affected areas.

Thus, risks to aquatic receiving environments from anthropogenic developments must consider the specific SOPCs and their modes of action to ensure that appropriate parameters are monitored. For example, in the specific case of selenium, it is not sufficient to simply monitor the abundance of different fish species, different age classes must also be monitored.

3. Adaptive monitoring

Monitoring must be able to adapt (e.g., in terms of design and/or components) as new knowledge and technologies are developed. There are three primary reasons that monitoring is conducted, the first of which is not a valid reason for conducting monitoring and the second of which may be technically questionable:

1. because data collection is possible (i.e., "fishing expeditions" – collect data now, think later);
2. for regulations (per legal stipulations); and,
3. for assessment of current status to determine trends (temporal and spatial) relative to predicting future status, and/or the possible need for management action(s).

Monitoring conducted to assess current status, the most valid reason for conducting monitoring, will be site- and situation-specific in design, frequency and duration. Such monitoring should be adaptive (i.e., continuously improving), based on principles outlined in Lindermayer and Likes (2009) to avoid the three major problems hindering monitoring effectiveness: the wrong drivers (e.g., politics rather than good science); poor initial design; and, lack of clarity regarding goals and components. Doing so will not only avoid unnecessary data collection and miscommunication with stakeholders (e.g., "what should be monitored?"), but will also promote assessment of the long-term effectiveness of any management action(s).

There are four generic monitoring objectives:

1. to bound natural variability;
2. to assess temporal and spatial changes;
3. if appropriate and necessary, to provide information for investigative studies to determine causation and significance of any observed changes; and,
4. to provide necessary information for informed management decision-making.

The above four objectives should lead to testable hypotheses. An example of a testable hypothesis related to objective 1, above, could be: variations in a fishery population are within the bounds of natural variability. Or, relative to objective 3, above, another example could be: variations in a fishery population outside the bounds of natural variability are due to specific SOPCs. These hypotheses may be refined and/or new hypotheses developed as monitoring develops new information.

Monitoring should also:

- be based on appropriate ecosystem-level conceptual diagrams;
- have a robust experimental design with high quality data collection and careful attention to field data quality;
- be relevant (i.e., based on collaborative partnerships including scientists, regulators, managers, policy makers, and Aboriginal peoples as appropriate);
- have clear management relevance and necessity, including periodic review (i.e., there is no point to doing monitoring for its own sake as noted above);
- be transparent (e.g., repeatable, with all data freely available) and technically defensible (e.g., appropriate quality assurance/quality control – QA/QC); and,

• be integrative (internally and externally, linking with regional or other relevant monitoring programs).

Other necessary monitoring components include good *a priori* statistical design, adaptation to new knowledge and techniques that maintains the integrity of the long-term data record; and, termination when appropriate. Trends in SOPCs and other trends (e.g., changes in factors modifying biota viability such as habitat or changes in factors modifying contaminant bioavailability) should be identified. In some cases delays in the recovery of population structure after management actions can be due to secondary factors, for instance despite removal of chemical residues, biotic interactions such as intraspecific competition may obviate complete recovery (Liess and Foit 2010).

4. Ecosystem services

Costanza and Daly (1992) related economic growth and environmental sustainability, describing Nature as a fixed stock of capital capable of sustaining a limited flow of ecosystem services. This concept has been widely embraced (e.g., USEPA, 2008) but has also been criticized on the basis that its simplicity blinds humans to the complexity of their predicament and is only part of a larger solution (Norgaard, 2010).

Ecosystem services can be defined as: the products of ecological functions or processes that directly or indirectly contribute to human well-being, or have the potential to do so in future; or, as the benefits of nature to households, communities, and economies (Costanza and Daly, 1992; Daly and Farley, 2004; Fisher et al., 2009). They represent ecological processes and resources expressed in terms of the goods and services they provide.

Ecosystem services are a metaphor that can be expressed in terms of service providing units (SPUs; Luck et al., 2003). SPUs can serve as part of technically defensible approaches not only for biodiversity conservation (Cognetti and Maltagliati, 2009) but also for the design of adaptive monitoring programs to determine the need for or effectiveness of management actions related to the three types of SOPCs that anthropogenic developments can impose on aquatic receiving environments: biological; physical; and, chemical (Table 1).

SPUs can effectively comprise the assessment endpoints in any adaptive monitoring program (i.e., what it to be assessed and protected), for instance the viability of a fisheries and the food chain that fisheries depends upon. These must be directly related to quantifiable measures termed measurement endpoints, which comprise what is actually measured to assess and protect resources/ecosystems services. Munns et al. (2009) discuss assessment endpoints based on ecosystem services and the translation of measurement endpoints to ecosystem services losses.

Ecosystem services fall under the general categories of provisioning (food, water, energy), regulating (flood control, erosion prevention), cultural (recreation, spiritual value, sense of place) and supporting (nutrient cycling, oxygen) (Millennium Ecosystem Assessment, 2005). All of these general categories could potentially be affected by SOPCs, but not all are usually considered when determining the effects of such developments. For instance, cultural SPUs involving Aboriginal populations require inclusion of traditional ecological knowledge in monitoring program design and data interpretation (Chapman, 2007).

Evaluating changes to ecosystem services in aquatic systems potentially impacted by SOPCs using adaptive monitoring based on SPUs will arguably provide not only the most technically acceptable but also the most societally acceptable risk evaluations, and thus the best possible basis for any subsequent management action(s), including possible valuation of lost or threatened SPUs (Van Hecken and Bastiaensen, 2010).

Both SOPCs (Table 1) and effects (laboratory and/or field measurements) need to be considered site-specifically, with subsequent investigations of causation as necessary to determine appropriate remedial action(s). For example, effects may not be due to measured chemicals because of biotic or abiotic interactions (e.g., habitat change). Abiotic factors other than measured chemicals (e.g., particle size, organic carbon, unionized ammonia, sulphide) can cause effects that may be incorrectly attributed to measured chemicals. Abiotic factors (e.g., organic carbon, speciation, binding to particulates) can also ameliorate possible chemical effects.

5. Adaptive monitoring of SOPCs based on ecosystem services

Adaptive monitoring begins with the development of the crucial questions it is to address, which may change over time (Fig. 1). Thus, past, present and future trends in monitored parameters and in SPUs need to be considered. The crucial questions also determine the form of the monitoring, which can be based on values, SOPCs or effects, or some combination thereof as follows:

• Value-based monitoring (e.g., how to preserve fishery SPU values);
• SOPC-based monitoring (e.g., what is the effect of a stressor on fishery SPU values?); and,

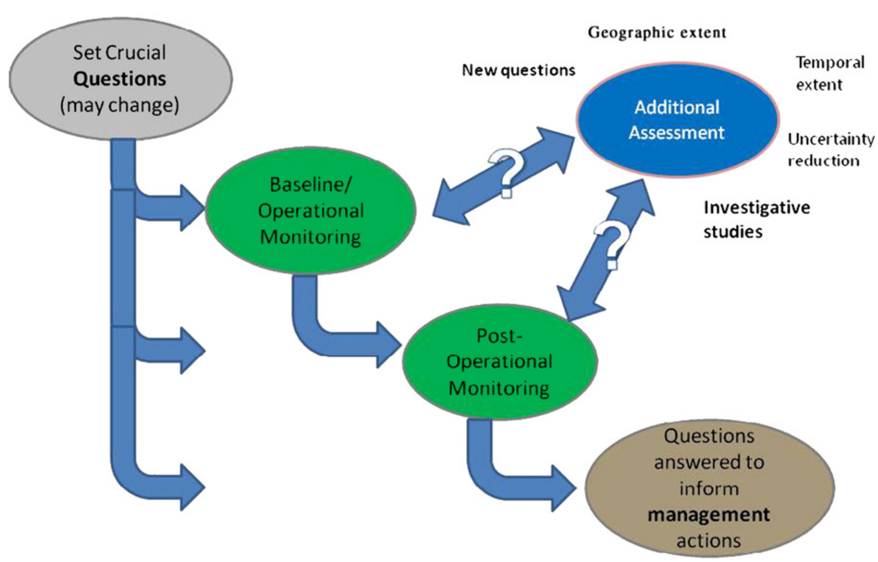

Fig. 1. Adaptive monitoring.

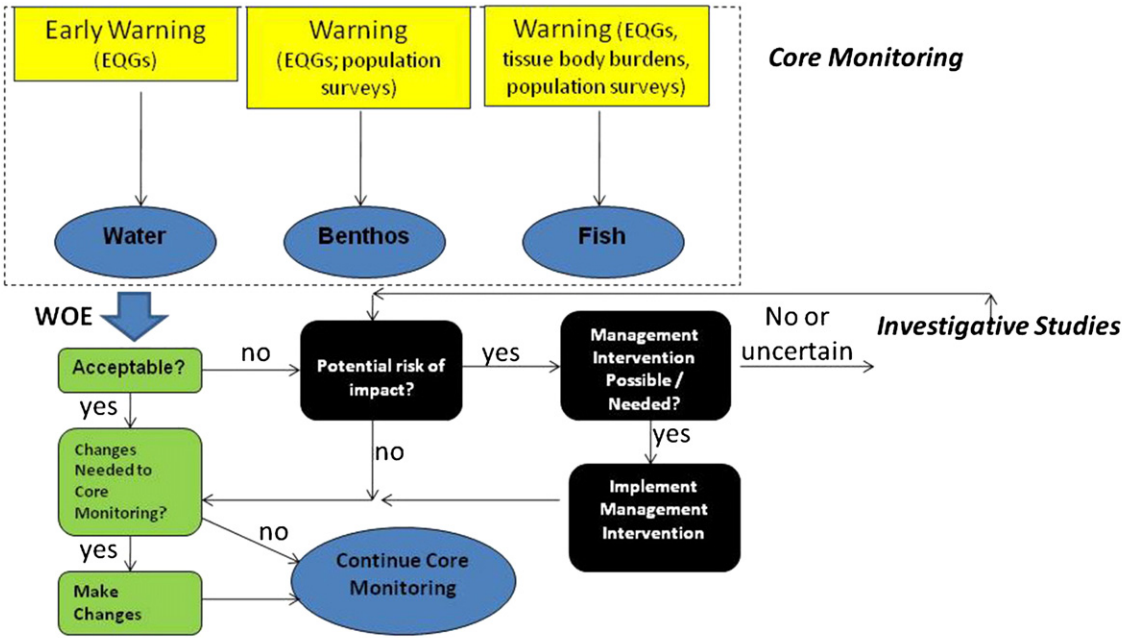

Fig. 2. An example of adaptive monitoring, with associated investigative studies. EQG = environmental quality guideline.

- Effects-based monitoring (e.g., is the state of an ecosystem in terms of SPU values below normal compared to, for instance, background or reference conditions and, if so, what factors prevent it from being normal?).

As a component of answering the crucial questions, acceptable natural background and/or reference conditions are described and natural variability bounded. Operational and post-operational monitoring are conducted informed by and modified by additional assessments as necessary. The end result of monitoring is the provision of answers to the crucial questions to inform management actions. These answers must be both technically defensible and explicitly recognize associated uncertainties.

There are three general types of uncertainty. Stochastic uncertainty refers to the inherent randomness of the system being assessed; as noted above, it needs to be described and bounded. Uncertainty arising from human error should be minimized by appropriate QA/QC. Uncertainty arising from imperfect knowledge should be reduced by appropriate additional assessments (Fig. 1) and investigative studies (Fig. 2). Investigative studies should comprise peer-reviewed research that is readily available (e.g., published in the peer-reviewed scientific literature).

Monitoring will not always provide sufficient certainty for decision-making. It will typically determine either there is not presently a problem requiring management intervention, or that there is a possible problem that may require management intervention. The latter possibility will require further assessment and likely changes to the monitoring program as the latter adapts to this new information (Fig. 2).

6. Final words

Ecosystems are shaped by a very large and changing set of environmental conditions, including anthropogenic and other stressors. Effective assessment and management of aquatic ecosystems require an understanding of natural variability as well as an understanding of the potential effects of SOPCs.

Monitoring is context-dependent, and will vary according to the SPUs to be protected, but must be firmly based on those SPUs. Doing so will not only avoid mindless data collection and protracted debates between stakeholders, but will ensure that necessary questions such as the effectiveness of management actions can be adequately addressed. Adaptive monitoring based on ecosystem services provides the best means to develop necessary information for informed decision-making (e.g., the need for or effectiveness of management actions that do not cause more environmental damage than they prevent).

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