# SC_18

# Thoughts on Adaptive Management

*John G. Williams*

"Adaptive management" has entered California hydrospeak. Whatever it means, it sounds good. After all, who would want to practice nonadaptive or maladaptive management? Unfortunately, the meaning of the term has been diluted in proportion to its popularity, so some have questioned whether any useful meaning remains, and a term that means different things to different people can only lead to misunderstandings. I argue that the term does have an important meaning, so either that meaning must be resurrected for adaptive management, or a new term must be devised.

If "adaptive management" means anything, then it must distinguish one kind of management from other kinds. I propose that adaptive management has two essential attributes: (1) it is a response to uncertainty about the system being managed, and (2) actions are designed, at least in part, to provide new information about the system. Other attributes can and should vary according to the system being managed and its political context.

This definition distinguishes adaptive management from "real-time" management, or management with a flexible, trial and error approach, although many people use the term with just those meanings. It also distinguishes a narrow meaning of adaptive management from an elaboration of the concept known as "Adaptive Environmental Assessment and Management," or AEAM, that involves a particular approach to implementing adaptive management. AEAM seems appropriate for the Bay/Delta, so it is tempting simply to call it adaptive management, and indeed the two terms are sometimes used interchangeably in the literature (e.g., Holling 1978; Walters 1986, 1997). However, the importance of maintaining a focus on uncertainty justifies distinguishing the two and introducing yet another term. The distinction is well explained in an excellent article by Volkman and McConnaha (1993), describing the application of adaptive management to the Columbia River:

> In 1984, Professor Kai Lee, then a member of the [Pacific Power Planning] Council, suggested that the [Columbia River salmon] problem lent itself to the idea of adaptive management: the notion that fish and wildlife measures should be seen as a series of experiments, with formal experimental designs to help answer critical questions about the interactions of humans and the ecosystem. By structuring salmon recovery measures as experiments, the Council could acknowledge scientific uncertainty, act on reasonable hypotheses, and learn from the results.
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> Adaptive management can be a radical doctrine. With traditional management, action is based on existing knowledge and established modes of operation. The course is altered if it appears unproductive, but information is not sought aggressively or strategically, and when it is gathered, it is drawn from a relatively narrow range of conditions. In contrast, adaptive management implies an active search for key hypotheses and a commitment to test them. In fisheries, adaptive management has been developed and applied largely within the harvest arena. Populations might be deliberately over- or under-harvested, for example, to examine the population's response to harvest pressures.
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> In principle, the need to learn more about the effects of other human activities on salmon recovery seemed no less compelling. It was apparent, however, that the Council could not apply an unadorned form of adaptive management even to the most critical uncertainties involved in salmon recovery. Applying the theory on a smaller scale, to harvest problems, is difficult; but it is at least limited to a single constituency (harvesters) and distinct population groups (chinook salmon off the coast of British Columbia, for example). The idea of extending the concept to an ecosystem, particularly an intensively-developed ecosystem such as the Columbia River Basin, promised a mare's nest of controversies.
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> The solution proposed by Dr. Lee was based on a modification of adaptive management called Adaptive Environmental Assessment and Management (AEAM), developed by C.S. Holling and his colleagues (Holling 1978). Holling's notion stressed explicit integration of scientific, economic, and social concerns into efforts addressing resource problems. Computer modeling and simulation would demonstrate the potential effects of alternative management actions and scientific uncertainty. Scientists, managers, policy makers, and the public, all bringing their own political, economic, and cultural concerns, would come together in an analytical process aimed at identifying appropriate cases for scientific probing. No one would be forced to pretend that she lives in a world where science alone matters. To the austere principles of adaptive management, then, Holling added a social process — a group conversation conducted with the help of computer models, focusing on data, but mindful that dogma is not far behind.

## The Importance of Uncertainty

The concept of adaptive management of living resources developed through the application of ideas from engineering and decision theory, particularly to the regulation of salmon harvest in the Pacific Northwest. As described by Walters and Hilborn (1976) in a seminal paper, "Adaptive control of fishing systems:"

> This paper addresses the question of how harvesting decisions should be modified to take account of statistical uncertainty. In seeking a formal framework for dealing with this question, we have been drawn to the literature on control system theory, where

the problem is addressed under the heading of "adaptive" or "dual" control (citation omitted).

Harvest management typically involves one or a few species. However, CALFED proposes the more difficult task of managing an ecosystem, involving a greater order of uncertainty. Healey (1997), citing O'Neil et al. (1986), points out that there is an inherent unpredictability about ecosystems because they are "medium number" systems, made up of too many interacting subsytems to deal with analytically, but of too few subsystems to deal with in terms of averages. Healey also notes that ecosystems may even behave chaotically in the mathematical sense, whereby very small differences in initial conditions can lead to very large differences in eventual outcomes. In consequence:

> The "unknowable" character of rivers and river basins is part of their fascination as ecosystems. But their "unknowableness" also means it is not possible to predict their behavior the way behavior of structural materials in a bridge or the airfoil of a jet plane can be predicted. Fortunately this does not mean that the goal of ecosystem management must be abandoned. What It does mean is that approaches to the management of ecosystems must differ from approaches to the management of traffic on highways or the exploitation of individual fish populations. In the latter two instances, management is based on simple analytic models that predict quantities (e.g., vehicles, fish) that can be accommodated or harvested in a specified period of time. Such quantitative statements about ecosystem behavior may never be possible.

Mangel et al. (1996) express a similar view:

> By identifying things that are critical to a given ecosystem (such as nutrient dynamics, life history parameters of critical species, need for migratory pathways, and/or major external threats or opportunities) one can design a management plan that accommodates a wide variety of human uses while preserving that which is most critical for the continued viability of the ecosystem. But a distinction must be made between managing a living resource with an ecosystem approach and managing an ecosystem. An individual species or population as a resource may be managed while taking into account its interactions with other elements of its ecosystem. This is resource management with an ecosystem approach. Managing ecosystems, on the other hand, means managing the entire system by integration of ecological, economic, and social factors to control the biological and physical systems (Wood 1994). Currently, this is difficult to do as an informed activity (Slocombe 1993) because the concepts are ill defined, great uncertainty exists about most ecosystems, and methods are just developing.

The increasing recognition of the inherent uncertainty associated with ecosystems is described in Appendix I of Mangel et al. (1996):

> The first is a change in the way ecosystems are perceived. Some call this "the new ecological paradigm." It should be emphasized that although the facts have been known by some ecologists, other scientists, and managers for many years, it is only recently that there is more widespread recognition of the knowledge. Formerly, the dominant paradigm was that of an ecosystem that was stable, closed, and internally regulated and behaved in a deterministic manner. The new paradigm is of a much more open system, one that is in a constant state of flux, usually without long-term stability, and affected by a series of human and other, often stochastic factors, many originating outside of the ecosystem itself. As a result the ecosystem is recognized as probabilistic and multi-causal rather than deterministic and homeostatic; it is characterized by uncertainty rather than the opposite.

The importance of uncertainty has been recognized by the courts as well as scientists. After reviewing the evidence on the flows needed to protect salmon and other public trust resources of the American River, Judge Hodge (1990) wrote that:

> As with the water quality issue, it is the fact of uncertainty which is left with the Court. There is simply no basis in the evidence for a reasoned selection among various of the competing positions. This represents not an abdication of court responsibility, but, rather, a recognition of existing scientific reality.

An important essay in *Science*, "Uncertainty, resource exploitation and conservation, lessons from history" (Ludwig et al. 1993), listed five attributes of effective resource management, culminating with:

> 5) Confront uncertainty. ... Most principles of decision-making under uncertainty are common sense. We must consider a variety of plausible hypotheses about the world; consider a variety of possible strategies; favor actions that are robust to uncertainties; hedge; favor actions that are informative; probe and experiment; monitor results; update assessments and modify policy accordingly; and favor actions that are reversible.

More recently, Castleberry et al. (1996) noted that the basic arguments of the Ludwig et al. paper apply to instream flow assessments, and emphasized the importance of acknowledging uncertainty:

> At an April 1995 workshop in Davis, all 12 participants agreed that currently no scientifically defensible method exists for defining the instream flows need to protect particular species of fish or ecosystems (citation omitted). We also agreed that acknowledging this fact is an essential step in dealing rationally and effectively with the problem.

Similarly, acknowledging the fundamental uncertainties about the Bay/Delta ecosystem is an essential step in dealing rationally and effectively with its restoration. The uncertainty problem is like a drinking problem; you have to admit that you have it in order to deal with it.

## Uncertainty and the Need to Act

Uncertainty is a two-edged sword. Historically, uncertainty about the causes of environmental problems worked to the benefit of the status quo. However, experience showed that the failure to act until the signal from specific causes could be clearly distinguished from the noise of ecological uncertainty put the environment at too great a risk. In the language of statistics, traditional policy emphasized the risk of acting on an incorrect hypothesis about the cause of a problem, a "Type I" error, but underemphasized the risk of failing to act on a correct hypothesis, a "Type II" error (McAllister and Peterman 1992).

Because adaptive management recognizes ecological uncertainty, it highlights the need to balance Type I and Type II errors. As a practical matter, this means acting despite uncertainty, as noted in the third of five principles of adaptive management that are commonly recognized, although they do not all follow as strict logical consequences of the definition given above. As stated succinctly by Hennessey (1994):

1. The purpose of adaptive management is the protection and restoration of living resources.
2. Projects are experiments; the choice is to make them good ones or bad ones. Some will fail; others will succeed.
3. Action is overdue. We do not delay action until enough is known.
4. Information has value, not only as a basis for action, but as a product of action.
5. Protection measures may be limited, but management is forever. (Lee and Lawrence 1986; Holling 1978; Walters 1986)

Similarly, the first attribute of effective management given by Ludwig et al. (1993) is "Act before scientific consensus is achieved."

## Management as Experiments

Adaptive management treats management actions or projects as experiments, and experiments require hypotheses to be tested. As stated by McAllister and Peterman (1992):

> Hurlbert (1984) identified the components of an experiment (1) a hypothesis, (2) experimental design, (3) execution of experiment, (4) data analysis, (5) interpretation of results. In this paper we are primarily concerned with experimental design. Advocates of experimental management emphasize that before management actions are taken, hypotheses should be clearly stated, possible biological models should be described mathematically, and experimental designs should be carefully chosen (Walters and Hilborn 1978; Walters 1986; Sainsbury 1988). Good experimental design is crucial to distinguish among alternative hypotheses (Hurlbert 1984).

Designing good experiments is a major challenge, so treating management actions as experiments increases rather than decreases the need for careful and creative thinking. Treating actions as experiments also means that managers should be held accountable for the design and execution of their actions, and not just for the results, since the results are assumed to be uncertain (Mangel et al. 1996).

Although adaptive management treats management actions as experiments, there can be more or less uncertainty about the results of a project or action. For example, there was not much uncertainty about the effect of Friant Dam on the San Joaquin River spring-run chinook salmon. Where there is not much uncertainty, not much can be learned by treating an action as an experiment. Moreover, all information is not equally useful, so not all experiments are worth conducting, and a bad idea cast as an experiment is still a bad idea.

## Adaptive Environmental Assessment and Management

The AEAM process is founded on the realization that "The value of modeling in fields like biology has not been to make precise predictions, but rather to provide clear caricatures of nature against which to test and expand experiences" (Walters 1986, p. 45). In consequence, the greatest benefit from models in biology comes from what is learned in the modeling process, and AEAM is a way to involve diverse people in the modeling process, creating the "group process conducted with the help of computer models" described by Volkman and McConnaha (1993). Holling, Walters, and others developed a workshop process for this purpose that has had considerable use, and is described at some length in Walters (1986). As described briefly by Walters (1997) [although he uses the term adaptive management instead of AEAM]:

> ... we generally use the term today to refer to a structured process of "learning by doing" that involves much more than simply better ecological monitoring and response to unexpected management impacts. In particular, it has been repeatedly argued (Holling 1978; Van Winkle et al. 1997; Walters 1986) that [AEAM] should begin with a concerted attempt to integrate existing interdisciplinary experience and scientific information into dynamic models that attempt to make predictions about the impacts of alternative policies. This modeling step is intended to serve three functions: (1) problem clarification and enhanced communication among scientists, managers, and other stakeholders; (2) policy screening to eliminate options that are most likely incapable of doing much good due to inadequate scale or type of impact; and (3) identification of key knowledge gaps that make model predictions suspect.
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> Most often the knowledge gaps involve biophysical processes and relationships that have defied traditional methods of scientific investigation for various reasons, and most often it becomes

apparent in the modeling process that the quickest, most effective way to fill the gaps would be through focused, large scale "management experiments" that directly reveal process impacts at the space-time scales where future management will actually take place. The design of management experiments then becomes a key second step in the adaptive management process, and a whole new set of management issues arises about how to deal with the costs and risks of large-scale experimentation (Walters and Green 1996). Indeed, AEAM modeling so regularly leads to recommendations for management experiments that practitioners like Walters (Univ. of British Columbia, pers. comm.) have come to use the terms "adaptive management" and "experimental management" as synonymous. In short, the modeling steps in [AEAM] planning allows us, at least in principle, to replace management learning by trial and error (an evolutionary process) with learning by careful tests (a process of directed selection).

From one point of view, anyone who thinks that he or she understands how something work has a model of it. Mathematical modeling has the virtues described by Walters because it makes people be explicit about the way that they think things work, and the numerical results of running the resulting model provide a check on the reasonableness or importance of the ideas. AEAM seems particularly attractive for management directed at specific species or ecosystem functions. However, complete ecosystems are so complicated that developing models that are useful "clear caricatures" for the whole system may not be possible; at the least, they would involve even greater degrees of abstraction. It may be more appropriate to use different models for investigating different aspects of the ecosystem, within a conceptual framework that reminds us that each is incomplete.

## Active and Passive Adaptive Management

Walters and Holling (1990) distinguish three types of management that can be considered adaptive in any sense:

> (1) evolutionary or "trial and error," in which early choices are essentially haphazard, while later choices are made from a subset that gives better results; (2) passive adaptive, where historical data available at any time are used to construct a single best estimate or model for response, and the decision choice is based on assuming this model is correct; or (3) active adaptive, where data available at each time are used to structure a range of alternative response models, and a policy choice is made that reflects some computed balance between expected short-term performance and the long-term value of knowing which alternative model (if any) is correct.

From a scientific or information-gathering point of view, there are good reasons to favor an active adaptive approach, which typically involves some deliberate change in the management of the system that is large enough to be informative. However, such large changes may be politically infeasible, and small changes may produce little information despite being economically disruptive.

This point is perhaps best explained by the example of harvest management. Traditionally, management of salmon harvest was based on the idea that the number of young salmon "recruited" to the fishery is related to the number of spawners by some non-linear curve that reflects density-dependent mortality. With the classic Ricker (1954) model, the curve is dome-shaped, such that some number of spawners maximizes the number of recruits, and either more or fewer spawners produces fewer recruits. With the Beverton-Holt model, which makes different assumptions about the nature of the density-dependent processes that affect survival, the number of recruits levels off as the number of spawners increases, so beyond some number additional spawners are in effect "excess," but do not result in an absolute decrease in the number of recruits.

The obvious objective of harvest management is to provide the optimum number of spawners; however, this is generally an uncertain number. The number of recruits is affected by many other factors besides the number of spawners, and estimates of numbers are often of dubious accuracy, so inevitably a plot of recruits over spawners shows a great deal of scatter. Accordingly, there is uncertainty regarding which of various spawner-recruit relations best describes the population of salmon in question, and there is also uncertainty about the proper values of the parameters of the various curves.

A straight-forward approach is to select the curve and parameter values that best fit the available data on numbers of spawners and recruits, and calculate a "best guess" optimum number of spawners. Then, harvest can be managed to keep the number of spawners close to the estimated optimum, and the numbers of spawners and recruits can be monitored and used to refine the estimate of the optimum number of spawners. This is what Walters and Holling call a passive adaptive approach.

However, this approach gives rise to a dilemma. If harvest is managed to keep the number of spawners close to the original estimated optimum, then subsequent data points will be affected mainly by other variables and measurement errors, and will provide little additional information about the optimum number of spawners. An original bad guess may remain unrecognized, particularly if the estimated optimum is too low, with a resulting loss of part of the productive potential of the habitat. Managing the harvest to provide for small changes in the number of spawners will not help much, either. On the other hand, managing the harvest to allow some substantially different number of spawners will entail large losses if the original estimate is close to correct, and these losses must be weighed against the potential value of the information gained by the experimental harvest.

Presumably, this dilemma generalizes from the relatively simple case of harvest management to more complex questions of ecosystem management. However, doing the balancing for harvest management is complicated enough (Walters and Hilborn 1976), and it is not clear that it is even possible for other situations except by essentially political decisions. For such reasons, there is a strong temptation to try passive rather than active adaptive management.

There may be an escape from this dilemma when there is significant natural variation in the system of interest. For example, there is substantial year-to-year variation in delta outflow, regardless of management. There is inconvenience, expense and delay associated with monitoring the system over a long enough period for uncontrolled variation to cover a range of conditions, and there is more danger that study results will be confounded by co-variation among variables, or by long-term changes in the environment. However, these disadvantages may be small compared to the problems associated with deliberate major changes in management.

## Monitoring for Adaptive Management

For management actions to be treated as experiments, there must be a way to measure the response of the system being managed: a monitoring program. Good monitoring is more difficult and more expensive than many people realize. Many questions of interest concern small organisms in large and often muddy rivers, and there is no easy way to answer them. As noted in Appendix I of Mangel et al. (1996):

> Two types of uncertainty are involved in living resource conservation. The first could be considered "ecological uncertainty," which refers to the probabilistic nature of biological systems discussed in the previous paragraph. [Quoted above.] The second type is uncertainty in the estimation of parameters such as abundance, birth and death rates, etc.: this is measurement "uncertainty." Both of these types of uncertainty are central concerns to any model or management regime, and there is often confusion between them when uncertainty is discussed.

Accordingly, it is important to consider carefully how well proposed monitoring programs can be expected to detect the response of the system to experimental management, which can often be done by computer simulations (Ludwig and Walters 1985). If responses can be detected only if they are very large, or after many years, then the "experimental design" of the proposed management should be reconsidered.

Good monitoring in adaptive management is also important for three other reasons. First, unsuccessful but politically attractive measures may be repeated if failures are not recognized (Kondolf et al. 1996). Second, as noted above, randomization and replication are ordinarily impossible in adaptive management experiments, so it is important to monitor potential confounding factors. The Vernalis Adaptive Management Program, for example, will test the effect of different flow and export rates on the survival of juvenile chinook salmon in the San Joaquin River. Survival will be measured by releases of coded-wire tagged hatchery smolts. However, it seems sensible also to monitor potential confounding factors such as water temperature, measures of the condition of the smolts at release and at recapture, indicators of exposure to toxics, etc. Besides reducing uncertainty in the interpretation of the results of the main experiment, such data can also be useful for testing hypotheses about the mechanisms by which the alternative management regimes effect smolt survival. Third, science advances by observations as well as by experiments, and observations often provide the inspiration for experiments (Power et al., in press).

## Scientific Difficulties with Adaptive Management:

Doing good experiments is difficult even in the controlled conditions of a laboratory, and it is much more difficult in the field. Writing about ecological studies generally, Hilborn and Mangel (1997) point out that:

> ...the following attributes of ecological systems often make experiments difficult:
> —Long time scales: Many ecological systems have times scales of years or decades
> —Poor replication: Many ecological systems are difficult to replicate, and replicates are rarely, if ever, perfect
> —Inability to control: One can rarely, if ever, control all aspects of an ecological experiment
> Because of these factors it is often harder to get clear, unambiguous results in ecological experiments (cf. Shradder-Frechette and McCoy 1992).

The same difficulties apply, usually more strongly, to adaptive management experiments. Management experiments that involve only part of a system or a short period of time may fail to detect or recognize unanticipated factors that can render the experiment not just invalid but also misleading. For example, many biologists now believe that the survival rate of salmon in the ocean varies over a timescale of decades (Pearcy 1997). Experimental management of freshwater habitat during a period of changing ocean survival could easily give misleading results if the experiment were monitored only in terms of numbers of adults. Field experiments with small spatial scales can give similarly misleading results (Peterman 1991; Walters 1997).

Replication is also a problem. There is only one Stanislaus River, so it is not possible to replicate experimental management of the Stanislaus. Experimental management of the Toulumne and the Merced rivers could be useful approximations to such replication, but would not be the real thing, and although it might be the best that can be done, the meaning of the results of such experimental management will be to some degree compromised. Measurement uncertainty adds to the difficulties.

There is no easy solution to these problems, so it is not reasonable to expect adaptive management experiments to produce unambiguous results within a few years. On the positive side, analytical and statistical methods have been developed or applied in ecology (e.g., Hilborn and Mangel 1997) that could be applied as well to adaptive management. However, these methods, such as Bayesian statistics, are unfamiliar to most scientists working on Bay/Delta issues.

## Political Difficulties with Adaptive Management

Resource management is complicated by social as well as scientific uncertainty (Halbert 1993), and even in the context of fisheries, adaptive management can fail through unanticipated social responses to management experiments. As noted by Volkman and McCannaha (1993), applying adaptive management to ecosystems promises "a mare's nest of controversies:"

> The notion that we are willing to take dramatic steps in order to learn — to create control cases, and then to depart sharply from them — can, in a high-stakes setting like the Columbia River, be exceedingly problematic. It is difficult to convince people of the wisdom of investing public funds, or risking harm to a species on the brink of extinction, while embracing the scientific method's root principle that failure is not only possible, but likely, and may be necessary in order to learn.
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> The notion that we place a high value on learning ignores the fact that in some instances, ignorance has value. As long as key questions are open, parties remain free to take political positions. In the long term, the truth may set us free, but in the short term, it can reduce our room to maneuver. "Good science" becomes that which supports one's position.
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> The supposition that we are willing to wait patiently for answers that may take decades to determine, runs against the grain of politics. If salmon are declining, the political impulse is to change course, regardless of whether we understand the problem.
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> Good science can run into equity considerations. Is it fair to ask Indian tribes, whose harvest has been in sharp decline for decades, to go slow on hatchery technology that has fueled non-Indian harvest for decades because we need to explore the long-term effects on salmon populations.
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> All of these factors point to a simple, but very hard lesson: adaptive management does not take these decisions out of the political arena. Decision makers still have to gain political support to test important hypotheses. All of the aversion to risk and expense, the impatience with slow answers, the uses of ignorance, the bureaucratic inertia from all quarters, and the fear of failure still come into play. Adaptive management does not allow us to escape unscientific pressures.

## Conclusions

Adaptive management as described here is a bitter pill, and despite its therapeutic benefits is accordingly difficult to implement. On the one hand, scientists must acknowledge that in some sense they do not know what is going on, and managers must acknowledge that in a similar sense they do not know what they are doing; on the other hand, those subject to management actions must acknowledge that uncertainty does not justify inaction. All must accept that progress will be slow, and that substantial sums must be allocated to monitoring and evaluation, probably at the expense of additional restoration efforts. Only the alternatives are less palatable.

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## Third Delta Smelt Workshop is Set for October

The Third Delta Smelt Workshop is scheduled for October 1-2, 1998. A location will be chosen based on the number of responses to this announcement and an earlier e-mail solicitation of interest. The workshop will provide updates on the progress in understanding delta smelt biology since early 1996, when the last workshop was held.

The first day of the workshop will consist of presentations of new and ongoing work regarding delta smelt biology. A panel discussion will occur toward the end of the day. The second day will consist of a one-half day meeting of technical experts to discuss the nuts and bolts of delta smelt monitoring and research. The first day is open to all interested individuals. The second day is limited to technical experts with direct involvement in planning or implementing delta smelt projects.

Products expected from the workshop include an IEP newsletter article, and an IEP technical report including abstracts of the presentations, a complete delta smelt bibliography, a summary of the meeting by one or more of the Science Advisory Group, and a summary of issues discussed at the second day of the meeting.

If you are interested in attending and DID NOT respond to the earlier e-mail solicitation of interest, please send a note, preferable via e-mail, to Larry Brown, U.S. Bureau of Reclamation, 2800 Cottage Way, Sacramento, CA, 95825, Phone: 916-978-5043, FAX: 916-978-5055, e-mail: lbrown@mp.usbr.gov. A final

# Measuring Bioavailability of Sediment-Associated Contaminants

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## Introduction

There is frequently a need to assess the risk that contaminated sediments pose to aquatic biota, and for this purpose the concept of bioavailability is crucial. While the need to measure the bioavailable contaminant fraction is apparent, doing so in practice has proven to be quite difficult. However, a new technique designed to mimic digestive processes is under development that provides a straight-forward means to measure bioavailability in a wide variety of risk assessment scenarios and to study the basic mechanisms of how organisms accumulate contaminants from sediments.

Chemical methods of extraction are generally designed to recover the total, rather than the bioavailable, contaminant. There have been some selective extractions proposed (e.g., a weak acid extraction for trace metals) that purport to quantify the bioavailable fraction, but none of these have been generally accepted or broadly adopted. Biological methods such as toxicity or bioaccumulation testing are currently used widely to measure bioavailability, yet interpretation of results can be confounded by other factors unrelated to bioavailability. Toxicity can be a function of the organisms prior acclimation or adaptation, not bioavailability alone. Bioaccumulation as a measure of bioavailability is confounded by behaviors affecting exposure (e.g., feeding and respiration rates) as well as metabolism of the contaminant of interest.

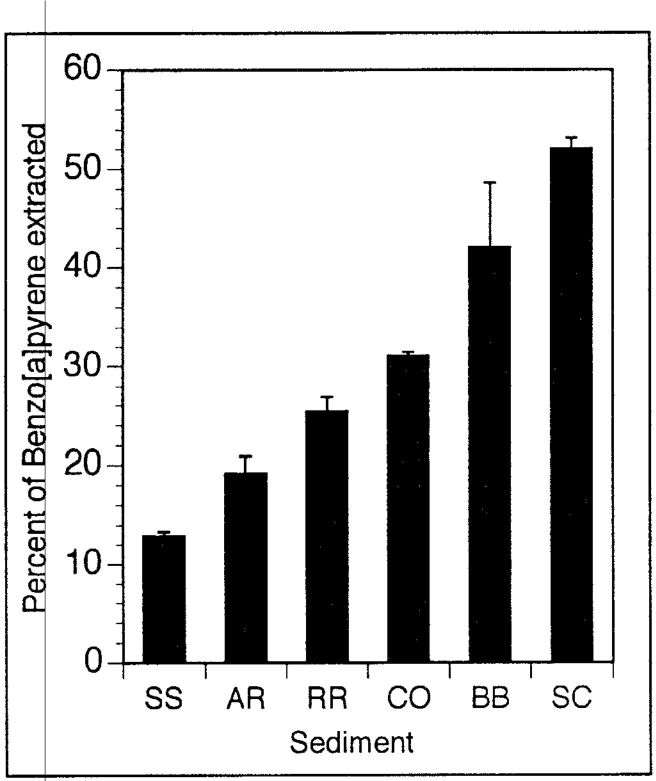

Figure 1

Proportion of sediment-associated benzo[a]pyrene extractable by digestive fluid of *Arenicola brasiliensis*. Each of the six sediments tested is denoted by an arbitrary two-letter designation.

We are currently developing in vitro digestive fluid extraction as a technique to measure sediment-bound contaminant bioavailability (Mayer et al. 1996; Weston and Mayer 1998a,1998b). When a deposit-feeding organism ingests sediment, the chemistry of the gut environment determines if the associated contaminants can be desorbed from the particles and are available for dietary absorption. We mimic this process in vitro, by incubating the sediments of concern in digestive fluid and expressing bioavailability as the percentage of contaminant that has been solubilized in those fluids. The approach presumes that the contaminant extractable by digestive fluid is implicitly a far better indicator of the bioavailable fraction than that extractable by the strong acids or exotic organic solvents typically used in a chemical analysis. Our approach is essentially a chemical extraction, but with a biologically relevant extractant.

## Results

The polychaete *Arenicola brasiliensis* has been a source of digestive fluid for most of the work to date simply because of its large size and the amount of digestive fluid that can be recovered. We have used this fluid to extract sediments from throughout California contaminated with either polycyclic aromatic hydrocarbons (PAH), PCBs, or trace metals. Results have included the following observations:

- Gut fluid pH of a wide variety of invertebrates is near neutral, questioning the biological relevance of the strong acid extractions used in traditional chemical analyses for metals.
- Much of the contaminant that is extractable by traditional chemical means is not extractable in digestive fluid. When six California sediments were spiked with PAH, only 12 to 50% of the PAH were solubilized in an in vitro digestive fluid extraction (Figure 1). Thus, any assessment based on total PAH would have over-estimated the risk posed by these sediments by a factor of 2-8 times.
- In vitro contaminant extraction is similar to that obtained in vivo. Allowing intact *A. brasiliensis* to feed on contaminated sediments and then analyzing the PAH content of