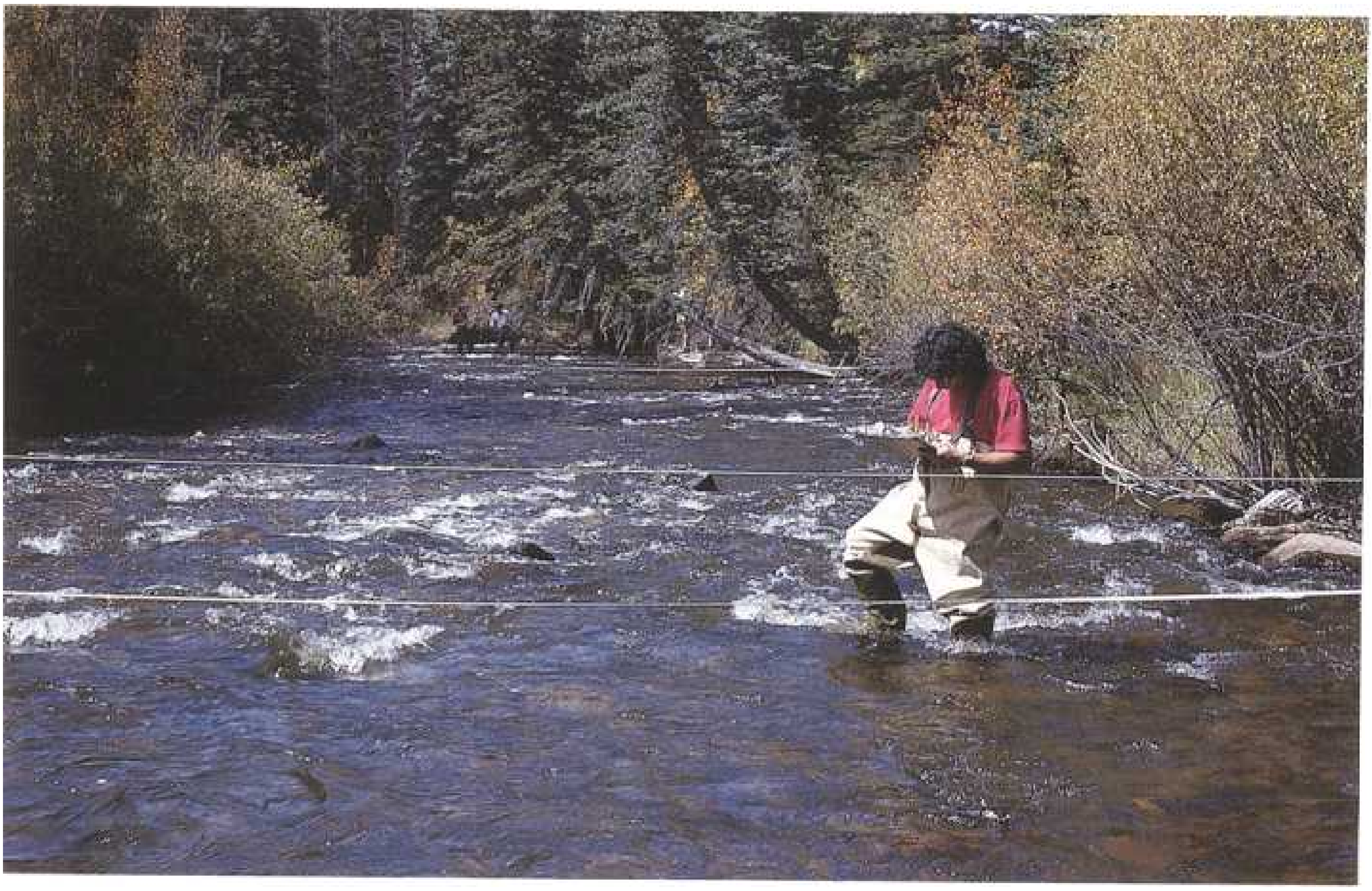

Developing a monitoring project

Lee H. MacDonald

Monitoring means "to watch or check on" (*9*). In resource management, monitoring is an essential step from both a resource and a legal perspective (*5, 6, 7, 10*). In particular, monitoring is essential to evaluate management effects on a given resource; justify the expenditure of funds for pollution control, alternative resource management practices, and restoring degraded resources; optimize the allocation of funds among management alternatives; increase our understanding of the systems being monitored, particularly their temporal and spatial variability; and document compliance with regulatory requirements.

If our primary concern is water quality, for example, monitoring is used to evaluate compliance with water quality standards and the effects of management activities on water quality (*3, 4, 5*). If water quality is not satisfactory, a strategy must be developed to reduce incoming pollutants, and monitoring—often coupled with modeling — is essential to determine the most cost-effective approach. Thus, monitoring is essential to responsible, effective, and efficient resource management, and monitoring is increasingly a required component of water pollution control programs (e.g., *5, 6*)

Nevertheless, remarkably little attention has been given to the explicit and iterative process necessary for the efficient design and execution of monitoring projects. Boynton (*2*) developed a stepwise process of preparing water quality surveillance plans based on his experience with the U.S. Forest Service in California. Similar but more extensive guides to developing water quality monitoring plans have been developed for the U.S. Forest Service (*15, 16*) and the U.S. National Park Service (*11*). Although these guides were specific to agency needs, each emphasized the importance of a conscious, rigorous procedure for developing and exe-

Photo above: Students measuring discharge and channel characteristics in the Little South Fork of the Poudre River, Colorado. Measurements by successive classes can yield monitoring data if data collection techniques are consistent over time. Replicated measurements and other procedures are necessary to assess variability and provide quality assurance/quality control.

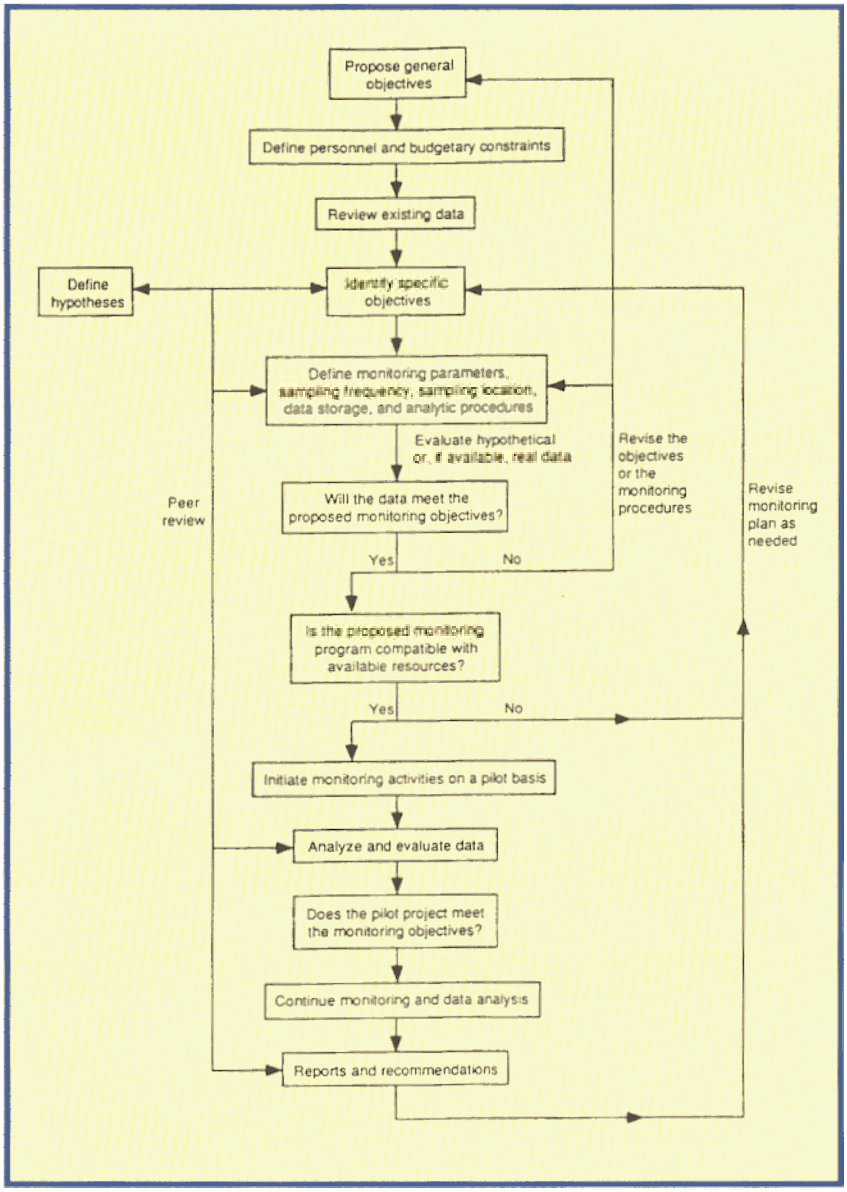

Figure 1. Flow chart for developing a monitoring project.

cuting monitoring projects.

A workshop at the East-West Center in 1986 developed guidelines for surveying and monitoring watersheds. The primary focus was on the acquisition of statistically-sound information in a cost-effective manner (*14*). Statistical aspects of designing monitoring networks are discussed in more detail in Sanders et al. (*17*) and Ward, Loftis, and McBride (*21*). Brooks et al. (*3*) discussed the role of monitoring and evaluation within the context of watershed management projects. Stednick (*20*) also briefly discussed the design of water quality monitoring projects in a recent manual on wildland water quality sampling and analysis.

A more detailed procedure for designing and executing monitoring projects was developed by MacDonald, Smart, and Wissmar (*13*). Ostensibly this was specific to monitoring the effects of forestry activities on streams in the Pacific Northwest and Alaska, but the high level of interest in this publication suggested that the basic principles were more broadly applicable.

In the last two years, the author has led workshops on monitoring in nine Western states, participated in several other workshops and conferences on monitoring (e.g., *12*), and prepared a guidance document on the inventory and monitoring of water resources for the National Park Service. These workshops and discussions have verified the validity and broader applicability of the basic procedure outlined in MacDonald, Smart, and Wissmar (*13*), while suggesting some additional points and refinements. The recently published evaluation of the Experimental Rural Clean Water Program (*7*) provides independent support for many of the concepts which led to the development of this paper.

The purpose of this article is to present a revised and more generally applicable procedure for designing and implementing monitoring projects. By definition a monitoring project consists of measuring selected variables in time and space in order to diagnose change. Cause-and-effect generally cannot be proven due to a lack of randomly-allocated treatments and controls, but may be inferred by linking changes in water quality to changes is land treatment (*19*). The complexities of natural systems causes monitoring to be a difficult compromise between what is feasible and what is desirable. Hence, a conscious, explicit process is needed to formulate monitoring projects which minimize costs while still having a relatively high likelihood of providing the desired information (*3, 17, 21*).

All too often, monitoring projects are initiated with a minimum of forethought, and result in a collection of poorly-documented data which are never analysed, provide little or any feedback to resource managers, and contribute little or nothing to our understanding of the systems being monitored. This wastes time and resources, and implies that we'll keep making the same mistakes.

It is important to note that the procedure discussed here is most applicable to more quantitative and rigorous monitoring projects. Qualitative, "walk-in-the-rain" monitoring can be very effective in terms of identifying key processes and problem areas (*12*), but a more rigorous and quantitative approach will typically be required for regulatory compliance and to justify substantial changes in management practices. Probably the most effective approach is to use qualitative observations to help design and check on the applicability of quantitative observations (*12*). Bauer suggests a reconnaissance to assess condition and define issues prior to initiating a monitoring project (*1*).

Design of a monitoring project

The key steps in the design and execution of a monitoring project can be summarized as follows:

(1) propose general objectives;

(2) define approximate budget and personnel constraints;

(3) review existing data;

(4) define specific ojectives and hypotheses;

(5) determine variables to be monitored, sampling locations, sampling procedures, and analytic techniques;

(6) evaluate hypothetical or a comparable set of real data;

(7) reassess the specific objectives and compatibility with available resources;

(8) initiate monitoring on a pilot basis;

(9) analyze and evaluate data from the pilot project;

(10) reassess monitoring objectives and compatibility with existing resources, and modify the monitoring project as appropriate;

(11) continue monitoring;

(12) prepare regular reports and recommendations.

This process is shown schematically in Figure 1. The figure is schematic in nature because it shows only a few of the most important feedback loops, and it indicates the process is linear and stepwise. In practice, the key steps are often not nearly as distinct and sequential. Decisions made at one step often have repercussions for other components of the monitoring project, and these repercussions may in turn force a reassessment of previous steps.

It also is not necessary that every step be done in exactly the order indicated. The actual process will vary among agencies and the broader context of the monitoring project, i.e., is the project part of a court-mandated evaluation of an entire river basin or an internal review of a particular management activity? The key point is that each step must be explicitly addressed. Failure to do so almost inevitably causes difficulties later on, as the project doesn't meet the objectives of a key user group or has basic flaws in its design. It is my hope that this paper will lead to improved monitoring by setting out the key steps to developing and implementing a successful monitoring project.

The following sections provide the rationale for, and a description of, each step in the monitoring process.

Propose general objectives. The first step is to identify the general objectives. This is best done by managers in consultation with technical staff. Managers should play the lead role as they are responsible for setting priorities and achieving resource management objectives. However, the managers must consult with the technical specialists so that the former are fully aware of the resource management issues and the role of monitoring in facilitating effective and responsible resource management (*2*).

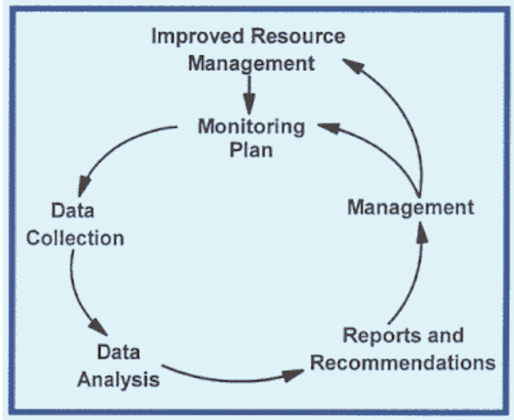

Figure 2. The monitoring feedback loop.

There are several reasons why a manager should take the lead in defining the general objectives of a monitoring project. First, by helping to define the project the manager is effectively buying into the project, and the manager is then more likely to provide continuing financial support (*7*). Second, if the manager plays the lead role in defining the objectives, the project is more likely to provide useful information to guide management actions rather than focussing on the particular interests of the technical specialist (J. Rector, USFS, pers. comm., 1992). Finally, the manager will be aware of the project and expect some results; this will help ensure that the feedback to managers actually takes place (i.e., data are analysed, reports are prepared, and recommendations are made and passed on to management) (Figure 2).

Define personnel and budgetary constraints. Once the general objectives have been identified, the next step is to define the approximate personnel and budgetary constraints. This step is necessary to ensure that the subsequent monitoring plan is realistic. Again managers should play the lead role, as they must allocate the resources for executing a monitoring project. In simple terms, are you planning a five-year, multimillion dollar project, or is there only a part-time technician available for the summer field season? These basic resource allocation decisions must be made by managers rather than technical specialists.

Evaluate existing information and data. At this point the technical specialist takes over the lead role in formulating the monitoring project. The first task is to evaluate existing knowledge about the resource and to collect existing data. If past data are available, changes over time can be assessed if the same measurement techniques and sampling locations are employed. If past data are unavailable, there is greater flexibil-

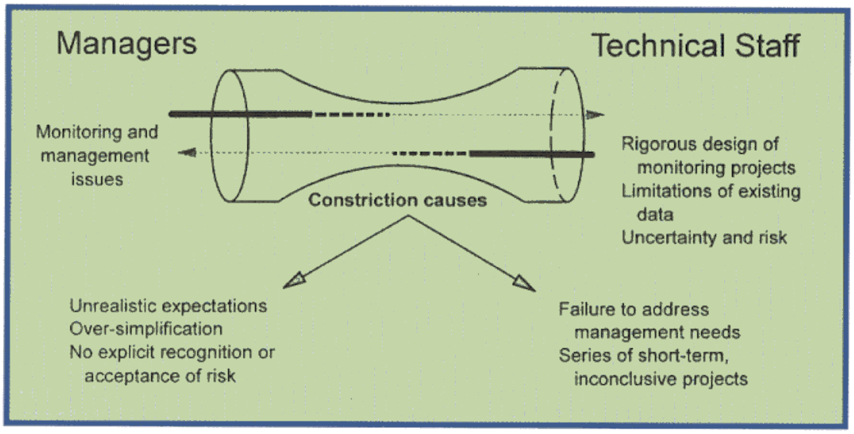

Figure 3.
The communication pipeline.

ity in the selection of monitoring parameters, sampling locations, and measurement procedures. A review of past studies and monitoring projects, including unsuccessful efforts, is important to avoid repeating mistakes and to minimize the learning curve associated with all monitoring projects. A review of other work also can indicate the magnitude of the spatial and temporal variability of the systems to be monitored, and this is necessary to determine the level of change which can be statistically detected (*13, 14*).

Formulate specific objectives. The next step is to formulate the specific objectives of the monitoring project. Experience suggests that this is the most important and most difficult step in the entire monitoring process (*2, 12, 16*).

Managers and technical staff should work together to ensure that the specific objectives are both technically and financially feasible. The importance of this interaction is often overlooked, and a failure in communication between the manager and the technical specialist can lead to a variety of problems (Figure 3). In particular, the manager must be aware of the uncertainty and limitations inherent in the monitoring project, while the technical specialists must ensure that the monitoring project provides the information neccessary for effective resource management and protection. Input from both the managers and the specialists is needed to achieve the proper balance between the need for more data and the cost of acquiring those data.

In most cases the technical specialist will take the lead role in formulating the specific objectives because the specialist is more familiar with previous monitoring efforts, the technology of monitoring natural resources, and the behavior of the resource to be monitored.

A clear definition of objectives is crucial because the objectives, if sufficiently specific, should largely define the variables to be monitored, the frequency and location of sampling, the data analysis techniques, and the duration of the monitoring project. Vague objectives such as "the role of buffer strips in protecting water quality" or "the effects of visitors to Yosemite National Park on water quality in the Merced River" provide little guidance on what, where, and when to monitor. In all cases it is necessary to define as specifically as possible the resource of concern and the processes, natural or man-induced, which are the most likely causes of change (*16*). This definition immediately clarifies what should be monitored as well as the frequency, timing, and location of measurements. Figure 4 illustrates how the general concern about the effects of buffer strips on water quality provides very little guidance for monitoring, whereas more focussed questions lead to specific, well-defined monitoring projects.

Defining the monitoring objectives as specific hypotheses helps focus the design of a monitoring project. Putting the objectives in the form of hypotheses also forces one to explicitly consider the statistical trade-offs and data analysis procedures discussed below. For management purposes, data on the cause of an observed change are just as critical as the data used to document a change in the resource of concern (*7, 19*).

Determine variables, sampling frequency, sampling location, and analytic procedures. Once the specific objectives have been formulated, the next step is to select the variables to be monitored, define sampling frequency and locations, establish measurement protocols, and specify sample and data analysis procedures.

Frequency, duration, and location of measurements will be influenced by the statistical trade-offs among sample size, variability, confidence level, and power (*13, 14*). Again these decisions should follow from the objectives. Is the project attempting to detect small or large changes? What is the background variability of the sample population? Which variables are sensitive indicators, and in which geographic locations is the problem or issue of greatest concern? Answers to these questions should be explicitly stated in, or derived from, the monitoring objectives. Gale et al. (*7*) concluded that trends in agricultural nonpoint source pollution are most effectively detected by frequently sampling a small number of key variables.

Quality assurance and quality control procedures must be established to assess the precision and accuracy of the monitoring data (*21*). Explicit, written procedures help ensure consistency in the data and lessen the dependence upon one or two individuals.

Test the proposed project using real or hypothetical data. Probably the best means to evaluate the feasibility of the objectives is to develop and test a set of hypothetical or real data. This is rarely done, but it can be extremely helpful in terms of refining field procedures and predicting whether the objectives are attainable. If one is concerned about the effects of forestry on the amount of large woody debris (LWD) in stream channels, for example, one might compare the amount of LWD in similar stream types in harvested and unharvested areas. This sounds relatively straightforward, but as soon as one is in the field a series of questions arise. Should one measure LWD in terms of the number of pieces or volume? If one is counting the number of pieces per unit stream length, what is the minimum size? Does one count pieces lying on the banks, and if so, where is the upper boundary? How should one count accumulations of LWD such as beaver dams or debris jams? Should a distinction be made between branches, boles, and root wads, or between coniferous and deciduous species? This step forces one to define the experimental unit and population of interest, and thereby ensure that the data collected will be relevant to the problem at hand (*8*).

The point is that for any given variable there usually is considerable scope for varying the frequency and location of measurements as well as the measurement procedure. Such issues are best addressed when formulating the monitoring project rather than trying to deal with them on an ad hoc basis during data collection or data analysis. Sampling protocols can greatly affect the accuracy and precision of the data, and hence the level of change which can be detected with a specified level of significance. In my opinion, the best way to identify and address these questions is to take a set of real or imaginary data and determine whether those data meet the project objectives.

As indicated in Figure 1, such questions may lead to a reformulation of the objectives, a change in the variables to be measured, or a change in sampling design. Hence this step is a necessary prelude to assigning responsibility for each component of the monitoring project.

Data entry, storage, and analysis. Another issue which is commonly ignored in the planning stage is the procedure for data entry, data storage, and data analysis. Monitoring just seven variables (e.g., discharge, pH, conductivity, nitrates, phosphates, and total alkalinity) at four locations (e.g., two control and two treated sites) on a weekly basis yields nearly 1,500 data points per year. In most cases, several years of pre- and post-project data are necessary to detect trends (*18*). Hence one must plan for the entry, error-checking, storage, and analyis of data (*7*), as the raw data generally yield little information or guidance.

Inexpensive personal computers and software programs greatly facilitate data storage and analysis, but these issues still must be addressed in the design stage. Often the need for protocols to input, check, and archive the data is not recognized until the data begin to accumulate, and this greatly increases the risk that the data will simply be filed and never properly analysed or stored. If the person who collected the data is then removed from the project, the data probably will never be analysed or used. In such situations it becomes very difficult to justify the collection of those data, and such experiences will hinder the development of future monitoring projects.

Determine the costs of the proposed project. If the specific objectives are determined to be feasible, the next step is to obtain a final cost estimate in terms of staff time, equipment, and outside expenditures. Delaying the final cost estimates until this stage may seem peculiar, but the advantages are, first, that managers have already bought into the project by helping to define it, making it easier to obtain the necessary support, and, second, the monitoring objectives play a more prominent role in guiding the design of the monitoring plan, rather than the monitoring plan being primarily a function of available staff and expertise (*2, 16*). At this point the relative trade-offs between cost and additional data should be evident, and this helps the manager to make an informed choice between costs and data. Clearly the balancing of monitoring needs and objectives is an iterative process, and this is the reason for the feedback loops shown in Figure 1.

If the proposed monitoring plan substan-

General objective: Are buffer strips protecting water quality? (No guidance with regard to variables, frequency, or location of monitoring.)

Specific objectives:
(1) Are buffer strips minimizing increases in streamwater temperatures? (Monitor stream temperature during summer low flows and riparian canopy density.)

(2) Are buffer strips minimizing disturbance of the stream channel? (Monitor channel cross-sections and bank stability on an annual basis.)

(3) Are buffer strips providing for the future recruitment of large woody debris? (Monitor the amount of large woody debris in the stream channel and the type and size of riparian vegetation on no more than an annual basis; use growth models to predict future recruitment.)

(4) Are buffer strips trapping sediment from upslope areas? (Identify and monitor the primary flow paths for discharge and sediment, emphasizing high flow events; monitor sediment in the stream channel.)

Figure 4. Usefulness of general vs. specific objectives in terms of defining a monitoring plan.

tially exceeds the available resources, the monitoring objectives may need to be revised. Alternatively, some cost reductions can be achieved by reducing the number of sampling sites, reducing the number of variables to be measured, or reducing the frequency of sampling (*13*). The danger in adjusting sampling intensity rather than the objectives is that expectations will remain unchanged while the capability or sensitivity of the monitoring project is reduced. If managers participate in the planning process, they are aware of how reductions in the monitoring budget are likely to alter the breadth and reliability of the anticipated results. Realistic expectations are essential to the credibility of any monitoring project.

Peer review. At this point the proposed monitoring project can be written up as a monitoring plan. In theory the monitoring activities could then be initiated on a pilot basis, but experience has shown that monitoring plans should be circulated for peer review. Often this step is avoided because, first, it further delays data collection and, second, people are reluctant to have their work critiqued. In reality, peer review helps ensure that the proposed project is realistic and appropriate. The peer review process also is an excellent educational tool, as it leads to an exchange of ideas and a broadening of one's perspective.

Over time, peer review becomes less stressful as people recognize their own limitations and the educational benefits of peer review. Even more importantly, peer review greatly decreases the likelihood of serious problems, and helps maximize the efficiency and relevance of the proposed monitoring project. These potential benefits far outweigh any delays, and this is why peer review should be regarded as an essential step in designing monitoring projects.

Pilot project. The next step is to begin collecting data, but the first phase of data collection should be explicitly designated as a pilot project for four reasons. First, pilot projects, by definition, have the flexibility to adjust sampling procedures and locations to the variability and conditions found in the field. Inevitably there are unforeseen factors which force some modifications to the project. Second, designation as a pilot project helps ensure that the data are analysed in a timely manner. Rapid data analyis is needed to indicate whether the project is feasible as planned. Third, the recognized flexibility of a pilot project makes it much easier to modify the project without offending the original designer(s). Finally, pilot projects force more extensive consultations among managers, technical specialists, and technicians, and this helps build a team approach which in turn should make the monitoring project more relevant, realistic, and efficient.

All too often a monitoring plan, once developed, is considered final. In such cases there is less incentive to analyze the data in a timely manner. Data then accumulate, and it may be several years before somebody realizes that the efficiency and quality of data collection could have been improved, or that the original monitoring objectives could not be achieved. Such projects reflect badly on those responsible, and make managers skeptical of monitoring.

Figure 1 indicates the pilot phase can lead to a revision of the monitoring project or to continued monitoring. In most cases a pilot project, if properly formulated, will result in some modifications but will not force basic changes in the project design or objectives. Even if basic changes are required, it clearly is better to make these as early in the project as possible.

Continued monitoring and data analysis. Conclusion of the pilot phase permits the monitoring project to move into the regular data collection phase. During this phase changes in data collection procedures or sampling locations are to be avoided, as this will preclude statistical comparisons and the detection of change. Timely data entry, error-checking, and annotation of the data are essential because memories are short and personnel change. Unusual or inconsistent data must be quickly identified, as it may be possible to either repeat the measurement or identify the cause. Any information not written down must be considered lost, and for this reason data collection efforts should be documented through the use of field books and written protocols.

Reports and recommendations. The final step in Figure 1 is the preparation of reports and recommendations. This is the proverbial bottom line, as in this step monitoring results are transformed into useful guidance (Figure 2). Report content and frequency will depend on the objectives and type of monitoring project. Since these reports will be the primary legacy of the monitoring project, they must clearly spell out the objectives, methodology, results, and conclusions.

Although it may not be possible to define a universal format, the standard scientific format of introduction, methods, results, discussion, and conclusions is an excellent start. A good monitoring report is complete in itself, comprehensible without prior knowledge of the project, and clear and readable. As much as possible the raw data should be presented in graphical form and not simply described with summary statistics. A brief paper on the suggested content and format of monitoring reports is available from the author.

A peer review process also should be utilized in this phase. Peer reviews helps ensure that the conclusions and recommendations are consistent with the data and communal understanding of the resource(s) being monitored. A qualified statistician also should be included in the review process if the project includes quantitative data analyses or statistical inferences. Again an additional benefit of the peer review process is that it helps improve one's own skills and knowledge, and this ultimately is beneficial to the individual as well as the resources of concern.

Conclusions

Designing a monitoring project requires considerable effort and thought. Often there is a reluctance to invest much time in the design and pilot phases because of the perceived need to immediately begin collecting data. In such cases the data typically are the wrong data, incomplete, or from the wrong locations. Having learned from their mistakes, people then go back and design a more efficient and effective monitoring project. In view of the limited staff and resources available for monitoring, it is unconscionable that time and funds be spent on poorly-designed monitoring projects which will not faciliate management objectives or increase our understanding of the resource(s) being monitored.

The development and execution of a monitoring plan must be viewed as an explicit, complex, and iterative process. Monitoring is a remarkable difficult task, and this stems in part from the complexity and inherent variability of most natural resources. Defining the specific objectives is the most important step in monitoring; if this is done properly, the chances of success are greatly enhanced.

REFERENCES CITED

1. Bauer, S., and T.A. Burton. In press. *Monitoring protocols to evaluate water quality effects of grazing management on Western rangeland streams.* EPA 910/R-93-017, U.S. Environmental Protection Agency Region 10, Seattle, WA, 179 pp.
2. Boynton, J.L. 1972. *Managing for quality–a plan for developing water quality surveillance programs on National Forests in California.* In S.C. Csallany et al. (eds.), *Watersheds in Transition,* Am. Water Resour. Assoc., pp. 84-90.
3. Brooks, K.N., H.M. Gregersen, A.L. Lundgren, and R.M Quinn. 1990. *Manual on watershed management project planning, monitoring, and evaluation.* ASEAN-US Watershed Project, College, Laguna, Philippines 4031. 274 pp.
4. EPA, 1987. Surface water monitoring: a framework for change. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. 41 pp.
5. EPA. 1991. Guidance for water quality-based decisions: the TMDL process. EPA 440/4-91-001. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. 59 pp.
6. EPA. 1993. *Guidance specifying management measures for sources of nonpoint pollution in coastal waters.* Publication 840-B-92-002, Office of Water, U.S. Environmental Protection Agency, Washington, D.C.
7. Gale, J.A., D.E. Line, D.L. Osmond, S.W. Coffey, J. Spooner, J.A. Arnold, T.J. Hoban, and R.C. Wimberly. 1993. *Evaluation of the Experimental Rural Clean Water Program.* NCSU Water Quality Group, Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, NC, EPA-841-R-93-005.
8. Gilbert, R.O. 1987. *Statistical methods for environmental pollution monitoring.* Van Nostrand Reinhold, New York, N.Y.
9. Guralnik, D.B., (ed.). 1972. *Webster's New World dictionary of the American language.* World Publishing Co., New York, N.Y., 1692 pp.
10. ITFM. 1992. *Ambient water quality monitoring in the United States: first year review, evaluation, and recommendations.* Intergovernmental Task Force on Monitoring Water Quality, Washington, D.C.
11. Kunkle, S., W.S. Johnson, and M. Flora, 1987. *Monitoring stream water quality for land-use impacts.* International Forestry, U.S. Forest Service and International Park Affairs, National Park Service, Washington, D.C.
12. MacDonald, L.H., and A. Smart. 1993. *Beyond the Guidelines: additional lessons for monitoring.* Envir. Monit. and Assessment 26: 203-218.
13. MacDonald, L.H., A. Smart, and R.C. Wissmar, 1991. *Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska.* EPA/910/9-91-001, U.S. Environmental Protection Agency Region 10, Seattle, WA. 166 p.
14. Mar, B.W., W.S. Mitter, R.N. Palmer, and R.A. Carpenter. 1987. *Cost-effective data acquisition: guidelines for surveying and monitoring watersheds.* Workshop Report No. 1, East-West Envir. and Policy Inst., East-West Center, Honolulu, HI, 106 pp.
15. Ponce, S.L. 1980. *Water quality monitoring programs.* USDA Forest Service Technical Paper WSDG-TP-00002, Fort Collins, CO.
16. Potyondy, J.P. 1980. *Technical guide for preparing water quality monitoring plans.* Intermountain Region, USDA Forest Service, Ogden, Utah. 43 pp.
17. Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1987. *Design of networks for monitoring water quality.* Water Resources Publ., Littleton, CO.
18. Spooner, J., D.A. Dickey, and J.W. Gilliam. 1989. *Determining and increasing the statistical sensitivity of nonpoint source control grab sample monitoring programs.* In Proceedings: Design of Water Quality Information Systems, Info. Series No. 61, Colo. Water Resour. Res. Inst., Fort Collins, CO, pp. 119-135.
19. Spooner, J., and D.E. Line. 1993. *Effective monitoring strategies for demonstrating water quality changes from nonpoint source controls on a watershed scale.* Wat. Sci. Tech. 28(3-5): 143-148.
20. Stednick, J.D., 1991. *Wildland water quality sampling and analysis.* Academic Press, Inc., New York, N.Y.
21. Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. *Design of water quality monitoring systems.* Van Nostrand Reinhold, New York, N.Y.

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