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The "Data-rich but Information-poor" Syndrome in Water Quality Monitoring

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ABSTRACT / Water quality monitoring conducted routinely over time at fixed sites has been a part of most water quality management efforts for many years. It has been assumed that such monitoring plays a major role in management. However, the lack of routine data analysis, and reporting of information derived from such analysis, points up the fact that the exact nature of the role of routine, fixed-station monitoring is poorly defined.

There is a need to very clearly define this role in the design of such systems if routine monitoring is to efficiently and effectively meet the information expectations placed on it. Design of routine monitoring systems will therefore have to consider not only the where, what, and when of sampling, but also why. A framework for including the "why" of monitoring in the design process is proposed and experience with using the framework in New Zealand is discussed.

Most professionals involved in the design or operation of water quality monitoring programs recognize the symptoms: file cabinets bursting with data sheets or boxes and boxes of floppy disks full of numbers; large monthly bills for sampling and laboratory analyses; observations coming in daily, weekly, or monthly and piling on top of other observations; managers, government agencies, legislative bodies, and John Q. Public constantly asking nagging questions like, "Is the water quality in our area actually getting better or worse?"; and, finally, no way to answer them. The disease is, of course, the "data-rich but information-poor" syndrome, which appears to permeate throughout the water quality management field. Many cures have been proposed by practitioners and researchers (including the authors) alike. In spite of these suggestions, water quality data often keep piling up without being utilized to provide needed information. This is indeed a precarious position for monitoring programs to be in during these days of budget slashing.

The authors, frustrated by the failure of technological innovation to extract meaningful information from water quality monitoring programs, have spent the past year reviewing their own previous work and that of others in an attempt to identify the weak links in monitoring system design and to suggest ways of strengthening them. It is their hope that this fresh look at the lack-of-information problem will help to improve both well-established monitoring programs, such as those found in the United States, and new efforts, such as those anticipated for New Zealand.

KEY WORDS: Water quality monitoring; Data analysis; Monitoring systems design; Monitoring goals; Network design

Background

First, what do we mean by *monitoring*? For the purpose of this discussion, *water quality monitoring* will be defined as any effort by government or private enterprise to obtain an understanding of the physical, chemical, and biological characteristics of water via statistical sampling. Both routine (ongoing) and special survey (one off) programs are included. Monitoring is performed in support of water quality management and is universally recognized as indispensable for effective management. The two key terms—*water quality management* and *water quality monitoring* can take on varied meanings among the various professions involved. For example, water quality management to a sanitary engineer can often mean the design, construction, operation, and maintenance of a wastewater treatment plant. Water quality management to a planner can often mean a series of plans: (a) basin planning, (b) regional planning, (c) planning for a specific treatment plant, and (d) planning for the programs that control the quality of water.

Likewise, water quality monitoring to a biologist means some form of biological measurement, while to a lawyer it would refer to measurements related to the water quality variables in standards. A statistician may view water quality monitoring in statistical terms, while a hydrologist may view it in terms of flow-related processes. Consequently, there is not yet widespread agreement on *what* constitutes effective water quality management or on *how* monitoring should support it. (It should also be pointed out that the word *quality* itself is ambiguous.)

In the United States, the inadequacy of monitoring

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systems for water quality management purposes has been described by three major studies. The National Academy of Sciences (1977) noted the need to recognize monitoring as a statistical sampling process and to design accordingly. The Council on Environmental Quality (1980) was an attempt to better coordinate monitoring to avoid duplication of effort while still providing the needed information. The General Accounting Office (1981) addressed the need to have monitoring results more closely tied to management decision making. The general consensus of all three studies is that a much more scientific and systematic approach to water quality monitoring is required if it is to efficiently meet the information needs of water quality management.

What these reports have not done is to propose solutions to the more basic problem, that of achieving a clear definition of "management" and of promoting a thorough understanding of the relationship between management and monitoring. For each management program that involves water quality monitoring, the *interface* between management and monitoring should receive far more attention than it has to date. Only in this way can clear and achievable monitoring system design criteria be formulated.

Case Study: Larimer–Weld Monitoring Program

In order to illustrate the importance of the management/monitoring interface, let us briefly examine a local water quality monitoring program which was carefully designed in 1979 and might be viewed as representative of the state of the art for that time. The Water Quality Monitoring Program for the Larimer–Weld Region (Pitts 1980) was planned and implemented as a part of the Continuing 208 Planning Process for the region. It was designed to support an Area-Wide Water Quality Management Plan developed by the Larimer–Weld Regional Council of Governments. The plan was certified by the governor of Colorado and approved by the US Environmental Protection Agency (Pitts 1980). Quoting:

> The Area-Wide Plan recognized the need for developing a coordinated water monitoring program in the region to insure that future investments in water pollution control are made in a wise and efficient manner, and to insure protection of beneficial uses throughout the region.
>
> The Area-Wide Water Quality Management Plan identified the principles of monitoring program design, regional goals related to the program, program objectives, general recommendations, and criteria for program design. These factors together constituted the basis for development of the Regional Water Quality Monitoring Program. . . .
>
> A Water Quality Monitoring Program Advisory Committee was established by the Larimer–Weld Council of Governments to assist in review of existing programs and identifying future program needs. . . . The Advisory Committee established priorities for water quality monitoring within the region.

The *management* goal and supporting objectives which were adopted by the Larimer–Weld Regional Council of Governments and identified in the plan as relevant to monitoring are as follows (Pitts 1980):

> Goal: Encourage maintenance and enhancement of surface and underground water quality consistent with the use of these waters.
>
> (Supporting) Objectives
> 1. Develop and implement an efficient and effective regional management plan for collection and treatment of wastewater.
> 2. Assure that the quality of surface and underground water is monitored by the appropriate agencies.
> 3. Support controls that will maintain and improve the region's water quality consistent with its use.
> 4. Encourage communication with water resource management and waste-water treatment agencies.

The *monitoring objectives* stated in the regional 208 plan and utilized for the monitoring program design are as follows (Pitts 1980):

1. Define the impacts of discrete point source discharges on water quality within the region;
2. Define the impacts of non-point sources such as agriculture, silviculture, mining, urban runoff, septic tanks and leach fields, and natural background conditions on water quality;
3. Define the relationships between non-point source pollution, natural background pollution, and point source pollution in the region.
4. Define the relationship between water quality parameters which can be measured and the beneficial uses of water recognized in the region;
5. Provide the basis for evaluating the effectiveness of measures implemented by municipalities, industries, and others involved in pollution control in the region;
6. Provide an indication as to the degree of pollution of groundwater supplies in the region, their significance on beneficial uses, future trends, and sources of pollution;
7. Provide the data necessary to insure protection of beneficial uses in the region;
8. Provide the data necessary to indicate trends in water quality.

These objectives seem reasonable, inclusive, and supportive of the stated management goal, and, unlike most monitoring programs, they were documented. They are, however, entirely qualitative. The plan did not address how the monitoring program, with its stated objectives, would provide information that will affect management decisions.

Moving on to the details of the design, the Water Quality Monitoring Program for the Larimer–Weld Region does include a thorough review of existing monitoring activities by the state of Colorado, the US Geological Survey, and other entities. These activities are evaluated in terms of the stated objectives of monitoring, and deficiencies are noted. An extensive list of suggested changes (additions and deletions) to current activities is provided and includes locations, variables, and frequencies of monitoring. The list is comprehensive, providing for measurement of flow, chemical constituents, and biological variables. An effort is made to accomplish stated objectives at minimum cost, and cost estimates for the suggested changes are included.

All this is quite impressive. Even more impressive is the fact that the suggested program was actually documented and implemented and continues to function today. In retrospect, however, it is possible to see that a necessary step of the monitoring system design was left out—that of how the data were to be processed into the information required in the stated objectives of monitoring. Consequently, the program is afflicted by the aforementioned "syndrome," and the data continue to pile up without routinely providing information. (Data have been analyzed when a specific need for information arises at a specific site.) Had a preplanned method for periodically processing the data into the desired information been defined as part of the initial design, the monitoring program would be better able to document that its monitoring objectives are being achieved. The program managers, aware of this fact, are now making a serious study of the system design in an effort to rectify the situation.

Framework for Complete Design

Our purpose is not to criticize previous efforts[1] but to use them to illustrate recent advancement in the state of the art. What can we learn from the shortcomings of the past? Simply put, a monitoring system must be viewed as a *complete system* from the first if it is to be effective. This implies that the system designer must see the monitoring program not only from the *top down*—water quality goals supported by management objectives, which in turn imply monitoring objectives, which finally suggest monitoring activities—but also from the *bottom up*. This latter view starts with water quality samples to be analyzed, and continues with data recording, data storage, and statistical data analysis. Finally, reports must be generated and supplied to users, who in turn make management decisions. These decisions will affect water quality and will also affect future monitoring activities. No step can be left out. Otherwise, the users will probably not receive the information they need, if they receive anything at all (Ward 1979).

Table 1. Steps in the design of a water quality monitoring system.

Step 1 Evaluate information expectations
Water quality goals
Water quality problems
Management goals and strategy
Monitoring role in management
Monitoring goals (as statistical hypotheses)
Step 2 Establish statistical design criteria
Statistically characterize "population" to be sampled
Variation in quality
Seasonal impacts
Correlations present (independence)
Applicable probability distributions
From many statistical tests, select most appropriate (match test requirements to population characteristics)
Step 3 Design monitoring network
Where to sample (from monitoring role in management)
What to measure (from water quality goals and problems)
How frequently to sample (from needs of statistical tests)
Step 4 Develop operating plans and procedures
Sampling routes
Field sampling and analysis procedures
Sample preservation and transportation
Laboratory analysis procedures
Quality control procedures
Data storage and retrieval hardware and data base management systems
Data analysis software
Step 5 Develop information reporting procedures
Type of format of reports
Frequency of report publication
Distribution of reports (information)
Evaluation of report ability to meet initial information expectations

The design framework presented in Table 1 represents a formalized design procedure that has evolved from the authors' monitoring system design efforts (Sanders and others 1983, Ward and others 1982, Ward and Loftis 1983, and Ward and McBride 1985). This design framework helps to ensure that water quality monitoring systems are designed in a systematic and scientifically sound manner and that they are capable of producing the information initially agreed upon. The framework permits a "holistic treatment" of the total monitoring system.

As part of initiating any design (or evaluation of an existing design) there must be a clear purpose in mind. Step 1 of the monitoring system design process, as outlined in Table 1, involves determining what information is sought—why is the monitoring being undertaken? A major task in step 1 is to evaluate manage-

[1]The Larimer–Weld example was selected not because it represents a poor design, but because it is one of the best documented monitoring program designs available.

ment's need for the type of information the monitoring system is to acquire. Such an evaluation should be designed to stimulate a discussion among information users and monitoring system designers regarding not only what the user wants, but what the monitoring system is capable of producing. This discussion will, invariably, cover the water quality goals, management strategies, and the role of monitoring in management if an acceptable compromise between information "demand and supply" is to be reached. Two recent papers (Cairns 1985, Herricks and others 1985) are particularly timely in discussing the need to establish exactly why data are being collected by a water quality management effort.

Specifics on water quality problems, water quality goals, and the role of monitoring in management become input for later aspects of network design. Likewise, a formulation of information expectations in terms of statistical hypotheses plays a large role in future sampling frequency determinations. Output of step 1 is a mutually agreed upon (by information user and system designer) and carefully documented statement detailing the information the monitoring system is expected to produce.

In step 2 of the design framework, statistical design criteria are established. Water quality monitoring is gradually becoming recognized as a statistical sampling procedure (Ward and Loftis 1983). This is especially true for the more conventional pollutants, which have been studied more thoroughly. The question of which statistical procedures are best suited for use in design and operation of monitoring programs continues to confront practitioners. However, recent work has contributed to our understanding of water quality as a stochastic process (that is, influenced by the random effects of nature and society). The reader is referred to Hirsch and others (1982), Lettenmaier (1976), Loftis and Ward (1980), Ponce (1980), Loftis and others (1983), and Sanders and others (1983) for discussions of specific statistical methods which are appropriate in monitoring.

Establishing statistical design criteria involves two major tasks: (a) evaluating the statistical characteristics (for example, underlying frequency distributions and dependence structure) of the water quality population to be sampled, and (b) using the above information to select the most appropriate statistical tests with which to obtain the desired information from the collected data. Knowledge of which statistical tests are most appropriate plays a role in determining sampling frequencies in step 3. Thus, in step 2, the statistics of the monitoring program are dealt with in a quantitative manner, *before* sampling begins. This implies that either data are available from an existing monitoring effort or knowledge about behavior of water quality random variables has been regionalized from data collected in a similar, nearby setting. Only in a completely new water quality management effort would there be no existing knowledge. This was the case in much of the USA when the 1965 Federal Water Quality Act initiated water quality monitoring as we know it today. With the data now in hand, the situation has changed greatly, and thus step 2 becomes feasible *before* revising the design of a monitoring system.

In step 3 the physical details of the monitoring network (that is, the where, what, and when of sampling) are specified. Sampling sites are identified and precisely documented as to the exact spot where the sample will be taken. The reason for location of a site is documented in the goals identified in step 1. The variables to be measured are derived from the water quality problems and goals of the management effort (step 1) and the correlation structure between variables (step 2). It may not be necessary to measure two variables that are highly correlated—measuring one provides information on the other. The frequency of sampling, and measurement frequency of different variables (which may be different from the sampling frequency) are selected on the basis of the requirements of the statistical tests that were chosen for future data analysis as part of step 2. The mechanics involved in network design are described in detail by Sanders and others (1983).

Step 4 involves defining the means by which samples will be collected, analyzed, and verified and the data stored and retrieved. Quality control is a major concern at this point. Computer hardware and software are specified. The monitoring system operations, as defined by Ward (1979), are spelled out in detail during this step. Literature and standard methods may be heavily relied upon. The key point is that in step 4 the operation of the entire system will be defined in sufficient detail to enable different people working in the monitoring effort to generate identical results. Nothing, operationally, should be left open to interpretation. To do so is to generate data that may not be comparable (that is, useless for its intended purpose).

Step 5 insures that the monitoring system will produce final products (written reports) that are designed to convey the information expected in step 1. The monitoring system design comes full circle at this point. To communicate the expected information effectively, reports must be prepared in an understandable format and distributed at a frequency that matches both the needs of the users of the information and the ability of the monitoring system to generate information. The most appropriate reporting methods and procedures should be identified as part of the monitoring system design, but they should not be beyond future fine tuning. In fact, a procedure to continuously evaluate the reporting methods, and the entire monitoring system, should be designed into the reporting procedure.

The results of the entire design process, all five steps, should be documented in a written report. Such a report serves to provide consistency to the monitoring effort and therefore greatly enhances the value of the data and information. It also helps users evaluate the quality of information.

The five steps in the monitoring system design framework represent a large amount of work prior to initiating a new monitoring effort or modifying an old one. This type of effort, before initiating monitoring for regulatory water quality management purposes, is rare. However, many management efforts (both public and private) are discovering that no amount of post data manipulation can cover up the lack of initial design. Given the cost of monitoring over, say, a 20-year time frame, the question becomes, what percentage of this total should be devoted to initial design? Most people would not consider building a large wastewater treatment plant without proper initial planning and design, but little similar logic is applied in the design of a monitoring program that may ultimately spend millions of dollars.

Many management efforts are also discovering that many unrealistic information expectations are placed on monitoring programs without any counter-definition of what information can actually be obtained. The systematic approach to monitoring system design proposed herein should minimize such problems in the future.

Case Study: Applying the Systems Design Concept in New Zealand

The "systems" approach to the design of routine, fixed-station water quality monitoring program, summarized in Table 1, is currently being applied to the possible establishment of a national water quality monitoring program for New Zealand (Ward and McBride 1985). The application of steps 1, 2, and 5, in particular, have involved a considerable amount of effort because of the absence of past work on these topics and the multifaceted nature of a large water quality management effort. Once the objectives are quantified, steps 3 and 4 can be accomplished by making use of the large body of literature available in the field and experience developed from past operations (particularly with respect to sampling, laboratory analysis, and quality control/quality assurance procedures).

In applying the design concepts to the New Zealand situation, it proved extremely difficult to develop a concensus on the quantitative information expectations to be placed on the monitoring effort. The approach of the monitoring system designers was to first visit the principal information users. These are the staff of the Soil and Water Directorate in the Ministry of Works and Development in Wellington and the staffs of the 20 regional water boards located around the country—an organizational structure not unlike that used in the USA with the USEPA on the national level and the states on a more regional level. These initial contacts served to permit the designers and information users to state their respective positions in a nonthreatening situation—no expectations had yet been formulated.

Following the initial meetings, the monitoring system designers attempted to formulate the information expectations. These expectations were based not only on the discussions but also on the laws and regulations affecting water quality management in New Zealand. This evaluation of information expectations, along with follow-up discussions with New Zealand's water quality managers, pointed up a major split in the expectations. The major water quality management legislation in New Zealand (the National Water and Soil Conservation Act of 1967 as amended) contains ambiguous, and possibly conflicting goals for water quality, and these conflicts have filtered down into the management structure. Many managers in New Zealand feel that their water quality goal is to "maintain or improve water quality," while others feel it is to "promote conservation and best use of natural water." Both statements appear in the act, but neither "water quality" nor "conservation" is defined, which leaves room for considerable ambiguity.

An evaluation of the monitoring system design criteria required to support these two different goals is presented in Table 2. It is clear that the definition of goals can greatly influence the design of a national monitoring system. Discussions are currently underway to develop a consensus as to which goal has highest priority from a national perspective. Alternatives to declaring one national goal are also being considered (for example, regional goals or dual monitoring systems).

Leaving these divergent information expectations unreconciled prior to designing the monitoring system can open the way for a number of water quality managers in the future to declare the monitoring system to

Table 2. Implications of alternative goals for design and operation of a routine monitoring system.

Item	Goal (= why): Maintain or improve water quality	Goal (= why): Promote conservation and best use of natural water
Information needed for design	Objective definition of *water quality*	Objective definition of desired water uses
Information expected from operation	Changes in that water quality over time	Compliance with standards for those uses
Design criteria[a]	Sites "representative," tend to be spread uniformly Frequency related to trend detection Characteristics determined by definition of *water quality*	Sites concentrated where water use conflicts anticipated Frequency related to definition of *compliance* Characteristics related to water quality requirements of all desired uses
Reporting	Goal met when trends are either absent or improving	Goal met when probability of violation of water quality requirements in acceptable range

[a] Sites = where; frequency = when; and characteristics = what (e.g., BOD_5, pH, invertebrates, and bacteria).

be inadequate and not supportive of their management efforts. In order to avoid this pitfall, system designers simply must not assume an information objective and proceed. The National Academy of Sciences (1977) makes this point very clearly in its criticism of the senior author's early efforts, as well as those of other monitoring system designers.

Step 2 in the New Zealand application also posed a major stumbling block. The existing water quality data were not widely computerized, and in many cases, known data were difficult to locate even on the laboratory reporting sheets. The data that were computerized were rarely in a consistent format and had not been verified. A considerable amount of effort was and is being spent on developing a computerized water quality data base containing consistent, verified data.

Data now available via computer are being analyzed to describe their statistical characteristics. The knowledge gained from this task will be invaluable in insuring that the monitoring system design recognizes the unique behavior of New Zealand's water quality variables.

Step 3 awaits the outcome of steps 1 and 2. Too often in the past the urgency felt to immediately proceed to step 3 has led to the "syndrome" discussed in this article. Step 4 proceeds primarily from using the expertise currently involved in the monitoring efforts around the country.

Step 5 was approached indirectly during the discussions with the information users. Often the reporting frequency which the information users expect from *new* water quality information is beyond the monitoring system's capability. This fact was discussed in connection with the time required for, say, monthly sampling to accurately predict a significant trend. Annual reports, summarizing the year's water quality picture, appear to be essential, but the top-level administrators involved are very concerned about the political ramifications of these reports. This issue is a major concern, which remains to be addressed.

More detail on the application of the systems design approach to the New Zealand situation can be found in Ward and McBride (1985).

Concluding Remarks

The best treatment for the "data-rich but information poor" syndrome is preventive medicine. Thus, water quality monitoring system design is undergoing evolution as efforts are made to ensure that the data collected can be developed into information supportive of society's efforts to manage water quality. Perhaps the greatest advancement in the next few years will come in the identification of the exact (statistical) nature of information sought. These information expectations must be based on a "total system" concept of monitoring and must be tempered, beforehand, by the ability of monitoring to accurately describe the stochastic behavior of water quality variables.

This evolution will also lead to more precise documentation of the operational details of the design—including sample collection and analysis, routine data analysis, information reporting, and information dissemination. Future monitoring systems must be operated in a manner which is more consistent with their information objectives. This consistency can be achieved through complete designs with thorough documentation.

Again, looking to the future, we see the evolution of monitoring extending beyond those variables that are currently routinely monitored. Although biological monitoring is not a major topic of this article, no discussion of future monitoring activities should ignore the fact that biological monitoring will play a role of ever-increasing importance. The integration of quatitative information from biological monitoring with that from chemical and physical monitoring to form a complete picture of water quality is a crucial topic for current discussion and research. Perhaps equally important is the problem of extracting meaningful information from monitoring of "new" chemical water quality variables—such as hazardous organic compounds—which are important in current hazardous waste management programs but which behave much differently (chemically and statistically) from the "conventional" variables.

The above, and many other, issues confront monitoring system designers today. However, the problem definition attempted in this article along with the suggested framework for approaching monitoring system design provide designers with an organized approach for dealing with many of the ills which currently afflict the design and operation of water quality monitoring systems. It is the author's hope that the perspective presented here will lead to monitoring efforts that more effectively provide information support for water quality management in the future.

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Literature Cited

Cairns, J., Jr. 1985. Evaluating options for water quality management. *Water Recources Bulletin* 21:1–6.

Council on Environment Quality. 1980. Final report of the interagency task force on environmental data and monitoring. Available from National Technical Information Service, US Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161, 21 March.

General Accounting Office. 1981. Better monitoring techniques are needed to assess the quality of rivers and streams. US General Accounting Office Report CED-81-30, Washington, DC, 30 April.

Herricks, E. E., D. J. Schaeffer, and J. C. Kapsner. 1985. Complying with NPDES permit limits: when is a violation a violation? *Journal of the Water Pollution Control Federation* 57:109–115.

Hirsch, R. M., J. R. Slack, and R. A. Smith, 1982. Techniques of trend analysis for monthly water quality data. *Water Resources Research* 18:107–121.

Lettenmaier, D. P. 1976. Detection of trends in water quality data records with dependent observations. *Water Resources Research* 12:1037–1046.

Loftis, J. C., and R. C. Ward. 1980. Water quality monitoring: some practical sampling frequency considerations. *Environmental Management* 4:521–526.

Loftis, J. C., R. C. Ward, and G. M. Smillie. 1983. Statistical models for water quality regulation. *Journal of the Water Pollution Control Federation* 55:1098–1104.

National Academy of Sciences. 1977. Analytical studies for the US Environmental Protection Agency, vol. 4: Environmental monitoring. National Academy of Sciences, Washington, DC.

Pitts, W. T. 1980. Implementation plan for regional water quality monitoring program. Report no. 36, Larimer–Weld Regional Council of Governments, Loveland, Colorado, Tom Pitts and Associates, Loveland, Colorado.

Ponce, S. L. 1980. Statistical methods commonly used in water quality data analysis. Technical Paper WSDG-TP-00001. Watershed Systems Development Group, USDA Forest Service, Fort Collins, Colorado.

Sanders, T. G., R. C. Ward, J. C. Loftis, T. D. Steele, D. D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resources Publications, Littleton, Colorado.

Ward, R. C. 1979. Regulatory water quality monitoring: a systems perspective. *Water Resources Bulletin* 15:369–380.

Ward, R. C., and J. C. Loftis. 1983. Incorporating the stochastic nature of water quality into management. *Journal of the Water Pollution Control Federation* 55:408–414.

Ward, R. C., and G. B. McBride. 1985. Design of water quality monitoring systems in New Zealand. Miscellaneous Publication. Water and Soil Directorate, Ministry of Works and Development, Wellington, New Zealand (in press).