Designing a complex multi-objective water quality monitoring network: the New York City water supply example

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Biographical sketch of author

David G. Smith is Section Chief, Information Management and Reporting, for New York City's Bureau of Water Supply. His background in the design of water quality monitoring networks began with the design of New Zealand's national network for rivers and lakes in 1989. Subsequently he successfully managed that network and produced several papers on the topic including its design, status interpretation, sampling and analytical requirements for trend detection, and trend detection itself. He used this experience to lead the redesign of the complex monitoring network for New York City's drinking water supply. He also has numerous publications in the field of human perception of natural waters and has co-authored a book on optical water quality.

Abstract

The design of a water quality monitoring network with many stakeholders and multiple objectives can be daunting. The starting point, and key to successful design, is the derivation of an appropriate set of objectives that are based on stakeholders' requirements. These objectives should be defined as precisely as possible, although this step may not be easy. Next, based on the requirements of each objective, the field sampling (including frequency) and measurement, and the laboratory analytical requirements are rigorously specified. The setting up of a database and reporting requirements also require addressing. Many of these requirements have been discussed in the literature but the starting position, the derivation of objectives, has received little attention. This paper describes this process in the way it led to the design of the New York City water supply system monitoring network. It also describes some aspects of this network which are a consequence of, and highly dependent on, each independent objective. The Hydrology monitoring Program will be discussed as an example of the processes involved, especially the derivation of the objectives.

Introduction

Historically, water quality monitoring networks have been designed almost exclusively on determining "what" and "how" to monitor and rarely examining the question of why (Sanders *et al*., 1983). Typically, such designs produce large amounts of data which are difficult to analyze and often more difficult to interpret. This phenomenon is described by Ward *et al*. (1986) as "data rich and information poor" and is prevalent in many, if not most, routine water quality monitoring programs. The problem is associated with not adequately defining the informational goals of the program prior to the design of the monitoring network. The result is an accumulation of data that contributes little or no information to the understanding of the system. The data collection process often becomes an end in itself. In addition, individual studies and investigations traditionally have not been conducted in concert with existing "fixed" monitoring programs. This often results in disjointed, inconsistent information and at times, a duplication of effort resulting in limited applicability.

The difficulty of converting existing water quality data into water quality information has been recognized for some time. Considerable effort has been made over the years to define the logic and science to be used in designing water quality monitoring networks. Ward (1996) describes a detailed summary of these efforts and further argues that water quality monitoring programs must be thought of, and designed as, water quality information systems. This philosophy, as discussed by Ward *et al*. (1990), emphasizes the need to: define the information goals; define what information can be furnished by the monitoring effort; design the monitoring network; document data collection procedures; and document the information and reporting procedures.

Similarly, Smith and McBride (1990) describe a similar approach used in designing the national water quality network for New Zealand. Careful consideration was given to a comprehensive list of tasks before the network was implemented. These included: define goals and objectives; confirm statistical design criteria; produce a list of analytes; recommend data analysis procedures; and recommend reporting procedures. In considering the goals and objectives, the stakeholders' requirements were considered essentially *by proxy*, that is, what, in the opinion of the designers, who were in fact acting in a stewardship role, were the requirements of the people of New Zealand.

Recently, the National Water Quality Monitoring Council, whose mission is to provide a national forum to develop a national monitoring strategy, developed a framework for collaboration and comparability among programs (Figure 1—NWQMC, 2002). As explained later, we believe that this framework misses an essential ingredient, *that of the requirements of the stakeholders,* without whose input, directly or by proxy, a monitoring network cannot really be designed.

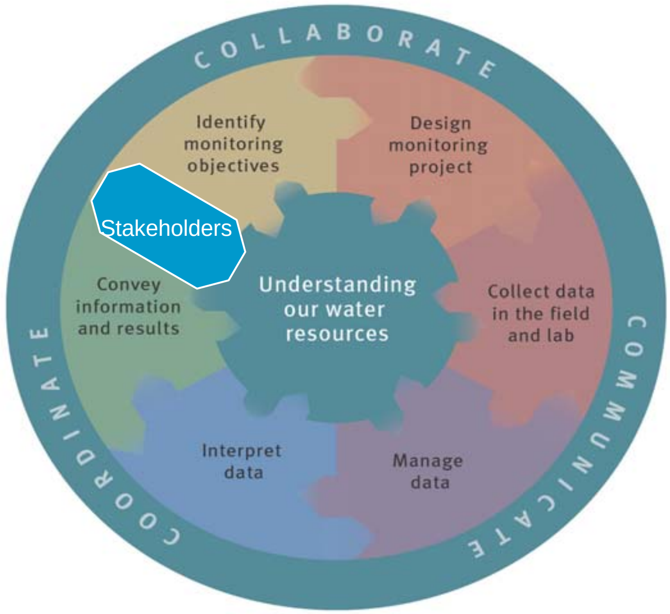

Figure 1. The NWQMC framework for monitoring with suggested additional segment for 'Stakeholders'.

The information requirements of water managers (who are, in effect, acting in a stewardship role for taxpayers) and others often require the network designers to address water quality issues, which demand distinct, spatial and temporal monitoring efforts. These efforts may, for example, require a combination of surveys, fixed frequency-long term and intensive-short term strategies. The design of a water quality monitoring network must recognize the significance of coordination and integration in monitoring strategies. The integration of distinct water quality monitoring efforts is essential in providing consistent and applicable water quality information (Ward *et al*., 1990; Payne and Ford, 1988).

We stress that *the information needs and goals must define the monitoring network design.* These are derived from the stakeholders and may not be easy to establish. Once the information needs are clearly defined, consideration must be given to determining what information the monitoring effort is capable of providing and whether or not this meets the expectations of management and others. By addressing these issues initially, a statistically-based, goal-oriented monitoring network can be designed to provide the necessary information for managers to adequately manage the resource, and for other data users to receive the data or information they need to satisfy their requirements. This effort, in conjunction with integrating supplemental investigations and programs with “fixed “monitoring networks, will result in a monitoring program that produces both consistent and useful water quality information.

This concept has been applied here and has resulted in the complete redesign of the water quality monitoring network of the DEP’s Division of Drinking Water Quality Control's upstate Hydrology, Limnology and Pathogens programs. This paper describes the rationale used, with a brief example of the Hydrology Program design. The overall design is intended to establish an integrated monitoring framework, which addresses both short-term and long-term water quality requirements for a multiplicity of stakeholders.

Design framework

The New York City water supply system is a very complex cascading array of rivers, 19 reservoirs and 3 controlled lakes occupying over 5,000 ha (Figure 2). The system is the world's largest unfiltered water supply, and it is, therefore, essential that adequate water quality monitoring of these waters is carried out. Additionally, because such monitoring is consumptive of much field and analytical staff time (there are approximately 170 river and 100 reservoir/lake sites for the Hydrology and Limnology programs alone), this network must be as efficient as possible.

Prior to redesign, the individual objectives of the monitoring programs were difficult to extract because initially they were not well defined and documented. The program had evolved over time into a somewhat amorphous amalgam of sampling sites, sampling frequencies, and analytes. The program was very resource consumptive. The stakeholders were not explicitly identified and their requirements not specifically documented so it was difficult to justify much of the combination of sites, analytes, and sampling frequencies. This also resulted in a program which was difficult to change.

The purpose of the redesign was to derive a formalized framework for the Hydrology, Limnology and Pathogens water quality monitoring Programs conducted by the New York City, Department of Environmental Protection. The conceptual framework used to produce the monitoring network for each Program is depicted in Figure 3. *The key aspect of this framework was a rigorous identification of all of the stakeholders (information end users).* This was the starting point of the redesign.

Figure 2. The New York City water supply watersheds.

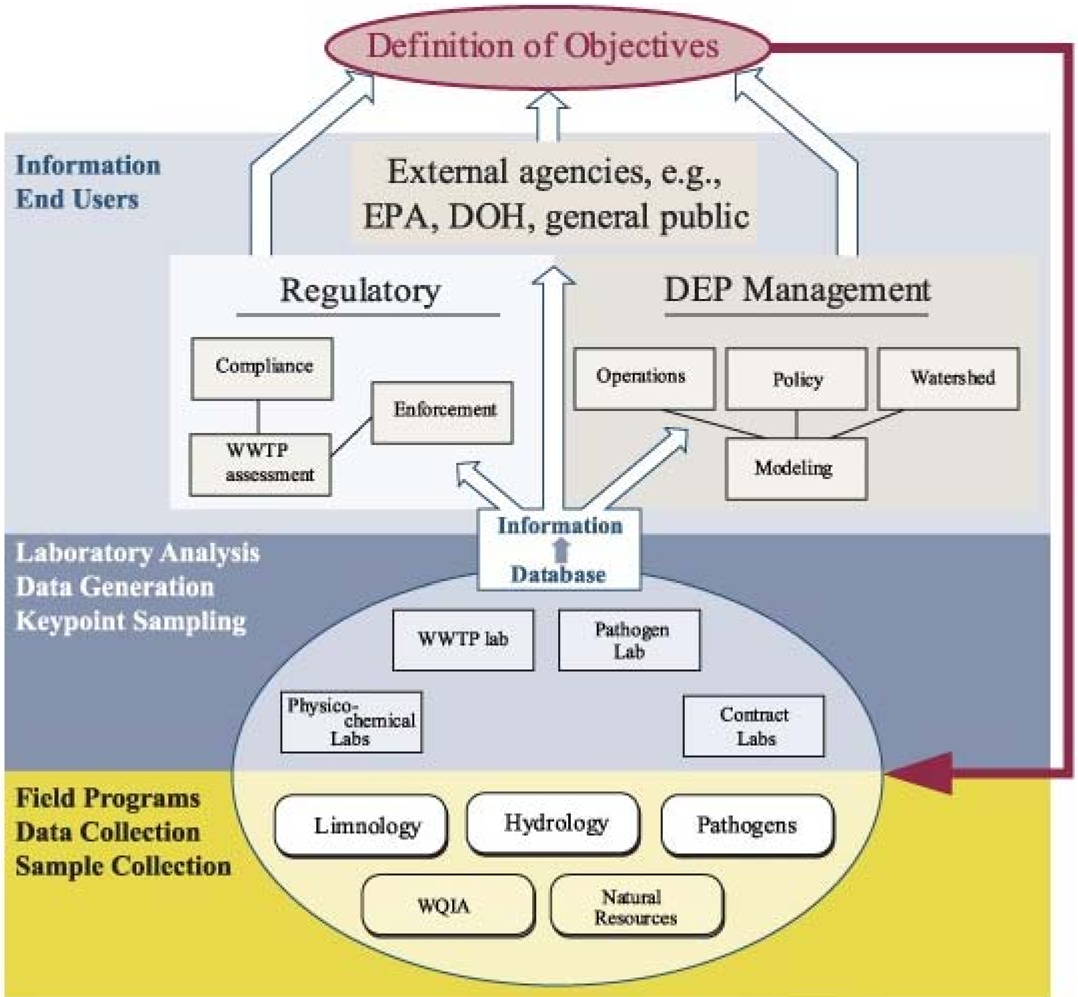

Figure 3. The conceptual design framework.

The goal of this framework was to establish a water quality monitoring network to provide scientifically defensible information regarding the understanding, protection, and management of the New York City water supply. The information needs required to achieve this goal are compiled as objectives (from the requirements of the stakeholders, each of which is clearly defined (in statistical terms if possible). Each objective specifies, and justifies where possible: sampling sites; statistical design criteria (including sampling frequency); analytes; and data analysis protocol. These attributes are synthesized for each objective within each Program (Figure 4).

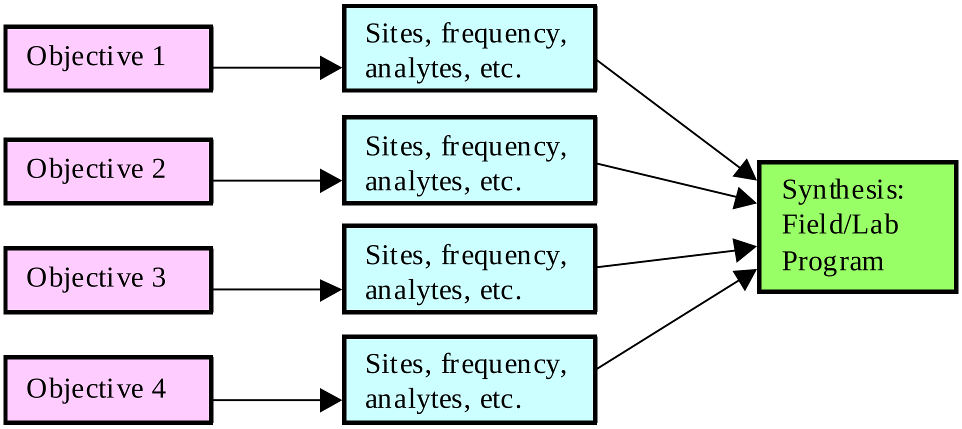

Figure 4. The conceptual model used to derive the monitoring and analytical requirements for each Program.

The design now provides the rationale and justification for a comprehensive and where possible, integrated monitoring network which fulfills the present information goals of the department through clearly defined objectives (and sub-objectives). The strategy employed is based on; defining the objectives of each Program; quantifying the required information needs; determining the information which can be produced by diversified monitoring efforts; and designing a monitoring network that provides the necessary information.

The programs are designed to meet the expanding scope of DEP's data and information needs including requirements for watershed and reservoir models, numerous legally binding mandates and agreements, regulations, and water management requirements. Also addressed were comments recently received on the monitoring programs from a variety of agencies, including the EPA.

The monitoring Programs are integrated with each other wherever possible through their objectives' data requirements. Sometimes two Programs contribute to a single data use (e.g., Reservoir Modeling which requires coordinated stream and reservoir data) so it is essential that data production from each collection program be coordinated. Statistical features of the historical database and site locations were used to guide the sampling design, where possible and appropriate. All fixed-frequency monitoring is stratified with respect to time of day and days of the month.

Inherent in the design of any long-term program is data continuity. It is essential that any observed changes in data reflect changes in the environment and not be a consequence of methodological changes (e.g., Shapiro and Swain, 1983; Smith *et al*.,1996; Smith, 2000). This is important not only for trend analysis where step-trends, i.e., sudden increases or decreases in mean values (whether visually apparent or not) can cause data trends, but also for other data where year-by-year comparisons are made, e.g., in P-restricted basin studies and modeling. Field and laboratory analytical methods must remain constant wherever possible because it has been shown that even very small changes in methods (even filters) can cause differences in results produced (Newell and Morrison, 1993). Because analytical changes are sometime unavoidable, DEP will endeavor to account for such method changes by running paired method comparisons (e.g., Newell *et al*., 1993) wherever possible.

Another aspect of laboratory data which can create problems for trend detection, in particular, is that of non-reporting data below the "analytical detection limit"; this is called "data censoring" and its effects, including trend masking and trend induction, have been reported in the literature (e.g., Gilliom *et al*., 1984; Bell, 1990; Porter *et al*., 1988; Ellis and Gilbert, 1980). DEP will not be censoring data and values less than the detection limit will be reported, as appropriate.

We need to be aware that this design should never be considered as 'final' because of the changing needs of stakeholders over time, and field and laboratory staff availability. It is intended to revisit the design at least annually to ensure that it is still providing the required information, and document any changes.

Hydrology Program

The overall goal here is to establish a stream water quality monitoring network which provides scientifically defensible information regarding the understanding, protection, and management of the New York City water supply.

Based upon discussions with potential stakeholders (for instance, supply system managers, DEP scientists who require monitoring data for, say, modeling purposes, and external agencies) we determined that there were eight major objectives. Surprisingly, it was a relatively time-consuming task to ensure that all stakeholders were identified and we were convinced that their requirements were covered. Because the main intent of this paper is the design philosophy, the details (i.e., sites, analytes, sampling frequencies) of the most of redesigned program will be omitted here.

The first objective, *Trend Detection*, is a fixed frequency monitoring design, intended to detect a monotonic trend in the mean value of approximately the standard deviation of the detrended data over a five year period with reasonable confidence and power ($\alpha = \beta = 15\%$). This objective is required to establish if the quality of the drinking water supply to the reservoirs is improving, staying the same, or deteriorating. For main tributary monitoring, sites immediately upstream of the West of Hudson reservoirs will be sampled twice a month to provide greater trend detectability ($\alpha = \beta = 5\%$) for the most important analytes: TP; turbidity; and coliform bacteria. Data from this objective will also serve to provide the requirements for status reporting which is based on three years of data.

The second objective *Landscape Scale Water Quality Monitoring* is a variable frequency monitoring design to evaluate spatial and temporal changes in stream flow chemistry that occur through various land-use types. The hydrologic and water quality requirements for the first two objectives were developed and justified by Hydrology Program staff.

Reservoir and Watershed Modeling Support constitute the third and fourth objectives, respectively. The data collected are used to calibrate, validate and optimize reservoir and terrestrial models to enable them to be of optimal management value. Both reservoir and terrestrial modeling programs require adequate daily and monthly loads for selected determinands. This is accomplished by combining fixed frequency and storm event monitoring at selected gauged reservoir tributaries. The hydrologic and water quality requirements for this objective have been developed and justified by staff of the Modeling Program.

The stream chemistry data collected for Objective Five, *Biological Monitoring Support*, is used to develop an understanding of watershed-specific relationships between water quality and the macrobenthic community. Macroinvertebrates are collected annually at two types of sites, fixed routine and synoptic supplemental. The program requires selected water quality determinands to be collected at base flow conditions during the month of macroinvertebrate collection. The hydrologic and water quality requirements for this objective have been developed and justified by staff of the Water Quality Impact and Assessment Program.

In accordance with Addendum E of the DEC/DEP Memorandum of Understanding, *The Effects on Stream Water Quality from Waste Water Treatment Plants* are assessed in Objective Six. Water quality samples are collected above and below twelve selected treatment plants once each month. Selected determinands, as specified in Addendum E, are analyzed and used to track treatment plant performance. Water quality downstream of the discharge is examined for violations of State Ambient Water Quality Standards. The hydrologic and water quality requirements for this objective have been developed and justified by staff of the Water Quality Impact and Assessment Program.

Objective Seven is a compilation of the investigation of *Best Management Practices (BMPs)*. Studies described within this objective and are intended to be of relatively short duration. Currently, these investigations include: 1) *Assessment of BMPs on Turbidity Reduction in the Batavia Kill Sub-basin*; 2) *Assesment of BMP effectiveness two New Croton Reservoir Sub-basins*; and 3) *Assessment of BMP effectiveness on Kensico Reservoir Tributaries*. The hydrologic and water quality requirements for the first two objectives were developed and justified by Hydrology Program staff.

Policy and Management Based Surveillance Monitoring constitutes Objective Eight. The monitoring efforts embodied within this broad objective are designed to fulfill the Department's water quality policy/management based goals, which are not addressed with other existing water quality monitoring efforts. The specific surveillance monitoring designs (i.e. site selection, sampling frequency, etc.) associated with each monitoring effort, are determined based upon the Department's policy as directed by management. Surveillance monitoring, as defined in this objective, is intended to be of long duration. In accordance with this definition, *Trace and Other Metal Occurrence Monitoring* has been included in this objective. For Catskill and Delaware Districts, sampling sites are located on the major tributary for each reservoir at the terminal USGS site and upstream in the centroid of the watershed, whever possible. Because of the cascading reservoir design of the East of Hudson District, metal monitoring sites have been located at reservoir releases and main inflow tributaries. Samples are collected quarterly and comparison made with various water quality standards. There are two other sub-objectives within this objective—*Source Water Tributary Monitoring* is designed to provide additional surveillance of tributary streams to Kensico, and West Branch Reservoirs, and *Croton Watershed Consent Decree Monitoring* which addresses the stream monitoring requirements of the Croton Consent Decree. The hydrologic and water quality requirements for this objective have been developed and justified by the NYC, DEP managerial staff.

Following our conceptual model, once the sites, analytes, and sampling frequencies were identified, the requirements were pooled to provide the design of the Hydrology Program. In total, the Hydrology Program comprises 173 monitoring sites and results in over 3,200 samples per annum with around 52,000 laboratory analyses being conducted.

The Limnology and Pathogens Programs were redesigned in a similar manner. Following this, all three programs were integrated wherever possible, for example with sampling timing and laboratory analysis, to provide the best, and most efficiently gathered, information for stakeholders.

Summary

The design of a water quality monitoring network must first define the information needs of the stakeholders. The information needs and goals then define the monitoring network design. By addressing these issues initially, a statistically-based, goal-oriented monitoring network can be designed to provide the necessary information for managers to adequately manage the resource, and for other data users to receive the data or information they need to satisfy their requirements.

The goal here was to establish a water quality monitoring network that provides scientifically defensible information regarding the understanding, protection, and management of the New York City water supply. The information needs required to achieve this goal were compiled as objectives (from the requirements of the stakeholders, each of which is clearly defined (in statistical terms if possible)). Each objective specified, and justified where possible: sampling frequency; statistical design criteria; analytes; and data analysis protocol.

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