DISSERTATION

A FRAMEWORK FOR EVALUATING WATER QUALITY INFORMATION SYSTEM PERFORMANCE

Submitted by

Harvey P. Hotto

Department of Civil Engineering

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 1994

COLORADO STATE UNIVERSITY

October 21, 1994

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY HARVEY P. HOTTO ENTITLED A FRAMEWORK FOR EVALUATING WATER QUALITY INFORMATION SYSTEM PERFORMANCE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Adviser

Department Head

ABSTRACT

A FRAMEWORK FOR EVALUATING WATER QUALITY INFORMATION SYSTEM PERFORMANCE

Water resource and water quality managers are being held increasingly accountable for the programs they manage. Much progress has been made in applying total systems perspectives to the design and operation of water quality monitoring and information programs, and towards rationalizing those programs with respect to management objectives and information needs. A recent example of that progress is the development of data analysis protocols to enhance the information system design process. However, further work is necessary to develop approaches which can help managers confront the water quality management environment of the future, which will be characterized by: (1) fewer purely technical questions, (2) more complex problems with social, economic, political and legal ramifications, and (3) actively managed and continuously improved water quality information systems.

This research concludes that the management of water quality information systems for continuous improvement requires: (1) a competent system design _process_, (2) comprehensive documentation of system design and operation, and (3) a routine and thorough performance measurement and evaluation process. The framework for evaluating water quality information system performance presented in this dissertation integrates the experience of several disciplines into an instrument to help water quality managers accomplish these requirements. The framework embodies four phases: (1) evaluation planning, (2) watershed and management system analyses, (3) information system analysis, and (4) information system performance evaluation.

The application of the framework is demonstrated in the evaluation of water quality monitoring programs associated with a unique municipal water transfer project. Water quality professionals of the U.S. Environmental Protection Agency and the U.S. Geological Survey are surveyed as to its potential application to large (e.g., regional or national) systems. Those exercises indicate the framework to be a convenient, economic, and flexible instrument useful towards enhancing water quality information system performance. Recommendations for future research to refine the framework and to extend its scope and utility are also presented.

Harvey P. Hotto
Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523
Fall 1994

ACKNOWLEDGEMENTS

The author wishes to extend his sincere gratitude to the members of his graduate committee for the encouragement, support, and professional inspiration each provided towards the success of this research. Dr. Thomas Sanders, Dr. Robert Ward, Dr. Billy Thornton, Dr. Darrell Fontane and Dr. Wade Troxell all generously contributed their time and attention, and those contributions are greatly appreciated. Thanks are also due to the many friends and fellow students at Colorado State University who enriched and enhanced my graduate school experience in uncountable ways. Finally, many thanks to my wife, Carol, for her love and patient support during this long and demanding endeavor.

TABLE OF CONTENTS

Chapter		Page
1	INTRODUCTION	1
	Problem Statement	1
	Objectives and Methodology	11
	Scope	13
	Organization	14
2	LITERATURE REVIEW	16
	The Systems Approach	18
	Information Systems	28
	Water Quality Information Systems	53
	Recapitulation	101
3	A FRAMEWORK FOR EVALUATING WATER QUALITY INFORMATION SYSTEM PERFORMANCE	120
	Introduction	120
	Water Quality Information System Performance Evaluation	122
	Framework for Evaluating Water Quality Information System Performance	126
	Water Quality Information System Performance Evaluation Criteria	139

TABLE OF CONTENTS (Continued)

Chapter **Page**

4 APPLICATION OF THE FRAMEWORK TO A MUNICIPAL MONITORING PROGRAM - Part One 151

Introduction 151

Case Background 152

Application of the Framework 155

Summary 199

5 APPLICATION OF THE FRAMEWORK TO A MUNICIPAL MONITORING PROGRAM - Part Two 206

Introduction 206

Application of the Framework 209

Summary 235

6 SURVEY ON THE FRAMEWORK: PROFESSIONAL AND EXPERT OPINION 241

Introduction 241

Survey Approach 244

Survey Responses and Conclusions 249

Discussion 265

7 SUMMARY AND CONCLUSIONS 267

Summary 267

Conclusions 270

Caveats 272

Recommendations for Future Research 274

TABLE OF CONTENTS (Continued)

Chapter **Page**

REFERENCES 280

APPENDIX A: User's Manual for Evaluating Water Water Quality Information Systems Performance A-1

APPENDIX B: The Analytic Hierarchy Process (AHP) B-1

APPENDIX C: Illustration of Water Quality Systems Performance Evaluation Using the Analytic Hierarchy Process C-1

APPENDIX D: Water Quality Information System Performance Evaluation Survey: Survey Documents D-1

APPENDIX E: Water Quality Information System Performance Evaluation Survey: Survey Summary; USEPA Regional Water Quality Monitoring Coordinators E-1

APPENDIX F: Water Quality Information System Performance Evaluation Survey: Survey Summary; USGS NAWQA Study Unit Project Chiefs F-1

GLOSSARY G-1

LIST OF TABLES

Table		Page
2-1	Systems Performance Evaluation Questions	102
2-2	Information Systems Performance Evaluation Questions	105
2-3	Water Quality Information Systems Performance Evaluation Questions	109
3-1	Framework for Evaluating Water Quality Information Systems Performance: Evaluation Considerations	129
5-1	Decision Attribute Definitions for Comparison of Water Quality Information System Alternatives	214
5-2	Attribute Ratings from Paired Comparisons	224

LIST OF FIGURES

Figure		Page
3-1	Framework for Evaluating Water Quality Information System Performance	128
3-2	Analytical Hierarchy Process Decision Schema - A Hierarchy with k Levels (Zahedi, 1986)	138
4-1	Framework for Evaluating Water Quality Information System Performance	157
4-2	Framework Phase 2 - Watershed Description	162
4-3	Framework Phase 2 - Management System Description	169
4-4	Framework Phase 3 - Information System Background	175
4-5	Framework Phase 3 - Information System Design Analysis	180
4-6	Framework Phase 3 - Information System Operations Analysis	195
5-1	Framework Phase 4 - Evaluation Hierarchy and Criteria Definition	208
5-2	Decision Hierarchy for Comparison of Water Quality Information System Alternatives	213

CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT

Commenting on environmental information, the United States Council on Environmental Quality observes in its 1974 annual report that:

> " The general public and many decision makers in government and industry .... must be supplied with comprehensive assessments of the significance of these data on a timely basis, thereby enabling these individuals to appreciate the feasible options and the consequences of alternative decisions...In general, however, the response of both the Federal Government and the scientific community to this important need and mandate has been inadequate."

Jay Messer of the U.S. Environmental Protection Agency, commenting in 1989 on consumers of environmental information, including the U.S. House of Representatives, concludes that:

> "They are not content to know that something is being done, but express a right to know whether the current

pollution control expenditures of $70-80 billion each year are solving the problem. There have been increasing calls from Congress, scientists, and the public for programs that disseminate environmental statistics to the public that could be used to judge the success of current efforts and the need for new ones".

Public support of measures to protect and clean up the environment can be expected to intensify in the twenty-first century. These issues will be of concern in the many developing nations as well as in the industrialized nations. Traditional local-scale environmental management problems, such as water pollution control and solid waste management, will be joined by complex regional and global concerns such as global warming and the dumping of wastes into the oceans.

As the comments above indicate, the public is not convinced that it is getting its money's worth for environmental management spending. This dissatisfaction is likely to continue, as environmental costs contribute to larger budgets, higher taxes and higher prices for goods and services. Recent and pending water quality legislation (e.g., Safe Drinking Water Act of 1986, Clean Water Act Amendments of 1987, and 1994 Clean Water Act reauthorization efforts) will impose additional and more stringent water quality standards upon all water providers and users

(Pontius, 1991a, 1991b). The costs of satisfying those new requirements will exacerbate budgetary pressures. Total environmental expenditure by all levels of government in the United States is predicted to increase 37.5% to $55 billion in the year 2000. (United States Environmental Protection Agency, 1990c).

Hard questions from the public and its representatives can be expected with regard to how well that money is spent. In the water-related portion of the environment, those questions will be directed towards two groups:

* water quality managers; i.e., those individuals or organizations in the private or public sector who have the authority and responsibility to take action to ensure that water quality standards or expectations in a given watershed are met, and
* water quality regulators and "consultants"; i.e., the universe of water quality professionals who create the rules under which water quality managers must operate and/or advise them in carrying out their management duties.

What are the questions these people must answer? What must they do in order to carry out their water quality management roles and to provide justification to the public for their share of water quality management expenditures? Two major questions address the quality of water, and the performance of the water quality management system, as follows.

"What is the quality of the water?"

This is the fundamental question that water quality managers must answer to the public and its representatives, whatever the scope or size of the management system of interest. The state and behavior of the water and watershed in question must be conveyed in a clear, understandable, credible and timely fashion. This is "State of the Environment Reporting" (e.g., 305b reporting and the National Water Quality Inventory), and is intended to portray watershed performance with respect to the goals, expectations, and desires of the parties to which the water quality manager must respond. The question as expressed implies that those considerations are known. It may be that they are not, in which case the manager's first job may be to clearly define "quality of the water".

"Is the water quality management system to which resources are allocated effective and efficient?"

Management system performance reflects the ability of water quality managers to use information and resources at their command to set realistic management objectives, identify criteria and assign priorities, and make the necessary decisions to achieve the objectives. Several factors affect that performance, including:

- the manager's perspective on management (style) and understanding of the management system,
- the effectiveness and efficiency with which information required for decisions is provided, and
- the effectiveness and efficiency of the decision process itself, including the manager's decision-making skills and tools employed.

An analysis which exhaustively addresses these concerns, particularly for a large water quality management system, would necessarily draw upon many disciplines and require considerable time and resources. A more manageable approach is to divide that extensive analysis into a series of focused studies, each building upon previous research and experience. This dissertation is perhaps the first in such a series, and focuses specifically upon evaluating the performance of water quality information systems in supporting water quality management and decision processes.

The literature indicates that the general perspective on water quality data and information has evolved through several phases over time:

- No formal water quality data collection or information generation
- Rudimentary data collection and storage, with minimal attention to information needs and their satisfaction

- Improved data collection and storage techniques, with increasing attention to information needs and the stochastic nature of water quality
- Continued development of data collection and storage methods, with refined statistical characterization of water quality variable behavior, and an emerging water quality information system viewpoint
- Continued development in data collection and statistical analyses, accompanied by development of frameworks and protocols to guide and document the design of more comprehensive water quality information systems
- Refinements of all the above efforts, with increasing recognition of their contribution to and significance within broad water quality management systems and, ultimately, ecological management systems

Recent research (Ward, 1988; Harcum, 1990; Ward et al., 1990; Adkins, 1992) has emphasized that proper specification of water quality information needs (or goals and objectives) is absolutely imperative to the rational design of a water quality information (monitoring) system. That sentiment, in conjunction with the concurrent promotion of statistical interpretations of water quality data, has led to the evolution of "standard operating procedures" for the specification of statistical information needs. These procedures, or Data Analysis Protocols (DAPs), define the questions to be posed and the form of the answers to be derived from a water quality data set. Based upon the designer's knowledge of pertinent regulatory or other requirements, the DAP is used to specify the statistical measures (e.g., mean or variance) coherent with those requirements, the mode of interpretation (i.e., the hypothesis to be tested), and the necessary precision of the measurement (i.e., confidence level or confidence interval).

Although DAPs hold much promise for "tightening up" the link between statistical information needs and monitoring data collection practices, they may not adequately address more basic water quality management information needs. The fundamental purpose of water quality information is to support management decisions. As noted by Ward (1994), protocols usually are not "connected" to the ultimate interpretations of requirements (regulatory or managerial) and corresponding management decisions. In some cases, statistical information is called for, but it may not be sufficiently targeted (with respect to its measure or precision) to decision needs. Also, to the extent that those decisions are not based upon water quality statistics (or, for that matter, any water quality considerations), DAPs are not useful. In these cases, the relevant non-monitoring information needs must be identified.

Another notion receiving more attention recently in the water quality community is that of "accountability". As budget pressures increase and as public demands for demonstrable results from water quality management efforts intensify, water quality managers will be forced to adopt a more "bottom-line" perspective towards their duties. They will be asked more frequently to show what past water quality expenditures have accomplished, and to justify future program expenditures. In order to meet those demands, managers must be armed with the proper information; both to make necessary decisions and to clearly demonstrate water quality outcomes to the public.

It is the thesis of this research that to meet these responsibilities and expectations, water quality managers will require:

- an expanded definition of water quality information,
- an extended process to identify and document water quality information goals, and
- a practical method (protocol) to audit and evaluate the effectiveness of water quality information systems in helping achieve water quality goals.

This research presumes that the fundamental understanding needed to accurately identify information needs and to competently evaluate and reconfigure an information system will come from an exhaustive evaluation and documentation of the associated watershed and water quality management systems. Water quality managers and their consultants are encouraged to "back up" and perform those analyses prior to the design or redesign of any water quality information system.

This research assumes that knowledge to help water quality managers address these needs resides in several disciplines. That knowledge can be abstracted and expressed in a water quality management context to help evaluate and improve water quality information system effectiveness. Operationally, those ideas will be incorporated into a performance evaluation framework which extends the DAP concept in two directions: (1) backward, to better define the management system and all of its decision information demands, and (2) forward, to comprehensively audit the information system's response to those demands.

A practical and recognized performance evaluation process will help managers redesign water quality information systems to attain water quality goals, achieve public support, and secure regulatory agency approval. Such enhanced information systems will:

- generate and communicate information to support <u>all</u> management system objectives and information needs,
- generate and distribute unambiguous evidence (proof) of watershed and management system performance to the public and its representatives,

- support a variety of the large number of decision-making tools techniques which can be advantageously applied to water quality management problems,
- address the generic problem often phrased as: " Lots of (good) data is being collected, but it's just sitting there. Managers can't get the resources necessary to make it into information.",
- report on the satisfaction of the goals and needs of those concerned about the water as well as on the quality of the water,
- show the direct connection between information system performance (and potential improvement) and watershed improvement, and that improved communication of water quality conditions to the interested public is a hallmark of an improved information system,
- identify all relevant and important information users (targets) and satisfy their information needs,
- prioritize information needs in order to allocate resources, and
- collect, process and communicate both objective (quantitative) and subjective (qualitative) types of data and information.

In summary, water quality information systems should report on water quality management methods as well as the condition of the water. The management system should be responding to worthy and documented watershed goals (with economic or utility measures attached), and information system reports should reiterate and remind people of these goals, measures and results. Water quality information systems require regular performance assessment and evaluation in order to determine if the systems accomplish what they are designed to do, and to point out opportunities to accomplish water quality management program objectives more effectively.

OBJECTIVES and METHODOLOGY

The primary objective of this research is to present and demonstrate a framework that a water quality manager or consultant can use to analyze and evaluate the performance of a water quality information system. The framework is an auditing and documentation process, coupled with a quantification procedure (or evaluation model) that the manager can employ to compare and/or rank alternative systems if desired. The Framework for Evaluating Water Quality Information System Performance embodies three major activities:

* Characterization and documentation of the watershed and all relevant water quality management systems
* Analysis of the effectiveness and efficiency of the water quality information system(s) in supporting water quality management objectives

- Evaluation (quantification) of the water quality information system's performance

A second general objective of this research is to adapt and integrate the knowledge of several disciplines to create a comprehensive and consistent approach to water quality information system analysis. The studies of systems engineering, management systems, management information systems, and water quality information systems all contribute insights critical towards developing the performance evaluation Framework.

The research described in this dissertation was accomplished in several tasks:

Task 1: Literature Review

The literatures of systems analysis, management information systems and water quality information systems were researched to: (1) establish confirmation of the need for comprehensive evaluation of water quality information systems, and (2) identify the essential considerations of system performance analysis, particularly evaluation criteria.

Task 2: Development of the Framework

The Framework presented in this dissertation was developed by applying the principles and experience of several disciplines, including: (1) general systems analysis, (2) management information systems, (3) water quality monitoring and information systems, (4) decision analysis, and (5) performance measurement. Ideas from various water quality professionals also contributed to the development of the Framework.

Task 3: Evaluation of the Framework

The Framework is evaluated in two ways. First, it is applied to an actual water quality information system improvement analysis in which the author participated, to determine if it could provide an assessment superior to the approach actually used. Second, U.S. Geological Survey and U.S. Environmental Protection Agency water quality professionals were surveyed with respect to the utility and design of such an evaluation process.

SCOPE

The Framework presented in this dissertation is intended to help an individual water quality manager or professional decide how well a water quality information system serves its intended purposes or objectives. It is a process engineering and management instrument, not a tool for specific technical or statistical analyses. The Framework helps the manager or analyst ask relevant and incisive questions about what information the system is supposed to provide, and how well the information is provided.

In following the suggested Framework, the manager will identify many specific shortcomings in both management and information systems and will define their magnitudes and relative importance. Any system improvement opportunities suggested are likely to be complex, sensitive and expensive. The order and methods by which those opportunities are addressed are necessarily the subjects of subsequent decisions and analyses.

ORGANIZATION

The first chapter of this dissertation has served to outline a number of current concerns in the field of water quality management and information systems and to recommend the development of a process to help water quality managers address those issues. Specifically, Chapter 1 proposes the merits of a framework for evaluating water quality information system performance as a tool to enhance water quality management capability and outlines the research methodology employed to support that proposition.

Chapter 2 reviews the research of several disciplines which contribute knowledge towards describing and understanding water quality information systems' performance. The literature reviewed covers these broad areas:

* general perspectives on the systems approach and system performance,

- management information systems and their performance, and
- water quality information systems and their performance.

In Chapter 3, the attributes of a practical water quality information system performance evaluation process are defined and discussed. Criteria upon which that evaluation can be made are cataloged. Then, the "Framework for Evaluating Water Quality Information Systems Performance" is defined and explained.

A case study is presented in Chapters 4 and 5, in which the Framework is demonstrated as applied to the evaluation of an genuine water quality management and information system.

In Chapter 6, a survey of U.S. Geological Survey and U.S. Environmental Protection Agency water quality professionals regarding the utility of a proposed framework is described.

The dissertation closes with Chapter 7, where the conclusions regarding the applicability and utility of the Framework are recapitulated, and where opportunities for future research are identified.

CHAPTER 2

LITERATURE REVIEW

The purpose of this research is to develop a Framework for Evaluation Water Quality Information System Performance. Such a framework must reflect fundamental system performance assessment principles, as well as those uniquely attributable to water quality information systems. Accordingly, the literature review proceeds from universal to specific considerations of system performance evaluation.

In the first section, the general systems approach (systems analysis) is studied, seeking basic concepts applicable to the assessment of any system's performance. Then, in a more specific search, management systems and information systems literature is surveyed to reveal performance assessment considerations pertinent to those disciplines. Finally, the water quality management and water quality information systems literature is reviewed to identify the performance concerns of researchers in those specific domains. In this review, the essential themes and concerns at each level of the search are described and, to summarize, a set of questions is derived that could be posed with respect to the performance of a water quality information system. It is from these progressively specific concerns and questions that potential explicit criteria for evaluating information system performance will be defined.

As anticipated, the literature search revealed that the disciplines of systems analysis, management systems, information systems, and water quality management information systems all contribute knowledge essential to advancing the state of the art of water quality management and information systems development. Several insights integrate the wisdom of those disciplines and are offered here to provide a general context for contemplating the research discussed below:

* A total management system perspective is necessary to performance analysis of a water quality information system. All of a system's components and interactions must be considered.
* Management information systems, by definition, incorporate a data collection or monitoring function. A "monitoring and information system" is redundant. Information without monitoring is impossible; monitoring without producing information is pointless.
* Defined and measurable criteria are fundamental to constructive system performance assessment.
* Information systems are created to enhance organizational performance by meeting management objectives. The proper analytical perspective is that

of the information user (typically a manager) rather than that of the data collector, data analyst or statistician.

- Water quality management activities and concerns are similar to those in other fields of endeavor. Analytical strategies and solutions developed in those areas are applicable in the water quality arena.
- Systems are dynamic and evolutionary. Good system designs recognize this fact and are sufficiently flexible to be usefully modified over time.
- Documentation of system design and operations is essential to the continual analyses of performance necessary to keep systems viable.
- Regular audits and evaluations of system performance promote management accountability and lead to improved system performance

THE SYSTEMS APPROACH

Definition of Systems

Although used casually and ubiquitously, the word "system" denotes a formal field of study. The terms "Systems Approach", "Systems Engineering", "Systems Analysis", and "Systems Philosophy" all describe a comprehensive and disciplined approach to the design, operation, management or analysis of human and natural processes. The systems approach is, of course, not new; but its organization and documentation accelerated in response to many complicated and critical problems faced during World War II, and have continued to evolve with the rapid technological and social developments of the post-war world. Even in the decade of the 1950s, systems philosophers such as Goode and Machol (1957) noted the dramatically increasing complexity of human interactions, and that the development of systems and the systems approach reflected man's attempt to cope with that complexity.

Hicks' (1984) definition of a system is typical: "In the abstract, a system is defined as a set of interacting components that operate within a boundary for some purpose. The boundary filters the types and rates of flow of inputs and outputs between the system and its environment. The specification of the boundary defines both the system and the environment of the system."

All systems, regardless of classification, share a number of fundamental characteristics (from Goode and Machol, 1957; Miles, 1973; Machol and Miles, 1973; Hicks, 1984):

- A system is a whole; composed of parts. System analysis and design concentrate on the whole, not the separate parts.
- Systems have "integrity". All parts of a system must contribute to achieving its objective.

- A system has boundaries (e.g., in time, space or function), which help to define its place and objectives within some larger environment.
- Systems produce outputs from inputs. Inputs are often unpredictable (e.g., their timing and magnitude) and outputs are often less than optimal.
- Systems variables are related in complex ways. Changes in one variable typically affect many others.
- Systems change through feedback. Feedback is information comparing a system's output to some standard or expectation.
- Systems are competitive. Systems compete for limited resources when originally approved, designed and implemented. In system operations, competitiveness implies effective and efficient performance to maintain user utility and avoid obsolescence.

Systems Development

The purpose of systems development (design) is to produce a system which accomplishes defined objectives or solves some problem in a competent manner. It is widely recognized that analysis and evaluation must occur throughout the life of a system. Systems are continuously open to modification; some researchers (eg., Rubin 1986) view a current system as merely the latest prototype in an ongoing redesign process.

The traditional steps of systems development are well established. Miles (1973) presents a typical series of systems development steps:

- Goal definition or problem statement
- Objectives and criteria development
- Systems synthesis
- Systems analysis
- Systems selection
- Systems implementation

Systems development entails many types of analyses. Ellis and Ludwig (1962) describe systems design as a farsighted planning and evaluation process which requires a number of unique analyses:

- <u>Operational analysis</u>: to examine the general operating environment in which the system must perform, in order to clarify primary system objectives and requirements.
- <u>Requirements analysis</u>: to determine the capabilities a system must possess to achieve stated objectives.
- <u>Constraint analysis</u>: to ascertain and document imposed system requirements and limitations, e.g., cost limits, deadlines, etc.).
- <u>Feasibility analysis</u>: to identify a set of systems alternatives which, under the current state of the art, could satisfy the primary and imposed requirements, or,

to determine if a specific alternative system can meet given specifications or achieve given objectives.

- Capabilities analysis: to determine the specifications or objectives a proposed or existing system can meet.
- Extension analysis: to determine the characteristics of an ultimate system which could satisfy the requirements and objectives, without regarding current limitations in the state of the art.
- Growth potential analysis: to predict how a feasible system might evolve into the ultimate system. Possibilities include technological breakthrough followed by total redesign, discrete technical advance with attendant major redesigns, or, smooth advances in the state of the art allowing continuous redesign without downtime. Feasible systems of the third type are said to have "growth potential".
- Evaluation analysis: to define the criteria for a relative evaluation of feasible systems.
- Initial optimization: to select the feasible system with growth potential which best meets the evaluation criteria
- Evolution analysis: to map out the expected evolutionary path from the initial selected system to the ultimate system.

Systems Management and Performance Evaluation

Systems development, design and operation are a seamless continuum. This philosophy of systems design continuity and evolution is repeatedly emphasized by researchers, from Ellis and Ludwig (1962) to Rubin (1986). Performance evaluation is most effective when performance expectations are documented early in the development process and routinely refined in the course of the system's evolution.

Systems researchers (Goode and Machol, 1957; Ellis and Ludwig, 1962; Miles, 1973; Machol and Miles, 1973; Ramo, 1973; Chase, 1974; Hicks, 1984; Rubin, 1986) cite a number of principles and caveats which, if observed, increase the likelihood of effective system design and management.

* **Understand the problem and develop realistic expectations of a system's ability to solve it.**

It is advisable to map out the general nature of the problem and its potential causes prior to "jumping in" to a solution design process.

* **Specify reasonable system objectives and scope.**

The designer or manager must remember that the system only exists to satisfy some user's requirements. It is imperative that the designer identify all system users or customers and document their needs and expectations.

Successful systems can only be developed when targeted problems are adequately described and bounded.

System designers and managers must predict the expected useful life of the system and anticipate the form and timing of relevant events during its life-cycle. Time and timing assumptions may generate constraints in financing, scheduling, product specification and other system development and operation activities. Uncertainty regarding system reliability increases when forecasting too far into the future.

* **Define system performance, how it will be measured, and by whom.**

Performance implies improvement or deterioration with respect to some criterion, standard or expectation. Problems must be recognized, and a manager sufficiently concerned to investigate and correct the cause. System performance must be defined and its evaluation planned during the system design effort. When designs are competing for approval, selection criteria are established from key performance attributes. Following implementation, system performance is routinely compared to user expectations.

Performance measurement and evaluation efforts must continue for the life of a system, from prototype testing to eventual operational obsolescence, and should provide information towards design modification or improvement of follow-on designs. Performance measures may be subjective or objective and may have different utility to different system participants or observers. However quantifiable a performance criterion, individual judgment will govern its application and use in an evaluation situation. Improvement of component or subsystem performance does not necessarily improve overall system performance; it may in fact degrade it.

A system's product or output must have defined and measurable worth to someone, and its value warrant its costs. ".. The real proof of a system's utility comes from the customer's satisfaction with its quantitative and qualitative performance and design characteristics" (Chase, 1974).

Value is often abstract and difficult to measure. Simple parameters are often used as compromises when values are not easily represented numerically and such approximations may be too rough to be meaningful. To address measurement difficulties, many researchers turn to the concepts of utility and weighting functions to define system value. In these analyses, the analyst or user may construct a performance or utility index upon which aggregate system performance is assessed. A familiar example of such a performance measure is the water quality index (WQI), discussed at some length later in this review. Ott (1978) exhaustively describes the construction and use of water quality indices.

* **Assure effective information flow.**

The need for effective communication in systems development and management is universally recognized. Information flow is a critical aspect of all systems. All primary systems (including information systems) must have a companion information subsystem which monitors operations, determines if performance objectives are achieved, and relays that performance information ("feedback") to some adjustment process for action. Systems and supporting information subsystems must be designed to highlight problems, i.e., flag deviations from system performance standards.

To be useful, information must be clear, easily accessed, and efficiently transmitted. A thorough documentation of all phases of the systems design process and a comprehensive database of system performance data are critical.

* **Get all of the people and skills necessary to design and manage the system.**

Problem magnitude and complexity usually put the tasks of systems design and management beyond the capability of an individual and beyond the scope of a single discipline. Goode and Machol (1957) reflect a wide consensus in stating that large system design must be a multi-disciplinary team approach. Technical specialists and expertise are rarely sufficient; Ramo (1973) emphasizes that flexibility, imagination and experience are required to successfully mesh technical and nontechnical systems development factors. Because of this mix of backgrounds, the team must operate under some formal set of rules that assures the necessary communication among all participants.

Systems Approach Summary

The principles and concepts of the systems approach can be adapted to evaluate the design or performance of <u>any</u> type of system. A practical way to summarize those concepts is to put them into the form of specific questions that an analyst could pose when assessing a system's design or operation. Table 2-1, found at the end of this chapter, contains a list of such evaluation questions derived from the general systems research. They can easily be expressed in the water quality management and water quality information system context.

INFORMATION SYSTEMS

Attributes of Information

"Information is useful knowledge derived from data" (Hellriegel and Slocum, 1992), whereas "data are raw, unsummarized, and unanalyzed facts" (Daft, 1991). The essential thrust is that information is data transformed and communicated for the purpose of expanding a user's understanding of the organization or the environment.

Value or utility is routinely imputed to information. The phrase "garbage in, garbage out" is commonly heard in reference to processes in which poor information input results in low value information output. Attributes of information value often cited include quality, accuracy, relevance, quantity, timeliness, and verifiability.

Characteristics of Information Systems

A recurring theme in the literature declares that information systems are subsets of and serve the purposes of management systems, which are in turn devoted to accomplishing the ultimate objectives of some organization or enterprise. Although a preponderance of the literature assumes that information is generated and stored by computer, the information system definitions and descriptions given below are open and inclusive. An information system can be formal or informal, manual or computerized, personal or organizational (Raymond, 1987).

Both structured (routine) and unstructured (non-routine) decision processes can and must be supported.

Two perspectives of the relationship between management and information systems are potentially useful in examining information system performance. The first and most familiar perspective views information systems on the organization's line and staff structure, as a "federation of functional information systems" (Hicks, 1984). A second perspective emphasizes the purposes of information, specifically that of assisting managers to make decisions. Raymond (1987) describes a model in which an information subsystem provides the crucial communication link between "object" and "decision" subsystems of an integrated project management system. Each perspective contributes valuable insight into information systems design and evaluation: (1) the integrated model stimulates detailed questions about information system activities and components, and (2) the functional model emphasizes overall organizational objectives and the potential for systems integration. In reality, of course, elements of both perspectives are employed concurrently in most system development efforts.

Information systems are categorized with respect to the scope of decisions and/or the level of management served. An often-mentioned hierarchy of organizational information systems follows (O'Leary and Williams, 1985; Daft, 1991):

- Transaction Processing Systems (TPS) are used by operations personnel to carry out routine real-time business interactions and data processing.
- Operations Information Systems (OIS) are used by first line managers to deal with short-term, well-defined operating concerns.
- Management Information Systems (MIS) are used by mid-level managers to address tactical, intermediate-term decisions.
- Executive Information Systems (EIS) are used by top managers in making long-term, unstructured strategic decisions.

The components or activities of an information system are typically categorized as:

- Data Collection - A monitoring process gathers facts (data) with respect to the state or behavior of the organization or function being managed.
- Data Processing - Input data are screened to eliminate errors and organized into formats convenient for storage or information production.
- Data Storage - Data are collected in a record keeping system called a database, according to established format and retention rules.
- Information Generation - Data are combined or transformed using models or procedures appropriate to

the decision process being served. Reports or other representations of monitored conditions constitute information upon which a manager can take some action.

* Information Communication - Information is conveyed to the decision maker in a timely and understandable manner.

Data are an essential information system resource (Hicks, 1984) deserving management attention. Data entry, processing and storage are often controlled under the umbrella of a database management system (DBMS). A well-designed DBMS inspires confidence in data integrity and provides the flexibility to share data or use them for unanticipated purposes.

Development of Information Systems

Information system development processes are artificially distinguished for the sake of illustration and explanation. None of the approaches to development discussed are "pure" and aspects of several are often used in an effort to achieve an effective information system design.

Hicks (1984) points out four fundamental philosophies of information system development:

* Ad Hoc systems are designed in response to problems as they arise, without considering other problems or the potential integration of systems.

* Bottom Up efforts develop systems which solve individual problems and may eventually be integrated into a larger coherent system.

* Top Down system development assesses overall organization needs first and then addresses specific problems.

* Data Base development focuses on the prior design of a complete and coordinated database, under the assumption that managerial problems cannot be adequately anticipated.

Recognizing these fundamental philosophies, two major approaches to the actual information system development process have evolved: the "classical approach" and the "structured approach". Classical approaches to information systems development focus upon the output of the system to be provided, i.e., determining the information needs of managers and their decision processes. The basic assumption of the classical approach is that managers can clearly identify or foresee the problems or decisions which will arise and can specify the information which will be required to address those issues. Many researchers doubt the validity of this assumption. Ackoff (1967) notes that it is unrealistic to expect managers to define information needs prior to encountering a defined problem. Raymond (1987) concludes that systems designed in this manner can become ineffective or managerially irrelevant, particularly in complex and changing environments.

The structured approach to information systems design attempts to avoid the pitfalls of classical development by focusing instead on system input, i.e., devising a "data representation" of the object system. The structured approach assumes that information needs cannot be precisely forecasted and that the best chance for an effective system lies in designing a data format sufficiently complete and flexible to be useful when an actual decision demand arises. Managers' changing information needs can be addressed "... by the same basic data if the content of the database truly mirrors the evolving state of the object system" (Raymond, 1987). Often this development approach is referred to as "data-based" or "data-driven".

Each development approach embodies one of the many variations of the "systems development cycle" presented in the literature, and all exhibit the five major phases described by O'Leary and Williams (1985):

Phase (1): System Investigation

Information needs are derived from an audit of the decision process (Hellriegel and Slocum, 1992), which defines the scope of decisions (i.e., strategic, tactical, etc.) to be made and the decision maker's objectives and problems. Information system alternatives (including existing systems) are generated and their feasibility is evaluated against economic, technical and organizational constraints.

Investigation phase findings are documented to facilitate the planning of subsequent development steps. O'Leary and Williams (1985) suggest that a "System Study Charter" be prepared which provides: (1) descriptions of existing information systems, (2) a summary of current and future information needs, (3) a summary of proposed alternative information systems, (4) a report on the feasibility of the proposed alternatives, (5) a statement of system development unknowns and potential problems, (6) a development schedule, and (7) a recommended course of action, with justification statements.

Phase (2): System Analysis

In the classical approach to systems analysis, the analysis of identified user information system needs is expanded. Interviews, questionnaires, direct observation, paperwork investigations and other devices establish the specific information requirements to be met. Major information flows, files to be created, and required reports are described.

Classical systems analysis culminates with an "system requirements report" (O'Leary and Williams, 1985) or "functional specification document" (Hicks, 1984) which: (1) specifies information system scope and objectives, (2) describes the present information system and its faults, (3) estimates new information system requirements, (4) presents a revised system development schedule, and (5) requests management approval to proceed with system design.

The structured approach to analysis and design relies on two techniques: "system partitioning" and "data flow diagramming". Partitioning successively divides a system into appropriate levels of detail or modules and defines their interfaces. Data flow diagrams graphically portray the data and information transformations that occur between and within the modules. Physical data flow descriptions (who and how) are converted to corresponding "logical equivalents"; i.e., content (what) descriptions.

The product of the structured analysis is the "structured system specification", an integrated package including : (1) system goals, objectives and background information, (2) all data flow diagrams describing the partitioned system, (3) a data dictionary, which lists all data to be used in the system and summarizes all pertinent information necessary to define and understand each datum, (4) data transform descriptions, (5) input and output documents, and (6) security, control and performance standards.

Phase (3): <u>System Design</u>

Classical system design is an evolutionary process in which alternative conceptual methods of addressing system requirements are proposed and are evaluated against increasingly well-defined constraints and feasibility criteria. Typical steps in the classical design process include (1) preliminary design, (2) hardware investigations, (3) detailed design, and (4) program coding and testing (Hicks, 1984). Eventually, a preferred design emerges or is selected which promises an acceptable performance with respect to the criteria. Again, documentation of the process is required to secure implementation approval and to guide that subsequent phase. That design report should describe the preferred design's performance specifications and indicate its probable impact on the organization, both in economic and human terms.

The structured approach to design is also an evolutionary process, extending earlier partitioning and data flow evaluations to construct system structure charts; from which hardware studies and processing software programming efforts are carried out.

Phase (4): System Implementation

The transition from systems design to implementation is not necessarily distinct. Many researchers consider the final detailed software programming and hardware selection to be implementation tasks. Implementation activities are similar in classical and structured approaches: (1) software design (both computer programs and system operating procedures), (2) hardware specification and purchase, (3) system "walkthroughs" and testing, (4) personnel training, and (5) conversion to the new system.

Phase (5): System Audit and Maintenance

The final stage of the development cycle is often referred to as a post-implementation audit, where system design and implementation are reviewed to assess how well information needs and design expectations have been met. Because most decision makers are in dynamic organizations and environments, the need for information system evaluation and update will be continuous. Audit and modification continues until the system is terminated or replaced within some future system development cycle.

Rubin (1986), in a discussion of information systems for public management, extends the notion of continuous system audit and maintenance into a fundamental design approach and philosophy. Noting that the conventional systems development cycle is usually rigid, time consuming, and expensive, he advocates active user participation and control of an "iterative system development cycle". This is a continuous and adaptive process in which any information system is explicitly assumed to be a prototype for a succeeding design. Each prototype's development employs steps similar to the traditional cycle, but they are more efficiently managed than when a massive redesign upon termination is assumed or contemplated.

Evaluation of Information Systems

Performance is evaluated throughout the life cycle of an information system. In the original investigation, design options are repeatedly assessed to select those with the greatest potential for success. Following implementation, performance is compared to the expectations established. From the adaptive design view, performance analysis and assessment are the central information system management efforts. Regardless of life cycle perspective or purpose in evaluating an information system's performance, the fundamental evaluation considerations are quite similar.

Performance evaluation must be carried out with respect to overall organizational objectives, regardless of the evaluator's position or status. In order to specify the value of information systems, Ahituv (1980) notes that those defining value, those evaluating value, and the evaluator's definition of value must all be identified. Dearden (1972) notes that ".... anyone who fails to design an information system for its users is incompetent." The same can be said for evaluating those systems.

The literature offers several general methodologies for evaluating information system performance. Most researchers allude to performance evaluation indirectly, typically in connection with specific phases of the system development cycle. The choices required in the system analysis and system design stages require that selection criteria be identified and used in some decision process which predicts system success. Criteria related to system effectiveness and efficiency are described but the process in which they are applied typically is not. Similarly, post-implementation audits are typically critiques of the development process, where analysts compare the actual development process to an ideal "textbook" process and actual outcomes to predicted outcomes. Again, evaluation processes are seldom discussed in detail.

Many discussions of information system analysis (e.g., Mader and Hagin, 1974; Hamilton and Chervany, 1981a; Dominick, 1987; Ameen, 1989) allude to the fundamental distinction between system effectiveness and system efficiency. Effectiveness implies that the system enhances the organizations's ability to accomplish its objectives

(Hamilton and Chervany, 1981a), or the degree to which it provides value beyond the resources it consumes (Mader and Hagin, 1974). Efficiency implies that outputs are produced with minimal resource inputs, irrespective of the value of the outputs.

Ameen (1989) advocates the development of procedures to monitor information system performance and notes that improvements in effectiveness and efficiency may be mutually exclusive. The critical steps in such an evaluation process are: (1) identification of crucial performance variables, (2) establishment of methods to collect measure and analyze performance, (3) determination of the nature of corrective action, and (4) evaluation of the evaluation process itself.

Ameen (1989) also presents general guidelines for information system performance evaluation:

* Performance reviews should be regularly scheduled.
* Evaluation efforts and equipment should receive special budgetary allocation.
* Performance records must be maintained for historical analyses.
* Continual analysis of results is necessary to check for reasonableness and to detect trends.
* Recommendations must be made following reviews and corrective action taken as necessary.

Information system benefits and performance criteria are commonly classified as quantitative or qualitative in nature. Rivard and Kaiser (1989) note that systems analysts and managers often consider qualitative benefits as "icing on the cake", and neglect or reject systems offering high returns from intangible or merely difficult-to-quantify factors. Several approaches to identify and process intangible factors are suggested: (1) focus groups, (2) in-depth interviews, (3) expert opinion gathering techniques; i.e., Delphi methods, and (4) process observation. Whatever approach to information system analysis is employed, Rivard and Kaiser (1989) advocate several practices as beneficial:

- User involvement in the analysis
- Attention to the user's "critical success factors",
- Solicitation of multiple user perspectives,
- Explicit identification of the decisions and decision processes affected, and
- Documentation of the assumptions underlying benefit identification.

Ahituv (1980) states that information systems are generally evaluated either pragmatically, as in traditional cost/benefit analyses, or theoretically, using decision theory concepts. He demonstrates a multi-attribute utility function approach in the assessment of an information reporting system.

Information System Effectiveness:

An effective information system is based upon a fundamental understanding of the business, its management and its environment (McFarlan et al., 1973). Several considerations necessary to that understanding are emphasized throughout the information systems literature:

- User Identification:

  To achieve coherent and integrated designs, Nolan (1971) and others advocate a "total system", "top-down" look at all organizational levels to identify information users and their needs. Also, in the assessment of existing systems, the analyst must be alert to the existence of potential, unknown, informal or unintended users.

- Critical Success Factors (CSF):

  Critical success factors are the issues crucial to organizational success or of value to managers (McFarlan et al., 1973; Rockart 1979; Daft, 1991). CSFs vary among organizations and within organizations, making it necessary to document managers' goals and their techniques for assessing goal attainment. CSF identification allows precise identification of information needs and avoids the collection of useless data.

* Management Decision System:

Management objectives are continuously addressed in managerial decision-making processes. Information needs and information value cannot be defined without understanding those processes and the decisions which are required (Forrester, 1968; McFarlan et al., 1973).

Decision support information is related to three levels of management planning and control (McFarlan et al., 1973): (1) Strategic Planning; where decisions define organization objectives and identify the necessary resources, (2) Management Control; where decisions are aimed at effective and efficient use of resources in attaining organizational objectives, and (3) Operational Control; where decisions assure that specific tasks are carried out effectively and efficiently.

Mader and Hagin (1974) conclude that information value to decision making should be judged by its impact on user productivity, i.e., it should lead to improved outcomes. They define information as a message to the user and define its utility in terms of the "surprise" it presents. If information has some element of surprise, system changes or opportunities for system improvement may be identified. Unsurprising information which confirms earlier learning has value only if it reduces uncertainty or shortens a decision process.

Carter (1985c) notes that the value of information provided depends upon the point in the decision process at which it becomes available, which may be either: (1) prior to the planning or decision making process, (2) after the manager has gathered other available information and decided what action to take, or (3) after implementation of the decision, when it's possible to observe its effects.

Another important management system factor to consider is the capability of the managers and decision makers. In order that the information system itself remain viable and responsive to user needs, its manager(s) must have sufficient authority, responsibility, skills and experience. Dearden (1972) points out that ".... the principle cause of poor information systems is that we have put incompetent or ineffective people in charge of these systems."

With respect to managers and decision makers in general, Carter (1985a) points out that the knowledge level of the manager and his or her ability to fully understand information affect the value of information received, and, thereby, the information system's effectiveness. Information not formed from data, not recognized as pertinent, or not used due to a manager's incompetence is significantly devalued. Davis (1979) and Ahituv (1980), however, note that any manager's capacity to process information is limited by underlying psychological phenomena.

Carter (1985a) also notes that "it is a fact of life" that managerial power and position affect the valuation of information. Information which enhances standing in an organization's culture is likely to be highly valued by an individual, even if not particularly important with respect to organizational goals and needs.

An information system must fit with other systems supporting management decisions (e.g., accounting systems, decision support models, and expert systems) (Hellreigel and Slocum, 1992). Similarly, integration with communication systems must be achieved to facilitate transmission of information within and between organizations.

* Information Resource Management (IRM)

Recognizing the considerable investment required to collect data and create information, many researchers allude to the need to manage information as a organizational resource. These notions have given rise to a sub-discipline called Information Resources Management (IRM). IRM assumes that information is a resource equivalent to personnel, material, or capital resources and that it has administrative, managerial, operational, evidentiary, legal, fiscal, research and historical/archival values. Settani (1986) presents a methodology for prioritizing the importance of records (data or information) and a process which effectively controls each phase of a record's life cycle, from its creation through utilization, organization, retention, transfer, and eventual disposal.

A number of information system effectiveness (value) criteria appear repeatedly in the literature. For convenience, they are listed here and briefly defined:

- Sufficiency (or completeness) refers to the adequacy of the information for its intended purpose. (Snavely, 1967; Godfrey and Prince, 1971; Mader and Hagin, 1974; Epstein and King, 1982; Iselin, 1988; Daft, 1991)
- Understandability implies that information is easily communicated and comprehended. (Snavely, 1967; Munroe and Davis, 1977; Epstein and King, 1982)
- Freedom from bias indicates that information is free from systematic error. (American Accounting Association, 1965; Snavely, 1967; Feltham, 1968; Epstein and King, 1982)
- Timeliness implies that information is available when needed for decision purposes. (Snavely, 1967; Feltham, 1968; Godfrey and Prince, 1971; Mader and Hagin, 1974;

Ahituv, 1980; Epstein and King, 1982; Carter 1985a, 1985c; Daft, 1991; Hellreigel and Slocum, 1992)

- Reliability implies that information can be counted upon to be available and that all information system activities, from data collection through information reporting, protect against the introduction of errors. (American Accounting Association, 1965; Snavely, 1967; Mader and Hagin, 1974; Epstein and King, 1982)
- Accuracy (or quality) connotes that information portrays reality and is free from errors. If the accuracy can be confirmed, it is said to be verifiable. (Ahituv, 1980; Carter, 1985a)
- Relevance is most often defined as decision-relevance, i.e., a measure of how well information assists in decision making. (Snavely, 1967; Feltham, 1968; Mader and Hagin, 1974)
- Comparability (or consistency, or uniformity) indicates that information can be compared with similar information concerning other systems (locations) or from the same system at different periods of time. (American Accounting Association, 1965; Snavely, 1967; Godfrey and Prince, 1971; Ahituv, 1980; Epstein and King, 1982)
- Quantitativeness (or quantifiability) refers to the ability to apply a numerical measure to the value of information or an information system's performance.

(American Accounting Association, 1965; Snavely, 1967; Epstein and King, 1982). Mader and Hagin (1974) state flatly that to evaluate an information system one must be able to quantify the value of the information provided and propose several monetary quantification approaches. Ahituv (1980) proposes quantifying information system value on the basis of utility.

Information System Efficiency:

Efficiently operating information systems provide information outputs using a minimal or optimal mix of resources. Among those resources are time, money and human skills. Several commonly cited attributes related to efficiency are listed here:

* Cost-Efficiency pertains to all information systems components (individually or in the aggregate) and refers simply to the relationship between the costs incurred and the benefits realized (Epstein and King, 1982). Mader and Hagin (1974) note that an analysis of the "efficiency frontier" can help pinpoint a best system design. The efficiency frontier maps the information value-cost relationship of the set of feasible system alternatives or operating conditions. Theoretically, the best alternative or operating condition that the inflection of this curve, where marginal value equals marginal cost. Ahituv (1980)

assumes a similar phenomenon in the multi-attribute utility approach to evaluating information reporting systems. Although conceptually simple to use, efficiency frontiers are tedious and expensive to specify. Carter (1985b) points out that information system costs and values should reflect the potential consequences of bad or missing information to the decision maker as well as the known costs of collecting data and converting those data to knowledge.

* Reporting Cycles are dictated by the user's decision process time spans and cycles (Godfrey and Prince, 1971; Epstein and King, 1982). Efficient information systems synchronize reporting cycles with correlated decision process cycles.

* Prior information availability dilutes the value of current information (Carter 1985a). It is a waste of resources to collect redundant data or generate redundant information.

* The quantity of information provided should match needs closely. Resources are wasted when more data and information are provided than a decision maker can use due to time or capacity constraints. Similarly, the resources invested in inadequately aggregated information are wasted. (Carter, 1985a; Iselin, 1988, 1989; Ahituv, 1990; Hellreigel and Slocum, 1992)

Contributors and Impediments to Successful Information Systems:

Researchers point out a number of factors contributing to information system success which do not neatly fit into effectiveness and efficiency classifications:

* Management Support:

Managers throughout the hierarchy of the user organization must believe in the utility of information systems in general and the need for any specific systems proposed. It is imperative that top managers are convinced that information systems contribute to achieving the goals and promoting the competitive strategy of the organization (Daft, 1991).

The literature is divided on whether systems development should proceed from the "top-down" or from the "bottom-up". Top down approaches emphasize a thorough understanding of the decisions made at each level of the management hierarchy prior to soliciting specific information needs and without particular regard to existing systems (Nolan, 1971, and Hicks, 1984). In bottom-up development, users are asked what information they need and individual information systems are designed accordingly, proceeding from the foundation of existing databases and programs. To the extent that top-down approaches minimize the detachment of design from objectives, they are more likely to result in well-integrated information systems and thereby generate coherent management commitment and support throughout the organization. Of course, in reality an effective development process works in both directions, as appropriate to the application.

- User Involvement

Ives and Olson (1984) question the common wisdom that user involvement in the development process leads to more effective information systems. They appear to be nearly alone in this opinion. The overwhelming consensus of researchers is that user participation in all phases of the development cycle is critical. Hellriegel and Slocum (1992) note that users must know the quality and relevance of data and information sources and how the system works in order to trust the data, and information produced, enough to use them.

User involvement in system development also minimizes the formation of unrealistic expectations. Daft (1991) points out that the fragmented, reactive and ambiguous aspects of some managerial activities (e.g., coalition building) cannot be expected to be served by an information system.

The assumption that more information leads to better decisions is often unfounded. Users may be unable to judge how much or what information they need (Ackoff, 1967), and are limited in information assimilation capacity. Likewise, improving data or information flow does not necessarily improve management performance. Improved coordination and decision-making are also affected by attitudes, competition and many other organizational factors.

Hellriegel and Slocum (1992) also note that many individuals resist technological innovation and may exhibit behaviors such as avoidance, projection, aggression, and anxiety or stress when impacted by information system development. They suggest that user participation, user orientation, and a phased system introduction will foster acceptance and adjustment. Furthermore, any individual performance expectations created or raised by the information system must be specified and understood.

Daft (1991) warns that organizational power and control issues can be prompted or exacerbated by information system implementation, perhaps resulting in under-used or sabotaged systems. He suggests that phased implementation or prototyping with user involvement will minimize these problems.

Table 2-2, found at the end of this chapter, lists questions that could be posed about information system performance, based upon concepts discussed in the management systems and information systems literature.

WATER QUALITY INFORMATION SYSTEMS:

This literature is reviewed chronologically and describes the evolution of water quality information systems in the United States.

Water quality management programs and supporting water quality information systems have existed in some form and at some level of sophistication for as long as human civilization has been recorded. The reasons for the early and continued development of these systems are obvious: the ubiquity of water and its crucial importance to human survival. Specifically, water quality management systems evolved to control nuisance and maintain health.

In the modern era, the motivation driving water quality management and the need for water quality information remains the same: to provide the quantity and quality of water necessary to allow a sustainable environment and to maintain human health. In the 20th century United States, legal and regulatory impetus has been provided through the enactment of federal pollution prevention and environmental statutes and the activities of the U.S. Public Health Service, U.S. Geological Survey, U.S. Environmental Protection Agency, and several other Federal executive agencies. From the institution of laws such as the Rivers and Harbors Act of 1899, and continuing to the current efforts to reauthorize the Clean Water Act, one can see that these fundamental goals have remained constant.

Developments Prior to 1970:

Prior to World War II, a number of states had developed water pollution control efforts, generally prompted by local or regional nuisance and public health concerns. Drawing upon the experience of pollution surveys in the 1920s and 1930s, Hoskins (1938) provides early Federal guidance on planning and executing water quality monitoring programs and offers suggestions which presage those of researchers to the present day.

After World War II, Federal water pollution control laws were passed (e.g., PL 80-845, the Federal Water Pollution Control Act of 1948, and PL 84-660, the Federal Water Pollution Control Act Amendments of 1956), which provided the original impetus towards more uniform and systematic efforts to gather water quality information (Ward et al., 1990). Much of the early definition of water quality information was developed by sewage and industrial waste treatment researchers. Velz (1950) outlines a systematic three step process to determine stream water quality conditions which stresses the need to convert data to information and recommends a careful statistical approach to the analysis of water quality data. Clark (1950), commenting on Velz' paper, also anticipates future information concerns in stating that accurate prediction of water quality conditions requires (1) an appreciation of the complex relationship among physical, chemical and biological variables and (2) the careful application of the laws of probability and statistics.

Building upon earlier studies, McKee (1952) compiled an exhaustive compendium of water quality criteria and considerations (<u>not</u> standards) intended to encourage consistent approaches to water quality management problems and to provide the necessary informational support for sound decisions at the local or regional level. In addition to describing technical water quality characteristics, McKee (1952) reviews judicial perspectives and information considerations, including the uses of non-scientific standards and the treatment of expert opinion.
In a later edition of that compendium, McKee and Wolf (1963) note that the tendency to allow criteria to become rigid and simply "ripen" into standards should be avoided. "Criteria should be regarded as flexible information to be kept constantly under surveillance."

In a treatise focusing upon the planning of sampling and analytical activities to promote consistency, reliability and representativeness, Haney and Schmidt (1958) stress that: (1) an over-all strategy built upon clearly defined objectives is crucial, (2) representativeness is critical and must be clearly defined, (3) information must be targeted to the decision criteria of the user and should be formatted to conform to the "rules" under which it will be used (e.g., qualitative information for court procedures), (4) measures of central tendency can be abused, (5) methods identifying correlation among multiple factors may be appropriate and reduce expense, and (6) programs founded upon well-defined objectives and featuring effective data analysis and reporting procedures will nonetheless produce weak information outputs if the fundamental data collection process (i.e., sample collection and sample analysis) is not carefully planned and executed.

Emphasizing the necessity to coordinate water quality objectives and their mode of expression, Pomeroy and Orlob (1967) address several information-related needs identified by agencies trying to devise water quality management systems: (1) consistent water quality terminology, (2) definition of criteria used to describe water quality objectives, (3) statistical description of water quality characteristics, (4) non-numerical expressions for desirable levels of water quality, and (5) guidelines for minimum surveillance programs required to achieve policy objectives. The criteria and minimum data requirements to allow statistically significant description of variation over space or time are also discussed.

In remarks at a major water quality management symposium (see Kerrigan, 1970), Lyon (1970a) promotes water quality information systems as a critical tool for achieving cleaner waters and notes that: (1) "The present state of water quality information systems is chaos and disorder.", and (2) "If Congress would ask today which of the nation's streams were getting cleaner and which were getting more polluted, we could not answer the question. Such is the state-of-the-art of water quality information systems."

Langford and Doyel (1970) discuss efforts and mechanisms to promote coordination and cooperation in water quality management and emphasize that a knowledge of all factors (hydrologic, social, and economic) related to water quality management issues is essential.

Murdock (1970) presents a comprehensive overview of the application of systems analysis principles to water quality management and describes the development of a water quality information system for the State of Pennsylvania based upon those concepts. He notes that although the application of systems approaches have met with technical success, "the results have generally been rejected by the political process."

Anticipating the development of "data analysis protocols", Thomann (1970) notes that data collection efforts must be designed with a preplanned program of interpretation (e.g., mathematical modelling of the system) in mind. Also stressed is the need for timely feedback to help avoid the indefinite accumulation of large amounts of unanalyzed or unused data.

Petri (1970) notes that programs aimed at collecting data for water quality planning must reflect the needs of all parties sharing the resource, not only those with foresight to be willing to contribute to the cost of data collection.

Showen (1970) states that middle and top managers must be included in the design team in order to engender the attitudes of program "ownership" which will lead to smoother program implementation.

Roche (1970) describes the organization of the Water Quality Surveillance Program for San Francisco Bay-San Joaquin Delta and Estuary, a Bureau of Reclamation-coordinated effort of several Federal and State agencies. A significant feature of the program was that each agency was only asked to contribute what it could to assist the program. It was found that minor program changes often allowed the needs of agencies lacking manpower, expertise or funding to be accommodated. The coordinated approach and continued contact throughout the program led to efficient use of men and equipment, avoided duplicate effort, and obtained accurate and consistent area-wide data useful to all the participants.

Edwards (1970) pointed out the need for conversational ability and compatibility among systems and emphasizes that compatibility must extend beyond the computer system to encompass the entire data collection and processing environment. An effective way to achieve system compatibility is to promote common exchange of ideas and techniques among users in the system design process.

Moody (1970) proposes that water quality data serve three purposes: (1) to provide base level information, (2) to support water resources planning and development efforts, and (3) to support continuing water resources management activities. He notes that an effective data collection program is dynamic and adaptive and presents an approach in which data collection can be routinely updated to improve hydrologic and planning models. Regretfully, he indicates: "Unfortunately, the process usually ends with the model. There is no sensitivity analysis of a planning decision to errors in the hydrologic data."

Moody (1970) makes several other noteworthy observations with respect to collecting data to support water resources planning and development:

- Water resources managers seek to reduce the risk and uncertainty associated with various courses of action. They attempt to control the potential political, economic and social penalties associated with poor decisions by increasing the number of data available for analysis or by improving their analytical methodology.
- Economic variables and political variables may have more relative impact than physical or hydrological variables in a specific water resources planning

decision process. If a physical constituent's variance has little impact on the variance of the total planning model, efforts to reduce its variance may not make sense.

- the use of increasingly sophisticated hydrologic models (which require large numbers of data) as input to planning models " may not substantially improve the decision making process until similar improvements are made in estimating the economic and political variables."

Leavitt (1970) labels water quality monitoring programs as "Resource Surveillance and Control Systems" (RSC), recognizing them as a special subset of general information systems. He reminds us that RSCs exist solely to satisfy the information needs of human user functions and defines performance of an RSC in terms of: (1) information content, (2) timeliness of information transfer, (3) presentation mode, and (4) presentation media. Leavitt also stresses that the need to assess system performance is continuous and designs must provide for the reality that systems invariably require modification and improvement throughout their useful life.

Steele (1970) advises that analysis of historical data may provide more information than an equivalent effort to collect new data and may indicate where additional data are not necessary. He encourages ascertaining the limitations of available data prior to attempting statistical analyses and interpretation, and recommends concurrent data analysis and data collection to take advantage of recent knowledge of water quality conditions.

Johnson (1970) recommends the systems approach to water quality planning and operation, "..to provide solutions which best serve the purposes of the organization as a whole." and encourages renewed emphasis on it as a "unified concept of planning". An multi-step systems development process is presented with the caveat that the systems approach is not a "cure-all", due to the complex goals, dynamic environments, and limited resources which often characterize water quality projects.

Lyon (1970b), summarizing the symposium mentioned earlier, calls for: (1) better attention to the public's information needs, (2) a national water quality information system which addresses the relevance of data to action, (3) measurement of a broader and more relevant set of parameters, (4) a more precise definition of data needs and data system methodology, (5) better conversational ability between information systems, and (6) improved management control systems and the use of systems approaches. He indicates that "..information systems really are the crux of water quality management.."

Developments from 1970 through 1983:

In a landmark paper, Brown et al. (1970) document several professional calls for better water quality information:

- The Committee on National Water Policy of the Conference of State Sanitary Engineers proposes a uniform method of measuring water quality. (January 1959)
- The Environmental Pollution Panel of the President's Science Advisory Committee recommends development of a method to assign a numerical index of chemical pollution to water samples. (November 1965)
- The Environmental Study Group of the National Academy of Science calls for development and use of various environmental indices which could be weighted and incorporated into an overall Environmental Quality Index. (January 1970)
- The "Report to the Senate Committee on Public Works" by the Oak Ridge National Laboratory points out the high priority need to develop environmental quality indices. (January 1970)

Brown et al. (1970) also note shortcomings with respect to the generation and reporting of water quality information:

- "..no provision has yet been made to for keeping the public informed, in simple and understandable terms as to what this (pollution control) effort and expenditure is achieving-or not achieving in water quality enhancement "
- "...quality-explicit communication between professionals and the public has not been developed.."
- "Federal, state and local agencies collect data on a myriad of individual parameters which end up in voluminous files or occasionally get published in booklets in a form which is hard to digest and assimilate."

In the 1960s, a number of American and European researchers (e.g., Horton, 1965 and Liebman, 1969) suggested that water quality would be better characterized and understood if water quality variable data were incorporated into an aggregate or composite numeric measure called a Water Quality Index (WQI). Horton (1965) outlined the design and application of such an index and noted that an index number system allows water quality: (1) to be evaluated (over space or time) on a comparative rather than absolute value basis, and (2) to be rated by according to the influence of several individual quality characteristics.

A WQI scores a waterbody's quality (usefulness) with respect to one or more contemplated uses (or desired conditions) of the water. Borrowed from the fields of operations research and the decision sciences, WQI algorithms (several variations exist) are multi-attribute utility functions which: (1) specify the relative importance (weight) of relevant water quality variables, (2) translate water quality measurement data into utility scores, and (3) compute a composite utility score from the individual utility scores and their relative importance.

Water quality indices became increasingly popular devices for transmitting water quality information in the 1970s. The United States Council on Environmental Quality, in its annual report for 1974, notes:

* " The general public and many decision makers in government and industry .... must be supplied with comprehensive assessments of the significance of these data on a timely basis, thereby enabling these individuals to appreciate the feasible options and the consequences of alternative decisions."
* The National Environmental Policy Act of 1969 (NEPA) dictates that all Federal agencies "...should identify and develop methods and procedures...which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decisionmaking along with economic and technical considerations...In general, however, the response of both the Federal Government and the scientific

community to this important need and mandate has been inadequate."

- "To form reasonable judgements about environmental conditions and trends, we must conduct monitoring programs that experimentally ask needed questions; we must obtain and analyze data that are valid, accurate and representative; and we must make a number of scientific and socioeconomic decisions about how to weigh these data in forming interpretations and judgements."
- In interpreting water quality data, high accuracy and representativeness may demand complicated techniques understood only by technically trained people; simplicity in communicating assessment of environmental quality may risk misrepresenting reality.
- Problems using environmental (aggregated numerical) indexes as interpretive techniques include: (1) lack of consensus on index design and factor weighting, (2) loss of the ability to appreciate the shortcomings and limitations of the data when hidden in an index, and (3) loss of information resulting from the mathematics of index calculation.
- Questions about the validity of a particular index (or interpretive technique) should not distract us from the effort to develop improved interpretive techniques to facilitate better public information.

- An effective index or other data interpretation (information generation) technique: (1) facilitates improved communication of environmental quality information to the public, (2) is readily derived from available monitoring data, (3) strikes a balance between oversimplification and complex technical conceptualizations, (4) imparts an understanding of the significance of the data it represents, and (5) is objectively designed but amenable to comparison with expert judgement in order to assess its validity.

Ott (United States Environmental Protection Agency, 1978a) also warns that simplification of data inevitably removes information and that: "... the important point in evaluating indices is to determine the target audience for which the index is intended and the ultimate context in which the index results will be used." Ott summarizes the literature and the opinions of survey respondents to conclude that an ideal water quality index:

- is relatively easy to apply,
- strikes a reasonable balance between oversimplification and complexity,
- imparts an understanding of the data it represents,
- includes variables that are widely and routinely measured,

* includes variables that have clear affects on aquatic life, recreational use, or both,
* includes toxic substances,
* easily accommodates new variables,
* is based on recommended limits and water quality standards,
* is developed from a logical scientific rationale or procedure,
* has been tested in a number of geographical areas,
* shows reasonable agreement with expert opinion,
* shows reasonable agreement with biological measures of water quality,
* is dimensionless,
* has a clearly defined range,
* exhibits desirable statistical properties, permitting probabilistic interpretations to be made,
* avoids eclipsing,
* shows sensitivity to small changes in water quality,
* is applicable for showing trends over time, for comparisons of different locations, and for public information purposes,
* includes guidance on how to handle missing values, and
* clearly documents the limitations of the index.

Ott (1978) also recognizes the need for representing environmental phenomena that may be somewhat more abstract than physical, chemical and biological variables. Approaches for gathering, assessing, and interpreting non-monitoring information to enhance understanding of basic relationship and to support decision making are encouraged.

Wolman (1971) notes the need to serve the public's ability to evaluate the return on investment for water quality improvement alternatives and observes a number of concerns related to attaining the necessary information:

- Are the water quality parameters being measured those that best measure the perceived conditions or qualities the public or society is interested in?
- "Definitions of water pollution are often rightly subjective..".
- A number of factors contribute to the dearth of adequate statistical studies to pinpoint parameter changes over time, including: (1) short hydrologic records, (2) changes in observation and analytical techniques, (3) changes in location or frequency of observation, (4) lack of correlation information between water quality parameters and hydrologic behavior, (5) lack of knowledge of natural background or temporal variability of a parameter, and (6) lack of knowledge of the economy and land use of an area.
- Observational programs are not designed specifically to measure the quality of the river or the river environment. Sampling programs emphasize the

measurement of specific characteristics primarily related to water use by industry and municipalities. Few observational programs combine the necessary hydrology with measurements of water quality, river characteristics, and biology.

- Interpretation is a vital task in water quality assessment. Interpretation requires the knowledge and skill of analysts familiar both with the data and with the changing characteristics of the land use and economy of the drainage basin.
- The emphasis on quality of the environment demands continuing assessment and interpretation.

During this era, several water quality researchers began to more fully develop the statistical approaches and techniques suggested earlier. Sanders (1974, 1980) was among the early researchers to identify water quality as a random variable and to call for stochastically defined criteria in the selection of sampling locations and frequencies and in the analysis and interpretation of water quality data. Loftis (1978) introduces statistical techniques to predict confidence intervals about means for water quality constituents which consider serial correlation and seasonal variation. Sanders and Ward (1978) emphasize that water quality sampling is a statistical process and that water quality data should be expressed in statistical or probabilistic terms. Sanders and Adrian (1978) use statistical concepts to establish criteria and a methodology to determine sampling frequencies. Sanders (1980) suggests that the statistical analysis of water quality variables can be extended into the area of risk analysis, to provide a rational basis for integrating the factors affecting pollution control decisions.

Loftis and Ward (1980a, 1980b) discuss the effect of random changes, seasonal factors and serial correlation on water quality sampling statistics and on sampling frequency. They examine the practical considerations involved in matching statistical analysis techniques to sampling frequency and define the information value of water quality data as the width of confidence interval for the sample statistic of concern (e.g., the annual sample geometric mean). Tradeoffs between sampling frequency and a network's ability to determine annual water quality means with confidence are discussed.

Shnider and Shapiro (United States Environmental Protection Agency, 1976b) develop a "first cut approach" to monitoring network design evaluation, defining a procedure applicable to networks whose main objective is to document compliance with standards or regulations. Major operational characteristics of a monitoring network (i.e., first level evaluation criteria) identified include: (1) Network design, (2) Personnel, (3) Facilities and Equipment, (4) Sampling,

(5) Quality Assurance, (6) Data distribution and dissemination, and (7) Agency Interactions. Government agency expert opinion was solicited to specify the relative weights to be applied to each major characteristic, which are then further divided into "elements" (i.e., subcriteria). Tables of very specific attributes to consider are included. Checklists and documentation forms are provided to guide the analysis of each characteristic, score its elements, and calculate a composite score. A composite network operation score is derived by summing the products of the scores and weights of the characteristics. Shnider's and Shapiro's method produces a performance index for monitoring system operation, similar in concept to a water quality index. A major benefit is that the analyst is forced to document evaluation criteria and assign relative values to them. If adapted to personal computers and modern software, the procedure would be a more convenient system design and analysis tool.

Ward et al. (1976) discuss the lack of connection between water quality data and water quality management decision-making. They note that monitoring: "...is an integral part of a total information system within a water quality management program" and encourage data utilization planning during the system design process to better link monitoring and management decision making.
They define information utilization as the step between

information generation and decision-making which involves "satisficing"; where the decision maker subjectively selects a combination of reports, formats etc. of practical use. Also, data (information) from non-monitoring sources is recognized as essential to water quality management decisions.

Ward et al. (1976) recommend a design framework which incorporates a system evaluation phase that asks: "Was the information adequate?". A cost-effective water quality monitoring system is defined as one which: (1) translates its outputs into readily understandable terms to those not familiar with data collection and analysis, (2) relates data collected to well-defined environmental objectives, and (3) exhibits knowledge and understanding of the other (non-environmental) objectives of the management decision makers.

Moss (1979) stresses that "..network design is an iterative process; any design should be reevaluated and updated periodically". He emphasizes that users often need more than statistical information; that they require integrated measures of information and must weigh the value of less-than-perfect hydrologic information based on the decision to be made. Also, designers must know the procedures by which water quality information will be incorporated into decisions.

Because of vague goals, implicit multiple uses, and the wide variation of hydrologic processes, Moss (1979) suspects that a rational consideration of data uses is impossible in the design of large multi-purpose (national) networks. Perhaps the major role of large national networks should be to act as "contingency networks" to use-specific networks, providing data to be used in a "what-if" planning mode. The coordination and resource duplication implications of multiple specific use networks are detailed.

Moss (1979) also urges that system effectiveness be addressed as well as efficiency and that information effectiveness at the national water policy level must be related to the policy management steps of: (1) development, (2) implementation, and (3) evaluation. Policy development often requires that data be collected and analyzed fast enough to be useful to affect political momentum. Effectiveness in policy implementation may depend upon the efficiency of the data system and the structure of the policy itself. Policy evaluation effectiveness requires data and information which can be used to measure changes that result from the policy. Finally, Moss notes that data and information have no utility if there is no provision for remedial policy action. If data or information show a policy to be ineffective and it is not or cannot be changed, the data or information are worthless.

Langford and Kapinos (1979) describe the rationale and design of the National Water Data Network. Recognizing that data must be collected with an understanding of the hydrologic system and are often used for purposes other than those planned, the network's design objectives were set by: (1) determining the adequacy and availability of data on hand or expected from on-going programs, and (2) forecasting future data needs. A "Catalog of Information on Water Data" is compiled in the National Water Data Network; an information file on water data activities which includes: (1) identification of sites for which water data are available, (2) location of those sites, (3) organizations collecting the data, (4) the types of data available, and (5) the measurement frequency of the major data types.

Lane et al. (1979) describe an evaluation and decision process to determine if certain research project water quality data collection networks should be continued (as is), expanded or discontinued. The decision process used assumes bounded rationality (i.e., the perceptive and cognitive limitations of the decision makers) and constructs a simplified model of the decision problem, a "problem-data matrix", from which a "satisficing" (satisfactory) rather than "optimizing" solutions were sought. The decision analysis revealed that some data collected were unrelated to research on problems reflecting current high public needs, and the value of some data records was decreasing over time. The evaluations indicated that some networks could indeed be discontinued without compromising research objectives.

Lettenmaier (1979) defines three water quality network types based upon data utilization objectives: (1) ambient, (2) intensive survey, and (3) enforcement or abatement. He discusses dealing with the "dimensionality" (complexity) of water quality systems and regrets that management agencies pay little attention to specification of objectives and criteria. Also, " Researchers have also proven guilty of underemphasizing this step. There is inevitably temptation to fit a problem to the tools available; in so doing, the problem which is solved may not be the one which has been posed."

Dawdy (1979) states that to produce information which supports water resources planning and management objectives and decisions, network designs must consider the worth of data, which can be defined by their expected contribution to the improvement of design decisions. In addition to marginal analyses of data worth and cost, approaches to determining data worth include: (1) an information variance approach, (2) a transfer function-variance approach, and (3) a more general economic framework, which considers social, political, and economic factors as well as hydrologic data. Simplicity of solution and ease of understanding are required if methods for determining data worth are to be useful to decision makers.

Langbein (1979), summarizing issues raised at a conference on water quality, offers a number of observations on providing water quality information:

- Efficiency may not be a primary objective in guiding network design. Politicians and leaders prefer strategies which reduce political or interagency conflict and promote consensus. The higher political and information costs of rational planning tend to minimize comprehensive analyses.
- The complexity of water quality objectives at regional and national levels may make system optimization at those levels a nonsensical goal. Perhaps "... regional design, let alone national design, is impossible."
- Shannon's (see Shannon and Weaver, 1949) view of information is important because it addresses the relevance (usefulness) of the signal as well as its "telegraphic" content. "Data that do not change the probability of an event convey no information because they are inaccurate, incorrectly interpreted, or irrelevant."
- Congress is more sensitive to undersupply rather than oversupply of data. PL92-500 and its attendant regulations prescribe large data collection programs but "... legal codification of the kinds of data, and the place and manner of their collection, in the regulations tends to freeze out inquiries about effectiveness or utility."

- Decision makers rarely cooperate by defining objectives. "One of the byproducts of research on network design may be that it will suggest to users and decision makers the kinds of questions they need to ask of the data system."
- More feedback is required regarding the need for a separate water quality data agency. As long as their needs are met, individual data users are not sensitive to redundancies, inefficiencies, levels of error, long term uses, other's needs, or information transfer opportunities.
- Optimization (efficiency) is not necessarily the sole or major system design criterion. A mix of criteria, some based on judgmental analyses (e.g., trade-offs with flexibility or contingency needs) may be appropriate.
- The scope of monitoring programs should be broadened, to pay attention to physical, chemical and biological relations as well as statistical techniques
- Examine or audit water quality networks to see how well they fulfill the objectives stated at their creation as well as currently perceived objectives. Suggested audit process steps include:
  (1) Describe the network and its financing and identify its uses.

(2) Attempt to define network objectives as they have evolved over time.

(3) Assess errors and pinpoint sources of error in estimating parameters (throughout the system); noting that " Error assessment is part of the information provided by the data network".

(4) Analyze results, network efficiency, redundancies or gaps, and data transfer methods.

(5) Study the implications of the network on public policy and the effectiveness of water programs. Determine the validity of claims of insufficient data.

* Pursue technological coordination among networks, including:

  (1) incorporation of technical and hydrological relations among networks to increase their joint usefulness (e.g., to allow the use of groundwater information in surface water networks estimating low flows),

  (2) coordination of data factors used in several models to allow application of data to various problems ("Can the data for one model help another?"),

  (3) information transfer to allow serving multiple objectives, and

  (4) balancing the utility of different types of data.

In 1981 the U.S. General Accounting Office (GAO) reported to Congress on the state of water quality monitoring in the United States (United States General Accounting Office, 1981a). The title of the report, " Better Monitoring Techniques Are Needed To Assess the Quality Of Rivers and Streams", indicates the critical conclusion of the investigation. Specifically, the GAO recommends that: (1) three national fixed-station water quality networks (USEPA's National Water Quality Surveillance System [NWQSS], USGS's National Stream Quality Accounting Network [NASQAN], and USEPA's Model State Operating Plan) be discontinued and the sponsoring agencies shift to a program of special studies, and (2) the use of other (e.g., biological) indicators of progress toward cleaner water be promoted. The GAO's reasons for that recommendation included:

* "Water quality assessments must be based on reliable, meaningful data if they are to be useful. However, the networks (USGS and USEPA) cannot provide sufficiently sound data for these assessments. Samples are taken too infrequently and stations are placed too sparsely to deal with the complex nature of water quality. Inconsistencies and errors in field and laboratory performance make network water quality data even less reliable."

- Federal water quality information systems include EPA's STORET and USGS's WATSTORE systems. In general, the computerized data lack associated information needed for accurate interpretation. Neither agency qualifies water quality data with local condition information or laboratory information which could affect results or interpretation.

In response, the EPA and USGS acknowledge some of the concerns presented but disagree with the recommendation to discontinue their national water quality networks. The agencies believe that statistical analysis can overcome the complexity and frequency concerns and that changes in water quality can be meaningfully analyzed without understanding the reasons for the changes. The GAO was not persuaded by the agencies' arguments.

Loftis and Ward (1982), responding to an EPA plan to de-emphasize routine monitoring in favor of special studies (in reaction to criticism by the General Accounting Office, 1981), argue for a combination of fixed frequency (routine) monitoring programs and special studies to answer different water quality information needs. They urge that the efficiency, reliability and economy of existing monitoring systems be improved first, then the savings realized be devoted to any needed special surveys. Factors cited to improve monitoring systems effectiveness include: (1)

statistical objectives for monitoring, (2) data analysis procedures, (3) procedures to establish station location, sampling frequency, and representativeness of sampling and (4) data utilization practices.

From the perspective of realism, Loftis and Ward (1982) suggest that routine monitoring of a list of constituents is the simplest method of satisfying the real water quality management objective of the various states and agencies; which is to satisfy (barely) the letter of the law (i.e., the implementable and enforceable regulations derived from stream standards and effluent standards). They speculate that satisfying the intent of the law (i.e., continual improvement of the water quality) is necessarily a secondary concern due to resource limitations, presumably a factor leading to the GAO's observations and recommendations.

In a companion article, Schaeffer (1982) agrees with Loftis and Ward and notes several reasons for under-utilization of water quality data:

- Confusion caused by the political, administrative and regulatory maze results in ill-considered and confused data acquisition.
- Data are collected for outdated or inappropriate information needs.
- Access to the data is sometimes denied to those people who need it.

- Sophisticated mathematical skills and tools may be required to interpret the data.

Smillie and Flug (1982) attempt to provide a basis of understanding for developing effective water quality management programs and rational water quality strategy in the National Parks. A multi-step monitoring network and sampling design process is presented and questionnaire to guide the monitoring network design process is included. They warn that the statistical representation of the data must be coupled with understanding of the physical system represented in order to avoid misinterpretation of water quality statistics.

Ward et al. (1982) and Smillie (1982) address the development and testing of statistical procedures used to assess river water quality from available routinely collected water quality variable data, including: (1) probability density function modelling, (2) multiple linear regression, (3) conditional probability modelling, (4) water quality indexes indicating changes in water quality, and (5) water quality indexes indicating compliance of variables with stream standards. Both conclude that the use of statistical information for water quality management decisions is appropriate and that water quality management agencies can learn much from following the example of other disciplines which deal with stochastic systems.

Ward et al. (1982) examine the policy implications of introducing statistical sampling and water quality hydrology concepts into water quality management decisions. Water quality is recognized as a stochastic process and statistical sampling and analysis techniques are advanced to address the difficult task of separating natural (stochastic) and societal (deterministic) effects. The water quality management model and techniques described are intended to help managers determine if pollution control expenditures are improving water quality under current fixed station monitoring and data analysis methods.

Sanders et al. (1987) cement the view of water quality monitoring from the systems and stochastic perspective. Monitoring is viewed as a total system, from sample collection through information utilization in water quality management decision-making. A shift of emphasis (premises) from <u>how</u> we monitor to <u>why</u> we want to monitor is encouraged. Designers are encouraged to examine operational and informational monitoring activities by: (1) asking policy makers about data use, (2) asking themselves what types of statistical analyses are appropriate for the network, and (3) determining the best way of presenting the data; "...the network designer must be sure to include the policymakers in all aspects of network design. A monitoring systems matrix is presented to demonstrate the tie between monitoring activities and monitoring goals. This device indicates the shift in emphasis (and resource allocation) from sampling-laboratory activity (i.e., data collection) to data analysis and information generation activities. Accordingly, recommendations for improvement in water quality monitoring must consider the relationship between management goals, management strategy and the needed decision-making information.

Developments from 1983-1993:

Recent water quality monitoring and information system literature further develop the major research thrusts previously described, namely: (1) the application of statistical concepts to the analysis of water quality behavior, (2) the analysis of water quality monitoring in a total information system context, and (3) the identification of water quality management objectives and information needs as necessary prerequisites to the design of meaningful monitoring programs. Also, responding to current economic conditions and emerging environmental management philosophies, a number of investigators are extending water quality research to ask fundamental questions about the management systems and the decision processes that these information systems serve.

In a survey of satisfaction with fixed station, special study and biological monitoring programs in the 50 states, Perry et al. (1984) discovered that only 7 states offer detailed monitoring strategies that outline rationale, goals or objectives for monitoring programs and that most others are dissatisfied with their programs. Most state monitoring programs fill legal obligations rather than test hypotheses about water quality conditions and place ".. too much emphasis on data collection and too little emphasis on information utilization." They conclude that few states are prepared to deal with anticipated budget cuts in a rational way.

Ward and Loftis (1986) review the systems approach to the design of water quality monitoring programs and suggest a multi-step design process that emphasizes defined information expectations, data analysis methods, operating plans and procedures, and information reporting procedures.

Mar et al. (1986) promote cost-effective monitoring methodologies to support environmental impact assessment, natural resources management, and environmental quality regulation. In addition to satisfying statistical information needs, they encourage the integration of monitoring programs by multi-objective ranking with respect to overall program goals. The difficulties in making multiple criteria decisions in an atmosphere of unwritten agendas and inarticulate goals and criteria are discussed. Pairwise comparison and ranking processes (e.g., that of Saaty) are identified as potentially useful in such situations.

Specific statistical approaches and considerations related to monitoring and data utilization in surface and groundwater water quality management are addressed by Ward and Loftis (1986), Loftis et al. (1986), Porter (1986), Loftis et al. (1987a, 1987b), and Harris (1988). The implications of regulatory objectives are discussed, as well as specific methods for dealing with imprecise, censored, and near-detection-limit water quality data. Helsel (1990) discusses the statistical treatment of data below the detection limit ("less-thans") and urges the development of summary statistics and hypothesis test procedures which can legitimately specify differences in data sets containing them. Several methods for estimating the appropriate summary statistics for "less-than" data sets of different types (e.g., distributions) are proposed and discussed. Bell (1991b) also discusses methods of handling and interpreting data sets containing below-detection-limit or censored data.

Steele (1987) indicates that identifying monitoring program goals and objectives is a fundamental and continuing step in the design or evaluation process. The dynamic nature of monitoring calls for "occasional evaluation of a network's effectiveness" which involves review of stated objectives and their relevance. The value of data (based on worth of the information; i.e., a user's willingness to pay for it) must be estimated in order to assess program cost-effectiveness. Anticipating future concerns, he notes that "In order to perform such a task, insight into the decision-making process to perceive how information is used and the sensitivity of information detail and its underlying uncertainties to the resultant outcome of a decision should be judged." Steps to a cost-effective and efficient network are presented.

Loftis et al. (1987b) describe a whole system approach applied to historical monitoring data from an industrial wastewater monitoring program. Monitoring goals and supporting objectives were reviewed and statistical methods applied to the data. To facilitate acceptance of the redesigned system, the designers encourage an integrated and simple approach which tailors the data management system to the users, making it user friendly regardless of their computer background.

Ward et al. (1988) advance the notion that, in addition to the traditional water quality sampling and laboratory analysis protocols, monitoring data analysis protocols (DAP) are also necessary. A state-of-the-art DAP is one that yields desired management information while acknowledging data limitations. Advantages of standardized protocols are postulated:

* A consistent approach in analyzing data can be achieved.

- A defined step-wise approach allows defensible data analysis to be accomplished by non-statisticians.
- The program can be audited if questions about results arise, allowing a focus on the process and not on subjective or untraceable conclusions.
- Better use of existing knowledge may be made, allowing reduced need for preliminary data characterization, shorter data records and earlier availability of quantitative management information.

Ward (1988) champions the concept that water quality monitoring programs should be viewed as information systems which support management systems. To develop and support that assertion, he indicates:

- The evolution of our "information society" has highlighted the need to use information technology to bring order and value to otherwise useless data.
- Water quality management must be increasingly efficient and effective to meet future water use needs.
- Water quality management is changing in perspective from specific problem solving to the on-going management and description of water quality variable behavior.
- The evolution of water quality monitoring indicates little connection to water quality management.

- We need a framework for water quality monitoring design that accounts for the evolving role of water quality information within water quality management.
- We need to put water quality monitoring on a stronger scientific basis which can evolve with the desire to base water quality management decisions on society's needs and the condition of water being protected.
- A connection between information expectations and the statistical data analysis methods required to meet those expectations is key to the successful development of water quality information systems.
- A more systematic design process is required; information needs must be quantified and translated to design criteria.

Ward (1988) describes monitoring system design tasks and advocates documentation of the design to increase the probability that data may be useful for purposes not anticipated by the designer. Noting that water quality monitoring design is currently an art as much as a science, Ward outlines a number of difficulties facing the designer:

- Judgment will always be required in design decisions.
- Defining information expectations can be awkward and difficult for users. Asking users to justify their need for information or to interpret laws and

regulations will require creativity on the part of both designer and user.

- Statistics can be confusing. Problems such as dealing with non-detects complicate its application and can effect information product representativeness
- Consistent operations are required to assure that the data convey water quality variability and not sampling (system) variability.

Loftis et al. (United States Environmental Protection Agency, 1989) and Taylor and Loftis (1989) refine broad water quality information goals established by legislation (Acid Precipitation Act of 1980) into statistical hypotheses upon which statistical tests can be employed as part of a data analysis plan. Seven statistical tests are tested and identified as capable of providing desired trend information. Non-parametric statistics and tests are recommended for water quality trend detection under annual or seasonal sampling frequencies.

Shafer and Davis (1989) note that conventional economic analysis is often not suited to environmental management decision-making and that methods are available that include perceived quantitative and qualitative values and can "..evaluate trade-offs between money, environmental quality, health, happiness, and social entities." Managers are encouraged to "..stop making simplifying assumptions to suit..quantitative models and deal with complex assumptions as they are." A decision procedure is described which is intended to facilitate consensus, define priorities, reflect the stated values of decision makers, and provide a decision "audit trail".

Moss (1989), in a summary of the current state of water quality monitoring, notes that information system design must anticipate the decision-making technology that will be used to address the objectives underlying the system's creation. The U.S. Geological Survey's National Stream Quality Accounting Network (NASQAN) experience is cited as a result of inattention to decision and data analysis technologies: "..inevitable budgetary pressures have caused NASQAN to be modified without benefit of knowledge as to how the changes would impact the network objectives." Moss also comments on the content and convenience tradeoffs of robust data management systems (e.g., STORET, WATSTORE) and calls for increased "synergism" of water quality information systems, to be accomplished through proper preservation of data and information, use of information to understand water quality processes, and adoption of others' new approaches and technologies for water quality information system design. He notes that "..Poorly informed managers and users...are perhaps the biggest drawback to attaining the desired synergistic effect."

Messer (1989), speaking of the USEPA's Environmental Monitoring and Assessment Program (EMAP), states that monitoring goals and objectives must be tied to decisions. EMAP's "..objectives are to determine whether the sum total of our environmental protection efforts are truly protecting our ecosystems and, if not, where additional efforts should be targeted". Monitoring information is needed to address the remaining complex, subtle and long term problems and to help focus limited resources where risk or potential damage is the most serious. He indicates that the increasing costs of problem solving are making environmental consumers more cost-conscious. Citing several sources, including the U.S. House of Representatives, he notes that: " There have been increasing calls from Congress, scientists, and the public for programs that disseminate environmental statistics to the public that could be used to judge the success of current efforts and the need for new ones".

Bell (1989) states that to transform data to information one must know the reason for collecting the data, the planned use (i.e., the statistical analysis and reporting) of the data, and the uncertainties inherent in the data. Defining information expectations is a crucial first step; allowing the design of a consistent and auditable monitoring program which is transferable to new management and operating personnel. The core elements of such a program include: (1) a set of information expectations, (2) a data analysis protocol, (3) a quality assurance program, and (4) a database management system. Bell identifies other development opportunities to enhance water quality information systems design:

* Visual methods of data interpretation.
* Clarification of the role of the legal community in development of water quality information systems.
* Education of the legal community regarding uncertainty in water quality data collection and information generation
* Education of water quality professionals regarding the need for water quality information systems and of the importance of a rational and controlled design process.

Ward (1989) presents a water quality information system design framework which emphasizes a total systems approach and the need to quantify information expectations. Information protocols are urged in order to: (1) allow complete documentation of system design, (2) permit auditing of data analysis methods, (3) introduce consistency of data analysis and information reporting (among sites and personnel and over time), and (4) incorporate state-of-the-art knowledge into monitoring system design and operation.

Blacker (1990) reviews the application of Total Quality Management (TQM) principles to USEPA activities, focusing upon the development and promotion of data quality objectives (DQO). DQOs specify the type, quality (tolerable error) and quantity of data needed from a monitoring program to make reliable regulatory decisions. DQOs document information user needs in a manner that ensures that the producer understands what information must be delivered. The concepts are discussed with respect to laboratory data and quality control, but are easily extended to more comprehensive information system applications.

Harcum (1990) lays groundwork for water quality data analysis protocol (DAP) development. The impact of data record attributes (censored data, missing data and serial correlation) which can inhibit data analysis is examined and the potential of seventeen statistical procedures for inclusion in a DAP is examined. A five-component DAP is proposed:

- Identification of information goals and transformation into water quality conditions
- Data handling
- Identification of data record attributes
- Water quality evaluation
- Information reporting

Bell (1991a) describes the evaluation of IBM Corporation's existing monitoring programs to determine their ability to support prevention efforts, problem investigations, and remediation efforts. The evaluations were carried out in three steps: (1) Identification of the network's monitoring objectives, (2) Characterization of the water quality data collected, and (3) Evaluation of the network design.

Ward et al. (1990) consolidate the ideas of that movement which insists that monitoring must support a total water quality information system and provide information relevant to achieving management's watershed goals. Data analysis, information interpretation and information reporting concepts are extensively reiterated. A team approach to development of water quality information systems is urged, specifically the involvement of information users, system operators and designers. A system design framework is proposed and the authors recommend that all steps of system design and operation should be described in a formal design document. System evaluation is examined and analysts are encouraged to verify that information is actually being used to help make management decisions. Regular performance feedback is advocated, perhaps by user assessment forms which accompany information reports.

Ward et al. (1990) emphasize documentation as an invaluable aid to system design and evaluation. Documentation promotes standardization and suppresses variability in procedures and operations; thus reducing uncertainty about the data and producing more trustworthy and useful information. An "Information Expectations

Report" which captures the user's information needs is demonstrated and the authors suggest that users and system designers "sign-off" on the information expectation consensus reached. Data analysis protocols are recommended to force a careful translation of the information objectives into data analysis methods which can be audited to insure the required information can be provided. A comprehensive "Water Quality Information System Design Report" is demonstrated; a documentation which encompasses the entire monitoring system and clearly displays the results of the design effort. Finally, quality assurance and quality control (QA/QC) efforts must be documented. QA/QC denotes "monitoring of the monitoring system"; to insure that it is performing as designed and implies an evaluation of the entire water quality information system's performance with respect to design goals, not just of the data produced. Such an assessment can be accomplished through such devices as informal user inquiries, formal surveys, and evaluation reports. In conclusion, the authors cite the advantages of documentation in controlling system evolution, fostering smoother operations.

Loftis et al. (1991) touch upon general water quality information concerns and specific statistical information issues in examining the implications of scale on water quality decision making. They emphasize that statistical significance does not necessarily imply actual managerial significance: "... we are in danger of making serious errors in water quality management by basing important decisions on whether a given change is 'statistically' significant when there is likely to be little connection between statistical significance and genuine significance from the management standpoint." As an example, changes and trends which are not statistically significant may be very real and important from a management perspective; i.e., as related to management objectives over the time frame of interest.

MacDonald (United States Environmental Protection Agency, 1991), in a study prompted by concerns over forestry industry impact on watersheds in the Pacific Northwest, presents extensive guidance for the development of successful monitoring programs. A qualitative ranking of the utility of various parameters with respect to monitoring management activities is shown and an expert system to help select monitoring program variables is developed. An extensive listing and practical discussion of monitoring parameters is presented, including definitions, relationships to uses and management activities, measurement concepts, and assessment of utility.

Abubakar and Lord (1992) examine conflict arising in the management of municipal watersheds for multiple purposes. Watershed user conflicts result from: (1) uncertain factual information about the watershed, (2) differences in underlying social values among users, and (3) an imbalance in the sharing of water quality costs and benefits among users. The authors demonstrate that while the roots of conflict may lie in underlying value differences or a differential impact of policies among watershed users, attention may be inappropriately and unproductively focused on factual/technical issues. Assumptions by water quality professionals in earlier negotiations that additional technical information (i.e., monitoring data) on the impact of watershed management practices were necessary and sufficient to solve problems and resolve conflict were contradicted. The authors urge that analysts look at underlying institutional and managerial impediments to effective decision making rather than exclusively focus on technical issues.

Clark and Whitfield (1993) present a practical framework and management guide to integrate quality assurance across an entire environmental or water quality monitoring process. Although the protocol concept is extended to the entire monitoring process, giving a more total system view of quality assurance, it is not extended to encompass the entire information system. The authors view monitoring as an iterative process; a repeating cycle of 14 elements in which: (1) all activities are designed to meet the formal goals of the program, (2) all protocols and procedure are published and kept current, (3) personnel training is critical and all staff must be assigned quality assurance responsibilities, and (4) regular audits are performed, occasionally by an independent party.

Eagan and Ventura (1993) note that information necessary to make informed decisions about the utility of second-hand data (i.e., that collected for other purposes) is not available. To overcome these problems, the authors advocate and illustrate "data lineage reporting", a procedure in which all data processes and transformations, from original measurement to current form, are described and recorded. Data lineage reporting documents the data collection process and provides an overview of the relevant legal and organizational factors which explain the original purpose for the data collection. Anticipated benefits of data lineage reports include: (1) enhanced ability to interpret data by establishing how and why data were collected, (2) enhanced confidence and justification in using data for a particular purpose or decision, (3) improved integration of data for regional analyses, (4) improved information for risk communication, (5) reduced liability, (6) enhanced consistency in data distribution, and (7) counterbalance to the false sense of precision that may accompany raw environmental data. An example of a data lineage report format is presented.

Adkins (1992) describes a framework for developing data analysis protocols (DAP) for groundwater water quality monitoring systems. The DAP design framework is intended to be brief and easy to use; a "how to" manual for DAP writers which will produce meaningful and scientifically defensible statistical information to decision makers responsible for site program goals (e.g., RCRA hazardous waste facilities). A practical application of statistical methods is demonstrated within the outline of Harcum's (1990) generic framework, and specific steps to develop a DAP development framework presented. An extensive list of the attributes of an effective water quality data analysis protocol is developed. The many advantages in employing water quality data analysis protocols are outlined and a summary of statistical analysis methods applied to water quality data is provided.

Table 2-3, at the end of this chapter, poses many questions on water quality information system performance which are drawn from the insights of water quality monitoring and information system researchers. To provide organization, the questions in Table 2-3 are listed as related to:

- system design history,
- characterization of the water quality management system, and
- characterization of the water quality information system.

RECAPITULATION

The literature of system analysis, management information systems, and water quality monitoring and information systems has been reviewed in order to: (1) confirm the utility of water quality information system performance evaluation, and (2) identify water quality information system performance criteria. The utility of performance evaluation is noted (explicitly and implicitly) throughout the literature of each of these disciplines. Many performance criteria have been identified and are posed as performance evaluation questions in Tables 2-1, 2-2, and 2-3, which conclude this chapter.

Next, in Chapter 3, the development of the Framework for Evaluating Water Quality Information System Performance is described. That development draws heavily upon the performance evaluation criteria revealed in this literature review, which are consolidated there under the major headings of system effectiveness and efficiency. In addition, insights from industrial engineering, performance measurement and decision analysis references are cited directly as the Framework description unfolds.

Table 2-1
Systems Performance Evaluation Questions
(Derived from the General Systems Literature)

* What is the management system (i.e., the "supersystem") of which the information system is a component or subsystem?

* What are the purposes or goals of that management system?

* How does the information system "fit" within the management system and serve its goals?

* What are the specific goals of the information system?

* Who are the users of the information system and what are their information needs?

* What are the management system and information system boundaries (e.g., with respect to space, time, or function)?

* What are the systems' outputs (both management and information system) and how are they characterized (e.g., as to predictability, optimality, etc.)?

* What are the information system variables? How are they related? Which are relevant to particular management goals, issues, or problems?

* What feedback processes are designed into the information system itself? Are they used to modify its design or operating practices?

* Does the information system have competition? What is the form of that competition; e.g., political or organizational conflict, alternative sources of information, or general resource constraints?

* Was a rational (formal) system development process employed to design the information system?

* Is the system development process viewed as evolutionary?

Table 2-1, Continued

- Specifically, does (did) the system development process analyze and document:
  - (1) the system's general operating environment
  - (2) capabilities required to achieve system objectives
  - (3) constraints imposed on the system
  - (4) feasible alternative systems or feasibility of a proposed system
  - (5) potential capability of the system to meet objectives
  - (6) an ultimate or "optimal" system for satisfying the objectives
  - (7) the potential for feasible systems to evolve into the ultimate system
  - (8) the expected evolutionary path from feasible to ultimate system
  - (9) the evaluation criteria used to select among feasible systems
  - (10) the process used to select the preferred feasible system to begin the evolutionary process

- Do realistic expectations (i.e., of objectives and scope) underlie system design? Was a good "metadecision" (i.e., pre-planning) process employed?

- Was system performance defined, and its measurement planned for? Related questions include:
  - (1) Were performance criteria or standards defined in the design effort?
  - (2) Were measurement units and scales defined for all criteria?
  - (3) Were relative weights or importance assigned to criteria?
  - (4) What process was defined to integrate criteria into a composite or overall performance indicator?
  - (5) Were routine comparisons of performance relative to expectations planned? For the life of the system?
  - (6) Were specific performance feedback procedures designed into the system to facilitate appropriate design changes?
  - (7) Is the impact of system performance on the performance of related systems assessed?
  - (8) Is the value of system output defined by the user?
  - (9) Are user satisfaction assessments planned?
  - (10) Are systems performance measures simple, efficient, complete, and quantitative in nature?

- Are system redesign and modification anticipated? Are these procedures specified in the original design?

Table 2-1, Continued

- Is knowledge of information system performance effectively communicated and documented (e.g., as feedback within the larger management or problem resolution process)?
- Were the proper people (i.e., with respect to organizational position, skills, etc.) involved in designing and operating the system? Was a team design approach employed? Were people of diverse educational background and of specific technical expertise both represented?

Table 2-2
Information Systems Performance Evaluation Questions
(Derived from the Information Systems Literature)

* Is this an information system?
Is knowledge derived from data collected?
Does the system deliver a message?

* Are information value attributes defined? By whom?

* Is the related management system defined?

Are the specific organizational functions to be served by the information system identified?

Are the decisions or decision-making processes to be supported by the information system identified?

* Have information requirements been adequately defined with respect to the supported decisions and decision processes?

* Are all necessary information system functions (operations) defined?
(1) data collection
(2) data processing
(3) data storage
(4) information generation
(5) information communication

* What general information system development philosophy or approach was used, if any?

Was one of the "fundamental" development approaches (Ad Hoc, Bottom Up, Top Down, or Data Base..?) explicitly chosen?

Does (did) the development approach fit the management environment and user needs?

Was management support and commitment to the information system development effort secure(d)? From the top down?

* Were information users (managers and any other interested parties) involved throughout the development and design of the information system?

Table 2-2, Continued

- Were organizational power and control issues (relevant to information system development, operation, or output) identified and assessed?

- Was the ability of managers to define decisions, problems and information needs assessed?

- Was a classical or a structured, data-directed information system design process employed?

- Was a prototyping or adaptive information system design process assumed?

- Was some variant of the System Development Lifecycle (SDLC) process employed? SDLC calls for the execution and complete documentation of the following design steps:
  (1) System Investigation
  (2) System Analysis
  (3) System Design
  (4) System Implementation
    - phased implementation or conversion
    - testing
    - personnel training and procedure documentation
    - system backup and contingency planning
  (5) System Audit and Maintenance

- Was an information system performance audit or evaluation process explicitly defined and designed? Necessary attributes of such a process include:
  (1) regularly scheduled performance evaluations
  (2) adequate budgets for performance evaluation
  (3) documentation and maintenance of performance evaluation records
  (4) information user involvement in the performance evaluation process
  (5) performance evaluation criteria derived from organizational critical success factors (CSFs) and management system decision process requirements
  (6) identification of performance efficiency and effectiveness factors and any potential tradeoffs
  (7) documentation of both qualitative and quantitative performance attributes,
  (8) definition of information user utility, for both individual performance criteria and for all criteria taken as a group (i.e., composite, joint or multi-criteria utility)

Table 2-2, Continued

(9) definition of a corrective action policy, including recommendation, specification, initiation, confirmation and evaluation of corrective actions

(10) evaluation of the evaluation process itself, i.e., a regular review of its effectiveness

* Is information system performance evaluated with respect to <u>effectiveness criteria</u>? Effective systems exhibit:

(1) identification of all information users

(2) specification and documentation of each user's information needs

(3) specification and documentation of organizational goals, objectives and critical success factors (CSFs)

(4) the potential ability to support and improve the management decision system (and individual decisions) which would be indicated by:
  - information targeted to identified strategic, management control, or operational control activities
  - more efficient (shortened) management decision-making processes
  - reduced uncertainty in management decision-making
  - improved management coordination and flexibility
  - smaller management structures
  - improved organizational outcomes

(5) coherence with managerial (system or individual) competence and information processing capability, including:
  - matching management's ability to specify or forecast information needs
  - avoiding information "overload"; i.e., providing excessive information or allowing insufficient time to assimilate, interpret and act upon it

(6) coherence with other information systems (e.g., accounting systems) which support management decisions

(7) coherence with organizational communication systems and needs

(8) data and information managed as an organizational resource, including the employment of:
  - Information Resource Management (IRM) techniques
  - Data Base Management System (DBMS) concepts

Table 2-2, Continued

(9) information of defined <u>value</u>, i.e., information which exhibits:
   - sufficiency
   - understandability
   - freedom from bias
   - timeliness
   - reliability
   - accuracy
   - relevance
   - quantitativeness and quantifiability

* Is information system performance evaluated with respect to <u>efficiency criteria</u>? Efficient systems exhibit:

(1) cost management
(2) information reporting cycles which are synchronous with information needs
(3) proper quantity of information
(4) minimal redundancy with information previously available

Table 2-3

Water Quality Information Systems Performance Evaluation Questions

(From the Water Quality Information Systems Literature)

Design History:

* How is water quality defined? What are its descriptors and who has defined them?

* Was the information program developed consciously as an integral component of a broader water quality management system? How is that management system generally defined or described?

* Was a systematic approach (or total system perspective) applied to the design of the information system?

Is (was) the water quality information program designed or has it simply evolved in an ad-hoc fashion?

* Is there any documentation of why and how the program was conceived and developed, and how it has evolved into its present form?

* Can the developers and designers of the information system be identified? If so, what disciplines or areas of expertise were represented?

Water Quality Management System Characterization:

* Who is currently responsible for analyzing the water quality management system and evaluating the water quality information system? What are their qualifications or experience?

* Regarding the watershed of interest:

Are all hydrologic, social and economic factors related to water quality management issues understood and documented?

What are the uses of land and water in the watershed?

Are all water-related human interventions (physical) in the region documented?

Table 2-3, Continued

Is the distinction between natural and non-natural regimes understood and documented?

* With respect to system constraints and boundaries:

What political, legal and regulatory "systems" exert jurisdiction over the watershed? Examples include federal, state, and local governments and their agencies, quasi-governmental agencies such as utility districts or conservancy districts, established water rights, and water court decisions.

What specific laws, regulations and directives that emanate from those "systems" affect the watershed or its management?

What specific limitations do legislation, regulations and directives impose on water quality management efforts in the watershed? Do these demands contradict other management activities or concerns, directly or indirectly?

What are the time scales of interest in the watershed? What timeframes match management objectives, decision processes and information needs?

Do political or public opinion demands (momentum) place time and turnaround constraints on water quality management efforts and related information needs?

What is (are) the spatial scale(s) of interest in the watershed? How are geographic and hydrologic boundaries related to management objectives or decision processes?

* Regarding watershed "stakeholders" and their interests:

Who is the "general public" in the watershed? Who represents or articulates the interests of the general public?

Why is the public concerned with the management of the watershed? What is the public's "investment" in water quality management in the watershed?

What are the public's expectations regarding its investment and return in water quality improvement efforts?

Table 2-3, Continued

What are the private interests in the watershed, and what are their water-related investments and expectations?

As noted above, what demands do legislation or regulation (regulators) impose on water quality management efforts in the watershed? Are regulatory demands coherent and consistent?

Are academic and research interests present in the watershed and how are their needs addressed?

* Regarding specific watershed management and decision making activities:

How is a "water quality management system" defined? How many exist which exert control or influence over the watershed?

Who is (are) the water quality manager(s) or decision makers? Do they have the necessary attributes, skills, and training to perform their management tasks? What are their stated values and priorities?

What conflicts exist that must be resolved? What are the root causes?

Are there underlying institutional and managerial system conflicts or impediments to decision making? For example, are those who benefit from water quality efforts subjected proportionally to the costs of achieving the benefits? Similarly, do managers have the necessary authority to carry out their responsibilities?

Is firm financial support for the water quality management system in place? Are capital and skills available for the management and information systems?

Are any decisions actually being made with respect to water quality in the region? By whom? Can a current decision process be described and current decisions, both routine and non-routine, be listed?

Are reliable water quality forecasts and rapid problem responses among management's decision needs?

Table 2-3, Continued

What are management's decision criteria? What are the relative priorities of technical (quantitative) and non-technical factors? Is there a criteria priority assignment process?

What is the decision-making forum in which water quality information will be used? In what process and under what rules will decisions be made (e.g., in court)?

What procedures will be used to incorporate information into the decision making process?

What information timeliness (turnaround) and precision conditions are required by the water quality management decision process?

What agreements and vehicles (organizations) for communication and coordination of water quality information exist in the region?

Is the relationship between water quality management goals, management strategies and the required decisions clear and documented?

Is there a water quality management decision "audit trail"? Can decisions outcomes be traced after implementation?

Do provisions exist to take remedial action on problems? Is there a way to actually change problem policies or practices?

Is there a process in place to measure policy or decision impact; i.e., to indicate the effectiveness of water quality management efforts?

Are decision-assisting processes and models employed? Are they simple and easy to understand?

Are decision tools employed which can accommodate multiple objectives or criteria simultaneously?

Do decision processes recognize the perceptive and cognitive limitations of decision makers? Do they appreciate that "bounded rationality" may dictate "satisficing" rather than optimizing the management and information systems?

Table 2-3, Continued

Is the total variance (i.e., uncertainty or error) in water quality management, planning and decision processes defined? Are the error sources and their relative contribution to total variance understood?

Does the information provided reduce risk and uncertainty in making water quality management decisions? Are potential political, economic, or social penalties of poor decisions reduced?

Does the decision process recognize and deal with complex assumptions as they are, rather than simplifying or ignoring them to accommodate the use of quantitative models?

Can the decision process accommodate subjective judgment? Can it account for and conveniently scale quantitative and qualitative values in order to evaluate trade-offs between environmental, economic, social and political concerns?

* With respect to watershed management objectives and priorities:

What are the objectives of decision makers other than those related to water quality? Are social, political and economic objectives considered? What are their priorities and how are they traded off with water quality management objectives?

Is there a process in place to help stakeholders define water quality objectives; i.e., to assist them in asking the right questions towards establishing objectives?

Is the watershed or water quality management system too large to be reasonably (or optimally) characterized for purposes of information system design?

Are water quality objectives (or questions) being defined to fit available, convenient, or favored tools and techniques; possibly leading to generation of irrelevant information?

Are the water quality management efforts and their measures of effectiveness defined and documented? Are both subjective and objective criteria identified?

Table 2-3, Continued

How are stakeholders, their objectives, and their information needs prioritized in the water quality management and information systems?

How are conflicting stakeholder objectives documented and resolved?

Are consensus building and the reduction of political or interagency conflict more important than what a "rational" water quality planning or management process might dictate?

Is the satisfaction of regulatory and administrative goals the only <u>real</u> water quality management objective? Or, is management's objective to satisfy the intent of the law as well as obey the letter of the law?

Are we attacking the difficult water quality management problems? Are we addressing difficult and subtle "end point" (Messer, 1989) water quality issues or easy, low cost issues? Are water quality management goals categorized on this continuum?

Does the water quality management process effectively identify formally and informally defined objectives and criteria; i.e., both the written and unwritten agendas of interested parties?

What are meaningful measures of water quality management or information program success? For example, some measure of reduced risk may be more relevant than a simple count of the number of permits issued or inspections performed.

* Regarding available water quality information and current information systems:

Are current data and information sources known and cataloged as to scope, purpose and management?

Are other information sources available and easily shared - even among those who have not contributed to the cost of collecting data or information?

Is there an established vehicle for coordination and cooperation and exchange among information systems?

Is current information available and sufficient to address identified problems?

Table 2-3, Continued

Water Quality Information System Characterization:

* General design questions include:

Are (were) professional, trained personnel employed to design and operate the water quality information system? Are continuing qualification, certification, training and professional development needs identified, anticipated, and provided for?

Are (were) diverse technical expertise and knowledge engaged in design and operation of the system? Was expert opinion solicited?

* Regarding water quality information and information system users:

Are the information users clearly identified?
Does the information system have a champion to provide guidance, defense, cohesion and continuity?

Are there information users to be recognized outside the directly associated management and decision making processes (e.g., in the legal, academic and general water quality professional community)?

Are all information users included in all aspects of the design process?

Do system designers and operators interact continuously with information users and decision makers? Are information users stimulated and guided by systems designers to identify and articulate information needs and expectations?

Are the information expectations and needs of all users documented?

Is the information (data) system tailored to the user, and easy to use regardless of computer or mathematical background?

Is information clarity matched to the user's needs and sophistication? Is the extent of information simplification (i.e., the loss of information inherent in data through aggregation or processing) appropriate to the target audience?

Table 2-3, Continued

Has any provision been made to assess user satisfaction and the attainment of water quality goals?

Are provisions made in the system design to accommodate future unanticipated users or uses?

* Regarding identification of information objectives and information needs:

Are user's information objectives clear and agreed upon?

Is the information produced relevant to a decision or to a decision-making process?

Is the decision technology in which the information will be used known or predicted?

Does the information system match the needs of the question to be asked and no more?

Were objectives and an analytical framework determined before data collection began?

What is the information accuracy ultimately required by the user?

Are the design trade-offs between information accuracy and/or representativeness and simplicity addressed and properly balanced?

Are both technical and non-technical information needs documented? What non-monitoring information needs must be satisfied, perhaps to provide the basic understanding necessary to interpret technical information (e.g., land use)?

Were potential future information users and needs anticipated and documented?

What type and form of information fits the identified needs (e.g., visual graphs or water quality indexes)?

* Regarding specification of the system's information capability and the information product:

Was a comprehensive data analysis protocol specified as part of the design process?

Table 2-3, Continued

Were data and information accuracy capabilities specified?

Was information "loss" estimated and described? Were the information losses due to the transformation process (mathematics, model..) or the form of the ultimate message (index, indicator, statistic..) evaluated and documented? What is the information "price" of a robust system?

Can information produced be expressed in terms understandable to those not familiar with data collection and analysis?

Can required information be supplied from other information systems or databanks (e.g., the National Weather Service)

* With respect to the operational design of the information system:

Are (were) existing or previously available materials used to help guide the design and save resources?

Are the experiences and criticisms of previous information systems reviewed and incorporated into the design process?

Is compatibility and complementarity with existing systems (agencies) achieved without duplication of efforts or results?

Are the relationships among physical, chemical and biological variables considered in the design?

Does the information system emphasize parameters describing the river and regime (i.e., the watershed) as well as the water itself?

Are explicit feedback, a periodic review process, and a performance audit and improvement process included in the design?

Is the design flexible enough to accommodate unanticipated or uncontrollable factors?

Are the water quality information goals, network design process, data analysis procedures, and information reporting procedures all defined and documented?

Table 2-3, Continued

- Regarding water quality data collection and processing:

  Do all data collection and laboratory procedures conform to standard methods?

  Are data valid, accurate, and representative? Are these attributes clearly defined?

  Are data to be incorporated from existing systems? Are the limitations of those data known and documented?

  Are database design and management principles applied to the collection and storage of the data? Is the desired "megadata" (i.e., background information on the data) defined and a data dictionary included in the database management system?

  Are statistical sampling and probabilistic principles applied to data collection?

  Is data accuracy sufficient to support information accuracy requirements?

  Is data screening and error removal effective? Are statistical criteria used in the screening process?

- Regarding the generation and communication of water quality information:

  Is the data accessible for transformation to information? Are bureaucratic, personnel, security or other impediments to access and transfer minimized?

  Is adequate time for data analysis and information generation allowed?

  Is there a defined and documented process to communicate and interpretation information? Who are the communicators and interpreters and by what means do they interact with information users?

  Is information captured in a concise and understandable format for the intended user or audience? (e.g., graphical representations and photographs)

  Is statistical information (e.g., mean and variance) generated under the proper assumptions and with a sufficient degree of confidence?

  Is water quality terminology consistent?

Table 2-3, Continued

* Regarding Quality Assurance and Quality Control (i.e., evaluation, maintenance and modification) of the water quality information system:

How is the value of information produced defined?

Are efficiency of data collection and the effectiveness of information produced both considered?

Are all operational deviations from design specifications or normal (standard) practice documented in detail?

Can system-induced (laboratory) variability be distinguished from true natural system variability?

Is there a formal total system audit process in place? Is the information system flexible and its design and operation regularly reviewed?

Is a contingency plan in place which anticipates and specifies how to react to potential pressures on the information system (e.g., changing objectives or budget cuts)?

Are "sensitivity analyses" performed to ascertain the relationships between information (form and content) and the outcomes of corresponding management decisions?

Is system information being misinterpreted or misused? Is there a process to detect and respond to abuses of the system or its output?

CHAPTER 3

A FRAMEWORK FOR EVALUATING WATER QUALITY INFORMATION SYSTEMS PERFORMANCE

INTRODUCTION

It is asserted in Chapter 1 that a systematic process to evaluate water quality information system performance would help water quality managers, consultants, analysts and regulators in their efforts to make or guide water quality management decisions. In this chapter such a systematic process is presented and described. The "Framework for Evaluating Water Quality Information System Performance" guides the water quality professional toward the documentation and evaluation of that performance in four analytical phases: (1) a performance evaluation planning process, (2) a water quality management system analysis, (3) a water quality information system analysis, and (4) a water quality information system performance evaluation.

The Framework enables the water quality manager or analyst to identify and to rank information system performance criteria, and offers a performance evaluation model with which information systems can be evaluated against those criteria. The Framework provides a consistent and comprehensive analytical process which identifies and documents the criteria needed to compare one information system to another, either actual or theoretical.

The Framework directs the manager to analyze an information system's design (i.e., its effectiveness) and operation (i.e., its efficiency) and to identify opportunities for its improvement. The structure, procedures and documentation embodied in the performance evaluation model allow the evaluator to identify the performance impact of changes in effectiveness and efficiency factors. Also, if required, the model can be used to perform sensitivity (i.e., "what if") analyses of information systems performance; e.g., to isolate or predict the impact of changes in model assumptions.

The format, contents and application of the Framework are drawn from the author's experience and the literature sources reviewed in Chapter 2. In the next section, prior to a full elaboration of the Framework, the general requirements of water quality information system performance evaluation are discussed. In the last section of the chapter, following the description of the Framework, a summary of water quality information system performance criteria is presented.

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION

The purpose of performance measurement is to accurately identify opportunities for performance improvement in the system being measured. Many attributes are cited as characteristics of a useful performance evaluation process. Sink (1985) evaluates performance measurement systems on the basis of the following criteria:

* Validity - Are we really measuring what we think we are?
* Accuracy and precision - Does the measurement system faithfully and repeatably describe the behavior of the phenomenon of interest?
* Completeness or collective exhaustiveness - Are all of the relevant measurable variables included in the measurement system?
* Uniqueness or mutual exclusiveness - Are redundant or overlapping measures avoided?
* Reliability - Are measurement results consistently valid? Are error levels known and minimized?
* Comprehensibility - Are measures as simple as possible to convey the intended message? Does the measurement system match the user's skills and knowledge?
* Quantifiability - Are measures expressed numerically where appropriate and supplemented by relevant qualitative information when required?

* Controllability - Are we measuring the variables, factors and relationships over which we have control or influence?
* Cost effectiveness - Is the potential payback from performance measurement commensurate with the effort and resources expended?

With respect to the evaluation of water quality information systems, a useful measurement process is one which allows the water quality manager to assess information system performance on a consistent and continuing basis. The literature (see Chapter 2) and water quality professional opinion (see Chapter 6) suggest that such a process must be:

* convenient and easy for an individual to use; i.e., applicable without requiring consultants or extraordinary resource commitment (perhaps performed using a personal computer),
* inexpensive to develop and operate,
* easy to understand; i.e., correspond to the managers's analytical process and way of doing business,
* consistent and repeatable,
* easy to modify,
* accurate,
* useful in real time,
* easily completed in a short timeframe,

- sufficiently flexible to apply to many information system formats and complexities and, in particular, to the specific information systems alternatives in question,
- well documented and easy for others to understand and use; i.e., easily audited, delegated to subordinates, or turned over to a successor,
- able to clearly indicate management and information system improvement opportunities (e.g., cost savings or more relevant information products), and
- helpful in predicting the impact (or risk) of information system modifications; i.e., be useful in "what if" analyses

  which recast weights, rankings or relationships among factors in the information system under review.

The Framework presented in the next section scores highly with respect to all of these criteria. The planning and information gathering phases are straightforward and, for the most part, require little technical expertise (hydrological, mathematical or computer). They do demand the enthusiasm and skill required to ask the perceptive questions necessary to accurately document water quality management and information systems. Examples of such questions can be found in Tables 2-1, 2-2, and 2-3.

In the evaluation phase, the water quality manager or analyst is introduced to a widely-accepted decision technique that satisfies the evaluation process criteria indicated above. That technique is the Analytic Hierarchy Process (AHP), developed by T. L. Saaty in the late 1970s, and since applied in a wide variety of business, scientific and social decision analyses. Although any number of multi-attribute decision models could be applied to evaluate or compare information system alternatives, the AHP has two major characteristics which make it ideal for this application:

- The AHP process provides a visible decision structure that reflects the manager's own unique analytical process, defines all of the decision criteria relevant to the manager, and clearly indicates the relative importance of the criteria to the manager.
- The AHP allows the simultaneous consideration of both quantitative and qualitative criteria in the decision analysis.

User-friendly personal computer software packages have been developed which facilitate application of the AHP; magnifying its inherent process advantages. An extensive discussion of the theory and application of the Analytic Hierarchy Process can be found in Appendix B of this dissertation.

FRAMEWORK FOR EVALUATING WATER QUALITY INFORMATION SYSTEM PERFORMANCE

A total system perspective suggests that a water quality information system's performance must be judged with respect to the physical system it purports to describe and the management system it supports. The proposed Framework assumes that perspective, and guides the manager or analyst through four analytical phases:

Phase (1): Performance Evaluation Planning

The rationale for the water quality information system evaluation effort is described and the feasibility of a successful evaluation is established. An overall performance evaluation plan is documented.

Phase (2): Water Quality Management System Analysis

The watershed and the management system(s) which control or influence its behavior are characterized and documented.

Phase (3): Water Quality Information System Analysis

The design and operation of the water quality information system(s) are analyzed and documented.

Phase (4): Water Quality Information System Performance Evaluation

The design and operation of the water quality information system are evaluated using evaluation criteria and performance assessment information gained in Phase 2 and Phase 3.

These four phases are, of course, not perfectly distinct. Questions and observations in each phase will naturally stimulate revisiting issues raised in the others. Figure 3-1 illustrates the general structure of the Framework. The main factors which must be considered in each Framework phase are listed in Table 3-1 and discussed below.

Phase 1: Performance Evaluation Planning

Part A: Problem Definition

A prudent first step in the analysis of any management and information system is to define and plan the effort. Problem definition implies describing the motivation for the information system evaluation; i.e., Who is the investigation's champion and what issues have prompted it?

Part B: Evaluation Planning

An evaluation plan must identify:

* the analysts or managers conducting the evaluation;
    - What are their associations or responsibilities with respect to watershed management?
    - Why were they assigned to the investigation?
    - What is their experience and background?
    - What are their assigned or expected investigation roles and activities?

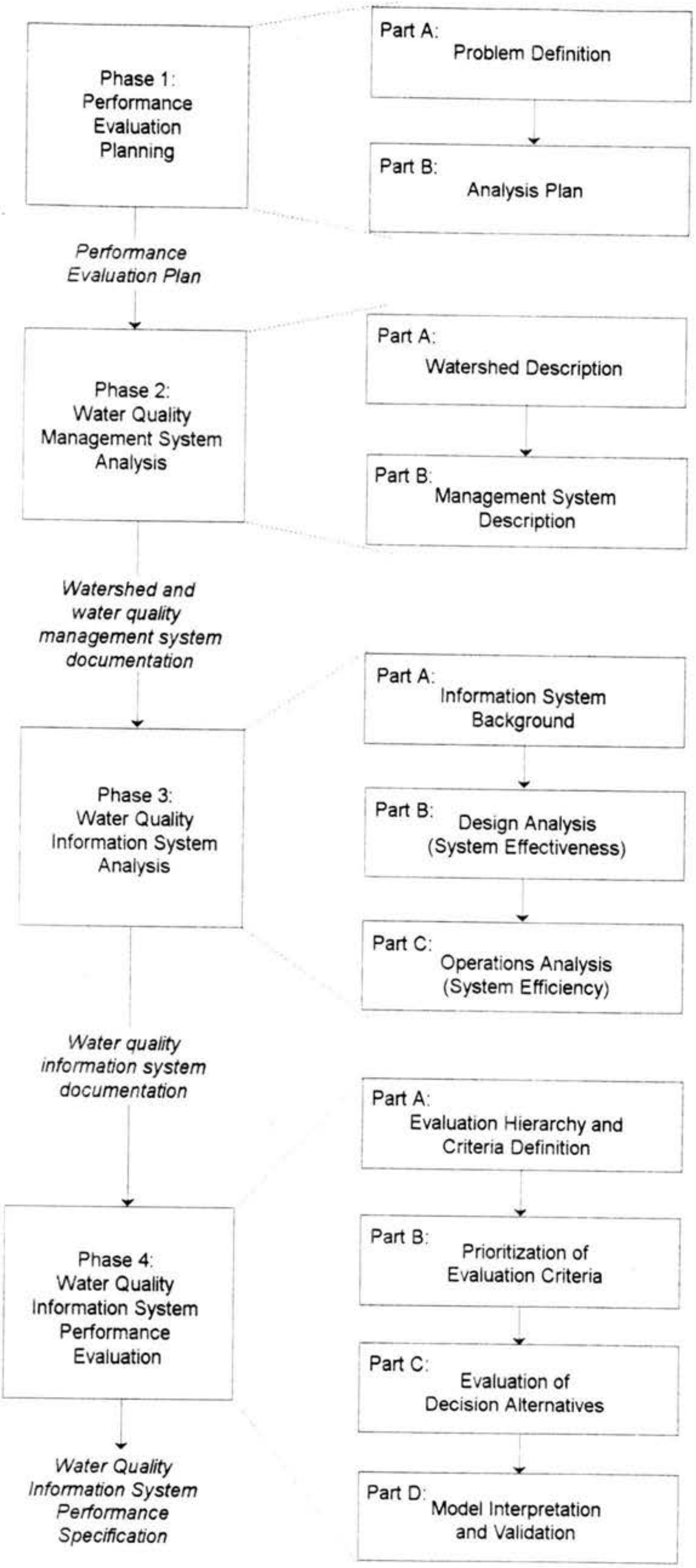

Figure 3-1: Framework for Evaluating Water Quality Information System Performance

TABLE 3-1
Framework for Evaluating Water Quality Information Systems Performance

Evaluation Considerations

PERFORMANCE EVALUATION PLANNING (Phase 1)

- * Problem Definition (Part A)
  - Motivation for the evaluation
  - Evaluation sponsor or champion
- * Analysis Plan (Part B)
  - Analytical skill requirements
  - Resource and funding requirements
  - Reporting expectations
  - Activities, tasks and schedule

WATER QUALITY MANAGEMENT SYSTEM ANALYSIS (Phase 2)

- * Watershed Description (Part A)
  - Boundaries; spatial, temporal, and jurisdictional
  - Land and water uses; historic, current and projected
  - Watershed status; economic, social, and regulatory issues
- * Management System Description (Part B)
  - Stakeholder definition and ranking
  - Stakeholder concerns
  - Management objectives and priorities
  - Management and decision-making processes
  - Problems and decisions to be addressed

WATER QUALITY INFORMATION SYSTEM ANALYSIS (Phase 3)

- * Information System Background (Part A)
  - Designer and design methodology
  - Development and operations documentation
  - Information clients and users
  - Sources of support and funding

TABLE 3-1, continued

- Design Analysis (System Effectiveness) (Part B)
  - Watershed definition
  - Management system specification
  - Information needs specification
  - Information capability specification
  - Information product specification
  - Database requirements specification
  - Operational design specification

- Operations Analysis (System Efficiency) (Part C)
  - Data collection; field, lab, or other
  - Data processing and storage
  - Information generation and reporting
  - Information analysis and interpretation
  - System quality assurance and enhancement

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION (Phase 4)

- Evaluation Model Hierarchy and Criteria Definition (Part A)
  - Evaluation decision objective
  - Evaluation decision alternatives
  - Evaluation criteria

- Prioritization of Evaluation Criteria (Part B)
  - Criteria comparison by pairs
  - Criteria priority computation

- Evaluation of Decision Alternatives (Part C)
  - Alternative scoring
  - Alternative ranking

- Model Interpretation and Validation (Part D)
  - Alternative ranking verification
  - Sensitivity analyses on model assumptions

- the expected outcome of investigation; i.e., what type of recommendation or report is anticipated, and when?
- funding and resources (required and committed)
- evaluation activities, tasks and schedule

Phase 2: Water Quality Management System Analysis

Assuming that a water quality information system exists to support one or more water quality management systems, a comprehensive understanding of those management systems, their objectives, and their components is required to clearly establish their information needs. Knowledge of the management systems must be documented, and in a form which facilitates description of information needs and helps establish their information priorities.

This Framework phase documents the fundamental watershed attributes and watershed management programs upon which an information system's design and operation are based. Knowledge is gathered in the following areas:

Part A: Watershed Description

Water quality management systems oversee or act upon a watershed. A coherent water quality information system is designed from a solid understanding of watershed attributes, including:

- boundaries; e.g., in terms of geography, hydrology, ecology, political jurisdiction or time,

- natural conditions and the impact of human activity, and
- current watershed status; e.g., economic conditions, land and water uses, regulatory limitations, and water quality issues.

Part B: Water Quality Management System Description

Information needs of water quality management systems are derived from an accurate and comprehensive definition of:

- watershed stakeholders and their concerns,
- water quality management objectives and priorities,
- water quality management and decision-making processes, and
- specific water quality problems and decisions to be addressed.

Information relevant to defining the watershed and its management goals can be gathered through literature searches, review of local records, surveys, and personal interviews. It is imperative that this fundamental understanding be developed and documented in order to make possible an incisive review of the performance of supporting information systems. A comprehensive "Water Quality Management System Analysis" guide to direct and document these efforts is illustrated in the User's Manual presented in Appendix A.

Phase 3: Water Quality Information System Analysis

An information system must be both effective and efficient. Effectiveness factors assess a program's design; i.e., its ability to satisfy defined information needs and support management objectives. Efficiency factors depict how well a program operates; i.e., its ability to provide information reliably and at a reasonable cost.

Part A: Information System Background

Prior to analyses of effectiveness and efficiency, the information system's history is documented, including:

- system title or description
- development impetus (original and current)
- system designer and design methodology
- clients and users (original and current)
- sources of support and funding
- age of the system (or its implementation date)
- design and operations documentation

Part B: Design Analysis

A water quality information system's effectiveness is assessed, i.e., how well it describes and documents:

- watershed characteristics and issues,
- water quality management systems and decision processes,
- water quality management information needs,
- system information capabilities,

- system information products, and
- the design of information system operations.

Part C: Operations Analysis

A water quality information system's efficiency is assessed at each system operation:

- data collection
- data processing and storage
- information generation and reporting
- information analysis, interpretation and utilization
- information system quality assurance; system enhancement.

The specific criteria upon which a program is evaluated can be drawn from the water quality management literature, the analyst's experience and from the experience of program personnel. Successful program performance evaluation depends upon thorough documentation of these criteria and a clear understanding of their relative importance. An extensive list of specific effectiveness and efficiency criteria in each of these areas can be found in the last section of this chapter. Also, a "Water Quality Information System Analysis" guide to direct and document these efforts is illustrated in the User's Manual found in Appendix A of this thesis.

Phase 4: Water Quality Information System Performance Evaluation

The findings from the watershed, management system, and information system analyses must be translated into specific evaluation criteria and those criteria rated as to their relative importance for the information system evaluation or comparison at hand. Finally, the information system(s) to be evaluated must be scored with respect to the criteria and some composite system grade(s) computed in order to perform the evaluation or comparison.

Performance is defined in terms of relative preference (priority) scores computed for the alternative systems being compared by the manager. An alternative system being compared may be another operating information program, a proposed or redesigned system, or some hypothetical "ideal" system postulated by the evaluator. Preference scores are derived using the Analytic Hierarchy Process (AHP), which establishes criterion priorities and computes the relative preferences among decision alternatives. The steps of the Analytic Hierarchy Process include:

Part A: Construct Decision (Evaluation) Hierarchy and Define Decision Criteria

The general decision goal (e.g., " Select the Preferred Water Quality Information System") is defined as the apex of the hierarchy. The decision alternatives (e.g., "Current Program" and "Proposed Program" are at the base. There is no limit to the number of alternatives which can be compared. Intermediate levels of the hierarchy contain decision criteria, broken down to the detail required to enable the manager to make a comfortable comparison of the alternatives. See Figure 3-2 for an illustration of an AHP decision hierarchy.

Part B: Weight Performance Evaluation Criteria

All decision criteria (and the decision alternatives) at the same hierarchy level with the same "parent" criterion at the next higher level are compared by pairs and ranked relative to each other using the "eigenvalue method", a matrix computation. Relative priorities with respect to the parent criterion's definition or purpose are computed.

Part C: Evaluate Decision Alternatives

Criteria priorities are combined progressively through the levels of the hierarchy to arrive at composite weights for the decision alternatives. These composite weights, normalized on a 0.00 to 1.00 scale, represent the manager's relative preference for each alternative with respect to satisfying the decision goal.

Part D: Interpret and Validate Model Results

The AHP's virtues include its ability to accommodate subjective and objective criteria in one decision process and to produce a composite numerical measure of an alternative's value (a "preference score"). Ironically, the ultimate interpretation of that score is also a subjective exercise. For example, preference scores of 0.55 and 0.45 may suggest a meaningful distinction between alternatives, but the evaluator must recognize that the actual significance imputed depends upon all of the assumptions built into the model. Would scores of 0.60 and 0.40 be more meaningful? The evaluator's confidence in selecting an alternative (and in the overall decision process) can be enhanced by subsequent sensitivity analyses, which test the stability of conclusions drawn with changes in those underlying assumptions.

An example of the AHP applied to a hypothetical water quality information system analysis is demonstrated in Appendix C. A review of that example application will facilitate the reader's understanding of the case study analysis presented in Chapter 4 and Chapter 5.

To recapitulate, the "Framework for Evaluating Water Quality Information System Performance" compels the water quality manager or analyst to define and document his or her information system performance criteria, and offers a convenient model with which the systems can be evaluated against those criteria. The systematic examination of the watershed and its associated management systems helps to assure the manager that "all bases have been covered" when assessing the utility of any supporting information system.

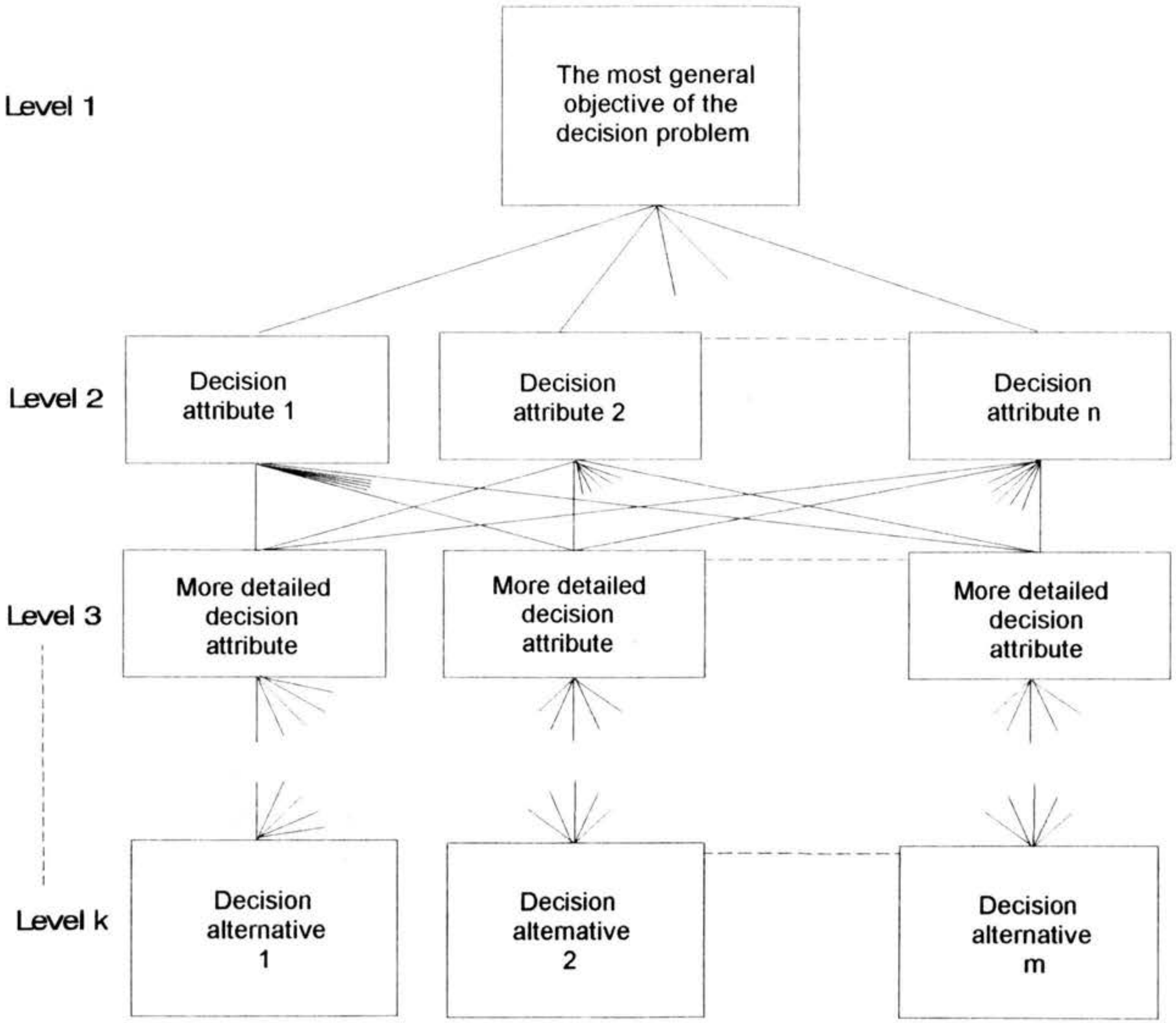

Figure 3-2: Analytic Hierarchy Process Decision Schema - A Hierarchy with k Levels (from Zahedi, 1986)

The performance evaluation model allows the evaluator to explicitly rank the criteria and score the system's performance with respect to his or her unique measures of utility.

A demonstration of the application of the performance evaluation Framework is provided in Chapter 4 and Chapter 5. To facilitate the presentation of that application, performance criteria that may be appropriate to a water quality information system evaluation are summarized in the following section.

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION CRITERIA

A major advantage of the Framework presented is that it can be used to develop a "customized" evaluation of the water quality information system; i.e., the evaluation criteria and the priorities assigned are chosen by the water quality manager or analyst and are applied to his or her unique watershed management problems. Nonetheless, a number of performance considerations and criteria are noted repeatedly by professionals and in the literature, and appear to be widely applicable. They are summarized here to stimulate and aid managers in defining their unique evaluation criteria. The criteria are identified as concerned with system effectiveness or system efficiency.

These performance evaluation criteria are derived from the concerns indicated in the performance evaluation questions found in Tables 2-1, 2-2 and 2-3, at the end of Chapter 2. A further elaboration of their intent and application can be found in the "Water Quality Information Systems Performance Evaluation User's Guide", located in Appendix A to this dissertation.

Watershed Information Documentation (Effectiveness)

The water quality information system must be based upon a clear understanding of all relevant watershed characteristics and must be able to document and convey this knowledge. Specific watershed characteristics (effectiveness subcriteria) include:

- Geographic and hydrologic boundaries of the watershed in question
- Waterbodies and watercourses of significance or concern within the defined watershed
- Hydrologic inputs and outputs of the defined watershed
- Organizational,political or jurisdictional boundaries applicable to the watershed
- Legislative (or regulatory) mandates and limitations applicable to the watershed (federal, state and local)
- Temporal boundaries (timeframes) applicable to the watershed or any associated management systems; either

as specified by a time interval or as delineated by defined events

- Watershed history; including its natural state and behavior, human activities affecting water quality, and past water quality programs or activities
- Current watershed status; including relevant economic and social conditions, land and water uses, and significant water quality issues

Management System Information Documentation (Effectiveness)

The water quality information system must be designed to respond to the needs of those managing or interested in the watershed; i.e., the water quality information users. Those users and their relationships must be defined and conveyed by the information system. To do so, the information system must address and document several factors:

- Stakeholder information (individual or organizational); e.g., relationships to the watershed or any associated management systems, relationships to one another, relative importance or priority, and any pertinent power, control or influence issues
- Watershed management problems and conflicts; including cause identification and any conflict resolution results

- Contemporary water quality or water resource management systems; operators, funding, decisions supported, communications provided, and any institutional impediments to decision making
- Contemporary management information systems (water quality, geographic information system, or other); operators, rationale, and data or information provided
- Water quality management system objectives and priorities; including water quality objectives, other (non-water quality) management objectives, relative priority of the objectives, and measurement of objective achievement
- Water quality management system attributes, including:
    - sources of support (financial and other)
    - management capabilities
    - decision responsibilities and requirements
    - sources and contributions of variance or uncertainty
    - specific problems addressed and decisions required
    - decision criteria
    - decision process(es) employed
    - remedial action policies
    - decision (or policy) impact audits

Information System Design Process (Effectiveness)

The water quality information system must be designed competently; i.e., following a rational, justifiable and "auditable" process. Following are the steps of such a process. The procedure employed and outcome of each step must be clearly documented:

- * Watershed definition and documentation (as discussed under Criterion #1, above)
- * Water quality management system definition and documentation (as discussed under Criterion #2, above)
- * Information system background, including:
    - formal design and implementation protocol employed
    - design team skills and qualifications
    - sponsors and funding sources
    - design documentation
    - operations implementation and documentation
- * Information needs identification, including:
    - translation of stakeholder concerns, management objectives, and decision processes into consensus on water quality information objectives (which indicate water quality <u>knowledge</u> required)
    - derivation of information needs from the information objectives (which indicate the water quality <u>messages</u> required). (These needs may be satisfied by technical or non-technical information, information from non-monitoring

sources, or may be future information and data needs.)

  - documentation of information structure, content and format requirements
  - documentation of users' consensus on information value and priorities, and ranking of users and information needs to be satisfied

* Information capability assessment and documentation, including:
  - deliverable quality of data and information (e.g., accuracy levels)
  - information loss (sources, estimates of magnitude and acceptable trade-offs)
  - probability or potential of satisfying information needs
* Information product specification; i.e., the design of the <u>information product package</u>, which:
  - accommodates the user's computer skill, mathematical background and familiarity with data collection and analysis
  - matches information simplicity to the users' needs
    - includes (shares) available information from existing sources
  - employs a comprehensive data analysis protocol

- documents the user's information system performance expectations

* Information system operations specification, including:

  General Considerations

  - use of available resources and materials
  - incorporation of knowledge and experiences (criticisms) of earlier systems
  - compatibility and complementarity with existing systems (without duplication of efforts or results)
  - documentation of all operating procedures
  - feedback, periodic review, and system performance assessment and improvement procedures

  Data Collection

  - data collection and laboratory procedures conforming to standard methods
  - data validity, accuracy, and representativeness clearly defined and sufficient to support information accuracy requirements
  - appropriate application of statistical sampling principles

  Data Handling and Storage

  - rigorous data screening and error removal, using statistical criteria as appropriate
  - data and information managed as an organizational resource, including the employment of Information

Resource Management (IRM) techniques and Data Base Management System (DBMS) design concepts

- defined "megadata", (information about the data and their limitations), and a data dictionary of that information within or connected to the database

Information Generation and Reporting

- defined and documented information communication and interpretation processes
- consistent water quality terminology
- data easily accessed for transformation to information; e.g., minimal bureaucratic, personnel, or security impediments
- adequate time for data analysis and information generation
- information in concise understandable format for the intended user or audience
- statistical information generated under proper assumptions (e.g., normal distribution) and at appropriate significance level
- adequate description of relationships among physical, chemical and biological factors

Information Analysis, Interpretation and Utilization

- information of value, i.e., information which exhibits:

  (1) sufficiency

  (2) understandability
  (3) freedom from bias
  (4) timeliness
  (5) reliability
  (6) accuracy
  (7) relevance
  (8) quantitativeness and quantifiability

- provides information which can help support and improve the management decision system (and decisions) by:
  (1) targeting on identified strategic, management control, or operational control activities
  (2) shortening the management decision-making process
  (3) improving management coordination and flexibility
  (4) permitting smaller management structures
  (5) improving organizational outcomes
  (6) reducing uncertainty in management decision-making
- impact of system performance on the performance of related systems supporting management decisions
- "sensitivity analyses" are performed to ascertain the relationships between information supplied (both form and detail) and the outcomes of corresponding management decisions

- information coherent with managerial (system or individual) competence and capability; i.e., it matches the manager's ability to specify information needs, and avoids information "overload"
- information coherence with overall organizational communication systems and needs

System Quality Assurance and System Enhancement

A total system perspective of quality assurance is encouraged. Assuming that the overall quality of an information system's product is dictated by the system's weakest features, it is imperative that all aspects of system be reviewed regularly. In such a quality assurance program:

- Quality assurance is a defined responsibility of all system personnel and appropriate training is provided for each person and with respect to each information system operation.
- The information system is assumed by its designers to be adaptive and to evolve based upon operating experience and routinely solicited user feedback.
- Specific provisions are incorporated for soliciting user feedback regarding system performance with respect to expectations and defined criteria in a routine formal performance assessment (audit) process.

- Systems performance measures are simple, efficient, complete, and, as appropriate, quantitative in nature.
- Measurement units and scales are defined for all criteria.
- Relative weight or importance is assigned to each criterion.
- Performance criteria are integrated into a composite, total system performance indicator
- All deviations from design, normal, or standard practice are documented in detail.
- Information system (e.g., laboratory-induced) variability can be distinguished from actual water quality variability.
- A contingency plan is developed which specifies how to react to potential pressures on the system (e.g., changing objectives and budget cuts).
- Processes are in place to detect and respond to misinterpretation, misuse or abuse of the system or its output.

Information System Operation (Efficiency):

Operating efficiency of a water quality information system is evaluated by assessing how well all of the operations discussed above are actually accomplished. Each system operation can be assessed with respect to one or more of the following efficiency factors:

- _Cost efficiency_ applies to all information system activities and implies that each is accomplished with a minimal expenditure of resources; usually measured in monetary terms
- _Timeliness of information_; information reporting cycles are synchronous with information needs
- _Sufficiency of information_; i.e., the proper quantity of information, without redundancy with respect to information previously available
- _System convenience and flexibility_; e.g., ease of modification, update, or accommodating new or unanticipated demands
- _Understandability of operations_; ease of learning and training, transfer of personnel
- _Trustworthy information_; i.e., freedom from bias, reliability, and accuracy

These effectiveness and efficiency criteria will be used in the application of the water quality information system performance evaluation process, which is demonstrated in Chapter 4 and Chapter 5.

CHAPTER 4

APPLICATION OF THE FRAMEWORK TO A MUNICIPAL MONITORING PROGRAM

Part One: Planning and Analysis Phases

INTRODUCTION

In this chapter and in Chapter 5, the Framework for Evaluating Water Quality Information System Performance is used to assess three water quality monitoring and information programs, all defined in connection with the investigation of the water quality information aspects of a unique municipal water transfer case. The assessment follows the defined phases of the Framework as follows:

* The evaluation planning process, watershed description and water quality management system analyses underlying each program are described here in Chapter 4. The advantages of thoroughly pursuing these activities are discussed.
* The water quality information system analysis associated with each program is also characterized here in Chapter 4. The benefits of the Framework's disciplined approach to the analysis of system design and operations are noted.

- In Chapter 5, the performance of each program, or "water quality information system alternative", as they are called, is evaluated and compared using the Analytic Hierarchy Process, a convenient and robust decision analysis model. Performance criteria are defined and an overall performance (or preference) score is computed for each program. Interpretation of the model's results and a discussion of its sensitivity and validity are included.

The water transfer case giving rise to the water quality information system alternatives being evaluated is introduced in the Case Background immediately below. Following that prologue, the water quality monitoring and information programs to be evaluated will be defined and the Framework-guided assessment will be presented. The case background and the analysis of monitoring program alternatives are presented in italic script, to distinguish them from general commentary on the Framework.

CASE BACKGROUND

The semi-arid Front Range region of Colorado has historically depended upon structural responses to meeting increasing agricultural and municipal water needs. An extensive system of trans-mountain pipelines, reservoirs, canals and ditches has evolved to capture and distribute *water to a burgeoning population and economy. In recent years, environmental, regulatory and economic pressures have dramatically curtailed these structural options for providing additional water supplies.*

In addition to climate and geography, unique legal constraints complicate the acquisition and distribution of water in Colorado. The prior appropriation doctrine and an independent water court system impose additional duties and costs upon municipalities or private interests seeking to change water uses.

Anticipating continued population growth, the City of Thornton (Thornton) has elected to augment its future water supplies through the purchase of existing water rights rather than rely solely upon traditional development procedures. A novel and disputed aspect of Thornton's plan is that the water associated with those existing rights will be transferred from and returned to the distant Cache La Poudre River (CLP) basin, where it is used predominantly for agricultural purposes. The water rights have been purchased from members of Water Supply and Storage Company (WSSC), a prominent water distribution organization in the CLP basin. Thornton's ownership of those rights implies an unprecedented formal and dominant position from which to influence the operation of WSSC and the uses of water in northern Colorado.

As a condition of the water rights purchase contract, Thornton was required to establish a water quality monitoring program to determine the quality characteristics of CLP basin water. The program's underlying purposes were to assist in: (1) determining the water's suitability for municipal use, (2) specifying design requirements for future water delivery and treatment systems, and (3) certifying that other CLP basin users could continue to use the water for traditional purposes, as dictated by Colorado water law.

The CLP basin water quality monitoring program operated for about three years (1986-1989) without formal review or analysis. During that period, a number of significant events occurred:

- *New information goals and information needs appeared.*
- *Key program personnel resigned or were reassigned.*
- *The program's scope was enlarged.*
- *Program procedures were modified.*
- *Program costs escalated.*

Based upon concerns raised in preliminary discussions and reported in other monitoring programs, Thornton's water quality managers authorized an investigation to determine CLP water quality monitoring program enhancements. The investigation agreed upon by Thornton's managers and consulting engineers included: (1) an initial specification of investigation objectives and expected outcomes, and (2) *system analysis and redesign recommendations. The investigation and redesign efforts were conducted from 1989 through 1992.*

APPLICATION OF THE FRAMEWORK

In the following sections, the performance evaluation Framework is applied to compare the characteristics of the original monitoring program design to those of the redesigned information system. Also, a third potential information system design will be compared; one defined by identifying the further benefits attainable had the extended Framework been available for use at the time of the investigation.

In the demonstration that follows, the three monitoring or information programs to be analyzed and compared are defined as:

* Thornton's original CLP basin monitoring program, denoted as the **Original Monitoring Program**,
* the CLP basin water quality monitoring and information program characterized by the recommendations of the investigation, denoted as the **Enhanced Monitoring Program**, and
* the CLP basin water quality information system potentially achievable through comprehensive application of the Framework, denoted as the **Potential Information System**.

The analysis and comparison of the three programs will follow the defined structure of the Framework. As each phase and section of the Framework is encountered, the extent to which its associated tasks are addressed or accomplished by each program is described. Figure 4-1 illustrates the Framework and the major issues it addresses. For further review, the reader is encouraged to reexamine the Framework descriptions found in Chapter 3 and in Appendix A.

PHASE 1: PERFORMANCE EVALUATION PLANNING

The first phase of the Framework is the planning process where: (1) the underlying motivation for the entire evaluation is clearly defined, and (2) the feasibility of the effort is established.

Original Monitoring Program:

There is no evidence that indicates a comprehensive water quality managerial planning effort was conceived in connection with the design of the original monitoring program. Project documents indicate that requirements of the water rights purchase agreement were the principal motivation for the design and implementation of the original program. Watershed, management system, and information system aspects of the program were narrowly defined. Future system modification was expected but no specific activities were planned. Engineering consultants to WSSC and Thornton

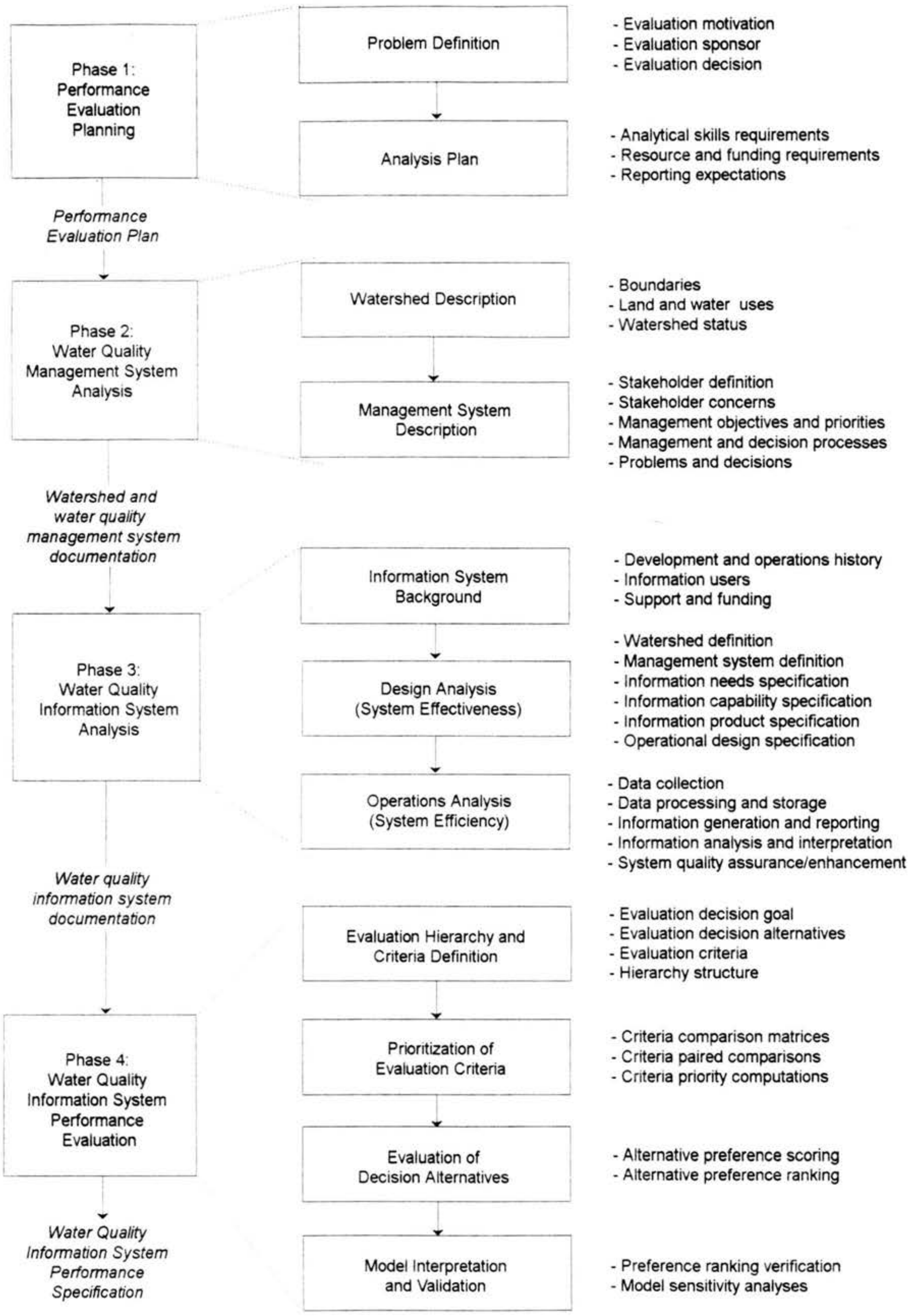

Figure 4-1: Framework for Evaluating Water Quality Information System Performance

specified the water quality data to be reported by Thornton water quality staff personnel. The basic characteristics of the original monitoring program included: (1) 55 water quality variables to be measured, (2) 24 sampling locations, (3) sampling at weekly, bi-weekly, monthly or quarterly intervals (Hotto, 1992). Thornton's primary managerial objective was to assure the reporting of those data as economically as possible.

Enhanced Monitoring Program:

The study to develop an enhanced monitoring program was sponsored and funded by the City of Thornton and administered through its Water Quality Division. The effort was initiated and promoted by Thornton's Water Quality Division Manager. A series of preliminary meetings took place among Thornton's water quality managers and their engineering consultants to plan the study (Hotto and Sanders, 1991). Those preliminary planning discussions led to the specification of several problem areas to be addressed in the evaluation of the original monitoring program and design of the enhanced program:

- *Cost - Opportunities to reduce program costs (particularly in sampling and testing) without loss of information were to be investigated.*

- *Purpose - The objectives of the program were to be stated and the information needs of all users documented as the basis of program design.*
- *Utility - Methods to assure routine conversion of data to information for decisions were to be outlined.*
- *Confidence - Procedures and documentation which would assure the scientific and legal soundness of program data information were to be identified.*

Thornton's water quality managers and engineering consultants agreed that the evaluation report should contain recommendations for an enhanced water quality monitoring program which would:

- *provide useful information for management decisions in a cost-effective fashion,*
- *be convenient to water quality managers and staff for analyses and decision-making,*
- *integrate easily with other current or future management and information systems (e.g., laboratory information management systems),*
- *be sufficiently flexible to accommodate future needs and changing management objectives, and*
- *employ scientifically sound and legally defensible methodologies in all activities.*

The resulting evaluation plan specified:

- *review and documentation of municipal water quality goals,*
- *review and documentation of water quality management information needs,*
- *review of the original monitoring program and documentation of its strengths and weaknesses,*
- *redesign of the original monitoring program into an enhanced program, and*
- *training of Thornton's water quality staff on the design and operation of the enhanced program.*

An evaluation budget was specified and reporting deadlines established. Reporting expectations included:

- *interim reports ranking the concerns to be addressed in the enhanced program design and summarizing the preliminary conclusions drawn from initial data analyses,*
- *a final report specifying the recommendations defining the enhanced program design, and*
- *occasional query responses and project status statements throughout the investigation.*

Potential Information System:

More thorough preliminary planning of the system evaluation and redesign process would facilitate the *subsequent analysis and design phases and the eventual system implementation. Specific issues deserving more prior definition include:*

- *resource commitment to the monitoring program and the redesign effort,*
- *water quality management system structure and decision responsibilities (including the role of legal advisors and technical consultants),*
- *organizational capabilities to implement, operate and utilize an enhanced water quality information program (e.g., personnel skills, resources and funding, etc.), and*
- *initial program circumstances (e.g., availability and condition of data records).*

PHASE 2: WATER QUALITY MANAGEMENT SYSTEM ANALYSIS

The second phase of the Framework entails the watershed and water quality management descriptions which are necessary to accurately define water quality management information needs. Figure 4-2 indicates the position of the first of these activities in the overall sequence of Framework activities.

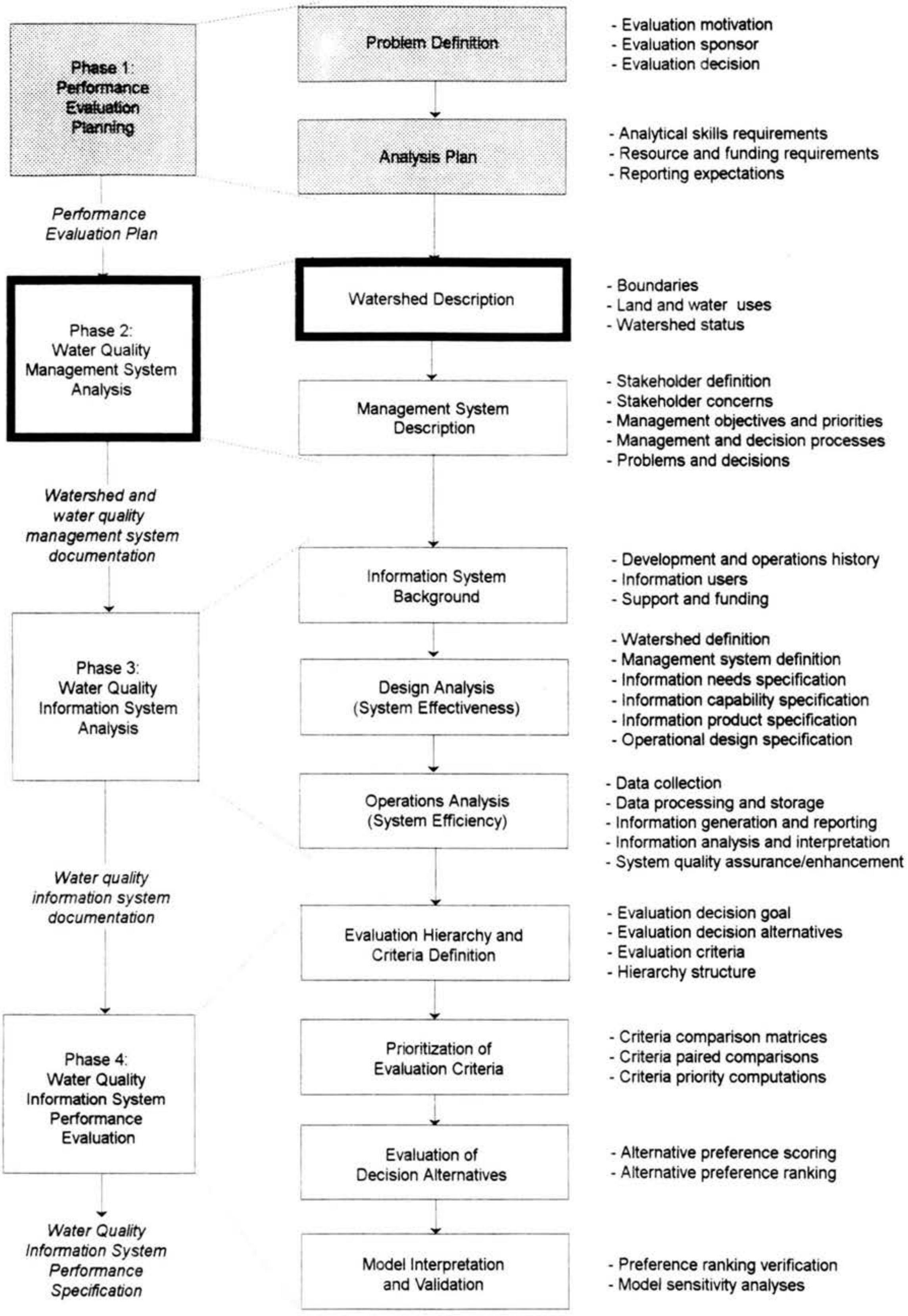

Figure 4-2: Framework Phase 2 - Watershed Description

Part A: Watershed Description

Original Monitoring Program:

The design of the original monitoring program did not include an explicit watershed definition effort. The rough geographic boundaries were implied by the reach of WSSC's distribution system and included waterways expected to experience return flows from the future water transfer system. Fundamental constraints imposed by Colorado water law, agricultural standards and drinking water standards were recognized, but no document reflects the many other watershed characteristics and concerns potentially related to managing basin water quality.

Enhanced Monitoring Program:

Watershed definition was incompletely documented in the design of the enhanced monitoring program. Although design participants had significant knowledge of the characteristics, occupants, and history of the watershed, no disciplined attempt was made to consolidate and document that knowledge. Had such knowledge been developed and shared early in the design process, a more efficient and comprehensive definition of Thornton's management objectives and water quality information needs could have been accomplished.

Potential Information System:

An expanded definition of the CLP basin watershed and a thorough documentation of its characteristics enables more precise definition of water quality management objectives and information needs. The comments below illustrate the form of the comprehensive CLP watershed documentation that the Framework is calling for. More exhaustive analyses in each category are possible, and they would be outlined in the performance evaluation plan. The more detailed the knowledge documented in each of these categories, the less likely that important information needs will be overlooked.

- *Geographic and Hydrologic Boundaries:*

  The basin encompasses approximately 500 square miles in Larimer and Weld counties. It extends from the mouth of the Cache La Poudre Canyon on the west to the confluence of the Cache La Poudre and South Platte Rivers on the east and is primarily defined by the members and distribution system of WSSC.
- *Hydrologic Inputs and Outputs:*

  Cache La Poudre River water enters the system at the Larimer County Canal headgate and is (will be) returned downstream. The Cache La Poudre discharges into the South Platte River east of Greeley. Precipitation is a negligible contributor, as are

transfers from adjacent water supply systems or groundwater sources.

- *Waterbodies and Watercourses of Significance:*

  Major waterbodies include the Cache La Poudre River, the Larimer County Canal and Pierce Lateral, WSSC reservoirs (7 major, several minor), and the South Platte River.

- *Organizational, Political and Jurisdictional Entities:*

  The principal jurisdictions represented in the watershed are: (1) the Federal Government, (2) the State of Colorado, (3) Larimer County, (4) the City of Fort Collins, (5) Weld County, (6) the City of Windsor, and (7) the City of Greeley. Non-municipal water supply organizations include Water Supply and Storage Company and the Northern Colorado Water Conservancy District. Farms and ranches, urban settlement, rural settlement, manufacturing industry, extractive industry, and general commercial development characterize human activity in the region. National Forest and National Grassland adjoin the watershed but are not impacted by watershed management activities.

- *Legislative, Regulatory and Legal Influences:*

  Federal influence on basin water quality management emanates from the dictates of the Clean Water Act, the Safe Drinking Water Act and their enabling regulations. Colorado statutes and Colorado

Department of Health regulations extend the mandate of the federal statutes. In addition, the relevant principles of Colorado water law (e.g., the prior appropriation doctrine), Water Court rulings, and the administrative processes of the State Engineer must be documented.

From a general legal standpoint, the contractual obligations imposed by the water rights purchase agreement must be met.

* *Timeframe(s) Applicable to this Analysis:*

The water transfer project will unfold in several stages over the next 40 years (Hotto, 1992). Water quality information needs will change as the project evolves, as follows:

(1) Adjudication of water rights and water transfer agreements in Colorado Water Court (1989-1993)
(2) Waiting period (1993-2000)
(3) Initial facilities construction and water transfers (2000-2028)
(4) Additional facilities construction and increased water transfers (2026-2034)
(5) Final facilities construction and increased water transfers (2034-2036)

* *Watershed History and Status:*

The watershed is in a semi-arid zone where annual irrigated agriculture consumes the major proportion of *the water supplied. Agricultural and urban users have been readily accommodated due to judicious acquisition of existing water rights (e.g., by the City of Fort Collins) and the development of supplies in past decades (e.g., the Colorado-Big Thompson Project). Water distribution is governed by the prior appropriation doctrine of Colorado water law, administered by the State Engineer, and executed by the Northern Colorado Water Conservancy District, WSSC and other water supply companies in the region.*

Recent decades have witnessed significant population growth and a marked demographic shift from a rural/agricultural to urban orientation in the watershed. Urban growth, coupled with decreasing public enthusiasm for traditional water development (intensified by federal funding restrictions), has led to severe constraints on the ability of municipalities to secure water supplies adequate to meet projected needs. As a result, conservation measures have received a great deal of attention, as well as more innovative strategies such as the purchase of existing water rights in remote basins. The legal and practical ramifications of trans-basin diversion are currently being debated in Colorado Water Court and in the court of public opinion. Significant opposition to Thornton's proposed water transfer has emerged, mainly *rooted in the fear of loss of local control over development in the CLP basin.*

Part B: Water Quality Management System Description

Figure 4-3 indicates the position of water quality management description activities within the Framework.

Original Monitoring Program:

The original CLP basin monitoring program was not established as part of an integrated water quality management system. Thornton's major objective was to satisfy the terms of the water rights purchase agreement. The purposes of the original program were to confirm basin water as suitable for municipal use and to certify that water transfer and return would cause no adverse impact on other basin users (Hotto, 1992). Specific water quality information needs based upon stated or implied management objectives were not formally identified; either for Thornton or any other watershed stakeholder.

Some water quality staff personnel assigned to manage and operate the original program did not participate in its specification and design, contributing, in part, to subsequent discontinuities in program operations.

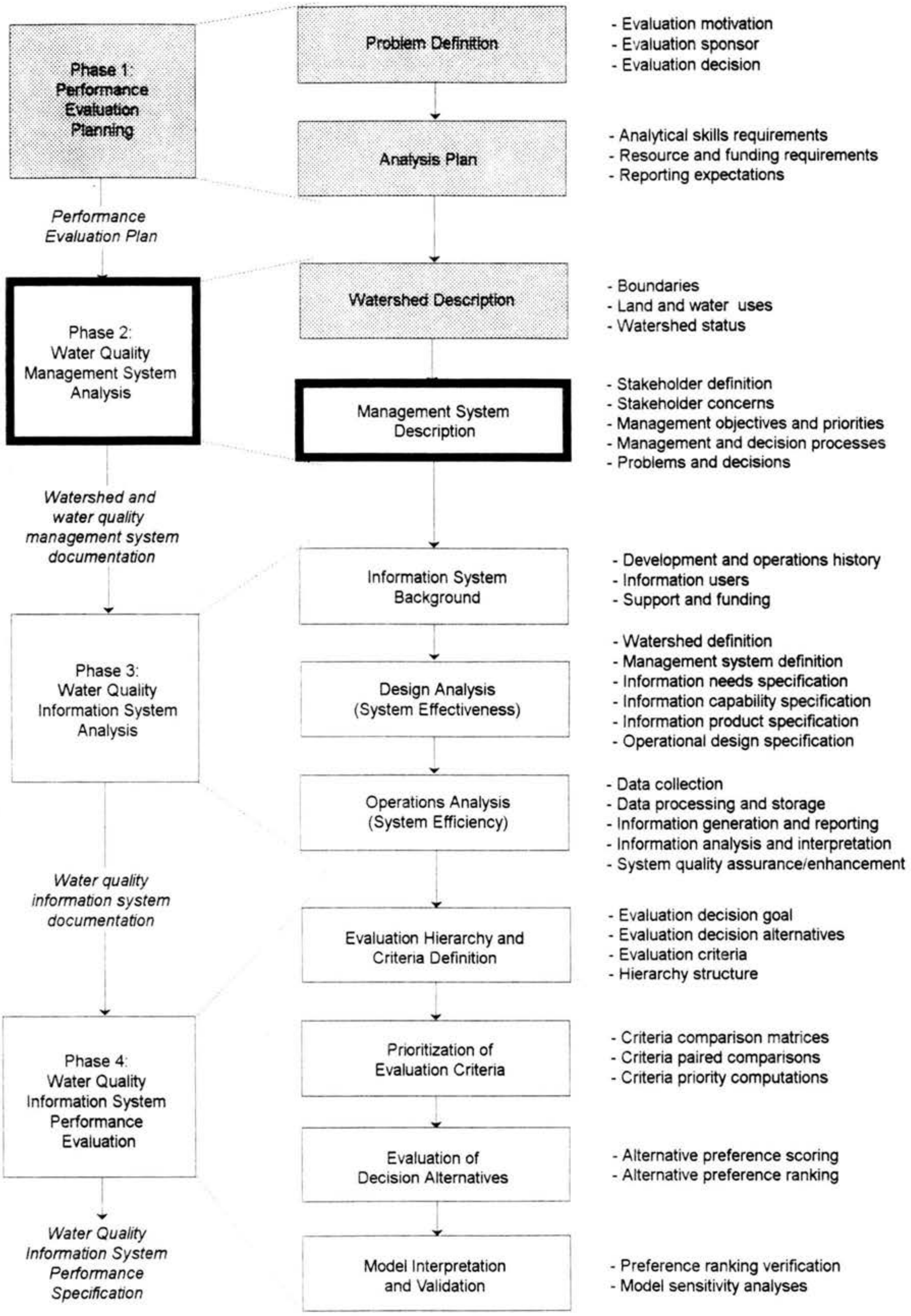

Figure 4-3: Framework Phase 2 - Management System Description

Enhanced Monitoring Program:

At the time of Thornton's decision to enhance its CLP basin monitoring program, several northern Colorado municipalities and organizations had identified themselves as stakeholders and associates (e.g., as "objectors" in the ensuing litigation [Knight-Sinner, 1990]) where no such perception previously existed with respect to this watershed. Also, Thornton's water transfer facilities planning process and the anticipated water rights adjudication had begun to come into focus, giving rise to water quality information needs on the part of the managers and their technical and legal consultants.

In the first phase of the enhanced program design, questionnaires and follow-up interviews with water quality managers were employed to identify Thornton's water quality goals. Responses were summarized, documented and shared with all participants. The water quality management objectives identified were quite general:

* *Provide high quality water in sufficient quantity.*

* *Minimize the cost of providing water.*

* *Meet purchase agreement obligations; i.e., satisfy CLP basin return water requirements.*

* *Limit liability exposure.*

* *Meet all regulatory requirements.*

Beyond soliciting Thornton's general water quality management objectives, the enhanced program designers produced no detailed documentation of stakeholder water quality management concerns, or water quality information needs. As indicated in the next section, a more probing analysis could have revealed specific concerns for which mitigating information could have been produced, possibly useful in relieving external stakeholder's anxieties or bolstering Thornton's adjudication arguments.

Potential Information System:

The following comments describe the information which could have been revealed if the management analysis questions embodied in the Framework had been applied. As in defining the watershed itself, the more detailed the description of management systems in the watershed, the more complete and accurate the identification of water quality information needs will be.

*   *Watershed Stakeholder Information*

The major stakeholders are: (1) the City of Thornton, (2) Water Supply and Storage Company, (3) City of Fort Collins, (4) Northern Colorado Water Conservancy District, and (5) Weld County. Other parties expressing interest included: (1) Platte River Power Authority, (2) Cache La Poudre Water Users Association, (3) Fort Morgan Reservoir and Irrigation Company, and (4) Jackson Lake Reservoir and

Irrigation Company (Knight-Sinner, 1990; Associated Press 1990). An analysis to document the relationships among these stakeholders, identify their common and unique watershed concerns, and prioritize those concerns is required to compile a complete definition of Thornton's watershed information needs. Information on watershed stakeholder's concerns could be gathered by several methods and from several sources, including (1) review of public information by or about the stakeholders, e.g., histories or news accounts, (2) interviews or surveys of stakeholders, and (3) analyses of stakeholder concerns revealed in adjudication processes.

* *Contemporary Watershed Management and Information Systems*

No contemporary water quality management systems which focus upon the defined CLP basin are known. Some water quality data from the watershed may be collected under federal (e.g., U.S. Environmental Protection Agency or U.S. Geological Survey) or state (e.g., Colorado Water Quality Control Division) programs, but not as a part of a unified water quality management program. The relatively recent definition of this watershed (by the water rights transaction and the objectors' interest) make it unlikely that stakeholders have generated data or information related to its water quality management objectives.

- *Water Quality Management System Definition:*

Thornton's CLP basin water quality management process exhibits behaviors and activities which can impede effectiveness and efficiency of a potential water quality information system.

Managers and Management Process:

CLP basin water quality management is the shared responsibility of Thornton's Water Quality staff and Water Resources staff. Water quality personnel are responsible for operating the monitoring program, while water resources people are responsible for developing and delivering CLP basin water, and using water quality information to predict the facilities implications of water quality conditions (Hotto, 1992). CLP basin management and water quality monitoring are new activities to both organizations, raising the potential for loss of program control and continuity due to ambiguous lines of authority and responsibility.

Support and Funding:

Water development and water quality management efforts are funded solely by the City of Thornton. Resources are limited and water quality management efforts severely constrained. Funding and resource requirements dictated by the management and information needs outlined above must be accurately compiled.

Management Capabilities:

Thornton's water quality managers and staff have limited experience in the design and operation of water quality information systems. Management skills and practices of other disciplines may be beneficially employed in the operation of Thornton's CLP basin water quality management and information systems. Training and consultation assistance are required in the areas of: (1) sample collection, (2) data processing and storage, (3) information creation and interpretation, and (4) system quality assurance.

PHASE 3: WATER QUALITY INFORMATION SYSTEM ANALYSIS

Part A: Information System Background

Figure 4-4 indicates the transition to Phase 3 of the Framework and the activities involved in documenting information system background factors.

In order to perceptively assess the performance of a water quality information program, a solid understanding of its history is essential. The purpose of this section of the Framework is to assure that the evaluator documents important system factors which may not be addressed in the subsequent design and operations analyses. When using the Framework to design a new system or to predict the performance of a proposed system, some of these background considerations may not be relevant. Such is the nature of

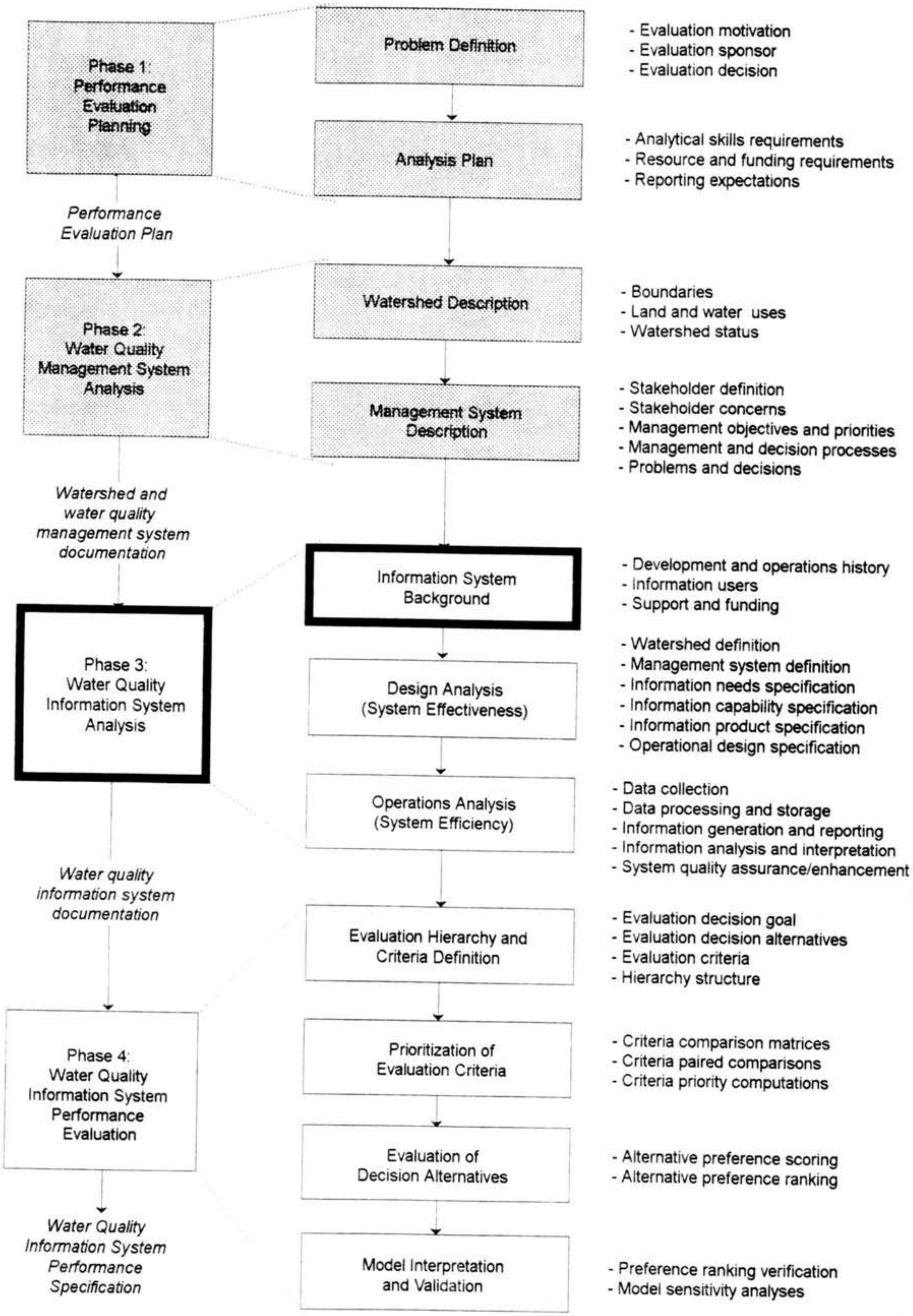

Figure 4-4: Framework Phase 3 - Information System Background

the alternatives addressed in this case study, and those situations will be identified.

Original Monitoring Program:

The original monitoring program was developed in 1986-1987 to fulfill the terms of the CLP basin water rights purchase agreement. The program had no formal title; data sheets were titled "Thornton North Project Water Quality Data". The program was funded entirely by the City of Thornton.

The designers of the original monitoring program were water resource engineers and water quality analysis specialists (Hotto, 1992). The program was designed based upon constituents and standards outlined in the water rights purchase agreement. Water quality data are filed at the Water Quality Division and transmitted periodically to WSSC's engineering consultants. Several minor program modifications have occurred as result of consultation with Water Supply and Storage Company and its advisors. Since the original program's implementation, a number of significant events have occurred:

- *Management concerns and water quality information needs have expanded, including:*
    - *(1) engineering information needs (to locate and design water transfer and treatment facilities), and*

(2) adjudication information needs (in terms of content and distribution control).

- *Repeated changes in key personnel and assignments have occurred.*
- *Program scope has expanded, including additional surface water sampling locations and a new groundwater monitoring program. These expansions in scope were undertaken without application of significant new resources to the program.*
- *Program procedures have been modified, including sample collection methods, on-site analysis techniques, data recording and storage methods, spreadsheet formats, and computational methods.*
- *Costs have escalated significantly, especially expenses for outside laboratory analyses.*

No comprehensive documentation of the design or operational history of Thornton's original water quality monitoring program was found. At the time of the enhancement investigation, records related to the implementation and subsequent modifications of the original program were located in several City of Thornton files.

Enhanced Monitoring Program:

The enhanced monitoring program was formally designated as the "Thornton Northern Project Water Quality Monitoring and Information System". This redesign of the original program was prompted by escalating system costs, questions about the system's usefulness, and questions on the relevance of the data produced, all prompted by the changes in the original program's environment as listed above (Hotto, 1992). The study leading to the recommendations constituting the enhanced program was championed by Thornton's Water Quality Division manager and funded entirely by the City of Thornton. The enhanced program information users are Thornton's water resource and water quality organizations and their consultants.

Formal information system and database management system design processes were not employed in developing the enhanced monitoring program. The design history of the enhanced monitoring program is documented in the systems analysts' design report to the City of Thornton (Hotto and Sanders, 1991). Since Thornton did not immediately adopt all of the recommendations embodied in the enhanced program design, feedback on its operational impact is incomplete.

Potential Information System:

The potential information system is defined as that attainable through rigorous and comprehensive application of all Framework steps. For the demonstration purposes of this case study, all relevant information system background and history are documented, including:

- *the designer of the system (skills and experience)*
- *the design methodology applied*
- *comprehensive documentation of system design and operations*
- *information users*
- *sources of support and funding*

Part B: Information System Design Analysis

Figure 4-5 indicates the position of the information system design analysis within the overall Framework.

A basic premise underlying the Framework is that a water quality information system's performance must be evaluated with respect to the watershed it purports to describe and the management system it supports. Accordingly, Phase 2 of the Framework encourages the evaluator to "back up" and make sure those two systems are well understood by the evaluator prior to information system evaluation. Then, here in Phase 3, where the information system's actual design process is scrutinized (or compared), "Watershed Description" and "Water Quality Management System Description" become system effectiveness criteria, and the evaluator determines how well these activities were carried out as a part of this system's design process. Due to the demonstrative and retrospective nature of this case study, the description of these activities in the two Framework phases is quite similar and may appear somewhat redundant.

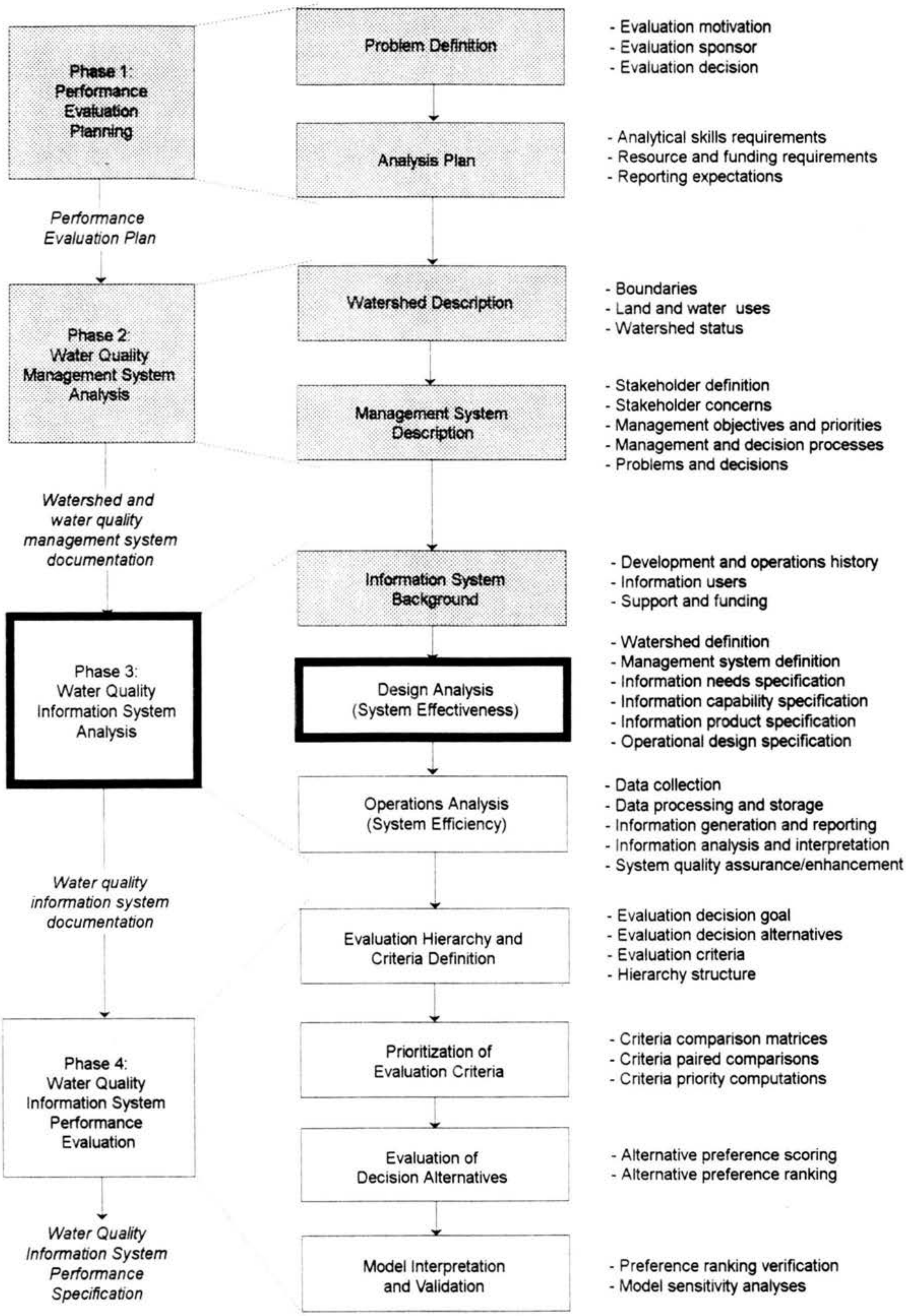

Figure 4-5: Framework Phase 3 - Information System Design Analysis

The reader is also alerted to a second area of potential confusion in applying this part of the Framework. The final step of Information System Design Analysis examines how the knowledge gained in watershed, management system, and information needs assessments is used to design the operational characteristics of the information system. It seeks to describe how each operation of the information system (i.e., data collection through information utilization) is specified to support management objectives and satisfy the information needs described, a measure of system effectiveness. A subsequent analysis looks at how efficiently each of these same operations is carried out. Although these effectiveness and efficiency analyses are described under the same operational headings, their aims are distinct.

Original Monitoring Program:

- *Watershed Definition and Documentation*

  The watershed's boundaries, limitations and history were generally understood by all those associated with the original program. No integrated documentation of watershed attributes was compiled.

- *Water Quality Management System Definition*

  The original program was designed to meet the monitoring and reporting requirements set out in the water rights purchase agreement. To a limited extent, *the monitoring program also evolved to serve the needs of the water transfer system designers and Thornton's legal advisors. No formal water quality management system was defined as a basis for the original program.*

- *Water Quality Management Information Needs Specification*

  The water quality information needs of Water Supply and Storage Company were implied by the standards and variables set forth in the purchase agreement. At a later date, the company's consultant requested several specific statistical tests and reporting formats, as well as documentation of the monitoring program's quality assurance plan.

- *Water Quality Information Needs Selection*

  At the time of the original monitoring program design, only two information users were recognized: Water Supply and Storage Company, and the City of Thornton. No other potential users were identified, nor were information needs forecasted beyond those set out in the purchase agreement.

- *Water Quality Information Capability Assessment*

  No information capability assessment was carried out in association with the original monitoring program design. The monitoring program was required to produce water quality variable data only.

- *Water Quality Information System Product Specification*

  The frequency and format of water quality data reporting to Water Supply and Storage Company was loosely specified. Thornton provided water quality data in tabular format, without interpretation.

- *Database Requirements Specification*

  Water quality data were entered into personal computer spreadsheets designed by Thornton water quality staff and consultants. A new data spreadsheet was created for each sampling date (sample collection trip). No database design specifications were documented, nor where data screening and data handling procedures set forth.

- *Water Quality Information System Operational Design*

  Water quality variables, sampling frequency and sampling locations in the original program where established by Thornton water quality managers and consultants and agreed to by WSSC. Sampling and laboratory procedures were devised by Thornton water quality staff, based upon standard methods and quality assurance practices. Similar standards were set for contracted laboratory services.

Enhanced Monitoring Program:

- *Watershed Definition and Documentation:*

  Although no single document of watershed attributes was compiled in the design of the enhanced program, watershed definition was significantly improved through:

  (1) redefinition of the watershed's hydrologic boundaries (e.g., the system input location),
  (2) specification of waterbody significance (from water transfer system design decisions), and
  (3) specification of timeframes of significance (i.e., water transfer milestones).

  Broader watershed status questions were not addressed, as indicated in the earlier (Phase 2) discussion.

- *Water Quality Management System Description*

  The enhanced program design embodied an indirect management system description. The documentation of Thornton's water quality management objectives and general information needs (as described below) revealed an emerging awareness on the part of Thornton's water quality managers of the broader uses of water quality monitoring data (Hotto and Sanders, 1991). Also, the recognition of information needs for transfer system design and adjudication indicated a perception of the larger water quality management structure to be defined and served.

- *Water Quality Management Information Needs Specification*

Questionnaires and interviews solicited information needs relative to Thornton's water quality goals. Responses and follow-up interviews were documented and shared with participants. Water quality information goals and needs identified by Thornton managers and staff included (Hotto and Sanders, 1991):

(1) Information useful for managerial decisions; i.e., statistics and analyses in addition to raw data

(2) Information helpful in water rights adjudication and litigation

(3) Information useful as input to other water quality models

(4) Easily accessible data and information

(5) Sound and defensible data collection and information generation processes (from both the scientific and legal viewpoints)

(6) Economical data collection and analysis, accomplished without loss of significant information

(7) Characterization of CLP basin water quality, to allow its evaluation as a municipal supply

(8) Ability to detect changes or trends in CLP basin water quality variables

(9) Ability to gauge the impact of water transfers on CLP basin groundwater quality

- *Water Quality Information User and Needs Selection*

  The ranking of users and information needs was accomplished only implicitly in the enhanced program design. A comprehensive analysis of other watershed stakeholders and concerns was not undertaken; thus an extensive list of information users and needs to be ranked was not established, nor were ranking criteria or processes devised. Also, Thornton's own water quality information needs were not adequately ranked for the purposes of program evaluation and redesign.

- *Water Quality Information Capability Assessment*

  Many recommendations were outlined to correct impediments to reliable data production and to provide basic water quality information on a regular basis (See the operational design discussion below). The costs and benefits of adopting these recommendations (both qualitative and quantitative) were projected, as well as the impact on the activities of the information system's operators (Hotto and Sanders, 1991). However, the analysts did not specify the additional capabilities necessary to address Thornton's broadly expressed water quality information needs.

- *Water Quality Information System Product Specification* *Information products were not specified directly in the design of the enhanced program. Graphical and tabular representations used to present original program data may be refined and continue to meet management information needs. Specific recommendations included: (1) an improved data spreadsheet design, (2) time series and statistical analyses of the data, and (3) routine analysis, reporting, and documentation of the water quality information, whatever its form.*
- *Water Quality Information System Operational Design* *An operational review of the original monitoring program was conducted, employing questionnaires, follow-up interviews and direct observation of sample collection, handling and testing procedures. Also, the original program's water quality data set was examined, including:*
  - *(1) a survey of data collection tools and methodologies,*
  - *(2) an evaluation of data screening and conversion procedures,*
  - *(3) preliminary statistical characterizations (e.g., means, trends, and variability), and*
  - *(4) follow-up statistical analyses (i.e., correlation and regression analyses) where necessary.*

Interim reports summarizing critical operational issues and presenting preliminary findings on water quality variable behavior were published and presented.

<u>Data Collection:</u>

(1) Water Quality Variables

Each of 55 original program variables was reviewed relative to Thornton's water quality goals and with respect to human health, agricultural, regulatory, and facilities design criteria. The review revealed that 17 variables contributed no information relative to these criteria and recommended that their measurement be discontinued. Also, two new variables related to human health were recommended for incorporation into the system.

(2) Sampling Location

The analysis indicated that water transfer facilities decisions had rendered 4 of 27 surface water locations irrelevant and that the information provided at a fifth location was redundant. It was recommended that those locations be eliminated. One location substitution was recommended to improve watershed input water quality information.

(3) Sampling Frequency

Sampling frequency, originally specified as weekly, bi-weekly, monthly or quarterly, had become *irregular, principally due to personnel turnover and resource constraints.*

Observed variable behavior indicated that information needs would remain satisfied if fewer variables were measured on each sampling excursion (i.e., sampling trip to the watershed). Also, it was recommended that locations be sampled on alternate excursions.

(4) Sampling Strategy and Procedure

To achieve a continuous watershed-wide information perspective, it was recommended that all watercourse types (river, ditch or reservoir) be included in each sampling trip. To assure independence of water quality variable measurements, it was recommended that all samples be taken in a downstream to upstream pattern. Also, to reduce program-induced variability, it was recommended that: (1) additional sampling planning and preparation tasks be observed, (2) a feedback-directed, self-modifying sampling procedure be adopted, and (3) adherence to documented operational and quality assurance practices be enforced (Hotto and Sanders, 1991).

<u>Data Handling and Storage Specification:</u>

In the original monitoring program, field and laboratory measurements for each sampling excursion date were consolidated by a water quality project *engineer and then entered into personal computer spreadsheets. The time- (i.e., date-) oriented database consisted of over 80 spreadsheets. Personnel and resource constraints caused data consolidation and data entry to be inconsistent, irregular and prone to error. Also, the sampling-date spreadsheets proved inconvenient when attempting to assess water quality behavior over time at any sampling location. To rectify these problems the enhanced design included:*

1. *procedures to standardize field sampling and measurement,*
2. *uniform field and laboratory data collection forms,*
3. *procedures to assure timely review of field and laboratory data collection forms,*
4. *consistent and direct data entry, and*
5. *location-oriented spreadsheets; to expedite data screening, to reduce data and transcription errors, and to facilitate the generation of variable behavior information over time at each sampling location*

Information Generation and Reporting Specification:

With respect to data analysis, the enhanced program recommended that "concern" and "immediate action" levels be established for each water quality variable, with clearly documented and predetermined *responses to foster routine comparisons and timely response. Also, Thornton's water quality staff was encouraged to routinely update and examine each variable's time series, and to continually reassess correlation relationships established among variables and/or locations.*

Regarding information generation and reporting, the enhanced program recommended:

(1) immediate modification of sampling schedules when dictated by the data analyses,

(2) immediate verification and notification when variable measurements exceed predetermined concern or action levels,

(3) periodic (e.g., quarterly) watershed status reports and discussions,

(4) periodic (e.g., yearly) across-the-board information system updates; to review water quality statistics at each location, and to modify variables, locations, action levels, procedures, etc., as appropriate.

Information Analysis and Interpretation Specification:

The enhanced program design did not provide recommendations for more extended analysis and interpretation of CLP basin water quality information.

System Quality Assurance and System Enhancement:

In the original monitoring program, quality assurance and quality control were associated with laboratory operations only. Quality assurance activities in other program operations were not specified.

The enhanced program promotes system quality in each operation through standardizing and documenting procedures as noted above. Periodic status reviews and information system updates will also improve system quality on a continuing basis. Sampling planning and preparation, a feedback-directed, self-modifying sampling procedure, and documented operational quality control practices all contribute to reduce total system variability.

Potential Information System:

Application of the effectiveness criteria suggested by the Framework impacts the design of the potential information system as follows:

- *Watershed definition - All water quality-relevant characteristics of the CLP watershed are defined (e.g., land and water uses, time and space boundaries, etc., as outlined in the earlier Phase 2 discussion).*
- *Management system definition - All watershed stakeholders are identified and their watershed*

concerns documented. All management and decision processes affecting the watershed are documented. Water quality management objectives and decisions to be supported by this information system are specified.

- *Information capability specification - Water quality management and decision requirements are translated into a prioritized set of water quality information needs.*
- *Information product specification - The form, format and timing of the reports required to meet each prioritized information need is specified.*
- *Operations design specification - The operations necessary to produce useful and trustworthy information include:*
    - *data collection and storage procedures specified using database management system (DBMS) principles*
    - *information reporting targeted to rigorously scrutinized information needs*
    - *routine information analyses and interpretation; promoting continuous system review and controlled system modification*

Part C: Information System Operations Analysis

Information system improvements such as those noted in the previous section often offer the potential to improve a monitoring program's efficiency as well as its effectiveness. The Framework documents efficiency improvement opportunities in each category of system operation observed. Efficiency improvements are recognized as resulting in: (1) cost savings (in all categories), (2) information sufficiency, (3) system convenience and flexibility, (4) system understandability, and (5) information trustworthiness (i.e., accuracy and reliability). Figure 4-6 locates this analysis within the Framework.

Original Monitoring Program:

Efficiency of operations was not considered in the design or execution of the original monitoring program.

Enhanced Monitoring Program:

* *Data Collection*

The number of variables routinely measured to provide sufficient water quality information was reduced by 30%; allowing significant savings, particularly in laboratory testing expense. Also, the enhanced program design identified several variables eligible to be estimated rather than measured routinely (based upon observed correlation relationships), also reducing field sampling and laboratory costs.

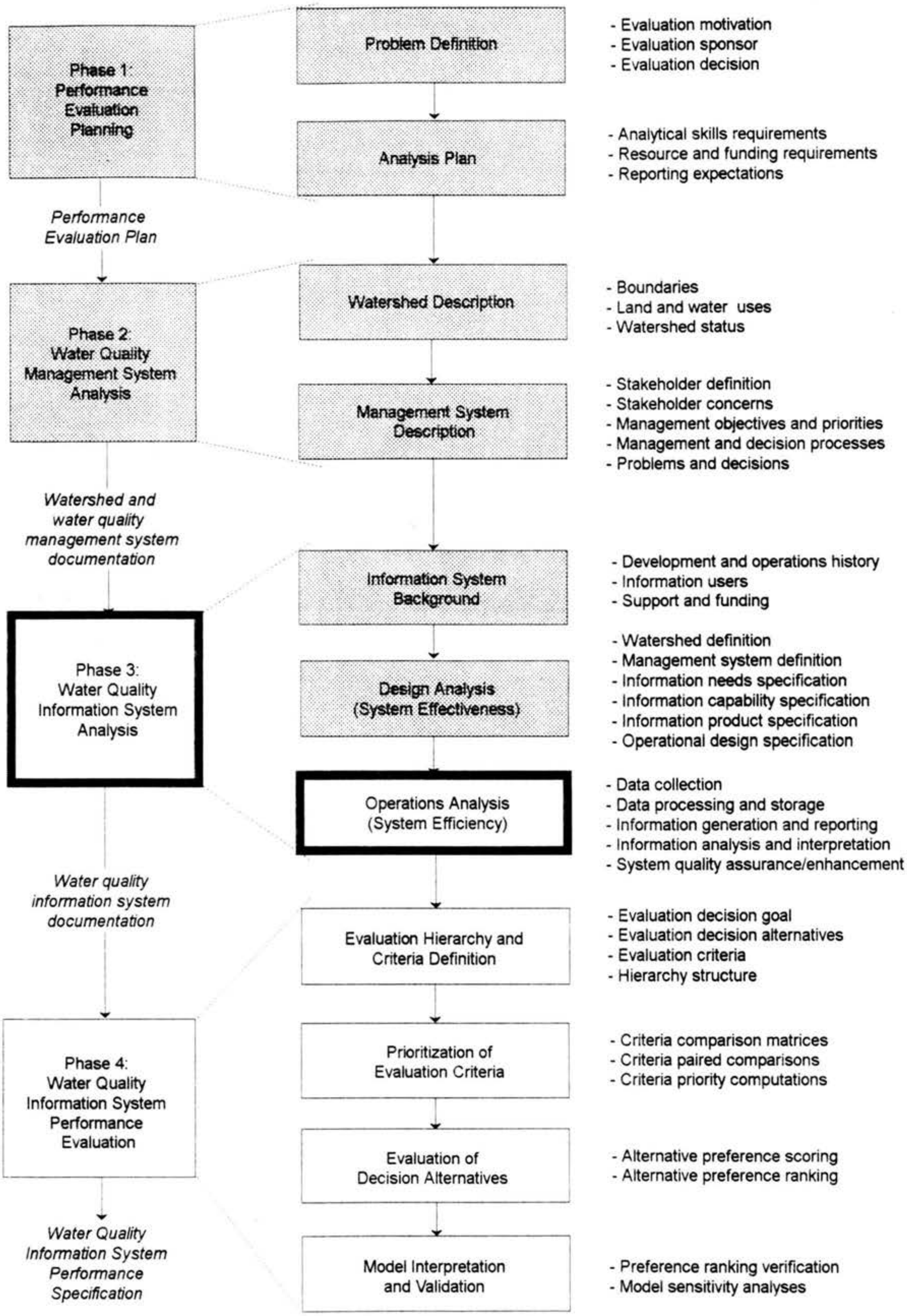

Figure 4-6: Framework Phase 3 - Information System Operations Analysis

The recommended 20% reduction in locations to be sampled was expected to result in directly proportional cost reduction throughout the system; e.g., in sampling labor, sampling equipment and supplies, field and laboratory analyses, and data entry and storage.

The reduction in sampling frequency due to all recommended sampling modifications would result in a 50 percent reduction in sample measurement.

The enhanced program incorporates sampling planning and preparation procedures, improved documentation and communication of sampling schedules, and a rationalization of sample routing; all expected to contribute to more balanced and predictable sampling and laboratory workloads. Recommended feedback-modified sampling procedures, coupled with more rigorous operational quality assurance practices, were predicted to: (1) reduce total system variability, (2) detect water quality problems earlier, and (3) promote earlier and cheaper problem solutions.

The uniform field sampling and laboratory data collection forms provided in the enhanced program will expedite resolution of data quality questions and enhance operating efficiency by providing consistent written guidance. Also, the "turn-around" time of reporting laboratory results will be significantly reduced.

- *Data Handling and Storage*

The uniform field sampling and laboratory data collection forms also encourage recording of all necessary variable data and all supporting information at the same time, thus expediting data entry, screening and interpretation tasks.

Recommendations for standardized data entry procedures, fewer data transcription steps and direct data entry to spreadsheets will: (1) reduce personnel costs, (2) reduce the probability of transcription errors, and (3) put data into a useful format more rapidly. Data storage in location-oriented spreadsheets will result in more convenient time series and statistical analyses of the data.

- *Information Generation and Reporting*

The recommended data analysis and feedback-initiated response procedures will identify and characterize problems earlier. Also, potential solution approaches can be generated more rapidly, leading to earlier adoption of appropriate sampling and testing modifications.

The recommended documentation of routine data analysis procedures will reduce the productivity losses associated with personnel turnover and will lower training costs.

Routine formal examination of water quality variable time series and correlation relationships will foster more rapid feedback on concerns and expedite corrective reactions (e.g., modification of variables, locations, action levels, procedures, etc.). In short, water quality problems will be detected, addressed and solved in a more timely manner.

* *Information Analysis and Interpretation*

The enhanced program design did not suggest any efficiency improvements with respect to the analysis or interpretation of water quality information

* *System Quality Assurance and Systems Enhancement*

The enhanced program made no integrated recommendations with respect to increasing the efficiency of system quality assurance efforts. The recommendations for standardization, documentation, and operational efficiency, as discussed in each category above, were each recognized as contributing to a reduction in program-induced variability and the production of more useful and trustworthy information for less cost over time.

Potential Information System:

In this case study, efficiency gains in information generation analysis and interpretation are not estimated. Systems operations are designed to be efficiently and *effectively executed. The Framework's management and information system analyses lead to small efficiency gains in:*

- *data collection, handling, and storage - from fewer variables, fewer locations, and reduced sampling frequencies to satisfy information needs*
- *system quality assurance - through improved system-wide documentation and operations review*

SUMMARY

The purposes of the case study are to illustrate the "mechanics" of applying the Framework's assessment and evaluation techniques, and to demonstrate how the Framework, when applied rigorously, can provide insightful analyses upon which beneficial water quality information system design modifications can be identified. In this chapter, the application of Phase 1, Phase 2 and Phase 3 of the Framework to three water quality information programs has been described. Summary observations on the application of those three phases are noted below.

- *Phase 1: Performance Evaluation Planning*

In the context of this case study, "performance evaluation planning" is synonymous with "program design planning". Initial planning of the original monitoring program was limited, particularly in regard to recognizing *resource requirements. The enhanced monitoring program design enjoyed more extensive pre-planning, but failed to recognize a number of management and organizational impediments to program design and implementation. The planning tasks suggested by the Framework would reveal and address potential problems early on, to allow smoother design and implementation of the potential information system.*

- *Phase 2: Watershed and Water Quality Management System Analyses*

No formal watershed or management system analyses were contemplated in the design of Thornton's original monitoring program. Simply put, many ramifications of the water rights purchase and the potential complexity of their resolution were not anticipated at that time.

In the effort to transform the original monitoring program into an enhanced monitoring and information program, these analyses were carried out in a more competent fashion, yet still to a limited degree. The enhanced program design process was successful in urging Thornton's water quality managers to identify municipal and organizational water quality management goals and information objectives, thus allowing a number of important design modifications to be identified. However, the lack of a thorough watershed review and a limited analysis of other stakeholders and *management systems resulted in poor anticipation of some information needs. As an example, had the watershed and management systems analyses suggested by the Framework been applied and documented more rigorously, it is likely that the larger group of water transfer objectors would have been identified and their concerns documented. Thus, the potential information system could have been designed to respond to the information needs arising from anticipated objector arguments or of the judicial process dealing with them.*

Also, the documentation of watershed and management systems afforded by the Framework would provide the foundation for more orderly modification or extension of the information system to serve changing information needs over the long term. As indicated, Thornton's water transfer project is scheduled to unfold over a period of 40 years, practically guaranteeing many changes, anticipated and otherwise. Information system redesigns to meet future needs will be accomplished more effectively when based upon a solid and continuously updated understanding of watershed conditions and stakeholder concerns.

- *Water Quality Information System Analysis*

Thornton's original monitoring program was designed to provide water quality data called for in the water rights purchase agreement with Water Supply and Storage Company

(WSSC). No watershed or management system analyses were undertaken to establish the foundation for specifying water quality information needs. No information needs (other than raw data) were specified for either WSSC or Thornton. Monitoring system procedures were incompletely documented and many undocumented operations modifications had occurred over the life of the program. Delivery of water quality data was irregular, and its use by WSSC or Thornton was indeterminate.

Prompted by escalating costs, Thornton's water quality managers instituted a study to rationalize the original monitoring program. The set of recommendations developed by the managers and their consultants constituted an enhanced monitoring and information program. Water quality objectives and information needs were documented and numerous design and operational suggestions were recommended to accomplish them. Major emphases in the enhanced program were placed on the consistent use of standardized procedures, and the pre-approval and documentation of all design and operating changes.

Additional benefits could have been gained had all phases of the Framework been rigorously applied. As mentioned above, a comprehensive watershed and water quality management system survey would have identified more information users and more specific information needs. Also, an effective ranking of those needs (or users) could *have been accomplished; in particular, a ranking reflecting the priority deserved by litigation needs. In another example, concise water quality information needs relevant to the decisions locating water transfer withdrawal and return positions could have been identified. The importance of water quality data or information to the transfer location decisions was not established in the original or enhanced programs.*

Consideration of those extended information needs, coupled with a more comprehensive information capability assessment, would have revealed that Thornton's professed information goals and requirements far exceeded the ability of the current or enhanced programs to deliver. This insight could have prompted an earlier and more realistic management appraisal of the resources and funding necessary to accomplish the general objectives and forced the managers to define the specific priority information needs that could reasonably be expected to be satisfied.

Similarly, regarding information product specification, more rigorous definition of the type of information required and to the details of report format and timing would force more direct involvement of the managers, engineers and consulting attorneys in the analysis, and point out crucial training needs (e.g., in statistical analysis).

Had the Framework been more rigorously applied, the analysis of program operations may have proceeded more *efficiently. Explicit prior definition of information needs and realistic information capability assessment would have resulted in a more astute listing of variable, location, and frequency questions to be resolved. Also, knowledge providing a foundation for more insightful observation of sampling, laboratory, and data handling operations would have been established.*

As with any management tool, the potential benefit of applying the Framework depends upon the willingness and ability of water managers to define, interpret and act upon water quality information. Managers must have the knowledge and skills required to describe their management and decision processes, be able to articulate the information required in those processes, and be able to define the actions that will be taken on the basis of the information received. A significant potential benefit of applying the Framework is that the incorporated management system and information system analyses can point out any enhancements in management knowledge and skill that may be necessary to allow an information system to be used to its full potential.

The effectiveness and efficiency insights gained in Phase 2 and Phase 3 of the Framework will allow the water quality manager to define and to prioritize the criteria upon which the overall performance or utility of the monitoring or information program can be evaluated. Phase 4 of the Framework provides a convenient process in which the manager can capture those criteria and apply them towards evaluating and improving program performance. That evaluation process is detailed next in Chapter 5, where the three programs of the case study are compared.

CHAPTER 5

APPLICATION OF THE FRAMEWORK TO A MUNICIPAL MONITORING PROGRAM

Part Two: Evaluation Phase

INTRODUCTION

In this chapter, the final phase of the Framework for Evaluating Water Quality Information System Performance is demonstrated. The case analysis discussed in Chapter 4 is continued and concluded. The performance of three water quality monitoring or information programs, based upon the City of Thornton's water transfer project, are to be evaluated and compared:

* Thornton's original Cache La Poudre River (CLP) basin monitoring program, denoted as the **Original Monitoring Program,**

* the CLP basin water quality monitoring and information program characterized by the recommendations of the improvement investigation, denoted as the **Enhanced Monitoring Program**, and

* the CLP basin water quality information system potentially achievable through comprehensive application of the Framework, denoted as the **Potential Information System.**

In Phase 4 of the Framework, "Water Quality Information System Performance Evaluation", the Analytic Hierarchy Process (AHP) is used to quantify the performances of one or more information systems and to compare those performances for the purposes of making some selection or evaluation decision. In this case, water quality management system and information system knowledge documented in Phases 1, 2, and 3 of the Framework is employed to construct a performance evaluation hierarchy, define and weight performance evaluation criteria, and to score information system alternatives against those criteria.

Figure 5-1 illustrates the Framework and indicates that Phases 1, 2, and 3 have been previously accomplished. The reader is referred to Appendix B of this report for background information on the theory and application of the Analytic Hierarchy Process (AHP). Also, an introductory illustration of the application of the AHP to a water quality information system evaluation can be found in Appendix C. In the following sections, as in Chapter 4, specific discussion of the evaluation of monitoring program alternatives is presented in italic script.

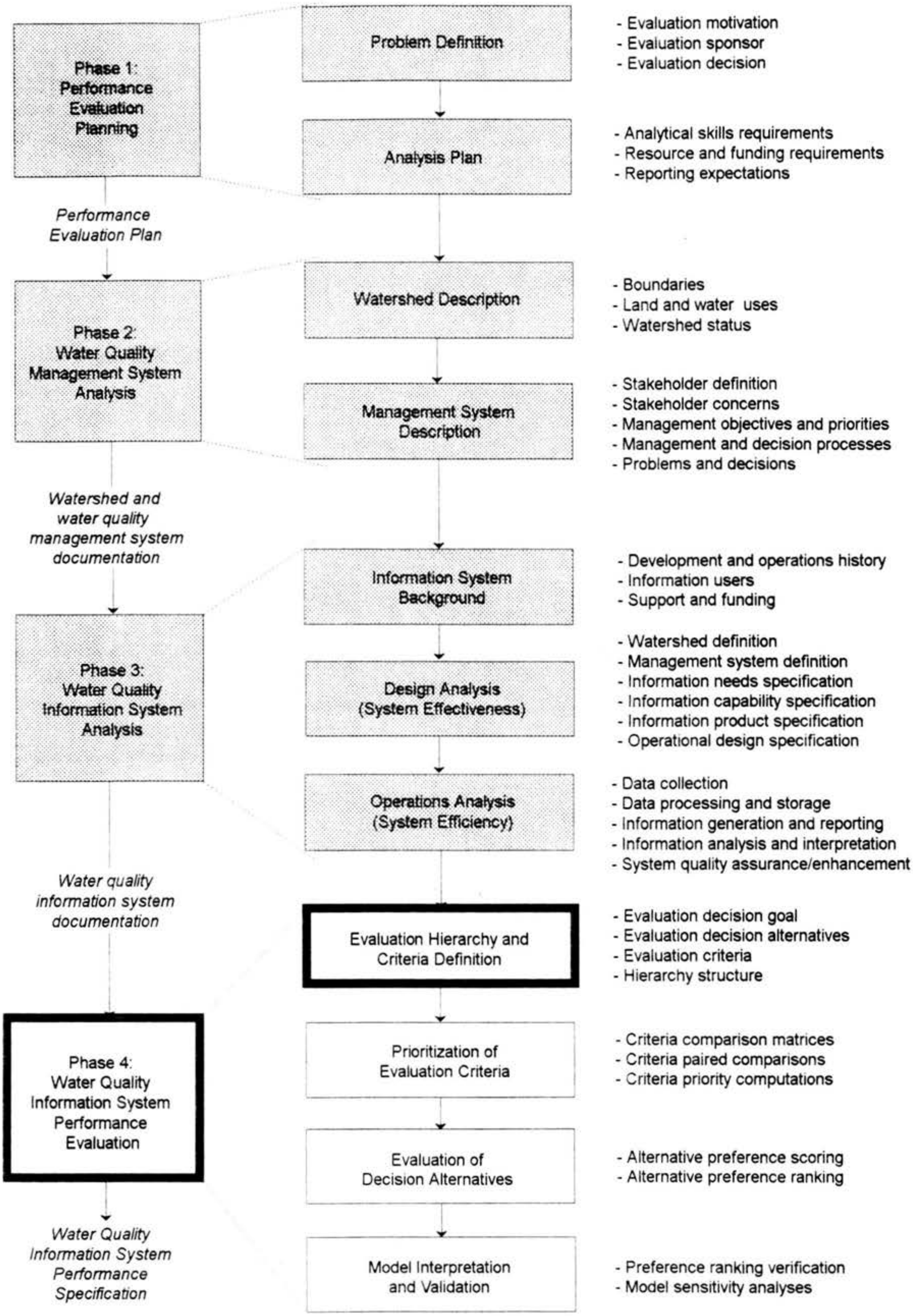

Figure 5-1: Framework Phase 4 - Evaluation Hierarchy and Criteria Definition

APPLICATION OF THE FRAMEWORK (continued from Chapter 4)

PHASE 4: WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION

Part A: Construct Performance Evaluation Hierarchy and Define Performance Evaluation Criteria

* *Hierarchy Level (1): Decision Objective*

In the performance evaluation, Thornton's water quality managers apply knowledge documented in the watershed, water quality management system, and water quality information system investigations to compare three alternatives: (1) the original monitoring program, (2) the enhanced monitoring program, and (3) the potential information system that could have been achieved by rigorously applying the Framework to the design. Thus, the evaluation decision objective could be stated as: "Select the Preferred Water Quality Information System Design Alternative" or "Predict the Potential Advantage of Water Quality Information System Design Alternatives". For this demonstration, the former statement is chosen.

* *Hierarchy Level (2): Primary Decision Criteria*

At the most fundamental level, the comparison of information systems is made on the bases of *effectiveness and efficiency. These primary decision criteria are defined as follows:*

(1) Water Quality Information System Effectiveness (C1)

Is the system designed to satisfy information needs which are derived from water quality management objectives?

(2) Water Quality Information System Efficiency (C2)

Does the system operate to satisfy those information needs in a manner which consumes minimal resources and effort?

* *Hierarchy Level (3):* *Second Level Decision Criteria*

Often, primary decision criteria are not sufficiently detailed to allow the decision maker to clearly or comfortably discriminate among alternatives. In this evaluation, each primary criterion is subdivided into several subcriteria or descriptive attributes. These subcriteria are defined as described in Chapter 4, and it is assumed, for the purposes of this demonstration, that their definitions are adequate to choose among the information system alternatives. If this assumption was not valid, the manager could define the additional subcriteria (hierarchy levels) required to allow the necessary discrimination among the alternatives.

Water Quality Information System Effectiveness (C1) is thus further defined by eight subcriteria:

1. *System Design Process Description (C11)*
2. *Watershed Description (C12)*
3. *Water Quality Management System Definition (C13)*
4. *Water Quality Management Information Needs Specification (C14)*
5. *Water Quality Information Needs Selection (C15)*
6. *Water Quality Information Capability Assessment (C16)*
7. *Water Quality Information System Product Specification (C17)*
8. *Water Quality Information System Operational Design (C18)*

Water Quality Information System Efficiency (C2) is similarly refined into five subcriteria:

1. *Data Collection (C21)*
2. *Data Handling and Storage (C22)*
3. *Information Generation and Reporting (C23)*
4. *Information Analysis and Interpretation (C24)*
5. *System Quality Assurance and System Enhancement (C25)*

- *Hierarchy Level (4):* *Decision Alternatives*

The water quality information systems being evaluated and compared are:

Alternative (1): Thornton's original CLP basin water quality monitoring program (Original Program)

Alternative (2): The enhanced CLP basin water quality monitoring program (Enhanced Program)

Alternative (3): The potential CLP basin water quality information system that could have been designed had the Framework been fully applied (Potential System)

Figure 5-2 illustrates the decision hierarchy constructed to evaluate the water quality information systems alternatives described. Table 5-1 lists the definition of all elements of the decision hierarchy.

Part B: Weight Performance Evaluation Criteria

Decision attributes (i.e., criterion or alternative at the same hierarchy level which share the same "parent" attribute at the next higher level are compared by pairs and ranked (weighted) relative to each other using the "eigenvalue method", a matrix computation (see Appendix D). The comparisons document the evaluator's assessment and assignment of: (1) the relative importance of the lower level criteria in defining a parent criterion (or satisfying

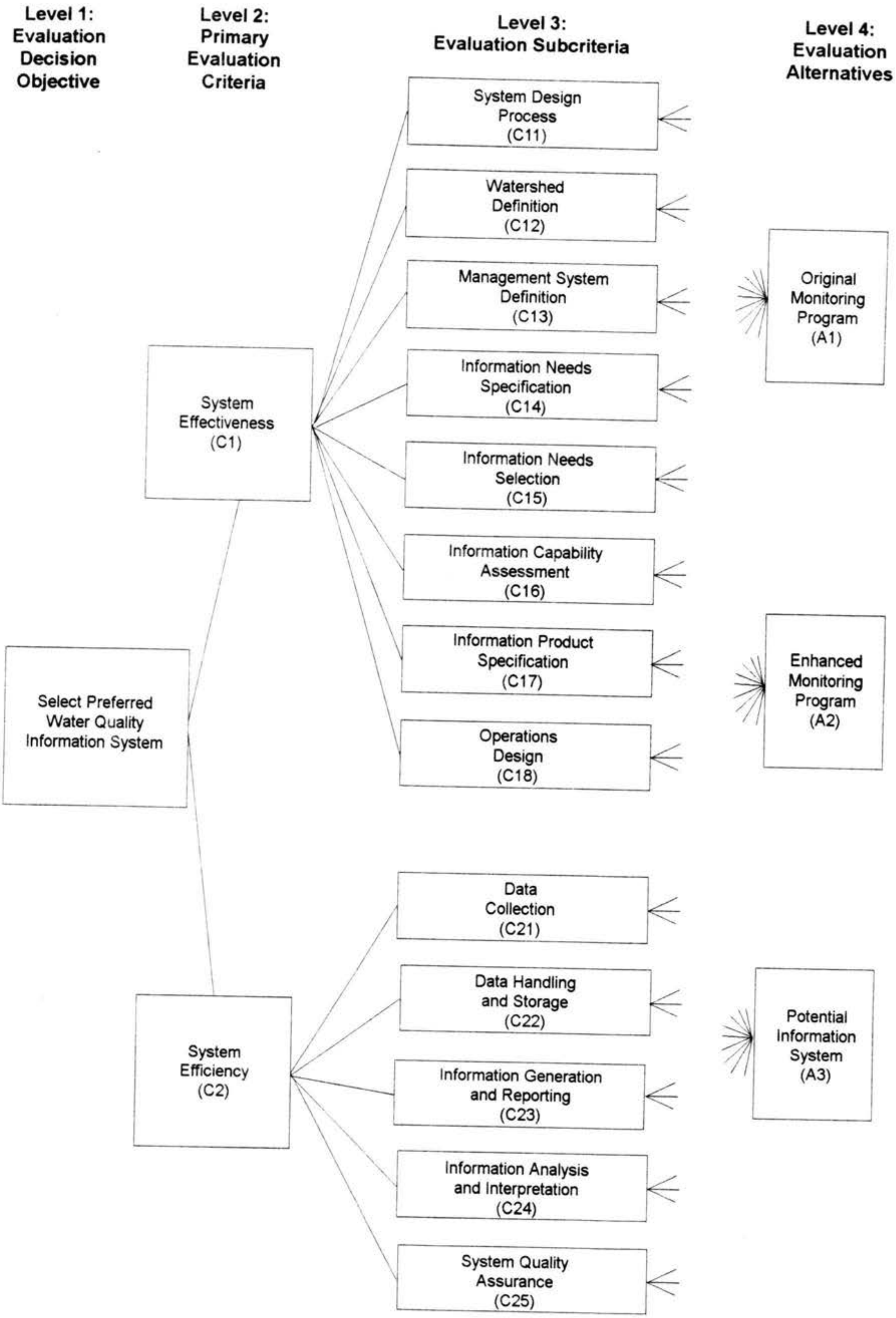

Figure 5-2: Decision Hierarchy for Comparison of Water Quality Information System Alternatives

Table 5-1
Decision Attribute Definitions for Comparison
of Water Quality Information System Alternatives

LEVEL 1 - DECISION OBJECTIVE:

Select the preferred water quality information system (i.e., monitoring program) design from the three alternatives described at Level 4, below.

LEVEL 2 - PRIMARY DECISION CRITERIA:

Water Quality Information System Effectiveness (C1):

The system's designed capability to satisfy information needs derived from water quality management objectives

Water Quality Information System Efficiency (C2):

The system's operating ability to satisfy those information needs using a minimum of resources and effort

LEVEL 3 - SECOND LEVEL DECISION CRITERIA:

Effectiveness Subcriteria:

System Design Process Description (C11):
The organization of the information system's original design process and the capabilities of its designer(s)

Watershed Description and Definition (C12):
The extent to which the underlying physical system is defined and documented as a part of the information system's design process

Water Quality Management System Definition (C13):
The extent to which the management system(s) served by the information system is defined and documented as a part of the system's design process

Water Quality Management Information Needs Specification (C14):
The extent to which management system objectives and decision processes are translated into clearly defined information requirements in the information system design process

Table 5-1, continued

Water Quality Information Needs Selection (C15):
The extent to which information users and their identified needs are prioritized and selected in the system design process

Water Quality Information Capability Assessment (C16):
The extent to which the feasibility of satisfying defined and prioritized information needs is addressed.

Water Quality Information System Product Specification (C17):
The detail and clarity with which the form, format and timing of information to be provided is specified.

Water Quality Information System Operational Design (C18):
The extent to which each system operation's design contributes to (or detracts from) the production of information meeting the specified needs.

Efficiency Subcriteria:

Data Collection (C21):

Data Handling and Storage (C22):

Information Generation and Reporting (C23):

Information Analysis and Interpretation (C24):

System Quality Assurance and System Enhancement (C25):
System efficiency is examined on a systems operations basis. Each operation listed is characterized with respect to its impact on system cost, information timeliness, information sufficiency, system flexibility, and information trustworthiness.

LEVEL 4 - DECISION ALTERNATIVES:

Alternative 1 (A1):
Thornton's original CLP basin water quality monitoring program

Alternative 2 (A2):
The enhanced CLP basin water quality monitoring program

Alternative 3 (A3):
The potential CLP basin water quality information system that could have been designed had the Framework been fully applied

---

its purpose), and (2) the relative satisfaction of (or potential to satisfy) decision criteria by the defined decision alternatives. Evaluator utility with respect to each decision criteria must be defined, comparison questions must be articulated by the evaluator in order to allow accurate and consistent comparisons.

Weighting decision attributes (i.e., criteria or alternatives) means establishing the relative priority of the attributes represented in a pairwise comparison matrix. The values of the elements of the eigenvector computed for each pairwise comparison matrix represent the relative priorities of the associated decision attributes with respect to satisfying the purpose of their parent attribute at the next higher level of the hierarchy.

Potential evaluator inconsistencies in comparing attributes are indicated by a "consistency ratio" (CR). A review of eigenvalue method terminology and mathematics can be found in Appendices D and E.

To illustrate, a comparison of Primary Criteria with respect to the Decision Goal is conducted as described in the following steps:

- *Identify the attributes to be compared: Primary (level 2) decision criteria are to be compared, namely:*
  - *(1) Water Quality Information System Effectiveness (C1)*
  - *(2) Water Quality Information System Efficiency (C2)*

- *Articulate the comparison question:*

  Is effectiveness (C1) or efficiency (C2) more important in selecting a preferred water quality information system alternative (i.e., satisfying the decision goal)?

- *Define the utility of decision attributes:*

  C1: Higher effectiveness is preferable; i.e., the more information objectives and needs satisfied (or objectives and needs more satisfied), the better.

  C2: Higher efficiency is preferable; i.e., the fewer resources employed to produce a satisfactory information product, the better.

- *Define the basis of comparison:*

  This comparison entails a qualitative or subjective judgment of relative importance; reflecting either the evaluator's opinion or some group consensus. The measure of relative importance is represented as 1,3,5,7, or 9; as defined by Saaty's importance intensity scale (see Appendix B-2).

- *Construct and evaluate the pairwise comparison matrix:*

  Specify each row attribute's importance relative to each column attribute's importance in satisfying the intent of the parent attribute, as follows:

Decision Goal: Select the best water quality information system alternative		*C1*	*C2*	*Weight*
Effectiveness	*C1*	*1*	*5*	*0.833*
Efficiency	*C2*	*1/5*	*1*	*0.167*

CR = 0.00

The evaluator has indicated that effectiveness is "strongly" (indicated by 5 on the importance intensity scale) more important than efficiency in evaluating or selecting a water quality information system alternative. Note that attributes are "equally important" to themselves; hence comparison matrices always display values of 1.0 on the diagonal. Also, logical consistency dictates that reverse comparisons exhibit reciprocal scores; i.e., if C1/C2 = 5.00, then C2/C1 = 1/5 = 0.20.

The eigenvalue computation has produced the normalized attribute weights (or preference scores) indicated in the right hand column. The weights indicate the proportion of total (1.00 or 100%) preference assigned to each attribute being compared. Note that the sum of attribute weights may not be exactly 1.000, due to rounding errors. The consistency ratio of 0.00 indicates that paired comparison ratios *among all elements in the matrix are sufficiently (and, in this example, absolutely) arithmetically consistent.*

A second example, from Level 3 of the hierarchy, illustrates the assessment of the relative importance of all of the subcriteria which define the primary criterion "Efficiency".

- *Attributes to be Compared: Level 3 decision subcriteria are to be compared, namely:*
  - *(1) Data Collection Efficiency (C21)*
  - *(2) Data Handling and Storage Efficiency (C22)*
  - *(3) Information Generation Efficiency (C23)*
  - *(4) Information Analysis Efficiency (C24)*
  - *(5) System Quality Assurance Efficiency (C25)*
- *Comparison Question:*
  Is efficiency (or efficiency improvement) achieved within the data collection operation (C21) more important than that achieved within the data storage and handling operation (C22)? The same question is asked of all ten possible subcriteria pairings.
- *Utility Definition of Decision Attributes:*
  Increases in efficiency in each of these information system operations is desirable.
- *Basis of Comparison:*
  Efficiency subcriteria are compared on the basis of several quantitative and qualitative factors:

(1) resources currently devoted to each operation (savings potential, based on current budget allocation),

(2) potential to stimulate efficiency gains in other activities,

(3) potential to avoid redundant efforts or rework,

(4) probability of achieving and identifying the potential gains, and

(5) potential to lower future costs or resource demands

* *Comparison Matrix:*

Parent Attribute: *Efficiency (C2)*	*C21*	*C22*	*C23*	*C24*	*C25*	*Weight*
C21 Data Collection	*1*	*5*	*7*	*7*	*1*	*0.397*
C22 Data Handling	*1/5*	*1*	*3*	*3*	*1/5*	*0.110*
C23 Information Generation	*1/7*	*1/3*	*1*	*1*	*1/7*	*0.049*
C24 Information Analysis	*1/7*	*1/3*	*1*	*1*	*1/7*	*0.049*
C25 System Quality Assurance	*1*	*5*	*7*	*7*	*1*	*0.397*

CR = 0.01

The evaluator has indicated that efficiency gains in Data Collection and System Quality Assurance activities are equally important (intensity score = 1), more important in both than in Data Handling and Storage (intensity score = 5), and much more important in both than in Information Generation and Information Analysis (intensity score = 7). Information Generation and Information Analysis efficiencies are equally important, but less so than those in Data Handling and Storage (intensity score = 1/3). the evaluator has been sufficiently consistent (CR = 0.01 < 0.10) in the direct and indirect attribute comparisons.

A third example illustrates the rating of the alternatives' performance against a level 3 decision subcriterion; in this example, "Data Collection Efficiency".

- *Attributes to be compared: Information system alternative designs to be compared:*
  - *(1) Alternative #1: Original Monitoring Program*
  - *(2) Alternative #2: Enhanced Monitoring Program*
  - *(3) Alternative #3: Potential Information System*
- *Comparison Question:*

  Which of the information system alternatives offers the greatest efficiency in data collection operations?

- *Utility definition of Decision Attributes:*

  The alternative offering the highest efficiency is preferred.

- *Basis of Comparison:*

  The alternatives are compared on the basis of total expected resource consumption of this operation, considered from a continuing, long-term operating perspective. Higher efficiency is defined as lower resource consumption for a given level of data collected.

- *Comparison Matrix:*

Parent Attribute: Data Collection Efficiency (C21)	*A1*	*A2*	*A3*	*Weight*
Alternative A1: Original Program	*1*	*1/7*	*1/8*	*0.061*
Alternative A2: Enhanced Program	*7*	*1*	*1/2*	*0.353*
Alternative A3: Potential System	*8*	*2*	*1*	*0.586*

CR = 0.01

The evaluator indicates that the enhanced monitoring program offers significant potential data collection efficiency gains with respect to the original monitoring program (intensity score = 7). Some additional gains can be expected in this operation if the extended Framework analysis is applied *(intensity score = 2). The consistency ratio computed for this set of paired comparisons is acceptable (CR = 0.01 < 0.10).*

In a fashion similar to those illustrated, all decision attributes and alternatives are compared. Table 5-2 summarizes all of the paired comparison ratings employed in this analysis.

Part C: Evaluate Performance of Alternative Systems

In order to accomplish the decision goal of identifying the preferable water quality information system alternative (Original, Enhanced or Potential System), criteria comparison information throughout the hierarchy must be linked and consolidated. A composite preference vector for describing the priorities of the alternatives is computed from the criteria priority vectors derived at each level of the hierarchy (see Appendices B and C). These composite priorities, again normalized on a 0.00 to 1.00 scale, represent the evaluator's aggregate relative preference for each alternative.

For the decision hierarchy and attribute comparisons outlined in this case (see Figure 5-1, Table 5-1 and Table 5-2), the composite priorities or preference scores for the water quality information system alternatives are:

Table 5-2
Attribute Ratings from Paired Comparisons

Note: Attribute weights at each hierarchy level may not sum to exactly 1.00 due to rounding error.

LEVEL 2:

Attribute Weights: *C1: 0.83*
C2: 0.17

Consistency Ratio: *CR = 0.00*

Comparisons: *C1 / C2 = 5*

LEVEL 3:

Parent Attribute: C1 (Effectiveness)

Attribute Weights:
C11: 0.03
C12: 0.07
C13: 0.32
C14: 0.32
C15: 0.07
C16: 0.07
C17: 0.07
C18: 0.07

Consistency Ratio: *CR = 0.01*

Comparisons:
C11/C12 = 1/3
C11/C13 = 1/7
C11/C14 = 1/7
C11/C15 = 1/3
C11/C16 = 1/3
C11/C17 = 1/3
C11/C18 = 1/3

C12/C13 = 1/5
C12/C14 = 1/5
C12/C15 = 1
C12/C16 = 1
C12/C17 = 1
C12/C18 = 1

C13/C14 = 1
C13/C15 = 5
C13/C16 = 5
C13/C17 = 5
C13/C18 = 5

C14/C15 = 5
C14/C16 = 5
C14/C17 = 5
C14/C18 = 5

C15/C16 = 1
C15/C17 = 1
C15/C18 = 1

C16/C17 = 1
C16/C18 = 1

C17/C18 = 1

Table 5-2, continued
Attribute Ratings from Paired Comparisons

Parent Attribute: C2 (Efficiency)

Attribute Weights:
C21: 0.40
C22: 0.11
C23: 0.05
C24: 0.05
C25: 0.40

Consistency Ratio: CR = 0.01

Comparisons:
C21/C22 = 5
C21/C23 = 7
C21/C24 = 7
C21/C25 = 1

C22/C23 = 3
C22/C24 = 3
C22/C25 = 1/5

C23/C24 = 1
C23/C25 = 1/7

C24/C25 = 1/7

__LEVEL 4:__

Parent	*CR*	*Attribute Comparisons*			*Attribute Weights*		
		A1/A2	*A1/A3*	*A2/A3*	*A1*	*A2*	*A3*
C11	*0.07*	*1/7*	*1/9*	*1/3*	*0.05*	*0.29*	*0.66*
C12	*0.03*	*1/3*	*1/7*	*1/5*	*0.08*	*0.19*	*0.74*
C13	*0.02*	*1/4*	*1/9*	*1/5*	*0.06*	*0.19*	*0.75*
C14	*0.01*	*1/7*	*1/9*	*1/2*	*0.06*	*0.35*	*0.60*
C15	*0.01*	*1/2*	*1/9*	*1/7*	*0.08*	*0.13*	*0.79*
C16	*0.00*	*1/2*	*1/5*	*1/2*	*0.13*	*0.28*	*0.60*
C17	*0.01*	*1/7*	*1/8*	*1/2*	*0.06*	*0.35*	*0.59*
C18	*0.01*	*1/7*	*1/8*	*1/2*	*0.06*	*0.35*	*0.59*
C21	*0.01*	*1/7*	*1/8*	*1/2*	*0.06*	*0.35*	*0.59*
C22	*0.03*	*1/6*	*1/8*	*1/3*	*0.06*	*0.28*	*0.66*
C23	*0.00*	*1/8*	*1/8*	*1*	*0.06*	*0.47*	*0.47*
C24	*0.00*	*1*	*1*	*1*	*0.33*	*0.33*	*0.33*
C25	*0.01*	*1/6*	*1/7*	*1/2*	*0.07*	*0.35*	*0.58*

Original Monitoring Program:	*0.069*
Enhanced Monitoring Program:	*0.281*
Potential Information System:	*0.650*

Part D: Interpret and Validate Evaluation Model Results

Interpretation of Model Output:

The preference scores computed by the AHP process indicate that: (1) the enhanced water quality program recommended to the City of Thornton presents significant potential benefits with respect to the original monitoring program, and (2) the potential water quality information system, had it been devised following all the steps of the fully developed Framework, offers significant benefit beyond those of the enhanced monitoring program.

The ultimate interpretation of AHP's alternative preference scores is a subjective exercise on the part of the evaluator. Preference scores may suggest strong distinctions among the decision alternatives, but the evaluator (manager) must keep in mind that the significance imputed to the scores is based upon confidence in all of the assumptions (i.e., criteria, priorities, etc.) that he or she has built into the model. The evaluator's confidence in using the alternative scores (and in the decision model itself) can be raised through sensitivity analyses, which test the stability of conclusions drawn with respect to variations in those assumptions.

In this example, the evaluator is initially surprised at the magnitude of the preference associated with potential information system; i.e., with the predicted additional benefit of applying the full Framework over the advantages offered by the enhanced monitoring program (as indicated by the preference scores of 0.650 and 0.281 respectively. To better understand the implications of the model's output and to resolve the evaluator's uncertainties, several sensitivity analyses of the decision hierarchy are undertaken to gauge the affect of variations in model assumptions on computed alternative preferences.

Sensitivity Analyses:

Sensitivity analysis is a model validation process. The goal of all model validation exercises is to determine how well a model's process and/or output represent "reality"; i.e., how accurately and repeatably the modeled system's behavior is portrayed by the model, over the entire range of actual or potential operating conditions. In modeling physical systems (e.g., when using mathematical simulation models), validation is achieved by comparing model projections with actual variable behavior, to see if agreement (within some predefined range) is attained. If it is not, the modeler is obliged to examine all assumptions incorporated in the model and its structure in order to revise the model to adequately reflect reality.

In the present example, the AHP decision model is validated with respect to the evaluator's expectations of the rank order and relative priority of the water quality information system design alternatives. Do these decision alternatives score in the order and in the proportion expected, given reasonable model assumptions and inputs (e.g., criteria, priorities, alternative performance scores)? If the answer is yes, a sensitivity analysis to refine or increase confidence in the model may be carried out by exploring the stability of the decision (i.e., the ranking of alternatives and the proportionality of their scores) across the measurement ranges appropriate to the various assumptions and criteria in the model. If useful to the decision process underlying the overall evaluation, the analysis could be extended to derive sensitivity relationships; perhaps to predict the conditions necessary to change the ranking of the decision alternatives. Also, if the ranking of the alternatives is very stable with respect to variation in a particular criterion, it may make sense to examine the sensitivity of the decision to the very inclusion of the criterion in the model. If the alternative ranking is not affected by changes in a criterion's relative priority, nor by changes in an alternative's performance against the criterion, the criterion may be irrelevant and possibly deleted from the decision model. Such insights point towards beneficial simplifications of water quality information system designs.

If model results are widely disparate from expectations, the evaluator must try to find out why, typically by:

- assuring that typographical or other simple model input errors are eliminated,
- confirming the alternative performance scores assigned with respect to all criteria (Does the decision vary significantly with changes in the scoring?),
- confirming the priorities assigned to criteria in the model, (How does the decision vary with changes in criterion weights?), and
- confirming the members of the criteria set (Are all relevant criteria included and irrelevant criteria deleted?).

In this example, the evaluator questions the relative priority (but not the ranking) of the three water quality information system alternatives examined in this case. A brief example of a sensitivity analysis to examine and resolve those questions follows.

- *Effectiveness and Efficiency Criteria:*

  Effectiveness (C1) and efficiency (C2) are weighted 0.853 and 0.167 respectively at level 2, a (seemingly) wide disparity which might overwhelm all *other comparisons in computing alternative preference scores. To judge the sensitivity of the alternative preference scores to the relative weighting of these two attributes, AHP model computations were repeated across the range of possible importance intensity ratings. In all trials (including those where efficiency was ranked more important than effectiveness), the order of alternative preference remained the same, with a preference score for the potential information system at 0.586 or above. It thus appears that the model constructed is stable with respect to these criteria (i.e., the variability and volatility of its output are small).*

The evaluator concludes that the criteria and priorities assigned at this level appear reasonable and that adjustments are not warranted.

* *Effectiveness Subcriteria*

Eight effectiveness subcriteria are defined at level 3 of the hierarchy (see Table 5-1). Relative priority among them was computed in two steps by: (1) assigning each an importance value on an absolute scale (i.e., as very high, high, medium, or low), and then (2) comparing and converting those values to importance intensity ratings (e.g., very high:high = 5, very high:medium = 7, etc.). Sensitivity of the model *output was tested with respect to each of those steps as follows:*

(1) All subcriteria were assumed to be of equal value (thus making all importance intensities = 1), followed by the assignment of artificially disparate values (resulting in more importance intensities = 9)

(2) The importance intensity scores assigned to each value ratio were adjusted (in tandem, maintaining consistency)

In each of these tests, little variation was observed in the computed order of alternative preference or in the preference scores. Again, it appears the model is stable and acts reliably given the assumptions built into this section of the model.

* *Efficiency Subcriteria*

A similar analysis was applied to test model sensitivity to the five efficiency subcriteria (see Table 5-1). A similar stability was observed in the tests, with little impact noted on the ranking or preference scores of the alternative information system.

* *Scoring Alternatives Against Effectiveness Subcriteria*

When testing the sensitivity of the model's results to variations in alternative performance *scores, the evaluator assumed that information system performance could not be degraded by adopting the enhancement recommendations or by applying the fully developed Framework. Alternative performance on each subcriterion is tested under two extreme assumptions: (1) that the performance of all alternatives is the same (i.e., no improvement in effectiveness can be expected) and (2) strong improvement due to the enhanced program and maximum improvement due to the potential information system. As a consequence of these assumptions, this sensitivity analysis cannot produce a condition which would result in a reversal of the alternatives' ranking. The evaluator is only examining the variability in the proportionality of alternative preference scores.*

In general, this analysis indicates the ultimate alternative preference scores to be relatively insensitive to variations in alternative performance scores against each effectiveness subcriterion. Minimal change in alternative preference was observed (less than 5%) when assuming extremes in performance on six of the eight effectiveness subcriteria, namely: Designer Qualifications, Watershed Definition and Documentation, Water Quality Information User and Needs Selection, Water Quality Information Capability Assessment, Water Quality Information System Product

Specification, and Water Quality Information System Operational Design.

However, alternative preference does seem to be sensitive to an alternative's effectiveness performance with respect to Water Quality Management System Description and Water Quality Information Needs Specification. Varying alternative performance on these subcriteria can cause a variation of as much as 15% in the alternatives' preference scores.

* Scoring Alternatives Against Efficiency Subcriteria

A parallel analysis was employed to examine the sensitivity of alternative preference to variations in alternative performance scores on each efficiency subcriterion. Again, no degradation was assumed, ruling out the possibility of rank reversal in the final selection.

The analysis indicated little sensitivity to changes in these performance scores. In all cases, variation in the ultimate alternative preference score was less than 5%, as computed assuming extremes in alternative performance against the efficiency subcriteria.

EVALUATION MODEL VALIDATION: CONCLUSIONS

Do the ranking and preference scores among the information system alternatives generated by this evaluation model reflect "reality"?

Despite the evaluator's initial surprise regarding the potential advantage predicted for application of the Framework, the sensitivity analyses indicate the ranking and preference proportionalities among the information system alternatives generated by this model to be consistent over the range of feasible attribute assumptions. The model is quite stable; i.e., no one criterion, assumption or estimate of alternative performance radically alters the behavior of the model or causes unexplainable results. Only two subcriteria seem to have the potential to significantly affect the proportionality of preference for the information system alternatives: (1) water quality management system description, and (2) information needs definition. High scores on these attributes may disproportionately elevate potential information system scores because these activities are fundamentally unique to the application of the Framework. In short, the evaluator believes the Framework to have substantial benefits and can be confident that the evaluation model reflects his or her thinking process faithfully.

What further model validation questions remain? What further analyses of the model could be attempted to examine those questions?

The need for extended or more refined sensitivity analyses depends upon the gravity and immediacy of the decision process in which the model results will be used. For example, if the results are intended to be used in a project justification effort, extra preference discernment might be called for, perhaps achieved through:

- *further defining current criteria (i.e., adding more levels to the current model hierarchy),*
- *adding or deleting criteria (i.e., expanding or contracting the hierarchy),*
- *examining the sensitivity of preference to consistency in attribute comparisons throughout the model, or*
- *changing the analytical approach (e.g., separate evaluation of benefit and cost hierarchies).*

SUMMARY

This fourth phase of the Framework provides a process in which the knowledge accumulated and documented in the watershed, management system, and information system analyses can be structured to provide a definitive quantitative evaluation of information system performance (or potential performance); provided such an evaluation is germane to some subsequent decision; e.g., one regarding the modification of the management or information system. The model chosen to guide this effort is the Analytic Hierarchy Process (AHP), described in Appendices B and C.

In this case, the AHP is used to quantify the evaluator's assessment of relative performance of the enhanced water quality monitoring program to that of the original monitoring program and, also, the potential performance of an information system designed under a more rigorous application of the proposed Framework. The model's output suggests that: (1) the enhanced water quality monitoring program offers a significant improvement in performance over the original program, as defined by the criteria and priorities incorporated in the model, and (2) more attentive application of certain Framework steps would add substantial additional improvement. The quantitative measures of performance derived prompted the evaluator to carefully reexamine the structure, inherent assumptions, and inputs of the model; leading to a greater confidence in the analysis and allowing increased certainty in making contingent water quality management decisions.

Further observations on the use of the performance evaluation process and AHP model:

* Advantages of employing AHP in the evaluation of water quality information systems include:

(1) It can be implemented easily and at low cost.

(2) It accommodates and integrates a wide range of decision attribute types (criteria, alternatives, actors, influences, etc.) in one decision structure and computational scheme.

(3) It can accommodate tangible (quantitative) and intangible (qualitative) decision attributes in the same model.

(4) Any interdependence among decision attributes can be accommodated.

(5) It captures and documents the judgment of experts and decision-makers in a logical and consistent manner.

(6) Matrix construction and pairwise attribute comparisons sharpen the manager's analysis and force refinement of the decision hierarchy. If a comparison question can't be articulated, if distinctions can't be determined, or if preference orientation can't be defined, then the hierarchy must be adjusted to improve its logical coherence.

(7) The evaluation process and software foster documentation of the systems analysis, thus promoting consistency and facilitating decision review and discussion.

(8) Several convenient and inexpensive PC-based software packages are available to assist the manager or consultant structure and analyze a

decision problem using AHP (e.g., CRITERIUM DECISION PLUS [Sygenex, 1994], and EXPERT CHOICE [Decision Support Software, 1984]). These programs and a graphics-capable personal computer system greatly facilitate constructing the hierarchy, comparing attributes and computing the priority vectors.

* Extensions and Enhancements of the AHP Model:

Beyond the relatively straightforward comparison of water quality information system alternatives, the AHP can be employed as a tool for:

(1) Risk Analysis

In the alternative comparison mode (as is employed in this demonstration), the AHP can be used to analyze risk by directly incorporating "risk" criteria and subcriteria into the hierarchy and testing the sensitivity of the decision to the risk attributes by varying their priorities or the performance ratings of the decision alternatives against them.

A second approach is to use AHP in a forecasting mode, where the decision goal would be to predict the probability or magnitude of risk reduction (or exposure) for alternative water quality information systems. Configuring the problem in this format prompts the manager to explicitly define all risks faced in the water quality management system and allows direct and detailed identification of the tradeoffs among risk, costs and benefits.

(2) System Planning

A decision hierarchy, once constructed, becomes a relatively stable representation of the attributes, relationships, and concerns embodied in a water quality information system. As such, it becomes a convenient device which allows and encourages a manager to review the water quality management and information systems on a regular or continuous basis. In addition to assessing explicit water quality information system alternatives, the hierarchy could serve as an impact analysis guide. The manager may "check off" on the hierarchy where any change, internal or external to the system, internally or externally initiated, would influence the management or information system and then gauge its impact on information system performance.

As an example, if a water quality manager anticipated changes in a water quality variable standard, he could pinpoint all of the hierarchy attributes potentially affected, assess the impact on information system performance, and forecast the consequences of various counteractive strategies. Continuous "what-if" investigations are facilitated and can result in constantly refined and improved water quality management and information systems.

(3) Optimization

AHP models can be used to produce variable relationships (curves) helpful in identifying optimal or acceptable system operating regions. As an example, an AHP model constructed to predict probabilities of risk reduction could be executed iteratively while varying cost to produce a risk vs. cost curve. The manager could then identify boundaries of optimal or acceptable risk/cost regions on the curve. Once such a region is identified, the manager could use the model in a "what-if" fashion to identify changes that would drive the system towards operating in that preferred region.

This concludes the demonstration of the Framework and related discussion. In the next chapter, the introduction of the Framework to a sample of water quality professionals is described and their assessment of its potential utility is discussed.

CHAPTER 6

SURVEY ON THE FRAMEWORK: PROFESSIONAL AND EXPERT OPINION

INTRODUCTION

The case described in Chapter 4 and Chapter 5 demonstrates the application of the Framework as an aid to evaluating the performance of a relatively small water quality monitoring program, with encouraging results. The Framework was shown there as able to effectively structure the evaluation, to accommodate all relevant decision criteria, and to produce a clear and convincing measure of information program performance.

A sensible next step in the appraisal and development of the Framework is to investigate its utility when applied to the analysis of larger scale, more complex water quality information system. In the United States, water quality information intended to address regional and national issues has traditionally been collected or coordinated by water quality professionals of the U.S. Geological Survey (USGS) and of the U.S. Environmental Protection Agency (USEPA). Currently, in addition to conducting traditional water quality monitoring activities, each of these agencies is developing a nationwide water quality (environmental) assessment program.

The USGS has instituted the National Water Quality Assessment Program (NAWQA), an attempt to create a "...well-planned, reliable water quality assessment program...designed to:

> 1. provide a nationally consistent description of current water quality conditions for a large part of the nation's water resources;
> 2. define long-term trends (or lack of trends) in water quality; and
> 3. identify, describe, and explain, to the extent possible the major factors that affect observed water quality conditions and trends." (National Research Council, 1990)

The USEPA has created the Environmental Monitoring and Assessment Program (EMAP), "...an innovative, long-term research, monitoring, and assessment program designed to measure the current and changing condition of the nation's ecological resources...to help provide answers to questions such as:

> What is the current geographic extent of ecological resources?
>
> What resources are degrading or improving, where, and at what rate?

Are affected resources responding as predicted to changing control and regulatory programs?

The ultimate goal of the program is to provide decision makers with sound ecological data to improve environmental risk management decisions." (U.S. Environmental Protection Agency, 1993)

The combination of water quality monitoring expertise and systems development awareness represented in these organizations suggested that they could provide credible feedback regarding the potential utility of a framework to evaluate the performance of large-scale water quality information systems. Accordingly, it was decided to introduce the concept of such a framework to selected water quality professionals in each agency and to solicit their opinion as to its applicability towards meeting their water quality information system responsibilities. The individuals identified to be surveyed were:

- USGS NAWQA Project Chiefs; 20 individuals assigned to the design and management of the initial group of NAWQA Study Unit (watershed) assessments (currently in progress), and
- USEPA Regional Water Quality Coordinators; the individuals at each of the 10 USEPA Regions responsible for overseeing monitoring activities initiated by federal regulation or agency programs.

SURVEY APPROACH

Step 1: Preliminary Discussions

In order to design an effective survey and to verify assumptions with regard to the duties and interests of the professionals to be polled, one NAWQA Project Chief and one USEPA Regional Water Quality Monitoring Coordinator were interviewed in advance of the survey. They were introduced to the Framework, asked to comment on the utility of such a tool, and asked to suggest questions that should be posed to their counterparts in such a poll. Several of the author's assumptions were tested in these discussions:

* Mounting public concern and continued resource limitations have prompted closer legislative scrutiny of water quality management programs.
* These concerns and limitations have resulted in funding constraints and have encouraged efforts to improve water quality program performance, including watershed management practices and inter-agency sharing of information and costs.
* All water quality professionals will be challenged to evaluate and improve the performance of programs with which they are associated.
* Investigation of system performance evaluation would be a constructive extension of current water quality monitoring and information system research.

* Specifically, a process and/or model to address water quality information system performance would be useful to water quality managers and professionals towards meeting future challenges. Such a process should incorporate effective information system design practice and reflect watershed management, holistic approaches, and other evolving water quality management concepts.

* Necessary characteristics of such an evaluation process would include:

  (1) explicit recognition and ranking of watershed "stakeholder" information needs,
  (2) concurrent consideration of objective and subjective evaluation criteria,
  (3) efficient sensitivity analyses with respect to evaluation assumptions, criteria and priorities,
  (4) documentation of the evaluation process,
  (5) ease of use, and
  (6) guidance for system redesign.

* The evaluation process and model may be usefully applied to the evaluation of 305(b) reports, to EMAP resource allocation decisions, to NAWQA retrospective analyses, and to local NAWQA project funding decisions. Extensions of the process to the evaluation of comprehensive programs (e.g., EMAP or NAWQA) are conceivable.

The preliminary interviews revealed substantial agreement with the first three general assumptions posed above. On how the anticipated challenges could be met, and as to how a water quality information system evaluation process could contribute, the response was less certain. Although in general agreement that some process with the suggested characteristics would contribute to improved system design, it was difficult for those interviewed to envision applying the process to their present jobs and responsibilities. As technical professionals, they were accustomed to using "analytical" models and processes, but not "management" models. However, they did acknowledge the possible utility of such a process in some aspects of their work, and suggested that in surveying their counterparts the process be described clearly enough to allow it to be accurately related to the management and decision-making parts of the job.

Step 2: Opinion Survey

Drawing upon the preliminary interviews, a survey was designed to solicit the opinions of the NAWQA Project Chiefs and USEPA Regional Water Quality Monitoring Coordinators. The survey approach and documents were developed using concepts of the Total Design Method of Dillman (1978).

* Questionnaire

The questionnaire package sent to these water quality professionals included a cover letter outlining the purpose of the questionnaire, the questionnaire, and a description of a performance evaluation framework for the recipient's reference. Information solicited included:

(1) a description of the water quality information programs managed or observed by the professional,

(2) the professional's responsibilities related to those programs (e.g., oversight, technical support, and resource allocation),

(3) a description of any decisions they face requiring an evaluation of water quality information programs (e.g., evaluation of state agency procedures, evaluation of compliance or audit programs, or comparisons for resource allocation and funding decisions),

(4) the criteria they consider important in evaluating or comparing water quality information programs,

(5) how they use performance criteria when evaluating water quality information programs, including the procedures followed, and any tools, techniques or models employed,

(6) the characteristics they deem important in a practical method of evaluating water quality information programs (e.g., inexpensive, easy to

understand, useful in real time, stand alone, PC-based, etc.), and

(7) a description of how a structured performance evaluation framework would assist them in analyzing or managing water quality information programs.

The questionnaire package and a list of all USGS and USEPA questionnaire recipients can be found in Appendix D.

* Questionnaire Follow-up

Approximately one month after mailing the questionnaire, a follow-up note was sent to all recipients who had not responded, reiterating the importance of their reply to the findings of the survey. An offer was made to send a new questionnaire, in the event the original had not been delivered. Also, returned questionnaires were redelivered with corrected addresses. Several responses were elicited by the follow-up note.

* Survey Summary and Reporting

The returned surveys were summarized, by topic and respondent's agency, and the author's conclusions and impressions documented. The survey results were reported to all recipients approximately 5 months after distribution of the questionnaire. Receipt of the summary report stimulated one last questionnaire response. Those summaries are reviewed below and reproduced in their entirety in Appendices E and F.

SURVEY RESPONSES AND CONCLUSIONS

Approximately 40% of the recipients in each agency responded to the questionnaire. The responses to each question are summarized here, by agency. The author's conclusions and impressions, drawn from the content and tone of the responses, are presented.

* Question (1) and Question (2):

Please describe the water quality information programs you manage or observe.

What are your responsibilities related to those programs (e.g., oversight, technical support, resource allocation, etc.)?

Response:

The specific responsibilities of USEPA Water Quality Monitoring Coordinators vary widely among the Regions. The monitoring programs of most concern in a Region are state and Indian tribe programs, USEPA's own ambient programs, and any other programs funded by USEPA grants. Program responsibilities cited include: (1) water quality assessment and data management, (2) oversight and coordination of federal, state and regional programs to support national priorities and regulations, and (3) development of USEPA goals and programs.

USGS NAWQA Project Chiefs are primarily concerned with water quality assessment and analysis in large watershed or basins; e.g., in the NAWQA Study Unit for which they are responsible. NAWQA program management activities include: (1) design and implementation, (2) management of project teams, and (3) reporting of policy-relevant results to managers and policy makers. Other general responsibilities mentioned include: (1) interpreting assessment information from various sources, (2) providing oversight and technical support, and (3) participating in cooperative water quality assessment programs.

Conclusions:

USEPA monitoring coordinators have little direct responsibility for the design, operation or management of water quality monitoring or information systems. In some regions, there is limited first-hand involvement with R-EMAP (i.e., preliminary EMAP projects) and USEPA ambient programs. The coordinators perform two major roles in water quality monitoring:

(1) Oversight or coordination of federal, state, tribal and local programs in the Region; to review quality assurance plans, to assure regulatory compliance (Section 305(b) reporting and Section 106, 319, and 604

grant programs), and to promote coherence with national priorities and policies

(2) Technical assistance and information distribution for all agencies in the region which operate monitoring programs

Other roles played by the USEPA's water quality monitoring coordinators include: (1) water quality data management, (2) water quality assessment, and (3) decision-making using water quality information.

NAWQA Study Unit (i.e., basin-wide or large watershed) management comprises the major portion of a NAWQA Project Chief's job. The specific activities described are accomplished principally in connection with that NAWQA project.

The wide range of response detail and depth (throughout the questionnaire) suggests that NAWQA Project Chiefs vary widely in their management approach (and style) and are quite autonomous with respect to the design and execution of their Study Unit assessments.

* Question (3)

What decisions in which you participate require an evaluation of water quality information programs? Examples may include evaluation of state agency procedures, evaluation of compliance or audit programs,

comparisons for resource allocation and funding decisions, etc.

Response:

USEPA monitoring coordinators make evaluation decisions when awarding or auditing state programs funded by federal grants, and when assessing any other state monitoring activities.

NAWQA managers make decisions when evaluating federal, state, local and USGS data collection activities in order to determine where NAWQA program assistance is needed. Decisions are made on the bases of data quality and information usefulness.

Conclusions:

Managerial decisions by USEPA monitoring coordinators, based upon evaluation of water quality information programs, appear to be limited to the awarding and auditing of Section 106, 319 and 604 grants.

Many "non-managerial" decisions are made by the USEPA coordinators and much guidance is provided, usually with respect to whether or not a program (or program feature): (1) meets regulatory or policy requirements, and (2) exhibits adequate quality assurance planning.

NAWQA Project Chiefs evaluate existing information and monitoring programs principally to decide if the data produced are useful and suitable for inclusion in the NAWQA database. That decision process is not uniform among the respondents. Approaches appear to vary significantly as to structure and formality.

An initial program evaluation (analysis) phase to identify watershed data and information needs is at least implied by all NAWQA project managers. A subsequent phase identifies watershed data and information needs not satisfied by existing programs. Succeeding decisions select programs to meet unsatisfied data and information needs and to allocate the necessary resources and funds. Presumably, the processes and criteria employed are similar to those applied to the evaluation of existing programs.

* Question (4)

What criteria do you consider important in evaluating or comparing water quality information programs? Please indicate the importance (Crucial, High, or Medium) of the following items and note any other criteria that you feel are significant.

Response:

The comparative ranking of the suggested criteria by the two agency groups is displayed below. The ranking rationale and an extensive list of additional decision criteria can be found in Appendices E and F.

Criterion	USEPA	USGS
Watershed Definition	3 (tie)	7
Stakeholder Identification	4	8
Defined Water Quality Management Objectives	1 (tie)	4
Defined Information Needs	1 (tie)	6
Information Systems and Database Design	2 (tie)	3
Data Collection and Storage	2 (tie)	1
Information Reporting	3 (tie)	5
Quality Assurance Procedures	1 (tie)	2

Conclusions:

Given the skewed rating scheme (i.e., no "low" rating choice was provided) and the small sample, definitive statements about the USEPA monitoring coordinators' rating of evaluation criteria are tenuous. However, the clear scoring breaks indicate that the USEPA coordinators:

(1) regard identification of water quality management objectives and information needs as paramount and demonstrably more important than specific data system or information system design concerns, and

(2) regard watershed definition, stakeholder identification and information reporting as less important than data system or information system design.

From a "total systems" perspective, item (1) indicates a logical and preferable information system design sequence.

However, it also seems that watershed and stakeholder identification would be necessary preliminaries to setting objectives and information needs. It is apparent that a wide variety of criteria are used in evaluating water quality information programs. Further questioning will be required to form a more definitive list and to fully understand the monitoring coordinators' evaluation priorities.

For similar reasons, definitive statements about the NAWQA Project Chiefs' opinions on evaluation criteria are precluded. However, the scoring breaks observed suggest a general hierarchy of concerns:

(1) Highest (almost crucial) importance is assigned to data collection and storage, and to quality assurance procedures.

(2) Defined management objectives and system design factors are of great importance; but not as crucial as data collection or quality assurance.

(3) Information needs identification, information reporting, and watershed definition enjoy still less unanimity as to crucial or high importance.

(4) Stakeholder identification appears to be of least general importance; no respondent regarded it as a crucial decision criterion.

Although considerable sentiment was expressed with regard to the importance of pre- and post-data information system activities, a predominantly data-oriented view of water quality information programs is suggested by the NAWQA Project Chiefs. Note that there is little insight as to the relative importance of the volunteered criteria and the criteria suggested in the questionnaire.

Given the historic mission and traditional activities of the USGS with respect to water quality monitoring, the perceived emphasis on data collection and associated quality assurance is understandable. The author assumes that USGS personnel associate quality assurance and quality control mainly with data collection and laboratory activities.

From a total systems design perspective, more emphasis on preliminary analyses (e.g., objective setting and information needs specification) and user/stakeholder satisfaction (e.g., information needs and information reporting requirements) would be expected. Again, it is apparent that a wide variety of criteria and emphases are employed by NAWQA Project Chiefs in evaluating information programs. A more in-depth investigation would be required to characterize them accurately.

* Question (5)

How do you use performance criteria when evaluating water quality information programs? Please describe

the process you follow and any tools, techniques or models that you employ.

Response:

USEPA monitoring coordinators use performance criteria to develop water quality monitoring strategy, to define program goals and to establish program objectives. Grant requirements and agreements may provide guidance towards evaluating state programs. One respondent noted that monitoring programs are not actively evaluated beyond basic technical considerations.

Several USGS respondents answered indirectly, noting that evaluation of water quality systems is a long and time-consuming process, or that the definition of "performance criteria" was unclear, or that criteria are used in combination with practical considerations to determine if information from a water quality program is useful. Two USGS respondents were more explicit:

(1) Performance criteria are used to determine adherence to protocols, innovation applied to protocols, representativeness of data collection sites, and personnel knowledge.

(2) Evaluation of water-quality information programs is conducted to determine if: (a) data is reliable, (b) information is accessible manageable, and documented, (c) technology can be transferred easily, (d) information is scientifically sound, and (e)

information is adequate to provide relevant and reliable conclusions.

Conclusions:

Evaluation procedures in awarding or auditing USEPA's Section 106 grants are established in grant-related regulations, in the grant literature, and in agreements reached with grant recipients.

USEPA respondents provided few insights into the actual evaluation process in which their evaluation criteria are employed. Reasons for that lack of response may include:

(1) Questionnaire communication failure - Respondents did not understand the intent of the question due to unfamiliar terminology or ineffective phrasing.

(2) Difficulty of response - Respondents were unable or unwilling to take the time or effort required to properly analyze and describe a complex process

(3) No process - Respondents have no defined process used to evaluate water quality monitoring programs

Nearly all of the USGS respondents appear to have a process in place to evaluate water quality information programs. In some cases, the response suggests that the process is formally structured and documented. Other responses (e.g., those noting such evaluations as a complicated or time consuming process), suggest that a more abstract and less formal process is at work, perhaps where clear articulation of the decision process has never been attempted.

None of the respondents (USEPA or USGS) outlines a clearly structured evaluation process. Consequently, no statement can be made as to how the respondents select and rank criteria, measure performance against criteria, or derive an overall program rating. Also, none of the respondents mention the use of any specific tool, technique, or model to assist the evaluation process.

* Question (6)

In your opinion, what characteristics describe a practical method of evaluating water quality information programs? Examples might include: inexpensive, easy to understand, useful in real time, stand alone, PC-based, etc.

Response and Conclusions:

USEPA respondents appear to agree that several of the suggested characteristics are important in an evaluation process, namely that it be inexpensive, easy to use, PC-based, stand-alone, and useful in real time. It was also noted that an evaluation system must be able to:

(1) work with available data (i.e., be flexible)

(2) demonstrate strong scientific foundation (i.e., present scientific credibility)

(3) present results visually (i.e., effectively communicate information to management)
(4) evaluate individual aspects or parts of large programs
(5) provide easily accessible information via personal computers and/or network connection (e.g., on the Internet)

A USEPA-wide definition of a minimal or optimal state information program would help the monitoring coordinators in making system evaluations and comparisons. A performance evaluation program characteristic based on this notion might be stated as: "defined and documented information program evaluation criteria and process".

One USEPA respondent notes that state programs are unique and that the evaluation of those programs should take into account individual program needs and the capabilities (i.e., resource available) to address those needs. This implies that another characteristic of a practical evaluation method may be stated as: "clearly indicates how well program needs are matched to available resources", or "clearly indicates which program gets the most from the resources applied". This response further implies that an information program evaluation process must itself be realistic, credible and effective; i.e., it must give the analyst confidence that the process of comparing information programs is logical and defensible.

Ease of use, ease of understanding, flexibility and statistical validity capture the essential characteristics of a water quality information program evaluation process for the USGS Project Chiefs. Rapid availability of results is also important.

One USGS respondent appears to believe that a practical method of evaluating water quality information is not important. Further investigation is needed to determine that this is indeed an accurate interpretation, and, if so, to ascertain the respondent's reasoning.

A warning against an "oversimplistic" process indicates that the evaluation process must be able to accommodate relevant considerations regardless of measurement convenience. The process must properly balance assessment expediency and adequacy.

*   Question (7)

How would a structured performance evaluation framework assist you to analyze or manage your water quality information programs? (An example of such a framework is attached.)

Response:

Several USEPA respondents indicate that a plan or strategy would be potentially helpful in: (1) enhancing problem identification and trend assessment capabilities, (2) evaluating the effectiveness of water quality management actions, and (3) promoting the use of available water-related data in Regional and State decision making. One respondent indicated that the utility of such frameworks may be scale-dependent, i.e., more useful for evaluating state and local programs than regional or nation-wide programs. Another respondent noted that a performance evaluation framework and documentation may be useful in understanding specific state support needs, promoting technology transfer between states, documenting the quality of state data, and selecting competitive grantees or contractors.

A number of USGS respondents indicated that such frameworks might be helpful, one noting that structured strategies are necessary to timely and reliable assessment of large volumes of information. Such a framework should exhibit a modular or flexible structure which can be customized to the specific needs or objectives of a project, and should include a relational database. Two USGS respondents indicated that the example framework presented did not appear to be helpful in their work.

Conclusions:

Responding USEPA coordinators generally agree upon the potential usefulness of a framework for evaluating water quality information programs. However, they are divided as to the scale at which such a framework could be appropriately applied. Three of four respondents appear to be able to relate the example framework to their concerns and their job activities. The fourth respondent viewed the example framework as applicable to management at geographical scales (e.g., local or watershed) more limited than the state or regional perspective required in his job. Possible explanations for this divergence of opinion include:

(1) diverse responsibilities - Assigned responsibilities and duties with respect to water quality monitoring vary substantially among the USEPA Regions. The individuals selected for this survey do not necessarily work on comparable programs.

(2) diverse perspectives - Since there is little USEPA-wide guidance on evaluating water quality information programs, each monitoring coordinator is free to shape his or her approach and select the scope at which to focus based upon individual skill, experience or preference.

(3) communication limitations - There was no opportunity to discuss the example framework with individual respondents and speculate on how it might apply to their specific duties.

USGS respondents are divided on the utility of a structured evaluation framework:

(1) Two respondents see no advantage to a structured framework (at least as represented by the example format).

(2) Several respondents appear to endorse the need for structured (or modular) assessment approaches.

(3) Several respondents acknowledge the potential usefulness of an evaluation framework which: (a) can be customized to accommodate specific project needs and objectives, (b) balances the needs for structure and flexibility, and (c) can deal with scale (time and space) properly for the project or problem under consideration.

From these responses and from others across the questionnaire, it appears that USGS personnel are inclined to focus on data collection and analysis activities; perhaps as a result of training, experience, and institutional tradition. Institutional expectation of a wider systems perspective and individual training in systems approaches may be necessary to stimulate investigation of the utility of a performance evaluation framework like that proposed.

A more detailed explanation of the example framework is required. Complete documentation of the process, and a demonstration of each step as applied to a specific program evaluation are necessary in order to allow a user to judge the framework's potential utility.

DISCUSSION

Responses to the survey lead the author to conclude that both NAWQA Project Chiefs and USEPA Water Quality Monitoring Coordinators are frequently engaged in water quality information program evaluation and view it as an essential aspect of their work. As noted, however, the formality and structure of these evaluation processes vary widely.

The author believes that systematic and structured approaches to defining and evaluating water quality information system performance will allow water quality professionals to make those evaluations more rationally and proficiently, leading to more effective and efficient systems, and the capability to manage and improve them on a continuing basis. An incomplete process description, terminology confusion, and a lack of reflection may have impeded the survey recipients' consideration of the example framework's potential as an aid in their management tasks. In addition to the content and tone of the questionnaire responses, other recent communications indicate that water quality professionals in both agencies recognize the need to evaluate monitoring and information system performance, and are receptive to exploring methods to do so. Examples of those communications include:

- requests from regional USGS NAWQA program administrators (the NAWQA National Leadership Team) to discuss evaluation frameworks at a near future meeting (Dennehy, 1994), and

- commentary supportive of the effort, for example: ".. The "Program Evaluation" portion of our strategic planning documents remains blank because we are not sure where to start. The results of your research will provide useful information that I hope to implement in our Region. Please keep us informed of your progress... " (Hotto, 1994).

These responses further corroborate the observation that USEPA and USGS water quality professionals are being held increasingly accountable for water quality management system and information system performance, and that evaluating the performance of these programs is a difficult problem deserving research attention. Continued development of systematic frameworks to guide performance evaluation will promote routine system management and satisfaction of that accountability.

CHAPTER 7

SUMMARY AND CONCLUSIONS

SUMMARY

As pointed out in the introduction to this dissertation, the public is not convinced that it is getting its money's worth for environmental management spending. This dissatisfaction is likely to continue, and, in the water resources arena, water quality managers, regulators and consultants will be forced to adopt a more "bottom-line" viewpoint in executing their duties. They will be more accountable to their public, and will be required to demonstrate the results of past water quality management expenditures, and to justify future program expenditures. In order to meet those demands, water quality managers must have information which can be directly related to regulatory or managerial requirements, and can support the corresponding management decisions processes.

To help managers obtain decision-relevant water quality information, this research has adapted and integrated knowledge from several disciplines to develop a comprehensive and consistent approach to water quality information system analysis. A "Framework for Evaluating Water Quality Information System

Performance" has been created; an auditing, documentation and evaluation procedure which embodies four major activities:

- Preplanning of the evaluation effort
- Characterization and documentation of the watershed and all relevant water quality management systems
- Analyses of the effectiveness and efficiency of the water quality information system(s) in supporting water quality management objectives
- Evaluation (quantification) of water quality information system performance with respect to effectiveness and efficiency criteria

Commentary in the literature and responses from the water quality professionals confirm that accountability demands upon water resources and water quality managers are increasing. Significant progress has been gained in applying total systems perspectives to the design and operation of water quality monitoring and information programs, and towards rationalizing those programs with respect to management objectives and information needs. A recent example of that progress is the development of data analysis protocols to enhance the system design process. It is apparent, however, that further work is necessary to develop approaches which can help managers confront the water quality management environment of the future, which will be characterized by: (1) fewer technical questions which require purely quantitative information, (2) more complex problems with social, economic, political and legal ramifications which require the appraisal of non-quantitative information, and (3) a demand for continuously and actively managed water quality information systems rather than the stand-alone, problem-oriented, reactive programs of the past.

To help water quality managers meet those future conditions, the literature has been searched and expert experience polled to impart the wisdom and methods of several disciplines (systems analysis, management science and information systems, water quality monitoring and information systems) to the design, operation, and evaluation of water quality information systems. This investigation concludes that the management of water quality information systems for continuous enhancement requires: (1) a competent system design <u>process</u>, (2) comprehensive documentation of system design and operation, and (3) a routine and thorough performance measurement and evaluation process.

The Framework presented in this dissertation integrates the knowledge and experience of those disciplines into a process which can help water quality managers accomplish the three critical information system responsibilities indicated above. The Framework is intended to help a water quality professional decide how well a water quality information system serves management's purposes. It is a management and engineering instrument, not a tool to perform specific technical or statistical analyses. The Framework helps the manager or analyst ask relevant and incisive questions about what information the water quality information system should provide, and how well the information is provided.

Application of the Framework to a comparison of water quality monitoring program performance is demonstrated, and its ability to provide a quantified measure of program performance, when required, is established. The potential application of the Framework to the analyses of larger or more complicated water quality management information systems is described.

CONCLUSIONS

A number of advantages of the Framework in supporting water quality management decision-making can be stated:

* **The Framework is effective.** Its process promotes fundamental system understanding and explicit identification of the water quality information needs and management decision objectives to be served. The performance of information system design and operations

is evaluated directly with respect to how those objectives and needs are (or should be) satisfied.

- **The Framework is user-oriented and user-friendly.** The assessment and evaluation tasks are straightforward and can be accomplished by the water quality manager with a minimum of assistance or consultation. The watershed, management system, and information system analyses provide straightforward guidance towards identifying and documenting the critical questions underlying assessment of information system effectiveness. The Analytic Hierarchy Process and the available software allow the manager to prioritize evaluation criteria, and to create and exercise a personalized performance evaluation process.
- **The Framework is flexible and widely applicable.** A water quality manager can apply the proposed assessment questions to the watershed, management system and information systems with which he or she is concerned, regardless of its size or complexity. As suggested by several responses to the survey of water quality professionals, Framework questions can serve the important function of characterizing system complexity, thus fostering a more consistent alignment of information needs, information product expectations, and information system capabilities. The Framework produces a customized analysis of the information

system, enhancing the manager's understanding of, confidence in, and commitment to any resulting decisions or actions.

- **The Framework is economical.** Management system and information system assessments can be carried out to whatever level of detail the manager deems appropriate or affordable. The performance evaluation model employs a known and accepted decision analysis technique for which affordable and convenient personal computer software packages are available. The potential financial investment is low and easily controlled. The risk and consequence of process or model obsolescence are minimal.
- **The Framework can be extended and enhanced.** Assessment strategies, performance criteria, and evaluation models can all be refined in future research to provide more powerful and persuasive information systems.

CAVEATS

Having described the benefits of water quality information system performance evaluation and demonstrated the utility of this Framework in performing and documenting such assessments, several caveats and acknowledgements are appropriate. The first is to note that the information system evaluation process presented here is neither definitive nor exhaustive. The Framework for Evaluating

Water Quality Information System Performance is exactly that - a framework - i.e., a general blueprint to guide the evaluation, design or redesign of a water quality information system. As with all general plans, circumstances at hand will force adaptations and shape the final implementation process. In the case of water quality information system evaluation, the wide variety of watersheds, stakeholders and water quality concerns encountered will give rise to many unique interpretations of information system performance measures, performance criteria, decision priorities and feasible problem solutions.

In applying the Framework, the water quality manager will identify many specific shortcomings in both management and information systems and will attempt to define their consequences and relative significance. System improvement opportunities suggested are likely to be complex, sensitive and expensive. The order and methods by which those opportunities are addressed are necessarily the subjects of subsequent analyses and decisions. It must be emphasized that simply posing questions and exposing shortcomings of water quality information programs do not solve the problems identified. However, diligent application of the Framework process and skillful use of the evaluation model can enable the manager to more resourcefully prioritize and exploit improvement opportunities presented.

Recognizing that it is impossible to specify all of the ramifications of applying the Framework, this research is expected to initiate a vigorous dialogue, eventually leading to the identification of innovative management approaches to help rationalize water quality monitoring and information programs across the nation. The number of future studies required to address the issues raised here is potentially enormous. In the following section, several general research directions are outlined with examples of specific studies which could be pursued. Also, many research suggestions are embodied in the questions raised and criteria discussed in Chapter 2 (Tables 2-1, 2-2, and 2-3) and Chapter 3.

RECOMMENDATIONS FOR FUTURE RESEARCH

Further refinement and clarification of each phase of the Framework will facilitate its use by a wide variety of water quality professionals. The water quality community is encouraged to continue to search broadly for knowledge and wisdom applicable to the numerous challenges cited throughout this dissertation. Progress towards more effective management of water quality information systems and public confidence in water quality information will be greatly promoted by adapting and integrating the experience of other disciplines in dealing with analogous issues and problems.

This dissertation concludes with a brief presentation of opportunities for research toward meeting future water quality management and information system challenges.

* With respect to performance evaluation techniques and models, research opportunities include:
  (1) Development of methods to specify water quality information and information system value; particularly valuation criteria and their measurement
  (2) Development of convenient and routine information system audit procedures
  (3) Investigation of the applicability and utility of other multi-objective performance evaluation models; e.g., water quality information system performance indexes
  (4) Description of effective sensitivity analyses and model validation techniques
  (5) Extension of evaluation models for use in optimization, forecasting, or other management analysis requirements

* Research opportunities regarding water quality information system analyses include:
  (1) Expansion of perspectives on the definition of water quality information, including the following subtopics:

- Linking water quality information to measures of management objective attainment
- Recognition of information sufficiency and overload
- Recognition and integration of qualitative and quantitative information
- Integration of various information types (e.g., chemical and biological, narrative and numeric, etc.)
- Expanded definition and application of composite water quality measures (e.g., water quality or ecological quality indices)

(2) Promotion of the application of state-of-the-art information system design principles and practices to the design of water quality information systems, including:

- Methods for identifying and documenting information needs which are clearly connected to management decisions and objectives
- Definition, specification and communication of information system capability
- Application of formal and documented design approaches; (e.g., classical, life cycle development, structured, data driven, etc.), as appropriate to the water quality management system under consideration

  - Application of formal database management system (DBMS) design concepts (e.g., "metadata" needs, data dictionary requirements, database standards, distributed database designs, etc.), as applicable to water quality databases,
  - Application of computer system networking and data sharing technologies
  - Methods to promote system-wide quality assurance perspectives
  - Definition of useful formats for documenting water quality information system design and operations

* Research suggestions in the areas of watershed definition and analyses of water quality management systems include:

  (1) Provide further guidance in defining watersheds (ecoregions) with respect to water quality issues; for example:
    - List sources of historical information
    - Demonstrate the documentation of legislative and regulatory requirements
    - List sources of technical information

- Survey and document the current methods and criteria by which federal (e.g., USEPA and USGS), state, and local agencies define watersheds and ecoregions

(2) Solicit and document "the public's" water quality desires and expectations:

- Define the universe of public entities interested in water quality or water quality information (e.g., Congress, federal agencies, state and local government bodies, special interest groups,...,the citizen at large).
- Specify methods for gathering and documenting the water quality and water quality management information expectations of the various public entities identified. Information content and process needs of each target audience should be identified.
- Execute surveys or other methods specified to document the water quality information expectations of the various public entities.

(3) Define "water quality management". The ubiquitous use of this term implies homogeneity with respect to management responsibilities, concerns and approaches. The present research suggests otherwise. Rationalization of water quality

information systems rests upon a thorough understanding of the similarities and differences among the wide range of management systems to be served. Specific water quality management issues requiring characterization include:

- Accountability, incentive, responsibility and authority
- Types of water quality management decisions and decision-making processes
- Institutional and management system impediments to decision making
- Water quality management skills and capabilities (e.g., general management, decision making, information need specification, and information utilization)
- Methods of obtaining and documenting watershed and management information
- Methods of cataloging "stakeholders" and establishing their <u>priority</u> in the consideration of watershed and water quality management issues
- Methods to promote continuous management and continuous improvement perspectives in the design and operation of water quality information systems

REFERENCES

AAEE (American Academy of Environmental Engineers) Ad Hoc Committee on Research. 1989. Environmental Engineering, Establishing Research Needs. Journal Water Pollution Control Federation, 61(4):453-459.

Abubakar, M.M., and W.B. Lord. 1992. Persistent Conflicts over Timber Production and Watershed Management: A Problem Analysis. Water Resources Bulletin, 28(5):845-852.

Ackoff, R.L. 1967. Management Misinformation Systems. Management Science, 4(2):B147-156.

Ackoff, R.L. 1978. The Art Of Problem Solving. John Wiley & Sons, New York.

Ackoff, R.L. 1981. Creating The Corporate Future. John Wiley & Sons, New York.

Ackoff, R.L., J. Gharajedaghi, and E.V. Finnel. 1984. A Guide To Controlling Your Corporation's Future. John Wiley & Sons, New York.

Ackoff, R.L. 1986. Management In Small Doses. John Wiley & Sons, New York.

Ad Hoc NEL Concept Committee, Oak Ridge National Laboratory. 1970. The Case For National Environmental Laboratories. Report to the Public Works Committee, United States Senate, U.S. Government Printing Office, Washington.

Adkins, N.C. 1992. "A Framework For Development Of Data Analysis Protocols For Ground Water Quality Monitoring Systems". Doctoral Dissertation, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins.

Adkins, N.C. 1993. A Framework for Development of Data Analysis Protocols for Ground Water Quality Monitoring. Colorado Water Resources Research Institute Technical Report No. 60, Colorado State University, Fort Collins, June.

Adkins, N.C. and R.C. Ward. 1992. Development of Protocols for the Statistical Analysis of Groundwater Quality Data: What Can We Learn From Existing Protocols? Proceedings of American Geophysical Union Twelfth Annual HYDROLOGY DAYS, Hydrology Days Publications, Atherton, California, pp. 1-14, March.

Ahituv, N. 1980. A Systematic Approach Toward Assessing the Value of an Information System. MIS Quarterly, 4(4):61-75.

Ahituv, N., D. Evan-Tsur, and B. Sadan. 1986. Procedures and Practices for Conducting Postevaluation of Information Systems. Journal of Information Systems Management, 3(2):61-65.

Alm, A.L. 1976. Is EPA A Success? EPA Journal, 2(3):7.

Ameen, D.A. 1989. Systems Performance Evaluation. Journal of Systems Management, 40(3):33-36.

American Accounting Association. 1965. A Statement of Basic Accounting Theory.

Amorocho, J., and B. Espildora. 1973. Entropy in the Assessment of Uncertainty in Hydrologic Systems and Models. Water Resources Research, 9(6):1511-1522.

Anselin, A., L. Anselin and P.M. Meire. 1989. Multicriteria Techniques in Ecological Evaluation - An Example Using the Analytical Hierarchy Process. Biological Conservation, 49(3):225-229.

Arbel, A. and A. Siedman. 1984. Performance Evaluation of Flexible Manufacturing Systems. IEEE Transactions on Systems, Man and Cybernetics, SMC-14(4):606-617.

Arbel, A., and S.S. Oren. 1986. Generating Search Directions in Multi-Objective Linear Programming Using the Analytic Hierarchy Process. Socio-Economic Planning Sciences, 20(6):369-373.

Arbel, A., T.L. Saaty and L.G. Vargas. 1987. Nuclear Balance and the Parity Issue - The Role of Intangibles in Decisions. IEEE Transactions on Systems, Man and Cybernetics, 17(5):821-828.

Assimakopoulos, N.A. 1989. Establishment of a Management Information System. Industrial Management & Data Systems (UK), 2:1-79.

Associated Press. 1990. "Weld county will join water district to battle Thornton over transfer." Denver Post, Denver, May 15.

Baker, M.N. 1949. The Quest For Pure Water. American Water Works Association, New York.

Banai-Kashani, R. 1989. A New Method for Site Suitability Analysis - The Analytic Hierarchy Process. Environmental Management, 13(6):685-693.

Bardwell, L.V. 1991. Problem-Framing: A Perspective on Environmental Problem Solving. Environmental Management, 15(6):603-612.

Beck, M.B. (ed.). 1987. Systems Analysis In Water Quality Management. International Association On Water Pollution Research And Control, Pergamon Press, New York.

Bell, H.F. 1989. Water Quality Information Systems: Past, Present & Future, An industrial Perspective. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Bell, H.F. 1991a. "Managing a Groundwater Quality Monitoring Program". Presentation at Design of Water Quality Monitoring Networks Short Course, Colorado State University, Fort Collins, June.

Bell, H.F. 1991b. "Non-Detects: The Problem With Not Detecting Something". Presentation at Design of Water Quality Monitoring Networks Short Course, Colorado State University, Fort Collins, June.

Belton, V. 1986. A Comparison of the Analytic Hierarchy Process and a Simple Multi-Attribute Value Function. European Journal of Operations Research, 26:7-21.

Belton, V. and T. Gear. 1982. On a Short-coming of Saaty's Method of Analytical Hierarchies. Omega, 11(3):228-230.

Bernhard, R.H. and J.R. Canada. 1990. Some Problems in Using Benefit/Cost Ratios with the Analytic Hierarchy Process. Engineering Economist, 36(1):56-65.

Black, P.E., and S.J. Nix (eds.). 1987. Proceedings of the Symposium on Monitoring, Modeling and Mediating Water Quality, American Water Resources Association.

Blacker, S.M., and S. Fratoni. 1990. Data Quality and the Environment. Quality, 29(4):38-42.

Bloem, D.M., and J.L. Glicker. 1989. The Evolution of a Water Utility's Water Quality Information System. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Brathwaite, K.S. 1990. Database Management and Control. McGraw-Hill, New York.

Brown, R.M., N.I. McClelland, R.A. Deininger, and R.G. Tozer. 1970. A water quality index-do we dare? Water and Sewage Works, pp. 339-343, October.

Bryson, J. 1970. The Evaluation and Interpretation of Water Quality Data. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Canada, J.R. and G.L. Hodge. 1988. Microcomputer Software Costing Less Than $1000 for Economic and Multi-Attribute Decision Analysis. Engineering Economist, 33(2):130-144.

Caravella, R.T. 1989. Aligning IS With User Expectations. Journal of Information Systems Management, 6(2):76-82.

Carter, M.P. 1985a. The Valuing of Management Information, Part I: The Bayesian Approach. Journal of Information Science, 10:1-9.

Carter, M.P. 1985b. The Valuing of Management Information, Part II: Using the Cost of Not Having Information. Journal of Information Science, 10:51-58.

Carter, M.P. 1985c. The Valuing of Management Information, Part IV: A Practical Approach. Journal of Information Science, 10:143-147.

Cerrulo, M.J. 1980. Information System Success Factors. Journal of Systems Management, 31(12):11.

Chase, W.P. 1974. Management of System Engineering. John Wiley & Sons, New York.

Chesnut, H. 1967. Systems Engineering Methods. John Wiley & Sons, New York.

Churchman, C.W. 1971. The Design of Inquiring Systems: Basic Concepts of Systems and Organization. Basic Books, Inc., New York.

Churchman, C.W. 1979. The Systems Approach And Its Enemies, Basic Books, Inc., New York.

Clark, M.J.R., and P.H. Whitfield. 1993. A Practical Model Integrating Quality Assurance Into Environmental Monitoring. Water Resources Bulletin, 29(1):119-130.

Clark, R.N. 1950. Discussion of Sampling for Effective Evaluation of Stream Pollution by C.J. Velz. Sewage and Industrial Wastes, 22(5):683-684.

Cleary, E.J. 1970. The Need for Data in Managing Water Quality. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Conrath, D.W., C.A. Higgins and A.R. Montazemi. 1987. Evaluating Information in Ill-Structured Decision Environments. Journal of the Operational Reserarch Society, 38(5):375-385.

Daft, R.L. 1991. Management, 2nd ed. Dryden Press, Chicago.

Davis, G.B. 1979. Comments on the Critical Success Factors Method for Obtaining Management Requirements, in article by John F. Rockart. MIS Quarterly, 3(3):57-58.

Davos, C.A. 1987. Group Environmental Valuation - Suitability of Single-Interest Approaches. Journal of Environmental Management, 25(2):97-111.

Dawdy, D.R. 1979. The Worth of Hydrologic Data. Water Resources Research, 15(6):1726-1732.

Dearden, J. 1972. MIS Is A Mirage. Harvard Business Review, January-February.

Decision Support Software Inc. 1984. Expert Choice, User Manual. McLean, Virginia.

Dennehy, K. 1994. U.S. Geological Survey. Informal discussion, August.

Dillman, D.A. 1978. Mail and Telephone Surveys. John Wiley & Sons, New York.

Dinardo, G., B. Golden and D. Levy. 1989. Using Decision Analysis to Manage Maryland River Herring Fishery - An Application of AHP. Journal of Environmental Management, 29(2):193-213.

Dominick, W.D. 1987. A Performance Measurement and Evaluation Environment for Information Systems. Information Processing & Management (UK), 23(1):7-15.

Dyer, J.S. 1990a. Remarks on the Analytic Hierarchy Process. Management Science, 36(3):249-258.

Dyer, J.S. 1990b. A Clarification of 'Remarks on the Analytic Hierarchy Process'. Management Science, 36(3):274-275.

Dyer, J.S. and R.E. Wendell. 1985. "A Critique of the Analytic Hierarchy Process". Working Paper 84/84-4-24, Department of Management, University of Texas at Austin.

Dyer, R.F., and E.H. Forman. 1992. Group Decision Support with the ILL Analytic Hierarchy Process. Decision Support Systems, 8(2):99-124.

Eagen, P.D., and S.J. Ventura. 1993. Enhancing Value of Environmental Data: Data Lineage Reporting. Journal of Environmental Engineering, 119(1):5-16.

Edwards, M.D. 1970. Compatibility of Systems and Interchange of Data. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

El-Shaarawi, A.H., and R.E. Kwiatkowski (eds.). 1986. Statistical Aspects of Water Quality Monitoring. Elsevier, Amsterdam.

Ellis, D.O., and F.J. Ludwig. 1962. Systems Philosophy. Prentice Hall, Inc, Englewood Cliffs, New Jersey.

Ellis, K.V. and S.L. Tang. 1991. Waste-Water Treatment Optimization Model for Developing World. ASCE Journal of Environmental Engineering, 117(4):501-518.

Environmental Board, National Academy of Sciences. 1970. "Institutions for Effective Management of the Environment". Report of the Environmental Study Group, National Academy of Engineering, Washington D.C.

Environmental Pollution Panel. 1965. Restoring the Quality of Our Environment. President's Science Advisory Committee, The White House, Washington, D.C.

Epstein, B.J. and W.R. King. 1982. An Experimental Study of the Value of Information. Omega, 10(3):249-258.

Erkut, E. and S.R. Moran. 1991. Locating Obnoxious Facilities in the Public Sector; An Application of the Analytic Hierarchy Process to Municipal Landfill Siting Decisions. Socio-Economic Planning Sciences, 25(2):89-100.

Everett, L.G. and K.D. Schmidt, (eds.). 1978. Establishment of Water Quality Monitoring Programs. American Water Resources Association, Minneapolis.

Fan, L.T., J.S. Shasty, and L.E. Erickson. 1970. On the Analysis and Use of Water Quality Data. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Feltham, G.A. 1968. The Value of Information. The Accounting Review, 43(4):684-696.

Fitchner, J. 1986. On Deriving Priority Vectors from Matrices of Pairwise Comparisons. Socio-Economic Planning Sciences, 20(6):341-345.

Forman, E.H. 1990. AHP is Intended for More Than Expected Value Calculations. Decision Sciences, 21(3):670-672.

Forman. E.H. 1992. Determining Certainty Factors with the Analytic Hierarchy Process. Expert Systems with Applications, 4(2):259-265.

Forrester, J.W. 1968. Principles of Systems. Wright-Allen Press, Cambridge, Massachusetts.

Frazelle, E. 1985. Suggested Techniques Enable Multi-Criteria Evaluation of Material Handling Alternatives. Industrial Engineering, 17(2):42-48.

Frost, R.A., (ed.). 1984. Database Management Systems. McGraw-Hill, New York.

Gholamnezhad, H. and T.L. Saaty. 1982. A Desired Energy Mix for the United States in the Year 2000: An Analytic Hierarchy Approach. International Journal of Policy Analysis and Information Systems, 6(1):47-64.

Gilbert, R.O. 1987. Statistical Methods For Environmental Pollution Monitoring. Van Nostrand Reinhold Company, New York.

Gilges, K. 1991. Eco-Audit: Green Eyeshades Take On a Whole New Meaning. Chemical Engineering, 98(5):82n-82v.

Gindelberger, J. and B. Hatami. 1991. Informal discussions.

Godfrey, J.T., and T.R. Prince. 1971. The Accounting Model From An Information Systems Perspective. The Accounting Review, 46(1):75-89.

Goicoechea, A., E.Z. Stakhiv, and F. Li. 1992. Experimental Evaluation of Multiple Criteria Decision Models for Application to Water Resources Planning. Water Resources Bulletin, 28(1):89-102.

Golden, B.L., E.A. Wasil, and P.T. Harker. 1989. The Analytic Hierarchy Process: Application and Studies. Springer-Verlag, Berlin.

Goldratt, E.M., and R.E. Fox. 1988. Theory of Constraints Journal. 1(3) Chapter 3.

Goldratt, E.M., and R.E. Fox. 1989. Theory of Constraints Journal. 1(4) Chapter 4.

Goode, H.H., and R.E. Machol. 1957. System Engineering. McGraw-Hill, New York.

Gorman, M.M. 1991. Database Mangement Systems: Understanding and Applying Database Technology. QED Information Sciences, Inc., Wellesley, Massachusetts.

Government Institutes, Inc. 1991. Environmental Law Handbook, 11th ed. Rockville, Maryland.

Gorry, G.A., and M.S.S. Morton. 1971. A Framework for Management Information Systems. Sloan Management Review, 13:55-70, Fall.

Greengard, T.C., and M.A. Anderson. 1989. Soil and Water Quality Monitoring Programs. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Griffin, M., W. Kreutzberger and P. Binney. 1991. Research Needs for Nonpoint Source Impacts. Water Environment & Technology, 3(6):60-64.

Grigg, N.S. 1989. Regionalization in Water Supply Industry: Status and Needs. Journal of Water Resources Planning and Management, 115(3):367-378.

Grigg, N.S. 1991. Closure comments on "Regionalization in Water Supply Industry: Status and Needs" by N.S. Grigg. Journal of Water Resources Planning and Management, 117(4):501-502.

Grigg, N.S. 1992. Discussion of "Water Management: Challenge and Opportunity" by W. Viessman. Journal of Water Resources Planning and Management, 118(1):102-104.

Grigg, N.S., and E.C. Vlachos. 1993. Drought and Water Supply Management: Roles and Responsibilities. Journal of Water Resources Planning and Management, 119(5):531-541.

Grigg, N.S. 1993. New Paradigm for Coordination in Water Industry. Journal of Water Resources Planning and Management, 119(5):572-587.

Grobler, D.C., J.N. Rossow, P. van Eeden and M. Oliveira. 1987. Decision Support System for Selecting Eutrophication Control Strategies. Systems Analysis in Water Quality Management, Pergamon Press, New York, pp.219-230.

Gray, P. 1984. Book Review of The Analytic Hierarchy Process and Decision Making for Leaders, by Thomas L. Saaty. Interfaces, 14(3):97-99.

Gunton, T. 1990. Inside Information Technology: A Practical Guide To Management Issues. Prentice Hall, New York.

Hamalainen, R.P., and Seppalainen, T.O. 1986. The Analytic Network Process in Energy Policy Planning. Socio-Economic Planning Sciences, 20(6):399-405.

Hamilton, S., and N.L. Chervany. 1981a. Evaluating Information System Effectiveness-Part I: Comparing Evaluation Approaches. MIS Quarterly, 5(3):55-69.

Hamilton, S., and N.L. Chervany. 1981b. Evaluating Information System Effectiveness-Part II: Comparing Evaluator Viewpoints. MIS Quarterly, 5(4):79-86.

Haney, P.D., and J. Schmidt. 1958. Representative Sampling and Analytical Methods in Stream Studies. Sewage and Industrial Wastes, 30(6):812-820.

Harcum, J.B. 1990. "Water Quality Data Analysis Protocol Development". Doctoral Dissertation, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, Summer.

Harker, P.T. 1987. Derivatives of the Perron Root of a Positive Reciprocal Matrix - With Application to the Analytic Hierarchy Process. Applied Mathematics and Computation, 22:217-232.

Harker, P.T., and L.G. Vargas. 1987. The Theory of Ratio Scale Estimation: Saaty's Analytic Hierarchy Process. Management Science, 33(11):1383-1403.

Harker, P.T. and L.G. Vargas. 1990. Reply to the 'Remarks on the Analytical Hierarchy Process' by J.S. Dyer. Management Science, 36(3):269-273.

Harris, J. 1988. "Statistical Analysis Of Ground Water Quality: Interaction Of Deterministic And Stochastic Components". Doctoral Dissertation, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, Spring.

Hays, W.L. 1963. Statistics. Holt, Rinehart and Winston, New York.

Hendricks, D.W. 1988. Lecture Materials for CE 540, Unit Operations of Environmental Engineering, Colorado State University, Fort Collins, Colorado.

Hellriegel, D., and Slocum, J.W. 1992. Management, 6th ed. Addison-Wesley Publishing Company, Reading, Massachusetts.

Helsel, D.R. 1990. Less than obvious; Statistical treatment of data below the detection limit. Environmental Science and Technology, 24(12):1766-1774.

Hicks, J.O. 1984. Management Information Systems: A User Perspective. West Publishing Company, St. Paul.

Hipel, K.W. 1992. Multiple Objective Decision Making in Water Resources. Water Resources Bulletin, 28(1):3-12.

Holder, R.D. 1990. Some Commments on the Analytic Hierarchy Process. Journal of the Operational Research Society, 41(11):1073-1076.

Holder, R.D. 1991. Response to the Response. Journal of the Operational Research Society, 42(10):914-918.

Horton, R.K. 1965. An Index Number System for Rating Water Quality. Journal Water Pollution Control Federation, 37(3):300-306.

Hotto, H.P. 1992. Thornton Northern Project Water Quality Monitoring and Information System. Personal communications and investigative records.

Hotto, H.P., and T.G. Sanders. 1991. Water Quality Monitoring and Information System. Unpublished project report to the City of Thornton, December.

Hotto, H.P. 1994. Performance Evaluation of Water Quality Monitoring and Information Programs - Summary of water quality professionals responses to survey questionnaire.

Hughes, W.R. 1986. Deriving Utilities Using the Analytic Hierarchy Process. Socio-Economic Planning Sciences, 20(6):393-395.

Hussain, D. and K.M. Hussain. 1985. Information Processing Systems for Management, 2nd ed. Richard D. Irwin Inc., Homewood, Illinois.

Hussain, D. and K.M. Hussain. 1988. Managing Computer Resources, 2nd ed. Richard D. Irwin Inc., Homewood, Illinois.

Hussein, F.M., M.A. Obeid, and K.S. El-Malahy. 1987. Site Selection of a Dual Purpose Nuclear Power Plant in Saudi Arabia. Nuclear Technology, 79:311-321, December.

IHD-WHO Working Group on Quality of Water. 1978. Water Quality Surveys. United Nations Educational, Scientific and Cultural Organization, Paris, and World Health Organization, Geneva.

Iselin, E.R. 1988. The Effects of Information Load and Information Diversity on Decision Quality in a Structured Decision Task. Accounting, Organizations and Society, 13:147, April.

Iselin, E.R. 1989. The Impact of Information Diversity on Information Overload Effects in Unstructured Managerial Decision Making. Journal of Information Science, 15:163-173.

Iselin, E.R. 1990. Information, Uncertainty and Managerial Decision Quality: An Experimental Investigation. Journal of Information Science, 16:239, July.

Ives, B., and M.H. Olson. 1984. User Involvement and MIS Success: A Review of Research. Management Science, 30(5):586-603.

Jarke, M. (ed.). 1986. Managers, Micros And Mainframes: Integrating Systems for End-Users. John Wiley & Sons Ltd, Chichester.

Johnson, B.R. 1970. Systems Approach to Water Quality Planning and Operation. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Johnson, C.R. 1980. Constructive Critique of a Hierarchical Prioritization Scheme Employing Paired Comparisons. Proceedings of the International Conference of Cybernetics and Society of the IEEE, Institute of Electrical Engineers, Cambridge, Massachusetts, pp. 373-378.

Kamenetzky, R.D. 1982. The Relationship Between the Analytic Hierarchy Process and the Additive Value Function. Decision Sciences, 13(4):702-713.

Kerrigan, J.E. (ed.). 1970. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management. Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Kepner, C.H., and B.B. Tregoe. 1976. The Rational Manager, 2nd ed. Kepner-Tregoe Inc., Princeton, New Jersey.

Khorramshahgol, R., Y. Gousty and H. Azani. 1988. An Integrated Approach to Project Evaluation and Selection. IEEE Transactions on Engineering Management, 35(4):265-270.

Knight-Sinner, J. 1990. "Water district to fight Thornton Plan." Fort Collins Coloradoan, Fort Collins, Colorado, May 12.

Ko, S. 1989. "Optimizing Reservoir Systems Operation with Multiobjective Decision Analysis". Doctoral Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Ko, S., D.G. Fontane, and J.W. Labadie. 1992. Multiobjective Optimization of Reservoir Systems Operation. Water Resources Bulletin, 28(1):111-127.

Koch, R.W., T.G. Sanders, and H.J. Morel-Seytoux. 1982. Regional Detection Of Change In Water Quality Variables. Water Resources Bulletin, 18(5).

Koehler, K.G. 1988. Keeping Tabs On Performance. CMA-The Management Accounting Magazine, 62:20, November.

Lahiri, S.B. 1992. Skill-Sets Migration Planning Via Analytic Hierarchy Process. Computers and Operations Research, 19(5):313-320.

Landwehr, J.M. 1979. A Statistical View of a Class of Water Quality Indices. Water Resources Research, 15(2):460-468.

Lane, E.F. and W.A. Verdini. 1989. A Consistency Test for AHP Decision Makers. Decision Sciences, 20(3):575-590.

Lane, L.J., D.R. Davis, and S. Nnaji. 1979. Termination of Hydrologic Data Collection (A Case Study). Water Resources Research, 15(6):1851-1858.

Langbein, W.B. 1979. Overview of Conference on Hydrologic Data Networks. Water Resources Research, 15(6):1867-1871.

Langford, R.H. and W.W. Doyel. 1970. Coordination - A Key to Effective Water Data Management. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Langford, R.H., and F.P. Kapinos. 1979. The National Water Data Network: A Case History. Water Resources Research, 15(6):1687-1691.

Lauro, G.L., and A.P.J. Vepsalainen. 1986. Assessing Technology Portfolios For Contract Competition: An Analytic Hierarchy Process Approach. Socio-Economic Planning Sciences, 20(6):407-415.

Leavitt, A.M. 1970. Visual Data Presentation. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Lee, Y.W., I. Bogardy and J. Stansbury. 1991. Fuzzy Decision-Making in Dredged-Material Management. ASCE Journal of Environmental Engineering, 117(5):614-630.

Lettenmaeir, D.P. 1979. Dimensionality Problems in Water Quality Network Design. Water Resources Research, 15(6):1692-1700.

Liebman, H. 1969. Atlas of Water Quality, Methods and Practical Conditions. R. Oldenbourg, Munich.

Loftis, J.C. 1978. "Statistical And Economic Considerations For Improving Regulatory Water Quality Monitoring Networks". Doctoral Dissertation, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, Fall.

Loftis, J.C., and R.C. Ward. 1978. Statistical Tradeoffs in Monitoring Network Design. Proceedings of the AWRA Symposium on Establishment of Water Quality Monitoring Programs, San Francisco, California, June, pp. 36-48.

Loftis. J.C., and R.C. Ward. 1980a. Sampling Frequency Selection For Regulatory Water Quality Monitoring. Water Resources Bulletin, 16(3):501-507.

Loftis. J.C., and R.C. Ward. 1980b. Water Quality Monitoring-Some Practical Sampling Frequency Considerations. Environmental Management, 4(6):521-526.

Loftis, J.C., R.C. Ward. 1982. Routine Fixed-Station Sampling - An Integral Part of Regulatory Water Quality Monitoring. Environmental Management, 6(4):279-280.

Loftis, J.C., R.H. Montgomery, J. Harris, D. Nettles, P.S. Porter, R.C. Ward, and T.G. Sanders. 1986. "Monitoring Strategies For Groundwater Quality Management". U.S.G.S. Grant 14-08-0001-G-1060, Colorado State University, Fort Collins, April.

Loftis, J.C., J. Harris, and R.H. Montgomery. 1987a. Detecting Changes in Ground Water Quality at Regulated Facilities. Ground Water Monitoring Review, 7(1):72-76.

Loftis, J.C., P.S. Porter, and G. Settembre. 1987b. Statistical Analysis of Industrial Wastewater Monitoring Data. Journal Water Pollution Control Federation, 59(3):145-151.

Loftis, J.C., G.B. McBride, and J.C. Ellis. 1991. Considerations of Scale in Water Quality Monitoring and Data Analysis. Water Resources Bulletin, 27(2):255-264.

Loganathan, G.V. and D. Bhattacharya. 1990. Goal-Programming Techniques for Optimal Reservoir Operations. ASCE Journal of Water Resources Planning and Management, 116(6):820-838.

Lucas, H.C. 1975. Why Information Systems Fail. Columbia University Press, New York.

Lucas, H.C. 1985. The Analysis, Design And Implementation Of Information Systems, 3rd ed. McGraw-Hill, New York.

Lyon, W.A. 1970a. Water Quality Information Systems - The Key to Cleaner Waters. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management. Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Lyon, W.A. 1970b. Symposium Summation. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Machol, R.E., and R.F. Miles, Jr. 1973. The Engineering of Large Scale Systems, in R.F. Miles, Jr., (ed.), Systems Concepts. John Wiley & Sons, New York.

MacDonald, L., and A. Smart. 1992. "Beyond the Guidelines: Practical Lessons for Monitoring". Paper presented at the Workshop on Improving Natural Resource Management through Monitoring, Oregon State University, Corvallis, Oregon, March 10-11.

Maddock, T. 1973. Management Model as a Tool for Studying the Worth of Data. Water Resources Research, 9(2):270-280.

Mader, C., and R. Hagin. 1974. Information Systems: Technology, Economics, Applications. Science Research Associates, Inc., Chicago.

Magnien, R.E. and M.S. Haire. 1989. Maryland's Chesapeake Bay Water Quality Monitoring Program: An Estuarine Water Quality Information System. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Mar, B.W., R.R. Horner, D.P. Lettenmaier, R.N. Palmer and J.S. Richey. 1986. Data Acquisition - Cost-Effective Methods for Obtaining Data on Water Quality. Environmental Science & Technology, 20(6):545-551.

Masuda, T. 1990. Hierarchical Sensitivity Analysis of Priority Used in Analytic Hierarchy Process. International Journal of Systems Science, 21(2):415-427.

McCosh, A.M., M. Rahman, and M.J. Earl. 1981. Developing Managerial Information Systems. John Wiley and Sons, New York.

McFarlan, F.W., R.L. Nolan, and D.P. Norton. 1973. Information Systems Administration. Holt, Rinehart and Winston, Inc., New York.

McGregor, D, 1967. The Professional Manager. McGraw-Hill, New York.

McKee, J.E. 1952. Water Quality Criteria. Publication No. 3, California State Water Quality Board, Sacramento.

McKee, J.E., and H.W. Wolf, (eds.). 1963. Water Quality Criteria, 2nd ed. Publication No. 3-A, California State Water Quality Control Board, Sacramento.

McLeod, R. 1986. Management Information Systems. Science Research Associates, Inc., Chicago.

Medine, A. 1990. "Water Quality Assessment Methodology". Seminar at Colorado State University, March 22.

Mendoza, G.A. and W. Sprouse. 1989. Forest Planning and Decision-Making Under Fuzzy Environments - An Overview and Illustration. Forest Science, 35(2):481-502.

Messer, J.J. 1989. Why Monitor? Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Miles, R.F. Jr., (ed.). 1973. Systems Concepts. John Wiley & Sons, New York.

Miller, G.A. 1956. The Magical Number Seven Plus or Minus Two: Limits on Our Capacity for Processing Information. Psychological Review, 63:81-97, March.

Millet, I., and P.T. Harker. 1990. Globally Effective Questioning in the Analytic Hierarchy Process. European Journal of Operational Research, 48(1):88-97.

Mock, T.J. 1971. Concepts of Information Value and Accounting. The Accounting Review, 46(4):765-778.

Moody, D.W. 1970. Organizing a Data Collection Program for Water Resources Planning, Development and Management. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Morgan, P.V. 1970. Basic Data Requirements to Evaluate Water Pollution in Quality Control Programs. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Morgan, P.V. 1970. Effective Use of Data. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Moss, M.E. 1979. Some Basic Considerations in the Design of Hydrologic Data Networks. Water Resources Research, 15(6):1673-1676.

Moss, M.E. 1989. Water-Quality Data In The Information Age. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Moss, M., D. Lettenmaier, and E.F. Wood. 1978. On the Design of Hydrologic Data Networks. Transactions American Geophysical Union, 59(8):772-775.

Munroe, M., and G. Davis. 1977. Defining Management Information Needs: A Comparison of Methods. MIS Quarterly, pp.55-67, June.

Murdock, G.B. 1970. A Systems Approach to Water Quality Data Management. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Murray, D.M. and K. VonGadow. 1991. Prioritizing Mountain Catchment Areas. Journal of Environmental Management, 32(4):357-366.

Mustafa, M.A. and J.F. Albahar. 1991. Project Risk Assessment Using the Analytic Hierarchy Process. IEEE Transactions on Engineering Management, 38(1):46-52.

National Research Council. 1990. A Review of the U.S.G.S. National Water Quality Assessment Pilot Program. National Academy Press, Washington, D.C.

Nelson, C.W., and R. Balachandra. 1991. Choosing the Right Expert System Building Approach. Decision Sciences, 22(2):354-368.

Nichols, A.B. 1990. The Costs of Environmental Protection. Water Environment & Technology, 2(11):47-53.

Nolan, R.L. 1971. Systems Analysis For Computer-Based Information Systems Design. DATA BASE, 3(4).

O'Connell, R. 1970. Using Computers as a Tool in Water Quality Management. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

O'Leary, T.J., and B.K. Williams. 1985. Computers and Information Processing. The Benjamin/Cummings Publishing Company, Menlo Park, California.

Olson, D.L., M. Venkataramanan, and J.L. Mote. 1986. A Technique Using Analytical Hierarchy Process In Multiobjective Planning Models. Socio-Economic Planning Sciences, 20(6):361-368.

Ott, W.R. 1978. Environmental Indices: Theory and Practice. Ann Arbor Science Publishers Inc., Ann Arbor.

Parker, M.M. and R.J. Benson, with H.E. Trainor. 1988. Information Economics. Prentice Hall, Englewood Cliffs, New Jersey.

Partovi, F.Y. 1991. An Analytic Hierarchy Approach to Activity Based Costing. International Journal of Production Economics, 22(2):151-161.

Partovi, F.Y., J. Burton, and A. Banjeree. 1990. Application of Analytical Hierarchy Process in Operations Management. International Journal of Operations and Production Management, 10(3):5-19.

Perry, J.A., R.C. Ward, and J.C. Loftis. 1984. Survey of State Water Quality Monitoring Programs. Environmental Management, 8(1):21-26.

Petri, L.R. 1970. Need for Water Quality Data in Planning Water Resource Developments. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Pomeroy, R.D., and G.T. Orlob. 1967. Problems of Setting Standards and of Surveillance for Water Quality Control. Publication No. 36, California State Water Quality Board, Sacramento, California.

Pontius, F.W. 1991a. Regulatory Status Report. Journal American Water Works Association, 83(1), pp. 12 ff.

Pontius, F.W. 1991b. Clean Water Act Reauthorization. Journal American Water Works Association, 83(6), pp. 18 ff.

Porter, P.S. 1986. "Statistical Analysis Of Water Quality Data Affected By Limits Of Detection". Doctoral Dissertation, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins, Fall.

Praskins, W. 1989. Monitoring To Improve Decision-Making In EPA And State Surface Water Quality Programs. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Rademacher, R.A. 1989. Critical Factors for System Success. Journal of Systems Management, 40(6):15-17.

Ramo, S. 1973. The Systems Approach. in R.F. Miles, Jr., (ed.), Systems Concepts, John Wiley & Sons, New York.

Raymond, L. 1987. Information Systems Design for Project Manangement: A Data Modeling Approach. Project Management Journal, 18(4):94-99.

Rhett, J.T. 1975. Billions for Clean Water. EPA Journal, 1(8):2.

Ridgely, M.A. 1992. Selection of Water-Supply Projects Under Drought. Journal of Environmental Systems, 2(3):207-221.

Rivard, E., and K. Kaiser. 1989. The Benefit of Quality IS. Datamation, 35(2):53-58, January 15.

Robey, D. 1979. User Attitudes and Management Information System Use. Academy of Management Journal, 22(3):527-538.

Roche, W.M. 1970. Organizing a Data Collection Program. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Rockart, J. 1979. Chief Executives Define Their Own Needs. Harvard Business Review, 57(2):81-93.

Roig, L.C. 1984. A Kalman Filter Application For The Design Of Water Quality Monitoring Programs. Master's Thesis, Department of Earth Resources, Colorado State University, Fort Collins, Summer.

Roper-Lowe, G.C. and J.A. Sharp. 1990. The Analytic Hierarchy Process and its Application to an Information Technology Decision. Journal of the Operational Research Society, 41(1):49-59.

Ross, R.G. 1978. Data Base Systems: Design Implementation and Management. American Management Associations, New York.

Rubin, B.M. 1986. Information Systems for Public Management: Design and Implementation. Public Administration Review (Special Issue), Vol.46, November.

Rumple, J.R., and V.E. Hampel, (eds.). 1984. Database Management In Science and Technology, North-Holland, Amstersdam.

Russo, J.E., and P.J.H. Schoemaker. 1989. Decision Traps: The Ten Barriers To Brilliant Decision-Making and How to Overcome Them. Simon and Schuster, New York.

Ryan, B. 1994. Informal discussions at Colorado State University, June.

Saaty, T.L. 1977a. A Scaling Method for Priorities in Hierarchical Structures. Journal of Mathematical Psychology, 15(3):234-281.

Saaty, T.L. 1977b. Scenarios and Priorities in Transport Planning: Application to Sudan. Transportation Research, 11(3):343-350.

Saaty, T.L. 1977c. The Sudan Transport Study. Interfaces, 8(1):37-57.

Saaty, T.L. 1977d. Modeling Unstructured Decision Problems: A Theory of Analytical Hierarchies. Proceedings of the First International Conference on Mathematical Modeling, University of Missouri-Rolla, 1:59-77.

Saaty, T.L. 1978a. Exploring the Interface Between Hierarchies, Multiple Objectives and Fuzzy Sets. Fuzzy Sets and Systems, 1(1):57-68.

Saaty, T.L. 1978b. Modeling Unstructured Decision Problems: The Theory of Analytical Hierarchies. Mathematics and Computers in Simulation, 20(3):147-157.

Saaty, T.L. 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.

Saaty, T.L. 1982a. Decision Making for Leaders; The Analytic Hierarchy Process for Decisions in a Complex World. Lifetime Learning Publications, a Division of Wadsworth, Atlanta, Georgia.

Saaty, T.L. 1982b. The Analytic Hierarchy Process: A New Approach to Deal with Fuzziness in Architecture. Architectural Science Review, 25(3):64-69.

Saaty, T.L. 1983. Priority Setting in Complex Problems. IEEE Transactions on Engineering Management, EM-30(2):140-155.

Saaty, T.L. 1986. Axiomatic Foundation of the Analytic Hierarchy Process. Management Science, 32:841-855.

Saaty, T.L. 1987a. Rank Generation, Preservation, and Reversal in the Analytic Hierarchy Process. Decision Sciences, 18:157-177.

Saaty, T.L. 1987b. Risk - Its Priority and Probability: The Analytic Hierarchy Process. Risk Analysis, 7(2):159-172.

Saaty, T.L. 1989a. Decision Making, Scaling, and Number Crunching. Decision Sciences, 20(2):404-409.

Saaty, T.L. 1989b. Hierarchical-Multiobjective Systems. Control - Theory and Advanced Technology, 5(4):485-489.

Saaty, T.L. 1990a. Multicriteria Decision Making; The Analytic Hierarchy Process, 2nd ed. RWS Publications, Pittsburgh.

Saaty, T.L. 1990b. Decision Making for Leaders; The Analytic Hierarchy Process for Decisions in a Complex World, 2nd ed. RWS Publications, Pittsburgh, 1990.

Saaty, T.L. 1990c. An Exposition of the AHP in Reply to the Paper 'Remarks on the Analytic Hierarchy Process'. Management Science, 36(3):259-268.

Saaty, T.L. 1991a. Response to Holder's Comments on the Analytic Hierarchy Process. Journal of the Operational Research Society, 42(10):909-914.

Saaty, T.L. 1991b. Response to the Response to the Response. Journal of the Operational Research Society, 42(10):918-924.

Saaty, T.L. and E. Erdener. 1979. A New Approach to Performance Measurement - The Analytic Hierarchy Process. Design Methods and Theories, 13(2):64-72.

Saaty, T.L. and H. Gholamnezhad. 1982. High-Level Nuclear Waste Management: Analysis of Options. Environment and Planning B, 9(2):181-196.

Saaty, T.L., and K.P. Kearns. 1991. Analytical Planning; The Organization of Systems. RWS Publications, Pittsburgh.

Saaty, T.L. and L.G. Vargas. 1984a. Comparison of Eigenvalue, Logarithmic Least Square, and Least Square Methods in Estimating Ratios. Journal of Mathematical Modeling, 5:309-324.

Saaty, T.L. and L.G. Vargas. 1984b. The Legitimacy of Rank Reversal. Omega, 12(5):513-516.

Saaty, T.L. and L.G. Vargas. 1991. The Logic of Priorities: Applications in Business, Energy, Health and Transportation, 2nd ed. RWS Publications, Pittsburgh.

Sanders, T.G. 1974. "Rational Design Criteria for a River Quality Monitoring Network". Doctoral Dissertation, Civil Engineering Department, University of Massachusetts.

Sanders, T.G. 1980. Water Quality As A Stochastic Process. ASCE Reprint 80-089, American Society of Civil Engineers, April.

Sanders, T.G., and D.D. Adrian. 1978. Sampling Frequency for River Quality Monitoring. Water Resources Research, 14(4):569-576.

Sanders, T.G. and R.C. Ward. 1978. Relating Stream Standards To Regulatory Water Quality Monitoring Practices. Establishment Of Water Quality Monitoring Programs, American Water Resources Association, pp.339-348, June.

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, 2nd ed. Water Resources Publications, Littleton, Colorado.

Schaeffer, D.J. 1982. Effective Data Use in Regulatory Water Quality Monitoring. Environmental Management, 6(4):280-281.

Schenkerman, S. 1991. Use and Abuse of Weights in Multiple Objective Decision Support Models. Decision Sciences, 22(2):369-378.

Schniederjans, M.J. and R.L. Wilson. 1991. Using the Analytic Hierarchy Process and Goal Programming for Information System Project Selection. Information and Management, 20(5):333-342.

Schoner, B. and W.C. Wedley. 1989. Ambiguous Criteria Weights in AHP: Consequences and Solutions. Decision Sciences, 20(3):462-475.

Schoner, B., W.C. Wedley, and E.U. Choo. 1992. A Rejoinder to Forman on AHP, with Emphasis on the Requirements of Composite Ratio Scales. Decision Sciences, 23(2):509-517.

Schroeder, R.G., and I. Benbasat. 1975. An Experimental Evaluation of the Relationship of Uncertainty in the Environment to Information Used By Decision Makers. Decision Sciences, 6:556-567, July.

Settani, J.A. 1986. Managing Records as a Viable Resource. Journal of Information and Image Management, 19(12):10-13.

Seward, H.H. 1975. Evaluating Information Systems, in F.W. McFarlan and R.L. Nolan, (eds.), The Information Systems Handbook. The Dow Jones Irwin, Homewood, Illinois.

Shafer, E.L. and J.B. Davis. 1989. Making Decisions About Environmental Management When Conventional Economic-Analysis Cannot Be Used. Environmental Management, 13(2):189-197.

Shannon, C.E., and W. Weaver. 1949. The Mathematical Theory of Communication. The University of Illinois Press, Urbana, Illinois.

Sharda, R., S.H. Barr, and J.C. McDonnell. 1988. Decision Support System Effectiveness: A Review and an Empirical Test. Management Science, 34:139, February.

Showen, C.R. 1970. Fundamentals of Systems Design. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Sink, D.S. 1985. Productivity Management: Planning, Measurement and Evaluation, Control and Improvement. John Wiley and Sons, New York.

Sink, D.S. 1991. The Role Of Measurement In Achieving World Class Quality And Productivity Management. Industrial Engineering, 23(6):23.

Smillie, G.M. 1982. "Water Quality Assessment With Routine Monitoring Data". Master's Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Spring.

Smillie, G.M., and M. Flug. 1982. Guidelines For Water Quality Program Development In National Park Service Areas. Report No. 82-2, National Park Service Water Resources Support Laboratory, Colorado State University, Fort Collins, September.

Snavely, H.J. 1967. Accounting Information Criteria. The Accounting Review, 42(2):223-232.

Stansbury, J., W. Woldt, I. Bogardi and A. Bleed. 1991. Decision Support System for Water Transfer Evaluation. Water Resources Research, 27(4):443-451.

Steele, T.D. 1970. Beneficial Uses and Pitfalls of Historical Water Quality Data. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin.

Steele, T.D. 1987. Water Quality Monitoring Strategies. Hydrological Sciences Journal, 32(2):207-213.

Stokes, S.L. 1991. The New IS Manager For The 1990s. Journal of Information Systems Management, 8(1):44-50.

Subramanian, G.H., and M. Gershon. 1991. The Selection of Computer-Aided Software Engineering Tools: A Multi-Criteria Decision Making Approach. Decision Sciences, 22(5):1109-1123.

Sumnath, D.J. 1984. Productivity Engineering And Management. McGraw-Hill, New York.

Sygenex, Inc. 1989. CRITERIUM USER'S GUIDE. Sygenex, Inc., Redmond, Washington, 1989.

Tang, V. 1991. The Organizational Implications of an EIS Implementation. Journal of Systems Management, 42(11):10-12.

Taylor, C.H., and J.C. Loftis. 1989. Testing For Trend In Lake And Ground Water Quality Time Series. Water Resources Bulletin, 25(4):715-726.

Thomann, R.V. 1970. Lessons to be Learned When Collecting Valid Data. Proceedings of the National Symposium on Data and Instrumentation for Water Quality Management, Water Resources Center, University of Wisconsin, Madison, Wisconsin

Thomann, R.V. 1972. Systems Analysis And Water Quality Management. Environmental Research and Applications Inc., New York.

Thornton, B.M. 1972. "Procedures For The Development Of Urban Water Planning Objectives". Doctoral Dissertation, Graduate College in Industrial Engineering, Texas A&M University, December.

Thornton, B.M. 1991. "Relevance Trees and the Analytic Hierarchy Procedure (AHP) in Managerial Decision-Making: A Software Demonstration", Presentation at Colorado State University, November.

Train, R.E. 1975. The Challenge of 1975. EPA Journal, 1(1).

Tsichritzis, D.C., and F.H. Lochovsky. 1982. Data Models. Prentice-Hall Inc., Englewood Cliffs, New Jersey.

United States Council on Environmental Quality. 1974. Environmental Quality: The Fifth Annual Report of the Council on Environmental Quality. United States Government Printing Office, December.

United States Environmental Protection Agency. 1973. Data Acquisition Systems in Water Quality Management. Report No. EPA-R5-73-014, May.

United States Environmental Protection Agency. 1976a. Procedures for Evaluating Operations of Ambient Air Monitoring Networks. Report No. EPA-600/4-76-043, August.

United States Environmental Protection Agency. 1976b. Procedures for Evaluating Operations of Water Monitoring Networks. Report No. EPA-600/4-76-050, September.

United States Environmental Protection Agency. 1977. Development of a Methodology For Designing Carbon Monoxide Monitoring Networks. Report No. EPA-600/4-77-019, March.

United States Environmental Protection Agency. 1978a. Water Quality Indices: A Survey Of Indices Used In The United States. Report No. EPA-600/4-78-005, January.

United States Environmental Protection Agency. 1978b. Development of a Pollutant Monitoring System for Biosphere Reserves. Report No. EPA-600/4-78-052, September.

United States Environmental Protection Agency. 1978c. Carbon Monoxide Monitoring Network Design Methodology: Application in the Las Vegas Valley. Report No. EPA-600/4-78-053, September.

United States Environmental Protection Agency. 1979a. Surface Water Quality Parameters for Monitoring Oil Shale Development. Report No. EPA-600/4-79-018, March.

United States Environmental Protection Agency. 1979b. Regulating Water Quality Monitoring Networks: Statistical and Economic Considerations. Report No. EPA-600/4-79-055, August.

United States Environmental Protection Agency. 1984. National Water Quality Inventory: 1982 Report to Congress. Report No. EPA-440/2-84-006, February.

United States Environmental Protection Agency. 1985. National Water Quality Inventory: 1984 Report to Congress. Report No. EPA-440/4-85-029, August.

United States Environmental Protection Agency. 1986. National Surface Water Survey: National Stream Survey Phase 1 - Pilot Survey. Report No. EPA-600/4-86-026, December.

United States Environmental Protection Agency. 1987. National Water Quality Inventory: 1986 Report to Congress. Report No. EPA-440/4-87-008, November.

United States Environmental Protection Agency. 1989. An Evaluation Of Trend Detection Techniques For Use In Water Quality Monitoring Programs. Report No. EPA/600/3-89/037, March.

United States Environmental Protection Agency. 1990a. A Preliminary Analysis of the Public Costs of Environmental Protection: 1981-2000. Administration and Resources Management Report PM-225, May.

United States Environmental Protection Agency. 1990b. Near Coastal Program Plan for 1990: Estuaries. Report No. EPA/600/4-90/033, November.

United States Environmental Protection Agency. 1990c. Environmental Investments: The Cost Of A Clean Environment; A Summmary. Report No. EPA-230-12-90-084, December.

United States Environmental Protection Agency. 1991. Monitoring Guidelines to Evaluate Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska. Water Division Report No. EPA/910/9-91-001, May.

United States Environmental Protection Agency. 1993. R-EMAP Regional Environmental Monitoring and Assessment Program. Report No. EPA/625/R-93/012, September.

United States General Accounting Office. 1981a. Better Monitoring Techniques Are Needed To Assess The Quality Of Rivers And Streams, Volume I. Comptroller's Report To The Congress CED-81-30, April.

United States General Accounting Office. 1981b. Better Monitoring Techniques Are Needed To Assess The Quality Of Rivers And Streams, Volume II. Comptroller's Report To The Congress CED-81-30, April.

United States General Accounting Office. 1991a. Environmental Protection: Meeting Public Expectations with Limited Resources. Report To The Congress, June.

United States General Accounting Office. 1991b. Hazardous Waste: Data Management Problems Delay EPA's Assessment of Minimization Efforts. GAO/RCED-19-131, June 13.

Van Nievelt, A. 1984. Managing Productivity and Information Technology. Information Strategy: The Executive's Journal, 1(1):9-15.

Vargas, L. 1986. Utility Theory and Reciprocal Pairwise Comparisons: The Eigenvector Method. Socio-Economic Planning Sciences, 20(6):387-391.

Varis, O. 1989. The Analysis of Preferences in Complex Environmental Judgements - A Focus on the Analytic Hierarchy Process. Journal of Environmental Management. 28(4):283-294.

Veerakool, V. 1988. "An Analytical Hierarchy Process Approach to Establish the Systems Analyst's Knowledge Base for Selecting an Information Requirements Determination Strategy". Doctoral Dissertation, University of Missouri-Rolla.

Velz, C.J. 1950. Sampling for Effective Evaluation of Stream Pollution. Sewage and Industrial Wastes, 22(5):666-682, May.

Veryard, R. 1987. Future of Information System Design Methodologies. Information and Software Technology (UK), 29(1):33-37.

Vuk, D., B. Kozelj, and N. Mladineo. 1991. Application of multicriterional analysis on the selection of the location for disposal of communal waste. European Journal Of Operational Research, 55:211-217.

Ward, R.C. 1988. "Water Quality Monitoring As An Information System". Paper presented at the United States Environmental Protection Agency National Symposium on Water Quality Assessment, Annapolis, Maryland, June.

Ward, R.C. 1989. Water Quality Monitoring - A Systems Approach To Design. Proceedings of the International Symposium on the Design of Water Quality Information Systems, Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Ward, R.C. 1994. Informal discussion, June 6.

Ward, R.C., K.S. Nielsen, and M. Bundgaard-Nielsen. 1976. Design Of Monitoring Systems For Water Quality Management. Contributions from the Water Quality Institute, Danish Academy Of Technical Sciences, Horsholm, Denmark, December.

Ward, R.C., J.C. Loftis, K.S. Nielsen, and R.D. Anderson. 1979. Statistical Evaluation of Sampling Frequencies in Monitoring Networks. Journal Water Pollution Control Federation, 51(9):2292-2300.

Ward, R.C., G.M. Smillie, J.C. Loftis, and T.G. Sanders. 1982. "Relating Stream Standards To Water Quality Monitoring Practices". Final Report for National Science Foundation Grant No. PRA-79313073, Colorado State University, Fort Collins, January.

Ward, R.C., and J.C. Loftis. 1986. Establishing Statistical Design Criteria For Water Quality Monitoring Systems: Review And Synthesis. Water Resources Bulletin, 22(5)759-767.

Ward, R.C., J.C. Loftis, H.P. Delong, and H.F. Bell. 1988. Groundwater quality: A data analysis protocol. Journal Water Pollution Control Federation, 60(11):1938-1945.

Ward, R.C., J.C. Loftis, and G.B. McBride (eds.). 1989. Proceedings of the International Symposium on the Design of Water Quality Information Systems. Information Series No. 61, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. Design of Water Quality Monitoring Systems. Van Nostrand Reinhold, New York.

Watson, H.J., A.B. Carroll, and R.I. Mann, (eds.). 1991. Information Systems For Management: A Book of Readings, 4th ed. Richard D. Irwin Inc., Homewood, Illinois.

Whipple, W. 1991. Discussion of "Regionalization of Water Supply Industry: Status and Needs" by N.S. Grigg. Journal of Water Resources Planning and Management, 117(4):500-501.

Willet, K. and R. Sharda. 1991. Using the Analytic Hierarchy Process in Water Resource Planning; Selection of Flood Control Projects. Socio-Economic Planning Sciences, 25(2):103-112.

Winkler, R.L. 1990. Decision Modeling and Rational Choice: AHP and Utilty Theory. Management Science, 36(3):247-248.

Wolman, M.G. 1971. The Nation's Rivers. Science, 174(4012):905-917.

Wren, D.A. 1987. The Evolution Of Management Thought, 3rd ed. John Wiley and Sons, New York.

Wymore, A.W. 1967. A Mathematical Theory of Systems Engineering - The Elements. John Wiley and Sons, New York.

Wu, B. 1992. Manufacturing Systems Design and Analysis. Chapman and Hall, London.

Yoon, K.S. and J. Kim. 1989. Multiple Attribute Decision-Analysis with Imprecise Information. IIE Transactions, 21(1):21-26.

Zahedi, F. 1985. Database Management System Evaluation and Selection Decisions. Decision Sciences, 16(1):91-116.

Zahedi, F. 1986a. The Analytic Hierarchy Process - A Survey of the Method and its Applications. Interfaces, 16(4):96-108.

Zahedi, F. 1986b. A Simulation Study of Estimation Methods in the Analytic Hierarchy Process. Socio-Economic Planning Sciences, 20(6):347-354.

Zahedi, F. 1987. Reliability of Information Systems Based on the Critical Success Factors - Formulation. MIS Quarterly, 11(2):187-203.

Zahedi, F. 1990. A Method for Quantitative Evaluation of Expert Systems. European Journal of Operational Research, 48(1):136-147.

Zahir, M.S. 1991. Incorporating the Uncertainty of Decision Judgements in the Analytic Hierarchy Process. European Journal of Operational Research, 53(2):.206-216.

APPENDICES

APPENDIX A : User's Manual for Evaluating Water Quality Information System Performance

APPENDIX B : The Analytic Hierarchy Process (AHP)

APPENDIX C : Illustration of Water Quality Information Systems Performance Evaluation Using the Analytic Hierarchy Process

APPENDIX D : Water Quality Information System Performance Evaluation Survey: Survey Documents

APPENDIX E : Water Quality Information System Performance Evaluation Survey: Survey Summary; USEPA Regional Water Quality Monitoring Coordinators

APPENDIX F : Water Quality Information System Performance Evaluation Survey: Survey Summary; USGS NAWQA Study Unit Project Chiefs

APPENDIX A

USER'S MANUAL FOR EVALUATING WATER QUALITY INFORMATION SYSTEM PERFORMANCE

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION

USER'S MANUAL

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION

CONTENTS

Introduction 3

- Background 3
- General Instructions 3

Phase 1: Performance Evaluation Planning 8

- Introduction 8
- Part A: Problem Definition and Feasibility Analysis 8
- Part B: Analysis Plan 8
- Documentation of Performance Evaluation Planning 9

Phase 2: Water Quality Management System Analysis 12

- Introduction 12
- Part A: Watershed Description 12
- Part B: Water Quality Management System Definition 14
- Watershed and Water Quality Management System Documentation 18

Phase 3: Water Quality Information System Analysis 24

- Introduction 24
- Part A: Water Quality Information System Background 24
- Part B: Design Analysis - System Effectiveness 26
- Part C: Operations Analysis - System Efficiency 35
- Water Quality Information System Documentation 36

CONTENTS, continued

Phase 4: Water Quality Information System Performance Evaluation 44

Introduction: Performance Evaluation Model 44

Part A: Evaluation Hierarchy and Criteria 45

Part B: Criteria Prioritization 46

Part C: Evaluation of Information System Alternatives 54

Part D: Model Interpretation and Validation 56

Extensions of the Performance Evaluation Model 58

Appendix I: The Analytic Hierarchy Process and Eigenvalue Method 60

Appendix II: Importance Intensity Scale 65

INTRODUCTION

Background

More than ever before, the public is demanding accountability from water quality managers and professionals. Water quality management programs are closely scrutinized to determine what, if any, water quality improvements are realized for the resources expended.

Information is critical to the manager's ability to direct water quality programs and to communicate their outcomes to the public. Effective and efficient water quality information programs provide knowledge relevant to water quality management objectives in an economic and timely manner. A systematic process to evaluate water quality information system performance will reveal opportunities to improve the knowledge provided and to achieve those management objectives.

The framework described in this manual is such a systematic process, providing the water quality professional a convenient and uniquely tailored approach to evaluate the performance of one or more information systems.

General Instructions

Water quality information system performance evaluation is accomplished in four phases (see Figure 1 and Table 1):

* Phase 1 - Performance Evaluation Planning

* Phase 2 - Water Quality Management System Analysis

* Phase 3 - Water Quality information System Analysis

* Phase 4 - Water Quality Information System Performance Evaluation (Model)

This manual is organized according to these phases and the user is urged to carry out the evaluation in this order, revisiting earlier steps as appropriate. In each section of the manual, the purposes of that analysis are reviewed, questions to stimulate and guide the evaluator are presented, and a form for documenting and reporting findings is presented.

The reader is reminded that the purpose of the framework presented in this manual is to provide meaningful analyses of specific water quality information systems. The questions posed and the factors considered throughout this manual are not exhaustive. The evaluator is encouraged to add or delete factors to make the evaluation more relevant and accurate with respect to his or her water quality management and information concerns.

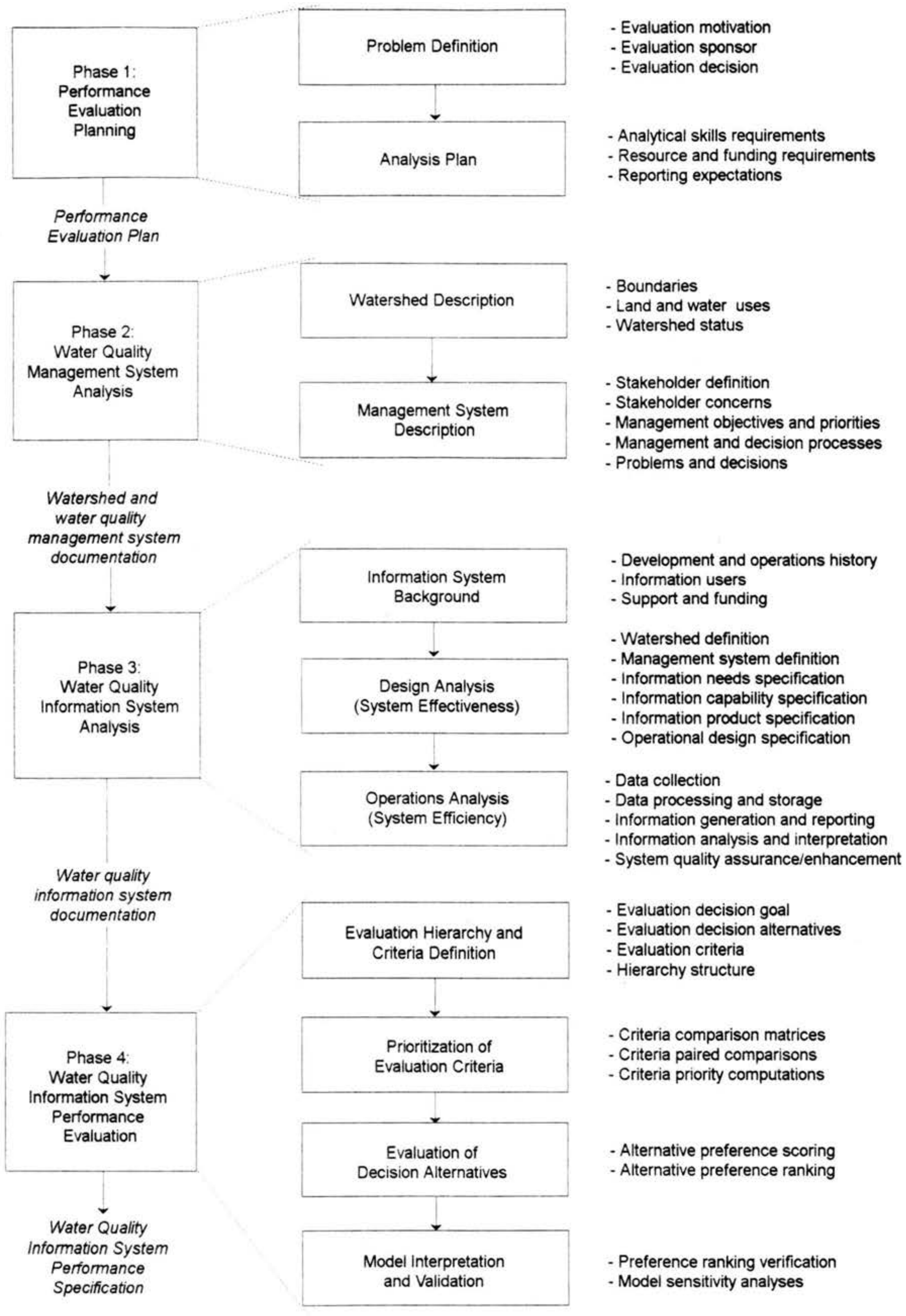

Figure 1: Framework for Evaluating Water Quality Information System Performance

---

TABLE 1
Framework for Evaluating Water Quality Information Systems Performance

Evaluation Considerations

PERFORMANCE EVALUATION PLANNING (Phase 1)

- * Problem Definition (Part A)
  - Motivation for the evaluation
  - Evaluation sponsor or champion
- * Analysis Plan (Part B)
  - Analytical skill requirements
  - Resource and funding requirements
  - Reporting expectations
  - Activities, tasks and schedule

WATER QUALITY MANAGEMENT SYSTEM ANALYSIS (Phase 2)

- * Watershed Description (Part A)
  - Boundaries; spatial, temporal, and jurisdictional
  - Land and water uses; historic, current and projected
  - Watershed status; economic, social, and regulatory issues
- * Management System Description (Part B)
  - Stakeholder definition and ranking
  - Stakeholder concerns
  - Management objectives and priorities
  - Management and decision-making processes
  - Problems and decisions to be addressed

WATER QUALITY INFORMATION SYSTEM ANALYSIS (Phase 3)

- * Information System Background (Part A)
  - Designer and design methodology
  - Development and operations documentation
  - Information clients and users
  - Sources of support and funding

TABLE 1, continued

- * Design Analysis (System Effectiveness) (Part B)
  - Watershed definition
  - Management system specification
  - Information needs specification
  - Information capability specification
  - Information product specification
  - Database requirements specification
  - Operational design specification

- * Operations Analysis (System Efficiency) (Part C)
  - Data collection; field, lab, or other
  - Data processing and storage
  - Information generation and reporting
  - Information analysis and interpretation
  - System quality assurance and enhancement

<u>WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION</u>
(Phase 4)

- * Evaluation Model Hierarchy and Criteria Definition (Part A)
  - Evaluation decision objective
  - Evaluation decision alternatives
  - Evaluation criteria

- * Prioritization of Evaluation Criteria (Part B)
  - Criteria comparison by pairs
  - Criteria priority computation

- * Evaluation of Decision Alternatives (Part C)
  - Alternative scoring
  - Alternative ranking

- * Model Interpretation and Validation (Part D)
  - Alternative ranking verification
  - Sensitivity analyses on model assumptions

PHASE 1: PERFORMANCE EVALUATION PLANNING

Introduction:

The first steps in the water quality information system evaluation process are to define and to map out the effort. In this pre-planning phase, all of the factors which establish the rationality and the feasibility of the performance evaluation effort are defined and documented.

Part A: Problem Definition

(1) Why is this evaluation being conducted?

What water quality management and information systems are being investigated?

What is the fundamental motivation prompting this evaluation of water quality management and information systems?

What water quality management decision(s) will be made or affected based upon the outcome of this evaluation?

(2) Who is the sponsor and/or champion of this evaluation?

What management individual or group is committed to carrying out the necessary studies and acting upon findings and recommendations?

Who is providing the necessary funding and resources for the required studies?

Part B: Analysis Plan

(1) What is the general analytical plan and expectations of the evaluation?

What types of background and experience are required to confidently carry out the anticipated watershed, management system, and information system analyses? Does the analytical effort employ an appropriate balance of diverse experience and specialized technical expertise?

What roles and activities are assigned to or expected of the analyst(s)?

What is the expected output (report) of the analysis? Is there a deadline? What resources are required? What budget has been allocated?

(2) Who is the systems evaluator? What individual or team will conduct the management system and information system assessments?

What is the experience and background of the individual(s) assigned to carry out these analyses?

What are the evaluator's affiliations or responsibilities with respect to the watershed, management system or information system in question?

Is the analyst a manager, consultant, or regulator?

By whom is the analyst(s) employed?

Documentation of Performance Evaluation Planning

The following Performance Evaluation Plan documents the basic strategy to be employed in evaluating the water quality information system(s). The list of factors considered here is not exhaustive. Until the evaluator is satisfied that all project-specific planning questions are identified, the evaluation's feasibility is not established, and the effort should not proceed. Variations of the Performance Evaluation Plan can serve as an evaluation project "contract". Supplementary planning documents should be attached.

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
PERFORMANCE EVALUATION PLAN

Part A: PROBLEM DEFINITION

(1) Motivation for the Evaluation:

(2) Sponsor of the Evaluation:

Part B: ANALYSIS PLAN (Attach Supplementary Documents)

(1) Required Skills, Background and Experience:

(2) Role and Responsibilities of the Evaluator(s):

(3) Report or Recommendation Format:

(4) Schedule and/or Deadline:

(1)

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
PERFORMANCE EVALUATION PLAN

Part B: ANALYSIS PLAN (cont.)

(5) Resources Allotted and Budget:

(6) Systems Evaluator: (for team efforts; include information on all members)

Name:

Organization and Position:

Address and Telephone::

Watershed or Management System Affiliation::

Education and Professional Experience:

(2)

PHASE 2: WATER QUALITY MANAGEMENT SYSTEM ANALYSIS

Introduction:

A critical determinant of a water quality information system's performance is its effectiveness, i.e., how well it serves the objectives of those managing the watershed. A realistic assessment of an information system's ability to satisfy those purposes must be based upon comprehensive understanding of the watershed and its associated water resource and water quality management systems. The purpose of this phase of the performance evaluation framework is to enable the water quality professional to carry out the investigation and documentation necessary to achieve that understanding.

In the next phase of the framework, an information system analysis, watershed and management system knowledge will be used to define and prioritize specific performance effectiveness criteria. Those criteria will in turn be used to evaluate how well the information system is designed; i.e., how well it satisfies the water quality management information needs of stakeholders and other water quality information users.

The water quality management system analysis is accomplished in two parts: (1) watershed description, where the physical (hydrologic) system of concern is characterized, and (2) management system description, where stakeholders, management issues, and management objectives are identified. Answers to the questions posed below will provide a solid understanding of the watershed and the necessary foundation for specifying related management information needs. The accompanying "Water Quality Management System Documentation" serves as a worksheet to capture the responses to the questions and as a formal record of the water quality management system analysis.

Part A: Watershed Description

(1) What are the geographic and/or hydrologic boundaries of the watershed associated with the water quality information system being evaluated?

(2) What are the waterbodies of significance within that defined watershed?

(3) What are the hydrologic inputs to and outputs from the defined watershed?

(4) What organizational, political or jurisdictional boundaries contain or intersect the watershed?

(5) What legislative and regulatory limitations apply to the watershed?

What federal, state, and local laws and regulations influence or dictate water quality management in the watershed?

What specific water quality management practices or water quality standards are imposed by these laws and regulations?

Which laws and regulations governing water quality in the watershed are incompletely defined, unclear, or inconsistent? Describe these regulatory gaps and inconsistencies.

(6) What are the time-related boundaries which apply to the watershed and its associated management and information systems?

Over what span of time is watershed management intended or appropriate (e.g., as specified by a time interval or as delineated by defined events)?

(7) What is the historical profile of the watershed?

What was the natural (before human intervention) state and behavior of the land and water within the watershed?

What land and water uses (past and current) characterize the watershed? What water quality problems were (are) created by those activities?

What programs (past or current) were initiated to deal with water quality problems in the watershed? What were their outcomes?

(8) What is the current status of the watershed?

What economic or social conditions within the watershed are relevant to water quality concerns?

Specifically, what are the current water quality issues in the watershed? To whom are these issues problems or concerns? What political or public opinion "momentum" (i.e., urgency) is attached to those issues?

Part B: Water Quality Management System Description

(1) Watershed Stakeholder Information

What individuals and organizations, i.e., stakeholders, are associated with, affected by, or otherwise interested in water quality issues in the watershed? Similarly, what individuals or groups are affected by or interested in the activities of any watershed water quality management program?

What is each stakeholder's specific interest in the watershed or any of its associated management systems?

What are the stakeholders' relationships to one another and to the watershed? Are all relevant power, control and influence issues recognized and understood?

(2) Stakeholder Concerns

What watershed management problems or concerns have been expressed by or imputed to each stakeholder? Can fundamental issues or causes for each be identified?

What are stakeholders doing currently to document and resolve their problems or conflicting objectives? Has any conflict resolution process been established to help stakeholders define problems or objectives and to assist them in asking the right questions? Examination of existing management systems may shed light on these issues - note the related questions below.

What criteria and process are used (by the analyst conducting this evaluation) to rate watershed stakeholders and their concerns?

Which stakeholders and/or concerns are most important?

(3) Contemporary Watershed Management and Information Systems

What water quality or water resource management systems (either internal or external to the watershed) influence water quality in the watershed? What are their goals, and by whom are they operated and funded?

What specific decisions are currently enacted with respect to water quality in the watershed? Who are the decision-makers and what decision processes are employed?

Are management systems in the watershed coherent or conflicting? Are interfaces and communication processes among them established which allow joint or shared efforts? Do fundamental institutional or managerial impediments to decision-making exist?

What management information systems (water quality, GIS, or other) exist which are related to the watershed? Why and by whom are they operated? What data or information do they provide relevant to water quality management in the watershed region or towards the resolution of stakeholder concerns? Do these systems share data and information?

How well are each stakeholder's information needs met by existing information systems?

(4) Water Quality Management System Description:

<u>What constitutes the management system served by the information system being designed or evaluated in this exercise?</u>

Is the watershed or water quality management system(s), as described, too large or too complex to be reasonably (or optimally) characterized for purposes of information system design?

What combination of existing and/or new water quality management processes will define the system which will address the identified water quality issues and generate specific water quality information needs?

Management System Attributes:

Who is the manager, organization, or group responsible for making water quality-related decisions?

What are the sources of support (financial and other) for the water quality management system?

Do the managers possess the attributes and skills necessary to identify problems and specify decision information needs? Will assistance be required to solve the identified problems? Is that assistance or training available?

Is the overall variance or uncertainty of the management process defined? Are the contributing sources of error, risk, and uncertainty identified and their relative contribution to total variance documented?

Decision Responsibilities and Requirements:

What are the management and decision responsibilities associated with this water quality management system? In addition to the resolution of current watershed conflicts, longer term or strategic issues (e.g., resource allocation) and other tasks may be of concern.

What are the specific problems this system(s) is designed to address and the specific decisions the manager(s) must make to resolve them?

What timeliness ("turnaround") and precision conditions must be met in making the required decisions?

Can the management system provide remedial action in response to problems? Are authority and procedures established to actually change problem policies or practices as a result of management decisions?

Is there a process to measure decision (or policy) impact or to indicate the effectiveness of water quality management efforts? Is there a decision "audit trail"? Can decisions be retraced and analyzed after implementation?

Decision Process Description:

What decision-making procedures are employed in the water quality management system in question? Who are the decision-makers (e.g., individuals or groups) and what decision processes (e.g., majority rule, consensus, or individual decision making) are used?

Do decision processes acknowledge the perceptive and cognitive limitations of decision makers and strive for "satisfactory" rather than optimal outcomes where appropriate? Are simplifying assumptions appropriate and documented?

What are the factors contributing to variance, uncertainty and risk in the decision process or its outcome?

Does the decision process recognize and deal with complex assumptions as they are, rather than simplifying them to suit quantitative models?

What are management's decision criteria? Does the decision process effectively identify both formal and informal (i.e., unwritten or not acknowledged) decision criteria? Can the decision making process accommodate both quantitative (objective) and qualitative (subjective) decision criteria?

Is there a criterion priority assignment process? What is the relative importance of technical (quantitative) and non-technical (qualitative) factors in the decision process?

Are decision-assisting processes and models employed? Are they simple and easy to understand? Can they accommodate multiple objectives or criteria simultaneously?

(5) Water Quality Management System Goals and Objectives:

<u>What, precisely, is the defined water quality management system and the supporting water quality information system trying to accomplish?</u>

Goal and Objective Identification

From the watershed issues and management decision responsibilities indicated above, identify this water quality management system's goals and objectives.

Both water quality and general objectives of decision makers must be identified.

What meaningful measures of objective achievement or program success are defined (e.g., "risk reduction" rather than "permits issued", "inspections performed", etc.)?

Goal and Objective Ranking

What criteria and process are used to establish the relative priority of the water quality management objectives identified?

Are difficult and potentially costly "end point" issues being addressed, as well as uncomplicated and low cost issues? Are water quality management goals categorized on this continuum?

What priority do general management objectives receive? How are they traded-off against strictly water quality-related management objectives?

Are objectives (or problems) defined or shaped to fit convenient or familiar tools and techniques, possibly leading to solution of the wrong problem?

Are risk and uncertainty in making decisions reduced? Are potential political economic and social penalties of poor decisions reduced?

Are consensus building and reduction of political or interagency conflict more important than what a "rational" planning/management process might dictate?

Is satisfaction of regulatory and administrative goals the only real water quality management objective? Is management's objective to satisfy the intent of the law as well as obey the letter of the law?

<u>Considering these criteria, list the goals and objectives of the defined water quality management system, noting their relative priority.</u>

Watershed and Water Quality Management Documentation

The following form, "Watershed and Water Quality Management System Documentation", illustrates the type of document which should be used to record the findings of the watershed and water quality management systems analyses.

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATERSHED AND WATER QUALITY MANAGEMENT SYSTEM DOCUMENTATION

Part A: WATERSHED DESCRIPTION (Attach Maps or Diagrams)

(1) Geographic and Hydrologic Boundaries:

(2) Significant Waterbodies:

(3) Hydrologic Inputs and Outputs:

(4) Organizational, Political and Jurisdictional Boundaries:

(5) Legislative and Regulatory Limitations (Federal, State, and Local):

(6) Timeframe(s) of Interest to this Analysis:

(7) Watershed Profile:

Natural Conditions of Land and Water:

Land Uses (Past and Current):

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATERSHED AND WATER QUALITY MANAGEMENT SYSTEM DOCUMENTATION

Part A: WATERSHED DESCRIPTION (cont.)

Water Uses (Past and Current):

Water Quality Programs (Past and Current):

(8) Watershed Status:

Economic and Social Factors::

Water Quality Issues and Concerned Parties:

PART B: WATER QUALITY MANAGEMENT SYSTEM DESCRIPTION:

(1) Watershed Stakeholder Information (for each stakeholder identified):

Name and/or Organization:

Address and Telephone:

Relationship to Watershed and Contemporary Management Systems:

Relationship to Other Stakeholders:

(2) Stakeholder Concerns:

Issues, Problems and Conflicts of Concern (of each stakeholder):

Stakeholder Actions Taken to Resolve Concerns:

Stakeholder Concerns Rating Criteria:

Priority List of Stakeholders and Concerns:

(2).

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATERSHED AND WATER QUALITY MANAGEMENT SYSTEM DOCUMENTATION

Part B: WATER QUALITY MANAGEMENT SYSTEM DESCRIPTION: (cont.)

(3) Contemporary Watershed Management and Information Systems:

Water Quality or Water Resource Management Systems:

Water Quality Decisions:

Contemporary Watershed Management Information Systems:

(4) Water Quality Management System Description:

Contributing or Participating Management Systems:

Water Quality Management System Attributes:

Manager (Individual, Organization, or Group):

Support and Funding:

Management Capabilities and Requirements:

Sources of Error and Uncertainty:

Decision Responsibilities and Requirements:

General Decision Responsibilities and Scope:

Part B: WATER QUALITY MANAGEMENT SYSTEM DESCRIPTION: (cont.)

Specific Problems to be Addressed and Priorities:

Specific Decisions Required to Resolve Problems:

Decision Timeliness and Precision Requirements:

Decision Implementation and Remedial Action Process:

Decision Audit Procedures:

Decision Process Description: (for each specified decision identified above)

Decision Maker or Forum:

Optimality Requirement or Expectation:

Factors Contributing to Variance, Uncertainty, or Risk:

Decision Criteria (Qualitative and Quantitative) Ranked by Priority:

Decision Aids or Models Employed:

Part B: WATER QUALITY MANAGEMENT SYSTEM DESCRIPTION: (cont.)

(5) Water Quality Management System Goals and Objectives:

Water Quality Goals and Objectives:

General Management Goals and Objectives:

Measures of Management Objective Achievement:

Water Quality Management System of Objectives:
(in priority order)

PHASE 3: WATER QUALITY INFORMATION SYSTEM ANALYSIS

Introduction:

The performance of a water quality information system is judged by its effectiveness and its efficiency. Effectiveness criteria determine how well the information system is designed; i.e., how well it can satisfy the information needs of watershed stakeholders or other users. Efficiency criteria establish how well the information system actually operates to satisfy those information needs.

In this phase of the framework, the water quality professional characterizes the design and operation of the information system with respect to its objectives. How and how well does the information system satisfy its performance expectations? The questions posed are not inclusive; the process is intended to prompt the evaluator to ask appropriately detailed questions relevant to his or her water quality management and information systems, and to gain a sense for their relative importance. From this analysis, the evaluator will be able to specify information system performance evaluation criteria and their priorities in the next phase of the framework.

Part A: Water Quality Information System Background:

(1) Information System or Program Title:

What is the title or designation given to the water quality information system under evaluation? If none, how is it identified or described?

(2) Date of Implementation:

When was the water quality information system designed and implemented?

(3) Development Motivation:

What was the original impetus for the design and implementation of the information system being evaluated?

What concerns or issues was it intended to address?

Do those original concerns and issues remain?

(4) Support and Funding:

Who (individual or organization) funded the original design, implementation and operation of the information system?

Who funds the current information system? Describe the reasons for any changes in support or funding of the information system.

(5) Clients or Users:

For whom (user or client) was the information system designed?

Who are the current users? Describe the reasons for any changes in the set of information system users.

(6) System Design History:

Who (individual or organization) originally designed and implemented the information system(s) being evaluated? What design methodology was employed?

Can the original system designer be contacted for information?

Why was the original system designer chosen? What professional qualifications and competencies were required?

Was diverse technical expertise and knowledge engaged in design of the system? Was expert opinion solicited?

Were any formal information system development processes employed to design and implement the system (e.g., Systems Development Life Cycle, Data-directed design, Database Management System concepts, etc.)?

Were continuing qualification, training and professional development needs anticipated and provided for?

(7) System Operations History:

Who currently administers and operates the information system being evaluated?

Has system operation been continuous and consistent (e.g., with respect to organization, personnel, and procedures)? What significant design or operating changes have occurred since its original implementation?

(8) System Documentation:

Do formal records exist which document system design, implementation, and evolution? Are system operations records maintained and available?

Where are systems records located?

Part B: Design Analysis - System Effectiveness:

Earlier, in Phase 2 of the framework, the evaluator was guided through watershed and management system analyses intended to establish the knowledge necessary to evaluate any associated information systems. In this phase of the framework, "watershed description" and "water quality management system description" are considered information system effectiveness criteria, and the evaluator applies the understanding gained in Phase 2 to compare information systems against these criteria.

(1) Watershed Definition and Documentation:

How well was the target watershed defined and documented during the information system's design? Indicate to what extent the following factors were addressed:

- Geographic and hydrologic boundaries
- Organizational, functional, and political boundaries
- Timeframes of concern
- Legislation and regulatory demands or limitations
- Waterbodies of significance
- Hydrologic inputs and outputs
- Watershed history (e.g., natural conditions, human activities, and water quality concerns)

- Current watershed status (e.g., relevant social and economic conditions, uses of land and water, water quality problems, and existing management and information systems)

(2) Water Quality Management System Definition

Was the Water Quality Management System defined and documented during the system design? Indicate to what extent the following factors were addressed:

- Watershed stakeholder information
    - Identification of stakeholders and their relationships regarding the watershed
    - Cataloging and ranking of stakeholders' water quality concerns
- Contemporary watershed management and information systems
    - Cataloging of existing management and information systems associated with the watershed
    - Do these existing systems compete for funding or resources?
- Water quality management system characterization

  Specification of the management and decision-making system(s) to be served, including:

    - responsible manager or organization
    - capability of the management system to specify problems and decision needs
    - sources of funding and support
    - specific problems to be addressed and managerial decisions to be made
    - decision processes and techniques employed

- * Water quality management system objectives

  Definition and documentation of the water quality management objectives to be pursued, including:

  - relative priority of the objectives
  - definition and measurement of objective achievement

(3) Water Quality Management Information Needs Specification

Were water quality management information needs and priorities specified prior to or in conjunction with the water quality information system design?

Were stakeholder concerns and the derived water quality management objectives translated into <u>information objectives</u>? What water quality <u>knowledge</u> was required or desired? To what extent were the following questions addressed in establishing information objectives?

- * Were information objectives clear and agreed upon?
- * Were information objectives directly related to a decision or to a decision making process?
- * What stakeholder management objective priorities were expressed; i.e., what were the stakeholders' "critical success factors"?
- * What measures or indicators of management objective achievement were specified?

Were water quality management system <u>information needs</u> defined from those information objectives? What <u>messages</u> were desired or required? To what extent were the following questions addressed in establishing information needs?

- * Were both technical and non-technical information needs documented?

  What non-monitoring information needs must be satisfied (perhaps to provide basic understanding necessary to interpret technical information, e.g., land use)?

- * Were future information and data needs anticipated and documented?

- * Was the decision technology in which the information was to be used known or predicted?

- * Were information needs specified to match the requirements of the objectives and no more?

- * Was information value defined?

- * Were information value trade-offs addressed and properly balanced (e.g., among accuracy, representativeness, simplicity, timeliness, cost, etc.)?

- * Were information structure, content and format required to fit identified needs specified (e.g., narrative, graphical, statistical, index, qualitative, quantitative, etc.)

(4) Water Quality Management Information Needs Selection

How was the set of users and user information needs to be satisfied by the water quality information system selected and prioritized?

- * What criteria were used to establish the relative priority of the user information needs previously identified? Were the following factors considered?

    - stakeholder or user "clout" (e.g., as a regulator)

    - potential cost of satisfying the need

    - potential capability (probability) of meeting the specified information need; i.e.," Are the information needs and expectations realistic and can they be feasibly met?"

- * What decision process was employed to select and prioritize the set of information needs to be satisfied by the water quality information system?

    - What group or individual was responsible for selecting and prioritizing the information needs to be met?

- How were information users involved in the selection process?

- Were parties other than users (e.g., in the legal, academic or water quality professional community) included in the selection process?

* Were users and information needs not to be accommodated by the initial information system design documented for future consideration in an evolving (or other) system?

* Was flexibility built into the system to accommodate unanticipated information needs.

List the water quality information needs to be satisfied and their relative priority.

(5) Water Quality Information Capability Assessment

Were the information production capabilities required of the information system (as dictated by the information needs selected to be satisfied) defined in detail?

* Were data and information quality criteria (e.g., accuracy and timeliness) specified and their measurement defined?

Were quality requirements with respect to those criteria specified?

Were criteria trade-offs (e.g., between accuracy and simplicity) considered and their resolution documented?

Were information losses (e.g., due to data aggregation, data transformation, or presentation format) evaluated and documented? What is the information "price" of a robust system?

* Was the probability of satisfying information quality requirements specified?

Was the prioritized list of information needs to be met revised based on an information capability assessment?

(6) Water Quality Information System Product Specification

How was the information system product package specified and designed?

- * Were delivered data and information tailored to the users, and made easy to use regardless of their computer or mathematical background?

  Was information put in terms understandable to those not familiar with data collection and analysis procedures?

  Was information simplicity matched to user utility? Was the amount of simplification or loss of information appropriate to the target audience?

- * Were existing information sources known and cataloged as to scope, purpose, and management? Was relevant information from those sources easily incorporated as appropriate?

  Was (is) generated information easily accessed and willingly made available to outside users or systems?

- * What information content and format specifications were defined?

- * What information distribution specifications were defined?

(7) Water Quality Information System Operations Design

How was each component operation of the water quality information system designed?

General Considerations

Were previously available materials used to help guide the system design to save time and resources?

Were the experiences of previous systems reviewed and applied to the design process?

Were compatibility and complementarity with existing systems (agencies) addressed, to avoid duplication of efforts or results?

Data Collection

Were statistical and probabilistic principles applied to sampling and data collection?

Were all data collection and laboratory procedures defined in conformance with standard and recognized methods?

Were data attributes specified sufficiently to support information quality requirements? For example, were data validity, accuracy, and representativeness clearly defined?

Were data to be incorporated from existing systems? Were their history and limitations documented; i.e., was the desired "megadata" defined?

Data Handling and Storage

Were uniform data screening and error removal procedures mandated? Were statistical criteria specified for data screening? Were uniform rules specified for treatment of "non-detect" or "below the reporting limit" data?

Were contemporary database management system (DBMS) design principles employed (e.g., data dictionaries)?

Information Generation and Reporting

Was an information communication and interpretation process defined and documented? Were those responsible for information communication and interpretation identified?

Was data accessibility assured? Were bureaucratic, personnel, security or other potential impediments to data access and transfer averted?

Was a comprehensive data analysis protocol specified as part of the system design process?

Was any statistical information (e.g., mean and variance) to be generated defined under the proper assumptions and with a sufficient level of confidence?

Were time and timing requirements for data analysis and information creation accurately identified and accommodated in the design?

Was information specified in concise and understandable format for all intended users? (e.g., graphics and photographs)

Were complex relations among physical, chemical and biological factors demonstrated and conveyed?

Was water quality terminology consistently used?

Information Analysis, Interpretation and Utilization

Were the users' definitions of information value solicited and clearly documented? Dimensions of information value include:

- sufficiency
- understandability
- freedom from bias
- timeliness
- reliability
- accuracy
- relevance
- quantifiability

Were specific opportunities to support and improve the management decision system considered in the system and product design? For example, were information products targeted towards specific strategic or operational control activities, perhaps to:

- shorten the management decision-making process,
- improve management coordination and flexibility,
- permit smaller management structures,
- improve organizational outcomes, or
- reduce uncertainty in management decision-making?

Were sensitivity analyses anticipated to ascertain the relationships between information supplied (both form and detail) and the outcomes of corresponding management decisions?

Was the information provided planned to match management (system or individual) capability? Was it planned to match the manager's ability to specify information needs, and to avoid information "overload"?

Were the information definition and interpretation capabilities of the users cataloged and any necessary guidance and training planned?

Was a routine review of the information product's satisfaction of information and decision needs planned?

Were provisions made to identify gaps in information needs or new information needs?

Were provisions made to detect misuse or misinterpretation of system information? Were processes to detect and respond to abuses of the system or its output defined?

System Quality Assurance and System Enhancement

Was a total system perspective of quality assurance incorporated into the information system design? Assuming that the overall quality of the system's product is limited by the system's weakest features, were all aspects of the system to be reviewed regularly? Features of an effective information system quality assurance program are described in the following statements:

- Quality assurance is a defined responsibility of all system personnel and appropriate training is provided for each person and with respect to each information system operation.
- The information system is assumed by its designers to be adaptive and to evolve based upon operating experience and routinely solicited user feedback.
- Specific provisions are incorporated for soliciting user feedback regarding system performance with respect to expectations and defined criteria, within a routine formal performance assessment (audit) process.
- The attributes of quality (i.e., performance) with respect to each system component operation are clearly defined.
- For each system operation, detailed guidance (e.g., standard operating procedures) is provided. Procedures are reviewed regularly and revised as appropriate.
- System operation performance measures are simple, efficient, complete, and, as appropriate, quantitative in nature.

- Measurement units and scales are defined for all system operation performance criteria.

- Relative weight or importance is assigned to each criterion.

- Performance criteria are integrated into a composite, total system performance indicator.

- All deviations from design, normal, or standard practice are documented in detail.

- Information system (e.g., laboratory-induced) variability can be distinguished from actual water quality variability.

- Contingency plans are developed which specify how to react to potential pressures on the system (e.g., changing objectives and budget cuts).

- Processes are in place to detect and respond to misinterpretation, misuse or abuse of the system or its output.

Part C: Operations Analysis - System Efficiency:

Operating efficiency of a water quality information system is evaluated by assessing how well each activity specified in the system design is accomplished. In general terms, efficiency is defined as accomplishing the purpose of each information system operation in a way that consumes the fewest resources necessary.

For a given information system operation, one or more specific criteria must be identified which measure "resource consumption", either directly or indirectly. Each efficiency criterion in the list below may apply to any of the information system operations. The list is not inclusive, and is intended to aid the evaluator in precisely defining the criteria appropriate to the operations in question. The following approach may prove to be helpful:

(1) Determine if the suggested efficiency criterion is relevant to the operation in question.

(2) Define and name the criterion to fit the circumstances of the operation and information system being evaluated.

(3) Define and list any efficiency criteria relevant to the operation, but not on the suggested list.

(4) Establish the measurement scale and efficiency standard for each criterion to be applied.

(5) Establish the relative priority of all criteria to be applied to an operation.

(6) Measure (rate) the performance of the operation against the criteria selected and the standards established.

Operations Efficiency Criteria for Water Quality Information System Evaluation:

Each information system operation can be assessed with respect to one or more of the following efficiency factors:

* Cost efficiency - operations are accomplished with a minimal expenditure of resources, usually measured in monetary terms (applies to all information system activities)

* Timeliness - operations are accomplished when needed (neither early nor late); e.g., information reporting synchronous with user information needs

* Sufficiency - operations and their outputs must be of proper magnitude (neither too much nor too little) e.g., the proper quantity of information, without redundancy with respect to information previously available

* Convenience and flexibility - operations must be easily executed and modified, e.g,. to accommodate unanticipated demands

* Understandability - operations must be easily learned and taught

* Trustworthiness - operations and outputs must exhibit relevance, integrity, reliability and accuracy

Water Quality Information System Documentation

The following "Water Quality Information System Documentation" is an example of the type of document needed to guide and to record the findings of a water quality information system performance analysis.

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATER QUALITY INFORMATION SYSTEM DOCUMENTATION

Part A: INFORMATION SYSTEM BACKGROUND

(1) Information System or Program Title:

(2) Date of Implementation:

(3) Development Motivation:

(4) Support and Funding:

(5) Clients or Users:

(6) System Design History:

System Designer:

Name (Individual or Organization)

Current Availability:

Address and Telephone:

Qualifications Required:

Expertise and Experience Represented:

Designer Responsibilities\Assignment::

Information Systems Design and Development Process:

(1)

(7) System Operation History:

System Operator or Administrator:

Name (Individual or Organization):

Address/Telephone:

Design or Operating Changes Since Implementation:
(Organizational, Procedural, or Personnel)

(8) System Documentation:

Part B: INFORMATION SYSTEM DESIGN ANALYSIS (SYSTEM EFFECTIVENESS)

**(1) Watershed Definition and Documentation:
(Completeness of Description)**

Geographical and Hydrologic Boundaries:

Organizational, Functional and Political Boundaries:

Timeframes of Concern:

Legislative and Regulatory Limitations:

Waterbodies of Significance:

Hydrologic Inputs and Outputs:

Watershed History:

Natural Conditions:

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATER QUALITY INFORMATION SYSTEM DOCUMENTATION

Part B: INFORMATION SYSTEM DESIGN ANALYSIS (SYSTEM EFFECTIVENESS) cont.

Human Activities:

Water Quality Concerns and Resolution:

Watershed Status:
- Social and Economic Conditions:
- Land and Water Uses:
- Water Quality Problems:
- Existing Water Quality Management and Information Systems:

(2) Water Quality Management System Definition:
(Completeness of Description)

Watershed Stakeholder Information:
- Stakeholder Identification:
- Stakeholder Issues and Problems:
- Ranking of Stakeholder Concerns:

Contemporary Water Quality Management and Information Systems:

Water Quality Management System Characterization:
- Responsible Manager or Organization:
- Management Capabilities and Deficiencies:
- Funding and Support:

(3)

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATER QUALITY INFORMATION SYSTEM DOCUMENTATION

Part B: INFORMATION SYSTEM DESIGN ANALYSIS (SYSTEM EFFECTIVENESS) cont.

Decision System Description:

Problem and Decision Recognition Ability:

Problem and Decision Identification:
(Responsibilities, specific decisions, priorities, uncertainties)

Decision Process Description:
(Procedure, criteria, techniques used, implementation, audit)

Water Quality Management System Objectives:

Objective Definition and Measurement of Achievement:

Ranking of Objectives:

(3) Water Quality Management Information Needs Specification:

Stakeholder Information Objectives Identification:
(Knowledge Requirements and Attributes)

Stakeholder Information Needs Identification:
(Message Requirements and Attributes)

(4) Water Quality Management Information Needs Selection:

Criteria for Ranking Information Users and Needs:

Information Needs Selection Process:

(4)

Part B: INFORMATION SYSTEM DESIGN ANALYSIS (SYSTEM EFFECTIVENESS) cont.

Provisions for Meeting Future Information Needs:

Information Needs Selected (Priority Order):

(5) Water Quality Information Capability Assessment:

Data and Information Quality Criteria:

Potential or Probability of Need Satisfaction:

(6) Water Quality Information System Product Specification:

Match to User Capabilities:

Use of Existing Sources:

Information Content or Format Specification:

Information Distribution Specification:

(7) Water Quality Information System Operations Design:

General Considerations:

Data Collection Specification:

Data Handling and Storage Specification:

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATER QUALITY INFORMATION SYSTEM DOCUMENTATION

Part B: INFORMATION SYSTEM DESIGN ANALYSIS (SYSTEM EFFECTIVENESS) cont.

Information Generation and Reporting Specification:

Information Analysis, Interpretation and Utilization Specification:

System Quality Assurance and System Enhancement Specification:

(5)

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION
WATER QUALITY INFORMATION SYSTEM DOCUMENTATION

Part C: OPERATIONS EFFICIENCY ANALYSIS

OPERATION: ______________________________

Criterion	Definition	Measurement	Standard	Rating
COST:				
TIMELINESS:				
SUFFICIENCY:				
CONVENIENCE:				
FLEXIBILITY:				
UNDERSTANDABILITY:				
RELIABILITY:				
OTHER:				

PHASE 4: WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION

Introduction: Performance Evaluation Model

In this performance evaluation phase, the findings from the watershed, management system, and information system analyses are translated into specific information system performance evaluation criteria. Those criteria are rated as to their relative importance and the information system(s) to be evaluated are scored against the criteria.

Information system performance is defined by a composite information system preference score, computed for each alternative system being evaluated. An alternative system may be: (1) another operating information program, (2) a proposed or redesigned system, or (3) some hypothetical "ideal" system postulated by the evaluator.

Information system alternative preference scores are derived using the Analytic Hierarchy Process (AHP), which establishes criterion priorities and computes the relative preferences among decision alternatives. The AHP is a powerful, convenient, and widely-accepted decision analysis technique developed by T. L. Saaty in the late 1970s, and has since been applied in a wide variety of business, scientific and social decision situations.

Although other multi-attribute decision models could be applied to evaluate or compare information system performance, the AHP has several characteristics which make it ideal for this application:

* The AHP provides a visible decision structure that reflects the evaluator's unique analytical process, defines all of the relevant decision criteria, and clearly indicates the relative importance of the criteria to the evaluator.

* The AHP allows the simultaneous consideration of both quantitative and qualitative criteria in the decision analysis.

* User-friendly personal computer software packages have been developed which facilitate application of the AHP; magnifying its inherent process advantages.

An AHP decision model is constructed and applied in four parts:

Part A: Construct a decision (evaluation) hierarchy and define decision criteria.

Part B: Weight (prioritize) the evaluation criteria.

Part C: Evaluate the decision alternatives.

Part D: Interpret and validate the results of the model.

In the following sections, the rationale and methodology of each part of the AHP is described. With each description is an example of its application in the performance comparison of two hypothetical water quality information systems. A discussion of the theory of the Analytic Hierarchy Process can be found in Appendix I of this manual.

Two personal computer software packages provide excellent assistance in structuring AHP decision models and carrying out the necessary computations:

(1) CRITERIUM; by SYGENEX, Inc., and

(2) EXPERT CHOICE; by EXPERT CHOICE, Inc.

Part A: Evaluation Hierarchy and Criteria

Description:

The purpose of constructing the evaluation hierarchy is to provide a "customized" structure of the decision situation, i.e., one which captures the evaluator's perspective on the evaluation and his or her evaluation criteria. AHP requires that the decision problem be structured as follows:

(1) Define the decision to be made, i.e., clearly state the ultimate goal, objective or choice the process is intended to assist.

(2) Clearly delineate and define the alternatives among which decision-makers must compare or choose.

(3) Break down the decision problem into a hierarchy of interrelated decision attributes (i.e., criteria, subcriteria, actors, influences, etc.)

The general decision goal (e.g., selection of a preferred water quality information system) is defined at the apex of the hierarchy. Alternatives to be evaluated (e.g., a current and proposed information system) are at its base. There is no limit to the number of alternatives which can be compared.

Intermediate levels of the hierarchy contain evaluation criteria and subcriteria, broken down to the detail required to enable the evaluator to accurately compare of the alternatives. It is not required that the hierarchy be symmetrical or complete. A decision attribute at one level need not be associated with all attributes at lower levels. Figure 2 illustrates the general AHP decision hierarchy.

Example:

In this hypothetical example, a water quality professional (the evaluator) is required to evaluate the relative merits of a proposed redesign of an organization's water quality information system. The decision goal is stated as " Select the best water quality information system (WQIS)". The alternatives to be compared are the current and redesigned systems; referred to as WQISC and WQISR, respectively.

The evaluator will compare the alternative systems on the basis of three criteria: (1) cost (C), (2) information value (IV), and (3) satisfaction of regulatory reporting requirements (RRR).

Figure 3 illustrates the AHP hierarchy representing the example decision process and criteria.

Part B: Criteria Prioritization

Description:

In the AHP, the relative priority of decision attributes (i.e., criteria or decision alternatives) is established in two steps: (1) pairwise comparisons of attribute importance, and (2) computation of attribute weights.

Step 1: Pairwise Comparison of Attributes

> The AHP evaluates decision attributes by comparing them in pairs. All criteria at one hierarchy level sharing the same "parent" criterion at the next higher level are compared by pairs to identify which best satisfies the meaning or objectives of the parent criterion. The comparisons can be specified by an individual evaluator or group consensus.

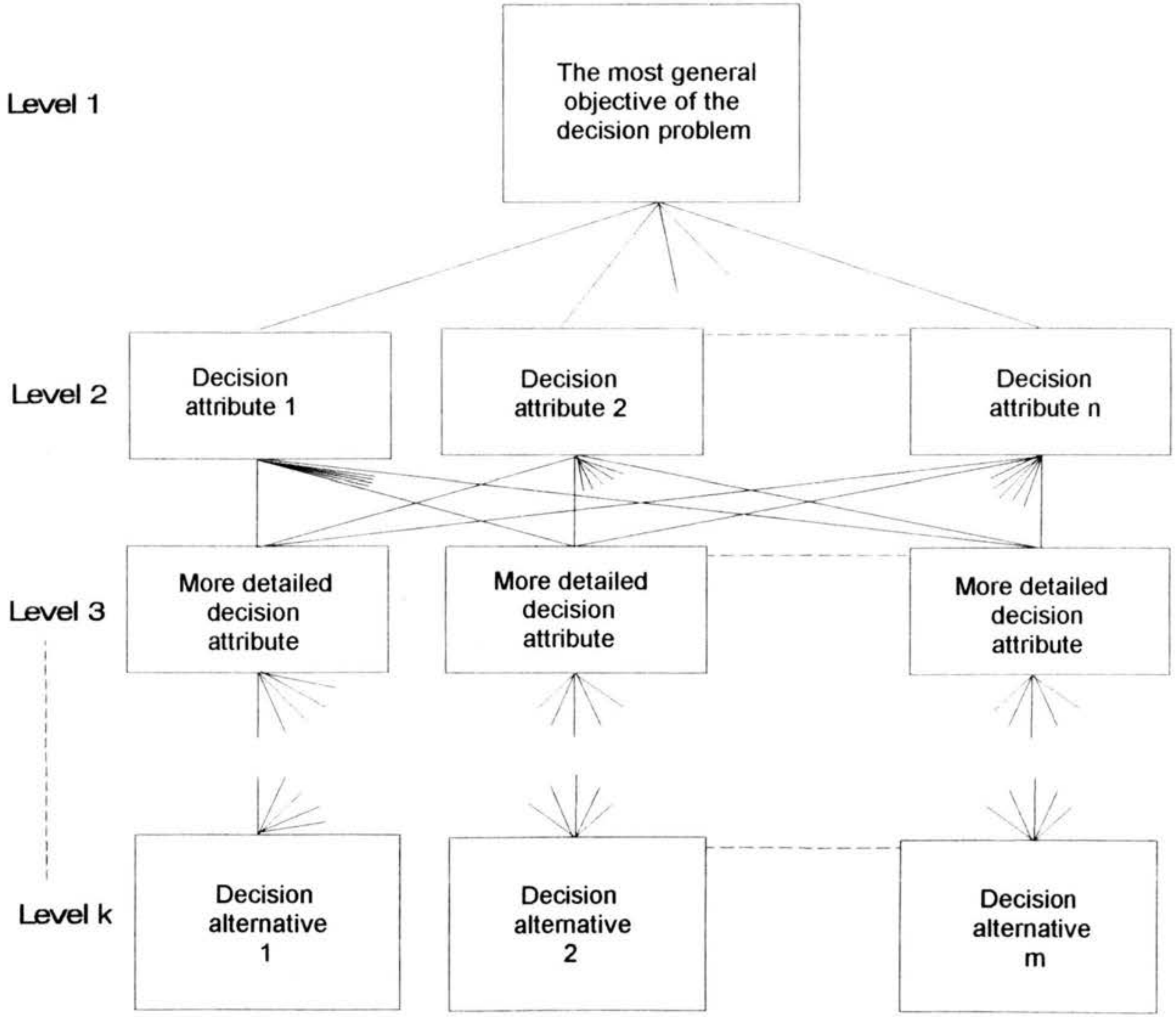

Figure 2: Analytic Hierarchy Process Decision Schema - A Hierarchy with k Levels (from Zahedi, 1986)

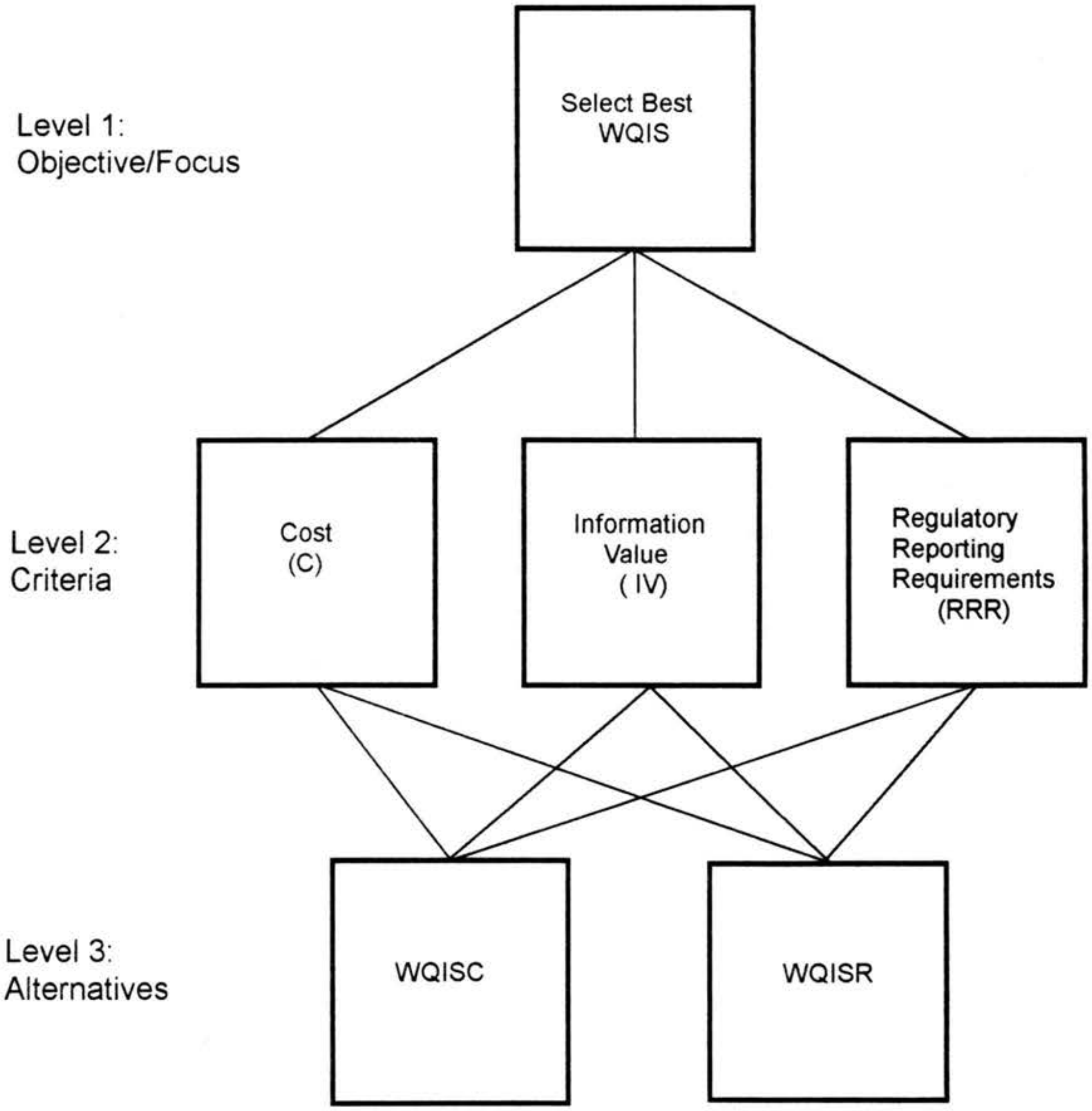

Figure 3: Water Quality Information System Selection Decision Hierarchy

The criteria comparisons are captured in a matrix format. The elements of the comparison matrices are "importance intensity" scores - measures of how strongly the row attribute is favored over the column attribute with respect to satisfying the objective or intent of the parent attribute. Importance scores range from 1 (equal importance) to 9 (absolutely more important) as described by Saaty's intensity scale (see Appendix II). As expected, reverse comparisons exhibit reciprocal scores and diagonal elements (where an attribute is compared to itself) always equal 1.0.

Step 2: Priority Computation:

The AHP converts the pairwise comparison scores at each level of the hierarchy into sets of relative attribute weights (priorities). AHP assumes that pairwise comparisons of more than two attributes will be made inconsistently, thus making precise specification of the resulting attribute weights unlikely. Several procedures are available which estimate attribute weights while demonstrating inconsistencies. The most commonly used is the "eigenvalue method", which employs matrix algebra theory to identify a set (the "right eigenvector") of relative decision attribute weights at a given level of the hierarchy. A description of the eigenvalue method and a discussion of related consistency measures are given in Appendix I.

The matrix computations to achieve an exact solution of the right eigenvector require computer assistance. A good approximation to the right eigenvector of each comparison matrix is the "priority vector". The elements of the priority vector are the estimated relative weights of the compared decision criteria with respect to the parent attribute.

To compute the priority vectors, comparison matrices are manipulated as follows:

* Matrix columns are normalized (i.e., each element is divided by its column total), to permit comparison of attributes on the same numerical scale (0.0 to 1.0).

* Elements of each row of the normalized matrix are averaged, to produce the relative attribute weights which comprise the priority vector.

Example:

Step 1: Pairwise Comparison of Attributes

Continuing the example introduced in Part A, Matrix (1) captures the paired comparisons among the three information system performance criteria with respect to the decision goal. These scores indicate that the evaluator regards meeting regulatory reporting requirements as demonstrably most important (6) in selecting a preferred water quality information system. Information value is somewhat more important (3) than system cost.

Matrix (1): For the decision goal of selecting the best information system alternative,

Select Best WQIS	Cost	Information Value	Regulatory Reporting Requirements
Cost	1	1/3	1/6
Information Value	3	1	1/3
Regulatory Reporting Requirements	6	3	1
Column Sum	10	4 1/3	1 1/2

Note: Column sums are used in later calculations.

In a similar fashion, Matrices (2), (3), and (4) contain the comparisons of alternative performance with respect to cost (C), information value (IV), and the satisfaction of regulatory reporting requirements (RRR), respectively. These comparisons indicate:

* With respect to cost, the evaluator has determined that the current system is much less expensive than the redesign. Hence, WQISC receives a "strongly favorable" score (7).

* The evaluator feels that features of the redesigned system result in more valuable information produced. Consequently, WQISR is assigned a "slightly favorable" score (3).

- * The evaluator expects the redesigned system to be much more capable of meeting regulatory requirements. The "strongly favored" score (6) for WQISR reflects that dramatically increased capability.

Matrix (2): For the Cost criterion,

Cost (C)	WQISC	WQISR
WQISC	1	7
WQISR	1/7	1
Column Sum	1 1/7	8

Matrix (3): For the Information Value criterion,

Information Value (IV)	WQISC	WQISR
WQISC	1	1/3
WQISR	3	1
Column Sum	4	1 1/3

Matrix (4): For the Regulatory Reporting Requirements criterion,

Regulatory Reporting Requirements (RRR)	WQISC	WQISR
WQISC	1	1/6
WQISR	6	1
Column Sum	7	1 1/6

Step 2: Priority Computation:

Matrices (5), (6), (7) and (8) are the normalized versions of matrices (1) , (2), (3), and (4) respectively, and display the priority vectors (i.e., the weights of the row attributes).

Matrix (5): Comparing the criteria against the decision goal,

Select Best WQIS	Cost	Information Value	Regulatory Reporting Requirements	Row Sum	Priority Vector
Cost	1/10	1/13	1/9	0.288	0.096
Information Value	3/10	3/13	1/4.5	0.753	0.251
Regulatory Reporting Requirements	6/10	9/13	1/1.5	1.959	0.653

CR = 0.01

The priority vector indicates that meeting regulatory requirements is nearly 3 times (0.653/0.251) as important as improved information value and over 6 times (0.653/0.096) as important as any additional costs which may be incurred.

CR is the "consistency ratio" computed for this set of paired attribute comparisons. AHP assumes that concurrent paired comparisons of more than two attributes will likely yield inconsistent proportionality in the ratings. A consistency ratio of less than 10% (CR < 0.10) is considered acceptable.

Matrix (6): Comparing the alternatives against cost,

Cost (C)	WQISC	WQISR	Row Sum	Priority Vector
WQISC	7/8	7/8	7/4	0.875
WQISR	1/8	1/8	1/4	0.125

CR = 0.00

On the basis of cost, the current system is 7 times (0.875/0.125) preferable than the redesigned system.

Matrix (7): Comparing the alternatives against information value,

Information Value (IV)	WQISC	WQISR	Row Sum	Priority Vector
WQISC	1/4	1/4	1/2	0.250
WQISR	3/4	3/4	6/4	0.750

CR = 0.00

On the basis of information value, the redesigned system is preferable to the current system by a factor of three (0.750/0.250).

Matrix (8): Comparing the alternatives as able to satisfy regulatory reporting requirements,

Regulatory Reporting Requirements (RRR)	WQISC	WQISR	Row Sum	Priority Vector
WQISC	1/7	1/7	2/7	0.143
WQISR	6/7	6/7	12/7	0.857

CR = 0.00

On the basis of reporting to regulatory agencies, the redesigned system is nearly 8 times (0.857/0.143) preferable to the current system.

Part C: Evaluation of Information System Alternatives

Description:

Priority vectors are consolidated progressively through the levels of the hierarchy to arrive at composite weights for the evaluation alternatives. These composite weights, normalized on a 0.00 to 1.00 scale, represent the evaluator's relative preference for each alternative with respect to satisfying the decision goal (as stated at the apex of the hierarchy).

The priority vector (or eigenvector) computed for each comparison matrix is weighted by the priority of the next-higher-level attribute to which it is connected. The procedure is repeated throughout the hierarchy, to compute the weight of each element at every level and to use these weights to compute composite weights for succeeding levels. Ultimately, composite weights for decision alternatives with respect to the decision objective are computed and the preferred alternative can be identified.

Example:

In order to accomplish the decision goal of selecting the preferable alternative (WQISC or WQISR), comparison information throughout the hierarchy must be linked and consolidated.

In this application, the consolidation is accomplished by the series of matrix operations described below.

PV(Hierarchy) = PV(1,3) = B(1,2) * B(2,3)

Where:

PV(Hierarchy) indicates the composite priority vector which links the entire hierarchy and thus allows selection of the preferred alternative.

PV(1,3) indicates the composite priority vector linking level 3 decision attributes to level 1 attributes. In this case PV(1,3) and PV(Hierarchy) are identical since the hierarchy has only three levels.

B(1,2) and B(2,3), (i.e., B[i-1,i]), are matrices formed by combining all the priority vectors computed at level(i) with respect to level i-1 (i.e., the next higher level) decision attributes. B(i-1,i) columns (level i priority vectors) must be ordered as the rows of B(i-2,i-1), i.e., displaying the same sequence of decision attributes.

$$PV(\text{Hierarchy}) = B(1,2) * B(2,3)$$

$$= \begin{array}{c|c|} & \text{Select WQIS} \\ \hline \text{C} & 0.096 \\ \text{IV} & 0.251 \\ \text{RRR} & 0.653 \\ \hline \end{array} * \begin{array}{c|ccc|} & \text{C} & \text{IV} & \text{RRR} \\ \hline \text{WQISC} & 0.875 & 0.250 & 0.143 \\ \text{WQISR} & 0.125 & 0.750 & 0.85 \\ \hline \end{array}$$

$$= \begin{bmatrix} 0.875 & 0.250 & 0.143 \\ 0.125 & 0.750 & 0.857 \end{bmatrix} * \begin{bmatrix} 0.096 \\ 0.251 \\ 0.653 \end{bmatrix}$$

and thus,

$$PV(\text{Hierarchy}) = \begin{array}{c|c|} & \text{Select Preferable WQIS} \\ \hline \text{WQISC} & 0.240 \\ \text{WQISR} & 0.760 \\ \hline \end{array}$$

This vector of composite weights (decision alternative preference scores), indicates that the redesigned water quality information system (WQISR) has a preference score of 0.760, indicating a clear advantage over the current system, which scored 0.240. As indicated earlier, these computations are carried out by the AHP-oriented decision analysis software packages. Summaries produced by the software packages provide excellent documentation of the performance evaluation model.

Part D: Model Interpretation and Validation

Description:

The AHP's virtues include its ability to accommodate subjective and objective criteria in one decision process and to produce a composite numerical measure of an alternative's value (a "preference score"). The ultimate interpretation of preference scores is also a subjective exercise. For example, scores of 0.55 and 0.45 may suggest a meaningful distinction between two alternatives, but the evaluator must recognize that the actual significance depends upon all of the assumptions built into the model. Would scores of 0.60 and 0.40 be more meaningful? The evaluator's confidence in selecting an alternative (and in the overall decision process) can be enhanced by subsequent sensitivity analyses, which test the stability of conclusions drawn with changes in those underlying assumptions.

Example and Discussion:

In this hypothetical example, the redesigned water quality information system has been shown to offer significant advantage over the current design (preference scores of 0.760 and 0.240, respectively). The following discussion indicates how those results might be interpreted and tested.

* Priority of Criteria:

The evaluators's pairwise comparisons of criteria with respect to the overall decision objective yield coherent priorities when:

(1) all relevant criteria are identified and included in the analysis,

(2) the criteria are defined to be independent, or interdependence is explicitly accounted for,

(3) the criteria can be and are compared on the same scale (importance, magnitude, probability, etc.), and

(4) the orientation of criterion values with respect to the decision question is correct (e.g., higher cost is detrimental or not preferred).

"Consistency" implies reasonably constant proportionality among the pairwise comparisons of related elements. If A is 3 times as important as B, and B is twice as important as C, then perfect consistency dictates that A is 6 times as important as C. In large and ambiguous decision problems, perfect consistency is unlikely. A consistency ratio (CR) of 0.10 or less is considered acceptable. Large ratios (CR > 0.10) should prompt the evaluator to reexamine the set of criteria, the comparison values, or both.

In this example, the evaluator has limited the decision framework to 3 criteria which are inclusive and easily defined. CR = 0.01 (< 0.10) indicates adequate consistency in the assessment of their relative importance.

The evaluator has indicated that the ability to meet regulatory reporting requirements is almost 7 times as important as water quality information systems cost and 2 1/2 times as important as the information value produced; all else being equal. Discomfort with these ratios may also prompt a review of criteria definitions and comparison values.

* Performance of Alternatives:

Similar considerations apply when the evaluator compares the performance of alternatives with respect to the criteria. Is the set of alternatives complete? Are the alternatives distinctive (independent)? In this example, the evaluator limited the alternative set to two, facilitating the direct comparison on each criterion and avoiding consistency complications.

With respect to cost, the current system appears 7 times preferable to the redesigned system. If this ratio does not reflect expected expenditures, the evaluator may wish to revisit cost and/or expense assumptions.

From the perspectives of information value and meeting regulatory reporting needs, the redesigned system, WQISR, performs better by factors of 3 and 6 respectively. Discomfort or uncertainty with respect to these ratios should prompt the manager to check the definitions and measurement "yardsticks" applied in the comparisons.

* Selection of the Preferable Alternative:

The priority vector for the entire hierarchy links the alternatives to the decision objective, and identifies one alternative as "best". The elements of that vector are composite weights which represent relative preferences for the alternatives with respect to that choice. Here, the evaluator finds the redesigned system to be preferable by a factor of more than 3 (0.760/0.240). Presumably the redesigned system would be implemented if possible.

Because alternative preference scores are a mathematical consolidation of all previous inputs, earlier resolutions of consistency and coherence questions are incorporated. At this stage of the analysis, any discomfort with the composite weighting of the alternatives is likely to be due to fundamental hierarchy mistakes (i.e., missing criteria or attributes) rather than inaccurate or inconsistent attribute comparisons.

Extensions of the Performance Evaluation Model:

Beyond the relatively straightforward comparison of water quality information system alternatives, AHP models can be used in:

* Risk Analysis

When used to compare alternatives, AHP can be used to analyze risk by incorporating risk into the hierarchy as a comparison criterion and then conducting sensitivity analyses by varying its priority or its relationship to other attributes.

A second approach uses AHP in a forecasting mode; i.e., where the decision goal is to predict the probability (or magnitude) of risk exposure for alternative water quality information systems. Configuring the problem in this format prompts the evaluator to explicitly define all risks faced in the water quality management system and allows direct and detailed identification of risk/cost tradeoffs.

* System Planning

A decision hierarchy, once constructed, documents the attributes, relationships, and concerns embodied in a water quality information system and becomes a convenient device to facilitate the review of water quality management and information systems on a regular basis.

The hierarchy and model can serve in "total system" sensitivity analyses. The manager may "check off" on the hierarchy where any change to the system (internally or externally initiated) would influence the management or information system and then gauge its impact on information system performance. As an example, if a water quality manager anticipated changes in a water quality variable standard, he or she could pinpoint all of the hierarchy attributes potentially affected, assess the impact on information system performance, and forecast the consequences of various counteractive strategies. Continuous "what-if" investigations are facilitated to provide constantly refined and improved water quality management and information systems.

* Optimization

AHP models can be used to produce variable relationships (curves) helpful in identifying optimal or acceptable system operating regions. As an example, an AHP model constructed to predict probabilities of risk reduction could be executed in iterative fashion while varying cost, to produce a risk-cost curve. A water quality manager could then identify boundaries of optimal or acceptable risk/cost regions on the curve. Once such a region is identified, the manager could again use the model in a "what-if" fashion to identify changes that would drive the system towards those desired operating conditions.

APPENDIX I

Analytic Hierarchy Process
and
Eigenvalue Method

(From Zahedi, 1986)

Using the Analytic Hierarchy Process (AHP) in solving a decision problem involves four steps [Johnson, 1980]:

Step 1 - Setting up the decision hierarchy by breaking down the decision problem into a hierarchy of interrelated decision elements,

Step 2 - Collecting input data by pairwise comparison of decision elements,

Step 3 - Using the "eigenvalue" method to estimate the relative weights of decision elements,

Step 4 - Aggregating the relative weights at a set of ratings for the decision alternatives (or outcomes).

At step 1, which is perhaps the most important aspect of the AHP, the decision analyst should break down the decision problem into a hierarchy of interrelated decision elements [Saaty 1977a, 1977b, 1977c, 1977d, 1987b, 1980]. At the top of the hierarchy lies the most macro decision objective, such as the objective of making the best decision (or selecting the best alternative). The lower levels of the hierarchy contain attributes (objectives) which contribute to the quality of the decision. Details of these attributes increase at the lower levels of the hierarchy. The last levels of the hierarchy contain decision alternatives or selection choices. The decision schema, hence, has a standard form as depicted in Figure 1.

In setting up the decision hierarchy, the number of levels depends on the complexity of the problem and on the degree of detail the analyst requires to solve the problem. Since each level entails pairwise comparisons of its elements, Saaty [1980] suggests that the number of elements at each level be limited to a maximum of nine. This constraint, however, is not a necessary condition of the method and has not been adhered to in all applications.

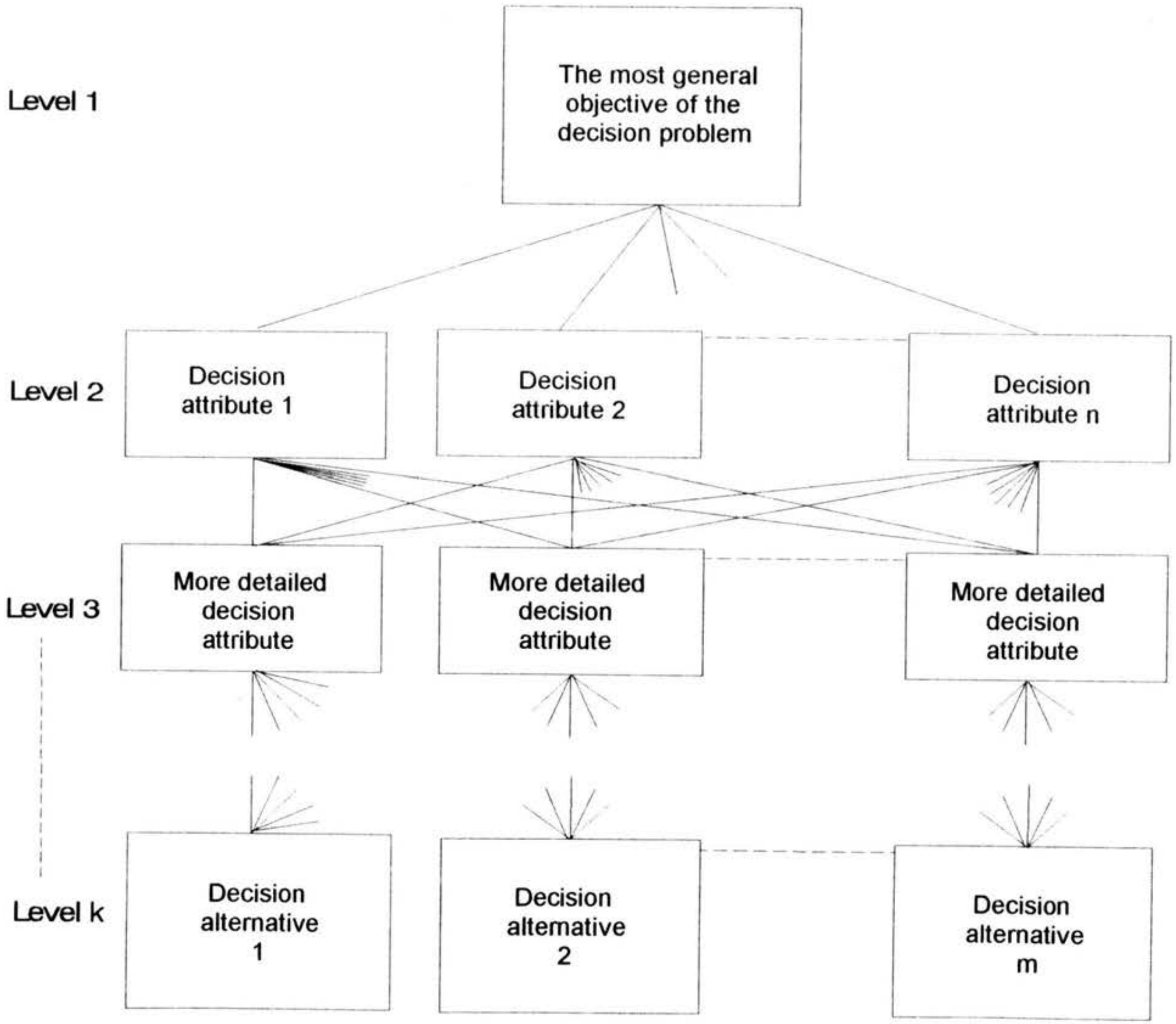

Figure 1: Analytic Hierarchy Process Decision Schema - A Hierarchy with k Levels (from Zahedi, 1986)

In step 2, the input data for the problem consists of matrices of pairwise comparisons of elements of one level that contribute to achieving (or satisfying) the objectives of the next higher level.

When compared with itself, each element has equal importance. Diagonal elements of the input matrix, therefore, always equal one, and lower triangle elements of the matrix are the reciprocal of upper triangle elements. Thus, pairwise comparison data are collected for only half of the matrix elements, excluding diagonal elements.

One may argue that it is possible to assign weights directly to elements of a level....... The argument in AHP is that such direct assignment of weights is too abstract for the evaluator and results in inaccuracies. Pairwise comparisons, on the other hand, give the evaluator a basis on which to reveal his or her preference by comparing two elements. Additionally, the evaluator has the option of expressing preferences between the two as equally preferred, weakly preferred, strongly preferred, or absolutely preferred, which would be translated into pairwise weights of 1,3,5,7 and 9, respectively, with 2,4,6 and 8 as intermediate values. (*Author's Note: See Appendix II for an explanation of the pairwise weighting scale.*)

In step 3, the solution technique of the AHP takes in as input the above pairwise comparisons and produces the relative weights of elements at each level as output. The argument for the solution methodology is as follows [Saaty 1977a, 1977b, 1977c, 1977d, 1980, 1982a]. If the evaluator could know the actual relative weights of n elements (at one level of the hierarchy with respect to one level higher), the matrix of the pairwise comparisons would be

$$A = \begin{array}{c|ccccc|} & 1 & 2 & 3 & \ldots & n \\ \hline 1 & w_1/w_1 & w_1/w_2 & w_1/w_3 & \ldots & w_1/w_n \\ 2 & w_2/w_1 & w_2/w_2 & w_2/w_3 & \ldots & w_2/w_n \\ 3 & w_3/w_1 & w_3/w_2 & w_3/w_3 & \ldots & w_3/w_n \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ n & w_n/w_1 & w_n/w_2 & w_n/w_3 & \ldots & w_n/w_n \end{array} \qquad (2)$$

In this case, the relative weights could be trivially obtained from each one of n rows of matrix A. In other words, matrix A has rank 1; and the following holds:

$$A \cdot W = n \cdot W \tag{3}$$

where $W = (w_1, w_2, \ldots, w_n)^T$ is the vector of actual relative weights, and n is the number of elements. In matrix algebra, n and W in (3) are called the eigenvalue and the right eigenvector of matrix A.

AHP posits that the evaluator does not know W and, therefore, is not able to produce the pairwise relative weights of matrix A accurately. Thus, the observed matrix A contains inconsistencies. The estimation of W (denoted as $\hat{W}$) could be obtained similarly to (3) from

$$\hat{A} \cdot \hat{W} = \lambda_{\max} \cdot \hat{W},$$

where $\hat{A}$ is the observed matrix of pairwise comparisons, $\lambda_{\max}$ is the largest eigenvalue of $\hat{A}$, and $\hat{W}$ is its right eigenvector. $\hat{W}$ constitutes the estimation of W......

In (4), $\lambda_{\max}$ may be considered the estimation of n in (3). Saaty [1980] has shown that $\lambda_{\max}$ is always greater than or equal to n. The closer the value of computed $\lambda_{\max}$ is to n, the more consistent are the observed values of $\hat{A}$. This property has led to the construction of the consistency index (CI) as

$$CI = (\lambda_{\max} - n) / (n-1), \tag{5}$$

and of the consistency ratio (CR) as

$$CR = (CI/ACI) * 100, \tag{6}$$

where ACI is the average index of randomly generated weights [Saaty 1980]. As a rule of thumb, a CR value of 10 percent or less is considered acceptable. Otherwise, it is recommended that $\hat{A}$ be re-observed to resolve inconsistencies in pairwise comparisons.

Saaty [1977a] shows that the estimation of W from (4) could be accomplished via an iterative computation. His computation algorithm is now available in a software product called "Expert Choice" [Decision Support Software Inc. 1984] which includes consistency checks for input matrices as well.

In sum, the "eigenvalue" method (4) in AHP is one method for estimating the relative weights - W - from the matrix of pairwise comparisons. As discussed later, a number if other estimators also exist; none, however, is as well known and widely applied as the "eigenvalue" method.

Step 4 aggregates relative weights of various levels obtained from Step 3 in order to produce a vector of composite weights which serve as ratings of decision alternatives (or selection choices) in achieving the most general objective of the problem. The composite relative weight vector of elements at kth level with respect to that of the first level may be computed from [Saaty 1980, Zahedi 1985a]

$$C[1,k] = \prod_{i=2}^{k} B_i, \tag{7}$$

where $C[1,k]$ is the vector of composite weights of elements at level k with respect to the element on level 1, and B_i, is the n_{i-1} by n_i matrix with rows consisting of estimated $\hat{W}$ vectors. n_i represents the number of elements at level i and is the same as n in (3) but is subscripted to show that it belongs to level i.

Repeating this simple aggregation yields relative weights of elements at the lowest level of hierarchy (where choices are located) with respect to the most aggregate objective of the decision at the first level. These composite weights may also be called decision alternatives scores and they form the basis for selecting an alternative.

ACKNOWLEDGEMENT: The material presented in this appendix is taken directly from "The Analytic Hierarchy Process - A Survey of the Method and its Applications", by Fatemeh Zahedi of the University of Massachusetts, published in the July-August 1986 issue of INTERFACES. Many books and articles are available which discuss the background, theory and application of the AHP in great detail. For further information on the AHP, the reader is urged to consult the references cited by Zahedi (1986) and the numerous works of T.L. Saaty, the originator of the methodology.

APPENDIX II

Importance Intensity Scale

(from Saaty and Gholamnezhad, 1982)

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgement strongly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgement strongly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored, and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgements	Compromise is needed between two judgements
Reciprocals of above (non-zero)	If activity i has one of the preceding numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	Reasonable assumption

Comments:

In quantifying judgements, a scale is used with values ranging from 1 to 9 as defined above. There are several reasons for choosing such a scale (Saaty, 1980):

(1) The qualitative distinctions are meaningful in practice and have an element of precision when the items being compared are of the same order of magnitude or close together with regard to the property used to make the comparison.

(2) The ability to make qualitative distinctions is well represented by five attributes: equal, weak, strong, very strong, and absolute. Comparisons can be made between adjacent attributes when greater precision is needed. The totality requires nine values and they may well be consecutive-the resulting scale would then be validated in practice.

(3) The psychological limit of 7 ± 2 items in a simultaneous comparison suggests that if 7 ± 2 items are taken which satisfy the description under reason (1), and if they are all slightly different from each other, nine points would be needed to distinguish these differences (Miller,1956).

The quantities used in this scale are absolute rather than ordinal numbers, and if numbers larger than those appearing in the scale are needed, the hierarchy itself is used to cluster the elements, and to compare the clusters before comparing their elements. Thus we assume that the factors being compared fall within the same order of magnitude implied by the scale.

Acknowledgement: The material in this appendix is taken from "High Level Nuclear Waste Management: Analysis of Options", by T.L. Saaty and H. Gholamnezhad, in Environment and Planning B, Volume 9, No. 2, 1982. For further information, the reader is referred to the numerous works of T.L. Saaty, the originator of the Analytic Hierarchy Process (AHP).

APPENDIX B

THE ANALYTIC HIERARCHY PROCESS (AHP)

Appendix B-1: The Analytic Hierarchy Process and the Eigenvalue Method

Appendix B-2: Importance Intensity Scale

APPENDIX B-1

Analytic Hierarchy Process
and
Eigenvalue Method

(From Zahedi, 1986)

Using the Analytic Hierarchy Process (AHP) in solving a decision problem involves four steps [Johnson, 1980]:

Step 1 - Setting up the decision hierarchy by breaking down the decision problem into a hierarchy of interrelated decision elements,

Step 2 - Collecting input data by pairwise comparison of decision elements,

Step 3 - Using the "eigenvalue" method to estimate the relative weights of decision elements,

Step 4 - Aggregating the relative weights at a set of ratings for the decision alternatives (or outcomes).

At step 1, which is perhaps the most important aspect of the AHP, the decision analyst should break down the decision problem into a hierarchy of interrelated decision elements [Saaty 1977a, 1977b, 1977c, 1977d, 1978b, 1980]. At the top of the hierarchy lies the most macro decision objective, such as the objective of making the best decision (or selecting the best alternative). The lower levels of the hierarchy contain attributes (objectives) which contribute to the quality of the decision. Details of these attributes increase at the lower levels of the hierarchy. The last levels of the hierarchy contain decision alternatives or selection choices. The decision schema, hence, has a standard form as depicted in Figure 1.

In setting up the decision hierarchy, the number of levels depends on the complexity of the problem and on the degree of detail the analyst requires to solve the problem. Since each level entails pairwise comparisons of its elements, Saaty [1980] suggests that the number of elements at each level be limited to a maximum of nine. This constraint, however, is not a necessary condition of the method and has not been adhered to in all applications.

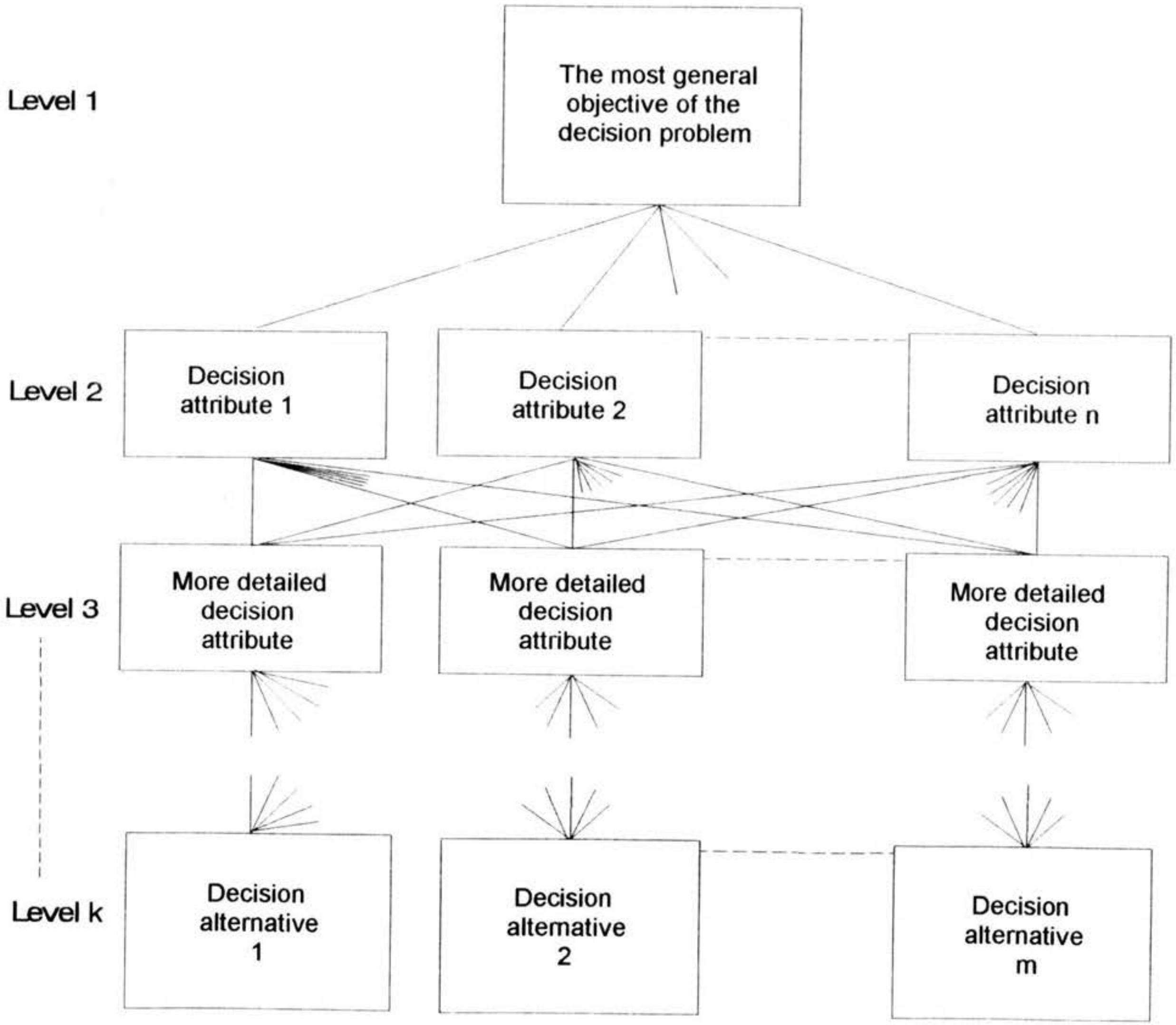

Figure 1: Analytic Hierarchy Process Decision Schema - A Hierarchy with k Levels (from Zahedi, 1986)

In step 2, the input data for the problem consists of matrices of pairwise comparisons of elements of one level that contribute to achieving (or satisfying) the objectives of the next higher level.

When compared with itself, each element has equal importance. Diagonal elements of the input matrix, therefore, always equal one, and lower triangle elements of the matrix are the reciprocal of upper triangle elements. Thus, pairwise comparison data are collected for only half of the matrix elements, excluding diagonal elements.

One may argue that it is possible to assign weights directly to elements of a level...... The argument in AHP is that such direct assignment of weights is too abstract for the evaluator and results in inaccuracies. Pairwise comparisons, on the other hand, give the evaluator a basis on which to reveal his or her preference by comparing two elements. Additionally, the evaluator has the option of expressing preferences between the two as equally preferred, weakly preferred, strongly preferred, or absolutely preferred, which would be translated into pairwise weights of 1,3,5,7 and 9, respectively, with 2,4,6 and 8 as intermediate values. (*Author's Note: See Appendix B-2 for an explanation of the pairwise weighting scale.*)

In step 3, the solution technique of the AHP takes in as input the above pairwise comparisons and produces the relative weights of elements at each level as output. The argument for the solution methodology is as follows [Saaty 1977a, 1977b, 1977c, 1977d, 1980, 1982a]. If the evaluator could know the actual relative weights of n elements (at one level of the hierarchy with respect to one level higher), the matrix of the pairwise comparisons would be

$$A = \begin{array}{cc} & \begin{array}{ccccc} 1 & 2 & 3 & \ldots & n \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \\ \cdot \\ \cdot \\ \cdot \\ n \end{array} & \begin{pmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 & \ldots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \ldots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & \ldots & w_3/w_n \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \ldots & w_n/w_n \end{pmatrix} \end{array} \tag{2}$$

In this case, the relative weights could be trivially obtained from each one of n rows of matrix A. In other words, matrix A has rank 1; and the following holds:

$$A \cdot W = n \cdot W \qquad (3)$$

where $W = (w_1, w_2, \ldots, w_n)^T$ is the vector of actual relative weights, and n is the number of elements. In matrix algebra, n and W in (3) are called the eigenvalue and the right eigenvector of matrix A.

AHP posits that the evaluator does not know W and, therefore, is not able to produce the pairwise relative weights of matrix A accurately. Thus, the observed matrix A contains inconsistencies. The estimation of W (denoted as $\hat{W}$) could be obtained similarly to (3) from

$$\hat{A} \cdot \hat{W} = \lambda_{\max} \cdot \hat{W},$$

where $\hat{A}$ is the observed matrix of pairwise comparisons, $\lambda_{\max}$ is the largest eigenvalue of $\hat{A}$, and $\hat{W}$ is its right eigenvector. $\hat{W}$ constitutes the estimation of W......

In (4), $\lambda_{\max}$ may be considered the estimation of n in (3). Saaty [1980] has shown that $\lambda_{\max}$ is always greater than or equal to n. The closer the value of computed $\lambda_{\max}$ is to n, the more consistent are the observed values of $\hat{A}$. This property has led to the construction of the consistency index (CI) as

$$CI = (\lambda_{\max} - n) / (n-1), \qquad (5)$$

and of the consistency ratio (CR) as

$$CR = (CI/ACI) * 100, \qquad (6)$$

where ACI is the average index of randomly generated weights [Saaty 1980]. As a rule of thumb, a CR value of 10 percent or less is considered acceptable. Otherwise, it is recommended that $\hat{A}$ be re-observed to resolve inconsistencies in pairwise comparisons.

Saaty [1977a] shows that the estimation of W from (4) could be accomplished via an iterative computation. His computation algorithm is now available in a software product called "Expert Choice" [Decision Support Software Inc. 1984] which includes consistency checks for input matrices as well.

In sum, the "eigenvalue" method (4) in AHP is one method for estimating the relative weights - W - from the matrix of pairwise comparisons. As discussed later, a number if other estimators also exist; none, however, is as well known and widely applied as the "eigenvalue" method.

Step 4 aggregates relative weights of various levels obtained from Step 3 in order to produce a vector of composite weights which serve as ratings of decision alternatives (or selection choices) in achieving the most general objective of the problem. The composite relative weight vector of elements at *k*th level with respect to that of the first level may be computed from [Saaty 1980, Zahedi 1985]

$$C[1,k] = \prod_{i=2}^{k} B_i, \qquad (7)$$

where $C[1,k]$ is the vector of composite weights of elements at level k with respect to the element on level 1, and B_i, is the n_{i-1} by n_i matrix with rows consisting of estimated $\hat{W}$ vectors. n_i represents the number of elements at level i and is the same as n in (3) but is subscripted to show that it belongs to level i.

Repeating this simple aggregation yields relative weights of elements at the lowest level of hierarchy (where choices are located) with respect to the most aggregate objective of the decision at the first level. These composite weights may also be called decision alternatives scores and they form the basis for selecting an alternative.

ACKNOWLEDGEMENT: The material presented in this appendix is taken directly from "The Analytic Hierarchy Process - A Survey of the Method and its Applications", by Fatemeh Zahedi of the University of Massachusetts, published in the July-August 1986 issue of INTERFACES. Many books and articles are available which discuss the background, theory and application of the AHP in great detail. For further

information on the AHP, the reader is urged to consult the references cited by Zahedi (1986) and the works of T.L. Saaty (1980, 1990a, and 1990b), the originator of the methodology.

APPENDIX B-2

Importance Intensity Scale

(from Saaty and Gholamnezhad, 1982)

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgement strongly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgement strongly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored, and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgements	Compromise is needed between two judgements
Reciprocals of above (non-zero)	If activity i has one of the preceding numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	Reasonable assumption

Comments:

In quantifying judgements, a scale is used with values ranging from 1 to 9 as defined above. There are several reasons for choosing such a scale (Saaty, 1980):

(1) The qualitative distinctions are meaningful in practice and have an element of precision when the items being compared are of the same order of magnitude or close together with regard to the property used to make the comparison.

(2 The ability to make qualitative distinctions is well represented by five attributes: equal, weak, strong, very strong, and absolute. Comparisons can be made between adjacent attributes when greater precision is needed. The totality requires nine values and they may well be consecutive-the resulting scale would then be validated in practice.

(3 The psychological limit of 7 ± 2 items in a simultaneous comparison suggests that if 7 ± 2 items are taken which satisfy the description under reason (1), and if they are all slightly different from each other, nine points would be needed to distinguish these differences (Miller,1956).

The quantities used in this scale are absolute rather than ordinal numbers, and if numbers larger than those appearing in the scale are needed, the hierarchy itself is used to cluster the elements, and to compare the clusters before comparing their elements. Thus we assume that the factors being compared fall within the same order of magnitude implied by the scale.

APPENDIX C

ILLUSTRATION OF WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION USING THE ANALYTIC HIERARCHY PROCESS

APPENDIX C

ILLUSTRATION OF WATER QUALITY INFORMATION SYSTEMS PERFORMANCE EVALUATION USING THE ANALYTIC HIERARCHY PROCESS

BACKGROUND:

The Analytic Hierarchy Process (AHP), is a technique devised by T.L. Saaty (1980) which provides "a framework designed to cope with the intuitive, the rational and the irrational in decision situations involving multiple objectives, multiple criteria and multiple decision makers; it has no limits on the number of alternatives and makes no demands with respect to certainty or uncertainty." (Thornton, 1991). In a 1986 survey, Zahedi identifies over twenty different areas where AHP has been applied, including energy and environmental problem solving.

Saaty and Gholamnezhad (1982) describe AHP as "... a method of breaking down a complex unstructured situation into its component parts; arranging the parts or variables into a hierarchic order; assigning numerical values to subjective judgements on the relative importance of each variable; and synthesizing the judgements to determine the overall priorities of the variables". They also emphasize the advantages of the approach in promoting discipline, structure and cohesiveness in the decision-making process.

The AHP is a decision process similar to decision tree or relevance tree techniques. These techniques have been applied to a wide variety of management decision problems, ranging from simple expected benefit computations to complex multi-alternative, multi-criteria, multi-level analyses.

In this appendix, the methodology of the Analytic Hierarchy Process is briefly reviewed and the approach is used to analyze a simple water quality information systems assessment problem. The AHP can be configured to address several varieties of decision questions or problems. In this demonstration, the AHP is employed to select a preferred course of action from a set of two or more alternatives.

AHP PROCEDURE:

Step (1): Set Up Decision Hierarchy

As in all decision processes, the first phase is that of definition. AHP requires that the decision problem be structured as follows:

(1) Define the decision to be made, i.e., clearly state the ultimate goal, objective or choice the process is intended to assist.

(2) Clearly delineate and define the alternatives among which decision-makers must compare or choose.

In this application, the alternatives are unique water quality information system options (e.g., current and redesigned systems).

(3) Break down the decision problem into a hierarchy of interrelated decision attributes (i.e., criteria, subcriteria, actors, influences, etc.)

Hierarchy definition involves the sequential decomposition of the decision problem into its factors or elements (Saaty and Gholamnezhad, 1982). It is not required that the hierarchy be symmetrical or complete. A decision attribute at one level need not be associated with all attributes at lower levels. Figure C-1 shows the fundamental structure of an AHP decision hierarchy.

Step (2): Collect Input Data

AHP input data are measures of pairwise comparisons of all the decision attributes at a given level of the decision hierarchy with respect to the associated attributes at the next higher level. The comparisons identify which of the paired attributes best satisfies or achieves the objectives of that next higher level attribute (the "parent" attribute). The comparison measures are captured in a matrix format.

The comparisons can be specified by an individual decision-maker or derived by some group consensus process. Figure C-2 is a tabular presentation of pairwise comparison data for three hypothetical information system attributes: (1) cost, (2) information value, and (3) satisfaction of management objectives.

Step (3): Establish Decision Attribute Priorities

The AHP combines the pairwise comparisons at each level of the hierarchy into a set of relative attribute weights. AHP assumes that pairwise comparisons at any level will be made inconsistently, making direct and

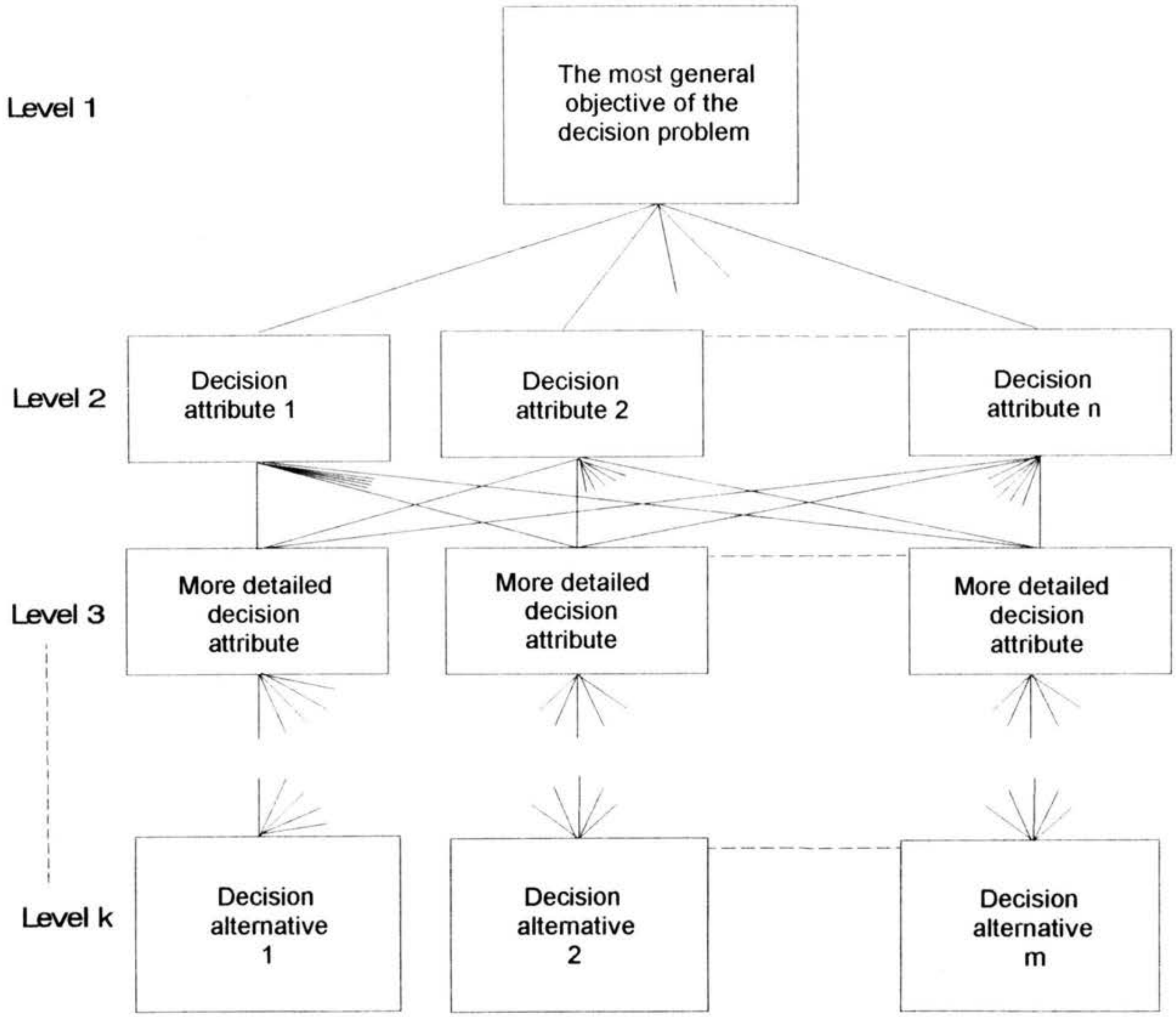

Figure C-1: Analytic Hierarchy Process Decision Schema - A Hierarchy with k Levels (from Zahedi, 1986)

	COST	INFORMATION VALUE	SATISFACTION OF MANAGEMENT OBJECTIVES
COST	1.0	0.667	0.5
INFORMATION VALUE	1.5	1.0	0.667
SATISFACTION OF MANAGEMENT OBJECTIVES	2.0	1.5	1.0

Matrix elements represent the ratio of the row attribute's importance to that of the column attribute

Figure C-2: Pairwise Comparison Measures of Information System Attributes

precise specification of relative attribute weights impossible. Several procedures are available which estimate attribute weights while demonstrating inconsistencies. The most commonly used is the "eigenvalue method", which employs matrix algebra concepts to produce a "priority vector" of estimated relative weights of the decision attributes in a given level of the hierarchy. A detailed mathematical description of the eigenvalue method and a discussion of consistency measures are given in Appendix B.

Step (4): Rate the Decision Alternatives

Decision attribute priorities at all hierarchy levels are aggregated to produce a set of composite weights which rate the decision alternatives with respect to the ultimate decision goal. The priority vector (eigenvector) computed for each comparison matrix is weighted by the priority of the attribute to which it is connected in the next higher level of the hierarchy. The procedure is repeated downward in the hierarchy, computing the weights of each element at every level and using these to compute composite weights for succeeding levels (Saaty and Gholamnezhad, 1982). Ultimately, composite weights for decision alternatives with respect to the decision objective are computed and the preferred alternative can be identified.

EXAMPLE APPLICATION OF THE ANALYTIC HIERARCHY PROCESS

The following example illustrates the application of the AHP to the evaluation of alternative water quality information system designs.

Scenario:

(1) A water quality manager is required to evaluate the relative merits of a proposed redesign of his organization's water quality information system. He will refer to the alternatives as the current and redesigned systems; WQISC and WQISR respectively.

(2) The manager will compare the alternative systems on the basis of cost, information value and the satisfaction of regulatory reporting requirements.

Analysis: Analytic Hierarchy Process Methodology

(1) Decision Hierarchy and Criteria

Figure C-3 illustrates the AHP hierarchy derived from the scenario description.

(2) Input Data

At each level of the hierarchy the water quality manager compares all attributes by pairs in a matrix. The elements of the comparison matrix are "importance intensity" scores - measures of how strongly the row attribute is favored over the column attribute with respect to satisfying the objective or intent of the parent attribute. The scores range from 1 (equal importance) to 9 (absolutely more important) as described by Saaty's intensity scale (see Appendix B). As expected, reverse comparisons exhibit reciprocal scores and diagonal elements always equal one.

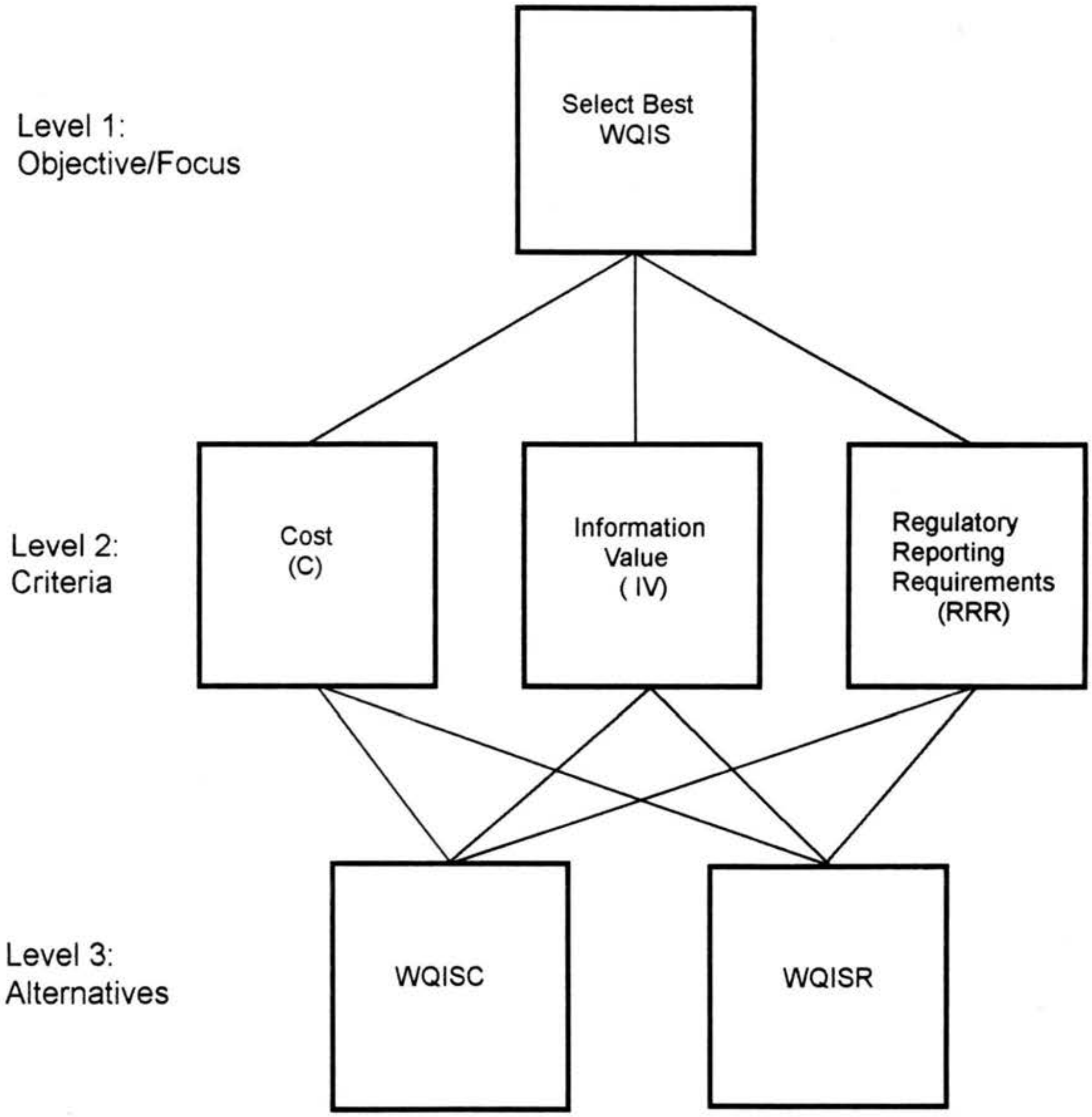

Figure C-3: Water Quality Information System Selection Decision Hierarchy

Level 2 - Comparison of Criteria:

Select Best WQIS	Cost	Information Value	Regulatory Reporting Requirements
Cost	1	1/3	1/6
Information Value	3	1	1/3
Regulatory Reporting Requirements	6	3	1
Column Sum	10	4 1/3	1 1/2

These scores indicate that the manager regards meeting regulatory reporting requirements as demonstrably most important (6) in selecting a preferred water quality information system. Information value is somewhat more important (3) than system cost.

Note: Column sums are included here for convenience and will be used in later calculations.

Level 3 - Comparison of Alternatives with respect to Criteria:

For the Cost criterion;

Cost (C)	WQISC	WQISR
WQISC	1	7
WQISR	1/7	1
Column Sum	1 1/7	8

In comparing the alternatives with respect to cost, the manager has determined that the current system is much less expensive than the redesign. Hence, WQISC receives a "strongly favorable" score (7).

Similarly, for the Information Value criterion

Information Value (IV)	WQISC	WQISR
WQISC	1	1/3
WQISR	3	1
Column Sum	4	1 1/3

The manager feels that features of the redesigned system may result in more consistent and accurate information produced. Consequently, he gives WQISR a "slightly favorable" score (3).

Finally, for the Regulatory Reporting Requirements criterion;

Regulatory Reporting Requirements (RRR)	WQISC	WQISR
WQISC	1	1/6
WQISR	6	1
Column Sum	7	1 1/6

Unlike the current system, the redesigned system promises to deliver complete reports to state and federal agencies in a timely fashion. The "strongly favored" score (6) for WQISR reflects that dramatically increased capability.

(3) Decision Attribute Priorities

Decision attributes are weighted at each level using the eigenvalue method (see Appendix B). The estimated right eigenvector of each comparison matrix is the priority vector with respect to the parent attribute. The elements of the priority vector are the relative weights of the compared decision attributes.

To compute the priority vectors, the comparison matrices are manipulated as follows:

- Matrix elements are normalized over each decision element (i.e., divided by column totals) to permit comparison on the same numerical scale (0.0 to 1.0).
- Elements of each row of the normalized matrix are averaged to produce the relative decision attribute weights which comprise the priority vector.

Level 2 - Normalized Comparison Matrix and Priority Vector

Select Best WQIS	Cost	Information Value	Regulatory Reporting Requirements	Row Sum	Priority Vector
Cost	1/10	1/13	1/9	0.288	0.096
Information Value	3/10	3/13	1/4.5	0.753	0.251
Regulatory Reporting Requirements	6/10	9/13	1/1.5	1.959	0.653

CR = 0.01

The priority vector synthesizes the paired comparison judgements into relative criteria weights. Here the manager discovers that his criteria comparisons show that meeting regulatory requirements is nearly 3 times (0.653/0.251) as important as improved information value and over 6 times (0.653/0.096) as important as any additional costs which may be incurred.

CR is the "consistency ratio" computed for this set of paired attribute comparisons. AHP assumes that concurrent paired comparisons of more than two attributes will likely yield inconsistent proportionality in the ratings. A consistency ratio of less than 10% (CR < 0.10) is considered acceptable.

Level 3: Normalized Comparison Matrices and Priority Vectors

- Comparing the alternatives against cost:

Cost (C)	WQISC	WQISR	Row Sum	Priority Vector
WQISC	7/8	7/8	7/4	0.875
WQISR	1/8	1/8	1/4	0.125

CR = 0.00

On the basis of cost, the current system is 7 times (0.875/0.125) preferable than the redesigned system.

- Comparing the alternatives against information value:

Information Value (IV)	WQISC	WQISR	Row Sum	Priority Vector
WQISC	1/4	1/4	1/2	0.250
WQISR	3/4	3/4	6/4	0.750

CR = 0.00

On the basis of information value, the redesigned system is preferable to the current system by a factor of three (0.750/0.250).

- Comparing the alternatives as able to satisfy regulatory reporting requirements:

Regulatory Reporting Requirements (RRR)	WQISC	WQISR	Row Sum	Priority Vector
WQISC	1/7	1/7	2/7	0.143
WQISR	6/7	6/7	12/7	0.857

CR = 0.00

On the basis of reporting to regulatory agencies, the redesigned system is nearly 8 times (0.857/0.143) preferable to the current system.

(4) Rating Decision Alternatives

In order to accomplish the decision goal of selecting the preferable alternative (WQISC or WQISR), comparison information throughout the hierarchy must be linked and consolidated. Consolidation is achieved by computing a composite priority vector from the priority vectors derived at each level of the hierarchy. The priority vectors at any given level (k) are combined into a single "level *k* priority matrix" which is then multiplied by the priority vector of the next higher level (k-1) to produce the composite priority vector which weights level *k* decision attributes with respect to associated level *k-2* attributes. This composite vector can then, in turn, be used to create a second composite vector which weights the original level *k* decision attributes with respect to level *k-3* attributes. The process is extended until the bottom level attributes (alternatives) are weighted with respect to the top level decision objective, allowing identification of the preferred alternative.

In this application, the consolidation is accomplished by the series of matrix operations described below.

$$PV(Hierarchy) = PV(1,3) = B(1,2) * B(2,3)$$

Where:

PV(Hierarchy) indicates the composite priority vector which links the entire hierarchy and thus allows selection of the preferred alternative.

PV(1,3) indicates the composite priority vector linking level 3 decision attributes to level 1 attributes. In this case PV(1,3) and PV(Hierarchy) are identical since the hierarchy has only three levels.

B(1,2) and B(2,3), i.e., B(i-1,i), are matrices formed by combining all the priority vectors computed at level *i* with respect to level *i-1* decision attributes. B(i-1,i) columns (level *i* priority vectors) must be ordered as the rows of B(i-2,i-1), i.e., the same sequence of decision attributes.

PV(Hierarchy) = B(1,2) * B(2,3)

$$= \begin{array}{c|c|} & \begin{array}{c}\text{Select}\\ \text{WQIS}\end{array} \\ \hline \text{C} & 0.096 \\ \text{IV} & 0.251 \\ \text{RRR} & 0.653 \\ \hline \end{array} \; * \; \begin{array}{c|ccc|} & \text{C} & \text{IV} & \text{RRR} \\ \hline \text{WQISC} & 0.875 & 0.250 & 0.143 \\ \text{WQISR} & 0.125 & 0.750 & 0.85 \\ \hline \end{array}$$

$$= \begin{bmatrix} 0.875 & 0.250 & 0.143 \\ 0.125 & 0.750 & 0.857 \end{bmatrix} * \begin{bmatrix} 0.096 \\ 0.251 \\ 0.653 \end{bmatrix}$$

and thus,

$$\text{PV(Hierarchy)} = \begin{array}{c|c|} & \begin{array}{c}\text{Select}\\ \text{Preferable}\\ \text{WQIS}\end{array} \\ \hline \text{WQISC} & 0.240 \\ \text{WQISR} & 0.760 \\ \hline \end{array}$$

The manager concludes from this vector of composite weights, also called decision alternative preference scores, that the perceived advantages of the redesigned water quality information system (WQISR) make it the clearly preferable alternative.

DISCUSSION:

Interpretation of Results:

- Priority of Criteria:

The manager's pairwise comparisons of criteria with respect to the overall decision objective yield coherent priorities when:

(1) all relevant criteria are identified and included in the analysis,

(2) the criteria are defined to be independent, or interdependence is explicitly accounted for,

(3) the criteria can be and are compared on the same scale (importance, magnitude, probability, etc.), and

(4) the orientation of criterion values with respect to the decision question is correct (e.g., higher cost is detrimental or not preferred).

"Consistency" implies reasonably constant proportionality among the pairwise comparisons of related elements. If A is 3 times as important as B, and B is twice as important as C, then perfect consistency dictates that A is 6 times as important as C. In large and ambiguous decision problems, perfect consistency is unlikely. Saaty (1980) and others suggest that a consistency ratio (CR) of 0.10 or less is acceptable. Large ratios should prompt the manager to reexamine the set of criteria, the comparison values, or both.

In this case, the water quality manager has limited his decision framework to 3 criteria which he finds to be inclusive and easily defined. CR = 0.01 (< 0.10) indicates that he has been quite consistent in his assessment of their relative importance in selecting a preferred water quality information system design.

Operations on the normalized comparison matrices produce normalized priority vectors, i.e., the elements add to one. Thus, the manager has indicated that the ability to meet regulatory reporting requirements is almost 7 times as important as water quality information systems cost and 2 1/2 times as important as the information value produced; all else being equal. Discomfort with these ratios may also prompt a review of criteria definitions and comparison values.

* Performance of Alternatives:

Similar considerations apply when the manager evaluates the performance or behavior of alternatives with respect to the criteria. Is the set of alternatives "complete"? Are the alternatives distinctive (independent)? In this example, the water quality manager limited the alternative set to two, facilitating the direct comparison on each criterion and avoiding consistency complications.

With respect to cost, the current system, WQISC, appears 7 times preferable to the redesigned system. If this ratio does not approximate expected relative expenditures, the manager may wish to revisit his cost model and/or expense expectations.

From the perspectives of information value and meeting regulatory reporting needs, the redesigned system, WQISR, performs better by factors of 3 and 6 respectively. Discomfort or uncertainty with respect to these ratios should prompt the manager to check the definitions and measurement "yardsticks" applied in the comparisons.

* Selection of the Preferable Alternative:

The priority vector for the entire hierarchy links the alternatives to the decision objective, which is to identify or choose one alternative as "best". The elements of that vector are composite weights which represent relative preferences for the alternatives with respect to that choice. Here, the manager finds the redesigned system, WQISR, to be preferable by a factor of more than 3 (0.760/0.240). If necessary funding could be secured, he would presumably implement the redesigned system.

Because these composite weights are a mathematical consolidation of all previous inputs, earlier resolutions of consistency and coherence questions are incorporated. At this stage of the analysis, any discomfort with the weighting of the alternatives is likely to be due to fundamental hierarchy mistakes (i.e., missing criteria or attributes) rather than inaccurate or inconsistent attribute comparisons.

Utility of the AHP Process:

- Effort and Resources Required:

  The AHP process undertaken in the above application consumed approximately 8 hours, including manual computations and an occasional reference to review matrix algebra techniques. Note that in this case the manager worked alone and all comparisons and assessments are his.

  Real-life water quality information system evaluations are likely to be much more complex and subtle, and require input from many individuals. Soliciting and aggregating group consensus adds cost and time to all decision processes, however. AHP is not relatively disadvantaged to other multi-attribute decision processes in this regard.

  Several PC-based software packages (Sygenex, 1989) are available to assist the manager or consultant structure and analyze a decision problem using AHP. These programs and a graphics-capable personal computer system greatly facilitate constructing the hierarchy, comparing attributes and computing the priority vectors.

- Process Benefits:

  Advantages and benefits of employing AHP in the evaluation and selection of water quality information systems include:

  (1) it can be implemented easily at low cost, as indicated previously,

  (2) convenient personal computer packages are available,

  (3) it is flexible enough to be easily revised to deal with decision system changes, or to conduct sensitivity analyses

  (4) it accommodates and integrates a wide range of decision attribute types (criteria, alternatives, actors, influences, etc.) in one decision framework and computational scheme,

  (5) it can accommodate tangible (quantitative) and intangible (qualitative) decision attributes in the same model by providing scales for measuring the intangibles,

(6) any interdependence among decision attributes can be accommodated, and

(7) it captures and documents the judgement of experts and decision-makers in a logical and consistent manner.

* Extensions and Variations:

Beyond the relatively straightforward comparison of water quality information system alternatives, AHP can be employed as a tool for:

(1) Risk Analysis

When used to compare alternatives, AHP can be used to analyze risk by incorporating risk into the hierarchy as a comparison criterion and then conducting sensitivity analyses with respect to the alternative preference by varying its priority or relationship to other attributes.

A second approach is to use AHP in a forecasting mode; i.e., where the decision goal would be to predict the probability or magnitude of risk reduction (or exposure) for alternative water quality information systems. Configuring the problem in this format prompts the manager to explicitly define all risks faced in the water quality management system and allows direct and detailed identification of risk/cost tradeoffs.

(2) System Planning

A decision hierarchy, once constructed, becomes a relatively stable representation of the attributes, relationships, and concerns embodied in a water quality information system. As such, it becomes a convenient device which allows and encourages a manager to review the water quality management and information systems on a regular or continuous basis. In addition to assessing explicit water quality information system alternatives, the hierarchy could serve as an impact or sensitivity analysis tool. The manager may "check off" on the hierarchy where any change, internal or external to the system, internally or externally initiated, would influence the management or information system and then gauge its impact on information system performance. As an example, if the water quality manager anticipated changes in a water quality variable standard, he could pinpoint all of the hierarchy attributes potentially affected, assess the impact on information system performance, and forecast the consequences of various counteractive strategies. Continuous "what-if" investigations are facilitated and can result in constantly refined and improved water quality management and information systems.

(3) Optimization

AHP models can be used to produce variable relationships (curves) helpful in identifying optimal or acceptable system operating regions. As an example, an AHP model constructed to predict probabilities of risk reduction could be executed in iterative fashion while varying cost, to produce a risk-cost curve. The manager could then identify boundaries of optimal or acceptable risk/cost regions on the curve. Once such a region is identified, the manager could again use the model in a "what-if" fashion to identify changes that would drive the system towards those operating conditions.

APPENDIX D

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION SURVEY:

SURVEY DOCUMENTS

Appendix D-1: Survey Package: Cover Letter

Appendix D-2: Survey Package: Questionnaire

Appendix D-3: Survey Package: Framework Description

Appendix D-4: Survey Follow-Up Letter

Appendix D-5: Survey Summary: Cover Letter

Appendix D-6: Survey Recipients: United States Environmental Protection Agency

Appendix D-7: Survey Recipients: United States Geological Survey

APPENDIX D-1

January 25, 1994

Ms. Diane Switzer
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region I
John F. Kennedy Federal Building, Room 2203
Boston, MA 02203

Dear Ms. Switzer:

I'm sure that you would agree that public concern and resource limitations continue to foster close scrutiny of water quality management programs. These pressures encourage all water quality professionals to improve the performance of programs with which they are associated. Recent research at Colorado State University has underscored the complex and subtle nature of decisions required to evaluate water quality information programs. We believe that a structured framework for conducting such performance evaluations would be a useful managerial tool. We need your help to verify that belief.

You are one of ten USEPA Regional Water Quality Coordinators or twenty USGS NAWQA Study Unit Project Managers whose opinions are being solicited. We have targeted these individuals because they routinely evaluate regional, state or local water quality monitoring programs. Because our sample is so small, it is extremely important that each questionnaire be completed and returned. We appreciate your time and effort in responding to our request.

Your responses to the questionnaire are confidential. Please be assured that your name will never be placed on the questionnaire and that responses will be summarized anonymously. The identification number will be used to check responses off the mailing list and to contact you for any necessary clarifications.

The results of this survey will help us refine a prototype performance evaluation framework and point out future research directions in water quality information program evaluation. We will send you a summary of those results and a statement of anticipated research activities.

A brief description of a performance evaluation framework is attached. Please give me a call at (303) 223-6096 with any additional questions you might have. Thanks very much for contributing to the water quality research program at Colorado State University.

Sincerely,

Harvey P. Hotto
Research Associate

APPENDIX D-2

Performance Evaluation of Water Quality Monitoring and Information Programs

January, 1994

Survey Number:

Please describe the water quality information programs you manage or observe.

What are your responsibilities related to those programs (e.g., oversight, technical support, resource allocation, etc.)?

What decisions in which you participate require an evaluation of water quality information programs? Examples may include evaluation of state agency procedures, evaluation of compliance or audit programs, comparisons for resource allocation and funding decisions, etc.

What criteria do you consider important in evaluating or comparing water quality information programs? Please indicate the importance (**C**rucial, **H**igh, or **M**edium) of the following items and note any other criteria that you feel are significant.

* Watershed definition (C / H / M)
* Stakeholder identification (C / H / M)
* Defined water quality management objectives (C / H / M)
* Defined information needs (C / H / M)
* Information systems and database design (C / H / M)
* Data collection and storage (C / H / M)
* Information reporting (C / H / M)
* Quality assurance procedures (C / H / M)
* Other Criteria:

APPENDIX D-2, continued

How do you use performance criteria when evaluating water quality information programs? Please describe the process you follow and any tools, techniques or models that you employ.

In your opinion, what characteristics describe a practical method of evaluating water quality information programs? Examples might include: inexpensive, easy to understand, useful in real time, stand alone, PC-based, etc.

How would a structured performance evaluation framework assist you to analyze or manage your water quality information programs? (An example of such a framework is attached.)

APPENDIX D-3

Harvey P. Hotto
Colorado State University

January, 1994

A Framework for Evaluating Water Quality Information System Performance

To evaluate a water quality information program's performance, a three step process could be employed:

(1) Management System Analysis:

This step identifies and documents all of the relevant factors which describe the watershed being managed and the methods employed to manage it.

Watershed factors might include:
- boundaries, both spatial and temporal
- historic and current uses of land and water
- historic and current conditions of land and water
- potential or anticipated uses of land and water

Watershed management factors might include:
- stakeholder concerns
- stakeholder standing and priority
- decision processes employed; e.g., group or individual
- watershed problem specification and ranking
- watershed management objectives and priorities

(2) Information System Analysis:

Using the watershed and management system knowledge has been recorded in the first step, vital factors for evaluating the supporting information system's performance can be defined and documented. These factors describe the effectiveness and efficiency of the program; i.e., how well its design reflects management needs and how proficiently it operates to meet those needs.

Effectiveness (design) factors may include definition and specification of the:
- watershed
- watershed management system
- information needs of stakeholders and managers

- feasibility of satisfying information needs
- information product (routine or non-routine)
- database requirements
- operating parameters (sampling, laboratory, data processing)

Efficiency (operating) factors might include:
- data collection (field, laboratory and other sources)
- data processing and storage
- information generation and reporting
- information analysis and interpretation
- quality assurance
- system maintenance

(3) Information System Evaluation:

In the final step of the framework, the watershed, management and information system factors documented earlier are used to compare the information system's performance to that of some potential or alternative system. The Analytic Hierarchy Process (AHP) is used to structure the comparison and identify the preferred alternative.

In the AHP, factor knowledge is applied to create comparison criteria which are broken down and interrelated in a multi-level decision hierarchy. Within the hierarchy, the criteria are prioritized through a sequence of paired comparisons, and the alternatives are rated with respect to satisfaction of the criteria. The preferred alternative is that with the highest composite preference score; which is calculated using the eigenvalue method, a matrix computation. That preference information can then be incorporated into whatever larger analysis required the performance evaluation.

Note:
Many techniques have been developed which specify and weight decision criteria, score alternatives against criteria, and compare alternative scores to facilitate a decision. The utility of a such models depends upon cost, convenience and applicability to the problem at hand. From a practical standpoint, results should be easily interpreted and the model easily modified to allow sensitivity analyses on criteria, weights and scores. The Analytic Hierarchy Process (AHP) has proven to meet these standards in preliminary applications of this performance evaluation framework.

APPENDIX D-4

This follow-up notice was sent by postcard to those recipients not reponding to the initial survey request.

February 18, 1994

Several weeks ago a questionnaire seeking your opinions on evaluating water quality information systems was mailed to you. You were one of several USEPA regional Water Quality Monitoring Coordinators and USGS NAWQA Project Chiefs asked to participate.

Because the survey involves such a small number of respondents, it is extremely important that your reply be included in order to fairly summarize the opinion of these water quality professionals.

If by chance you didn't receive the questionnaire, or it was misplaced, please give me a call at 303-223-6096 and I'll send another right away. Again, thanks for participating.

Sincerely,

Harvey P. Hotto

Research Associate
Colorado State University

APPENDIX D-5

July 1, 1994

Ms. Diane Switzer
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region I
John F. Kennedy Federal Building, Room 2203
Boston, MA 02203

Dear Ms. Switzer:

As you recall, in January I distributed a questionnaire to a number of USEPA Regional Water Quality Monitoring Coordinators and USGS NAWQA Study Unit Project Chiefs, soliciting information and opinion on a number of items related to the evaluation of water quality information programs. A summary of your group's responses to the questionnaire is attached.

Approximately 40% of those polled in each group responded and, as you can see, a wide range of opinion is evident in the responses to each question. It does appear, however, that sufficient interest exists in the evaluation of water quality information monitoring programs to warrant further study and development. Indeed, the framework described continues to evolve and I plan to draft an evaluation protocol to assist in the design and audit of water quality information systems. I will send that evaluation protocol out for comment and review when it is available.

I hope that you find these observations useful in your work on water quality information programs. A questionnaire is enclosed for those interested in responding at this time.

Please give me a call at (303) 223-6096 with any additional questions you might have. Thanks again for contributing to the water quality research program at Colorado State University.

Sincerely,

Harvey P. Hotto
Research Associate

APPENDIX D-6

USEPA Survey Recipients:

Ms. Diane Switzer
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region I
John F. Kennedy Federal Building, Room 2203
Boston, MA 02203
617-860-4377

Mr. Randy Braun
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region II
26 Federal Plaza
New York, NY 10278
908-321-6692 (NJ Office)

Mr. Charles Kanetsky
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region III
841 Chestnut Street
Philadelphia, PA 19107
215-597-8176

Ms. Larinda Tervelt
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region IV
345 Courtland Street, N.E.
Atlanta, GA 30365
404-347-2126

Ms. Donna Williams
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region V
77 West Jackson, MS SQ-14J
Chicago, IL 60604
312-353-6175

APPENDIX D-6, continued

Mr. Charlie Howell
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region VI
1445 Ross Avenue, 12th Floor, Suite 1200
Dallas, TX 75202
214-655-8354

Mr. Jerry Anderson
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region VII
726 Minnesota Avenue
Kansas City, KS 66101
913-551-5066

Philip C. Johnson, Ph.D.
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region VIII
999 18th Street, Suite 500
Denver, Colorado 80202-2466
303-293-1581

Mr. Chris Faulkner
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region IX
215 Fremont Street
San Francisco, CA 94105
415-744-2012

Ms. Gretchen Hayslip
Water Quality Monitoring Coordinator
U.S. Environmental Protection Agency - Region X
1200 6th Avenue
Seattle, WA 98101
206-553-1685

APPENDIX D-7

Harvey P. Hotto January 1994
WQIS Performance Evaluation Questionnaire

USGS Survey Recipients:

Mr. Stephen P. Garabedian
Project Chief; Connecticut Valley Study Unit (3)
U.S. Geological Survey
26 Lord Road, Suite 280
Marlborough, MA 01752
508-490-5005 / Fax 508-490-5068

Mr. Ward Freeman
Project Chief; Hudson River Basin Study Unit (4)
U.S. Geological Survey
P.O. Box 1669
Albany, NY 12201
518-472-2649 / Fax 518-472-2805

Mr. Kevin Breen
Project Chief; Lower Susquehanna River Basin Study Unit (7)
U.S. Geological Survey
840 Market Street
Lemoyne, PA 17043-1586
717-730-6970 / Fax 717-730-6997

Mr. James Gerhart
Project Chief; Potomac River Basin Study Unit (9)
U.S. Geological Survey
208 Carroll Building
8600 LaSalle Road
Towson, MD 21286
410-828-1535 / Fax 410-828-1538

Mr. Charles G. Crawford
Project Chief; White River Basin Study Unit (14)
U.S. Geological Survey
5957 Lakeside Boulevard
Indianapolis, IN 46278
317-290-3333 / Fax 317-290-3313

APPENDIX D-7, continued

Mr. James Setmire
Project Chief; Western Lake Michigan Drainage Study Unit (17)
U.S. Geological Survey
6417 Normandy Lane
Madison, WI 53719
608-276-3810 / Fax 608-276-3817

Mr. Jeffrey D. Stoner
Project Chief; Red River of the North Study Unit (19)
U.S. Geological Survey
2280 Woodale Drive
Mounds View, MN 55112-0049
612-783-3270 / Fax 612-783-3103

Mr. Timothy B. Spruill
Project Chief; Albemarle-Pamlico Drainage Study Unit (20)
U.S. Geological Survey
3916 Sunset Ridge Road
Raleigh, NC 27607
919-571-4088 / Fax 919-571-4041

Mr. David J. Wangsness
Project Chief; Appalachicola-Chattahoochee-Flint River Basin Study Unit (23)
U.S. Geological Survey
Peachtree Business Center
3039 Amwiler Road, Suite 130
Atlanta, GA 30360-2824
404-903-9100 / Fax 404-903-9199

Mr. Edward T. Oaksford
Project Chief; Georgia-Florida Coastal Plain Study Unit (24)
U.S. Geological Survey
227 N. Bronough Street, Suite 3015
Tallahassee, FL 32301
904-681-7357 / Fax 904-681-7650

Mr. David Freiwald
Project Chief; Ozark Plateau Study Unit ((32)
U.S. Geological Survey
2301 Federal Building
700 W. Capitol Avenue
Little Rock, AR 72201
501-324-6391 / Fax 501-324-5179

APPENDIX D-7, continued

Mr. Larry F. Land
Project Chief; Trinity River Basin Study Unit (34)
U.S. Geological Survey
8011 Cameron Road, Building A
Austin, TX 78754-3898
512-873-3005 / Fax 512-873-3090

Mr. Thomas L. Huntzinger
Project Chief; Central Nebraska Basin Study Unit (36)
U.S. Geological Survey
4821 Quail Crest Place
Lawrence, KS 66049
913-832-3514 / Fax 913-832-3500

Mr. Kevin F. Dennehy
Project Chief; South Platte River Basin Study Unit (41)
U.S. Geological Survey
Building 53, Denver Federal Center
Mail Stop 415, Box 25046
Lakewood, CO 80225-0046
303-236-4882 / Fax 303-236-4912

Mr. Sherman R. Ellis
Project Chief; Rio Grande Valley Study Unit (46)
U.S. Geological Survey
4501 Indian School Road NE
Suite 200
Albuquerque, NM 87110-3929
505-262-5350 / Fax 505-262-5398

Mr. Walton H. Low
Project Chief; Upper Snake River Basin Study Unit (49)
U.S. Geological Survey
230 Collins Road
Boise, ID 83702-4520
208-387-1385 / Fax 208-387-1372

Mr. Alex Williamson
Project Chief; Central Columbia Plateau Study Unit (51)
U.S. Geological Survey
1201 Pacific Avenue, Suite 600
Tacoma, WA 98402
206-593-6510 / Fax 206-593-6514

APPENDIX D-7, continued

Mr. Dennis A. Wentz
Project Chief; Willamette Basin Study Unit (54)
U.S. Geological Survey
10615 SE Cherry Blossom Drive
Portland, OR 97216
503-251-3296 / Fax 503-251-3470

Mr. Hugh E. Bevans
Project Chief; Nevada Basin and Range Study Unit (56)
U.S. Geological Survey
333 West Nye Lane
Carson City, NV 89706
702-887-7688 / Fax 702-887-7629

Mr. Neil Dubrovsky
Project Chief; San Joaquin-Tulare Basins Study Unit (57)
U.S. Geological Survey
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825
916-978-4648 / Fax 916-978-5529

APPENDIX E

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION SURVEY:

SURVEY SUMMARY

USEPA REGIONAL WATER QUALITY MONITORING COORDINATORS

APPENDIX E

Performance Evaluation of Water Quality Monitoring and Information Programs

H.P. Hotto
June 1994

Questionnaire Summary: Responses of USEPA Regional Water Quality Monitoring Coordinators

---

(1) Please describe the water quality information programs you manage or observe.

(2) What are your responsibilities related to those programs (e.g., oversight, technical support, resource allocation, etc.)?

Summary of Respondent Comments:

Water quality information programs managed or observed:

- R-EMAP (EPA "on the ground" participation)
- Ambient programs (EPA Regional)
- State programs
- Indian tribe programs
- Any program funded by EPA grants; either dictated by legislation or EPA discretion

Program Purposes/Activities/Responsibilities:

- Development of EPA agency goals and directions
- Development and implementation of EPA monitoring programs (e.g., R-EMAP or other regional ambient programs)
- Oversight (policy guidance) and coordination of Region, other Federal agency, State and regional programs to support national priorities and EPA regulations
- Water quality assessment, using:
  - EPA Region program water quality data
  - State-supplied data

* Water quality data management, including:
  - entering data into national databases,
  - assuring data availability (in some database}

* Use of water quality information in regional or state decision making

* Review and comment on quality assurance project plans for projects and studies

* Rank Non-point Source workplans submitted for competitive funding (in regional workgroups)

<u>Conclusions and Impressions (H.Hotto)</u>:

* EPA regional water quality monitoring coordinators have limited direct responsibility for the design, operation or management of water quality monitoring or information systems. In some regions, there is some direct involvement with R-EMAP and EPA regional ambient programs.

* EPA regional water quality monitoring coordinators have two major roles in water quality monitoring:

  (1) Oversight and coordination of federal, state, tribal or other programs in the region to review quality assurance plans, to assure regulatory compliance (section 305(b) reporting and section 106, 319, and 604 grant programs) and to promote coherence with national priorities and policies

  (2) Technical assistance and information clearinghouse for all agencies in the region operating monitoring programs

* Other roles played by EPA regional water quality monitoring coordinators include:

  (1) Water quality data/database management

  (2) Water quality assessment

  (3) Decision-making using water quality information

(3) **What decisions in which you participate require an evaluation of water quality information programs? Examples may include evaluation of state agency procedures, evaluation of compliance or audit programs, comparisons for resource allocation and funding decisions, etc.**

Summary of Respondent Comments:

- * Evaluation of State programs to award Section 106 grants
- * Audit of State programs funded by Section 106 grants to assure compliance with grant requirements and agreements
- * Evaluation of State programs and activities, including:
  - general input (not approval) on program methods and procedures
  - state-wide water quality assessments for purposes of planning Section 305 (b) reports

  - audits of field activities
  - site-specific water quality assessments
  - recommendation for approval or non-approval of individual quality assurance project plans
  - evaluation of existing data quality for study planning purposes

Conclusions and Impressions (H. Hotto):

- * Managerial decisions (i.e., those involving responsibility, authority and action) by EPA regional water quality coordinators, based upon the evaluation of water quality information programs, appears limited to the awarding and auditing of Section 106, 319 and 604 grants.
- * Many "non-managerial" decisions are made and much guidance is given; usually with respect to whether or not a program or feature will meet regulatory or policy requirements and exhibits adequate quality assurance planning.
- * "Meeting regulatory or policy requirements" and "having adequate quality assurance procedures" are implied decision criteria and are also noted below under question (4).

(4) What criteria do you consider important in evaluating or comparing water quality information programs? Please indicate the importance (Crucial, High, or Medium) of the following items and note any other criteria that you feel are significant.

Respondent Rating and Ranking:

- * Defined Water Quality Management Objectives: Crucial importance
- * Defined Information Needs: Crucial importance
- * Quality Assurance Procedures: Crucial importance
- * Information Systems and Database Design: Very high importance
- * Data Collection and Storage: Very high importance
- * Watershed Definition: High importance; Note: Importance depends upon focus of study or project; e.g., state level or watershed level emphasis.
- * Information Reporting: High importance
- * Stakeholder Identification: High importance
- * Other Criteria mentioned:

In answering Question (4):
- Ecoregion definition
- Reference site information
- water quality standards
- personnel/human resources
- laboratory capability
- integration with other networks or studies
- participation in interagency quality assurance reviews

In answering Question (3):
- meets regulatory or policy requirements
- adequate quality assurance procedures

In answering Question (5):
- Programs should be well-rounded and include physical, chemical, biological and habitat monitoring techniques.
- What are monitoring goals? (most important step)
- Is design appropriate to meet these goals?

- Are parameters appropriate?
- Statistical tests and reporting schedule defined up-front?
- QA/QC outlined?

In answering Question (6):

- Visuals (such as GIS or graphics/charts) are critical if presenting information to upper management
- As mentioned above, easy to use, PC-based are important
- Must work with readily available data.
- Strong <u>scientific</u> foundation

<u>Conclusions and Impressions (H. Hotto)</u>:

* Given the skewed rating scheme (i.e., no low rating choices) and the small sample, definitive statements about the EPA coordinators' rating of evaluation criteria are tenuous. However, the clear scoring breaks indicated here suggest that EPA water quality monitoring coordinators:

(1) regard identification of water quality management objectives and information needs as paramount and demonstrably more important than specific data system or information system design concerns, and

(2) regard watershed definition, stakeholder identification and information reporting as less important than data system or information system design.

From a "total systems" perspective, item (1) indicates a logical and preferable information system design sequence. However, it also seems that watershed and stakeholder identification would be necessary preliminaries to setting objectives and information needs.

* It is apparent that a wide variety of criteria are used in evaluating water quality information programs. Further questioning will be required to form a more definitive list and to understand EPA water quality monitoring coordinators' priorities.

(5) How do you use performance criteria when evaluating water quality information programs? Please describe the process you follow and any tools, techniques or models that you employ.

Summary of Respondent Comments:

- * Use Section 106 grant guidance to evaluate state programs
- * Define current program and its objectives
- * Make recommendations to develop a monitoring strategy to define program goals and establish objectives.
- * Do not actively evaluate programs beyond basic technical considerations

Note: Several respondents provided actual evaluation criteria in reply to this question. Those comments have been included in the summary of Question (4) above.

Conclusions and Impressions (H. Hotto):

- * Evaluation procedures in awarding or auditing Section 106 grants are established in grant-related regulations, literature and agreements with grantees.
- * In general, respondents provided few insights into the actual evaluation process in which their evaluation criteria are employed. Reasons for that lack of response may include:
  - (1) Questionnaire communication failure - Respondents did not understand the intent of the question due to unfamiliar terminology or ineffective phrasing.
  - (2) Difficulty of response - Respondents were unable or unwilling to take the time or effort required to properly analyze and describe a complex process
  - (3) No process - Respondents have no defined process used to evaluate water quality monitoring programs

(6) In your opinion, what characteristics describe a practical method of evaluating water quality information programs? Examples might include: inexpensive, easy to understand, useful in real time, stand alone, PC-based, etc.

<u>Summary of Respondent Comments</u>:

- * Example characteristics given are very important and appropriate.
- * No two state programs are alike.
- * The evaluation must be based on state capability and available resources.
- * A state program must be based on resource capability and program needs.
- * EPA has yet to define minimum/optimum state programs.
- * Visuals (such as GIS or graphics/charts) are critical if presenting information to upper management
- * As mentioned above, easy to use, PC-based (Internet accessibility?) are important
- * Must work with readily available data.
- * Strong <u>scientific</u> foundation
- * Tiered format or approach to allow evaluation of individual aspects of a large program

<u>Conclusions and Impressions (H. Hotto)</u>:

- * Respondents appear to agree that the suggested characteristics are desirable or important:
    - inexpensive
    - easy to use
    - PC-based, stand-alone
    - real-time
- * Several additional important characteristics of an evaluation system were offered. In some cases, it is unclear if the respondent meant these criteria to apply to the evaluation of (1) an information system or (2) an information system evaluation process. Since they reasonably apply in either

case, they are listed here and in the summary to question (4):

- ability to work with available data (i.e., flexibility)
- strong scientific foundation (i.e., scientific credibility)
- visual presentation of results (i.e., effective communication of information to management)
- ability to evaluate individual aspects or parts of large programs
- provide easily accessible information via PCs and/or network connection (e.g., Internet)

* An EPA definition of minimal or optimal (State) information programs would help the coordinators in an evaluation or comparison. An evaluation program characteristic based on this notion might be stated as:

> "defined and documented information program evaluation criteria and process"

* One respondent notes that state programs are unique and that the evaluation of state programs should take into account individual state program needs and capabilities (i.e., resource availability) to address those needs. This implies that another characteristic of a practical evaluation method is: "clearly indicates (quantifies?) how well program needs are matched to available resources" or " clearly indicates which state program gets the most from the resources applied".

Also, however, it seems that this respondent is further implying that an information program evaluation and comparison process must itself be realistic, credible and effective; i.e., it must give the analyst confidence that the process of comparing information programs is logical and defensible.

---

(7) How would a structured performance evaluation framework assist you to analyze or manage your water quality information programs? (An example of such a framework is attached.)

Summary of Respondent Comments:

- Having a plan of action always helps.

- Framework or strategy is necessary; attached framework is fine.

- Region (is) evaluating need to develop a regional monitoring strategy

- Enhance state and Regional capabilities to carry out characterization, problem identification and trend assessment

- Increase the ambient follow-up monitoring for use in evaluating the effectiveness of water quality management actions.

- Promote the use of available water-related data in Regional and State decision making.

- Areas of assistance:
  1. Resources
     - expertise
     - equipment
     - laboratory
  2. Management needs
  3. Program needs
  4. Information systems
  5. Program evaluation

- The model described in the hand-out seems very data-intensive - not appropriate at state-wide or "regional" level. Might be good for a watershed planner/manager dealing with a more localized scale. The revised Clean Water Act is moving more to watersheds, thus this might be appropriate. Watershed planning will undoubtedly involve less top down control (i.e., EPA). You should send your survey to state or local level watershed managers as well.

- A performance evaluation framework would offer the potential to move from essentially no overall evaluation to conducting evaluations. Such an evaluation would provide an improved understanding of specific State support needs and offer an opportunity for technology transfer between States. Evaluation documentation would provide a mechanism for documenting the quality of data collected by our States. The documentation would also provide an improved basis for selection of competitive grantees or contractors based on past performance.

Conclusions and Impressions (H. Hotto):

- Responding EPA coordinators seem to generally agree upon a need for and potential usefulness of a framework for evaluating water quality information programs.

- Responding EPA coordinators are divided as to the scale at which such a framework could be appropriately applied. Three of four respondents appear to be able to relate the example framework to their concerns and their job activities. The fourth respondent viewed the example framework as applicable to management at geographical scales (local or watershed) more limited than the state/regional perspective required in his job. Possible explanations for this divergence of opinion include:

  (1) different responsibilities - Assigned responsibilities and duties with respect to water quality monitoring vary substantially among the EPA Regions. The individuals selected for this survey do not necessarily work on the same programs.

  (2) different perspectives - Since there is little EPA-wide guidance on evaluating water quality information programs, each monitoring coordinator is free to shape his or her approach and select the scope at which to focus based upon individual skill, experience or preference.

  (3) communication limitations - There was no opportunity to discuss the framework with individual respondents and speculate on how it might apply to their specific duties.

APPENDIX F

WATER QUALITY INFORMATION SYSTEM PERFORMANCE EVALUATION SURVEY:

SURVEY SUMMARY

USGS NAWQA STUDY UNIT PROJECT CHIEFS

APPENDIX F

Performance Evaluation of Water Quality Monitoring and Information Programs

H.P. Hotto
June 1994

Questionnaire Summary: Responses of Study Unit Project Chiefs; USGS National Water Quality Assessment (NAWQA) Program

---

(1) Please describe the water quality information programs you manage or observe.

(2) What are your responsibilities related to those programs (e.g., oversight, technical support, resource allocation, etc.)?

Summary of Respondent Comments:

Water quality information programs managed or observed:

- NAWQA / NWIS-I
- Stream and aquifer water quality assessment programs
- Basin-wide scale water quality analysis
- Large watershed/river basin water quality assessment programs

Program Purposes/Activities/Responsibilities:

- Describe water quality conditions
    - status and trends
    - occurrence and distribution of water quality characteristics
    - changes in water quality characteristics in time
    - define effects of natural and human factors
    - relate assessment results to important issues
- Project Chief / water quality assessment program manager
    - overall design and implementation of assessment program (develop a scientific approach)

  - administer (allocate) personnel resources; manage scientific and technical people in team functions
  - manage program execution (team efforts)
    - design of experiments
    - field data collection
    - data management and information systems (QA and transfer to NWIS-I)
    - data interpretation (hydrologic analysis)
    - data and interpretive reporting; publication of results
  - report activities and results
  - provide policy-relevant results to managers and policy makers

- Gather and interpret assessment information from various sources (e.g., WATSTORE, GIS, other information databases, etc)

- Provide oversight and technical support

- Participate in cooperative programs with other organizations and agencies involved in water quality assessment

<u>Conclusions and Impressions (H. Hotto)</u>:

- It appears that NAWQA project (i.e., basin-wide, large watershed..) management comprises the major portion of a NAWQA Project Chief's job. The specific activities described are accomplished principally in connection with his or her NAWQA project.

- The wide range of response detail and depth (throughout the questionnaire) leads to the impression that NAWQA project chiefs vary widely in their management approach (and style) and are quite autonomous with respect to the design and execution of their study unit assessments.

---

(3) What decisions in which you participate require an evaluation of water quality information programs? Examples may include evaluation of state agency procedures, evaluation of compliance or audit programs, comparisons for resource allocation and funding decisions, etc.

Summary of Respondent Comments:

- * Evaluation/comparison of federal, state, local and USGS data collection programs to determine where NAWQA assistance is needed
- * Comparisons of programs for resource allocation decisions
- * Comparisons of programs for funding decisions
- * Technical reviews of programs to assure reliability, comparability of data sets, and valid interpretive results
  - field collection protocol reviews
  - laboratory QA programs for certification
  - fiscal and management audits
  - prepublication report reviews
- * Comparison of information program's data quality objectives to the data quality objectives (needs) of the user (analyst). The necessary background on water quality data collection procedures and QA practices is rarely available.
- * Cost-benefit evaluations (comparisons) of approaches to estimating regional surface water and groundwater quality status, trends, and causal processes
- * Indirect evaluation of information programs; interact with "information programs" to decide if the information available is useful

Conclusions and Impressions (H. Hotto):

- * The evaluation of (existing) information and monitoring programs is accomplished principally to decide if data produced are useful and suitable for inclusion in the NAWQA database.

  That decision process is not uniform among the responding Project Chiefs. Approaches appear to range from structured and formal to interactive and informal procedures.

  Several specific decision criteria are mentioned or implied (these are also included in the summary of responses to Question 4 below):
  - reliability
  - comparability of data sets

  - valid interpretive results
  - data quality objectives
  - costs
  - benefits (e.g., ability to estimate status, trends, causes..)

- A preliminary evaluation (analysis) phase to identify watershed data and information needs is at least implied by all respondents

  A subsequent phase identifies watershed data and information needs not satisfied by existing programs

  Subsequent decisions select programs to meet unsatisfied data and information needs and to allocate resources and funding. Presumably, the processes and criteria employed are similar to those applied to the evaluation of existing programs.

---

(4) What criteria do you consider important in evaluating or comparing water quality information programs? Please indicate the importance (Crucial, High, or Medium) of the following items and note any other criteria that you feel are significant.

<u>Respondent Rating and Ranking</u>:

- Data Collection and Storage: Crucial-Very high importance

- Quality Assurance Procedures: Crucial-Very high importance

- Defined Water Quality Management Objectives: Very high importance; potential relationship to best management practice noted

- Information Systems and Database Design: Very high importance

- Defined Information Needs: High importance

- Information Reporting: High importance

- Watershed Definition: High importance

* Stakeholder Identification: High-Medium importance; potential importance of "who paid for the data" noted

* Other Criteria mentioned:

In answering Question (4):
- Geographic information system linkage
- Methodology (Crucial)
- Machine readable data storage (i.e., computer)

In answering Question 3:
- reliability
- comparability of data sets
- valid interpretive results
- data quality objectives
- costs
- benefits (e.g., ability to estimate status, trends, causes..)

In answering Question (5):
- Is the information referenced to latitude and longitude?
- Is it clear why the information was collected?
- For concentration data, is there associated flow measurement?
- For ground water, how was the well completed?
- For ground water, in what aquifer is the well perforated?
- What quality assurance data are associated with the information?
- Does the data make sense with other historic data at site?
- degree of adherence to established protocols
- degree of innovation applied to protocols
- representativeness of data collection site to meeting objectives
- scientific knowledge of personnel
- Does the data have a measure of reliability such as sample quality control and documented field protocols?
- Is the information accessible and manageable using standardized computer software, and is it documented with a useable dictionary?
- Can copyright or proprietary constraints be accommodated on the long term so that current and future technology transfer efforts are unhampered?

- Is the information adequate to provide relevant and reliable conclusions, and will the analysis of the information be scientifically sound?

In answering Question (6):
- must have QA/QC data
- must have data collection techniques
- must define sampling site and reason for collecting sample
- Data should be machine (computer) readable.
- clear objectives of data collection
- Does the program have support to help the user?
- Can the person who collected the information be identified?
- Are the reasons for collecting the information available?
- Does the information program consider aquifers and watersheds?
- Major parameters to evaluate water quality must be included.
- flexible
- statistically valid comparisons

<u>Conclusions and Impressions (H. Hotto)</u>:

* A skewed rating scheme (i.e., no low rating choices) and small sample size preclude definitive statements about NAWQA Project Chiefs' views (or an "average opinion") on evaluation criteria. However, the scoring breaks observed suggest a general hierarchy of concerns:

(1) Highest (almost crucial) importance is assigned to data collection and storage, and to quality assurance procedures.
(2) Defined management objectives and system design factors are of great importance; but with less unanimity as to cruciality.
(3) Information needs identification, information reporting, and watershed definition enjoy still less unanimity as to cruciality or high importance.
(4) Stakeholder identification appears to be of least general importance; no respondent regarded it as a crucial decision criterion.

Although considerable sentiment was expressed with regard to the importance of pre- and post-data information system activities, a data-oriented view of water quality information programs is suggested. Note that we have little insight as to the relative importance of the volunteered vs. the suggested criteria.

Given the historic mission and activities of the USGS with respect to water quality monitoring, the focus on data collection and associated quality assurance is understandable. (Note: It is my assumption that USGS personnel probably associate QA/QC specifically with data collection and laboratory activities.)

From a total systems design perspective, more emphasis on preliminary analyses (e.g., objective setting and information needs specification) and user/stakeholder satisfaction (e.g., information needs and information reporting requirements) would be expected.

- Obviously, a wide variety of criteria and emphases are employed by NAWQA Project Chiefs in evaluating information programs. A more in-depth investigation would be required to characterize them accurately.

---

(5) How do you use performance criteria when evaluating water quality information programs? Please describe the process you follow and any tools, techniques or models that you employ.

Summary of Respondent Comments:

- "Performance criteria" needs additional explanation!

- I do not use performance criteria to evaluate the program. Criteria are used in combination with practical considerations to determine if information from a water quality program can be used to answer the questions I need to answer.

  Note: Specific evaluation criteria included with this response have been included in the summary of Question (4) above.

- Tools are a means (to achieve) true representation of a system

* Performance criteria are used to establish:
  - degree of adherence to established protocols
  - degree of innovation applied to protocols
  - representativeness of data collection site to meeting objectives
  - scientific knowledge of personnel

Note: These items can also be considered as performance or evaluation criteria and are also included in the summary of Question (4), above.

* This is a long and time consuming process

* Evaluation of water-quality information programs would be conducted by answering the following questions:
  a) Does the data have a measure of reliability such as sample quality control and documented field protocols?
  b) Is the information accessible and manageable using standardized computer software and is it documented with a useable dictionary?
  c) Can copyright or proprietary constraints be accommodated on the long term so that current and future technology transfer efforts are unhampered?
  d) Is the information adequate to provide relevant and reliable conclusions and will the analysis of the information be scientifically sound?

Note: These items can also be considered as performance or evaluation criteria and are also included in the summary of Question (4), above.

<u>Conclusions and Impressions (H. Hotto)</u>:

* Nearly all of the respondents appear to have a process in place to evaluate water quality information programs. In some cases, the response suggests that the process has been well thought out and is perhaps structured or formally documented. Other responses, including those simply citing a complicated or time consuming process, may suggest a more abstract and less formal process is at work; perhaps where clear articulation of the decision process has never been attempted.

- None of the respondents outlines a clearly structured evaluation process. Consequently, no statement can be made as to how the respondents select and rank criteria, measure performance against criteria, or derive an overall program rating.

- None of the respondents mention the use of any specific tool, technique, model or method to assist the evaluation process.

---

(6) In your opinion, what characteristics describe a practical method of evaluating water quality information programs? Examples might include: inexpensive, easy to understand, useful in real time, stand alone, PC-based, etc.

Summary of Respondent Comments:

- Unimportant!
- Ease of use
- Major parameters to evaluate water quality must be included
- If oversimplistic may not be able to adequately assess the program
- Flexible
- Statistically valid comparisons
- A practical method of evaluating water quality information would:
    a) be completed in a relatively short time frame
    b) criteria would be objective and easily understood
    c) flexible enough to apply to many formats and complexities

Conclusions and Impressions (H. Hotto):

- Ease of use, ease of understanding and flexibility capture the essential characteristics of an evaluation process. Quick availability of results is also important.

- Some respondents interpreted this question as asking for specific information system evaluation criteria rather than the characteristics of the evaluation process in which they would be used. Those criteria and items mentioned which could apply in either case are listed in the summary to Question (4).

- One respondent appears to say that a practical method of evaluating water quality information is not important. Further investigation is needed to determine that this is indeed an accurate interpretation, and, if so, to ascertain the respondent's reasoning.

- The comment warning against an "oversimplistic" process indicates that the evaluation process must be able to accommodate relevant considerations regardless of measurement convenience. The process must properly balance assessment expediency and adequacy.

---

(7) How would a structured performance evaluation framework assist you to analyze or manage your water quality information programs? (An example of such a framework is attached.)

Summary of Respondent Comments:

- Structured information and evaluation strategies are the only way large volumes of information are assessed with timely and reliable results.

- Modular frameworks are mandatory!

- Somewhat - the NAWQA is more concerned with QA/QC data, collection techniques and data storage - Most USGS professionals are trained in data evaluation (and are) doing data evaluation

- The structure should be customized to the specific needs or objectives of a project.

- A relational functioning database!

- The suggested framework must accommodate scale to issue

- The more structured the framework, the less flexible it may be.

- * I'm not impressed (with the attached example framework)
- * It's not apparent to me how helpful this would be for me.

Conclusions and Impressions (H. Hotto):

- * Respondents are divided on the utility of a structured evaluation framework:

  (1) Some respondents see no advantage to a structured framework (at least as represented by the example format)

  (2) Some respondents appear to clearly endorse the need for structured (or modular) assessment approaches

  (3) Several respondents acknowledge the potential usefulness of an evaluation framework which:

    - can be customized to accommodate specific project needs and objectives
    - balances the needs for structure and flexibility
    - can deal with scale (time and space) properly for the project or problem under consideration

- * From these responses and from others across the questionnaire, it appears that USGS personnel are inclined to focus on data collection and analysis activities; evidently as a result of training, experience, and institutional tradition. Institutional expectation of a wider systems perspective and individual training in systems approaches may be necessary in order to motivate investigation of the utility of a performance evaluation framework like that proposed.
- * More detailed explanation of the framework is required. Complete documentation of the process, and a demonstration of each step as applied to a specific program evaluation are necessary in order to allow a user to judge the framework's potential utility.

GLOSSARY

AHP
Acronym for the Analytic Hierarchy Process

Alternative
Choice or option available in a selection process; in AHP models, the lowest level of attribute in the hierarchy

Attribute
Generic term for any member of an AHP hierarchy

Bounded Rationality
Decision-making model which recognizes the limits of individual rationality

Composite Weights
Weights or priorities relating attributes in non-adjacent levels of an AHP hierarchy

Consistency
Congruity in the assignment of relative importance among a set of attributes being compared in pairs

Criteria
Decision attributes upon which an alternative is evaluated or selected

Eigenvalue Method
Matrix algebraic procedure used to derive priority vectors (of attribute weights)

Eigenvector
The vector of attribute weights (priority vector) computed by the eigenvalue method

Element
A member of a matrix

Hierarchy
Multi-level representation of a decision problem indicating the decision objective at the top,alternatives at the bottom, and all relevant decision attributes and relationships at intermediate levels.

Importance Intensity

A numerical measure of the relative importance of two attributes with respect to a third; on a ratio scale ranging from 1 (equal importance) to 9 (absolutely more important)

Independence (of Attributes)

When attributes have nothing to do with each other and can be assessed without information about the other, or affecting one another

Interdependence (of Attributes)

When attributes share some common influences, features or impact; the opposite of independence

Matrix Operations

Addition or multiplication of matrices according to the rules of matrix algebra

Normalization

Summing a number of scores and dividing each by the total in order to derive a set of relative scores between 0.0 and 1.0 which sum to 1.0

Optimization

Manipulating a model in order to construct relationships or functions which can be used to identify ideal system operating points or regions

Pairwise Comparison

Evaluating and scoring the relative importance of a set of attributes, two at a time

Preference Number

An alternative's composite overall weight as derived by the AHP

Priority

The weight of an attribute with respect to the next-higher-level attribute with which it is associated

Priority Vector

The set of weights derived by applying the eigenvalue method to any matrix of paired comparisons

Satisficing

The decision-making practice of selecting acceptable or satisfactory solutions rather than optimal solutions

Sensitivity Analysis

Measurement of the change in a system's output (or results) with changes in input, or with changes in underlying assumptions

Validation

Testing a model to determine how closely it is able to reflect the real situation it purports to describe

Weight

Relative importance of a decision criterion or attribute; usually multiplied by some measurement or score to compute that criterion's contribution to a composite alternative score