CONCEPTUAL DESIGN REPORT FOR A NATIONAL RIVER WATER QUALITY ASSESSMENT PROGRAMME

by

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Report to the Water Research Commission on the project
"Development of water quality monitoring strategies
and procedures for data interpretation"

Project Leader : Dr J. Harris

WRC Report No 204/1/92 ISBN 1 874858 60 8

EXECUTIVE SUMMARY

BACKGROUND

This project was undertaken to address the need for reliable water quality information on which to base management decisions. The original motivation for the project noted that "water quality monitoring is becoming a larger and more important part of assessment of the impact of man on the environment, the development and management of water resources and the regulation of water quality."

The cost of water quality monitoring is high and when data is collected, but not used, the ratio of cost to benefits obtained is unacceptable.

AIMS

The aim of the project was to make available and increase the reliability of water quality information for different water resources development, regulatory and research objectives by:

1. Developing cost-effective and practical monitoring strategies to satisfy the information requirements, and
2. Developing procedures for interpreting (analysing) water quality data in such a way as to provide reliable information on which to base decisions.

APPROACH

The initial approach to achieving the aims was to design a monitoring system for a single catchment and use the concepts developed during that design as the basis for stating broad water quality monitoring strategies. It soon became obvious that the process would not succeed. The types of information needed for large-scale systems are different from those for small-scale systems. Identical monitoring strategies cannot be used for both scales. Other differences, such as a need to know water quality at a shorter time interval in a smaller scale system and additional logistics and communication problems in large scale systems, added to the problems of scaling up a catchment monitoring system.

A National River Water Quality Assessment Programme (NRWQAP) was, therefore, selected as the appropriate system for the initial design efforts. The programme was limited to fresh water excluding marine water, to rivers excluding impounded water, and to water quality assessment excluding water quality processes description. The concepts and expertise developed during the design efforts can be applied to other national assessment programmes, such as for reservoirs, ground water, and estuaries. The design expertise could also be transferred to smaller scale systems.

RESULTS OF THE PROJECT

National River Water Quality Assessment Programme Design

The major result of the project is a monitoring system design for assessment of river water quality that has been presented to the Department of Water Affairs and Forestry with recommendations for implementation. The design efforts began with an assessment of existing water quality monitoring within the Department. The monitoring needs of the Department were classified into four categories, national assessment, regional monitoring, compliance monitoring, and special studies.

The system designed in this project belongs to the national assessment category. Additional systems will be required to assess other classes of water resources.

The design specifications for the NRWQAP included a statement of the objectives of the programme, a list of variables that are required for an adequate description of overall water quality, an estimate of the appropriate sampling frequency for the variables, general recommendations for sampling procedures and analysis methods, suggestions for reporting formats, and a discussion of future evaluation of the design.

Analysis of data records of electrical conductivity and pH measurements indicated that a monthly frequency will allow the detection of a change equivalent to 2.0 times the standard deviation of the variable at the site after 2 years of data collection, with a significance level of 0.10 and a power of 0.90. Significance level refers to the probability of incorrectly saying a trend exists when it does not. Power is the probability of correctly saying a trend exists when it does.

Additional analysis will be required to determine the sampling frequency of other variables.

The Analytical Hierarchy Process was used to select the variables for inclusion in the National River Water Quality Monitoring System. They were:

Total dissolved solids (TDS)
Turbidity,
E. coli
Chlorophyll *a*
pH,
Dissolved oxygen (DO).

In a separate project, the construction of an index was investigated to combine information from these six variables into a single number. Individual rating curves were developed for each variable that show the "fitness for use" rating (on a scale from 1-100) as a function of the measured value. Weights were assigned to each variable according to its importance in defining fitness for use.

By combining the two measures, rating curves and weighting factors, the index value will indicate the general fitness for use of the specific combination of the six measurements at each site.

The choice of sampling sites in any water quality monitoring system is influenced by the objectives of the system. The two objectives of the NRWQAP that determine the distribution of sampling sites are:

(a) To assess river water quality of Southern Africa;
(b) To describe how river water quality changes over space.

Sampling sites were chosen near the outflow of each tertiary drainage region, with additional sites located on tributaries which drain at least 60 to 70% of the tertiary drainage region.

In order to describe how water quality changes over distance, each major river or stream will be monitored over its entire length. A major river or stream was defined as one that drains at least a secondary drainage region. The tertiary drainage regions were used to determine the maximum distance between sampling sites. Each major river will be monitored where it passes through a tertiary drainage region, as close as possible to the point where it leaves the drainage region.

In addition, each river will be monitored just upstream of the confluence with any major tributary. The tributary will also be monitored just upstream of the confluence. A major tributary is defined as a stream that drains at least a tertiary drainage region.

All results of analyses will be stored on the Water Quality Data Base of the Hydrological Information System (HIS), developed in a separate project. Provision was made for a standard series of retrieval options for supplying data to general data users. Users with more data-intensive demands can get direct access for data retrieval.

The current water quality status can be determined by examining the statistics for each of the six variables separately and in combination. Rank order statistical methods are recommended for data analysis. The statistics to be calculated for each variable at each point are the 10th, 25th, 75th and 90th percentiles. The percentiles would be calculated for the year under review and the values for each point reported.

In order to allow easy assessment of the fitness for use, an index will be used to report the water quality in terms of the combined variables. A water quality index is one way of summarizing water quality data to present concise information on the suitability for use of water.

In order to allow the user to put the current water quality into perspective, information on the historical water quality will be provided. Any trends that are detected by making use of the whole record would indicate long term changes taking place in the catchment. Trends detected with the last three years of data would indicate sharp changes over a short period.

Maps showing drainage regions with a positive, negative, or no trend for each variable and for the index are proposed. These will be colour-coded to indicate negative trend, no change, positive trend or insufficient data. The graphical presentations can also be used to provide information on spatial changes.

Annual reports are proposed. The need for more frequent reports will be evaluated, based on requests for information. Procedures for immediate reporting of significant deviations from historical values have been developed.

The programme will be evaluated regularly to determine whether or not the stated objectives are being met.

The Department of Water Affairs and Forestry has, in principle, decided to implement this design.

Statistical Procedures for System Evaluation

In assessing existing water quality monitoring within the Department, it became clear that the selection of sampling sites is one of the most critical activities in the production of sufficient water quality information. A great deal of effort was, therefore, devoted to developing statistical procedures to provide assistance in that activity.

Procedures were developed to determine if the sampling sites within a region produce redundant information and can therefore be eliminated.

In further attempts to address the problem of inadequate information, statistical procedures were suggested for filling gaps in time series data and for dealing with gaps caused by intermittent flow.

Identification of Additional Water Quality Monitoring Needs

A survey of the DWAF regional offices was conducted to determine the scope of water quality information needs at a scale smaller than national. In the process of conducting the survey, additional needs were identified in terms of technical guidance.

CONTRACT OBJECTIVES

The results of the project have fulfilled the aims stated in the original proposal.

A relatively practical monitoring strategy has been developed to provide information for the assessment of river water quality on a national scale. The system will probably be cost-effective, but no criteria are available against which to judge sufficient cost effectiveness. In producing annual reports that will disseminate the information, the proposed programme will be more cost-effective than a programme that merely builds a database.

While the proposed NRWQAP does not meet all the information needs, much progress has been made in identifying and classifying water quality information needs. Future development work will be required to address those needs.

Statistical procedures have certainly been developed that can provide reliable information for water quality managers. In addition to the procedures noted above that are intended to determine redundant sampling sites and account for periods of missing data, a protocol was developed for the NRWQAP to be used in routine analysis of the data produced by that programme.

PROJECT REPORT

The report for the project contains two separate sections,

(1) *Conceptual Design Report for the National River Water Quality Assessment Programme* by J Harris, M van Veelen, and T C Gilfillan

(2) *Procedures for Identifying Redundant Stations, the Handling of Missing Values and Appropriate PC Software* by E M Basson and T C Gilfillan

The first describes the design of the NRWQAP and the second describes the statistical procedures for identifying redundant sampling sites and for accounting for missing data.

The sections are stand-alone documents that have different authors and objectives, but taken together they present an analysis of the existing water quality monitoring situation, specific proposals for additional water quality monitoring and a solution to some of the identified problems relating to statistical analysis.

FURTHER RESEARCH

It is recommended that the NRWQAP be implemented to provide a description of water quality in the Republic of South Africa. Additional programmes should be designed to describe water quality in ground water, reservoirs, estuaries, and coastal marine water.

Water quality information on a smaller scale, and at a shorter interval, is necessary for efficient management. A programme to address these water quality information needs should be designed.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission, the Department of Water Affairs and Forestry, and the CSIR. It was entitled:

"The development of water quality monitoring strategies and procedures for water quality data interpretation."

The Steering Committee responsible for this project consisted of the following persons:

Dr M J Pieterse	Water Research Commission (Chairman)
Mr P W Weideman	Water Research Commission (Secretary)
Mr H M du Plessis	Water Research Commission
Mr H J Best	Department of Water Affairs and Forestry
Dr H R van Vliet	Department of Water Affairs and Forestry
Dr P J Ashton	CSIR, WATERTEK
Dr D C Grobler	CSIR, Environmental Services
Mr M van Veelen	Department of Water Affairs and Forestry
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The financing of the project by the Water Research Commission and the contributions of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

Colorado State University, Dr R C Ward and Dr T G Sanders for assistance, advice, and support;

Department of Water Affairs and Forestry, Regional offices staff for valuable discussions; the **Water Quality Information Studies section** of the HRI, in particular, **Mr U Nell, Mr D Grobler**, and **Mr F van Wyk**.

CSIR, INFOTEK, Ms Bettie Basson, Ms Elise Swart, Ms Esté Gouws for skilled data analysis. **Drs Jackie Galpin** and **Hans Ittmann** for insightful contributions.

CSIR, WATERTEK, Mr D R Hohls for his substantial contribution to the survey of Regional offices and report production; **Ms Chris A Moore** for a variety of input, particularly in the development of an index, **Ms Cwayita V Dunjwa** and **Mr Robert W Skoroszewski** for excellence in report production.

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EXTENDED ABSTRACT

The Department of Water Affairs is responsible for managing the water resources of the Republic of South Africa. The Department recognizes that "in time, quality may become a more important factor than quantity as regards the availability of water in some areas, particularly in the interior" (DWA, 1986). For that reason, water quality management has become an important part of water resources management. As the possibility of solving water supply problems with new structures decreases because the economically feasible sites have been used, the importance of managing available water to maintain its quality will continue to increase.

Water quality management is intimately linked with water quality monitoring. In order for an agency to supply water of a sufficient quality to meet the needs of water users, the agency must have management tools, that is, procedures that can be effectively applied to control water quality. It must also have information relative to the effectiveness of those management tools; information that comes from water quality monitoring. Some of the tools that are available to water quality managers in South Africa are the effluent standards, (General, Special, and Special Phosphate) in which river water quality is irrelevant, and receiving water quality objectives, in which river water quality is critical. Additional tools to control water quality include reservoir operation procedures and enforcement procedures, which cover the range from requests for cooperation to criminal charges for pollution. Encouraging industries with effluent problems to conduct special studies has also been used as a tool to improve water quality. Catchment studies that include water quality considerations are another tool that can be applied to set water quality objectives for entire catchments.

Of the tools available, the general effluent standard is probably the most often used and the one that has received the most attention from the Department of Water Affairs and industry. Uniform effluent standards do not require knowledge of receiving water quality.

Most of the long-term river water quality monitoring within the Department of Water Affairs is conducted by the Directorate : Hydrology. Samples are collected by personnel of the Directorate when they visit gauging weirs to change flow recorder charts. Samples are sent to the Hydrological Research Institute (HRI) for analysis. Typical analysis is for major cations and anions, nutrients, (nitrate, ammonia, Kjeldahl nitrogen, total phosphorus, and ortho-phosphate), electrical conductivity, pH, total organic carbon (TOC), and heavy metals.

The data are stored on the Department's mainframe computer in a data base operated by the Directorate : Hydrology.

Selection of the sampling sites has been driven predominately by the location of suitable sites for measuring flow quantities, although some sampling sites have been added in recent years based solely on the need for water quality information. Water quality sampling frequency decisions are driven predominately by the need to service flow recorders. The chemical analysis decisions are driven by tradition and special requests for individual analyses. All data are stored. The result is a very large data base that contains valuable information that can be used in the design of a water quality assessment programme, but that does not necessarily provide adequate information to effectively measure water quality changes over space and time.

Additional monitoring is conducted within each Region, usually as a result of site specific concerns. The data are generally available upon request, but are seldom stored in electronic media. Structured reporting formats exist, but are the exception rather than the rule.

There are many demands on the resources of any government agency. It is in the best interests of all concerned to ensure that the resources devoted to monitoring water quality provide essential information as efficiently as possible.

Existing river water quality monitoring activities will be preserved during implementation of additional monitoring procedures. Most of the knowledge of river water quality comes from these activities. A detailed evaluation of existing monitoring is recommended to determine the appropriate structure and interface between the existing and proposed monitoring functions.

Receiving Water Quality Objectives (RWQO) is an approach that is new in Southern Africa, but has been applied successfully for some time in other countries, notably the United Kingdom and the United States. The key to the approach is determining water quality needs defined by the uses of water. While the application of this approach in South Africa will be different from that in other countries, the need to know water quality in rivers will necessarily be an important feature.

Because water quality is naturally quite variable, it is important to provide consistent information over a long time in order to be able to distinguish changes in the underlying processes from the natural variability. The monitoring system must maintain a consistent goal in order to provide this information. If the rationale behind the design is known, decisions about changes to the system can be made with full knowledge of the purposes, the intent of the designers, and the wishes of the information users.

The purpose of this study was to design a National River Water Quality Monitoring System. This document describes the system that the designers propose. The document is intended to be used by the Department of Water Affairs and Forestry to guide decision makers (1) during implementation of the design and (2) when modifications are required during the course of water quality monitoring.

Because water quality information requirements cover a broad range of conditions, it is often advantageous to develop separate systems that can meet specific objectives. Several water quality monitoring programmes have been identified. The programmes have unique objectives to provide information for separate regulatory functions. Those programmes are the National Water Quality Assessment Programme, the Regional Water Quality Monitoring Programme, the compliance monitoring programme, and Water Quality Studies.

National Water Quality Assessment Programme

When water quality management is concerned with the quality of receiving water, it is essential to be able to assess existing water quality in rivers and streams. It must be possible to describe "what" the water quality is where water is supplied - the rivers and streams. Water supplied from dams is strongly affected by the quality of water in rivers and streams.

The fundamental information requirement is the need to describe existing water quality and how it changes over time and space. Assessment monitoring systems provide this information, which is necessary to evaluate the effectiveness of existing strategies and the need for changes in those strategies.

No system that exactly conforms to these requirements is in place in South Africa at this time, but some of the functions are met by existing river monitoring.

Regional Water Quality Monitoring Programme

Regional monitoring programmes can be introduced or changed in response to specific water quality problems identified in an assessment monitoring system or from other information sources. As in assessment monitoring, no systems that exactly conform to the requirements addressed here are in use at this time, but some of the functions are met by existing river monitoring.

Generally, the variables in an assessment system, such as the current design, are indicators of broad classes of water quality problems, therefore, regional monitoring systems are necessary in order to isolate the causes of changes in the indicators.

Regional monitoring can be short, medium, or long term. It would be controlled by authorities responsible for day-to-day management or implementation of the Water Act. It is designed or modified in response to known conditions in the catchment. The variables measured, the frequency of measurement, and the location of sampling sites can be different from those in the assessment monitoring programme. There is obviously no need for identical measurements, but a higher frequency, or additional sampling sites, may be needed for the variables also included in the assessment monitoring system.

If assessment monitoring systems measure "what" the water quality is, regional monitoring systems help to answer "why" the water quality is like it is. These systems will depend on the location of sampling sites relative to troublesome point or diffuse sources to quantify individual contributions to water quality. They will provide information on the effectiveness of the management strategies applied within the catchment.

These catchment monitoring systems are vital to the effective management of water quality. They describe water quality on a regional scale and provide the information necessary to manage water resources on a day-to-day basis. They are expensive systems because they must supply information to meet both the short-term management needs as well as the long-term, site-specific needs for evaluation. It is, therefore, essential that they be carefully designed to optimize the information supplied per unit cost.

Compliance monitoring

Compliance monitoring has as its objective the determination of the compliance of a specific effluent with its permitted value. This system has been in operation for many years in South Africa and is well-established. Many of the procedures have recently been evaluated. The information expectations, the statistical design criteria, the operating plans and procedures, network selection criteria, and reporting formats for the system have been described (Conradie, 1990).

Because there are no stream standards in South Africa, compliance monitoring does not apply to river monitoring. With total implementation of the receiving water quality objectives approach, however, the need for information on compliance of a river reach with its water quality management objectives will be a factor that must be incorporated in the objectives of water quality monitoring.

Water Quality studies

This programme contains special studies that are project scale monitoring programmes, usually short term and often associated with the description of processes which produce specific water quality problems. Information from these studies is often used in water quality modelling exercises. Other examples of water quality studies would be to investigate fish kills, to predict the effects of specific effluent on receiving water quality, and to isolate the effect of a particular condition, say atmospheric deposition of sulphur dioxide, on water quality in a particular area. This type of monitoring is often done by consultants for the Department of Water Affairs and Forestry.

INFORMATION EXPECTATIONS

A User Team composed of staff from the Department of Water Affairs and Foresty and WATERTEK, CSIR was consulted regarding fundamental decisions about information expectations of the system. The group was used as a forum for the discussion of many of the issues confronted during the design. Because the focus of pollution control was changing from a uniform effluent standard to a receiving water quality objective approach during the time of the discussions, many of the issues faced were based on anticipated needs rather than historical knowledge of information requirements.

The consensus of the group was that users expected to be able to identify areas where water quality is changing, areas where more information is needed, the areas where a high risk of problems exists, and areas where changes in water quality management are needed. Additional information needs were identified as verification that changes in water quality management have been effective, for example, "Has the water quality changed since the RWQO approach was implemented?" and "Is water quality better in the Vaal River than in the Crocodile River?"

The information users are principally within the Department of Water Affairs and Forestry. The most important information need identified was to demonstrate that the Department has executed its custodianship of the nation's water quality, to validate the management strategies, and to assist in decisions about allocation of resources.

Definition of water quality

One of the requirements identified early in the design process was the need to provide an operational definition of water quality. In South Africa, the definition of water quality can be inferred from the Water Amendment Act, (No. 96 of 1984) where the offence of water pollution is defined in Section 23 as

> . . . any act which could pollute public or private water, including underground water, or sea water in such a way as to render it less fit (i) for the purpose for which it is or could be ordinarily used by other persons (including the Government, the South African Transport Services and any provincial administration); (ii) for the propagation of fish or other aquatic life; or (iii) for recreational or other legitimate purposes.

The implication of this definition of water pollution is that water quality is determined by its fitness for the purpose for which it is used. In addition to the specific uses of propagation of fish or other aquatic life and recreational uses, three additional purposes are noted in Section 21 of the Act, namely industrial, urban, and domestic. It was assumed that fitness for the propagation of aquatic life was not limited to organized food production, but extended to natural systems and could be interpreted as the health of the aquatic ecosystem.

The implication of defining pollution as making water "less fit" for use is that there is no requirement for ensuring that the quality be preserved in or returned to some "pristine" state. As long as the quality of the water is sufficient for its uses, it has not been polluted in terms of the Water Act. The goal of water quality management is therefore to maintain the fitness of use for water.

Objective of the National River Water Quality Monitoring System

The following statement was accepted by the User Team as the objective of the National River Water Quality Monitoring System.

The objective is to produce water quality information that will describe the fitness for use of the water resources of southern Africa and the changes in quality over time and space.

The monitoring system is designed as an information system and will consist of a statement of the information requirements, statistical design criteria, operating plans and procedures, and reporting procedures and formats.

Initially it will be implemented in the Republic of South Africa, but cooperation with neighbouring states will be sought to encourage its implementation throughout the region.

Information on the fitness of water bodies for the purpose for which they are or could ordinarily be used will be regularly reported to Government officials and the public. The reports will describe average levels and the changes in those levels over time and space. The water quality variables reported on will be general indicators of the fitness of water for use. The major water uses that will be addressed in the monitoring system are:

Domestic water supply: The provision of raw water to facilities that will treat the water to drinking water standards.

Industrial water supply: The provision of water for use in any industrial setting, e.g. manufacturing, food processing, mining, and power generation.

Agricultural water supply: The provision of water for irrigation and stock watering.

Recreation: The use of water for angling, non-contact recreation such as boating, contact recreation such as swimming or diving, and other forms of land-based recreation that are done near bodies of water, such as hiking or picnicking. In this category it is also recognized that, despite attempts to discourage it, some people drink raw, untreated, water.

Conservation: The uses of water bodies which require them to function as healthy, viable ecosystems.

It is important to stress that the National Water Quality Monitoring System is not intended to be the <u>only</u> monitoring conducted. There are important water quality information needs that cannot be met by any one system. Therefore, separate monitoring systems will be created that operate in parallel with this one, perhaps sampling from the same sites, but at different frequencies and analyzing samples for different variables.

Analysis of data records of electrical conductivity and pH measurements indicated that a monthly frequency will allow the detection of a change equivalent to 2.0 times the standard deviation of the variable at the site after 2 years of data collection, with a significance level of 0.10 and a power of 0.90. Significance level refers to the probability of incorrectly saying a trend exists when it does not. Power is the probability of correctly saying a trend exists when it does.

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The programme will be evaluated regularly to determine whether or not the stated objectives are being met.

The Department of Water Affairs and Forestry has, in principle, decided to implement this design.

I. PREFACE

This document reports on a project jointly funded by the Water Research Commission, the Department of Water Affairs and Forestry from both the then Directorate : Water Pollution Control and the Directorate : Hydrological Research Institute (HRI), and the CSIR, from both the Division of Water Technology (WATERTEK) and the Centre for Advanced Computing and Decision Support (DATATEK, now INFOTEK).

The project team was organized with J Harris as project leader from the CSIR's WATERTEK and M van Veelen as project leader from the Hydrological Research Institute (HRI). T C Gilfillan, from DATATEK, CSIR, was responsible for development of the statistical protocol. D R Hohls was responsible for the description of existing regional monitoring systems. The project coordinators from the Department of Water Affairs and Forestry were, initially, Dr D C Grobler and, finally, Dr H R van Vliet.

The combined responsibilities of HRI and CSIR for this project were to determine information expectations of the information users, develop the conceptual design of the operating plans/procedures, develop criteria for selecting the network design, and develop quality assurance/quality control concepts. A separate project, led by C A Moore of WATERTEK, CSIR, investigated the use of indices to report water quality information. The results of that study will be incorporated in the reporting format. Additional responsibilities of the Department of Water Affairs and Forestry, as the regulatory agency, are software development, computer hardware acquisition and maintenance, and most importantly, implementation of the design.

A group of information users, called the User Team, provided a forum for discussions of many of the issues surrounding water quality monitoring design. The members of the team and their affiliations at the time are listed below.

Mr W van der Merwe,	Director, Water Pollution Control, DWAF
Dr D C Grobler,	Deputy Director, Water Quality Management, DWAF, Chairman
Dr H R van Vliet,	Director, Hydrological Research Institute, DWAF
Mr J Schutte,	Directorate : Hydrology, DWAF
Mr J van Rooyen,	Directorate : Project Planning, DWAF
Mr F van Zyl,	Directorate: Project Planning, DWAF
Ms C A Moore,	Division of Water Technology, CSIR,
Mr P Howarth,	Directorate: Water Pollution Control, DWAF
Mr M van Veelen	Directorate: Hydrological Research Institute, DWAF

II. ORGANIZATION OF THE DOCUMENT

The document is divided into three parts. The first part is a brief introduction that describes the relationship between water quality monitoring and water quality management and the current status of water quality monitoring in South Africa.

The second section describes the fundamental principles of the process of designing an appropriate water quality monitoring system. A description of distinct monitoring systems is included in the second section, even though the need for the description became apparent during the development of information expectations for the current project. The location of any particular monitoring programme within the framework of the several types of monitoring is a fundamental concept that affects most of the following design conditions; therefore, the description of the framework is included in the "principles" section. In order to avoid the pitfalls experienced in current water quality monitoring, the second section also surveys concerns expressed about current water quality monitoring. It incorporates a discussion the needs of a water quality monitoring system, as seen from the ground.

The third section is a description of the application of those principles to the current design.

M van Veelen was responsible for the sections on the choice of sampling sites, sample collection procedures, data handling and storage, training, and reporting format. T C Gilfillan was responsible for the statistical protocol. J Harris was responsible for the remaining parts.

1 INTRODUCTION

The Department of Water Affairs and Forestry is responsible for managing the water resources of the Republic of South Africa. The Department recognizes that "in time, quality may become a more important factor than quantity as regards the availability of water in some areas, particularly in the interior" (DWA, 1986). For that reason, water quality management has become an important part of water resources management. As the possibility of solving water supply problems with new structures decreases because the economically feasible sites have been used, the importance of managing available water to maintain its quality will continue to increase.

Water quality management is intimately linked with water quality monitoring. In order for an agency to supply water of a sufficient quality to meet the needs of water users, the agency must have management tools, that is, procedures that can be effectively applied to control water quality. It must also have information relative to the effectiveness of those management tools; information that comes from water quality monitoring.

Some of the tools that are available to water quality managers in South Africa are the effluent standards, (General, Special, and Special Phosphate) in which river water quality is irrelevant, and receiving water quality objectives, in which river water quality is crucial. Additional tools to control water quality include reservoir operation procedures and enforcement procedures, which cover the range from requests for cooperation to criminal charges for pollution. Encouraging industries with effluent problems to conduct special studies has also been used as a tool to improve water quality. Catchment studies that include water quality considerations are another tool that can be applied to set water quality objectives for entire catchments.

Selection of the proper management tools can only be made if information relative to the tools' effectiveness is available. That information must be developed from river water quality monitoring data.

1.1 EXISTING RIVER WATER QUALITY MONITORING

River water quality monitoring within the Department of Water Affairs and Forestry is conducted by the Directorate : Hydrology and the Regional Water Quality Sub-directorates. Samples are collected by regional personnel when they visit gauging weirs to change flow recorder charts. Samples are sent to the Hydrological Research Institute (HRI) for analysis. Typical analysis is for major cations and anions, nutrients, (nitrate, ammonia, Kjeldahl nitrogen, total phosphorus, and ortho-phosphate), electrical conductivity, pH, and total organic carbon (TOC). The data are stored on the Department's mainframe computer in a data base operated by the Directorate : Hydrology.

Selection of the sampling sites is driven predominately by the location of suitable sites for measuring flow quantities, although some sampling sites have been added in recent years based solely on the need for water quality information. Water quality sampling frequency decisions are driven predominately by the need to service flow recorders. The chemical analysis decisions are driven by tradition and special requests for individual analyses. All data are stored. The result is a very large data base that contains valuable information that can be used in the design of a water quality assessment programme, but that does not necessarily provide adequate information to effectively measure water quality changes over space and time. Existing river water quality monitoring activities will be preserved during the present design process. Most of the current data on river water quality comes from these activities.

There are many demands on the resources of any government agency. It is in the best interests of all concerned to ensure that the resources devoted to monitoring water quality provide essential information as efficiently as possible.

The process of designing this national river quality monitoring system included discussions with those involved in the actual work of catchment monitoring. They identified concerns related to the efficiency and effectiveness of existing monitoring efforts. Continuing effort is required to ensure that well designed monitoring systems continue to function effectively.

1.2 APPROACHES TO WATER QUALITY MANAGEMENT

Receiving Water Quality Objectives (RWQO) is an approach that is new in Southern Africa, but has been applied successfully for some time in other countries, notably the United

Kingdom and the United States. The approach was announced a relatively short time ago (van der Merwe & Grobler, 1989). It therefore has a very limited history and few well-established policies or procedures. The following is a description of the general concepts of a receiving water quality approach as those concepts have been applied elsewhere.

The key to the approach is determining water quality needs defined by the uses of water. The method used in the US is to classify stream reaches based primarily on the aquatic environment, principally the types of fish in the reach. Specific requirements, called criteria by the US Environmental Protection Agency (EPA), to maintain the quality of fisheries have been developed and published for many water quality constituents (USEPA, 1986). Permits to discharge effluent are evaluated by predicting the effect of an effluent on the receiving water and comparing the resultant water quality to the criteria for the particular stream reach classification (USEPA, 1984). If predictions of the effluent's effect indicate that the standards for that stream reach will be violated, additional treatment must be undertaken.

While the application of this approach in South Africa will be different from that in other countries, the need to know water quality in rivers will necessarily be an important feature.

The General Effluent Standard is the traditional basis of water quality management in South Africa. It has been applied for many years with the aim of assuring that any effluent discharged to the surface water would meet at least the minimum requirements of the General Standard. In many cases, it is the most appropriate management tool. The role of river water quality monitoring is primarily as an indicator of gross violation of the standards. Effluent monitoring for compliance with the standards has a far greater role in this approach to water quality management.

1.3 PURPOSE OF THIS STUDY

The purpose of this study was to assess water quality information needs and design a system to address those needs. This document describes the National River Water Quality Assessment Programme, the system that the designers propose to meet one set of those information needs. The document is intended to be used by the Department of Water Affairs to guide decision makers (1) during implementation of the design and (2) when modifications are required during the course of water quality monitoring.

Because water quality is naturally quite variable, it is important to provide consistent information over a long time in order to be able to differentiate changes in the underlying processes from changes that result from natural variability. The monitoring system must maintain a consistent goal in order to provide this information. If the rationale behind the design is known, decisions about changes to the system can be made with full knowledge of the purposes, the intent of the designers, and the wishes of the information users.

2 PRINCIPLES OF WATER QUALITY MONITORING DESIGN

2.1 INFORMATION EXPECTATIONS

The kinds of information expected from a monitoring system determine many of the features of the system. McBride (1986) discussed problems encountered in New Zealand with the design of a water quality information system. The problems were related to the lack of both a consensus on the definition of water quality and a clearly stated water quality management goal. Careful consideration of regulatory agency responsibilities and goals are necessary to avoid those kinds of problems.

In the evaluation of information expectations, Sanders *et al.*, (1987) recommend discussions with the ultimate users of the information and those allocating funds for the monitoring operation. Subsequent activities they recommend are the formulation of a written statement of the monitoring objectives and development of a consensus on the overall reasons for monitoring. They stress the importance of a written statement of all the monitoring objectives so that information users will be aware of the need to compromise when multiple objectives exist.

Because water quality information requirements cover a broad range of conditions, it is often advantageous to develop separate systems to meet specific objectives.

2.2 STATISTICAL DESIGN

Requirements of statistical analysis must be considered early in the design process. Concentrations of constituents of water quality are random variables and are, therefore, subject to all the constraints of any experimental design problem.

Existing data should be analyzed to describe the statistical characteristics that affect data analysis. Some of the relevant characteristics are the amount of variability, estimates of whether a normal or log-normal fits the sample distribution better, and serial correlation. Serial correlation is a measure of the amount of information repeated in adjacent observations. If data are serially correlated, the assumption of independent observations, which underlies many hypothesis tests, is violated. Information about serial correlation is useful input to decisions about sampling frequency. The time elapsed between samples can be increased if analysis shows significant serial correlation.

An analysis of existing data will also provide an estimate of the characteristics that affect the statistical tests selected. For example, if trend detection is considered an important part of the information expectations, sample distribution and variance in the observed data can be used to estimate the relationship between the number of samples and the power to detect a change of a particular magnitude relative to the variance.

With prior knowledge gained from analysis of existing data, a protocol can be developed that includes recommendations for specific steps in data preparation, appropriate tests, and a range of values to be expected in the results. Preliminary software selections are also made during this step.

2.3 DESIGN MONITORING NETWORK

Design of the network includes decisions about which variables to measure, where to locate the sampling sites, and how often to sample. Each of those decisions should be related to the information objectives of the system. The variables to be measured should be chosen to ensure that the information that can be developed will meet the needs established in the first step of the design process. For example, it is pointless to measure chemical oxygen demand when the information expectations are to be able to evaluate management options for eutrophication control. This is an obvious example; one should be alert to more subtle ones.

The location of sampling sites depends on ensuring that the sites are selected to provide information at relevant places, again referring to the information expectations developed in the first step. The location of sampling sites for assessment monitoring programmes should take into account the fact that the assessment must include water quality that is representative of the entire region, not just the parts where problems or poor water quality occur. Location of sampling sites just downstream of point source discharges may bias the assessment of total water quality; on the other hand, point sources are often located in population centres where many water users are congregated and information on water quality is essential. The selection of sampling sites must take these conflicting factors into account.

2.4 OPERATING PLANS AND PROCEDURES

Details of the monitoring network are specified in this step of the design process. Items such as the sampling route, sampling procedures, data storage and retrieval procedures, selection or development of computer software, designation of responsibilities, and many other similar items must be determined and documented.

Documentation of the procedures is vital to maintaining consistency throughout the system and over time. Without adequate documentation, the procedures are transferred by word of mouth and will be changed at least slightly with each new employee.

While this step is very important in the design of the system, it is difficult to specify many of the details that can be very different over the area covered by the monitoring system. For example, the sampling routes can be specified much better by individuals with knowledge of the physical aspects of each river, including things such as access.

Changes in the system must also be provided for. It is likely that, over the life of the monitoring system, changes will affect, for example, the sampling route or requirements for sample transport. Procedures to deal with those changes should be developed as part of the design process. A description of the changes and the reasons for them must be added to the design document. Information about the changes must also be distributed with the information reports.

2.5 REPORTING

It is important to consider reporting procedures in the design phase because, without communication, the monitoring system will have failed to relay its information and will not fulfil its purpose. The reports are the method by which the data collection procedures are converted to information that can be applied to water quality concerns.

The selection of reporting formats, frequency, and distribution is strongly related to the information expectations of the system developed in the first step. The information must be concise, accurate, and appropriate to those to whom it is distributed.

2.6 TYPES OF MONITORING SYSTEMS

Several categories of monitoring systems have been identified. The categories are groups of similar objectives that combine to provide information for separate regulatory functions. Those categories are described below.

2.6.1 Assessment monitoring

It is essential to be able to assess existing water quality in rivers and streams. It must be possible to describe "what" the water quality is in the places where water is supplied, the rivers and streams. Water supplied from dams is strongly affected by the quality of water in rivers and streams.

The fundamental information requirement is the need to describe existing water quality and how it changes over time and space. Assessment monitoring systems provide this information, which is necessary to evaluate the effectiveness of existing strategies and the need for changes in those strategies.

No system that exactly conforms to these requirements is in place in South Africa at this time, but some of the functions are met by existing river monitoring.

2.6.2 Regional monitoring

Regional monitoring programmes can be introduced or changed in response to specific water quality problems identified in an assessment monitoring system or from other information sources. As in assessment monitoring, no system that exactly conforms to the requirements addressed here are in use at this time, but some of the functions are met by existing river monitoring.

Generally, the variables in an assessment system, such as the current design, are indicators of broad classes of water quality problems, therefore, regional monitoring systems will be necessary in order to isolate the causes of changes in the indicators.

Regional monitoring can be short, medium, or long term. It would be controlled by authorities responsible for day-to-day management or implementation of the Water Act. It is designed or modified in response to known conditions in the catchment. The variables measured, the frequency of measurement, and the location of sampling sites can be different from those in the assessment monitoring programme. There is obviously no need for identical measurements, but a higher frequency, or additional sampling sites, may be needed for the variables also included in the assessment monitoring system.

If assessment monitoring systems measure "what" the water quality is, regional monitoring systems help to answer "why" the water quality is like it is. These systems will depend on the location of sampling sites relative to troublesome point or diffuse sources to quantify individual contributions to water quality. They will provide information on the effectiveness of the management strategies applied within the catchment.

These systems are vital to the effective management of water quality. They describe water quality on a regional scale and provide the information necessary to manage water resources on a day-to-day basis. They are expensive systems because they must supply information to meet both the short-term management needs as well as the long-term, site-specific needs for evaluation. It is, therefore, essential that they be carefully designed to optimize the information supplied per unit cost.

2.6.3 Compliance Monitoring

Compliance monitoring has as its objective the determination of the compliance of a specific effluent with its permit value. This system has been in operation for many years and is well-established. Many of the procedures have recently been evaluated. A document has been compiled (Conradie, 1990) that describes the information expectations, the statistical design criteria, the operating plans and procedures, network selection criteria, and reporting formats for the system. Considerable improvement in the system should result from the evaluation.

Because there are no stream standards in South Africa, compliance monitoring does not apply to river monitoring. With total implementation of the receiving water quality objectives approach, however, the need for information on compliance of a river reach with its water quality management objectives will be a factor that must be incorporated in the objectives of water quality monitoring.

2.6.4 Water Quality Studies

Water quality studies are project scale monitoring programmes, usually short term and often associated with the description of processes which produce specific water quality problems.

Information from these studies is often used in water quality modelling exercises. Other examples of water quality studies would be to investigate fish kills, to predict the effects of specific effluent on receiving water quality, and to isolate the effect of a particular condition, say atmospheric deposition of sulphur dioxide, on water quality in a particular area. This type of monitoring is often done by consultants for the Department of Water Affairs and Forestry.

2.7 Analysis of existing regional monitoring

At present no system exists identical to either the proposed national assessment system or a regional monitoring system. The monitoring currently executed by staff of the Department's Regional offices most closely resembles the description of regional monitoring given above. An investigation of existing regional monitoring systems was conducted to help evaluate the integration between the proposed NRWQAP and those existing monitoring activities and to determine if there are general issues of concern that should be addressed.

The monitoring requirements for regional scale systems are by far the most complex. Regional water quality managers need information for day-to-day operations as well as for long-term trend detection. There are also additional needs, including; the determination of appropriate exemption conditions, the identification of problems or potential problems, and the evaluation of management decisions.

In addition, any view of national river water quality in South Africa is composed of views of water quality in the different regions of the country. Any national water quality monitoring system would rely on the participation of the regional authorities. In assessing the needs related to water quality monitoring, it appeared that regional monitoring fills a critical function but currently has little structure and considerable variation. Some of the major conclusions from a survey of Regional staff involved in water quality monitoring are summarised in the following paragraphs.

2.7.1 Approach to the analysis

The major players in the field of catchment water quality monitoring within the DWAF are the Regional Water Quality Subdirectorates. Key personnel from within these regions were interviewed to gain an overall picture of monitoring within the Department. Information, opinions and suggestions from these interviews were then compiled to form a global picture of existing catchment water quality monitoring systems within the Department.

2.7.2 Regional monitoring systems designs

In many cases, the current regional monitoring systems have been 'inherited' ie. they have been developed slowly over the years and have become accepted. The introduction of additional monitoring sites is usually initiated by individual staff, if their judgement indicates it is necessary. These choices are later reviewed and modified if needed.

The reasons for initiating a regional monitoring system are many; some examples are:

- public pressure, if there is an actual or perceived threat of pollution;
- checking the effect of dischargers within a catchment - the nature and number of discharges strongly influences the location of monitoring sites;
- determining water quality for water uses within a catchment;
- providing historical water quality against which future impacts or developments can be measured;
- monitoring to ensure that a blending option is being carried out correctly.

2.7.3 Basis for designs

In general, the basis of design for regional monitoring is as follows:

- Identify catchment, including main tributaries;
- Identify potential sources of pollution within the catchment (both point and non-point) and their associated water quality variables;
- Identify water quality requirements for water uses; and
- Determine suitable monitoring points, taking the factors listed above into account.

While some sites might be monitored simply because of ease of access, most are selected for a particular reason. These are usually ones with known water quality problems, or definite water quality requirements (*eg*. where there are many users). Certainly, there is not the time or money to monitor every river within every catchment, so some prioritisation is necessary.

The rapid growth of informal settlements is recognized as one of the major factors currently affecting water quality. Many of these settlements are located near water sources, sometimes on smaller tributaries of major rivers. These effects can be exacerbated when the settlements are in areas over which the DWAF has no official jurisdiction.

Water quality requirements for river use on a national basis have not been clearly identified. In some cases (eg. water quality in rivers feeding national parks), the users are uncertain as to the specifics of their requirements. This in turn makes it difficult to select the appropriate water quality variables to be monitored.

Estuaries are very sensitive to water quality and so need to be carefully monitored, both to check the water quality status and to evaluate any sources of pollution which might be causing degradation. A number of specific issues related to monitoring systems design for estuaries have been identified:

- where to locate sampling points;
- how frequently to sample;
- how to ensure that samples are representative;
- what is the role of depth sampling;
- which water quality variables are to be analyzed;
- how to establish background or 'normal' levels against which to measure changes;
- how to set standards applicable to estuaries;
- how to determine the influence, if any, of ground water.

2.7.4 Documentation of the design

Documentation for many of the monitoring systems is organised according to particular river systems. Copies of details on monitoring site locations, sampling frequencies, and results are generally kept together in files.

No structures exist to encourage documentation, although it is one of the most efficient means to improve the system. The process of documentation provides a means whereby the system can be improved, through expansion, rationalisation or integration.

2.7.5 Updating and checking of the design

Some of the systems are regularly revised by reviewing the location and numbers of the monitoring sites, using the information obtained in the previous one/two years as a basis for doing so *eg.* checking if sites are redundant or if additional ones are needed because of development within a catchment.

2.7.6 Operating plans and procedures for regional monitoring

Historically, staff of the Directorate: Hydrology took regular samples at flow gauging weirs for analysis by the Hydrological Research Institute (HRI). Recent restructuring has moved the sampling activity to Regional control. Although they have the major responsibility for river sampling, additional samples are often needed in particular locations which are associated with industrial and municipal discharges. Water boards and municipalities collect samples in the areas under their jurisdiction. Industries often collect river samples, either as part of their discharge conditions or for their own information.

The Department of Health and National Population Development also collects water quality samples. These are mainly related to health aspects (eg. faecal coliforms), and are usually taken near sewage treatment works and informal settlements.

River water quality is sometimes sampled on an ad hoc basis eg. if the river 'looks bad', or if complaints have been received. Sampling frequency is dependant on the water quality ie. if the water quality is poor then the frequency will be increased and vice-versa. These samples can provide data on immediate concerns, but is often inefficient in quantifying long-term trends.

In view of the increasingly limited time and money available to most organizations, integration of all the water quality sampling programmes should receive immediate attention in order to provide the information necessary for adequate water quality management.

2.7.7 Sampling procedures

Sampling is most often at a monthly interval, depending on the sensitivity of the area involved and the staff available. Thus some sampling is only done on a quarterly basis because of geographical constraints. Long distances are especially critical for bacteriological analysis, where the samples must be taken to a laboratory as soon as possible. Sampling points are often limited by access, and determination of impacts of discharges on the river water quality can be difficult.

In some areas, automatic samplers are used to record half-hourly readings of electrical conductivity and pH. The reasons for the siting of these samplers have not always clearly been identified, but it is felt that their primary use is for pollution control and not long-term river monitoring.

Staff changeovers cause continuity problems in terms of training new people on sampling routes. This condition emphasizes the importance of documentation of the system design.

2.7.8 Variables analyzed

The water quality variables selected for analysis depend very much on the type of industries known or believed to have an impact on the receiving water body. Typical variables monitored include:

- bacteria
- organics
- metals
- inorganics

In some areas, standard lists of variables are monitored in all, or most, rivers. Examples of three different sets are:

- Dissolved Oxygen, pH, Ammonia, Electrical Conductivity, Phosphate, Nitrate, Oxygen Absorbed
- Suspended Solids, pH, Electrical Conductivity, Oxygen Absorbed
- Mineral analyses, Chemical Oxygen Demand, Ammonia, Phosphate, Nitrate

2.7.9 Data storage

Data from the water quality variables that are analyzed at the HRI are stored on the Hydrological Database which can then be accessed by the Regional staff. Most samples are analyzed locally and reported directly to the Regional office.

Most of the data values are written onto composite analysis sheets, and in some cases, transferred to spreadsheets on personal computers. The current departmental POLMON database only has provision for storage of data related to compliance monitoring. Thus there are problems in storing river water quality data in a standard readily retrievable format.

Data stored in paper files is subject to misfiling and valuable information can be irretrievably lost. Electronic data is also subject to loss or destruction and should, therefore, be protected by storing additional copies in places safe from the threat of fire, flood or theft.

2.7.10 Updating of the data

In most regional monitoring systems, data from analyses submitted by the laboratory is visually scanned to check for obvious anomalies; usually by a person familiar with the water quality history of the particular site/s. The data is then passed on for storage. In those areas where data is being stored electronically, a need for dedicated 'data typists' has been identified. The lack of such staff has been cited as justification for using only paper storage.

2.7.11 Statistical analysis

The major outside users of the DWAF's water quality data are the Department of Health and Population Development and local municipalities. In some cases, water quality data from samples collected by the Department of Health and municipalities are passed on to the Department.

There are additional users of data, who make use of water quality data when planning or developing new areas. Data sharing between various bodies often takes place via a Water Monitoring Committee which also acts as a forum for coordinating and streamlining data collection.

2.7.12 Reporting in existing regional monitoring systems

Regular reports are not often compiled and copies of sample reports were not available. There are a number of different types of ad hoc reports that are prepared from time to time, including:

- Data that has to be presented to industry in order to highlight changes in water quality.
- Reports for municipalities who must monitor industries within their municipal boundaries.
- Reports prepared for presentation to the public. These are often linked to public inquiries about water quality.

- Reports prepared for water users to help them understand the complexities of water quality management in their area;
- Reports prepared to show changes to, or a deterioration in, water quality.

Regular reports for use by Regional and Deputy Directors may be useful. These would enable tracking of trends and changes in water quality in each region, allow tracking of performance in meeting objectives, and would aid in better planning and decision making.

2.7.13 Financial and manpower considerations

Any well-designed monitoring system must take into consideration the financial constraints which always exist in any project. In the past, the Department has paid for studies which have resulted in the design of monitoring systems too costly, in terms of equipment and manpower, to implement. Any changes to existing monitoring practices should take into account the limited, and increasingly more constrained, budgets of the regions.

2.7.14 Inter-organisation liaison

The issue of managing water quality is multi-faceted and affects many people and organisations. DWAF does not have the sole responsibility in this area, but liaison with other organisations is of prime importance. In particular, interaction between other key government departments (Health and Environment Affairs) is of increasing importance.

2.7.15 Responsibilities for water quality monitoring

The perception is increasing that DWAF's role is to manage water quality, and this does not necessarily imply that the Department has to do all the day-to-day work of data collection. In some areas, water boards have assumed responsibilities for some water quality data collection; this responsibility might be extended to other organisations eg. regional services councils, local authorities etc.

The main aim of this study was to identify the fundamentals of a national water quality monitoring system, and to provide guidance on the implementation of the design. The ability of this work to overcome the concerns which have already been identified, and the concerns which almost certainly arise as the any new programme develops, is severely limited. The process of designing this system has identified a critical need to apply monitoring systems design concepts, not only to national scale issues, but also to regional scale issues.

Many of the needs identified or perceived during this study indicate the lack of a consistent guidance for water quality data collection and analysis activities. The need for information on the quality of receiving water will continue to increase as the Department moves toward adopting a broader environmental management approach rather than a narrow, effluent-focused approach. Developing and expanding the existing expertise in water quality monitoring will accelerate the process of providing that valuable information.

The following are the major requirements for regional monitoring systems:

- **Documentation of water quality monitoring programmes**
  Many of the problems identified during the survey could be improved by the process of documenting the data collection efforts. The task would be facilitated by providing guidance, support, and communication channels during the process. Optimisation of resource use will depend on accurate descriptions of existing systems. The documentation is, therefore, essential to improvement of the monitoring systems.

- **Supply of expertise or consulting advice on specific issues**
  Water quality problems are often site-specific ones that cannot be easily answered by general guidance. Problem-oriented consulting should be available for aspects of water quality information development.

- **Computer software to assist in analysing data and preparing reports**
  Software development is time-consuming and water quality monitoring staff have many other duties assigned. Analysis and reporting needs are similar for many regional monitoring systems. Software that is user-friendly and specific to the needs of the Department would facilitate the analysis of data and provision of information.

The existing situation with respect to regional monitoring systems is characterised by inefficiencies. In general, the data collection efforts appear to be adequate, but the information produced from the data could be improved. Clarification of the following points would provide structure that would facilitate efficient production of information.

- **The Department's role with respect to other organisations collecting water quality data.** This includes items such as: the possibility of assigning responsibilities for data collection to other agencies; the issue of obtaining and exchanging data with such agencies; and the options for establishing coordinating "Water Quality Monitoring Committees" with members from different organisations.

- **The priority that must be assigned to the development and implementation of additional monitoring systems.** This prioritisation is crucial in light of the changes that are being experienced within the Department following the adoption of the Receiving Water Quality Objectives approach. This will have important implications for staffing and budgetary requirements.

- **The function of current monitoring systems within the Department.** This includes items such as: the issue of the integration between the sampling programme of the Directorate: Hydrology and those of the Regional Water Quality Subdirectorates; the integration and use of data from compliance monitoring, regional monitoring and water quality studies; the use and development of data storage and retrieval systems for water quality monitoring data; and the need for having staff dedicated to the tasks of sample collection and data entry on computers.

The rest of this document describes the application of the principles, described earlier in this chapter, to the specific design of a river water quality assessment programme on a national level.

3 INFORMATION EXPECTATIONS

3.1 INFORMATION USERS

A User Team was formed from interested information users in the Department of Water Affairs and technical staff from WATERTEK, CSIR associated with a project to develop reporting formats for water quality monitoring information. The User Team was consulted regarding fundamental decisions about information expectations of the system. Specifically, the group was used as a forum for the discussion of many of the issues confronted by the designers. Because the focus of pollution control was changing from a uniform effluent standard to a receiving water quality objective approach during the time of the discussions, many of the positions of the User Team were based on anticipated needs rather than historical knowledge of information requirements.

The consensus of the group was that users expected to be able to identify areas where water quality is changing; areas where more information is needed; the areas where a high risk of problems exists; areas where changes in water quality management are needed. Additional information needs were identified as verification that changes in water quality management have been effective, *e.g.* "Has the water quality changed since the RWQO approach was implemented?" and "Is water quality better in the Vaal River than in the Crocodile River?"

The information users are principally within the Department of Water Affairs. The most important information need identified was to demonstrate that the Department has executed its custodianship of the nation's water quality, to validate the management strategies and to assist in decisions about allocation of resources.

3.1.1 Definition of water quality

One of the requirements identified early in the design process was the need to provide an operational definition of water quality. In South Africa, the definition of water quality can be inferred from the Water Amendment Act, (No. 96 of 1984) where the offence of water pollution is defined in Section 23 as

> . . . any act which could pollute public or private water, including underground water, or sea water in such a way as to render it less fit (i) for

> the purpose for which it is or could be ordinarily used by other persons (including the Government, the South African Transport Services and any provincial administration); (ii) for the propagation of fish or other aquatic life; or (iii) for recreational or other legitimate purposes.

The implication of this definition of water pollution is that water quality is determined by its fitness for the purpose for which it is used. In addition to the specific uses of propagation of fish or other aquatic life and recreational uses, three additional purposes are noted in Section 21 of the Act, namely industrial, urban, and domestic. It was assumed that fitness for the propagation of aquatic life was not limited to organized food production, but extended to natural systems and could be interpreted as the health of the aquatic ecosystem.

The implication of defining pollution as making water "less fit" for use is that there is no requirement for ensuring that the quality be preserved in or returned to some "pristine" state. As long as the quality of the water is sufficient for its uses, it has not been polluted in terms of the Water Act. The goal of water quality management is therefore to maintain the fitness of use for water.

3.1.2 Objective of the National River Water Quality Assessment Programme

The following statement was accepted by the User Team as the objective of the National River Water Quality Monitoring System.

> The objective is to produce water quality information that will describe the fitness for use of the water resources of southern Africa and the changes in quality over time and space.
>
> The monitoring system is designed as an information system and will consist of a statement of the information requirements, statistical design criteria, operating plans and procedures, and reporting procedures and formats.
>
> Initially it will be implemented in the Republic of South Africa, but cooperation with neighbouring states will be sought to encourage its implementation throughout the region.
>
> Information on the fitness of water bodies for the purpose for which they are or could ordinarily be used will be regularly reported to Government officials and the public. The reports will describe average levels and the changes in those levels over time and space. The water quality variables reported on will be general indicators of the fitness of water for use. The major water uses that will be addressed in the monitoring system are:

Domestic water supply: The provision of raw water to facilities that will treat the water to drinking water standards.

Industrial water supply: The provision of water for use in any industrial setting, e.g. manufacturing, food processing, mining, and power generation.

Agricultural water supply: The provision of water for irrigation and stock watering.

Recreation: The use of water for angling, non-contact recreation such as boating, contact recreation such as swimming or diving, and other forms of land-based recreation that are done near bodies of water, such as hiking or picnicking. In this category it is also recognized that, despite attempts to discourage it, some people drink raw, untreated, water.

Conservation: The uses of water bodies which require them to function as healthy, viable ecosystems.

It is important to stress that the National Water Quality Monitoring System is not intended to be the only monitoring conducted. There are important water quality information needs that cannot be met by any one system. Therefore, separate monitoring systems will be created that operate in parallel with this one, perhaps sampling from the same sites, but at different frequencies and analyzing samples for different variables.

4 STATISTICAL DESIGN

The following protocol was developed to meet the information requirements of the National River Water Quality Assessment Programme.

4.1 PREPARATION OF DATA

Data from water samples need to be processed before statistical comparisons over time or space can be made. Outlying values must be identified, the data adjusted for missing values, non detects, laboratory duplicates and field replicates. Recommended procedures are described below.

4.1.1 Outlying values

Outlying values may be due to errors in recording results or apparent severe departures from the past data record. Where recording errors or mistakes in the data explain the outliers these should be corrected or removed. Genuine outliers occur when the environmental conditions change in a subtle or dramatic way. An example is when a long period of drought ends with a period of sustained increased rainfall. For a given location, high concentrations of TDS occur frequently during the period of drought, relatively lower concentrations in the rare rainfall events. As rainfall becomes more frequent and abundant the higher concentrations become more rare and lower concentrations become more frequent. As the period of drought gives way to a relatively wetter period, rare low concentrations that are outliers to the drought period, may signal the coming of a period of more abundant rainfall. However, this can only be confirmed in time as more data become available.

With more data, lower values occur more frequently and what was diagnosed as an outlier is found to be part of the normal data record. The outlier of the dry period is the 'inlier' of the wetter period. A shift in mean concentration has occurred.

4.1.1.1 Long-tailed distributions

The unexpectedly large (or small) value that occurs in data collected over time need not automatically be suspect. Data sets with relatively few values to the left (or right) of the majority of the data, are often said to come from, or are generated by, an underlying long-tailed distribution. A well known example is the log-normal distribution where, by taking logs of the observations, the transformed values become equally spread about their median and the frequency distribution takes on the well-known bell shape of the normal distribution. It is not uncommon, however, for the frequency distribution of the logs of a water quality variable not to be bell shaped about the median. Occasional very large (or small) observations can occur with small probability. However, when such observations occur more often, it is unlikely that the same underlying distribution is generating the values. The environment is possibly in the process of changing, causing a shift in the median or an increase in the spread. An upwards (or downwards) shift in all the values may be occurring or the values may be more variable with larger swings towards smaller or larger values. Both a shift and increasing variability may be occurring.

Thus outliers may warn of changes in the environment and should never be discarded unless an obvious mistake has been made.

Of the water quality variables proposed for analysis: TDS, pH, turbidity, dissolved oxygen and chlorophyll *a*, data are available from a number of sampling stations. Data on *E. coli* are not available, however, two sets of faecal coliform data were obtained. Measures determined from this historical data will be proposed to identify possible outliers.

4.1.1.2 Identifying outlying values

Every sampling station will have its own natural, social and economic environment. Rainfall patterns, location within an urban and rural area, with manufacturing or agricultural industries nearby - all such factors influence the levels of concentration of the water quality variables. Given the information of each variable, charts can be prepared with upper limits of expected variability, so that potential outliers can be identified. These could account for any long term trend in concentration, and seasonal variation. This approach is analogous to the charts of industrial quality control. Until site specific procedures can be implemented, use must be made of the available data to establish some global criteria that may be used in the short term. The recommended approach is described below.

Establish, from historical data, limiting values of decreasing size (referred to as criteria) that the maximum absolute difference between the current value and those of the past eleven months, is increasingly likely to exceed. An example of such criteria appears in **Table 4.1** below, where three limits of decreasing size are given for six water quality variables.

Table 4.1 Proposed criteria for identifying possible outliers

Variable		100% Range	80% Range	50% Range
TDS	mg/L	600	480	220
pH		2.7	1.4	0.8
Turbidity	NTU	300	120	80
DO	mg/L	13	7.4	4.0
Chlorophyll *a*	μg/L	170	135	30
Faecal Coliform*	no/100ml	70 000	45 000	6 000

* Data sets of *E. coli* were not available. It is suggested that faecal coliform criteria may be helpful in establishing the equivalent *E. coli* criteria.

The historical data were divided into periods of relatively stable concentration. For each subset the range (maximum - minimum), the 80% range (90 percentile - 10 percentile) and the 50% range (75 percentile - 25 percentile) were established. Limiting values that seemed appropriate for each water quality variable were selected by comparing these measures. Referred to as the 100% range, 80% range and 50% range they are the criteria for identifying potential outliers. The process for selecting these criteria is rather subjective, largely influenced by the more variable data sets.

The absolute difference between the present observation and the smallest or largest value of the past eleven months, unless it is suspect, is not likely to exceed the 100% range. For one out of twelve months it may exceed the 80% range and could, in one out of two months exceed the 50% range. If it exceeds the 100% range the observation should be checked against previous values for recording or other errors. If it exceeds the 80% range the observation may signal a change. Compare the observation to those before and after it. If it is smaller or larger than the adjacent observations it should be checked. Successive differences will not consistently exceed the 100% and 80% ranges unless the environment is changing, becoming more variable or the observations are in error. The 50% range can be exceeded without the value necessarily being an outlier.

Where there is clear evidence of a recording or other error, values should be removed. Otherwise they must be retained and reconsidered when more data become available. Comparisons should be between the new value and those of the preceding eleven months.

Though eleven months of data are needed for the procedure, comparing the maximum absolute differences to the criteria when more than one observation is available, may be helpful.

After 12 months site specific estimates of the three criteria can be computed from the maximum, minimum and the 90, 75, 25 and 10 percentiles. The maximum absolute difference of the next observation and those of the previous 11 months may exceed the 100% range. If so it must be checked. If the difference only exceeds the 80% range the observation need only be checked if it appears to be isolated from the preceding and following observations. Accept a new observation and a new set of criteria can be calculated. If 'corrected' values cannot be found for confirmed outliers, the maximum absolute difference between the present observation and the past 11 months 'inliers' must be used. New criteria should not be computed until 12 consecutive months of 'inliers' are available.

To calculate the 90, 75, 25 and 10 percentiles and percent ranges, the 12 observations are ordered from smallest to largest. The ordered observations are referred to as 1st value, 2nd value, ..., 12th value in the following formula:

90 percentile = (0.30 * 11th value) + (0.70 * 12th value)
75 percentile = (0.25 * 9th value) + (0.75 * 10th value)
25 percentile = (0.75 * 3rd value) + (0.25 * 4th value)
10 percentile = (0.70 * 1st value) + (0.30 * 2nd value)

The percent ranges are:

100% range = maximum - minimum
80% range = 90 percentile - 10 percentile
50% range = 75 percentile - 25 percentile

Not all software packages use the same formula for computing percentiles. The SAS statistical package gives five formula. The above is their default.

Because only absolute differences are used and the procedure compares the present value to the past eleven values, it is not influenced by trend and takes account of seasonal variability.

Table 4.1 above, shows an estimate of proposed global criteria based on a few data sets that are not representative. The criteria proposed are very subjective and should only be used for new stations where local criteria cannot be estimated due to lack of data. They do not relieve the user from the responsibility of checking every value for possible recording or other errors. They may, however, give timely warning of errors in the data record. Data sets that were less variable did not display ranges of the sizes given in the table. This underlies the need for care when assessing the quality of data.

To adapt the figures in Table 4.1 to a specific site, record how frequently the concentrations are greater than or less than the 50% range. If they tend to be larger than the 50% range then the 90% and 100% ranges may be too strict. Alternatively if they tend to be smaller than the 50 range the other ranges may be too lenient.

4.1.2 Missing values

Missing values must be replaced with blanks. Replacing missing values with unlikely values (very large or very small) only confuses the statistical analysis.

4.1.3 Non-detects

Non-detects must be recorded as one-half the detection limit. Where available the actual reading should be given.

4.1.4 Laboratory duplicates

All laboratory duplicates are to be averaged to give one reading.

4.1.5 Mean or median?

All replicates taken on a sampling occasion to be averaged unless, for three or more replicates, one value is clearly different from the average of the remainder. In the case the median should be used. (The sampling occasion will be the day a sampling site is visited and the field replicates are the individual samples that are taken on that occasion).

The mean or average, where all the data is added and the result divided by the number of values, is commonly used to summarize data. This summary statistic is very sensitive to individual values that are clearly larger (or smaller) than the rest of the data. Then, as a cental value for summarizing the data, the mean can be misleading. However, it does have the advantage of being very simple to calculate.

The more useful central value is the median, found by arranging the data from smallest to largest and dividing the ordered data into two groups of the same size. The largest in the first group is never larger than the smallest in the second group. Furthermore the smallest observation is in the first group and the largest in the second group. Where the number of observations is even the groups are of the same size, half the total number, and all the observations are in one or the other group. Where the number is odd, for the groups to be of the same size one observation does not belong to either group. This value is neither smaller than the largest in the first group nor larger than the smallest in the second group. It is the median when the number of observations is odd. For an even number the median is the average of the largest of the first group and the smallest of the second. For example, the median of nine observations is the fifth ordered observation, the four smaller observations belong to the first group and the four larger to the second group. For twelve observations the median is the average of the sixth and seventh ordered observation.

To compare the mean to the median consider the following four replicates: 10, 13, 0.5 and 12. The set includes an unlikely value that is much smaller than the rest. First, assume it is a recording error. If it is 15, the mean and the median are 12.5. If it is 5, the median is 11 and the mean 10. Second, assume it must be retained without adjustment. The median remains 11, the mean becomes 8.88. Third, it is discarded as an outlier. The median is 12 and the mean 11.7. The four possible median values are 12.5, 11, 11, 12. They are very similar. In contrast, the four means are 12.5, 10, 8.88 and 11.7. The median is said to be more robust to outliers than the mean.

4.1.6 Summary - Preparation of data

At the end of the data preparation step every sampling interval is represented by one value, or a blank. Recording errors have been corrected, mistakes and missing values replaced by blanks, non-detects by one-half the detection limit or the actual reading, laboratory duplicates averaged and replicates replaced by either their average or median.

The data are ready to be prepared for graphical and statistical analysis.

4.2 PRELIMINARY ANALYSIS OF PREPARED DATA

The sampling interval of one month was chosen to ensure the independence of the observations. Observations that are not independent, taken at daily, weekly or fortnightly intervals, will be significantly serially correlated, with each observation repeating part of the information contained in previous observations. Therefore every monthly observation is assumed to contain full information. Where the data record contains more than one observation per sampling interval they must be replaced with one value.

When more than one observation is available for each month, and the sampling date is recorded, use observations that are a month apart for the statistical analysis laid down in this protocol. Where the sampling date is not available the median value for that month must be retained. (For two observations the median and the mean are the same.)

It is rare that the same number of observations are made during a sampling interval. Each observation is assumed to be made with the same precision, to have the same variability. Where the sampling intervals do not have the same number of observations, the precision of the means for these intervals are inversely proportional to the number of observations averaged - the more observations the more precise the estimate of the mean. If sampling intervals are represented by single observations, rather than means of varying precision, every observation in the data record will have the same precision.

4.2.1 Deseasonalized data

Seasonality occurs when one part of the year tends to produce consistently higher or lower values than other parts of the year. It artificially inflates the variability of the data, making it more difficult to detect a significant trend when less than five years of data is available and significant seasonality is present, it should be removed from the data series before the appropriate statistical test of trend can be done (Phillips et al., 1989). Where five or more years of data is available the appropriate statistical test for detecting trend is not affected by significant seasonality.

Provide sequence numbers for all monthly values, by month, quarter and year as shown in the example below. If the monitoring programme started in July of 1991 the sequence numbers for the first seven months of sampling would be:

Sequence	Month	Quarter	Year
1	7	3	1
2	8	3	1
3	9	3	1
4	10	4	1
5	11	4	1
6	12	4	1
7	1	1	1

Obtain deseasonalized values by subtracting from the monthly values the monthly mean. If sampling begins in January, at the end of the first year there will be no monthly mean. When data are available for two or more years the deseasonalized values will be monthly values adjusted by monthly means of two or more values. This can be done using the WQSTAT software (Phillips *et al.*, 1989).

The data are now ready for statistical analysis.

4.2.2 Evaluation of sampling frequency

Data collected at weekly or fortnightly intervals can be used to check the independence assumption for monthly observations. A record extending over many years contains extremely valuable information for re-evaluating the sampling frequencies.

4.3 PRELIMINARY GRAPHICAL EVALUATION AND TEST FOR SEASONALITY

Before undertaking formal analysis of the data it is essential to present the data in one or more graphical forms. A time series plot of the variable will indicate the presence of trend or seasonality. More specialized graphs allow comparisons of a variable over seasons or years.

4.3.1 Confidence and significance levels

Statistical tests are used to establish whether apparent seasonality or trend is in fact present. There always remains the possibility of an incorrect decision. Therefore a confidence level and a significance level is attached to the result of every test. The confidence level reflects how confident we are about the result of the test, the significance level reflects the likelihood that the test result occurred by chance. The two levels add up to 1 (and are expressed in percent). The confidence we have in a test result is high when the likelihood of getting that result by chance is correspondingly low.

The results presented in Tables 4.2, 4.3 and 4.4 below are given for confidence levels from 75% to 95%. The corresponding significance levels, from 25% to 5%, give a measure of the uncertainty attached to the result. A test that is significant at the 75% confidence level need not be significant at the 95% level. Less confidence can be attached to that result and the likelihood of being wrong is 25%. One is more confident of a result that is significant at the 95% level. The likelihood of taking a wrong decision is now only 5%.

4.3.2 Time series plot

The monthly values of the variable are plotted against time. Suspected outliers can be visually compared with the results for the preceding and the following months. Seen in context, a decision to retain a suspected outlier as a value worth taking seriously, or to discard it, can now be taken.

Seasonality can be visually examined. If a seasonal pattern is clearly visible then analysis for trends (for less than five years of data) should be done on the deseasonalized data. Its presence can be confirmed with a statistical test.

Figure 4.1 gives the time series plot of monthly TDS data from Engelbrechtdrift (referred to as ENGEL below) produced by the WQSTAT II software (Phillips *et al.*, 1989). The monthly data record was constructed by selecting the value closest to the 16th day of every month.

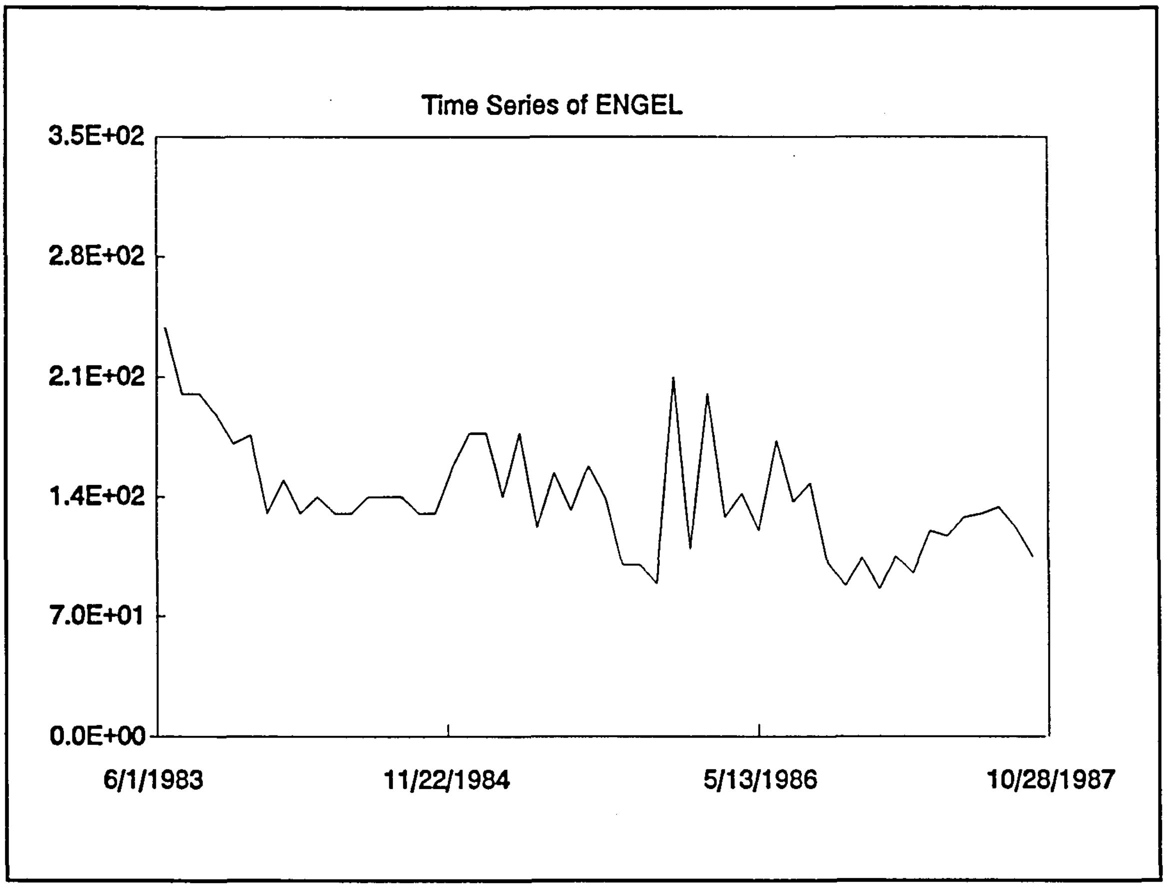

Figure 4.1 Time series plot of monthly TDS data from Engelbrechtdrift produced by the WQSTATII software.

4.3.3 Box and whisker plot

A useful data summary tool based on a five-number summary, consisting of the 90th, 75th, 50th, 25th and 10th percentiles. The 50th percentile, better known as the median, divides the data into 50% of the values below and 50% of the values above it. Similarly 95% of the values are below the 95th percentile and 5% are above it. The box is enclosed by the 75th and 25th percentiles and contains the 50th percentile. The whiskers join the box to the 90th and 10th percentiles at the upper and lower ends of the box respectively. Large and small extreme values are indicated beyond these limits. The NCSS software (Hintze, 1987) produces these plots. The WQSTAT II software package (Phillips *et al.*, 1989) does not include the 95th and 5th percentiles. The whiskers extend to the extreme values.

Figures 4.2 and 4.3 below give examples of seasonal and annual box and whisker plots of TDS data from Engelbrechtdrift using the WQSTAT II software.

Sets of data where the boxes are of similar length and the medians of similar value can be said to have similar variability and trend. In **Figure 4.2** the four seasons (quarters) are

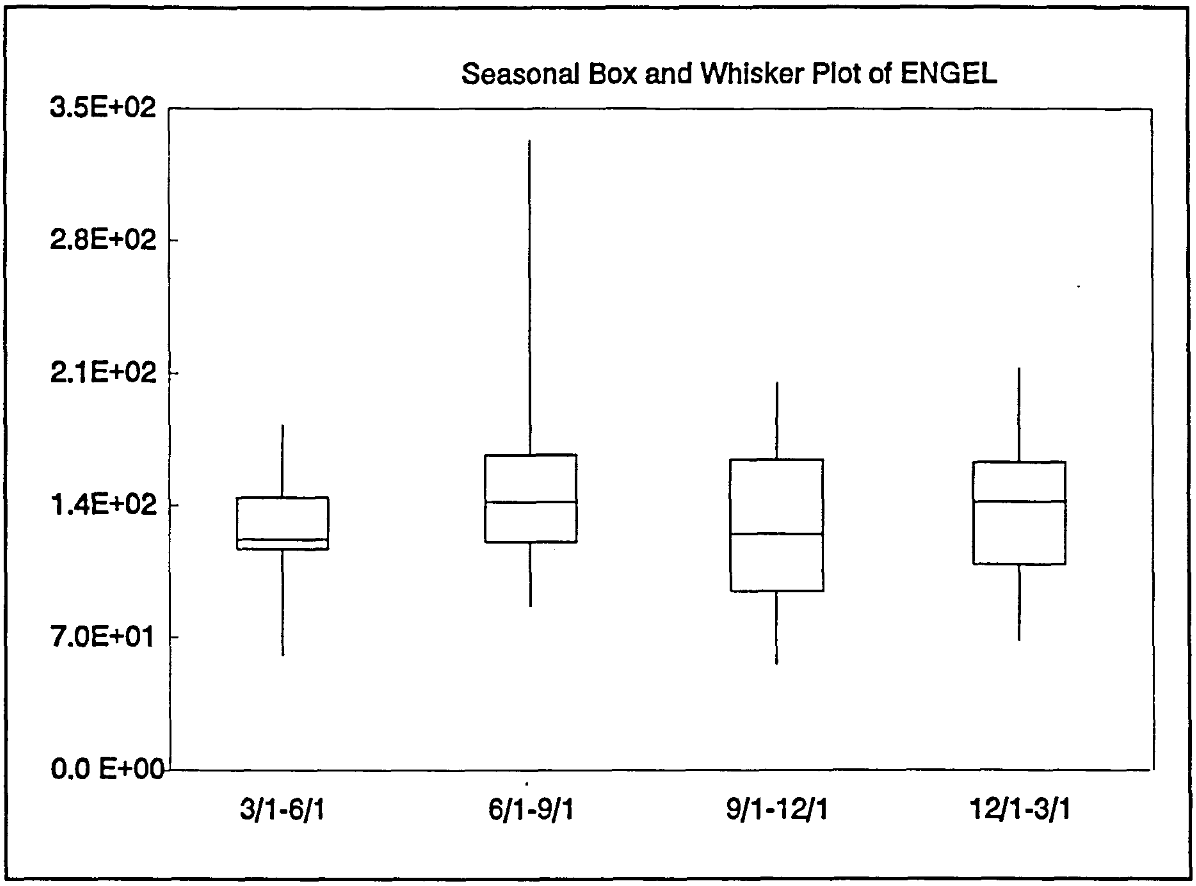

Figure 4.2 Example of a seasonal box and whisker plot of TDS data from Engelbrechtdrift using WQSTATII software.

similar in median but differ in variability. The test for seasonality (see Table 4.2 below) confirms the lack of significant seasonality. The plots for the years 1983 to 1987 in Figure 4.3 indicate a downward trend in concentration.

4.3.4 Test for seasonality

With less than five years of data it is not feasible to use monthly box and whisker plots to visually detect seasonality. Quarterly plots, based on three times as much data as monthly plots, are more realistic.

Where it is not clear from the time series plot that seasonality is present, and where the box and whisker plots for the four quarters are inconclusive, a formal statistical test is needed to resolve the issue. The hypothesis tested is that the seasonal means are not significantly different at a chosen level of confidence. The Kruskal-Wallis test (Gilbert, 1987), at the 90% confidence level, is the appropriate test to apply to the quarterly means of the data

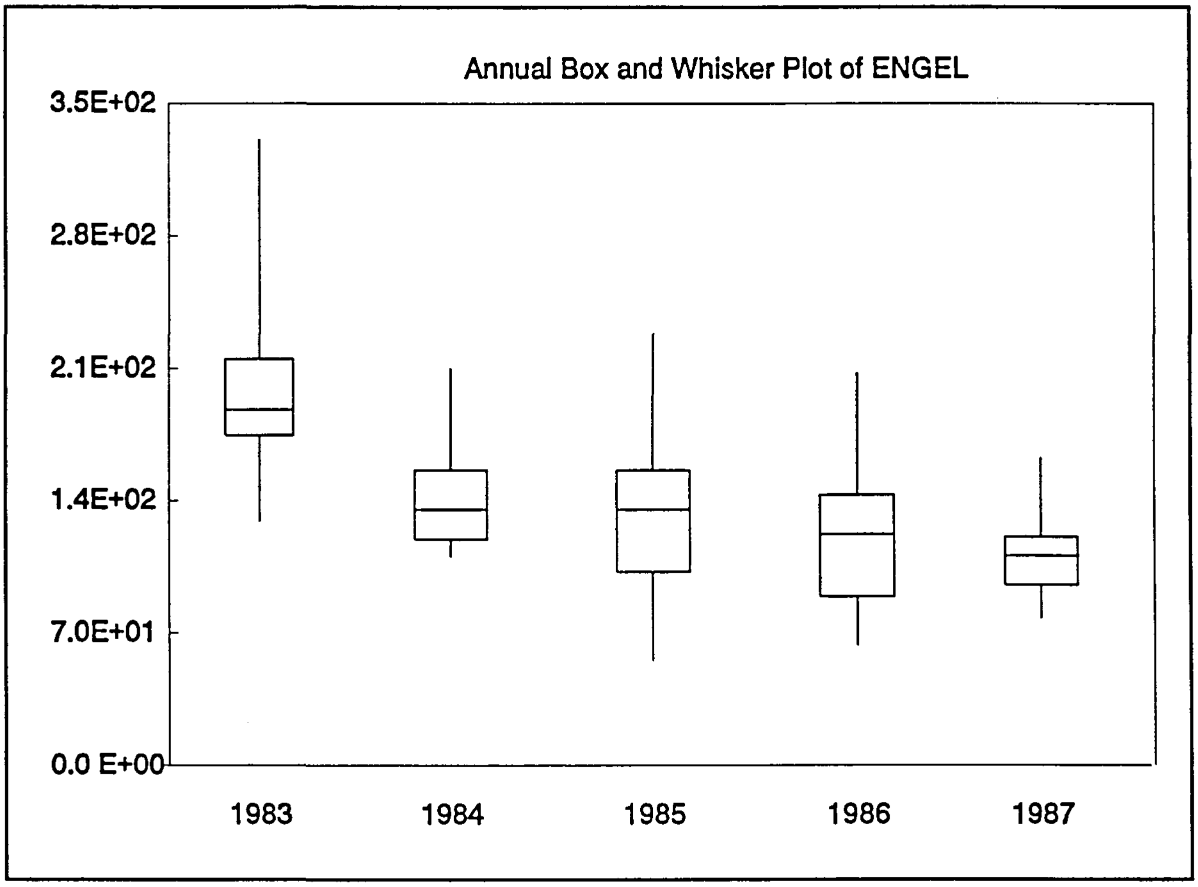

Figure 4.3 Example of an annual box and whisker plot of TDS data from Engelbrechtdrift using the WQSTATII software.

identified by the quarterly sequence numbers. The procedure is available on the WQSTAT II software package (Phillips *et al.*, 1989) and NCSS (Hintze, 1987).

Table 4.2 gives the results of comparing the four quarters of the Engelbrechtdrift data displayed in **Figure 4.3**. There is no significant seasonality at the confidence levels listed.

Table 4.2. Summary Statistics - Kruskal-Wallis test for Seasonality. Test Statistic = 4.04

Confidence level	Test	Significance
95%	4.04<7.81	Not significant
90%	4.04<6.25	Not significant
75%	4.04<4.11	Not significant

4.4 TESTING FOR TRENDS

A trend in the monthly values of a water quality variable is an increase, or decrease, in these values over time that is not due to seasonal variation nor natural variability.

In detecting significant trend statistically we are confirming significant long term changes that are apparent from a time series plot. They reflect, in terms of the variable, an improvement, or deterioration, in the quality of the water.

In their EPA reports, Loftis *et al.* (1989), through a study of simulated quarterly data sets of five years and more, recommend the seasonal Kendall test described in Hirsch *et al.* (1982) and Gilbert (1987) for detecting long term trends. This test is designed to take account of seasonality. For less than five years of data, significant seasonality must be removed from the data (Phillips *et al.*, 1989). This is necessary for the Kendall-tau test (Gilbert, 1987), proposed by Ward *et al.* (1988), to detect significant trend. In calculating the Kendall-tau test statistic the data is kept in the order of sampling, and the signs of the differences between all pairs of observations are determined. Negative differences are replaced by -1 and positive differences by +1. The statistic is their sum. The seasonal Kendall test takes account of seasonality by computing the Kendall-tau statistics for each month of the year. The sum of these statistics, over the twelve months, gives the seasonal Kendall statistic. The procedure for computing the statistic is available on WQSTAT II (Phillips *et al.*, 1989).

For the Engelbrechtdrift data, **Table 4.3** gives the results for the Kendall-tau and Seasonal Kendall tests at three confidence levels. A significant trend occurred over the period. The concentration decreased from June 1983 to October 1987 at the rate of 13.75 units per year. **Figure 4.4** shows the time series plot with the trend superimposed.

4.5 TESTING FOR CHANGES OVER SPACE OR TIME

In a catchment area the median of a water quality variable may, over the same period, differ from station to station. In some cases the difference may be substantial. These differences over space are revealed by superimposing the time series plots on the same time and concentration axis, or by "eye-balling" the station medians. Alternatively, for a given station, instead of changing gradually over a period of time the concentration remains roughly constant for a while, changes (increases or decreases) to another value, remains unchanged for a while, and changes yet again remaining at the new level till the end of the period. This is not a trend but a displacement in the median concentration from one time period to another.

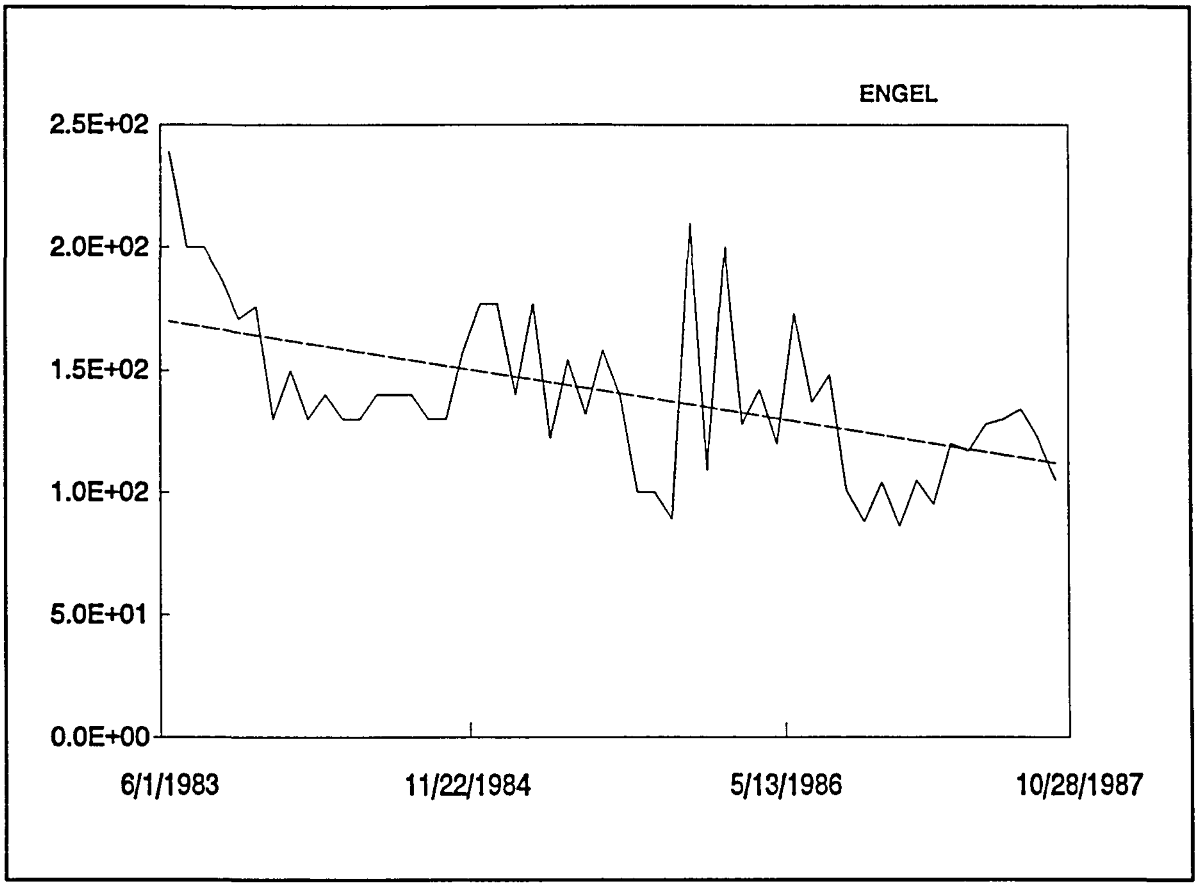

Figure 4.4 Time series plot of TDS concentration at Engelbrechtdrift with the estimated trend superimposed.

Table 4.3 Trend Test - Kendall Tau Test.
Test Statistic = - 4.478

Confidence level	Test	Significance
95%	-4.478<-1.960	Significant
90%	-4.478<-1.645	Significant
80%	-4.478<-1.282	Significant

Seasonal Kendall Test. Test Statistic = - 3.443

Confidence level	Test	Significance
95%	-3.443<-1.960	Significant
90%	-3.443<-1.645	Significant
80%	-3.443<-1.282	Significant
Sen Slope Estimate : Slope = -13.75000 units/year.		

4.5.1 Same sized data sets

For the case where data are available at the same frequency, monthly, bi-monthly or quarterly, sampling sites are compared over the same period, or periods of the same length are compared, season for season, at the same time. Where only two sets of data are compared, the observations can be paired off by season and tested for similar medians with the Wilcoxon signed rank test (Conover, 1980). The statistic is based on the ranks of the absolute differences between the paired values. The procedure for computing the statistic is available on WQSTAT II (Phillips *et al.*, 1989) and NCSS (Hintze, 1987).

The dotted lines in **Figure 4.5**, produced by WQSTAT II (Phillips *et al.*, 1989), are the medians of periods of two years each from the Engelbrechtdrift TDS data.

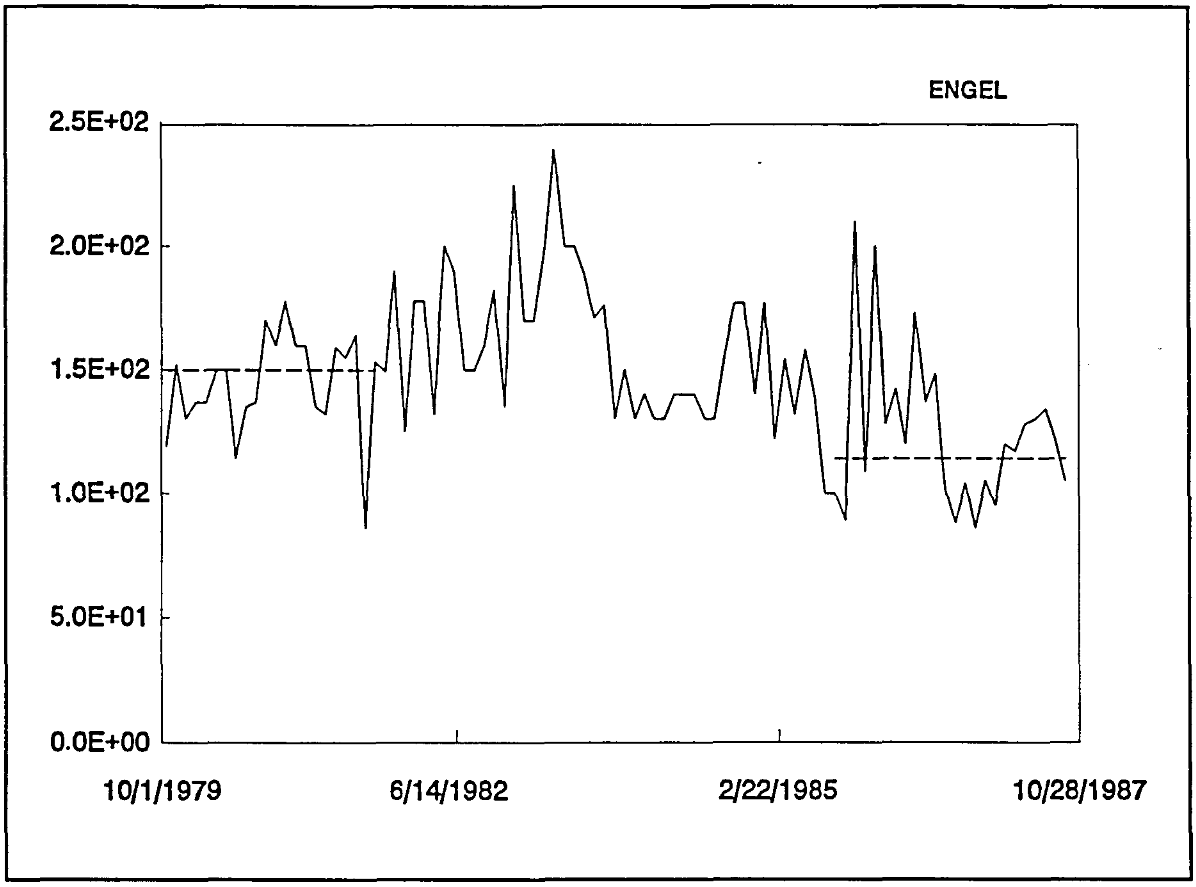

Figure 4.5 Concentration of TDS at Engelbrechtdrift with medians of two-year periods.

Table 4.4 shows the output from WQSTAT II for the Wilcoxon signed rank test on the data sets indicated above. The mean concentration for the two years October 1979 to October 1981 is significantly higher than for the period October 1985 to October 1987.

Table 4.4 Median analysis test - Wilcoxon signed Rank Test.
Test Statistic = 2.252

Confidence level	Test	Significance
95%	2.252>1.960	Significant
90%	2.252>1.645	Significant
80%	2.252>1.282	Significant
Seasonal Hodges-Lehmann Median Estimate Estimate of Difference in Medians = -34.000		

Where three or more sets of data are to be compared it is not possible to repeat the Wilcoxon signed rank test for each of the pairs of data sets, at the 95% confidence level, and expect that the chance of making at least one wrong decision, will remain at the 5% significance level. Every test has a 5% chance of wrongly deciding that the two data sets have distributions with different medians. For two comparisons the chance of at least one incorrect decision is 9.75% and for three comparisons (all comparisons of three sets of data) it is 14.26%. The confidence in the results drops accordingly. To peg the confidence and significance levels at acceptable values requires doing the test at higher confidence levels. For five sets of data each test will need to be done at the 99.5% confidence level for the chance of at least one incorrect decision to be less than 5%.

This is not a problem with Friedman's test (Gilbert, 1987). It is appropriate when three or more data sets of the same size are being compared. Rejecting the hypothesis that the data sets have the same distribution in common (the same median), means that at least one data set has a distribution with a different median. The procedure for computing the statistic is available on NCSS (Hintze, 1987).

Because the comparisons are according to the time of year, seasonal effects are removed. There is no need to deseasonalize the data if significant seasonal effects are present.

4.5.2 Data sets of unequal size

For the case where data are available at different frequencies, monthly, bi-monthly or quarterly, sampling sites are compared over the same or different periods, or periods of the same or different lengths are compared at the same site. Data are not paired off and comparisons are not done according to the time of year. Significant seasonal effects will need to be removed before comparisons can be made.

For comparing two data sets the Mann-Whitney, or the Wilcoxon Rank Sum test does not require equal numbers of observations. The test statistic is based on the sum of the ranks of the first data set after the combined data have been ranked. The test is described in Gilbert (1987) and Conover (1980) and the procedure for computing the statistic is available on WQSTAT II (Phillips *et al.*, 1989) and NCSS (Hintze, 1987).

For comparing more than two data sets the Kruskal-Wallis test, used to test for seasonality, is appropriate. If the hypothesis of a common underlying population for the sets of data is rejected WQSTAT II (Phillips *et al.*, 1989) identifies pairs of data sets that are significantly different in medians.

4.6 SUMMARY

This protocol proposes steps to be taken so that data accumulated at regular intervals can be used to establish the occurrence of trends over time, and shifts over space or time, of water quality variables. The protocol is designed to ensure that data analysis procedures are consistently implemented so that the decisions taken on the basis of these analyses can be verified, independent of changes in personnel. Water quality monitoring, to be effective, needs to be sustained over many years. For maximum benefit to be gained from the information collected, data preparation must be consistent.

4.6.1 Acknowledgments

In preparing this protocol considerable use was made of the work of Ward *et al.* (1988), Loftis *et al.* (1989) and the WQSTAT II manual of Phillips *et al.* (1989).

4.6.2 PC Software requirements

In the preparation and analysis of water quality data it is assumed in this section that access to one or more statistical software packages is possible. The statistical procedures referred to in this section can be found in statistical software packages for the PC.

Numerous references are made in this section to the WQSTAT II software (Phillips, 1989). This software is written for the analysis of water quality data. Therefore the plots and most of the statistical analyses proposed are possible with this software. The NCSS software (Hintze, 1987) for the PC written by Jerry Hintze is also suggested for the plots and some of the statistical analyses. Because it is not specifically designed to extract monthly or quarterly values of water quality data, as is WQSTAT II, the user must customize it for that purpose. The WQSTAT II software is available from CSIR.

5 DESIGN MONITORING NETWORK

5.1 SAMPLING FREQUENCY

Data records of electrical conductivity and pH measurements at 7 stations over a 13 year period were analyzed to determine the serial correlation and provide an estimate of the time required to elapse before observations could be considered independent (Gilfillan, 1989). Much of the record had to be eliminated because of missing data, so the recommendations are somewhat tentative; however, it appears that a monthly frequency will allow the detection of a change equivalent to 2.0 times the standard deviation after 2 years of data collection, with a significance level of 0.10 and a power of 0.90. Significance level refers here to the probability of accepting the hypothesis that a trend exists when it does not. Power is the probability of correctly accepting that a trend exists when it does.

The standard deviation of pH was in the vicinity of 0.3 at the stations with sample distributions that could be approximated by a normal distribution. The standard deviations of TDS ranged from 22 to 104 mg/L. The selected sampling frequency could detect a change of 0.6 pH units over 2 years and 44 to 208 mg/L changes in TDS.

The number of samples affects the precision of the estimate of the mean or median. If all the observations are independent, the width of a selected confidence interval on the estimate of the mean is a function of the standard deviation and the square root of the number of samples.

As the number of samples increases, the width of the confidence interval decreases thus yielding a more precise estimate. If the observations are not independent, the relationship is not so simple. Dependent observations do not yield as much information as independent observations, so the width of the confidence interval does not decrease as quickly.

5.2 SELECTION OF VARIABLES FOR ANALYSIS

One of the most critical and difficult parts of the design process is the selection of the variables to be measured. Because the National River Water Quality Assessment Programme is being designed to provide information on a large geographical area that will necessarily have many sampling sites, the selection of variables must be made very carefully to provide maximum information at minimum cost. The procedure used to select the variables was for a small group of people to identify a preliminary list of variables, then submit that list to a large number of water quality professionals for comment.

5.2.1 Analytical Hierarchy Process

The preliminary list of variables to be measured in the system was selected by a process called the Analytical Hierarchy Process (AHP). The AHP is a method of breaking down a complex, unstructured situation into its component parts, arranging these parts into a hierarchic order, assigning numerical values to subjective judgments on the relative importance of each component, and synthesizing the judgments to determine which components have the highest priority and should be acted upon. The Expert Choice software was used (DSS, 1986). The participants in the exercise were members of the User Team described in Section 3.1.

The product of the AHP is a list of components, in this case water quality variables, with a ranking assigned to each. The ranking is made up of two parts, one computed from the relative importance given to each variable in a pairwise comparison with every other variable, and the second computed from the relative importance of higher level components to which the variable belongs. The relative importance of the higher level components is also computed from a comparison of all pairs of components at that level. The importance of one of the pair compared to the other can range from "equal" importance to "strongly" more (or less) important.

Since water quality had been previously defined as its fitness for use, the first task was to determine the water uses and the relative importance of each. The five uses identified in the objectives of the National River Water Quality Assessment Programme were used, namely, domestic, industrial, agricultural, recreation, and conservation. More complete descriptions of those uses are given in the objectives, listed in Section 3.1.2.

5.2.1.1 Results of the Analytical Hierarchy Process

The results of the process are given in **Table 5.1**, which shows the relative ranking of each of the uses, ranging from a high of 0.446 for domestic use to a low of 0.036 for conservation. The "use" rankings were based on the User Team's assessment of the economic and societal benefits of providing water for those uses, as well as knowledge about the volume of water required for each use. **Table 5.2** is a description of each of the variables listed in Table 5.1.

Table 5.1. Analytical Hierarchy Process (AHP) rankings for five water uses and for each of the variables considered important for that use.

DOMESTIC	INDUSTRIAL	AGRICULTURAL	RECREATION	CONSERVATION
0.446	0.298	0.154	0.066	0.036
BACTERIA	TDS	TDS	BACTERIA	TOXICITY2
0.167	0.141	0.070	0.016	0.013
TOXICITY1	HARDNESS	SAR	FISH	DIVERSITY
0.145	0.049	0.048	0.016	0.010
CHLOROPHYLL	CORROSIVITY	pH	CHLOROPHYLL	D O
0.067	0.049	0.018	0.015	0.006
TDS	pH	SS	WEEDS	INVASIVES
0.038	0.025	0.011	0.008	0.004
SS	SS	CHLOROPHYLL	DEBRIS	SS
0.018	0.018	0.007	0.005	0.002
pH	Cl		SS	
0.011	0.011		0.003	
	Si		TEMPERATURE	
	0.006		0.002	

A composite list of all variables chosen for all water users with a graphical representation of their importance is shown in **Figure 5.1.** The percentages are weightings for the overall goal of selecting variables to monitor. These weightings are a combination of each variable's importance within all the water uses and the relative importance of those water uses.

Table 5.2 Description of each of the water quality variables considered in the AHP process as important for water uses.

Bacteria	A microbiological organism that will indicate the overall quality of water in terms of disease transmission
Chlorophyll	Concentration of chlorophyll-a
Cl	Concentration of chloride
Corrosivity	Capability of the water to corrode metal
D O	Dissolved oxygen, concentration and percent saturation
Debris	The presence of floating debris and litter
Diversity	Range of aquatic life
Fish	Quantity and diversity of the fish population
Hardness	Total hardness
Invasives	Presence of exotic aquatic life
pH	Activity of the H^+ ion
SAR	Sodium adsorption ratio
Si	Concentration of silica
SS	Suspended solids
TDS	Total dissolved solids
Temperature	Temperature of the water
Toxicity1	Toxicity of the water to humans
Toxicity2	Toxicity of the water to aquatic life
Weeds	The presence of nuisance aquatic plants

5.2.1.2 Sensitivity Analysis

A sensitivity analysis of the solution investigated the effects of different relationships of importance among the use categories. The greatest uncertainty was judged to be in the ranking of agricultural use. Irrigation is the single largest water user in terms of volume and there is some justification for increasing its relative importance.

When the importance of agricultural water use was increased to make it equal to industrial water use, and the relative importance of domestic water slightly reduced, there was no difference in the order of the first four variables. Sodium Adsorption Ratio moved to fifth place with a total rank of 7.0 compared to 5.8 for pH and 5.3 for suspended solids.

The results of the sensitivity analysis indicated that the order of the most important variables was not affected by increasing the importance of agricultural water use. The process assumes that the water quality variables are the appropriate ones and that all the important ones are included. The order would obviously be different if other variables were added.

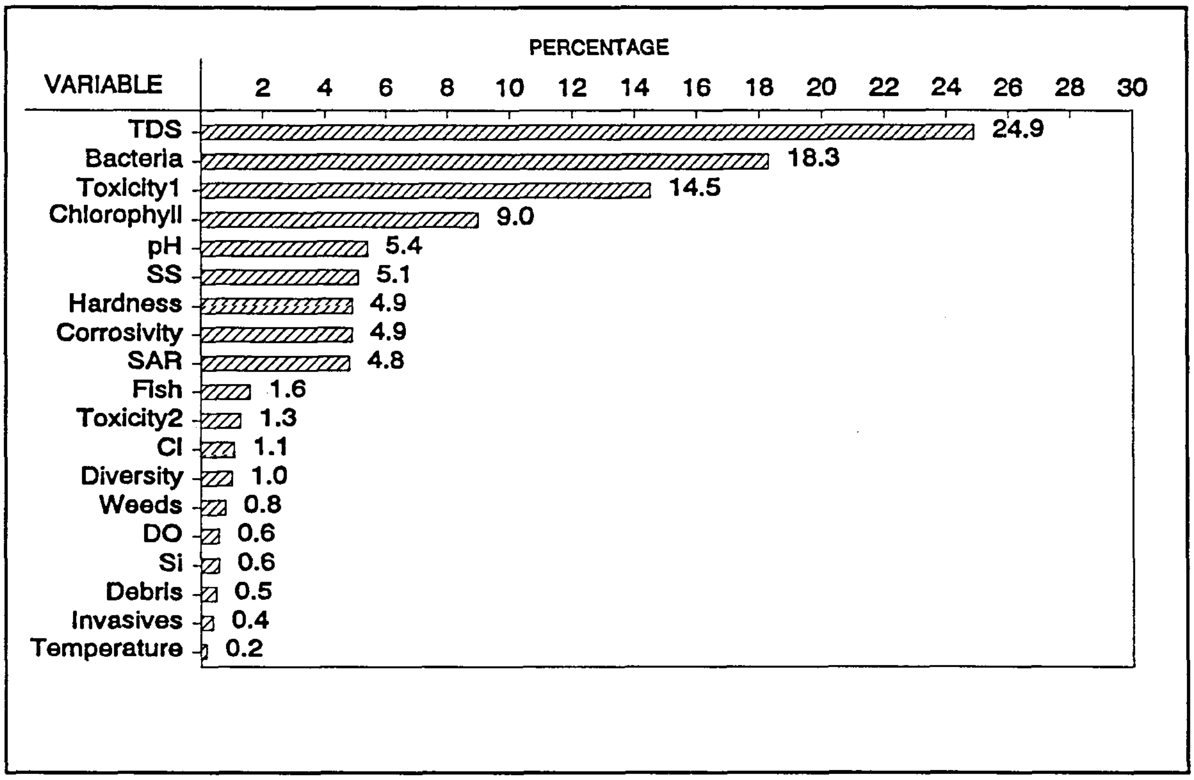

Figure 5.1 Graphical representation of the final ranking for all variables chosen in the AHP for all water uses.

5.2.2 Selection of the preliminary list

The preliminary list of variables to measure was selected from among the highest ranked variables. The selection was made on the basis of the factors listed below.

(1) Relative importance of the variables in this process -- the original cut-off point for consideration was the first 9 variables, each having an importance ranking near 5% or higher.

(2) Difficulties in measuring -- electrical conductivity was substituted for TDS because it can be measured *in situ*; turbidity was substituted for suspended solids because the test is much simpler; toxicity was not included as a result of this consideration, although it will be given high priority as part of a surveillance monitoring system, because of its high ranking.

(3) The method of determination -- SAR, hardness and corrosivity were eliminated because they are calculated as functions of other measured values.

(4) Whether the user category was represented by other variables or not -- dissolved oxygen (DO) was added because no other conservation variables were included. It was chosen over the other variables that were ranked as more important for conservation because DO measurement is more practical than diversity measurement.

The preliminary list of variables which the User Team agreed would be appropriate as part of the National River Water Quality Assessment Programme was electrical conductivity, turbidity, a microbiological variable, chlorophyll *a*, pH, and dissolved oxygen.

5.2.3 Requests for comments on the preliminary list

Water quality professionals were requested to comment on the appropriateness of including these variables in a monitoring system with objectives as determined for the National River Water Quality Assessment Programme. Specific comments were requested on the subject of the selection of the test organism for microbiological quality. The decisions regarding which professionals would be asked to contribute were made on the basis of subjective judgements of those people who were involved in the design process. The disciplines represented by the people chosen included academic, consulting engineering, industry, research, and government departments, principally Department of Water Affairs and Forestry but also the Department of Agriculture and the Department of National Health and Population Development.

The questionnaire is included as **Appendix A**. Of 115 questionnaires distributed, 70 were returned. In general, the inclusion of the variables was supported in most of the responses, but additional variables were suggested and many problems in measurement were pointed out.

For each variable, respondents were asked to indicate whether they felt it "definitely should be included," "probably should be included," or "should not be included" in the system. "No opinion" was a fourth option. The percentage of responses for each variable in each category is given in **Table 5.3**.

Table 5.3 Percentage of responses from 70 water quality professionals for each variable on the preliminary list submitted for comment.

	Should not be included	Probably should be included	Definitely should be included	No opinion
Electrical conductivity	1.4	0.0	98.6	0.0
Chlorophyll *a*	5.7	40.0	42.9	11.4
pH	2.9	25.7	71.4	0.0
Turbidity	4.3	18.6	74.3	2.8
Dissolved oxygen	8.6	20.0	65.7	5.7
Microbiological organism	5.7	14.3	67.1	12.9

5.2.4 Changes to the preliminary list

The responses to the questionnaire were analyzed to evaluate the chosen variables in light of the additional comments. Additional changes resulted from the decision that chemical analysis would be conducted at HRI whenever possible rather than in the field because of the large cost of supplying each sampler with the necessary equipment. That decision changed the relative costs of other options.

In order to increase the amount of information in the system, it was decided to measure individual ions and calculate total dissolved salts, rather than rely on a conversion from electrical conductivity. This decision was made possible by the fact that the analysis would be conducted at the HRI labs.

E. coli was selected as the microbiological test organism. This decision was one of the most controversial issues faced by the User Team. Relative merits of many test organisms were discussed, but the final decision was based on the information contained in *E. coli* counts with respect to contamination by human sewage. Many of the points raised on each side of the issue are discussed in the next section dealing with specific variables.

5.2.5 Final list of variables

The variables which were selected for inclusion in the National River Water Quality Assessment Programme are:

Total dissolved salts (TDS)
Turbidity,
E. coli
Chlorophyll *a*
pH,
Dissolved oxygen (DO).

The variables are indicators that represent the most important classes of water quality and associated problems, namely, salination (measured by total dissolved salts), eutrophication (measured by chlorophyll *a*), acidification from mines and atmospheric deposition and potential toxicity (measured by pH), health hazards of water contaminated by human sewage (measured by *E. coli*), the impact of erosion (measured by turbidity), and maintenance of a healthy aquatic ecosystem (measured by dissolved oxygen).

Each variable has advantages and disadvantages in its role as an indicator of very general classes of problems. Some of the major items discussed among the User Team members and in comments returned with the questionnaire related to the choice of each variable are given below.

5.2.6 Total Dissolved Salts (TDS)

In a water-sparse region, the reuse of available supplies of water is essential, but one of the consequences of reuse is the repeated input of dissolved constituents. In general, total dissolved salts refers to the inorganic ions that are dissolved in water. The principal anions include carbonates, bicarbonates, chlorides, nitrates, sulphates, and silica. The principal cations are calcium, magnesium, sodium, and potassium (CCREM, 1987). Many of the uses of water increase the amount of dissolved material in the water. Irrigation return flows leach soluble minerals from the soil, cooling water for industrial processes concentrates the dissolved material through evaporation, and wastewater treatment adds chemicals for such things as disinfection, neutralizing acidity, and precipitating heavy metals.

Total dissolved salts is an important water quality variable for many of the uses of water and the individual components are also important, particularly for irrigation. Some crops are sensitive to excess chlorides and the ratio of sodium to calcium and magnesium is important in maintaining soil permeability. The Sodium Adsorption Ratio (SAR) has been developed to provide an easy index to the quality of water for irrigation; it is based on the concentrations of sodium, calcium and magnesium. The SAR value is combined with electrical conductivity to identify effects on soil permeability that may occur after irrigation with the water. Excess TDS can create unpleasant tastes in drinking water, specific salts can cause scaling or fouling when used as cooling water and the TDS content of boiler water is the major chemical variable affecting steam purity (CCREM, 1987).

There are three commonly accepted methods to estimate total dissolved solids in water (Clesceri *et al.*, 1989). The fastest is to measure electrical conductivity *in situ* and convert to TDS in milligrams/litre (mg/L) with a proportionality constant. In the absence of additional information, TDS is taken as 6.5 times the numeric value of electrical conductivity in units of milliSiemens per metre (mS/m). A second method is to filter the sample to remove the larger suspended solids, then heat it to evaporate the liquid portion. The mass of material that remains after evaporation is used to calculate the concentration of dissolved solids. A third method is to measure the concentration of each of the major ions and calculate the concentration of TDS as their sum. The choice of method for the current system was to measure individual ions and store the results on the data base so that TDS can be calculated as required.

5.2.6.1 Advantages of using TDS measurements

The inclusion of TDS in the NRWQAP was one of the least controversial decisions made during the design process. There is a long history of TDS measurement and a great deal of expertise in interpreting the data. The choice of the method of measuring individual ions and calculating TDS from the result has the advantage of providing information to identify changes in the relationship of components. This can be important in describing the fitness of water for specific uses. Measuring the residue after evaporation is a more labour-intensive method and it does not provide any information about the individual ions. Another advantage, and the major factor in the decision to select this method, was that measurements can be made at the laboratory at HRI rather than having to equip each sampler with the instruments necessary to measure electrical conductivity.

5.2.6.2 Disadvantages of measuring individual ions

The major disadvantage of measuring individual ions is the increased load on the analytical laboratory.

5.2.6.3 Alternatives to using TDS measurements

Electrical conductivity, as described above, is often used as a fast, convenient method to estimate TDS. It is a measure of the ability of water to conduct an electric current. The presence of charged ionic species in solution makes the solution conductive. As ionic concentrations increase, conductivity of the solution increases. The relationship between ionic concentration and specific conductivity is fairly simple and direct in dilute solutions of single salts, however, natural waters are not simple solutions. The relationship between electrical conductivity, ionic concentrations, and TDS is not a simple one, but electrical conductivity can be useful as a general indication of TDS concentration (USGS, 1970).

5.2.7 *Escherichia coli*

The presence of pathogenic, or disease-producing, microbes in water significantly reduces the fitness for drinking water, contact recreation, irrigation of the crops that are usually eaten raw, and the propagation of shellfish. Most water-borne diseases (for example, gastroenteritis, amoebic dysentery, cholera and typhoid fever) are associated with water contaminated with human faeces.

The presence of pathogenic microbes is commonly estimated by the presence of indicator organisms that do not cause disease. Ideal indicator organisms meet the following criteria: they occur when the pathogens are present, do not occur when the pathogens are not present, they should be present in numbers much greater than the pathogen, they should respond to natural conditions and treatment processes in a manner similar to the pathogens, and they should be easily isolated, identified and enumerated in the laboratory (Pipes, 1982).

Total coliforms, faecal coliforms, and *Escherichia coli* are members of the coliform group that are often used as indicator organisms (Olivieri, 1982). The coliform group is defined in *Standard Methods* as "all aerobic and facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas and acid formation within 48 h at 35°C . . . or as applied to the membrane filter method, produce a dark red colony with a metallic sheen within 24 h on an Endo-type medium containing lactose (Clesceri *et al*, 1989). Organisms cultured under these conditions are reported as total coliforms. This test is sufficient for final drinking water quality because the presence of any coliforms after treatment is unacceptable.

An additional test is used to identify faecal coliform bacteria. The gut and faeces of warm-blooded animals generally host organisms capable of producing gas from lactose in a suitable culture medium at 44.5 $\pm 0.2°C$. Since coliform organisms from other sources often cannot produce gas under these conditions, this criterion is used to define faecal coliforms (Clesceri *et al*, 1989). This test does not distinguish between human and animal faecal contamination. *Klebsiella* satisfies this test and is capable of reproduction and growth in the presence of nutrient-rich effluent (Pipes, 1982).

Differentiation of faecal coliform colonies is necessary to identify coliform types that are of human faecal origin. A series of tests is administered to the colonies produced in the faecal coliform test and the results used to classify the colony's species. The identification of a particular species is not conclusive proof that the source was human faeces, although it can be strong evidence. All types of coliform organisms may occur in faeces. Although *E. coli* nearly always will be found in fresh pollution from warm-blooded animals, other coliform organisms may be found in fresh pollution in the absence of *E. coli* (Clesceri *et al*, 1989).

Differentiation of groups is considerably more complex than identification of faecal coliforms, but recent evidence (Dufour, 1984) has indicated that there is no correlation between faecal coliform and the occurrence of gastroenteritis in people who swam in water polluted with sewage. Dufour (1984) also reports that "*Escherichia coli* densities on the other hand show an excellent relationship to swimming-associated GI [gastro-intestinal] illness. Since *E. coli* is by definition a faecal coliform, this strong association to GI illness can only be attributed to the use of a highly selective differential enumeration method which effectively eliminates potential interfering organisms."

The decision of the User Team was that the additional effort and expense of differentiating *E. coli* would be worthwhile. There were some members who remained unconvinced at the end of the discussion; therefore, the designers recommend the numbers of both faecal coliform and *E. coli* be recorded for each sample for at least one year. At the end of that time, the data should be analyzed to determine if there is a strong correlation between the two variables. If so, then the differentiation of *E. coli* should be discontinued and faecal coliform included as the microbiological variable. If no strong correlation exists, then the additional tests to differentiate *E. coli* should be continued and faecal coliform should not be recorded.

5.2.7.1 Advantages of using E. coli measurements

E. coli densities will provide more confidence that the river is polluted with human sewage. The uncertainty associated with reporting only faecal coliform will be decreased.

5.2.7.2 Disadvantages of using E coli measurements

The differentiation of *E. coli* is very time consuming compared to tests for faecal coliform. In South Africa, General Effluent Standards currently require reports of "typical (faecal) coliform," (DWA, 1986) and guidelines for drinking water suggest limits for, among others, total and faecal coliform, but not *E. coli*, although there is a suggestion that additional tests to identify *E. coli* be conducted when total coliforms are isolated from drinking water (Smith & van Rossum, 1985). The infrastructure for differentiation of *E. coli* on a large scale is, therefore, not in place.

5.2.7.3 Alternatives to E. coli measurements

As discussed above, the use of faecal coliform densities as an indicator of pollution from human faeces is common. Its inclusion in this programme would, therefore, provide a basis for comparison with earlier data. The use of faecal coliform counts in the NRWQAP will be evaluated.

The ratio of faecal coliform to faecal streptococci has been used as an indicator of pollution from human faeces. Because the proportion of the coliform bacteria is different in humans and in other animals, the ratio can be used to distinguish the source of faecal pollution (Olivieri, 1982). The ratios of faecal coliform to faecal streptococci (FC/FS) are generally greater than 4.0 or human faeces and are less than 0.7 for most animals (Olivieri, 1982). There is evidence that those ratios for faeces of birds may be nearly the same as for faeces of humans under some conditions and the value of the ratio is only useful during the initial 24 hours of downstream travel from the point of discharge (Geldreich & Kenner, 1969). Use of the ratio obviously implies that both faecal coliform and faecal streptococci tests are conducted on each sample. Any cost savings that might result from substituting this ratio for the measurement of *E. coli* would be minimal.

5.2.8 Chlorophyll *a*

Chlorophyll *a* was included as a measure of the amount of planktonic algae present in a water body. The effects of excessive algal numbers are problems with water colour, taste, and odour, resulting in increased costs of water treatment; the water is less attractive for boating, swimming, and fishing; the more desirable types of fish may be eliminated; irrigation canals may become clogged (Gilpin, 1976); toxins produced by some of the algae may be fatal to livestock (CCREM, 1987). Giraffe and rhinoceros deaths have been attributed to the animals' drinking water with large amounts of *Microcystis* algae (Holden, 1970).

Maintaining a proper balance among life forms in lakes and in streams is a critical aspect of pollution control. Water bodies can be characterized in terms of their productivity, that is, the amount of organic material synthesized per unit of surface area in a given time. Those with a high productivity are termed "eutrophic" or nutrient-rich (USGS, 1970). The most important nutrients include phosphate and oxidized forms of nitrogen. The accumulation of nutrients is a natural process in lakes, rivers, and estuaries.

The presence of nutrients is essential to the growth of aquatic vegetation, including aquatic weeds and algae. The rate at which a particular nutrient is supplied may be the rate-controlling step of the productivity process (USGS, 1970), however, other factors such as turbidity, nutrient availability, and predators influence the formation of algal "blooms". Algal blooms are rapid increases in algal populations that may be blue-green, red, or brown in colour. The very rapid rates of production attained when a bloom appears represent a system temporarily out of control. The plants flourish, then die. The decay of these massive numbers of organisms has a substantial effect on the quality of water, particularly through the consumption of dissolved oxygen and release of nutrients. Dams are more susceptible to algal blooms than are rivers.

Biomass is a quantitative estimate of the total mass of living organisms within a given area or volume. It gives no information on community structure or function. Indirect methods for estimation of biomass include total organic carbon, bound organic nitrogen, and chlorophyll. Chlorophyll *a* is often used as an algal biomass indicator. Assuming that chlorophyll *a* constitutes, on average, 1.5% of the dry weight of organic matter of algae, the algal biomass is estimated as 67 times the chlorophyll *a* content (Clesceri *et al.*, 1989).

5.2.8.1 Advantages of chlorophyll a

The advantage of using chlorophyll *a* in the National River Water Quality Assessment Programme is that it gives an estimate of the biomass present. Large values of chlorophyll *a* always indicate that the fitness for use of the water has been diminished. The presence of excess vegetation cannot be directly inferred from chemical measurements. Excess nutrients are not a problem on their own; eutrophication is a problem only because it produces excess plant growth that creates problems.

5.2.8.2 Disadvantages of chlorophyll a

Chlorophyll *a* is an estimate of the total biomass and gives no indication of the species or community composition. A preponderance of, for example, *Microcystis aeruginosa*, a blue-green algae that can be toxic to animals, would have far different implications for water quality than some more benign algal species. An estimate of a constant relationship between chlorophyll *a* and biomass is not always accurate. Some diatoms have low chlorophyll *a* content, so a value of 10 μg/L chlorophyll *a* composed of these diatoms will represent a far larger amount of total biomass than a corresponding value composed of algae with a high chlorophyll *a* content.

The most severe problems with measuring chlorophyll *a* are logistic and economic rather than informational. Sample collection requires equipment for filtration and some considerable technical expertise and attention to detail in order to produce adequate samples. There is also a time constraint in analysing the samples.

5.2.8.3 Alternatives to using chlorophyll a measurements

Measurement of the concentration of nutrients can be used as an indirect indication that conditions are present that might allow the growth of excess algal biomass; however, knowledge of the concentrations of bound organic nitrogen and phosphate are not sufficient to predict the existence of nuisance algal blooms. Kjeldahl nitrogen and phosphate concentrations are routinely measured in samples submitted to HRI for water quality analysis.

Analysis of relationships between the nutrients, turbidity, and the presence of algae, after accumulation of additional data, would improve the information content of nutrient measurements. That option assumes, however, that information on algal numbers is available. An advantage of measuring nutrients directly is that water quality management strategies will involve the control of nutrients.

5.2.9 pH

The pH of a solution is the negative base-10 log of the effective concentration of the hydrogen ion (H^+) in moles/litre. Most river water in areas not influenced by pollution generally has a pH between about 6.5 and 8.5. Where photosynthesis by aquatic organisms takes up dissolved carbon dioxide during the daylight hours, a diurnal pH fluctuation may occur with maximum pH reaching as high as 9.0 (USGS, 1970).

Practically every phase of water supply and wastewater treatment, for example, precipitation, coagulation, disinfection, and corrosion control is pH dependent (Clesceri *et al*, 1989). Many equilibria in water are pH-dependent and pH affects the mobilisation, speciation and toxicity of metals and other compounds (Wolff *et al*, 1988). The pH also has a major effect on the type of fish and other aquatic species present. Trout and bass seem to prefer alkaline streams, although the effect of pH is probably increased by the additional advantage of the presence of more food (Sell, 1981). The degree of dissociation of weak acids or bases is affected by changes in pH. This effect is important because the toxicity of many compounds is affected by the degree of dissociation. Ammonia toxicity to fish increases as pH increases and cyanide toxicity increases as pH decreases (USEPA, 1986).

The pH of a water does not indicate its ability to neutralize additions of acids or bases without appreciable change. This characteristic, called "buffer capacity" is controlled by the amounts of alkalinity and acidity present, usually expressed as milligrams $CaCO_3$ per litre. Buffer capacity is the amount of strong acid or base needed to change the pH value of a 1 litre sample by 1 unit (Clesceri *et al*, 1989).

5.2.9.1 Advantages of using pH measurements

The instantaneous value of pH in a river does not, on its own, give very much information about the water's fitness for use unless the value is an extreme one. Changes in pH over time, however, are indicative of quite large changes in the water quality. Combining information about pH with other information, such as metal concentrations, can indicate potential problems.

5.2.9.2 Disadvantages of using pH measurements

The measurement of pH is straightforward and can be conducted at the facilities of the HRI. There are additional sampling restrictions that result from poorly buffered water in the western Cape region; the pH is subject to change after sample collection so that the measurement must be made *in situ.*

5.2.9.3 Alternatives to pH measurements

The only related variables that could be measured are alkalinity and acidity. As described above, they give a rough measure of the buffer capacity of the water and can provide useful information on the fitness for use of the water.

5.2.10 Turbidity

Turbidity in water is caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter, plankton and other microscopic organisms that are held in suspension (CCREM, 1987). Turbidity is an expression of the optical property of water that causes incident light to be scattered and absorbed rather than transmitted in straight lines through the sample (Clesceri *et al*, 1989). The concept of turbidity is related to, but different from, suspended and settleable solids because the solids affect the appearance of turbidity or water clarity in the river. The term suspended solids refers to the material which remains in suspension, but is too large to pass through a 1.5 μm filter (Clesceri *et al*, 1989). In contrast, the particles that cause turbidity in water range in size from colloidal dimensions (approximately 10 nm) to diameters in the order of 0.1 mm (CCREM, 1987). Settleable solids are the material that settles out of suspension within a specified time. There is no size restriction in the definition, but the particles that settle out tend to be large compared to those that do not settle.

There is a relationship between turbidity and suspended solids, but correlation of turbidity with the weight concentration of suspended matter is difficult. Light scattering is a function of the surface area, the particle shape, and the refractive index of suspended material. The same concentration of coarse material will give a lower turbidity than fine material. Plate-shaped particles produce more light scattering than spherical-shaped ones (Gippel, 1989). The relationship between turbidity and suspended solids appears to be site-specific, depending on characteristics of the catchment. The relationship can change with significant land use changes in the catchment, for example afforestation, or on a short-term scale within a rainfall event (Gippel, 1989).

Water clarity refers to the inverse of turbidity. It is gives an indication of the limit of visibility in water.

Turbidity is important in all five of the recognized water uses. In treatment for drinking water, turbidity is of great importance first because of the aesthetic consideration, and second because pathogenic organisms can hide on the tiny particles. Other health-related considerations include disinfection efficiency, biological nutrient availability, trihalomethane formation and concentrations of heavy metals and biocides (CCREM, 1987). A possible benefit is the sorption of organic material such as pesticides to the suspended inorganic material. When the suspended material settles or is flocculated, the organic material is removed from the water column (USEPA, 1986).

The effects of suspended solids on irrigation water is the formation of crusts on top of the soil, the formation of films on plant leaves which can reduce the marketability of some leafy crops like lettuce, and the reduction in capacity of irrigation reservoirs and canals (USEPA, 1986). Studies of the suspended sediment load in rivers can provide valuable information about erosion within the catchment (Gippel, 1989).

Water clarity is important in numerous industries producing materials destined for human consumption, such as the food and beverage industry and various manufacturing industries. In the paper industry, turbidity can affect the brightness or colour of white or tinted papers. At swimming beaches, high turbidity reduces the aesthetic appeal of the area and swimmers should be able to see under water. For conservation uses, research has suggested that suspended solids may have significant effects on succession because of shading, abrasive action, habitat alteration and sedimentation, as well as on community dynamics when they interfere with light transmission. An increase in turbidity in shallow, clearwater systems may potentially reduce stream primary productivity and be associated with an increase in suspended sediment concentration (CCREM, 1987). A reduction in primary productivity is not detrimental in eutrophic systems that might otherwise be prone to algal blooms.

5.2.10.1 Advantages of using turbidity measurements

Turbidity is commonly measured with a turbidimeter in a relatively straightforward procedure. It can be conducted at HRI, although *Standard Methods* (Clesceri *et al*, 1989) recommends measurement within 24 hours of sample collection as ideal.

Because of the influence of light on primary productivity, combining turbidity and chlorophyll *a* data can provide useful information relative to the likelihood of algal blooms.

5.2.10.2 Disadvantages of using turbidity measurements

For some water uses, information about suspended solids is often more important than turbidity. While the measurements are related, it is not possible to derive a conversion function that will be generally useful, although site-specific functions may be developed at locations where additional information on suspended solids is necessary. The development of those functions implies that suspended solids measurements will be available.

5.2.10.3 Alternatives to turbidity measurements

As discussed above, suspended solids is a concept closely related to turbidity. Some water uses, notably treatment of drinking water, are affected more by suspended solids than by turbidity. The suspended solids measurement involves filtration, oven drying, desiccation, and weighing, while turbidity measurements are read from an instrument. The correlation between turbidity and the weight concentration of suspended and settleable solids is often tenuous (CCREM, 1987).

Settleable solids measurement is a simple, but time-consuming, procedure. The particles that settle out are larger than those in the suspended solids term so settleable solids are a better estimate of the tendency for sediment accumulation. This measurement may be a better estimate of the impact of erosion than is turbidity.

The clarity of water is often measured using a Secchi disc. The point (depth of water) of the disc's disappearance and reappearance when suspended in water gives an indication of the limit of visibility in water. As it is a simple method, the Secchi disc measurement is often made at bathing beaches by relatively untrained people to estimate visibility. It obviously must be done *in situ*.

5.2.11 Dissolved oxygen

Oxygen is a fundamental constituent of natural waters. It is only moderately soluble in water. The amount of dissolved oxygen (DO) in natural water varies with temperature, salinity, water turbulence, and atmospheric pressure (CCREM, 1987).

Without DO, streams and lakes become uninhabitable to most aquatic life. Fish and other desirable clean-water biota require relatively high DO levels at all times. An adequate supply of dissolved oxygen is essential for the maintenance of self-purification processes in natural water systems and water treatment plants (Vesilind & Peirce, 1983).

Because the concentration of DO in water changes very easily, it presents special problems in measurement. The simplest procedure is to use a portable probe and measure the concentration *in situ*. This method provides the fastest results. A titration method (Clesceri *et al*, 1989) is often used to measure DO. It requires fixing the oxygen when the sample is collected, then measuring the concentration in the laboratory.

5.2.11.1 Advantages of using DO measurements

Dissolved oxygen is "probably the most important measure of water quality" (Vesilind & Peirce, 1983), at least for aquatic life. Aquatic life is so dependent on DO that low concentrations can indicate the unsuitability of the aquatic habitat in the absence of any other information.

Because DO often varies with depth of water, readings can be taken at several points in a cross-section to provide an estimate of the average concentration. The probe also eliminates the need to submit samples to regional laboratories for titration, since the titration must be completed within 24 hours of sample collection.

5.2.11.2 Disadvantages of using DO measurements

Wide diurnal fluctuations of dissolved oxygen can be created in response to biological activity. The oxygen content of a surface water body or stream is a highly transient property; a measurement is meaningful only for the spot of sampling and a brief time period.

5.2.11.3 Alternatives to using DO measurements

The biochemical oxygen demand (BOD) is a measure of some of the processes that consume oxygen in the water. It can indicate a tendency for decreased DO concentrations, but it does not, in itself, indicate that water is unfit for use. It does indicate that the water has been contaminated with organic material. It has the advantage of being a laboratory measurement and, therefore, eliminating the necessity to supply each sampler with a field instrument. It has several disadvantages, some of which are that it requires a minimum of five days, it has a large number of sources of error, and it has not been applied on a large scale in South Africa.

5.2.12 Combined information from variables

In a separate project, Moore (1990) has investigated the construction of an index to combine information from these six variables into a single number. Individual rating curves were developed for each variable that show the "fitness for use" rating (on a scale from 1-100) as a function of the measurement. Weights were assigned to each variable according to its importance in defining fitness for use.

By combining the two measures, rating curves and weighting factors, the index value will indicate the general fitness for use of the specific combination of the six measurements at each site.

5.3 CHOICE OF SAMPLING SITES

The choice of sampling sites is governed by the objectives of the system. The two objectives that determine the distribution of sampling sites are:

(a) To assess river water quality of Southern Africa;
(b) To describe how river water quality changes over space.

The goal in reaching the objectives is to obtain as much information as possible at the least possible cost. However, when optimising the number and distribution of sampling sites, the information needs of the users should be given high priority. The system should provide water quality managers with the proper information to make correct decisions.

5.3.1 Geographical distribution

In order to be able to describe the geographical distribution of water quality, sampling sites must be selected to describe the typical quality of water draining an area. The Department of Water Affairs and Forestry tertiary drainage regions were used as a basis for initial site selection to help meet the goal of locating a typical stream. A sampling site was chosen near the outflow of each tertiary drainage region; there are approximately 150 tertiary drainage regions. This compares with approximately 800 sites included in the current routine monitoring programme.

Some complications occurred with the use of only one criterion. All tertiary drainage regions do not have a single stream that drains them, especially those on the lower reaches of the major rivers and streams. In many cases a major river crosses through a tertiary drainage region, with a number of smaller tributaries draining the region itself. In those cases, a sampling site was located on the largest of the tributaries, if it drains at least 60 to 70% of the region. If no such large tributary exists, a sampling site on the main river or stream was designated to determine the water quality for that region. As most of the tertiary drainage regions where this situation occurs make only a relatively small contribution to the total runoff of the region, this was regarded as a valid approach.

5.3.2 Spatial changes

In order to describe how water quality changes over distance, each major river will be monitored over its entire length. A major river was defined as one that drains at least a secondary drainage region. Again, the tertiary drainage regions were used to determine the maximum distance between sampling sites. Each river will be monitored as close as possible to the point where it leaves a tertiary drainage region.

In addition, sampling sites will be located just upstream of a confluence with a major tributary and the tributary will be monitored upstream of the confluence. A major tributary is defined as a stream that drains at least a tertiary drainage region.

5.3.3 General

In cases where a dam is located on or close to the boundary of a drainage region, the inflow to the reservoir will be monitored. The water quality in a dam can be the result of a number of years of inflow, which will tend to mask short term changes. A separate monitoring system will describe water quality in dams and reservoirs.

Existing sampling sites and flow gauging stations were used as far as possible. Unfortunately, a significant number of these sites are not situated at the optimum water quality sampling sites in terms of the objectives of the system. During the implementation design phase, each existing site will be evaluated on its own merits, taking into account the loss in information against the saving in cost should the existing site be eliminated.

The locations of the proposed sampling sites are shown in **Figure 5.2.**

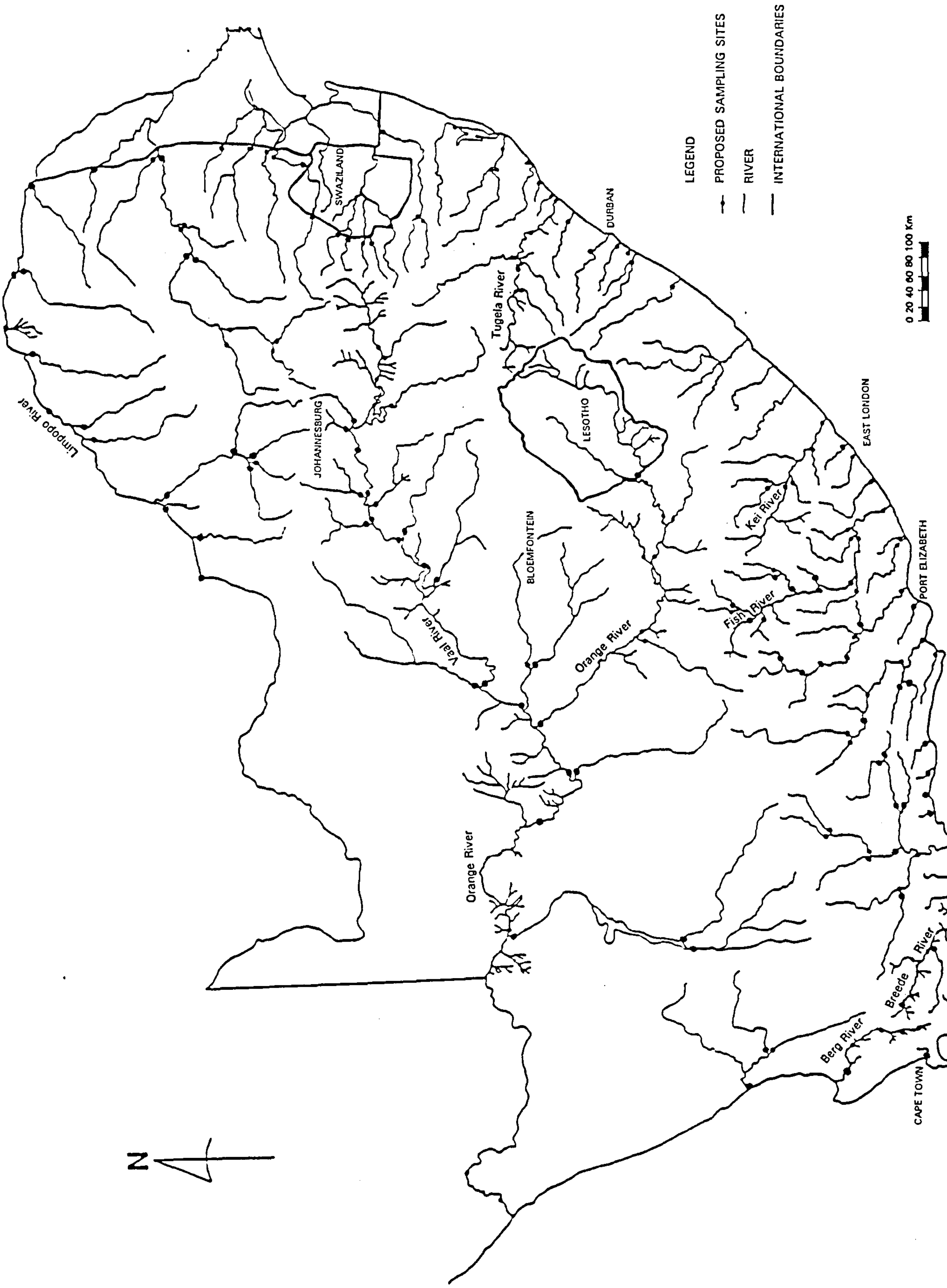

Figure 5.2 Location of proposed sampling sites

6 OPERATING PLANS AND PROCEDURES

Operating plans were developed with as much detail as possible, given the amount of dependence on site specific conditions for such things as sampling route.

6.1 SAMPLE COLLECTION PROCEDURES

The collection of samples is the first step towards providing water quality information. As such it is one of the most important facets of the network. Not only is the collection of samples in itself relatively expensive, but if it is not performed correctly and conscientiously, the network will yield unreliable information and the costs involved in analysis and data storage and handling will be wasted.

At the same time, correct and accurate sample analysis is of equal importance, because a wrong analytical result will negate all care that was taken in sample collection. All analytical methods that are used should therefore be proven and accepted standard methods which yield repeatable results.

It was originally envisaged that all the variables selected for this network would be determined in the field by making use of portable instruments. It was however soon realised that, due to the cost of the field instruments, a lack of properly trained field personnel and the time constraints under which they work, this would not be possible under present circumstances. With the exception of dissolved oxygen which must be measured *in situ*, all other variables will be determined by analyzing samples in a laboratory.

The following is a brief description of the sampling procedures and analytical methods for each variable.

6.1.1 Total Dissolved Salts and pH

There are three methods for the determination of the total dissolved salts (TDS) of a water sample, these are: (1) to measure the conductivity of the sample and then, using a previously determined relationship between conductivity and TDS, calculate an approximate value for

TDS, (2) filter and oven-dry the sample and then weigh the remaining residue, (3) analyze each of the major ions in solution and then sum the mass concentrations to give the TDS. The last method has been selected for use in this programme.

The pH of a water sample may be determined using (1) test-papers for an approximate determination, (2) colorimetric methods using a Lovibond comparator, (3) electrometric methods using a glass electrode and meter. The last method is found be most accurate and shows no interference for coloured or turbid water samples.

TDS and pH can be determined from the same sample for which in general the same sample collection rules apply.

6.1.2 Turbidity

Turbidity can be measured in three ways. The most common method measures the scatter of light in a sample in terms of nephelometric turbidity units (NTU). Other methods measure the amount of light which passes through a sample in terms of optometric turbidity units (OTU) or in terms of the fluorescence of the suspended material after being subjected to light (FTU). The first method is recommended for this monitoring system,

Although a variety of field instruments are available, the risk of introducing variability due to improper handling is high. Experience has shown that the measured turbidity is not affected by storing a sample for up to three weeks, as long as the sample is agitated to resuspend any sediment that may have settled to the bottom of the sample bottle before being analyzed.

Samples will be analyzed in the laboratories of the Hydrological Research Institute by a nephelometric turbidity meter with a range of 0-1000 NTU.

6.1.3 Chlorophyll *a*

Chlorophyll is the green pigmentation in algae and blue-green bacteria such as *Microcystis*; therefore a correlation between the chlorophyll concentration and the algal density exists.

Algal biomass is most commonly estimated indirectly by the determination of chlorophyll *a*, which constitutes 1 to 2% of the dry weight of organic material in phytoplankton. It is normally measured by means of a spectrophotometer after breaking down the cellular walls to release the chlorophyll.

Sample collection for the determination of chlorophyll *a* presents unique problems. Relatively deep, slow-moving sections of the river will characteristically contain higher concentrations of algae than sections where turbulent flow occurs. The choice of the correct sampling spot is therefore of critical importance.

The procedure for the extraction of chlorophyll *a* from the cells and the determination of the concentration in the extract, will follow standard documented procedures. Because of the time constraint placed on sample transportation, not all samples will be analyzed by the HRI. Strategically located regional laboratories will have to be found or established to analyze all samples collected outside a radius of about 300 km from Pretoria.

6.1.4 *Escherichia coli*

Escherichia coli is a member of the faecal coliform group of the family Enterobacteriaceae which are present in the intestines of all warm-blooded animals. As such the presence of *E. coli* in water is indicative of faecal pollution.

E. coli is determined by the indole confirmation test which is performed after culturing faecal coliform bacteria on an appropriate growth medium. The analytical method relies to a large extent on the assumption that bacteria are distributed homogeneously throughout the sample. This is not necessarily true, and the reported result should be seen as a "most likely" number.

Samples will be analyzed according to SABS methods 221 (SABS, 1986). In all cases triplicate analyses and a series of dilutions will be performed. Due to the time constraint between sample taking and sample analysis, a number of strategically located laboratories will be needed.

6.1.5 Dissolved oxygen

Dissolved oxygen can be reported in two ways; either as a concentration, or as a percentage of the saturation concentration. Atmospheric conditions, temperature, and salinity affect the solubility of oxygen in water. As the atmospheric pressure on the Highveld is only 80% of that at the coast, the saturation concentration for identical waters will differ by the same margin. A lower dissolved oxygen concentration in the high-lying parts of the country than at the coast does not therefore indicate that the fitness for use in terms of aquatic life is affected by any upstream activity. In order to be able to compare different waters in different parts of the country, the dissolved oxygen will be reported as a percentage of the saturation concentration.

6.1.6 Summary

In total, four samples must be collected at each sampling site, while dissolved oxygen must be measured at each site. In poorly buffered water, as in the South-western Cape, pH must also be measured *in situ*.

Some of the requirements for sample taking are mutually exclusive. For TDS and pH, the ideal sampling spot would be downstream of an area of turbulent flow, while this would yield inaccurate results for dissolved oxygen. In general, the ideal sampling spot would be in midstream of a reach where uniform flow occurs.

It is, however, not always feasible to sample in midstream, even if such an ideal spot does exist at the sampling site. Trade-offs will have to be made at certain sampling sites, and each site will have to be individually assessed to find the optimum sampling spot.

The table below lists some of the pertinent sampling requirements:

Table 6.1. General sampling requirements.

	TDS/ pH	Turbidity	Chlorophyll *a*	*E. coli*	Dissolved Oxygen
Sample size	350 ml	350 ml	1 litre	350 ml	N/A
Field book information	Yes	Yes	Yes	Yes	Yes
Maximum transport time	not critical	not critical	24 hours	12 hours	N/A
Central laboratory	Yes	Yes	No	No	in situ
N/A - Not applicable					

6.2 DATA HANDLING AND STORAGE

6.2.1 Data transfer from field/lab sheets to mainframe

All results of analyses will be stored on the new Water Quality Data Base of the Hydrological Information System (HIS).

Initially data could be transferred from field/laboratory sheets to HIS administrators on paper. When the required hardware is available in the regional offices/laboratories, data will be sent to the HIS on flexi-disk or magnetic tape or via a keyboard linked to the mainframe. The ultimate aim is to use sophisticated analyzers and local computers linked to the mainframe for direct data transfer.

The criteria for acceptance of data input values as valid measurements will be set during the implementation design phase of the project.

6.2.2 Reporting format on data handling errors

A control program can be run, for example every month, to identify outstanding or missing analyses and a feedback system to regions/labs will be developed during the implementation design phase of the system.

6.2.3 Location and format of data storage

Detailed information on the Water Quality Data Base is contained in a separate document (DWA, 1987).

Provision is made for the storage of data on the results of a variety of analyses e.g. bacteriological, chemical elements, biological, organic compounds and for colours, general physical, general chemical, calculated and miscellaneous variables. The system can be expanded as needed. Distinction can be made between analyses from different programmes - such as the National River Water Quality Assessment Programme.

6.2.4 Data retrieval

Data retrieval from the data base is documented in a Department of Water Affairs publication (1988). Provision is made for a standard series of retrieval options for supplying data to general data users. Users with more data-intensive demands can get direct access for data retrieval.

6.2.5 Data security and access control

The Department of Water Affairs and Forestry has described (DWA, 1988) a system for security of the data base. An overall security system has been developed for the HIS. Regular users will be registered on the HIS for direct access for data retrieval.

Since the data are acquired with public money, the data are, in general, freely available to the public. Provision is made to block data under certain conditions, e.g. from a specified monitoring point or project or for specified variables. Relatively high level departmental approval is needed to block specific data and approval must be renewed annually.

6.3 QUALITY MANAGEMENT

The usefulness of any water quality monitoring system rests squarely on the quality of the data produced. The quality can be measured by such features as a minimum of missing data and minimum variance due to sampling error.

There are two methods to control the quality of a monitoring system, quality assurance and quality control. Ward and Bell (1988) define quality assurance as efforts to assure that all procedures of the monitoring system are followed correctly. Quality control (QC) refers to efforts to assure that specific results of the laboratory analysis procedures are repeatable.

This design document and supporting documents are aimed at quality assurance inasmuch as they are intended to provide a consistent reference to the correct procedures. It is necessary to have a written reference so that the same procedures are available to each person who is introduced to the system. All levels of personnel, from upper level management to samplers and laboratory personnel, require a consistent reference.

QA activities include checking to see if (1) pre-sampling duties are performed, (2) samples are collected as required, (3) samples are stored and transported in a timely and correct manner, (4) equipment is cleaned, calibrated, and maintained, (5) the laboratory uses the correct analysis procedure, (6) the quality control procedures are being implemented as planned, (7) the data are screened and verified, and (8) the reports are accurate and are meeting the information needs defined earlier.

Items 1-4 are the responsibility of the person who supervises the sampler. The activity can be facilitated by a series of check lists and logs to help the sampler remember the correct procedures and to provide a record that can be used for evaluation. It is recommended that a standard format for the check lists and logs be developed. The effluent compliance monitoring programme has developed formats for reports on the sampling location, receipt of the monthly reports, and enforcement action (Conradie, 1990). It is recommended that similar formats be adopted in the National River Water Quality Assessment Programme to provide consistency between the programmes.

Item 2, checking to see if samples are collected as required, has two components, ensuring that the samples are collected, and ensuring that such requirements as the location and procedure are correct. The first component is the responsibility of the samplers' supervisor and the central authority for the monitoring system. The failure to collect a sample can stem from many factors; some beyond the control of the sampler and the supervisor, for example, inaccessibility of the sampling site due to high water, equipment malfunction, and lack of flow at the site.

7 REPORTING FORMAT

The reporting format should convey information in such a manner that all users can easily and accurately abstract the information they require. The users will represent a wide spectrum of expertise and experience and the information must be understandable to all. The proposed reporting format to meet these criteria is described below.

7.1 CURRENT WATER QUALITY STATUS

The current status can be determined by examining the statistics for each of the six variables separately and in combination. Adamson and Dixon (1983) found that water quality data is distributed as mixed log-normals. Since then more data have become available and the data record for some individual sampling points has virtually doubled. The Hydrological Research Institute is currently in the process of analyzing this data to determine whether the findings of Adamson and Dixon (1983) are still valid. This study will be completed in March 1992. Until appropriate probability distributions can be determined, rank order statistical methods will be used to analyze the data. The 10th, 25th, 75th and 90th percentiles will be calculated for each variable at each point for the year under review.

In order to allow the user to assess the fitness for use, an index, such as that developed by Moore (1990), will be used to report the water quality in terms of the combined variables. A water quality index is a useful way of summarizing water quality data to present concise information on the suitability for use of water.

An index was developed for the National River Water Quality Assessment Programme combining information on the variables proposed for that system (Moore, 1990). The variables are measured in different units, so to combine them to produce a single index value, they were converted to a single, consistent unit. This was done for each variable by assigning water quality rating values to different measurements of the variables. The water quality rating values were assigned using the descriptive scale given in **Table 7.1.**

Table 7.1 Descriptive scale used to assign water quality rating values.

Rating value	Descriptor
0 - 19	Totally unsuitable for use
20 - 39	Inadequate for most uses
40 - 59	Marginally suitable for use
60 - 79	Suitable for use
80 -100	Eminently suitable for use

Continuous curves that show the rating value for concentrations were developed for each variable. An example rating curve, for TDS, is shown in **Figure 7.1.** Five lines are shown in each graph. The centre line is the median of all responses from water quality professionals who consented to participate in the index development. The dotted lines show the 5 and 95 percentiles of the responses; the dashed lines are the 25 and 75 percentiles. Water quality rating values can be read from the graphs for any measured value of the variables.

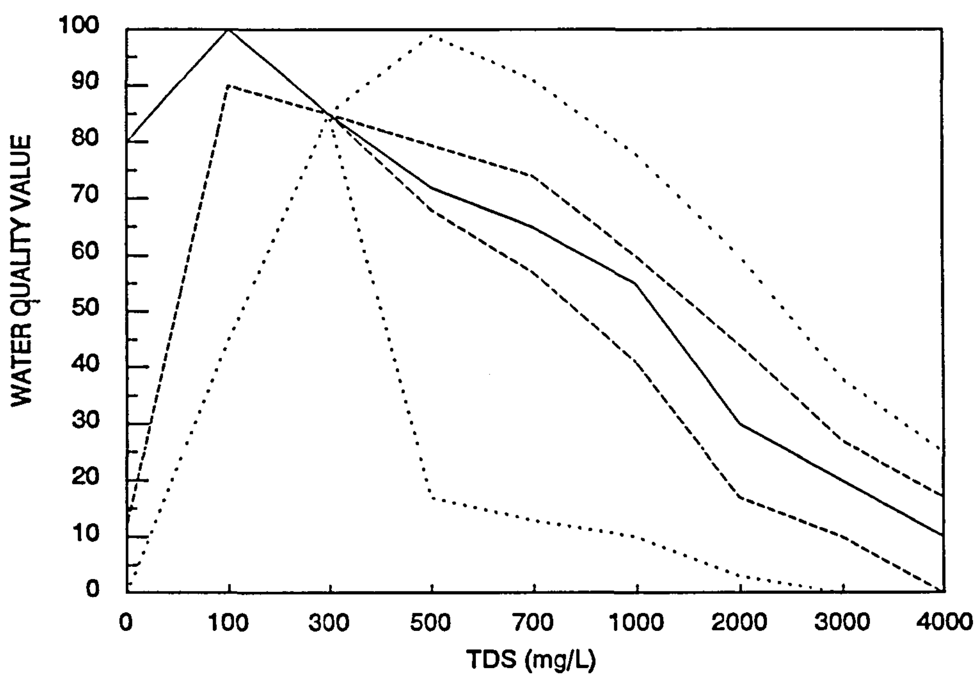

Figure 7.1 Rating curve for TDS showing the general fitness for use of water at different concentrations.

The six variables used were not considered to be of equal value as indicators of water quality, therefore, a weighting factor to describe its relative importance was assigned to each variable. The water quality professionals who contributed to development of the rating curves were also requested to provide input for the determination of the weighting factors.

The rating values and weighting factors for each variable can be combined using a formulation similar to that developed in the U.K. (House, 1989). This formulation is easy to compute, incorporates the weighting factors to express relative importance of the variables as indicators of water quality, and is relatively sensitive without bias toward either good or poor quality water.

The rating curves allow the fitness for use at a point to be expressed as a percentage. At the same time, a descriptive assessment can be given. The proposed classifications are:

- Eminently suitable for use
- Suitable for most uses
- Marginally suitable
- Unsuitable for most uses
- Totally unsuitable

Percentile values for the index will be reported. The index value for each site will be calculated and these values ranked to determine the index percentiles. The proposed format for reporting the current water quality at any given monitoring site is shown in **Figure 7.2.**

7.2 TEMPORAL CHANGES

In order to allow the user to put the current water quality into perspective, information on the historical water quality will be provided. The following format will be used:

(i) The same information as shown in Figure 7.2, but with values calculated from the record of the last three years,

(ii) Box and whisker plots showing maximum and minimum values, 25th, 50th and 75th percentile values and extremes for the previous ten years or the length of record, if less than ten years are available. Each box-and-whisker will represent a one-year period with the year under review as the last year **(Figure 7.3)**,

C5H008 - Q01 : Riet River at Riviera

October 1987 to September 1990

	TDS (mg/L)	pH	Turbidity (NTU)	Chlorophyll a (ug/L)	*E Coli* (no/100 ml)	Dissolved Oxygen (% saturation)	INDEX
10 th PERCENTILE RATING DESCRIPTION							
25 th PERCENTILE RATING DESCRIPTION							
50 th PERCENTILE RATING DESCRIPTION							
75 th PERCENTILE RATING DESCRIPTION							
90 th PERCENTILE RATING DESCRIPTION							

Figure 7.2 Proposed format for reporting on the current water quality at any given monitoring site.

(iii) Box-and-whisker plots containing the same information as in (ii), but for the individual months. All the values for each month over the ten-year period will be used for these plots. This will graphically represent any seasonality in water quality (Figure 7.3),

(iv) Trends will be reported as shown in **Figure 7.4**. Trends will be reported for two specific periods; the whole record and the last 3 years.

Any trends that are detected by making use of the whole record will be indicative of long term changes taking place in the catchment. A trend detected with the last 3 years of data will indicate sharp changes over a short period.

Maps showing drainage regions with a positive, negative, or no trend for each variable and the index will be supplied. These will be colour-coded as follows:

- blue : negative trend
- green : no change
- red : positive trend
- white : insufficient data

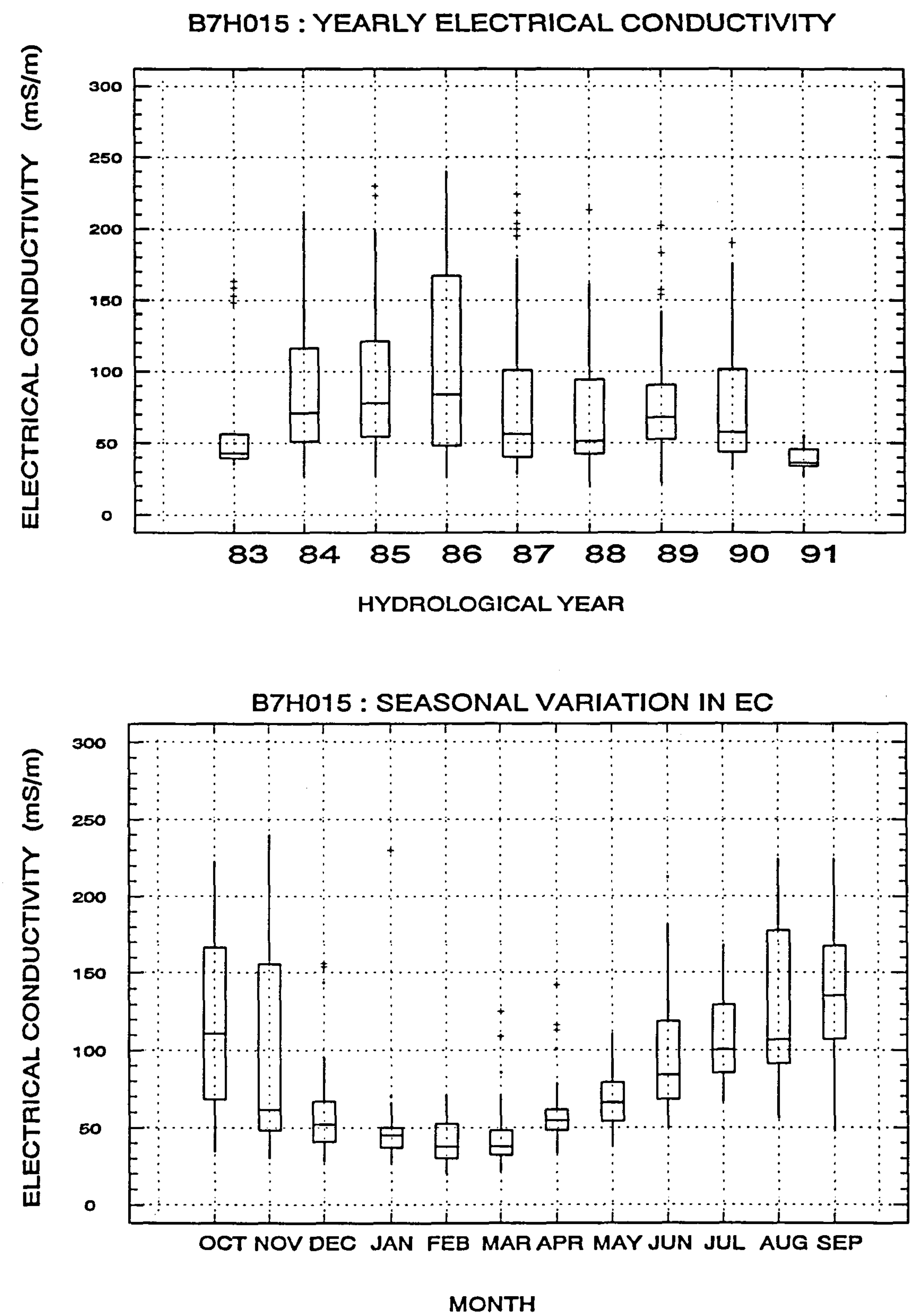

Figure 7.3 Example of the box and whisker plots proposed for reports.

C5H008 - Q01 : Riet River at Riviera October 1987 to September 1990			
Variable	Trend (units/year)	Significance level (%)	Standard Deviation (units)
TDS (mg/L)			
pH			
Turbidity (NTU)			
Chlorophyll a (ug/L)			
E. coli (no/100 ml)			
Dissolved Oxygen (% of saturation)			
Index			

Figure 7.4 Example of the proposed format for reporting trends.

7.3 SPATIAL CHANGES

In order to allow the user to assess the geographical distribution of water quality, the following information will be supplied:

(i) Duration distribution curves for each variable and the index. These curves will show, for a specific region, the relationship between the percentage of monitoring points, concentration or value and the 10th, 25th, 50th, 75th and 90th percentiles (**Figure 7.5**). Curves will be drawn for each primary drainage region and the country as a whole. Curves will be provided for the year under review as well as the whole record.

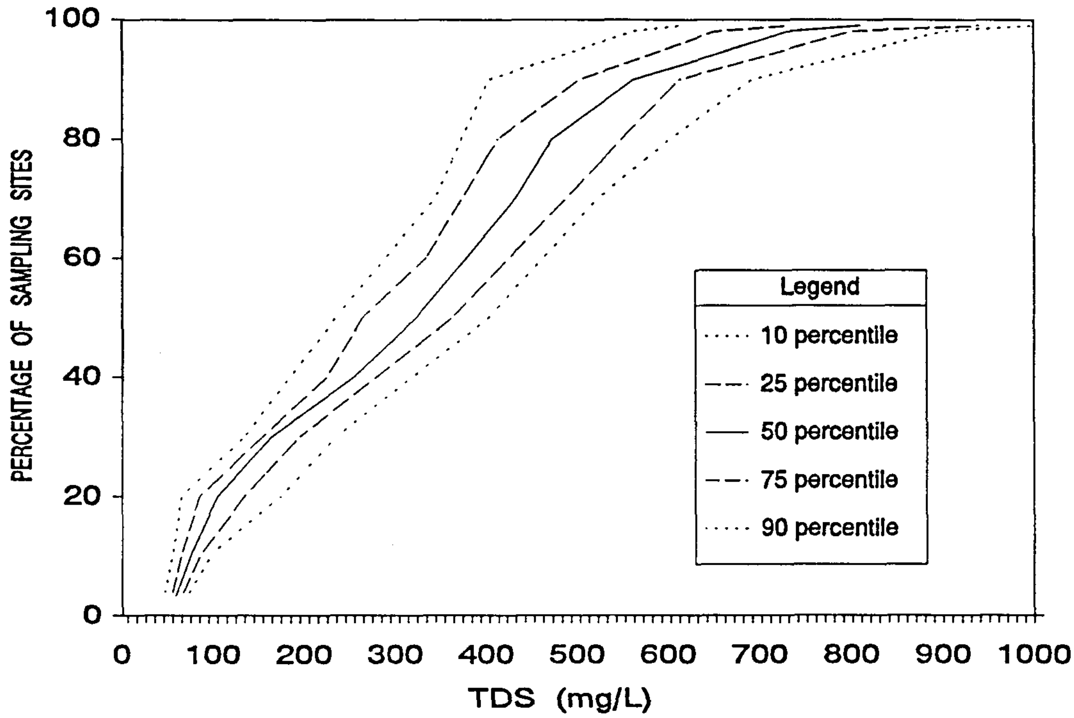

Figure 7.5 Example of duration distribution curves proposed to show the relationship between the percentage of monitoring points, concentration and percentiles.

(ii) Colour-coded maps where each tertiary drainage region is coloured according to its fitness-for-use classification. Different maps for each variable and the index will be provided, one set showing the 90th percentile values and the other the 75th percentile values. Only the values for the year under review will be used. Suggested colour codes are:

- Blue : Eminently suitable for use
- Green : Suitable for most uses
- Yellow : Marginally suitable
- Orange : Unsuitable for most uses
- Red : Totally unsuitable
- White : Insufficient data

(iii) Colour coded diagrammatical line drawings of the major river systems. The same colour code as described above will be used, while the width of the bar depicting a river reach will represent the runoff. The colour allocated to a river reach will be determined by the value of the downstream monitoring point. Again 75th and 90th percentile values for the year under review will be used.

(iv) Tables for each major river, i.e. rivers draining primary and secondary drainage regions, showing average differences between consecutive monitoring sites for the year under review (**Figure 7.6**).

VAAL RIVER

October 1989 to September 1990

	MEAN VALUES							AVERAGE DIFFERENCE *						
Station No.	TDS (mg/L)	pH	Turbidity (NTU)	Chla. a (ug/L)	E. coli (no/100 ml)	DO (% of sat.)	INDEX	TDS (mg/L)	pH	Turbidity (NTU)	Chla. a (ug/L)	E. coli (no/100 ml)	DO (% of sat.)	INDEX
C1H001	X	X	X	X	X	X	X							
								X	X	X	X	X	X	X
C1H002	X	X	X	X	X	X	X							
↓														

* Figures in bold depict significance level of 0,05

Figure 7.6 Example of the proposed table showing the average differences between consecutive monitoring sites on major rivers.

(v) Box-and-whisker plots as described above, but for the same rivers and monitoring points as described in point (iv) above. These box-and-whisker plots will show, for each variable, how the water quality changed along the river during the year under review.

7.4 REPORT STRUCTURE

For ease of reference the report will be divided into three sections reporting on the country as a whole, each drainage region, and each sampling point.

The report will be published in separate volumes:

Volume I:	Country as a whole; Each primary drainage region.
Volume II-VII:	Individual sampling sites, each volume covering a departmental region.

Each volume of the report will contain a short introductory chapter giving definitions, explaining the use of the index, etc. Following this will be a short discussion of the water quality in the specific region covered in the report. An audit of the sample taking (taking periods of no flow into account) and the laboratory analysis will be included. Any changes in the system will also be reported. Also included will be a tear-out page for comments and/or requests.

7.5 REPORTING FREQUENCY

Annual reports are proposed. The need for more frequent reports will be evaluated from time to time.

7.6 DISTRIBUTION LIST

The following list is proposed for distribution of the reports.

7.6.1 Department of Water Affairs

Management;
All Chiefs of Directorates;
All Regional Directors;
All Deputy Directors (Water Quality) in the regional offices;
All Deputy Directors/Deputy Chief Engineers in Directorate:
: Water Pollution Control;
: Hydrological Research Institute;
: Project Planning;
: Strategic Planning;
: Design Services;
: Hydrology;
: Water Utilization;
: Liaison Services;
: Chairman and members: Departmental Environment Committee.

7.6.2 Other Departments

Department of Constitutional Development and Planning;
Department of National Health and Population Development;
Department of Co-operation and Development;
Department of Trade and Industry;
Department of Agriculture;
Department of Mineral and Energy Affairs;
Department of Environment Affairs;
Department of Health Services and Welfare:
Administration:
: House of Assembly;
: House of Delegates;
: House of Representatives;
Department of Agriculture Development:
Administration:
: House of Assembly;
Department of Local Government, Housing and Agriculture:
Administration:
: House of Delegates;
: House of Representatives;
Provinces.

7.6.3 Other organisations

CSIR;
Water Research Commission;
ESKOM;
All Water Boards;
All Permanent Water Committees;
All Joint Permanent Technical Committees;
ASSOCOM;
South African Agricultural Union;
Chamber of Mines;
All Regional Development Advisory Councils;
All Regional Services Councils;
Development Bank of Southern Africa;
All Parks Boards;
South African Nature Foundation;
South African Consumer Council.

It is proposed that all other departments and organisations identified above will have to indicate every year whether or not they still want to receive the report. To this end, a pre-addressed card will be included in each report. Only if a card is received will the next set of reports or specific volumes of the report be sent to that department or organisation.

7.7 DATA VERIFICATION PROCEDURE

If the reported value for any variable differs significantly from the historical values for that month and/or the values of the previous months, this should be reported immediately by the network manager to the Regional Director in whose region the sampling site is located. A monthly report of the sampling points where such values were observed will be produced and distributed to the Regional Directors and the Director: Water Quality Management.

8 EVALUATION

Even though every attempt was made to involve the ultimate information users in the design of the system, it is not possible to approach every user nor is it possible to anticipate all the needs that those users have. In addition, water quality problems change and the need for information changes with them. An evaluation procedure will ensure that the system is as effective as possible.

Some aspects of the design were quite controversial, and therefore are obvious candidates for evaluation relatively soon after implementation. In particular, the measurement of *E. coli* rather than faecal coliform should be assessed at the end of one year to determine if the additional information gained from using the more difficult *E. coli* test allows decisions that are not possible with only faecal coliform results.

The sampling frequency should also be evaluated. A few selected sites should be sampled more frequently to provide a basis for comparison. Gilfillan (1989) has made suggestions regarding specific aspects of the evaluation procedure for sampling frequency.

Other variables reported should also be evaluated in terms of the following questions: Do they meet the objectives stated for the system? Are there other variables that have less variance that could be used instead? Are there other variables that are less costly to measure that could give equivalent information? Are there variables not measured now that information users would prefer to use? Are there variables now measured that do not contribute to meeting the objectives? Those questions should be answered by reference to information requests from users. A substantial effort should be made to contact the information users, both within the Department and outside it, to determine their answers to the questions.

The reporting function should also be evaluated in terms of the reporting format, frequency, and distribution - are they sufficient? The questions could be answered by requesting evaluation from those who routinely receive reports and those who do not receive the reports, but have specifically requested information developed from the National River Water Quality Assessment Programme.

It is important to maintain the objectives of the system and to ensure that changes in the system do not prevent the detection of water quality changes over time. It is also important to view the National River Water Quality Assessment Programme as a dynamic system that improves with time, rather than a highly rigid structure that will begin to resemble a dinosaur, incapable of changing to meet changing conditions.

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APPENDIX A

Questionnaire sent to selected water quality professionals

The Analytical Hierarchy Process (AHP) was used to arrive at a list of variables to include in a large-scale water quality monitoring programme. The AHP is a method of breaking down a complex, unstructured situation into its component parts, arranging these parts into a hierarchic order, assigning numerical values to subjective judgments on the relative importance of each component, and synthesizing the judgments to determine which components have the highest priority and should be acted upon.

The participants in the exercise were members of a "User Team" whose function is to guide an effort to design a large scale water quality information system. The goal of the information system is to describe water quality in Southern Africa and to detect changes in the water quality. The information developed in the system will be used by the Department of Water Affairs (DWA) in routine reports to its upper level management, to Parliament, and to the public. The system is not intended to produce detailed, process-level information; but it will operate in conjunction with other monitoring efforts which will produce that information.

The overall goal of the AHP exercise was defined as:
To determine a list of water quality variables to include in a large-scale monitoring programme.

Water quality had been previously defined as the fitness for use, so the first component level was determination of the major uses of water and the relative importance of each. The uses are:

(1) Domestic water supply: The provision of raw water to facilities that will treat the water to drinking water standards.

(2) Industrial water supply: The provision of water for use in any industrial setting, for example, mining, food processing, manufacturing, and power generation.

(3) Agricultural water supply: The provision of water for irrigation and stock watering.

(4) Recreation: The uses of water for angling, non-contact recreation such as boating, contact recreation such as swimming or diving, and land-based recreation such as picnicing or hiking done near bodies of water. In this category it is also recognized that, despite attempts to discourage it, some people drink untreated water.

(5) Conservation: The uses of water bodies which require them to function as healthy, viable ecosystems.

The product of the AHP is a list of components, in this case water quality variables, with a ranking assigned to each. The ranking is computed from the relative importance given to each pair of variables and the relative importance of higher level components to which the variable belongs.

The following list compiles the results of the analysis for both levels of categories, the water users and the variables. The users have been assigned weights, based on an analysis of the rankings assigned within the group of all users. The variables have been assigned weights, based on their rankings within uses and the ranking(s) of the use(s) for which the variable was judged to be important. A key on the following page describes each variable.

DOMESTIC	INDUSTRIAL	AGRICULTURAL	RECREATION	CONSERVATION
0.446	0.298	0.154	0.066	0.036
BACTERIA 0.167	TDS 0.141	TDS 0.070	BACTERIA 0.016	TOXICITY2 0.013
TOXICITY1 0.145	HARDNESS 0.049	SAR 0.048	FISH 0.016	DIVERSITY 0.010
CHLOROPHYLL 0.067	CORROSIVITY 0.049	pH 0.018	CHLOROPHYLL 0.015	D O 0.006
TDS 0.038	pH 0.025	SS 0.011	WEEDS 0.008	INVASIVES 0.004
SS 0.018	SS 0.018	CHLOROPHYLL 0.007	DEBRIS 0.005	SS 0.002
pH 0.011	Cl 0.011		SS 0.003	
	Si 0.006		TEMPERATURE 0.002	

A composite list of all variables chosen for all water users with a graphical representation of their importance is shown below. The percentages are weightings for the overall goal of selecting variables to monitor. These weightings are a combination of each variable's importance within all the water uses and the relative importance of those water uses.

Variable	%	
TDS	24.9	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Bacteria	18.3	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Toxicity1	14.5	XXXXXXXXXXXXXXXXXXXXXXXXXX
Chlorophyll	9.0	XXXXXXXXXXXXXXXX
pH	5.4	XXXXXXXXX
SS	5.1	XXXXXXXXX
Hardness	4.9	XXXXXXXX
Corrosivity	4.9	XXXXXXXX
SAR	4.8	XXXXXXXX
Fish	1.6	XXX
Toxicity2	1.3	XX
Cl	1.1	XX
Diversity	1.0	XX
Weeds	0.8	XX
DO	0.6	X
Si	0.6	X
Debris	0.5	X
Invasives	0.4	X
Temperature	0.2	

KEY

Bacteria - A microbiological organism that will indicate the overall quality of water in terms of disease transmission
Chlorophyll - the concentration of chlorophyll-a
Cl - Chloride
Corrosivity - Capability of the water to corrode metal
D O - Dissolved oxygen concentration and percent saturation
Debris - The presence of floating debris and litter
Diversity - Range of aquatic life
Fish - Quantity and diversity of the fish population
Hardness - Total hardness
Invasives - The presence of exotic aquatic life
pH - pH
SAR - Sodium adsorption ratio
Si - Silicon
SS - Suspended solids
TDS - Total dissolved solids
Temperature - Temperature of the water
Toxicity1 - Toxicity of the water to humans
Toxicity2 - Toxicity of the water to aquatic life
Weeds - The presence of nuisance aquatic plants

The final list of variables to measure was selected from among the highest ranked variables. The final selection was made on the basis of:

(1) relative importance of the variables in this process -- the original cut-off point for consideration was the first 9 variables, each having an importance ranking near 5% or higher,

(2) difficulties in measuring -- electrical conductivity was substituted for total dissolved solids because EC can be measured in situ; turbidity was substituted for suspended solids for the same reason; toxicity was not included as a result of this consideration, although it will be given high priority as part of another monitoring system, possibly for surveillance of potential problems,

(3) the number of uses for which the variable was important -- SAR was eliminated because it applies only to the description of irrigation water quality for specified crops; hardness and corrosivity were also considered to be too specific to be included in a broad scale monitoring programme,

(4) whether the user category was represented by other variables -- dissolved oxygen was added because no other conservation variables were included. It was chosen over other variables that were considered more important for conservation because its measurement is more practical.

The final list chosen from this process for routine measurement in a country-wide water quality monitoring system was:

Electrical Conductivity,	as an indicator of TDS
Turbidity,	as an indicator of suspended solids
A Microbiological Variable,	the specific organism to be determined later
Chlorophyll-a	
pH	
Dissolved Oxygen	

Please complete and return this form by 31 March 1989 to:

Dr Jane Harris
CSIR/DWT
P O Box 395
PRETORIA
0001

Mark the answer which most closely reflects your opinion of whether the variable should be included in a monitoring system to describe water quality.

	Should not be included	Probably should be included	Definitely should be included	No Opinion
Electrical Conductivity				
Chlorophyll-a				
pH				
Turbidity				
Diss. Oxygen				
Micro biological organism				

Please list any variables which you feel should be added or substituted and the water uses for which they would be most important.

We are also seeking specific information on the microbiological organism that would be most appropriate for this system. If you have information on this topic, could you please add comments.

Additional Comments