INTRODUCTION

In recent years, water quality monitoring has become increasingly important as a method of answering questions of both the public and governmental regulators regarding the safety and suitability of drinking water supplies. The purpose of this Blue Page Document is to provide drinking water utilities with a methodology to design water quality monitoring systems that will provide useful resource management information to answer questions and set water quality management goals.

The approach outlined in this Blue Paper is a logical and practical approach to the design of water quality monitoring systems. The approach was further developed by Ward (1997) and consists of the following five steps:

1. Define the surface water information needs of the water utility management
2. Define information needs that can be produced by monitoring
3. Design monitoring network
4. Document data collection procedures
5. Document information generating and reporting procedures

The information needs of management are in many ways dependent on the legal basis for monitoring and water quality management. The sources of the legal basis will vary depending on the country in which the monitoring system will be established. The group writing this document has examined and chosen Chapter 18 of the United Nations Declaration on Environment and Development (Rio de Janeiro 1992) as the universally accepted basis for the establishment of monitoring systems for surface water resources. This Declaration strongly supports the establishment of monitoring systems worldwide. Since the Declaration is only advisory the legal basis for monitoring systems must be established on a local basis. This local basis may be found in the national, regional, or local laws of the subject country. However, where this legal basis is lacking utilities have no other choice but to design and operate appropriate monitoring systems themselves.

DEFINE INFORMATION NEEDS OF MANAGEMENT

Chapter 18 of the Rio Declaration (“Protection of the Quality and Supply of Freshwater Resources”) sets forth a number of specific recommendations for water quality monitoring. The recommendations are as following:

18.2 Water is needed for all aspects of life. The general objective is to make certain that adequate supplies of good quality water are maintained for the entire population of this planet ... Innovative technologies are needed to fully utilize limited water resources and safeguard those resources against pollution.

In the activities recommendations the following is set forth:

18.12 (b) Integration of measures for the protection and conservation of potential sources of freshwater supply, including the inventorying of water resources ...

In the basis for action the following is stated:

18.35 Freshwater is a unitary resource. Long-term development of global freshwater requires holistic management of resources and a recognition of the interconnectedness of the elements...
related to freshwater and freshwater quality... A preventative approach, where appropriate, is crucial to the avoiding of costly measures to rehabilitate, treat, and develop new water supplies.

Under activities the following recommendations are made:

18.40 All States, according to their capacity and available resources... could implement the following activities:

(d) (vi) Water-quality monitoring, as needed, of surface and groundwaters potentially affected by sites storing toxic and hazardous materials

(g) Monitoring and surveillance of water resources and waters receiving wastes:

(i) Establishment of networks for the monitoring and continuous surveillance of waters receiving wastes and of point and diffuse sources of pollution;

(iii) Surveillance of pollution sources to improve compliance with standards and regulations and to regulate the issue of discharge permits;

(iv) Monitoring of the utilization of chemicals in agriculture that may have an adverse environmental effect;

(h) Development of national and international legal instruments that may be required to protect the quality of water resources, as appropriate, particularly for:

(i) Monitoring and control of pollution and its effects in national and transboundary waters:

Agenda 21 anticipated that the trend for increased environmental monitoring and enhancement will continue. As a part of their activities all states were recommended to strengthen monitoring and information at subnational and national levels as a sector management and advocacy/awareness creation tool. Agenda 21 also recommended the development of user-friendly software and Geographical Information Systems (GIS) and Geographical Resource Information Database (GRID) methods for the handling, analysis, and interpretation of monitoring data and for the preparation of management strategies. It was further recommended that training activities should be undertaken for specific aspects of water quality monitoring monitoring and control.

DEFINE INFORMATION THAT CAN BE PRODUCED BY MONITORING

Information that can be produced by monitoring can be defined from the universally accepted basis described above and from the information goals of water utilities. Table 1 demonstrates how the main water quality monitoring goals of Agenda 21 are related to general data analysis methods, and information reporting options. This table ties together the bases for presenting water quality information as well as the general approach to its development.

Water quality monitoring ought to be performed by state authorities. However if these authorities should fail to monitor the surface water resources adequately, water utilities may be forced to develop and operate their own monitoring system. Utilities faced with this situation should try to seek cost sharing from regional or national authorities.

Data Analysis Protocols

In order to further define information that can be produced by monitoring and in order to systematically connect the data analysis through the reporting procedures to the water quality monitoring goals, data analysis protocols should be specified. These data analysis protocols outline the methods to address data record attributes as well as data analysis methods. Additional information on data analysis protocols is available in Adkins (1993). A general discussion of both of these topics as well as suggested methods is outlined below.

Data Record Attributes

In order to have both consistency and reliability in the development of information utilized to report and document water quality information all protocols used for preparing data for analysis should be documented in writing prior to data analysis. These protocols should address a number of issues that typically arise in data analysis. These issues include:

- multiple observations
Multiple observations occur when additional samples are taken during a sampling period for Quality Assurance/Quality Control (QA/QC) purposes. A decision has to be made as to whether to consider the QA/QC data in the data record. The options are to either not use the QA/QC data or to average all data to obtain a single value for analysis. Averaging is typically recommended so as to eliminate the criticism of not using all the data collected by the monitoring program.

Outliers are values which are much higher or lower than the majority of the data set. Unless there is evidence to document that the data are in error, it is recommended that the outliers are retained and analyzed with the rest of the data. In some cases averaging of frequent or recurring outliers may not be appropriate however, e.g. where water quality is affected by tidal cycles or diurnal wastewater discharge fluctuations. This problem can be (partially)
overcome by careful protocols for sampling and statistical analysis.

Changing sample frequencies will make statistical analysis of the data record more difficult. In order to avoid this problem it is recommended that the sampling frequency be established prior to or at least early in the establishment of the water quality monitoring network.

Missing values should be noted, however numerical values should not be inserted into the data record in lieu of the value which was not obtained.

Censoring occurs when qualitative descriptions are inserted into the data record by the laboratory staff when there is uncertainty in the results of the analysis. The data may be reported as “ND”, “<T”, “less than LOD”, or “U”. Often this results when the data collected is less than the detection limit of the analysis. Even though the data collected may be less than the detection limits, it is recommended that data not be censored, all data should be reported with qualifying statements such as the level of uncertainty, detection limits or confidence limits. By reporting all data the possibility for confusion is reduced during data analysis. For statistical purposes < values in existing data sets are sometimes substituted with a value of 0.5 x (detection limit) in order to look at trends. This should only be done on a case by case basis and the values should still be reported in tables as <.

In addition other issues for dealing with non-normality of the data, seasonality, and serial correlation are important to address in the process of performing statistical analyses of the data. Methods used to identify or address these issues in the data record should be documented.

### Suggested Method for Data Analysis

Several methods have been suggested in Table 1 for use in developing water quality information which addresses the water quality monitoring goals. It is important to select data analysis methods that are easily understood, widely accepted, and present relevant information addressing the monitoring goals. Seven water quality goals have been set forth in Table 1. The suggested methods for data analysis are summarized below in six categories:

- **Watershed Mapping**
- **Graphical Methods**
- **Direct Comparison with Standards**
- **Information Inventory**
- **Statistical Methods**
- **Water Quality Modeling**

Watershed mapping is suggested to address the geographical information needs set out in the water quality monitoring goals. This watershed mapping would provide location maps to be used to place a geographic context to the analysis to be performed. The mapping would provide location maps as well as the overall watershed context to the water quality analysis. This could be accomplished using paper mapping procedures, however to ease the translation of the information to reporting it is suggested that computerized approaches (GIS) be utilized. Computerized approaches allow for the preparation of differing scale mapping and exhibits for the incorporation into data reports.

Graphical methods are suggested for addressing several information goals. Graphical presentations will show water quality trends over time at the water quality monitoring sites. This graphical presentation would show the concentration of selected parameters over time. These time series plots are useful in portraying trends or changes in concentration over time.

Direct comparison with standards is also recommended. This involves the comparison of individual concentration values to the water quality standards without the use of statistics. A summary of the annual proportion of violations (% in violation) could be developed. In addition the confidence limit of the proportion could also be calculated (many European countries normally apply 95% confidence limits, which means that one failure in 20 is admissible). The standards should be those set for the country in which the monitoring system exists. If no standards are available then guidelines from the World Health Organization could be utilized.

Information inventory is also recommended. This inventory should consist of preparation of summary information and bibliographies of the existing watershed protection, conservation, supply, and water quality information. In addition, inventorying the sales of agricultural chemicals and place of intended use is recommended in order to assist in quantifying the inputs to potential contamination by agricultural chemicals. Information inventory should also include industrial sites and storage sites for hazardous substances.

Statistical analysis of water quality trends is suggested to supply the information needed for several monitoring goals. It is suggested that the statistical methods employ a combination of graphical, estimation, and testing techniques to analyze and display
the data. A display technique such as monthly or seasonal Box-and-Whisker time series plots should be utilized. These time series plots will display the mean, a confidence interval (usually 5% and 95%), and extreme values for the data displayed. Trends may be estimated using linear regression and tested using a t-Test for significance of slope as described in Snedecor and Cochran (1980). An additional method is to use a Seasonal Kendall Slope Estimator and Seasonal Kendall test as described in Gilbert 1987. The Seasonal Kendall test is widely used in water quality analysis and accommodates seasonality of the data. Additional information on statistical methods is available in Loftis and McBride (1991).

Water quality modeling may also be utilized to predict impacts of potential sources of watershed contamination. Modeling will allow for the projection of water quality impacts from the utilization of chemicals in agriculture or other sources of pollutants. Through the use of modeling techniques projections may be made of the effects of present or proposed practices so modifications can be made to ameliorate impacts on the environment.

**DESIGN MONITORING NETWORK**

The recommended approach to water quality network design is to focus on the information goals and relate the network design to each information goal. The network design is specified through the designation of the sampling location, variables to be measured, and sampling frequency. A brief description of the basis for this design follows.

**Sampling Location**

The location of the sampling sites is guided by the information goals. The goals establish the “macro” location for sampling. The macro location will specify a river or stream reach, lake or reservoir location. Following this a specific location (often referred to as a “micro” location) is identified. The micro location is determined by access or the existence of a flow or water level measuring device and by the ability to obtain a representative sample at the specific sampling location. It should be noted that it is usually necessary to take 2 or more samples (from different depths) from the same location in the case of stratified lakes and reservoirs.

For the information goals specified above the following is suggested to guide the macro locations, the specific micro locations will need to be established for each water quality monitoring network based on site specific criteria. For all sources of supply it is recommended that a sampling location be established. In order to establish the impacts of pollution it is recommended that monitoring locations be established both above and below the location of the potentially harmful activity. This activity may include impacts from toxic and hazardous materials, point or diffuse sources of pollution, or chemical use in agriculture. In order to characterize a watershed the use of a stream ordering approach may be warranted. This approach is used to subdivide a river system into relatively equal contributing tributaries. Sampling locations are then specified to provide spatial coverage of the basin’s water quality. In addition to the stream water quality monitoring network major lakes and reservoirs should also be included in watershed characterization.

**Variables to be Measured**

The variables to be measured should be established to provide information to address the water quality monitoring goals as set forth above. These information goals are to a large extent addressed through the basic monitoring variables used in the United Nations GEMS/WATER program as outlined in Table 2. Further information on the GEMS/WATER program can be obtained from Bertram and Balance (1996). It is recommended that the GEMS/WATER variables be used as the initial basis for establishing the water quality monitoring program. In many cases it is advisable to monitor at least one variable which indicates the level of organic pollution such as TOC (Total Organic Carbon), BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand) or KMnO4 (potassium permanganate oxidability). Additional monitoring may be warranted if specific toxic or hazardous materials are suspected to be present in the watershed. It is recommended to screen surface water resources at least once for the presence of hazardous inorganic and organic micropollutants, if possible guided by information about (potential) pollutant sources upstream. If one or more of these substances are found in toxicologically relevant concentrations, they ought to be included in the regular monitoring program.

**Sampling Frequency**

Sampling frequency can be determined statistically for a given confidence level over the time frame in which the sampling occurs. Recommended sampling frequencies have also been established for GEMS/WATER stations by the World Health
Continuous Water Quality Monitoring

The information obtained from a well designed and operated monitoring network is useful for trend detection and compliance testing. It is inadequate however, if a utility’s water intake faces the risk of sudden water quality deterioration, e.g. from industrial spills upstream. In that case it is essential to install appropriate early warning (= continuous monitoring) devices or systems. Chemical warning systems provide information for certain types of spills and pollutants, but their narrow “analytical window” may not allow the detection of all potentially harmful events. Biological warning systems cover a wider range of events but provide no specific information on the identity of the involved pollutants. An overview of available early warning systems and their pro’s and con’s is given by Stoks (1998).

DOCUMENT DATA COLLECTION PROCEDURES

The final step in the design of a water quality monitoring system is to establish the operating plans and procedures. These operating plans and procedures consist of preparation for sampling, sampling procedures/field measurements, laboratory analysis methods, data storage and retrieval, and quality assurance/quality control. The operating plans and procedures should be written with an awareness of the ability of the operating staff. The goal of the procedures is to establish consistency in the data collection efforts and not to add to the variation of the
Preparation for Sampling

Preparation for sampling includes the development of check lists for field sampling procedures as well as access to all sampling sites in varying climatic conditions. Check lists should contain information such as the day, date, sampler's name, site location, field sampling checklist (for items such as field pH, flow, depth etc.), sampling method for samples taken for laboratory analysis, and comments by the sampler. Preparation for access in varying climatic conditions includes the provision of equipment for access in inclement weather.

Sampling Procedures

Sampling procedures for field measurements include methods for grab and composite samples. Grab samples should be specified with prescribed location, depth, and time. Composite samples involve taking a number of grab samples and integrating them to form a composite or average sample for the location. For each variable to be analyzed the recommended container, washing procedure, sample volume, preservative, and maximum permissible storage time should be specified. Each sample bottle should be labeled to ensure that the samples are correctly identified with the correct sampling site. Label identification should include study name, sampling site, depth, date and time, sampler's name, preservative, and other comments such as weather or results from field measurement.

Methods of Laboratory Analysis

Standard methods of laboratory analysis should be used to analyze the data collected in the field. Keith (1996) presents methods for sampling and laboratory analysis of about 1,700 chemicals. Alternatively, current ISO standard methods may be used. It is important that standard methods be used so that the results of the laboratory analysis are comparable to known standards and to the results of other water quality monitoring programs.

DOCUMENT INFORMATION
GENERATING AND REPORTING PROCEEDURES

All data produced should be systematically documented so that it can be stored in a computerized data base for later easy retrieval and analysis. Quality assurance and quality control refer to efforts to ensure that sampling, laboratory analysis and data storage and retrieval activities do not introduce error into the measurements. Significant improvements are made in the Quality Assurance of a water quality monitoring program by documenting the procedures followed in each step of the monitoring program. It is recommended that the documentation efforts be continuous throughout the life of the program and that a QA coordinator be appointed and that QA audits be performed at least twice per year. Quality control addresses the reliability of the equipment and procedures used in the field and laboratory measurements. QC requires that after a number of samples have been processed that blanks and/or standards be tested to insure continuous proper operation. Any drift or malfunction of the equipment and/or procedures can then be detected and corrected before erroneous data are entered into the data record.

It is important to ensure that appropriately trained staff are available to interpret data and to recognize unusual results or adverse trends. The generation of information must be designed to ensure that assessment of compliance with any legislative or operational requirements is easy to undertake.

SUMMARY

By using the approach outlined in this Blue Page Document water suppliers will be able to generate useful information to assist in the management of the water quality of their present or future surface water supplies. Using the information goals of the water supplier water quality monitoring systems may be designed in a cost effective manner to meet the water quality goals. As shown through this demonstration of the process using the goals of Agenda 21 water quality monitoring systems are able to be designed to assist in the process of making supplies of good quality water available for the entire population of the planet. In addition water quality monitoring systems assist in developing preventative approaches to avoid costly measures to treat and develop new water supplies.

ACKNOWLEDGEMENTS

This document was drafted by Prof. Robert C. Ward PhD. and Lloyd J. Gronning at the request of the IWA Task Group “Blue Page Document Quality Monitoring of Surface Water Resources” (chairman Dr. Peter Stoks). The draft was reviewed, amended and approved by the Surface Water Specialist Group of IWA (chairman Drs. Gijsbert Oskam).
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For access to references contact:
Dr. P.G. Stoks
N.V. Watertransportmaatschappij Rijn-Kennemerland
Waterwinstation ir. Cornelis Biemond
P. O. Box 10
NL-3430 AA Nieuwegein
NETHERLANDS
tel.: +31 -30 -607 27 20
tax: +31 -30 -603 24 00
e-mail: pgstoks@wrk.nl