Acquisition and Management of Lake-related Water Quality Information at the Global Level

Richard D. Robarts, Sabrina J. Barker, Scott Evans

Abstract

Although water quality monitoring and assessment programmes provide essential background information to scientific research, policy makers and water managers and keep societies informed of the state and trend of the Earth's vital aquatic ecosystems, their value has at times been called into question for very good reasons. This is because monitoring programmes can become focused solely on their own activities unless they are strongly linked to the needs of users and can generate large amounts of data at great cost that are unnecessary or are not used. In many countries decisions were made to cancel monitoring programmes 20 years or so ago, but these have been re-instated as environmental issues become an increasing concern worldwide. Modern monitoring programmes are designed to be effective keystone components of integrated water resources management. With the use of interoperable database technology, data can be shared amongst a wide number of users, providing a strong return on investment for governments and society generally. However, costs remain high for a modern water quality programme and there are remote areas where it is still not possible to monitor water quality; in some countries even simple monitoring programmes are beyond local means. Continued research and development of innovative new technology, therefore, are necessary to adequately meet the demands for environmental water quality information.

Introduction

Fresh water, like all natural resources, is under increased demand as the world's population grows. In many regions of the world people are removing water from rivers, lakes and aquifers faster than these systems can be recharged. It has been estimated that population growth alone will mean that the number of water-stressed, or water-scarce, countries will increase from 31 to 48 within the next 30 years (Hinrichsen et al. 1998). Additionally, the demand for fresh water has increased in response to industrial development, increasing reliance on irrigated agriculture, massive urbanization, and rising living standards (Shiklomanov 2000).

Global freshwater availability is shrinking not only in quantitative terms, but also in qualitative terms because many freshwater systems have become increasingly polluted with a wide variety of human, agricultural and industrial wastes (Shiklomanov 2000). In addition, climate change and variability are also expected to affect both the quantity and quality of water, creating competing demands for this resource from multiple sectors of society. Developing countries are faced with difficult choices as they find themselves caught between finite and increasingly polluted water supplies on the one hand, and rapidly rising demand from population growth and development on the other (Somlyódy et al. 2001). Water shortages and pollution are causing widespread public health problems, limiting economic and agricultural development, and harming a wide range of ecosystems, which may result in a series of local and regional water crises with global implications (CSD 1997). However, water quality has improved in many systems when local political will has resulted in resources and management plans bring necessary positive changes (UNEP GEMS / Water Programme 2007).

Lakes, unlike rivers, are mainly storage bodies and are estimated to contain more than 90 per cent of the liquid freshwater on Earth (ILEC 2003). Lakes are dynamic ecosystems, and in addition to their storage function they are the source of food and recreation for humans, support a large range of biodiversity goods and services and provide the foundation for people's livelihoods. When natural climatic conditions do not provide enough water, lakes can meet both human

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and ecosystem needs (ILEC 2003). Unfortunately, lakes are also among the most vulnerable and fragile aquatic ecosystems as they are a sink for a wide range of dissolved and particulate substances. In addition, climate change can interact with other lake stressors with both positive and negative consequences for specific lake systems as outlined in Table 1.

As a result, the number and complexity of issues determining water quality of lakes have increased so that monitoring of potential stressors and impacts is a challenge at the local scale and becomes even greater with the need for this data at a global scale. Reliable, consistent and appropriate information is the key to understanding and improving the world's supply and quality of fresh water. However, there is a general consensus that our knowledge of the state of the world's freshwaters needs to improve (WWAP 2006).

There are a number of reasons why a global monitoring system for water quality is needed. First, international multilateral agreements and conventions are formulated to preserve, protect and restore inland waters and a mechanism is required to measure their efficacy or failure, e.g., the Millennium Development goals, the POPs Convention. Second, many large lakes, rivers and ground waters cross one or more international boundaries so there is a need to compile data from different national jurisdictions for the purpose of managing such large systems. Third, many of the environmental issues of today impact large regional areas (e.g., acidification) or the globe as a whole (e.g., climate change, long-range transport of pollutants) but an assessment of the status and trends is not the responsibility of any national government. Therefore, we need an international organization designed specifically to do this.

There are only two possible approaches. The first is to build a team of laboratories and a monitoring network for each region. The costs to do this are prohibitive. In addition, it is unlikely that such a monitoring network would be allowed to function in many countries since the responsibility and management of inland water belongs to national governments. The second is to build a network of participating countries and organizations. In this model, countries with national water quality monitoring programmes would provide a copy or subset of their national monitoring data to a central global data base. Other organizations that carry out monitoring for research or other purposes would also be able to contribute data to this global data base. This is how the UNEP GEMS/Water Programme (www.gemswater.org and www.gemstat.org) has operated now for 30 years. It is the only global water quality monitoring programme for lakes, reservoirs, wetlands, rivers and ground waters and is described in more detail below.

The need for water quality monitoring and assessment programmes

Water quality monitoring programmes are essentially of two types: those in support of research, and those that provide essential information and assessments for management and policy needs. However, about a decade ago non-research long-term monitoring programmes were reduced in size and scope or cancelled in both developed and developing countries (e.g., monitoring of the Mackenzie River in Canada which can be seen from plots that can be produced on-line in GEMStat (see below and www.gemstat.org) because:

- Monitoring was viewed by some as not being real science, but only a fishing expedition that diverts resources from "real" science (Lovett et al. 2007).
- Programmes were large and expensive requiring sophisticated and expensive equipment.
- They were disconnected from the purpose of science or management as a result of organizational fragmentation.
- They became self-focused and their own sole purpose, i.e., monitoring for the sake of monitoring.
- Too many and unnecessary parameters were measured too frequently at too many stations. As new analytical technologies have become available it has become easier to measure large numbers of variables in water samples, which can lead to the collection of data that are unnecessary although at no real extra cost.
- Large amounts of data were collected but not used.

Table 1. The interaction of climate change with other lake stressors (from Schindler, 1997).

- Climatic warming may delay the recovery of acidified lakes.
- Decreasing DOC concentrations in warming lakes could be accelerated by acidification.
- Eutrophication problems may increase, even though nutrient loads may decrease because of increased retention times.
- Dissolved oxygen saturation decreases with increasing temperature so that the impact of oxygen consuming effluents may be more severe.
- Increased periods of stratification in eutrophic lakes could exacerbate hypolimnetic oxygen deficits.
- Increased UV radiation exposure of organisms may occur in lakes undergoing warming and acidification due to decreasing DOC concentrations.
- Climate warming interactions with toxins will be many and complex, ranging from reduced toxin loads, increased retention, to increased revolatilization, decomposition and cycling in lakes.
- Increased human use of water will interact with climate warming to compound already severe problems in water quantity and quality, which will impact all aspects of society and the environment.

- We cannot know today what crucial questions will need to be answered in the future.

But water quality monitoring when properly designed and integrated into decision-making processes provides crucial information for the development of policies and management plans that protect and preserve our essential lake ecosystems. In countries where this was realized and financial resources could be re-instated for monitoring, programmes became operational again. This can be seen in the Mackenzie River water quality data found on GEMStat. However, in many developing countries in Africa and elsewhere monitoring infrastructure was allowed to deteriorate to the point where it was not possible to resurrect it. But the importance of water quality to not only ecosystem health but also to human health has in an increasingly number of developing countries led to political support to try and find ways to revitalize these monitoring networks (a good example is Kenya).

Global water quality monitoring

The Global Environment Monitoring System (GEMS) was inaugurated in 1972 as a result of the United Nations Stockholm Conference on the Environment. Participating governments requested that a global monitoring programme be set up to determine the status and trends of key environmental issues. The GEMS/Water Programme commenced in 1978. The programme had two major objectives:

- The improvement of water quality monitoring and assessment capabilities in participating countries

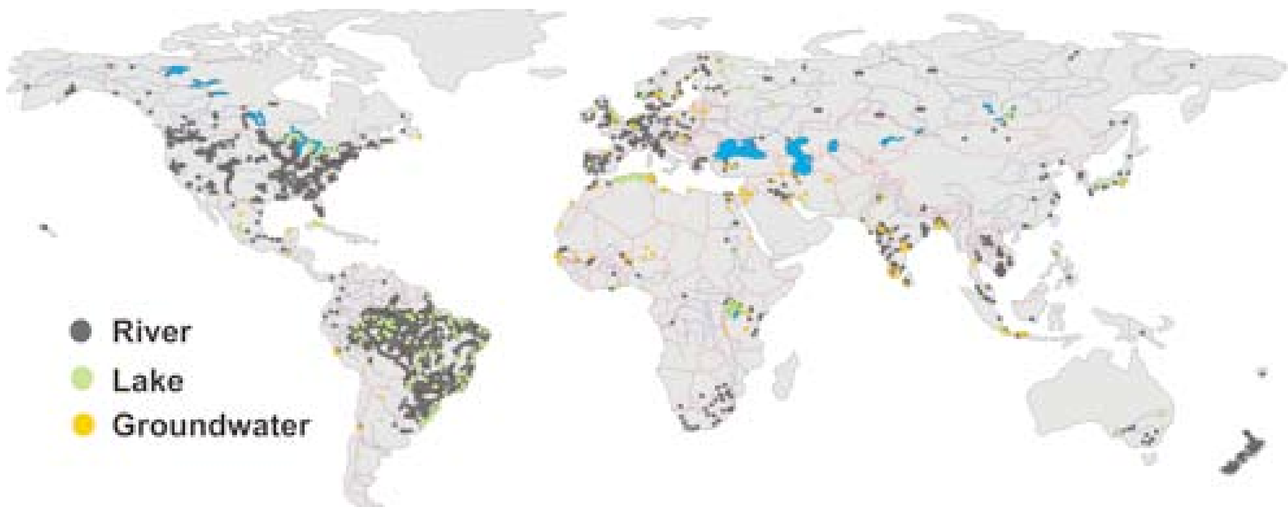
- To determine the status and trends of regional and global water quality through the development of a global network of selected monitoring stations for lakes, reservoirs, rivers, wetlands and ground waters and the compilation of a global database, GEMStat (www.gemstat.org). By compiling a global database from multiple countries, added value was made to country-level data as it could be used to undertake global and regional scale water quality assessments.

GEMS/Water does not actively undertake sampling programmes in countries but relies upon co-operative agreements with participating nations and organizations such as universities and other non-governmental organizations to provide data from their on-going water quality monitoring programmes. Operating in the same way is GEMS/Water's hydrological counterpart WMO's Global Runoff Data Centre (GRDC) located in Koblenz, Germany, which has data for more than 7,000 stations (http://grdc.bafg.de).

Monitoring programmes in 117 participating countries contribute data to GEMS/Water for >3000 stations worldwide (Fig. 1). Unfortunately, there are only 267 lake and reservoir stations (Fig. 2). This means that from an international perspective our ability to follow the status and trends of lake water quality is severely compromised, both in terms of the variety of lake types and the spatial distribution as vast areas of all continents (data from Brazil is most comprehensive) have no monitoring stations. In addition, with such a small number of lakes represented in GEMStat it is difficult to assess how general changes noted in lakes of one region maybe to lakes in another region. Therefore, there is a need to significantly increase this number. In addition, most of these data are for surface samples only and depth-profiles of nutrients, temperature and other parameters are limited to 44 lake/reservoir stations that have two or more sampling depths.

Currently GEMStat is composed of approximately four million data points covering over 100 water quality parameters. A broad classification of the data covers: physical/chemical parameters, major ions, nutrients, metals, microbiological parameters, and organics. New parameters are added in response to the changing needs of water managers and the availability of data. Metadata is also maintained for GEMS/Water to assist in making appropriate use of the information. Geographic distribution of the data contained

Figure 1. The location of GEMS/Water monitoring stations. The total number of stations in 2007 was 3021.



in the GEMS/Water database is widespread with a higher concentration of stations in European countries and the USA (Fig. 1).

The number of stations for which GEMS/Water has data continues to increase and new data received are processed into the database regularly. In this way, GEMS/Water maintains a living database that is continuously updated. Stations are characterized in three classes:

Baseline Stations are typically located in headwater lakes, undisturbed upstream river stretches, and in aquifers where no known direct diffuse or point-sources of pollutants are likely to be found. They are used to establish the natural water quality conditions; to provide a basis for comparison with stations having significant direct human impact (i.e., trend and global river flux stations); to determine, through trend analysis, the influence of long-range transport of contaminants and of climatic changes.

Trend Stations are typically located in major river basins, lakes or aquifers. They are used to follow long-term changes in water quality related to a variety of pollution sources and land uses; to provide a basis for the identification of causes or influences on measured conditions or identified trends. Since trend stations are intended to represent human impacts on water quality, the number of trend stations is relatively higher than the other categories of stations, in order to cover the variety of water quality issues facing various basins. Ideally, each country should cover all major human influences on water quality. Most of the stations are located in basins with a range of pollution-inducing activities. However, some stations are located in basins with single, dominant activities. Some trend stations may also serve as global river flux stations.

Flux Stations are located at the mouth of rivers as they exit to the coastal environment. They are used to determine integrated annual fluxes of critical pollutants from river basins to oceans or regional seas, thereby contributing to geochemical cycles. For calculation of chemical fluxes, it is essential that water flow measurements be obtained at the location of the global river flux stations. It is for this reason that GEMS/Water encourages station co-location with GRDC-designated stations.

Operational problems for a global water quality monitoring system and database

A variety of problems are inherent in operating a global water quality monitoring and assessment programme and generating a database of reliable information. These problems can be classified into three categories:

1. Variability of data between institutions within a country and between countries.

2. Geographical distribution of monitoring stations.

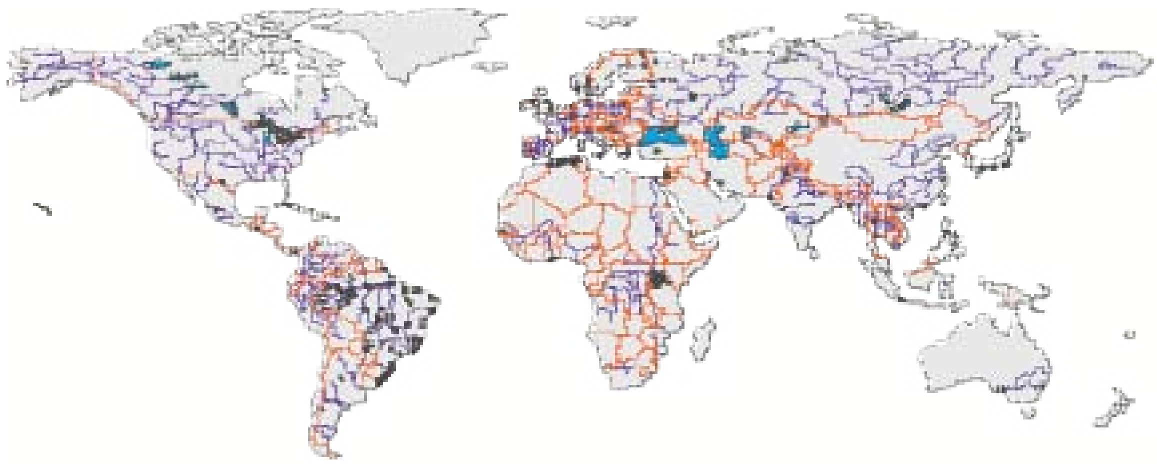
3. Time delays between the collection of data and its transfer to the global database.

Data variability

A number of factors influence the variability of data in the GEMS/Water database. These include such things as the technical capabilities of field and laboratory personnel in a country, quality of analytical equipment, methodology, and the presence of rigorous QA/QC (quality assurance and control) and laboratory accreditation programmes. Although GEMS/Water has a manual of analytical methods it recommends for use, many countries choose to employ their own methods with the result that data is compiled in GEMStat from a variety of methods (Table 2). In large countries with very extensive monitoring programmes, such as Russia, laboratories in different regions also may use different methods for the same parameter.

GEMS/Water operates a QA/QC programme for participating laboratories to help them improve the accuracy and precision of their results and ensure the comparability and validity of water quality analyses performed by laboratories around the world. In the laboratory performance evaluation

Figure 2. The distribution of GEMS/Water lake and reservoir monitoring stations.



studies sealed samples are sent to participating countries. Laboratories are assigned a code number and return the results of their analyses to GEMS/Water. The results are compared to the known concentrations. Each participating laboratory gets a report on their results that highlight their strengths and weaknesses and recommendations on how they can improve their analytical results. Recommended quality control criteria for analytical methods, where precision, accuracy, contamination, recovery and stability are continually monitored to ensure reliability of data, will be provided to laboratories. When the information for all participating countries has been received GEMS/Water also provides a report analyzing all laboratory performances (http://www.gemswater.org/quality_assurance/index-e.html). An example is shown in Fig. 3 which indicates that most laboratories were able to produce satisfactory results although a few are in need of improvement.

An Analytical Methods Dictionary for all methods used in GEMS/Water is also available at www.gemswater.org. The Dictionary provides information on the analytical principle for each method, the equipment required, the Method Detection Limit, and literature references, which will be very useful for both participating laboratories and GEMS/Water in comparing the performance of different analytical methods. In addition, there is a new wiki site where those engaged in water quality monitoring can share their experiences and knowledge about analytical methods (www.ungiwg.org/openwater).

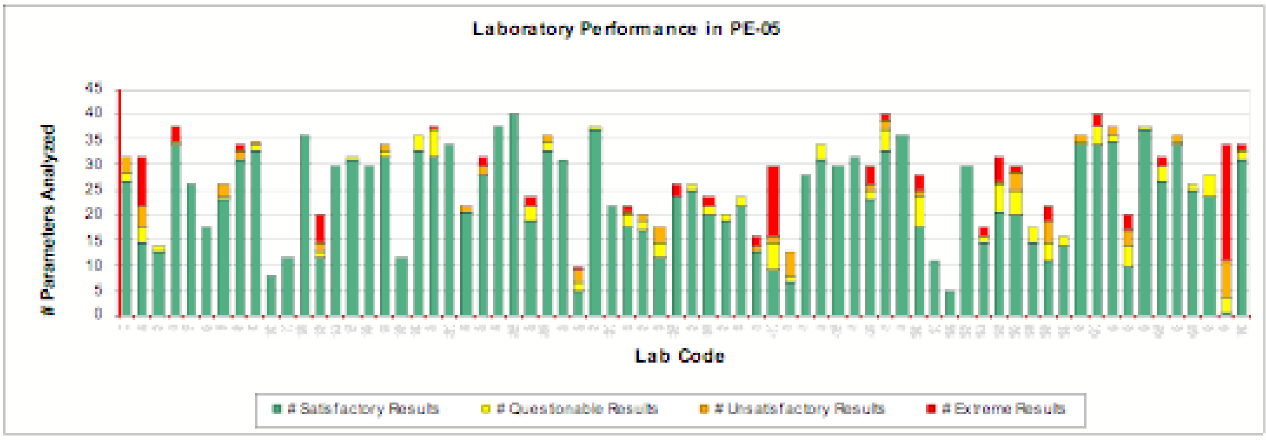
Geographic coverage

GEMS/Water through its network of National Focal Points (NFP = governmental organization in each country nominated by their government to be the official GEMS/Water contact) and Collaborating Focal Points (non-governmental organizations) is working to increase the distribution of stations worldwide to help improve the spatial coverage of stations so that all regions are more equally represented by the data and information in GEMStat. While it is unlikely that GEMS/Water will ever have the equivalent geographic coverage of stations that the GRDC has for hydrological data, significant increases in geographic coverage will

Table 2. Examples of the numbers of methods used per parameter and the range of method detection limits (MDL) of these methods in GEMStat.

Parameter name	Number of methods	Units	MDL range
Total boron	5	mg L^{-1}	0.002 to 40.
Dissolved boron	8	mg L^{-1}	0.02 to 0.06
Nitrate + Nitrite	6	mg L^{-1}	0.005 to 0.25
Ammonia	8	mg L^{-1}	0.001 to 0.5
Dissolved fluoride	6	mg L^{-1}	0.01 to 0.1
Orthophosphate	6	mg L^{-1}	0.0002 to 0.005
Total Phosphate	4	mg L^{-1}	0.002 to 0.005
Dissolved phosphate	2	mg L^{-1}	0.002 to 0.1
Inorganic phosphate	2	mg L^{-1}	0.002 to 0.005
Particulate phosphate	6	mg L^{-1}	0.0004 to 20
Dissolved sulphate	6	mg L^{-1}	0.01 to 5.
Dissolved chloride	7	mg L^{-1}	0.01 to 5

Figure 3. Results of the fifth laboratory performance evaluation study run by GEMS/Water to assess the quality of data being produced by contributing laboratories. Generally most laboratories received a satisfactory rating.



occur. For example, the number of stations for the United States increased from 21 in 2001 to 547 today.

Time delays in transferring data

Electronic based communications through the Internet and the use of email are now the main procedures for communications in GEMS/Water, although data are still provided in other formats. As a result, the age of data varies by country and in too many cases data are now as much as 20 years old. This is due to a number of reasons, including the internal cessation of water quality monitoring programmes for economic reasons. GEMS/Water maintains communication with representatives in many countries and this coupled with the growing recognition of the importance of water monitoring programmes and the ability of countries to carry out such programmes leads to a gradual increase in the number of countries participating in the Programme. GEMS/Water is also able to offer advice on how to set up a water quality monitoring network and on the suitability of a wide range of analytical procedures that will help countries establish and maintain modern water quality monitoring programmes (see Evaluation Services brochure at www.gemswater.org/quality_assurance/index-e.html).

New technologies for water quality monitoring that are rapid, quantitative, field deployable, comprehensive, simple to use, and cost effective are needed to increase the availability of world-wide water quality data as current in-situ technologies, the parameters they are capable of detecting and their high cost make them impractical except in special situations. Laboratory analyses, while comprehensive, are very expensive, labour-intensive and require skilled technicians. For many countries, this is not an option in the foreseeable future. Continued research and development of innovative new technologies are necessary to adequately meet the demands for environmental water quality data.

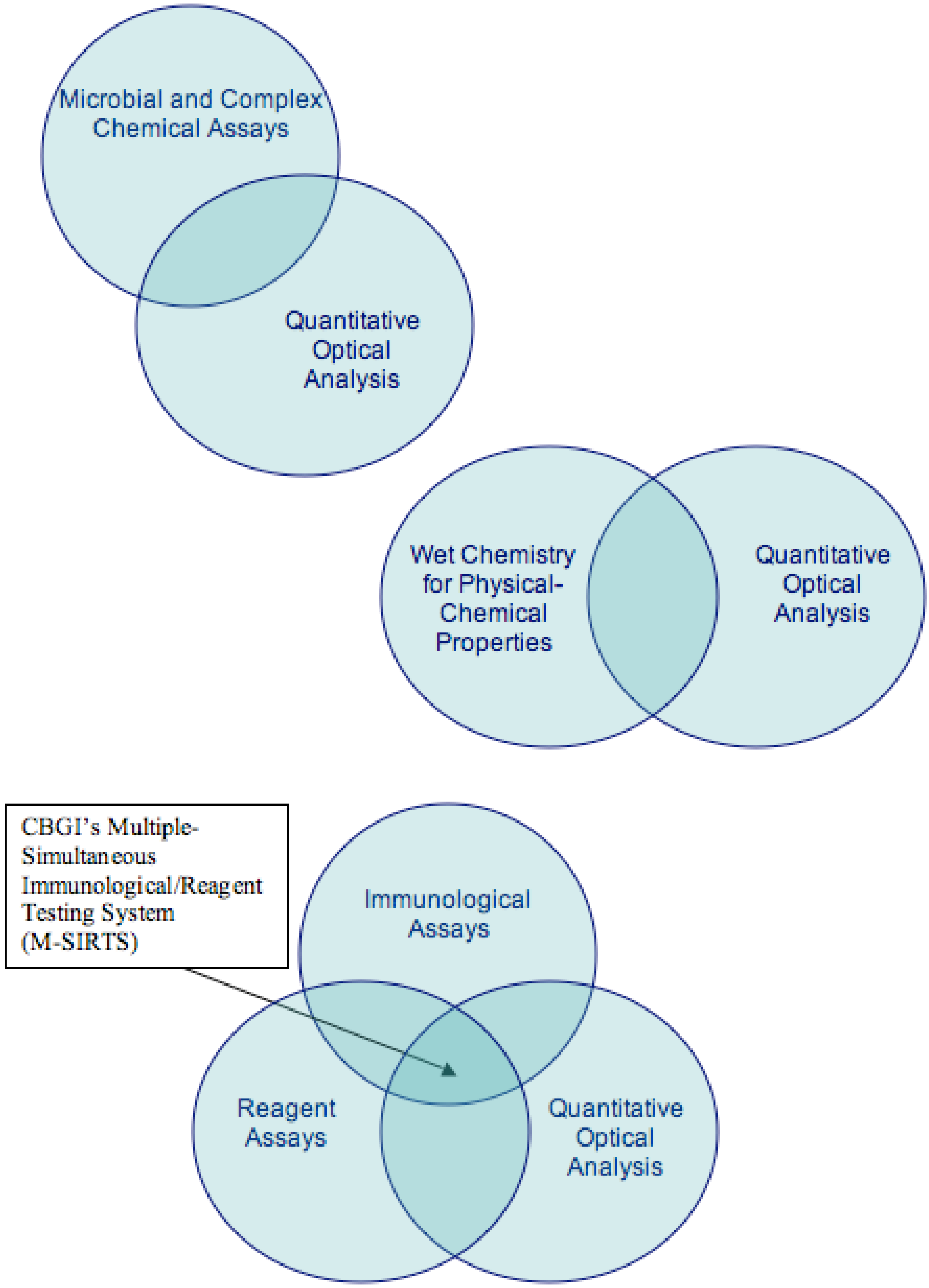
Development of novel, accurate, and precise tests for the detection of physical-chemical properties, biologicals or pollutants in water has mushroomed in the past decade as new technologies have become available. One of the most promising advances, the Sensicore WaterPOINT 870 Multi-Parameter Optical Water Quality Analyzer based on lab-on-a-chip technology, was introduced in 2006 and boasts up to 24 different physical-chemical results in just a few minutes. Other recent technologies used for physical-chemical detection include flow-injection immunoassays (Hennion and Barcelo 1998), dipstick immunoassays (Hennion and Barcelo 1998), test strips coated with colloidal gold particles (Verheijen et al. 2000; Putalun et al. 2004), liposome-amplified immunoassays, electrochemical immunoassays (Ka_ná and Skládal 2002), chemi-luminescent immunoassays (Oi and Zhang 2004), magnetic immunoassays (Liberti et al. 1997), and surface plasma resonance immunoassays (Svitel et al. 2000; Shimomura et al. 2001). Developing technologies for measuring microbial contaminants of waters include: 1) new enzyme/substrate methods that incorporate high-sensitivity fluorescence detection instruments, including dual wavelength fluorometry to simultaneously assess both enzymatic hydrolysis and the loss of substrate (Jadamec et al. 1999), 2) quantitative Polymerase Chain Reaction (qPCR) technology that relies on specific nucleic acid sequences (Noble et al. 2006), and antibody-antigen binding properties, which includes evanescent wave fiber optic biosensors (Wadkins et al. 1995), and 3) Rapid Bacteria Detection (RBD) system which is based on laser flow-through technology (Nobel and Weisburg 2005), and capture of the antigen by antibodies on magnetic beads (Lee and Deininger 2004).

Unfortunately, all of the methods currently being developed for chemical and microbial analysis rely on sophisticated, expensive, lab-based equipment and highly skilled operators. There is currently no single supplier or known technology capable of performing analyses for both physical-chemical and microbial properties in environmental water samples. Chipotle Business Group, Inc. (CBGI) in Texas intends to provide the first water testing system capable of performing multiple immunological and reagent assays, side by side up to 100 total assays, simultaneously using the same quantitative optical detector, thus allowing a much easier, faster, cost effective, and comprehensive testing method. CBGI combines the miniaturization of current reagent assays with a proprietary immunological assay; both types of analyses are preformed simultaneously in a purpose-built detector utilizing quantitative optical analysis as depicted in Figs. 4 and 5. These can be packaged as portable field-deployable units about the size of a medium briefcase, submersible autonomous monitoring units, in-line process flow units, and free-standing laboratory units. Portable/field deployable units and continuous submersible autonomous monitoring stations will allow for: 1) the collection of data in countries with no programme or laboratories; 2) extend existing monitoring areas without greatly increasing costs; and 3) ensure uniformity of quality data, especially for large countries with many regional labs of different standards.

Data and information sharing and use - GEMStat and Google Earth

Today data is sent to GEMS/Water mainly in an electronic format, either over the internet, by email, on disk and still occasionally in hardcopy form. While GEMS/Water has a preferred format for data, data can be accepted in most file types. These are then converted in the Programme Office using GEMSoft, a software package that was developed to generate the GEMS/Water format (Fig. 6). Following formatting, a number of statistical tests are run to look for outliers and other anomalies due to incorrect data entry or suspect analytical result. Incoming data are also compared with historical data to see if there have been major changes in any of the submitted parameters. If there are, the submitting NFP or CFP will probably be contacted for an explanation.

Figure 4. Conceptual models of current water quality analyses (microbiological and basic physical-chemical assays are done separately) as compared to the integrated one-step design of the CBGI approach, which is possible with miniaturization of the test units (see Figure 5).



Data entered into GEMStat are geo-referenced by latitude and longitude and they are also assigned a method code. A key to these methodological codes is available on the GEMS/Water website, which helps data users compare data collected from different laboratories around the world. In order for data users to access GEMStat on the web a mirror copy is migrated across a firewall (Fig. 6). Through GEMStat users can generate summary statistical tables and various types of graphs. Similarly, users can also produce graphs of loading data for some parameters at the joint GEMS/Water-GRDC stations. Station locations can be viewed in their geographical locations via Google Earth (Fig. 7). By clicking on the GEMS/Water icons GEMStat can be accessed.

Many governments around the world are becoming increasingly interested in developing national data and information systems, as well as in ensuring their interoperability. Interoperability refers to the ability of a database or system to exchange information and to use the information that has been exchanged. Often this is achieved using Open Web Services. Open Web Services refer to using the World Wide Web so that database services, like GEMStat, can promote their presence and capabilities, and other services can find and connect to them. Standards and specifications are developed by industry, academic, governmental and other interested parties. These groups include the Open Geospatial Consortium, OASIS, and the Open Archive initiative, and the specifications they develop are published openly, for use by their members or anyone else at no cost (see www.opengeospatial.org/pressroom/pressreleases/843). The outcome is flexibility to identify and fit services to particular needs.

Open Web Services also allow other agencies and researchers to incorporate GEMStat data into their own research and assessments, with less demand on GEMS/Water to select and prepare data. The result will be more extensive and more frequent use of GEMStat data, and more feedback from users to ensure the quality and utility of these data.

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Fig. 5. Disassembled CBGI multiple parameter cassettes. Each of the 100 wells represents an independent assay that can either be a reagent assay or high concentration immunoassay. A second cassette is required for very low concentration immunoassays and utilizes a standard 100 ml sample size.

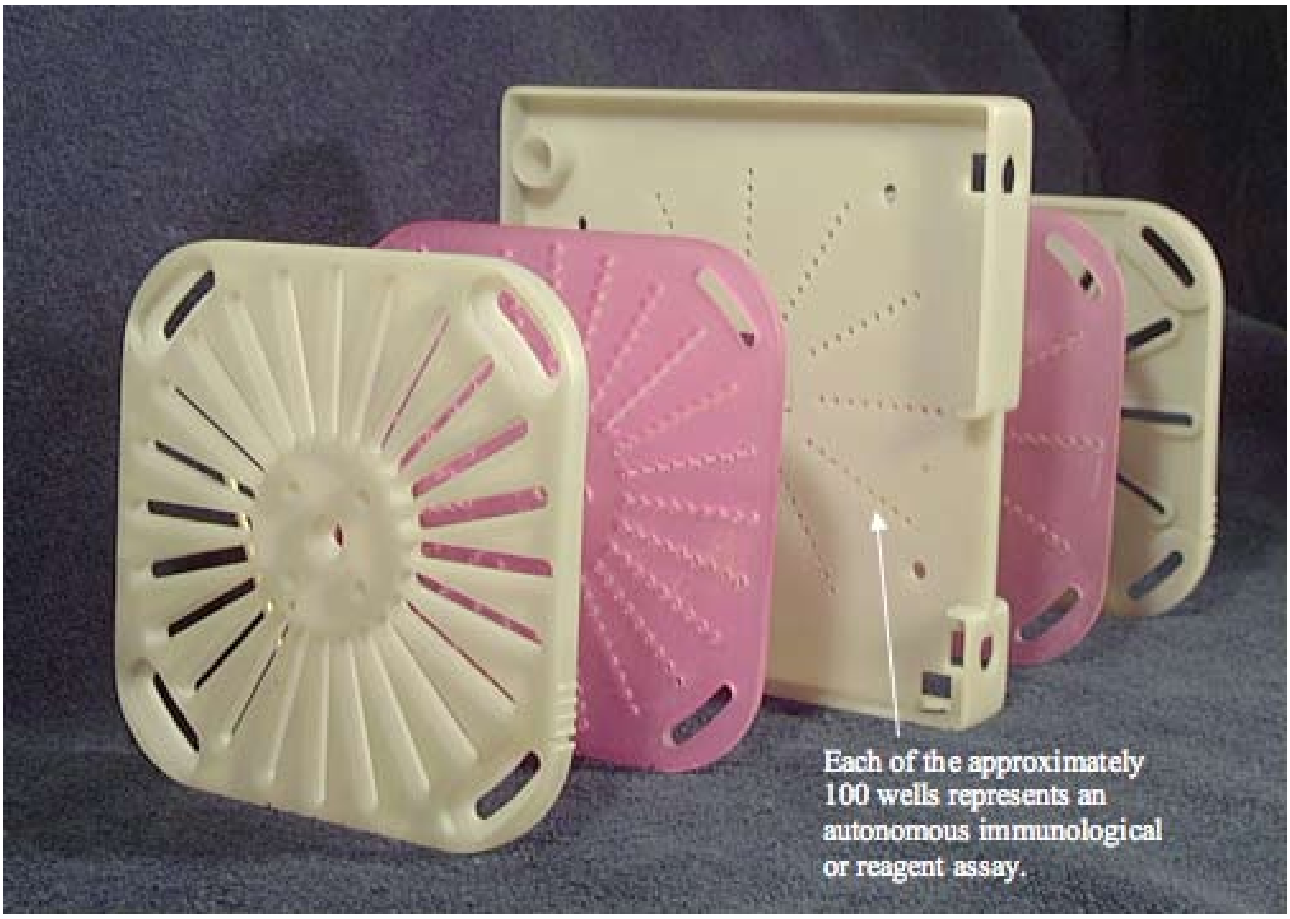

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Fig. 6 The UNEP GEMS/Water Programme's architecture.

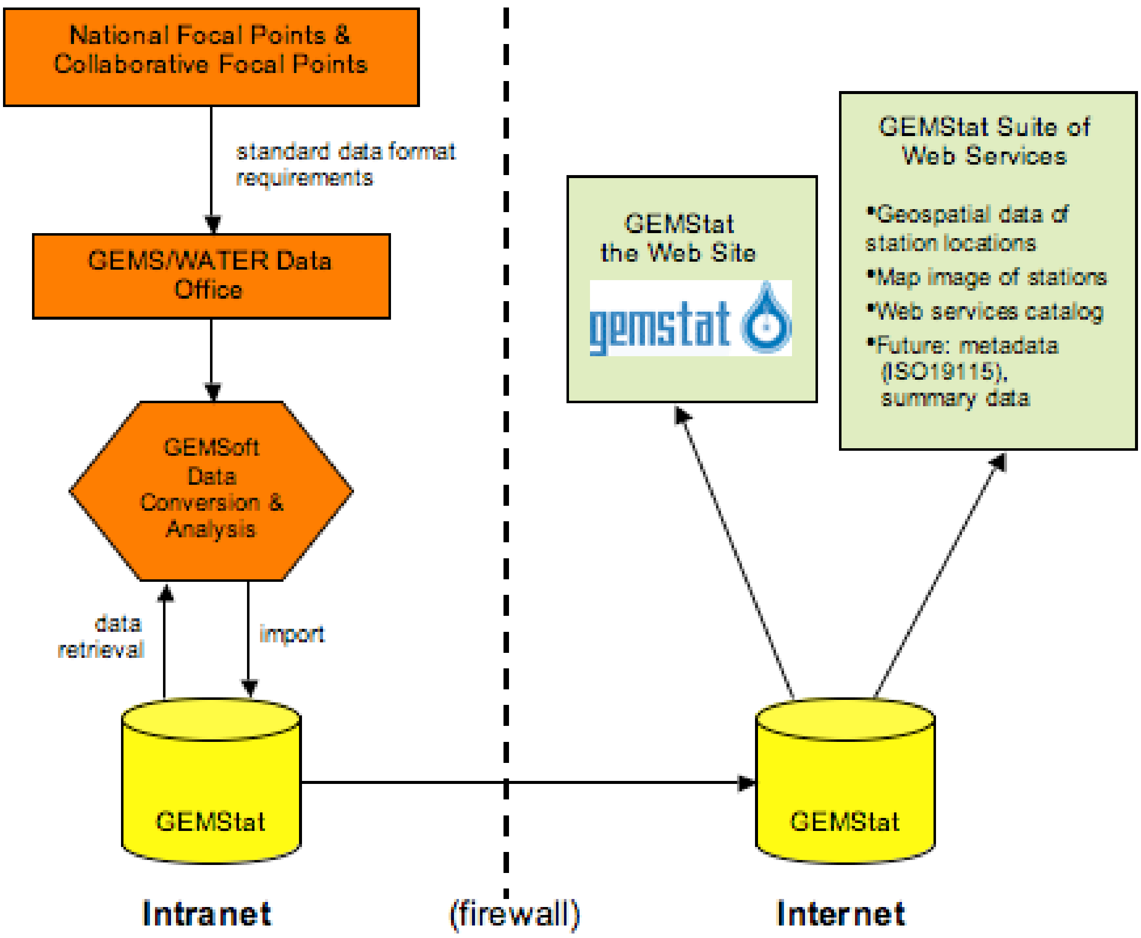

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Fig.7 Monitoring stations for all countries participating in GEMS/Water can visualized with Google Earth through www.gemstat.org. Shown in this example is the distribution of GEMS/Water Programme monitoring stations in India.