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Intelligent infrastructure for sustainable potable water: a roundtable for emerging transnational research and technology development needs

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Abstract

Problem statement: Recent commercial and residential development have substantially impacted the fluxes and quality of water that recharge the aquifers and discharges to streams, lakes and wetlands and, ultimately, is recycled for potable use. Whereas the contaminant sources may be varied in scope and composition, these issues of urban water sustainability are of public health concern at all levels of economic development worldwide, and require cheap and innovative environmental sensing capabilities and interactive monitoring networks, as well as tailored distributed water treatment technologies. To address this need, a roundtable was organized to explore the potential role of advances in biotechnology and bioengineering to aid in developing causative relationships between spatial and temporal changes in urbanization patterns and groundwater and surface water quality parameters, and to address aspects of socioeconomic constraints in implementing sustainable exploitation of water resources. *Workshop outcomes*: An interactive framework for quantitative analysis of the coupling between human and natural systems requires integrating information derived from online and offline point measurements with Geographic Information Systems (GIS)-based remote sensing imagery analysis, groundwater–

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surface water hydrologic fluxes and water quality data to assess the vulnerability of potable water supplies. Spatially referenced data to inform uncertainty-based dynamic models can be used to rank watershed-specific stressors and receptors to *guide researchers and policymakers in the development of targeted sensing and monitoring technologies, as well as tailored control measures for risk mitigation of potable water from microbial and chemical environmental contamination*. The enabling technologies encompass: (i) distributed sensing approaches for microbial and chemical contamination (e.g. pathogens, endocrine disruptors); (ii) distributed application-specific, and infrastructure-adaptive water treatment systems; (iii) geostatistical integration of monitoring data and GIS layers; and (iv) systems analysis of microbial and chemical proliferation in distribution systems. *Impact*: This operational framework is aimed at technology implementation while maximizing economic and public health benefits. The outcomes of the roundtable will further research agendas in information technology-based monitoring infrastructure development, integration of processes and spatial analysis, as well as in new educational and training platforms for students, practitioners and regulators. The potential for technology diffusion to emerging economies with limited financial resources is substantial.

Keywords: Sustainability; Potable water; Sensors; Information technology; Point-of-use treatment

1. Introduction

The sustainability of groundwater resources in coastal zones bounded by freshwater and saltwater bodies is affected by human activities as the result of residential, commercial, agricultural and industrial land use, which has resulted in overuse as well as microbial and chemical contamination (Francy et al., 2000; Thomas, 2000; Daughton and Ternes, 1999). The increased urbanization has affected the hydrological cycle in coastal regions whereby the increase in impervious surfaces has impacted aquifer recharge, and consequentially the flow of rivers and streams, groundwater–surface water interactions and, ultimately, the chemical and microbial quality of recycled drinking water (National Research Council, 1998). As a result, several national efforts have been initiated to quantify the cause-and-effect relationships between human activities, groundwater and surface water quality, and the recycling of potable water reserves. For example, the U.S. Geological Survey (USGS) National Water Quality Assessment Program (NAWQA) has during the last 10 years (Cycle I) investigated relationships between the occurrence and distribution of water quality constituents to natural and human factors, and has provided interpreted qualitative information to policy makers and resource planners (Francy et al., 2000). The Cycle II Program objectives are to focus on trend assessment and understanding of processes controlling water quality. The complementary efforts guided by the National Research Council and the American Chemical Society (ACS) on the recycling of potable water have highlighted the concerns and needs associated with the detection, treatment and removal of effluent-derived microbial and chemical contaminants (e.g. NRC, 1998; Sedlak et al., 2000).

The development of quantitative correlations between population settlement patterns and potable water quality will require the integration of: (i) a proper description and *definition of the systems boundaries (remote sensing and geostatistics), (ii) approaches to quantify systems interaction (modeling and trend analysis), (iii) selection of water quality indicators and sensing strategies, and (iv) appropriate methods for data interpretation, integration and use.*

Interactive frameworks for quantitative analysis of the coupling between human and natural systems in urban coastal environments, by integrating information derived from Geographic Information Systems (GIS)-based remote sensing imagery analysis with groundwater–surface water hydrologic fluxes and water quality data to assess the vulnerability of coastal aquifers to the deterioration of potable water supplies (Fig. 1). The concept incorporates the following elements: (1) online and offline spatially referenced microbial and chemical point measurements (sensing); (2) geostatistical integration of point measurements with GIS layers (uncertainty analysis); (3) distributed parameter models to describe the watershed in terms of connectivity and fluxes; (3) unbiased environmental forensics techniques for source apportionment (coding); and (4) spatially referenced distributed control technology networks (management).

By adopting an adaptive modeling approach coupled to geostatistical validation, it is expected that watershed-specific rankings of stressors and receptors will guide researchers and policymakers in the development of targeted sensing and monitoring technologies, as well as tailored applications for risk mitigation of potable water from microbial and chemical environmental contamination. Information dissemination on innovative sensing and source control strategies for microbial and chemical contamination in urban environments is a major sanitation and developmental priority in emerging economies and developing countries, with the spread of infectious diseases policy and response agendas. Considering the scarce resources available in less prosperous urban environments, regulators and city engineers would significantly benefit from decision support systems capable of targeting the spatial distribution of contaminant input into the raw water resources, and thus the implementation of early warning monitoring networks (for fecal or other input), source control systems and need/breakdown of water treatment strategies.

The diffusion of innovative technologies for environmental sustainability from developed nations to emerging economies was the topic of an Organization for Economic Cooperation and Development (OECD)-sponsored conference in Seoul, 2000 (www.waitro.org), and of the World Association of Industrial and Technological Research Organizations (WAITRO; www.oecd.org/dataoecd/19/60/2432617.pdf) conference in The Hague (2000). It was reported that the main impediments to closer integration are perceived to be issues of technological competition, economics of implementation and effective communication. Hence, early engagements through a roundtable discussion at smaller but focused venues such as International Society for Environmental Biotechnology (ISEB) 2002 will stimulate information dissemination and exploration of eventual partnerships in this effort on economically feasible technologies for sustainable potable water supplies. This venue is particularly relevant since attendance at ISEB conferences tends to include substantial participation of members from the Asian subcontinent, South and Central America, and European participants, as well as members of multilateral organizations.

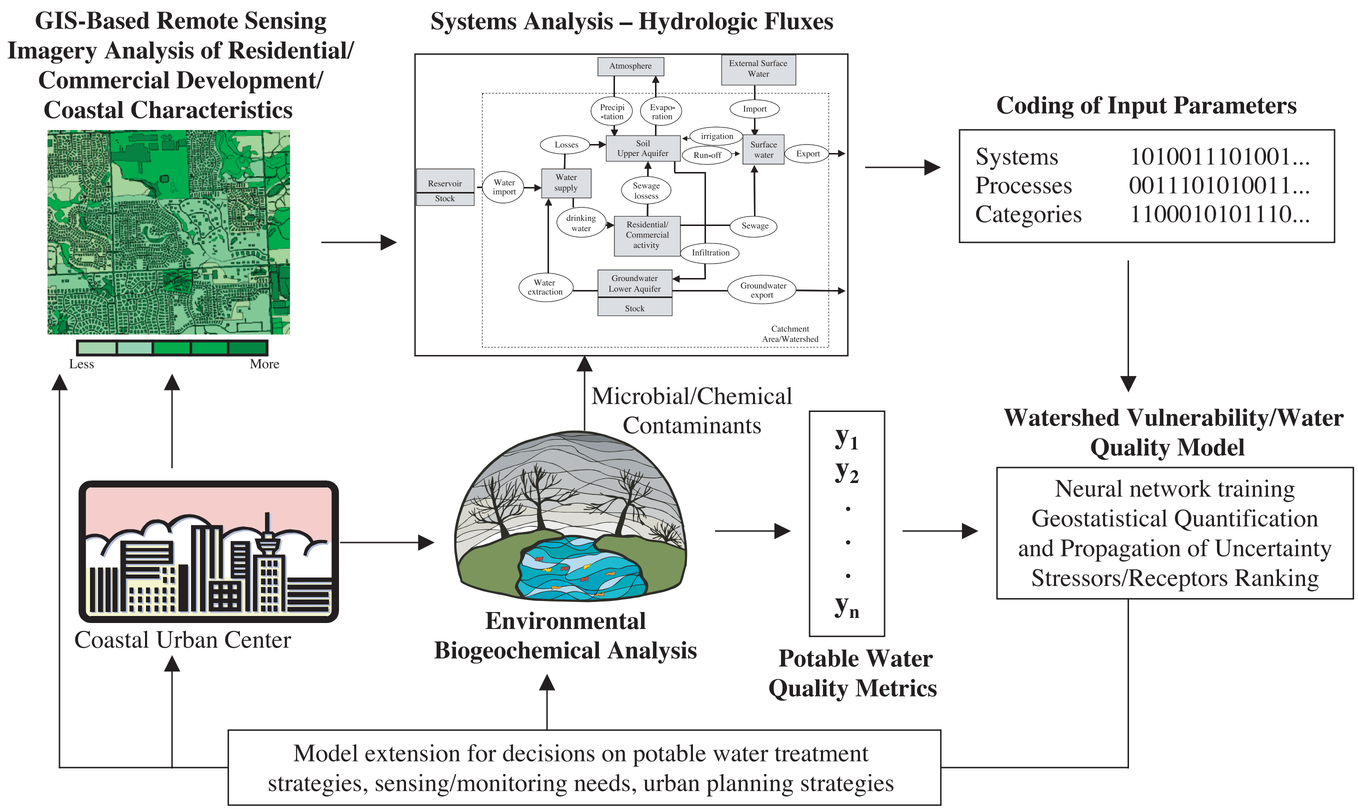

Fig. 1. Conceptual framework for an interactive decision support system.

2. Materials and methods

The roundtable involved five participants from leading organizations to provide a genesis for discussion in the ISEB forum. The lecturers were instructed to highlight key elements relevant to the enabling technologies required in this framework for 20 min each, followed by 2 h of discussion by the general audience. Specifically, the aim of the workshop was to frame questions and discussion within the following context:

(a) *Evaluate innovative monitoring technologies for watersheds and define research needs*. Chemical and microbial contamination of potable water supplies in urban coastal aquifers is mainly affected by nonpoint sources resulting from impervious surface coverage, and point sources such as wastewater effluent discharge. What is the current status of environmental mapping and microbial/chemical monitoring in wastewater, groundwater, surface water and drinking water? Issues that should be addressed include but are not limited to: central vs. decentralized monitoring, current and emerging chemical and microbial pollutants, the integration of point measurements and GIS layers, applications of sensors for offline and online monitoring.

(b) *Distributed water treatment technologies in urban centers and define research needs*. The changing land-use not only has affected water quality but increased the need to monitor for and treat both traditional and emerging microbial and chemical contamination in advanced and developing societies. Issues which were covered include: economic and technological merit of distributed (point-of-use) water and wastewater treatment systems, protozoan and viral disinfection efficiency in water treatment systems, and innovations in treatment technology aimed at advanced and poor economies.

(c) *Assess the requirements for data analysis, integration, and technology-based decision support systems*. Regulators, city engineers and planners require decision support systems for technology or management practice implementation. Considering the plethora of data that is collected on an on-going basis in many interconnected systems, at various spatial and temporal scales, a rational framework capable of quantifying uncertainty for decision-making should be implemented. Issues to be addressed here pertain to: data collection and integration, data interpolation and interpretation, modeling and (geo)statistical approaches aimed at combining and propagating associated uncertainties, interactive visual decision support systems.

(d) *Evaluate the needs for professional training and technical expertise*. Training and education of graduate students, practitioners and the public is central to the acceptance of technology implementation. New generations of experts with an in-depth knowledge of environmental processes, monitoring and control technology, and resource management will need to be educated. City managers and engineers have to be trained to understand and use innovations aimed at sustaining potable water production and propagation. The public needs to be brought into the discussion early on in the process to enable successful transitions into a new era of increased water reuse. Issues to be addressed are: types of interactive educational platforms, web-based training and education, new curriculum development, integration of local, regional, national and global perspectives with emphasis on technology diffusion between countries of variable socioeconomic development.

3. Results and discussion

3.1. Recent advances toward automated microbial analysis in natural and engineered aqueous systems (Skerlos)

Urbanization has impacted the public water supply in numerous ways that have resulted in an increase of chemical and microbial contamination. Moreover, new water management measures, such as direct injection of highly treated municipal wastewater to augment the raw water supply, are frequently implemented due to increasingly scarce new water sources and the demand of growing populations. It is expected that these trends will exacerbate microbial hazards in natural and engineered environmental systems. Whether intentional, or as the by-product of urbanization, microbial contaminants pose proven and potential risks to public health, and demand increasingly stringent water quality monitoring and treatment. This must include novel technology to enable online monitoring of microorganisms and their activity both in source and finished waters.

Solutions to the technological challenges of achieving automated, low-cost, and robust detection of microbial parameters of interest in field applications are currently under research in numerous laboratories around the world. The technological challenges are many and can be divided into three subcategories: (1) sample preparation, (2) sample detection, and (3) data analysis and interpretation. Current research approaches and advances in all three of these areas based upon a review of recent academic and industrial research activity indicate that distributed microbial detection and quantification is highly dependent on near-term technological capabilities for online microbial detection, quantification and analysis.

On-going research at The University of Michigan directed toward the development of an early warning microsensor infrastructure for the detection of microorganisms in aqueous systems has indicated that technology under development based on the principle of flow cytometry is promising for distributed microbial sensing. Rapid optical detection methods, based on proven technology such as flow cytometry, offer high-speed multiparametric data acquisition, are compatible with molecular detection and quantification methodologies, and are amenable to miniaturization. The overall requirements and constraints of distributed microbial sensing and control technology include: very low cost, large span, low maintenance, automated, compact, fast, versatile, artificially intelligent, networkable (desired). Whereas flow cytometry technology is standard bench-top methodology, our application is novel in that only the basic functions necessary for microbial detection and quantification have been maintained. As these functions have been miniaturized and integrated in accordance with recent advances in micro-electromechanical systems (MEMS) technology, the instrument is named the Micro Integrated Flow Cytometer (MIFC) (Fig. 2). The ultimate goal for the MIFC is to reduce the size and cost of flow cytometry technology applied for basic environmental field analysis by two orders of magnitude. The main challenges for this technology will require research

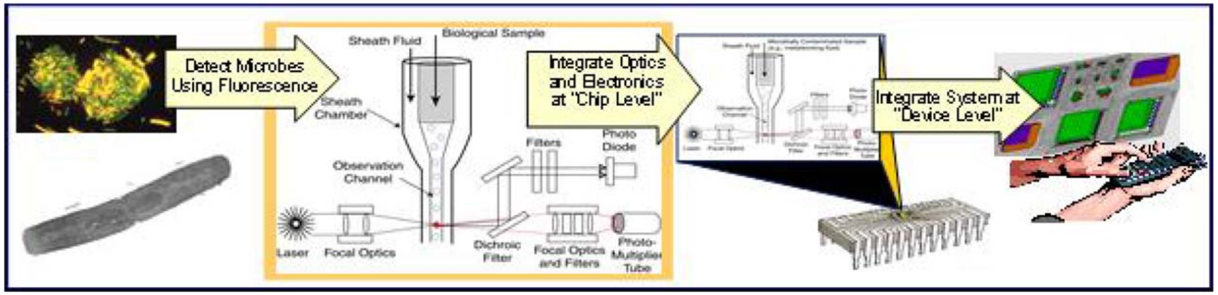

Fig. 2. Concept of microintegrated microflow cytometry for distributed microbial sensing (http://www.engin.umich.edu/news/flowcytometer/index.html).

advances in the areas of automated microbial sample preparation, detection and data analysis as they relate to the development of the MIFC. The technology development is currently in the pre-prototype stages, and the impact of miniaturization is being validated using *Mycobacterium parafortuitum* and protozoan cells as target screening organisms. Optical detection of the former is realized using general DNA stains, and fluorochrome-labeled antibodies and peptide nucleic acid (PNA) molecular beacons (Skerlos et al., 2001; Chang et al., in press; Gruden et al., in press).

3.2. Distributed chemical sensing capabilities based on microarrays (Edwards)

Wastewater effluents, municipal sewage and agricultural runoff following field applications of manure have been shown to introduce trace levels of endocrine-disrupting compounds (EDCs). The endocrine system controls cellular activities throughout the body, enabling the many cells and tissues of the body to work together as a single organism. Almost all actions undergone by animals are in some way regulated or influenced by the endocrine system, which also guides the organism's growth, development, and behavior. The endocrine system can be influenced by a wide range of chemical compounds. Bioactive compounds are found in most major classes of pollutants, including dioxins and furans, halogenated organic compounds, poly-chlorinated biphenyls, phthalate esters, pesticides (both banned substances such as DDT and others currently in use, such as atrazine) and a number of other pollutants, such as polyaromatic hydrocarbons, tri-butyl tin and heavy metals. Many of these compounds are highly persistent in the environment and are capable of bioaccumulation and biomagnification in living organisms (e.g. Hewitt and Servos, 2001). Many pharmaceutical products and medical wastes likewise influence the endocrine system, and disposal of these substances can introduce EDCs into the environment.

The detection of these trace compounds and their activity in the environment, and their potential for amplification in humans presents an enormous challenge to the scientific community due to the lack of understanding on their persistence and causal relationships in living systems. A variety of testing methods have been developed to investigate EDCs (for a review, see Jobling, 1998). These include physical and chemical fractionation methods, the study of biomarkers in sentinel species, in vitro and single mode of action (MOA) oriented in vivo and in ovo assays, and life cycle or multigenerational in vivo tests. Considered one of the most accurate means of environmental testing involves in vitro or single MOA-oriented in vivo and in ovo tests (Baker, 2001). At the same time, they are the most cumbersome, time consuming, and expensive to perform, unless one can capitalize on DNA microarray-based technology. This new genomics technology is revolutionizing our ability to achieve rapid throughput of thousands of simultaneous hybridization reactions at a time. Significant developments in robotics, surface chemistry and miniaturization have permitted rapid developments (Schena et al., 1995). In most configurations, a DNA microarray is a glass microscope slide onto which many thousands of DNA samples are spotted in a grid. DNA or messenger RNA is extracted from cells or tissues, labeled with specific fluorescent molecules and hybridized to the spotted DNA on the glass slide. The resulting image of fluorescent spots is visualized in a confocal scanner and digitized for quantitative analysis (Fig. 3).

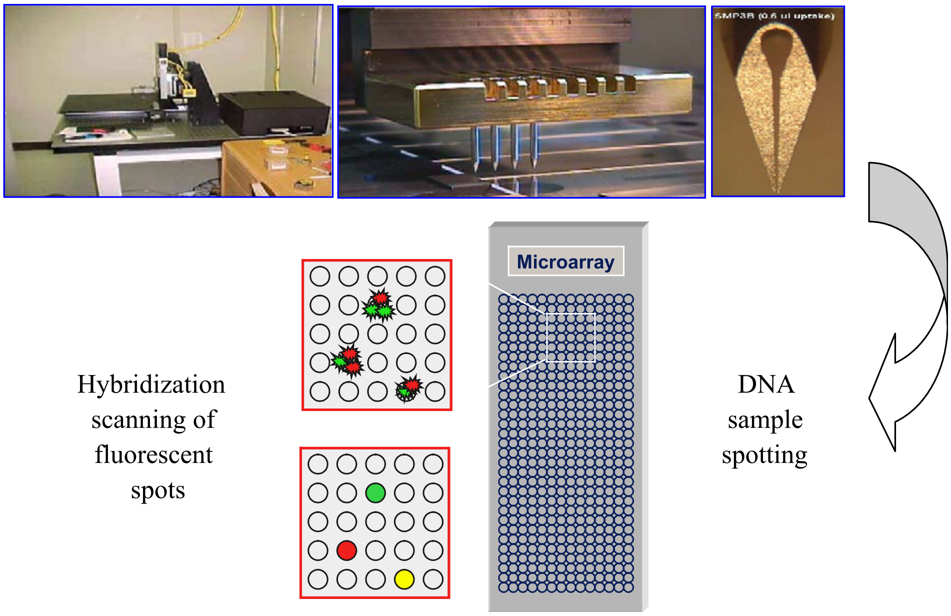

Fig. 3. Concept of microarray applications to screen the impact of EDCs on gene expression.

The approach presented here was illustrated using research conducted at the University of Toronto to assess the endocrine-disrupting capacity of bleached Kraft mill effluents of the pulp and paper industry using 19,000 immortalized human cell lines, including the breast cancer cell lines T-47-D and MCF-7 (Kandouz et al., 1999), which express the estrogen receptor, as the test system from which to extract mRNA. These cell lines have been well studied, are easy to grow and express a number of hormone receptors, including the estrogen and androgen receptors. The results indicated that DNA microarrays provide a "snapshot" of transcriptional activity in tissue samples, showing which genes were actively expressed within the cells at one point in time. By combining this technology with human cell lines grown in vitro, it should be possible to conduct relatively rapid and straightforward assays to identify EDCs by observing the changes in gene expression patterns in response to exposure (Francois et al., this issue). Future developments into rapid screening technology for EDCs in raw and treated waters should provide a better understanding of the contributing impacts of industrial and domestic sources towards the chemical quality of drinking water resources.

3.3. Geostatistical integration of monitoring data and GIS layers (Goovaerts)

One of the main issues pertaining to the measurement of water quality indicators is the uncertainty of quantitative point measurements, and its propagation in space and time. In other words, whereas the false positive/false negative specifications of monitoring tools may be validated, its propagation in spatially referenced domains may be much more significant than that of instrument specificity. Recent years have witnessed the development of GIS capabilities for conducting spatial analysis of environmental data, including the characterization of space-time structures (semivariogram analysis), the spatial interpolation of scattered measurements (e.g. kriging of meteorological data or soil properties) to create spatially exhaustive layers of information, the assessment of the uncertainty attached to spatial interpolation and more generally the quantification of the quality and accuracy of produced maps. Most of this analysis is being carried out using geostatistics, which provides a set of tools for incorporating the spatial and temporal coordinates of observations in data processing. Of critical importance when coupling GIS data and environmental models is the issue of error propagation, i.e., how the uncertainty in input data translates into uncertainty about model outputs. Methods for uncertainty propagation, such as Monte Carlo analysis, are critical for estimating uncertainties associated with spatially based policies in the area of agriculture or environmental health, and in dealing effectively with risks.

The first step to linking urbanization and water quality will require characterization of the main spatial patterns displayed by the organic constituents as well as their cross-correlation across the study area. The geostatistical analysis (Goovaerts et al., 1993; Goovaerts, 1997) needs to include the following steps: (1) computation of direct and cross-semivariograms to identify major scales of spatial variability and perform a first grouping of constituents according to their spatial patterns, (2) fitting of a linear model of co-regionalization and analysis of matrices of co-regionalization which describe the correlation between the different constituents at various spatial scales, (3) kriging and mapping of regionalized factors which summarize the major patterns at different scales. The so-called factorial kriging analysis can be viewed as a principal component analysis of constituents that takes into account the regionalized nature of the information available. Comparison of maps of regionalized factors with GIS layers will provide useful information on the factors (e.g. anthropogenic vs. natural) that likely influence the spatial distribution of constituents. For example, variables that are controlled mainly by the geological characteristics of the aquifer tend to display large-scale variability while the impact of human activities is more local and creates short-scale variability. The end product of this essentially descriptive study will be the selection of constituents that are likely influenced by urban developments (Fig. 4).

The second step necessitates the development and comparison of models that allow the prediction of water quality parameters identified in Step 1 from GIS-based layers of information. Following recent USGS work (Conrads and Roehl, 1999), two types of models appear to have substantial merit: deterministic (physics-based) models of transport and water quality phenomena that predict how a natural system will behave under scenarios of interest, and artificial neural networks (black box) that are large networks of extremely simple computational units, massively interconnected and running in parallel.

The approaches used at The University of Michigan (Fig. 4), using an example from Yoon (1996), illustrate that watersheds can be compartmentalized into geomorphologically defined areas first, after which source apportionment of chemical or microbial impact can be calculated using unbiased statistical tools (e.g., polytopic vector analysis, Barabas et al., in press) to quantify the weighted (coefficient A) contribution of each potential source (factor *F*). This will then ultimately allow for running 'what if' scenarios to determine possible watershed management strategies. Whereas the distributed models have been developed and validated against a range of watersheds, the integration of spatially

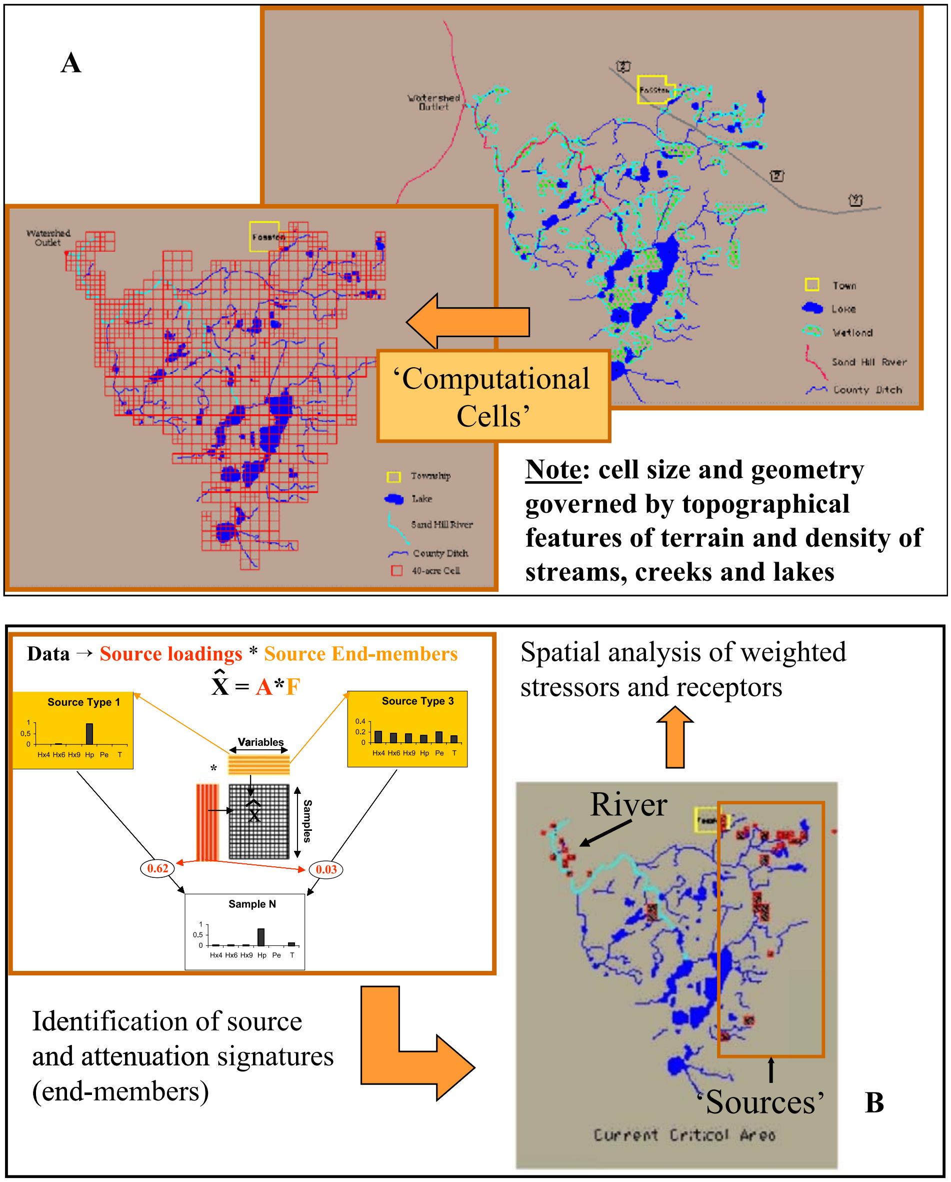

Fig. 4. Distributed computational model incorporating geographical features (A), and forensic analysis of potential source contributions to impacted watersheds (B).

referenced chemical and microbial sensing modules to allow for source apportionment and weigh their contribution has to date received scant attention, but clearly will be possible as computational strength, and the capacity of offline and online sensing improves. In the United States, the national Science Foundation (NSF) is attempting to address the latter via an initiative (Collaborative Large-Scale Engineering Assessment Network for Environmental Research, or CLEANER) currently being developed via a series of workshops. The ultimate goal of this initiative is to allow for systematic and dynamic evaluation of ecosystems conditions and flows across and within media, to improve management strategies for ecosystems by controlling anthropogenic inputs and applying remediation techniques.

In practice, it is commonly found that the statistical accuracy of physics-based models is poor because natural systems are too complex for deterministic modeling method, which was the reason Roehl and Conrads (2000) obtained more accurate predictions using artificial neural networks. Hence, a methodology needs to be developed to account for uncertainty attached to parameters of physics-based models and their input values, to propagate that uncertainty through the model (Heuvelink, 1998). The output of the deterministic models will no longer be a single value for the water quality parameter but a set of possible values with the corresponding probability of occurrence. The accuracy and precision of such models of water quality uncertainty then has to be integrated with well observations. A similar methodology will need to be adopted to conduct a sensitivity analysis (Helton, 1997) of the components of the models, which will help identifying the factors that have the largest impact on water quality parameters and thus need to be better monitored.

3.4. Distributed technology for water treatment in developing countries (Egli)

In recent years, the concept of point-of-use water treatment technologies has gained wide support at the research and policy levels, as this approach allows for technology development and implementation depending on water quality and water use characteristics, as well as depending on socioeconomic boundaries. Distributed optimal technology networks (DOTNet) concepts have been advanced to separate treatment requirements depending on end use (e.g, industrial, commercial, domestic and drinking water) from a range of waste streams (e.g. blackwater, recycled water, surface water and groundwater). Unproven at this time to be economically viable, the inherent assumptions made in the approach seek to optimize energetic benefit for optimal treatment of lesser amounts of material (water). In its technology optimization, DOTNet incorporates the entire suite of water treatment strategies available to consumers, ranging from desalinization, to membrane filtration, activated carbon filtration and biological treatment systems. The DOTNet approach also exhibits significant potential for technology export to emerging economies and developing countries as relevant to Africa.

One technology developed by the Swiss Federal Institute for Water Science and Technology (EAWAG), and endorsed by the World Health Organization (WHO) for developing countries is SODIS, or Solar Water Disinfection Process (Fig. 5). Its potential for impact is clear: Almost one third of the population in developing countries has no access to safe drinking water, resulting in 4 billion of cases of diarrhoea, 2.2 million of which are fatal primarily for children under 5 (WHO, 2001). The Solar Water Disinfection (SODIS) process is a simple technology used to improve the microbiological quality of drinking water (http://www.sodis.ch/). It uses solar radiation to destroy pathogenic microorganisms, which cause water-borne diseases (Wegelin et al., 1994). SODIS is ideal

Fig. 5. Principle of SODIS (www.sodis.ch).

to disinfect small quantities of water. Contaminated water is filled into transparent plastic bottles and exposed to full sunlight. Sunlight is disinfecting the water through two synergetic mechanisms: radiation in the spectrum of UV-A (wavelength 320–400 nm) and increased water temperature. In order to disinfect drinking water through radiation, the container needs to be exposed 6 h to full sunlight. If the water temperature raises above 50 °C, the disinfection process is three times faster.

Preliminary field studies in Bolivia, Burkina Faso, China and Colombia have shown that the process works, and indicate that the cases of diarrhoea may be reduced up to 80% by treating the water with SODIS before use. For example, it was determined that SODIS requires relatively clear water with turbidity of less than 30 NTU, and exposure length is dependent on cloud cover (6 h to 2 days). The most favorable region for SODIS lies between latitudes 15°N and 35°N. These semiarid regions are characterized by high solar radiation and limited cloud coverage and rainfall (3000 h of sunshine per year). The second most favorable region lies between the equator and latitude 15°N, the scattered radiation in this region is quite high (2500 h of sunshine per year). Various types of transparent plastic materials are good transmitters of light in the UV and visible range of the solar spectrum. Whereas in concept this approach is promising, the specifications will need to be adapted to the actual quality of the raw water supply under consideration, and hence, the dependence on the spatially referenced watershed quality parameters.

4. Conclusions

Raw water resources are increasingly stressed by chemical and microbial contamination due to urban development, industrialization, agricultural practice and overdrawing of aquifers, and require monitoring and data interpretation to meet the sanitation and drinking water needs of the global population. Whereas this issue is at the forefront of public and political debate, and solutions have been advanced in the realm of economics and public health policy, there is a role for professional organizations such as ISEB to help define the potential role of biotechnology and bioengineering in the scientific and educational debate.

This roundtable brought an applied research vision to capitalize on the integration of information technology and molecular-based sensing technology platforms such as microflow cytometers and DNA arrays to ultimately develop real-time data collection, interpretation and dissemination infrastructure across socioeconomic boundaries. Decision support systems, to help the regulatory and environmental public health communities manage stressed water resources, depend on distributed sensing platforms, and a robust means to integrate and interpret the data from a chemical and microbial perspective to allow for the implementation of point-of-use treatment technology. Emphasis was placed on technological innovations, which could be adapted for remote data collection, as a chemical and microbial baseline condition needs to be established against which anomalies are benchmarked. Hence, point measurements need to be integrated with GIS layers to develop a risk framework applicable to local or regional spatial (and temporal) scales. This emphasis is a truism whether drinking water supplies in rich or poor economies are considered; the difference is mainly based on how to approach the problem, once properly circumscribed. The availability and socioeconomic implementation of point-of-use treatment technologies have to be considered in light of the real and perceived threats on water resources and their associated risk characterization (e.g. diarrhoea, dehydration, etc.). Technology transfer to developing nations was illustrated by means of low-tech solar disinfection technology. Criticisms that high-tech detection platforms have no place in the developing world emphasize the need for technology implementation with grass-roots input of the population, and considerations for technology adaptation to the local infrastructure. It should be noted that remote sensing technology is developing to the point where some of these local infrastructure limitations can be overcome.

A second possible role for ISEB is in the advancement of biotechnology curricula and technology transfer courses relevant to sustainable potable water issues. The education barrier for implications and applications of biotechnology for sustainable watershed management is relevant across socioeconomic boundaries. For example, at The University of Michigan, curriculum development in this area takes place at three levels: graduate programs (e.g. Concentrations in Environmental Sustainability, ConsEnSus), development of user-friendly interactive mapping software for decision support systems and the development of a remote interactive system for microbial analysis to be used in graduate courses. NSF and NATO have recently supported technology transfer workshops for environmental assessment and remediation of contaminated sites with the aim to discuss areas of technology diffusion within the context of Eastern Europe (e.g. Reible and Demnerova, 2002) and Latin America. Of particular relevance to this workshop are the efforts of the Swiss Federal Institute for Water Research and Technology in the area of water and sanitation in developing countries (SANDEC; http://www.sandec.ch/). Its mandate is to assist in developing appropriate and sustainable water and sanitation concepts and technologies adapted to the different physical and socioeconomic conditions prevailing in developing countries. Perhaps, ISEB could capitalize on the participation of leading institutions in biotechnology-based applications for sustainable water issues, by developing a niche and role as a clearinghouse for expertise in this area.

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