Fall 2008

TECHNOLOGIES FOR CLEAN WATER

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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Promoting the technological welfare of the nation by marshalling the knowledge and insights of eminent members of the engineering profession.

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LINKING ENGINEERING AND SOCIETY

Editor's Note

Features

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Editor's Note

George Bugliarello

Water: Advances in the Supply and Management of a Vital Resource

We cannot live without water, and our civilization would collapse without it. But water can also destroy us and our way of life, because, since neolithic times, people have tended to settle near water—on deltas, near rivers, and along coastlines. It has been estimated that some 70 percent of the world population today lives in areas at risk from floods, tsunamis, storm surges, and changes in sea level as a result of bradyseisms and the consequences of climate change. Thus we are confronted by the twin imperatives of (1) finding enough water to satisfy our needs and (2) defending ourselves against the threat of disasters caused by water.

As the global population continues to grow, the water we need is becoming increasingly scarce. Thus we must recycle water, search for new sources of water, use water more efficiently, and reduce losses in water distribution systems. Ironically, even though water is abundant, its availability and accessibility for drinking, agriculture, and industrial uses are limited and unevenly distributed geographically.

As human activity intensifies, water throughout the world is increasingly threatened by pollution, exposing large populations to noxious, toxic, waterborne substances and infections. Concentrations of humans in urban aggregates present a multiplicity of challenges: how to supply and distribute necessary water; how to treat water to make it potable; and how to manage rainwater and storm water. These are major engineering and societal challenges.

The papers in this issue of *The Bridge* describe some recent advances in the search for water, in the distribution and treatment of water and wastewater, and in the modeling of complex water systems. Addressing these problems will require that engineers work closely with social, ecological, legal, and financial experts and with all levels of government.

The balance between water supplies and population varies by continent and region. Hence the urgency in some areas, like the deserts of Egypt and the Sudan, to find new sources of fresh water, for example, by using geohydrological observations from satellites, as described in the article by Farouk El-Baz (NAE).

The paper co-authored by Abu Hussam (the first winner of the NAE Grainger Prize for Sustainability, sponsored by the Grainger Foundation), Sad Ahamed, and Abul Munir addresses the problem of the natural presence of arsenic in groundwater, which affects the populations of 35 countries. In the Ganges-Meghna-Brahmaputra basin alone, as many as 500 million people are at risk.

Pete Loucks (NAE) shows how models of complex water resources are being used in making decisions about water supplies in cities, the restoration of ecologically important areas, and water management in complex river systems.

Vanessa Speight describes problems in water-distribution systems. Even in communities with extensive water-treatment systems, the quality of the water that reaches customers may be different from the quality of the water at the treatment plant. She describes how the age and weaknesses of many water-distribution systems exacerbate health risks to urban populations.

Glen Daigger (NAE) stresses the need for closed-loop, energy-neutral water systems, which will require more reliance on local resources, better access to clean water and sanitation, and responsible management of nutrients in wastewater streams—all facets of the global quest for sustainability. New approaches and technologies, such as advanced monitoring and control systems, microbial fuel cells that can extract electric energy from organic matter, and nanotechnology that can improve the performance of water-separation membranes, are all in development.

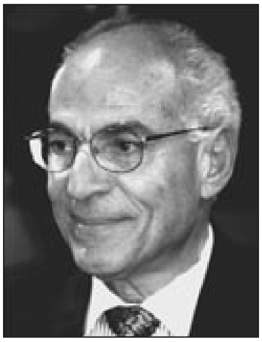
The themes of the preceding papers are underscored by Jerry Schnoor (NAE), who also stresses water and land limitations and the economic reverberations of the development of biofuels. He advocates, as per a current proposal to the National Science Foundation, a substantial capital investment to revolutionize the modeling and forecasting of water quantity and quality.

Problems related to water use and availability are a source of intense concern globally. Unless they are resolved, they will hamper social and economic development and accentuate disparities between water haves and have-nots and conflicts for the control and use of water among water-poor regions, as well as between cities and rural areas and among cities, regions, and nations. Unfortunately, water problems, for all of their urgency and importance, are just one of many infrastructural challenges facing the United States—and much of the world. Water problems add to their enormous magnitude and complexity.

Satellite images and sophisticated mapping techniques are revealing new sources of fresh water in surprising places.

Remote Sensing of the Earth: Implications for Groundwater in Darfur

Farouk El-Baz



Farouk El-Baz, research professor and director of the Center for Remote Sensing at Boston University, is a geologist, NAE member, and veteran of NASA's Apollo Program.

Images of Earth from space have improved steadily during the past 40 years. In the mid-1960s, photographs taken by astronauts of the Gemini, Apollo, Skylab, and Apollo-Soyuz missions using hand-held cameras with color film indicated the nature and composition of salient topographical features. Ancient rocks that contained a lot of iron and other dark elements appeared brown; limestone sediments looked bright; sands appeared golden yellow; and ocean currents were discernible. With those images, we were able to begin mapping hard-to-reach regions based solely on views from space.

In 1972, NASA initiated the next generation of images, which were relayed by digital sensors. From altitudes up to 920 kilometers above the Earth, sensing instruments looked down at rows of tiny spots, measured reflected sunlight from each of them, translated the light intensity into numbers, and beamed the numbers to receiving stations on the ground for study and analysis by researchers worldwide (Lillesand et al., 2004).

Detail in space images depends on two major factors: (1) the altitude of the spacecraft (the lower the orbit, the higher the resolution) and (2) the focal length of the camera lens (the longer the focal length, the greater the detail). However, ground resolution of space images was also determined by how much detail was allowable in images used for civilian purposes, as compared to images used for intelligence and military purposes. As the latter achieved more and more detail, the rules for civilian images were

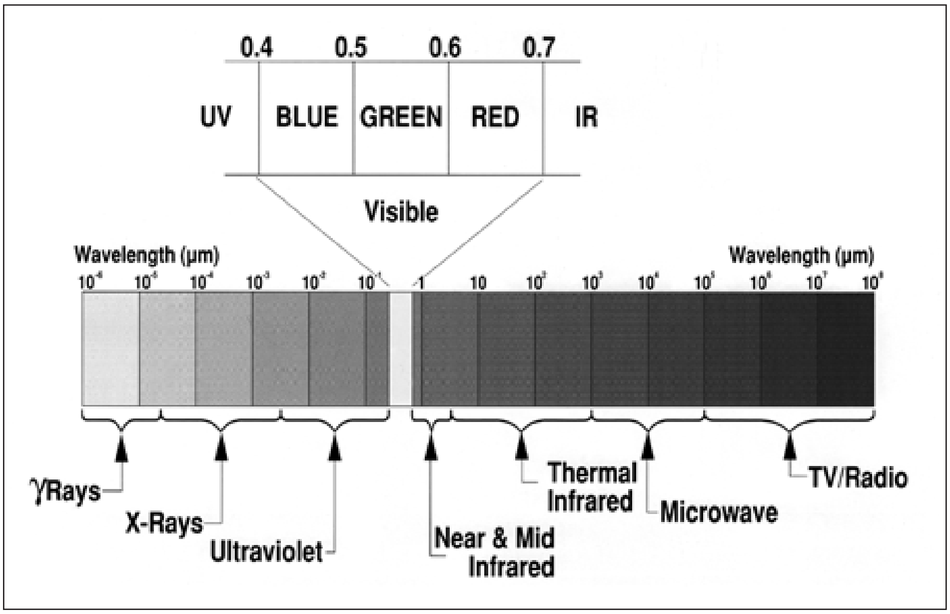


FIGURE 1 The electromagnetic spectrum, from gamma rays to radio waves, is shown on satellite images of particular wavelengths. Source: Adapted from *http://science.nasa.gov/newhome/help/glossfig1.htm.*

regularly relaxed. In the first satellite images, whole towns appeared as dots. Today a single car can be clearly identified in a high-resolution image.

One advantage of digital imaging from space is that a filter in front of a sensor's lens can separate reflected light into various wavelengths. When certain bands of Landsat are used, for example, they become equivalent to visible light (Figure 1). They can then be combined with an infrared band or a thermal band that measures differences in the temperatures of rock, soil, and sand.

Another significant advantage of digital remote sensing is that it provides repeat coverage of the same area from an equal height by the same instrument. The repetitions provide comparisons that can show changes over time, and when images are overlapped using computer software, we can produce very accurate "change-detection maps," which are essential to evaluating environmental changes due to natural processes and human activities.

This article includes a review of procedures for processing and analyzing satellite images followed by an example of how imaging data have been used to locate badly needed groundwater resources in the dry and troubled region of Darfur.

Image Processing

Satellite images are used to generate maps of drainage systems, geologic structures, thermal anomalies, geomorphologic features, and the distribution of vegetation. All of these factors are important to the understanding of a region, its environment, and its resources, particularly groundwater. Images must be preprocessed using radiometric and geometric corrections before data can be analyzed.

In radiometric corrections, images collected at different dates and times, and by different sensors, are normalized to each other so they can be directly compared. Geometric corrections are used to counteract sensor irregularities, terrain relief, and the effects of the curvature and rotation of the Earth. In some cases, geo-referencing involves transferring ground-control points.

Image Transformation

In image transformation, several multispectral bands (Figure 1) are used to generate a single image that highlights a particular feature or property of the land surface. Examples of transformations include image subtractions and ratios. Image subtractions are used to identify differences or changes among images of the same area acquired at different times. Image ratios are used to enhance particular information about the status of the land surface. For example, the normalized-difference vegetation index (NDVI) indicates the amount of green vegetation present in each picture element (pixel).

Enhancement

Enhancement procedures make it easier to interpret images by changing digital pixel values. These procedures are always the last step in the preprocessing of images. Enhancements can be either stretches (used with the image histogram) or spatial filters (used to highlight or suppress features based on pixel frequency). Density slicing, another type of enhancement, is used to select data ranges and colors for highlighting areas in gray-scale images.

Mosaicking

Mosaicking of individual satellite scenes provides coverage of an entire region. The purpose of a mosaic is to create a seamless image from a group of individual scenes that may vary in brightness. Mosaicking involves three steps: (1) re-sampling images to refine their resolution; (2) matching the brightness of images; and (3) blending overlapping areas (Figure 2).

Classification

The classification of image data is used to produce thematic maps. This procedure involves using information in a multispectral image to classify each pixel. Unsupervised classification is useful for preliminary discrimination of spectral classes. Supervised classification involves using a priori knowledge of data to "train" computer software to identify categories in an image (Lillesand et al., 2004).

Change Detection

The process of change detection is used to identify differences in the state of an object or a phenomenon by observing it at different times (Singh, 1989). Change-detection maps are particularly important in monitoring the types, stages, and distribution of vegetation.

Image Analysis

Drainage Mapping

Satellite images are ideal for studying the movement of water on the Earth's surface. Drainage maps, which are essential for flood control, searching for groundwater, and other water-related studies, can also be also used for mapping and interpreting regional drainage systems and individual stream courses for drainage-basin analyses. Such analyses include the study of drainage channels, as revealed in satellite images that reflect the influence of the fabric and structure of the underlying rocks.

Surface rocks may control the development of drainage systems by affecting the texture (shape) and density (spacing) of drainage. Both primary (in the rock fabric) and secondary (fracture-influenced) permeability of the surface rock are important. In areas where surface rocks are relatively impervious and easily eroded, a fine-textured surface drainage network of closely spaced channels develops. In areas of pervious rock, surface erosion is minimal because of infiltration, and coarse-textured drainage with widely spaced channels results.

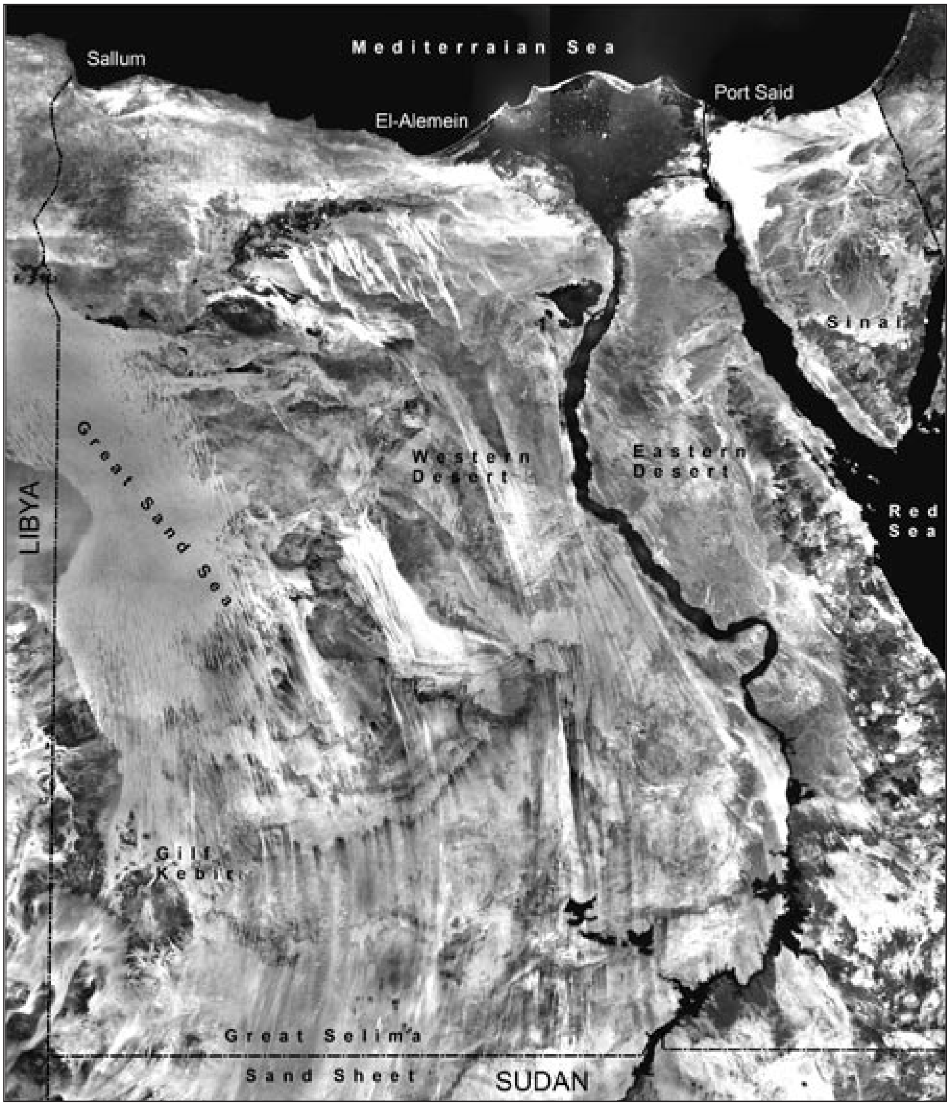


FIGURE 2 Digital mosaic composed of 65 Landsat images covering the total area of Egypt (more than one million square kilometers). Bright, parallel striations in the Western Desert are sand dunes shaped by prevailing winds from the north.

In most cases, the uniformity of drainage patterns is an indicator of rock types. For example, a branching pattern implies homogeneous rock with little structural control. Deviations from this pattern (e.g., an increase in angularity, parallelism, or angle of confluence) may indicate a change in rock type or an increase in structural control.

The climatic conditions at the time of channel formation and the amount of erosion also significantly affect the development of drainage patterns. Higher rates of precipitation increase erosion and result in finer textures and more completely integrated patterns than in areas with lower precipitation where the rock fabric is more uniform. Relatively young, underdeveloped patterns imply fewer groundwater resources.

Surface drainage patterns are mapped using Landsat image composites, but in places covered by dry, fine-grained sand, radar data can be used to map ancient drainage patterns (Figure 3). The use of radar data for detecting old, sand-covered channels is well documented (e.g., El-Baz, 1988; McCauley et al., 1986; Robinson et al., 2000).

Structural Analysis

Fractures induce secondary porosity in any type of rock, and fracture zones store large amounts of water, usually in a network (e.g., NRC, 1996). Fracture zones may (1) drain large areas and extend for tens of kilometers in length; (2) act as conduits for water from mountainous regions, where the recharge potential from rainfall is high, to areas of lower elevation; (3) connect several horizontal groundwater aquifers, thus increasing the volume of water; or (4) represent areas of potentially high artesian pressure where water drained from higher elevations accumulates beneath the surface.

Thermal Anomalies

Anomalous cool areas in thermal images may represent water at or near the surface. This is because the latent heat content of water slows the process of absorption and the emission of radiation, thus, at a given time in the diurnal heating cycle, slowing the warming of moist soil (Pratt and Ellyett, 1979). Similarly, cooling during the night is also slowed. Thus moist soils have higher thermal inertia, which shows up as an anomalous cold area in the thermal data collected during daylight hours (Figure 4). Freshwater seeps into the ocean can also be detected by temperature differences.

Geomorphic Classification

Determining water accumulation requires an understanding of the geology and geomorphology of an area, because the amount of accumulation depends on the infiltration rates of surface water and the nature of the host rock, which can affect groundwater chemistry. The processes described in the preceding section can be combined to ensure that as much information as possible is extracted for the finished product. The geomorphologic classification of satellite images is based on interpreting their spectral information—the higher the spectral resolution the more information.

Vegetation Mapping

The presence of vegetation in a region indicates that water is also present, either through irrigation or

FIGURE 3 A Shuttle imaging radar (SIR-A) strip superposed on Landsat data. The radar waves penetrate the desert sand cover to reveal courses of ancient rivers and streams in an area of North Darfur in northwestern Sudan. Source: Adapted from *http://pubs.usgs.gov/gip/deserts/remote/*.

shallow, near-surface water. Mapping and monitoring the spatial distribution, type, and stage of vegetation over time can help determine (1) evaporation-transpiration rates and (2) the amount and type of water used in agriculture. Vegetation mapping can also help in locating potential water-bearing structures or buried channels that may act as preferential flow paths for subsurface water. Vegetation associated with fault zones may also indicate near-surface water. When vegetation-distribution maps are correlated with structural maps, they might lead to the identification of possible sites of groundwater resources.

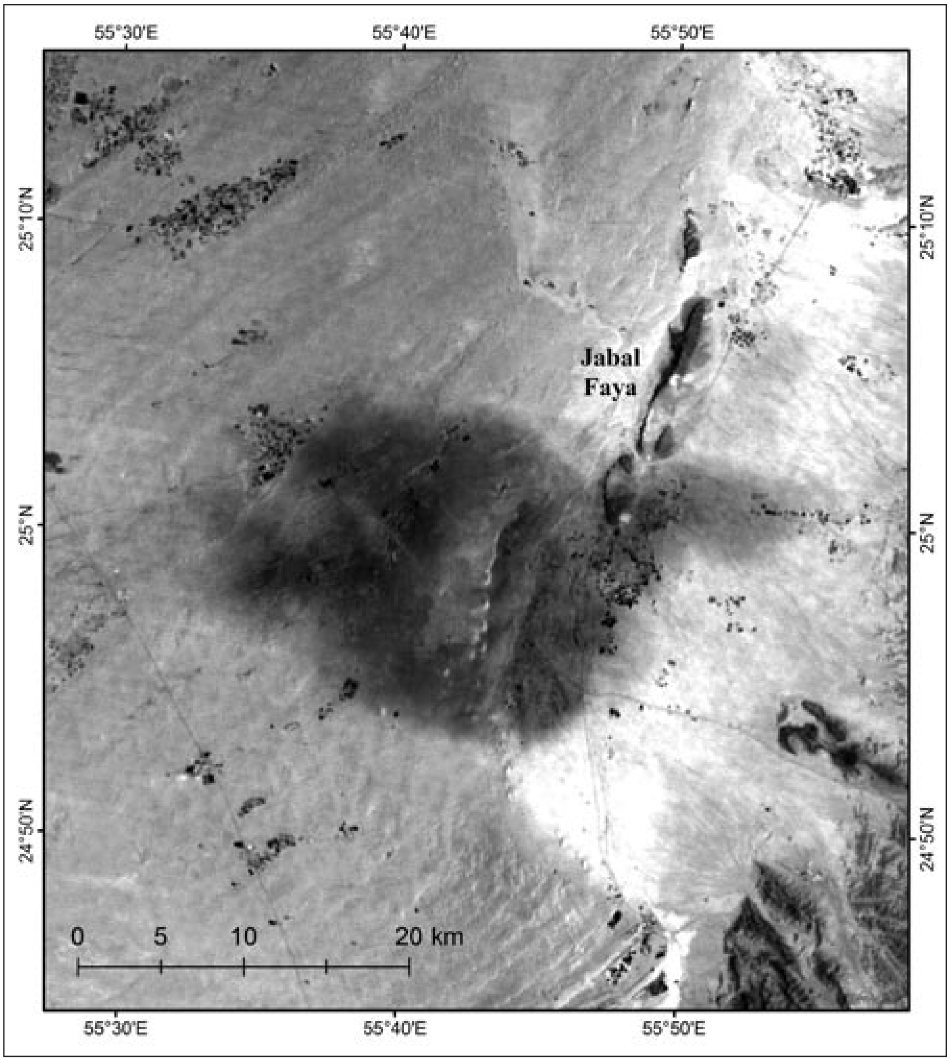


FIGURE 4 A dark patch (cool anomaly) in a thermal image of a sandy region in the Emirate of Sharjah (U.A.E.). The anomaly, which developed after rainfall on much higher topography further east, indicates water accumulation at or near the surface. Source: Center for Remote Sensing, Boston University.

Groundwater in Darfur

Water is essential for survival and for sustainable economic development. Water shortages already plague half the world's population, and the United Nations (UN) estimates that 1.8 million people die every year because of unsafe water. Thus two key targets of the UN Millennium Development Goals are access to safe drinking water and adequate sanitation. Furthermore, one of the goals in the NAE "Grand Challenges for Engineering" project is to "provide access to clean water." It is incumbent upon us as engineers to ensure that those who need it most have access to clean water.

Nowhere is the need more apparent than in the Darfur province of Sudan. The northern region of Darfur is part of the eastern Sahara of North Africa—the driest desert belt in the world—and the UN has declared that a shortage of water there during the past few decades is a major cause of the turmoil in the region (UNEP, 2008). Competition for meager water resources between sedentary farmers and nomadic populations has resulted in untenable violence and a major humanitarian crisis.

General Setting

Darfur is divided into three governorates. In Northern Darfur, which lies in the driest region on the planet, solar radiation is capable of evaporating 200 times the amount of rain the region receives (Henning and Flohn, 1977). Because of this hyper-aridity, human consumption and agriculture are completely dependent on groundwater resources. Growing populations, and the attendant increase in food and fiber requirements, have exacerbated the situation.

Recently, severe droughts have led to years of unrest and a vicious war in Darfur. Since 1968, the region has experienced seven-year cycles of dryness followed by cycles of meager rainfall (El-Baz, 1988). Because of water shortages during the dry cycles, sedentary farmers have encroached on wells that were usually used by nomads, which initiated many conflicts.

As described above, satellite images are an ideal tool for searching for groundwater resources in this region. The effectiveness of satellite images is enhanced by elevation data recently acquired by the Shuttle Radar Topography Mission (SRTM), which provides three-dimensional views.

Although the Sahara today is dry and subject to the erosive action of strong winds from the north, geological and archaeological data indicate that the climate was much wetter in the past. Surface water during moist periods formed lakes in topographic depressions, and much of the water from these basins may be stored in the underlying porous sandstone rocks. When the climate dried up, the wind covered these land features with sheets of sand.

The wind regime in the eastern Sahara traces a pattern that emanates from the coastal zone of the Mediterranean Sea (Figure 2). This pattern changes from southward in the northern areas to southwestward along the borders with the Sahel (El-Baz, 2000). Erosion scars throughout the desert suggest that this wind regime has been in effect for much of the last one million years. Careful observation reveals that sand accumulations in the eastern Sahara occur within or near topographic depressions, a characteristic that must be taken into account in any theory of the origin of the sand and the evolution of dune forms in space and time.

Radiocarbon dating and geo-archaeological investigations show that the eastern Sahara experienced a period of greater moisture from 10,000 to 5,000 years ago, as is evidenced by the numerous remains of human occupation throughout the Western Desert of Egypt and the neighboring region in northern Sudan (Figure 5). When a uranium-series technique was used to date lake carbonates from the Western Desert of Egypt and Northern Darfur, the results indicated that there have been five wet, paleo-lake-forming episodes in the past 320,000 years (Szabo et al., 1995). These wet episodes, which correlate with major interglacial stages, were separated by dry periods like the current one.

Two dynamic forces are at play in the relationship between sand and water in the eastern Sahara. First, surface water systems worked from south to north during humid phases of climate, just as the Nile River does today. Rivers were responsible for transporting particulate materials and depositing them at the mouths of river channels. Second, the prevailing wind system during dry episodes worked in the opposite direction, from north to south. As the wind became the principal agent of modification, water deposits dried up, and sand was shaped into the dunes and sheets that now cover the desert surface.

This scenario implies that sand must have been borne by water and then sculpted by wind. During wet episodes, water percolated into the substrate through the porous layers of sandstone and was stored as groundwater (El-Baz, 2000). Thus we may infer from present sand dunes that there are groundwater resources in the area.

Southwestern Egypt

A flat, round, sand-covered area, some 300 kilometers in diameter, straddles the border between Egypt and Sudan (Figure 6). Named the Great Selima Sand Sheet, after an oasis on its eastern border, this area is morphologically a depressed basin covered by sand deposits with a few exposures of solid rock.

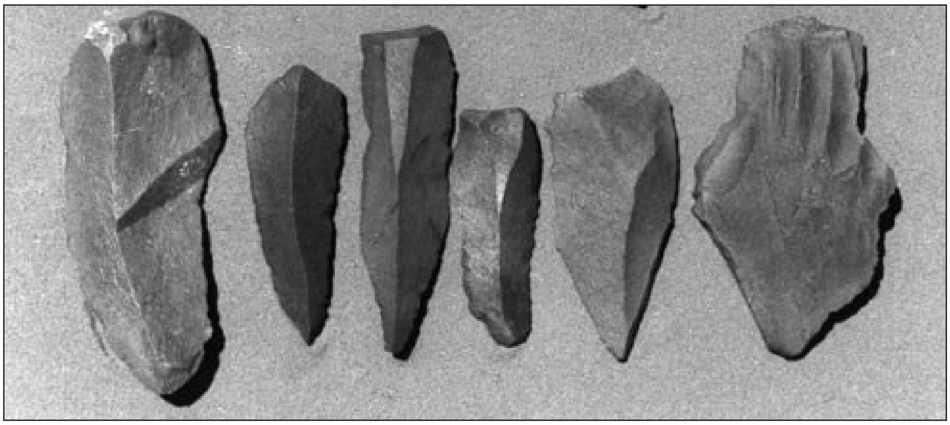


FIGURE 5 Hand axes and knives fashioned by humans from hard rock. These tools were dated by association to be from 6,000 years old (the smallest three) to more than 200,000 years old (the objects on either end). Such artifacts abound near ancient lake boundaries in southwestern Egypt and northwestern Sudan. Source: Photograph by the author.

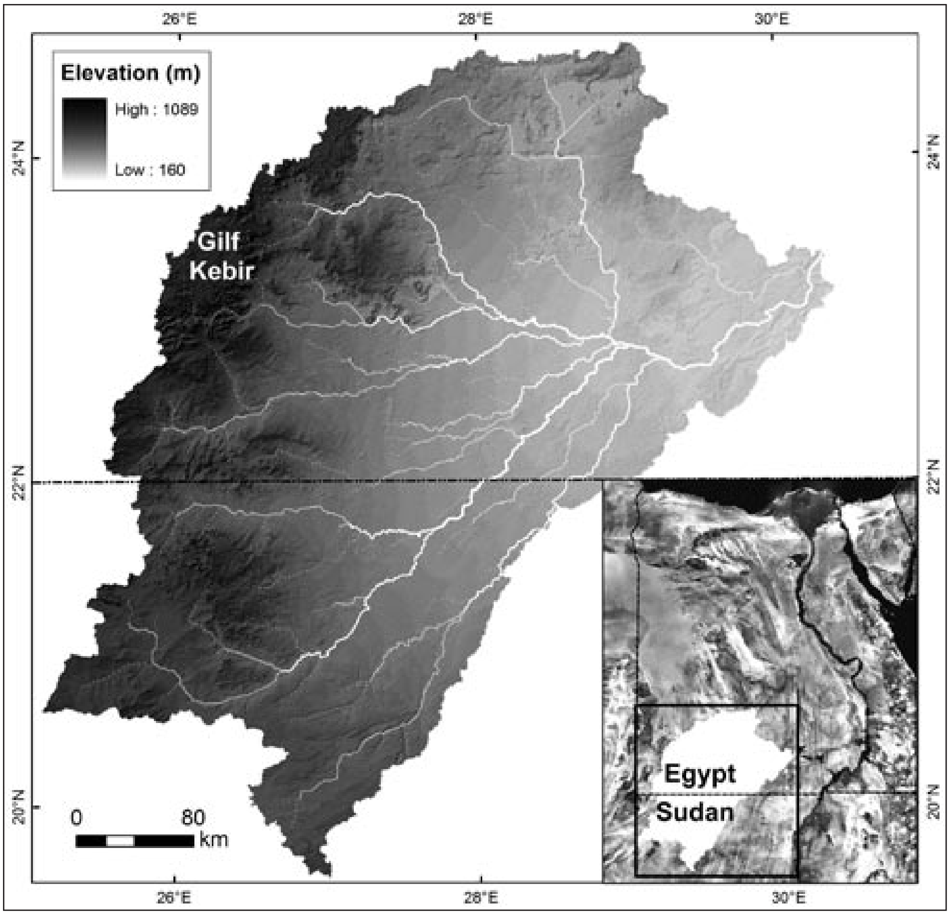


FIGURE 6 Numerous channels emanate from the Gilf Kebir plateau and neighboring highlands, as shown by SRTM data. All channels lead to the low area toward the east where wheat and other crops are being profitably grown. Source: Adapted from Robinson et al., 2000.

Field research conducted in 1978 was interpreted to indicate a groundwater accumulation in the lowest, eastern area in Egypt (El-Baz, 1988). Radar images obtained by the Space Shuttle and SRTM revealed the courses of rivers and streams leading to the area from highlands to the west and southwest (Figure 6). Hence, in 1995, the government of Egypt drilled exploratory wells, which were monitored for five years to ensure the presence of large amounts of groundwater.

Since 2000, 10,000-acre plots have been offered for agricultural development by the private sector in Egypt. Today wheat, chickpeas, peanuts, and other crops are being profitably raised in the region, irrigated by pervasive groundwater from the underlying porous sandstone (El-Baz, 2000). The salinity of this water is only 200 parts per million, which is lower than the salinity of Nile River water. Proven resources of this sweet, "fossil" water in the investigated area are large enough to support agriculture on 150,000 acres for 100 years.

Alluvial fans at the mouths of radar-revealed channels coincide with gentle slopes in the SRTM data, suggesting a long "stay time" of surface water and a high probability of finding groundwater. Indeed, groundwater wells in these regions are now producing low-salinity water. This is an example of how heterogeneous data from different sources can be used for the exploration for groundwater.

"1000 Wells for Darfur"

Interpretations of space-borne data for Northern Darfur suggest that water accumulated there in a lake-like expanse of 30,750 square kilometers, about the size of Lake Erie (Ghoneim and El-Baz, 2007). Horizontal sedimentary layers occur at 573 meters above sea level, the highest level of terraces formed at the shorelines of the lake water (Figure 7). Based on topographic information from SRTM data, the area of that lake would have been approximately 2,530 square kilometers.

During the residence time of ancient water in the Northern Darfur depression, for thousands of years before the lake dried up, much of it would have seeped into the substrate. This seepage probably occurred through the primary porosity of the underlying sandstone and/or secondary porosity caused by fractures in the rock, particularly the north-south-trending fault in the eastern part of the lake area.

Once the lake boundary had been completely mapped, based on space data, I conveyed this information to Omar Al-Bashir, president of Sudan, in the presence of Minister of Irrigation and Water Resources Kamal Ali, an engineer. President Al-Bashir stated that he recognized the importance of water shortages in the recurring crises in Darfur and the potential benefits of the discovery of this new water resource. He then announced an

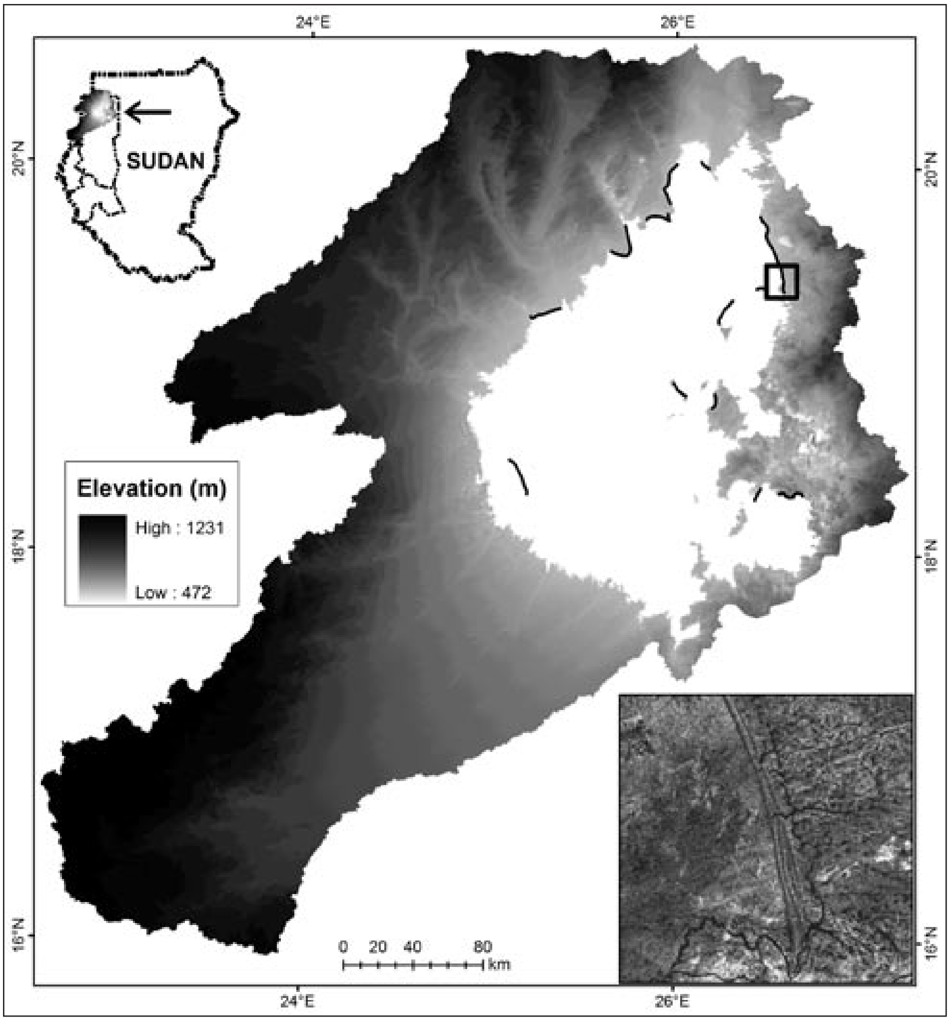


FIGURE 7 Topographic rendition of the ancient lake in North Darfur based on SRTM data. Black dashes mark the locations of former lake terraces, as revealed by radar images (Radarsat 1), and shown in the enlargement of the box at lower right; younger streams were held back by the terraces, except for the one at the bottom of the radar image. The sketch at upper left shows the location of the lake relative to North, West, and South Darfur in western Sudan. Source: Adapted from Ghoneim and El-Baz, 2007.

initiative called "1,000 Wells for Darfur." News of the initiative was well received in Darfur. Upon reviewing the data, Governor of North Darfur Osman Kebir declared that "this brings hope for a better future. I have seen smiles on faces in Darfur."

Shortly thereafter, the Egyptian Ministry of Water Resources and Irrigation offered to drill 20 wells to satisfy the urgent needs of the people of Darfur. Experts in this ministry have had a great deal of experience in drilling water wells in the nearly identical environment just north of Darfur.

In addition to the needs of the people of Darfur, the water will be used to meet the needs of a 26,000-strong UN-African Union peacekeeping force that will be deployed there. When I briefed UN Secretary General Ban Ki Moon, he immediately recognized the significance of the initiative and was amenable to placing it under the auspices of the UN, which will ensure both the expediency of the work and accountability for the spending of contributed funds. Efforts are under way to select the best sites for drilling. The well-drilling program will be a tangible example of how advanced space technology can be used to address a major humanitarian crisis.

Conclusion

As the Darfur example shows, using spaceborne data and innovative approaches can lead to a better understanding of the potential for groundwater resources in dry lands and can increase the chances of locating groundwater for people in dire need of it. In the meantime, we must pursue research on innovative engineering techniques for better site selection, the drilling and pumping of water, the use of renewable energy in remote locations, and efficient water transport and delivery systems. I appeal to the engineering community to contribute as much as possible to meeting the challenge of "providing access to clean water" in an effort to save the people of Darfur and similar dry regions of the Earth.

References

El-Baz, F. 1988. Sand accumulation and groundwater in the eastern Sahara. Episodes 21(3): 147–151.

El-Baz, F. 2000. Satellite observations of the interplay between wind and water processes in the Great Sahara. Photogrammetric Engineering and Remote Sensing 66(6): 777–782.

Ghoneim, E., and F. El-Baz. 2007. DEM-optical-radar data integration for palaeohydrological mapping in the northern Darfur, Sudan: implications for groundwater exploration. International Journal of Remote Sensing 28(22): 5001–5018.

Henning, D., and H. Flohn. 1977. Climate Aridity Index Map. UN Conference on Desertification. United Nations Environment Program, Nairobi, Kenya, August 29–September 9, 1977.

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman. 2004. Remote Sensing and Image Interpretation, 5th ed. New York: John Wiley and Sons.

McCauley, J.F., C.S. Breed, and G.G. Schaber. 1986. The megageomorphology of the radar rivers of the eastern Sahara. Pp. 25–35 in Publication 86-26. Pasadena, Calif.: Jet Propulsion Laboratory.

NRC (National Research Council). 1996. Rock Fractures and Fluid Flow. Washington, D.C.: National Academy Press.

Pratt, D., and C.D. Ellyett. 1979. The thermal inertia approach to mapping of soil moisture and geology. Remote Sensing of Environment 8(2): 151–168.

Robinson, C.A., F. El-Baz, M. Ozdogan, M. Ledwith, D. Blanco, S. Oakley, and J. Inzana. 2000. Use of radar data to delineate palaeodrainage flow directions in the Selima Sand Sheet, Eastern Sahara. Photogrammetric Engineering and Remote Sensing 66(6): 745–753.

Singh, A. 1989. Digital change detection techniques using remotely-sensed data. International Journal of Remote Sensing 10(6): 989–1003.

Szabo, B.J., C.V. Haynes, and T. Maxwell. 1995. Ages of Quaternary pluvial episodes determined by uranium-series and radiocarbon dating of lacustrine deposits of Eastern Sahara. Paleogeography, Paleoclimatology, Paleontology 113(2–4): 227–242.

UNEP (United Nations Environment Program). 2008. Sudan Post-Conflict Environmental Assessment–2008. Nairobi, Kenya: United Nations Environment Programme.

A simple filtration system used in Bangladesh and other countries removes dangerous arsenic from drinking water.

Arsenic Filters for Groundwater in Bangladesh: Toward a Sustainable Solution

Abul Hussam, Sad Ahamed, and Abul K.M. Munir

Abul Hussam

Sad Ahamed

Abul K.M. Munir

The natural presence of arsenic and other toxins in groundwater, the most common source of drinking water, is considered a worldwide public-health crisis and an unprecedented natural disaster. Thirty-five countries around the world have reported adverse health effects from groundwater contaminated by arsenic (Mukherjee et al., 2006). In the Ganga-Meghna-Brahmaputra basin alone, some 500 million inhabitants are at risk from drinking arsenic-contaminated groundwater (Chakraborti et al., 2004).

In Bangladesh, an estimated 77 to 95 million people of a total population of 140 million drink groundwater containing more than 50 micrograms per

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liter (μg/L), that is, 50 parts per billion (ppb) or 0.05 milligrams per liter (mg/L); the maximum contamination level (MCL) according to the Environmental Protection Agency (EPA) standard is 10 ppb. In Bangladesh alone, some 10 million tube-wells are contaminated (Chatterjee et al., 1995; Smith et al., 2000). However, the problem is not confined to Bangladesh. Millions of people in India, Nepal, Cambodia, Vietnam, and even the United States, to name just a few countries, are also vulnerable to the toxic effects of arsenic.

Drinking arsenic-contaminated water for a long period of time causes serious illnesses, such as hyperkeratosis on the palms or feet; fatigue; and cancer of the bladder, skin, and other organs (Figure 1) (IARC, 2001). In the long term, one in every 10 people with high concentrations of arsenic in their drinking water could die of cancer triggered by arsenic poisoning (Black, 2007).

FIGURE 1 Arsenicosis patient with hyperkeratosis and cancer on the palm.

Options for Providing Clean Water

The only solution to this crisis is to provide clean, potable water for the masses, water that is free of toxic chemical species and biological pathogens. Safe water options can be classified into three major categories: (1) treating surface water; (2) providing uncontaminated well water; and (3) filtering water.

The first option, the treatment of surface water, is used extensively worldwide to ensure that anthropogenic contamination does not degrade water quality. In most developed countries, surface water is extensively treated and filtered before it is piped through an elaborate and expensive network and delivered to consumers. However, in underdeveloped countries such as Bangladesh, where surface water is highly contaminated with pathogenic bacteria and is often not potable, treatment systems are either not available at all or are too expensive for large segments of the population.

For these and other reasons, millions of tube-wells were drilled to extract groundwater for drinking in hopes that they would provide uncontaminated water. Unfortunately, 30 to 50 percent of these wells turned out to be contaminated by high levels of arsenic and other toxic species, including pathogens (Islam et al., 2001). Thus the second option, providing uncontaminated well water, is also impractical in many areas. In Bangladesh, even though arsenic-free wells have been painted green to signal that they are safe and people have been strongly encouraged to collect water from these wells, many ignore the warnings for logistical reasons; for example, women must often travel long distances to reach these wells.

As sweet water becomes scarcer everywhere, and as potable water supplies become increasingly vulnerable to contamination, the development of affordable water-filtration systems, the third option, is becoming more attractive. Some simple, affordable, sustainable technologies are available for filtering water to remove contaminants.

The Grainger Challenge Prize for Sustainability

The elimination of arsenic from drinking water, an urgent need for millions of people, was the subject of the inaugural Grainger Prize for Sustainability, which was funded by the Grainger Foundation and administered by the National Academy of Engineering (NAE). The goal of the challenge was to recognize the creators of affordable, reliable, low-maintenance, electricity-free technologies for reducing arsenic in drinking water to an acceptable level for human consumption. In February 2006, NAE announced three winners of the Grainger Prize (NAE, 2007).

The first-place was awarded to the inventor (Abul Hussam) of the SONO filtration system, which is based on a composite-iron matrix (CIM). This system, which has been extensively tested and used in Bangladesh, meets or exceeds local government guidelines for arsenic removal. NAE recognized this innovative technology for its affordability, reliability, ease of maintenance, social acceptability, and environmental friendliness.

The second-place award was given to Arup K. SenGupta and his team for a community water-treatment system based on activated alumina. The third-place award was given to Procter & Gamble for its PUR technology, which uses calcium hypochlorite (bleach) to kill a wide range of microbial pathogens and ferric sulfate to remove arsenic through flocculation-precipitation.

Arsenic and the Nature of Groundwater

Groundwater is a complex matrix in which many chemical species are present. Table 1 shows the compositions of typical groundwater found in Bangladesh. The origin of soluble arsenic in the water is

TABLE 1 Water Quality of SONO Filtered Water Compared to EPA, World Health Organization (WHO), and Bangladeshi Standards (1 mg/L = 1000 μg/L). Empty entries indicate that data were not available.

Constituent	EPA (MCL)	WHO Guideline	Bangladeshi Standard[a]	Influent Groundwater	SONO Filter Water[b]
Arsenic (total) – μg/L	10	10	50	5–4000[c]	3–30
Arsenic (III) – μg/L				5–2000[d]	< 5
Iron (total) – mg/L	0.3	0.3	0.3 (1.0)	0.2–20.7	0.19 ± 0.10
pH	6.5–8.5	6.5–8.5	6.5–8.5	6.5–7.5	7.6 ± 0.1
Sodium – mg/L		200		< 20.0	19–25
Calcium – mg/L			75 (200)	120 ± 16	5–87
Manganese – mg/L	0.5	0.1–0.5	0.1 (0.5)	0.04–2.00	0.22 ± 0.12
Aluminum – mg/L	0.05–0.2	0.2	0.1(0.2)	0.015–0.15	0.11 ± 0.02
Barium – mg/L	2.0	0.7	1.0	< 0.30	< 0.082
Chloride – mg/L	250	250	200 (600)	3–12	4.0–20.0
Phosphate – mg/L			6	0.5–50	< 1.5
Sulfate – mg/L			100	0.3–12.0	12 ± 2
Silicate – mg/L				10–26	18 ± 6

[a] Bangladeshi standard values are given as maximum desirable concentration with maximum permissible concentration in parentheses.

[b] SONO filters. ICP multi-element measurements of Cu, Zn, Pb, Cd, Se, Ag, Sb, Cr, Mo, and Ni show concentrations below the EPA and WHO limits at all times. All other measurements show average of semi-continuous measurement of more than 394,000 L of groundwater filtered by us and ETVAM in at least eight different water chemistries in different regions of Bangladesh. Water chemistry parameters were recorded for 23 metals, 9 anions, E_h, pH, Temp, dissolved oxygen, conductivity, and turbidity for hundreds of samples. All prescribed parameters passed the drinking water standards of WHO and Bangladesh.

[c] One tube-well at Bheramara was found to contain As (total) 4000 μg/L. The filtered water had 7 μg/L. This well was later capped by the government.

[d] In some wells As(III) concentrations exceeded 90 percent of arsenic in all forms.

now believed to be the result of the bio-reduction by bacteria of iron-arsenic in the soil (Polizzotto et al., 2005). The groundwater, which has a pH of 6.5 to 7.5, contains inorganic arsenic primarily in two oxidation states, As(III) in H_3AsO_3 and As(V) in $H_2AsO_4^-$ and $HAsO_4^{2-}$.

In most groundwater in Bangladesh more than 50 percent of the total arsenic present is in the form of the neutral H_3AsO_3. The remaining 50 percent is divided equally between two As(V) species ($H_2AsO_4^-$ and $HAsO_4^{2-}$). An ideal filter has to remove all three species inexpensively, without chemical pretreatment, without regeneration, without producing toxic wastes, and in the presence of high-soluble iron, calcium, magnesium, phosphate, silicate, and other potentially interfering chemical species.

Development of the SONO Filtration System

Our work on water filtration began in 1997, about eight years before NAE announced the Grainger Challenge, when we set out to measure and mitigate arsenic levels in drinking water. We first developed a method and protocol for making accurate measurements of trace arsenic in groundwater in Bangladesh

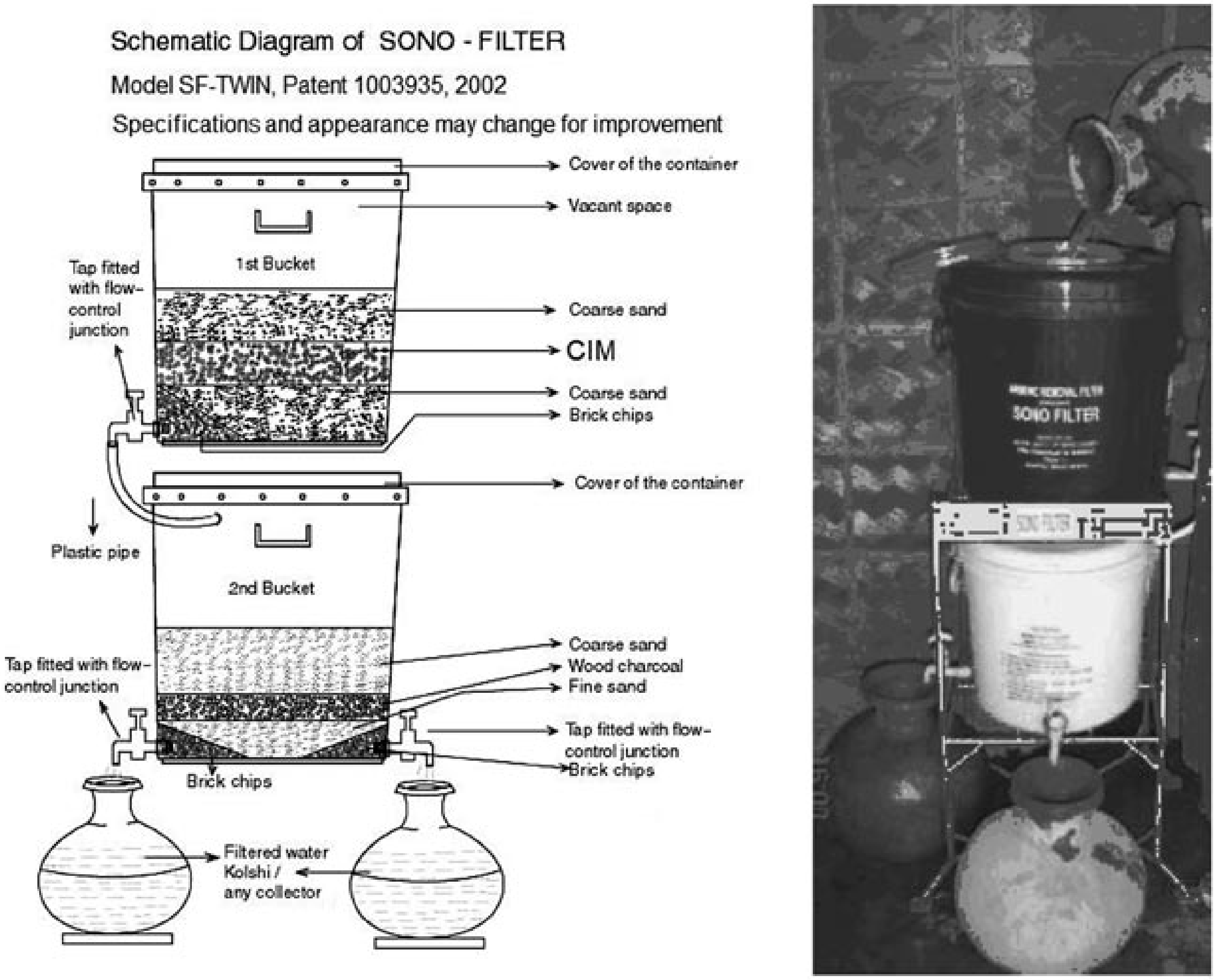

FIGURE 2 Schematic illustration of the SONO filter (left) and a filter in use in a village hut (right).

(IAEA, 2005; Rasul et al., 2002). Once we were able to measure contamination by arsenic on the ppb level, we were then able to test filtration technologies with groundwater in the field and to ensure quality control in the production of the filters. In our first paper on mitigation technology, published in 2000, we described the distribution of filters and the results in Bangladesh (Khan et al., 2000).

The SONO filter (Figure 2), a two-stage, pour-collect filtration system, was developed with Bangladeshi villagers in mind. The top bucket contains the arsenic-scavenging composite-iron matrix (CIM) sandwiched between two layers of sand. The bottom bucket is a simple sand and charcoal filter that cleans the water of residual iron and other impurities that may have drained from the first bucket. This design was selected for production after extensive experiments with alternative designs. Details of the materials, design, and function of the filter in the field, with extensive test data for other filter systems, have been reported elsewhere (Hussam and Munir, 2007).

Table 1 compares the quality of SONO-filtered water to acceptable water-quality standards. The SONO filter can produce 20 to 60 liters of potable water per hour for at least five years of normal use for about $40 per filter. The SONO filter, and its predecessor the 3-Kolshi filter (the round clay pitcher shown in Figure 2) satisfied many of the design requirements tested in various stages of the Environmental Technology Verification for Arsenic Mitigation (ETVAM) Program, which was conducted by the Bangladeshi government to screen commercial filters (Alauddin et al., 2001).

We realized from the beginning that the fastest way to test filter performance was to use real groundwater containing varied concentrations of arsenic, iron, and other inorganic species and to compare the results of filtering with potable water-quality parameters. The filtration efficiency of SONO was also compared in ETVAM field tests to filters using activated alumina, cerium hydroxide ion-exchange resin, and microfine iron oxide-based filters (BCSIR, 2003).

The Search for Active Materials: From Zero-Valent Iron to a Composite-Iron Matrix

Significant research has been done on the development of adsorbents and other materials for removing arsenic and other toxic species from water. A large number of adsorbents have been studied: oxides of granular metals, such as amorphous iron hydroxide (Pierce and Moore, 1982), hydrous ferric oxide (HFO) (Wilkie and Hering, 1996), granular ferric hydroxide (Driehaus et al., 1998), ferrihydrite (Raven et al., 1998), red mud (Altundogan et al., 2002), activated alumina (Lin and Wu, 2001; Rosenblum and Clifford, 1984; Singh et al., 2001), iron oxide-coated polymeric materials (Katsoyiannis and Zouboulis, 2002), iron oxide-coated sand (Thirunavukkarasu et al., 2003), Fe(III)–Si binary oxide (Zeng, 2004), iron oxide-impregnated activated alumina (Kuriakose et al., 2004), blast furnace slug (Kanel et al., 2006), iron-cerium bimetal oxide (Dou et al., 2006), iron-coated sponge (Nguyen et al., 2006), nanoscale zero-valent iron (Kanel et al., 2005; Lien and Wilkin, 2005; Yuan and Lien, 2006), sulfate-modified iron-oxide coated sand (Vaishya and Gupta, 2006), HFO incorporated into naturally occurring porous diatomite (Jang et al., 2006), crystalline HFO (Manna et al., 2003), crystalline hydrous titanium oxide (Manna et al., 2004a), granular hydrous zirconium oxide (Manna et al., 2004b), and iron(III)-tin(IV) binary mixed oxide (Ghosh et al., 2006).

Except for the classic method based on precipitation-coagulation of toxic impurities by flocculent iron-hydroxide precipitate, most of these studies were confined to determining removal capacity and kinetics. None of these materials was extensively tested in the field or passed through rigorous environmental technology verifications. It must be noted that the development, fabrication, in-field testing, production and distribution, user acceptability, maintenance, and sustenance of any of these technologies is very complex and time consuming, even for a very simple system such as ours.

Zero-valent iron has been used in the past to mitigate chlorinated hydrocarbons, arsenic, and other toxic species in the environment. The list of materials above shows that iron is the key component of many of them. However, iron-based technologies are subject to many problems: uncontrolled leaching and rusting, which can clog the filter media and filter outlets and render the filter useless; low capacity for arsenic removal; inability to remove As(III) species; and the complexity of regenerating and reusing the material in household filtration systems.

In our research, we invented a technique for processing easily available surplus iron into composite-iron granules (CIGs) and then into a composite-iron matrix (CIM). CIM is different from granular metal oxides in that the active medium is made from composite-iron granules into a solid, porous matrix by in situ processing inside the filter.

The "sandwich" of sand layers facilitates compaction, controls flow dispersion, controls pore formation, and reduces the production of fine particles. Thus this configuration has a low probability of clogging and a high probability of long-lasting field use without compromising water quality. The active material in the SONO filter removes inorganic arsenic species quantitatively by generating new complexation sites on CIM by in situ iron oxidation and surface-chemical reactions (Hussam and Munir, 2007). These reactions take place quickly for both As(III) and As(V) (Figure 3).

The two-stage filter system also increases the amount of arsenic removed through flocculation and the

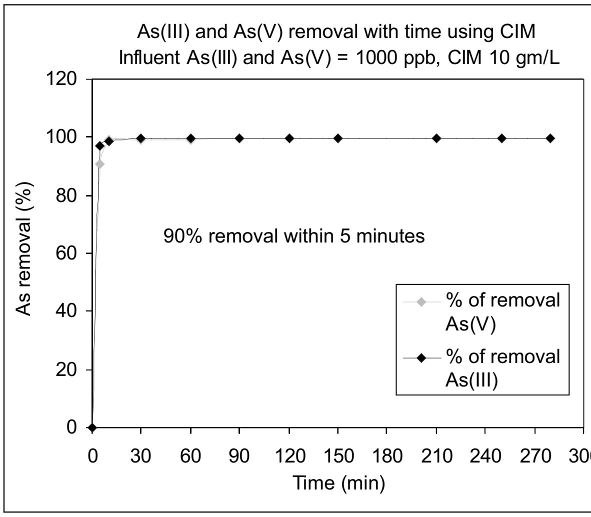

FIGURE 3 Figure showing that CIM can remove both As(V) and As(III) species from water almost completely within five minutes of contact.

precipitation of naturally occurring iron. The theoretical life span of a filter (for a 10 ppb breakthrough) could range from 5 to 200 years, depending on model assumptions. Experimental filters installed in the field at different times have functioned for three to six years in Bangladesh without breakthroughs, even with high-soluble iron (21 mg/L in one case), high phosphate content (50 mg/L), and varied water chemistries (Hussam and Munir, 2007).

Management of Spent Materials

Spent materials from all filtration technologies, including the SONO filter, are contaminated with high concentrations of toxicants. Thus the process and complexity of waste disposal affect their technical viability, cost, and social acceptability. At present, the only way to identify toxic waste is to leach the solid material, under simulated conditions, to determine if the levels of toxic species released into the environment exceed regulatory limits.

In our case, the measurements on used sand and CIM, by total available leaching protocol (TALP), showed that the spent material was completely nontoxic, with less than 5 μg/L of arsenic in all forms; this is 100 times lower than the EPA limit (NAE, 2006). The procedure was repeated, with similar results, using Bangladeshi rainwater (adjusted to pH7) to test the system with the primary mode of transport of water-soluble species during the rainy season.

Similar results were obtained by ETVAM with the backwash of filter waste using EPA's toxicity characterization leaching procedure (TCLP). Arsenic species in the used sand and CIM are present in oxidized form and firmly bound with insoluble-solid CIM, similar to a self-contained, naturally occurring compound in the Earth's crust. Thus disposing of them is almost like putting soil on soil.

Most important, in NAE's tests, the used CIM was characterized as "undetectable and nonhazardous (limit 0.50 mg/L)" by the TCLP (NAE, 2006). The EPA recommended limit for the land disposal of arsenic is 2 kilograms per hectare per year. This corresponds to arsenic from 10 million liters of water with a concentration of 200 mg/L (Khan, 2007). By this standard, the spent media from household filters used for 274 years at 100 liters per day could be disposed of on four square meters of land. Thus this iron-based arsenic filtration system appears to be benign and safe in terms of waste disposal.

Technology Use, Distribution, Cost, and Social Acceptance

At the time of the writing of this article, about 90,000 filters had been distributed in more than 18 districts throughout Bangladesh and Nepal. The large-scale procurement of the apparatus was primarily funded through local nongovernmental organizations (NGOs), local governments, and international institutions (e.g., UNICEF). The filters were transported on flatbed trucks and distributed in villages by flatbed rickshaws. Two other popular modes of transport are shown in Figures 4a and 4b.

At a cost of $35 to $40 for five years (the equivalent of the one-month income of a village laborer in Bangladesh), SONO is one of the most affordable water filters

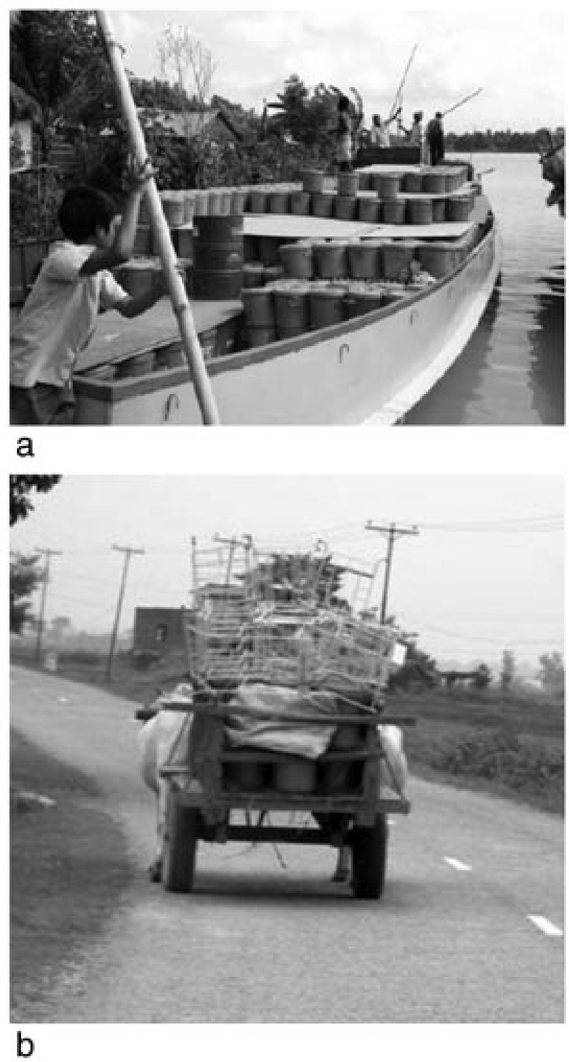

FIGURE 4 a. SONO filters being transported by boat in Bangladesh. b. SONO filters transported by oxcart in Nepal.

being used in that country. The system is made even more affordable by monthly payment schedules available through the NGOs that distribute the filters.

Because the filters do not require chemicals or consumables, the estimated operating cost is no more than $10 for five years (if the flow controller needs replacement). One unit can meet the needs of two families for drinking and cooking water for at least five years. Following simple instructions and at no cost, the user can set up the system in 20 minutes. Potable water is collected within two to three hours (the first two batches must be discarded), and most people like the taste of the soft water.

Our experience shows that water collection and maintenance of the SONO filter are done mostly by women, who like the system because they do not have to walk the distance to and from the closest arsenic-free well. People who drank the filtered water for two years showed some improvement in arsenical melanosis and reported a general sense of well-being and improvement in health. Because the filter has a flow rate of 20 liters per hour, it produces enough water for drinking and cooking, of course, but also for other purposes, such as cleaning and washing cooking utensils. In fact, we found no social or cultural stigma associated with the dissemination or use of the filter. Filters have been installed in hundreds of schools, and many children carry home bottles of filtered water at the end of the school day.

The SONO filter requires no special maintenance, except for the replacement of the upper sand layers when the apparent flow rate decreases. Experiments show that the flow rate may decrease 20 to 30 percent per year as a result of the formation and deposition of natural HFO in the sand layers if the groundwater has high iron content (more than 5 mg/L). The presence of soluble iron and the formation of HFO precipitate are common problems in all filtration technologies.

Other Benefits

Tube-wells were drilled to extract groundwater so that people would not have to drink surface water contaminated with pathogenic bacteria. However, pathogenic bacteria are still present in drinking water because of unhygienic handling and because many shallow tube-wells are located near unsanitary latrines and ponds (Islam et al., 2001). Tests for bacteria from 264 filters showed that 248 of them had no thermo-tolerant coliform (ttc) in 100 milliliters (mL) of water; 16 had 2 ttc/100 mL (VERC, 2007).

Pouring five liters of hot water into each bucket every month has been shown to kill all pathogenic bacteria and to eliminate the coliform count. In places where coliform counts are high, this protocol can be followed once a week. We have no record of diarrhea or other waterborne diseases from drinking SONO-filtered water. Thus it appears that the SONO filtration system, per se, does not foster pathogenic bacteria.

Except for basic training in hygiene, no special skills are required to maintain the filter, which will produce potable water for at least five years (the time span of our continuing test results). The active media does not require any backwashing or chemical regeneration. The actual life span of the filter will be

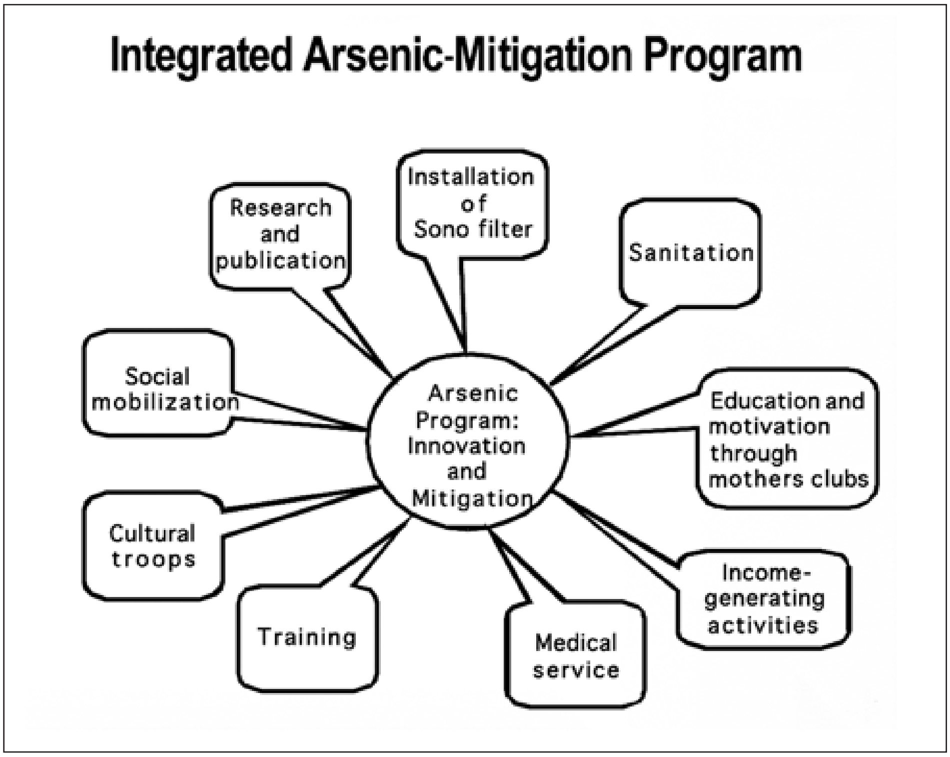

FIGURE 5 Diagram of an integrated arsenic-mitigation program.

determined by the life span of the experimental filters running in the field.

Except for manufacturing defects, mechanical damage due to mishandling, transportation, or natural disasters (e.g., flooding), none of the filters has shown the maximum contamination level (50 ppb) breakthrough so far. Our experience in Bangladesh shows that careful filter distribution and initial setup appear to be the most challenging tasks for large-scale distribution of the technology.

The SONO filter is now manufactured by an NGO (Manob Sakti Unnyan Kendro-MSUK in Kushtia, Bangladesh) from indigenous materials in batches of 200 to 500 units. All of the materials are available almost anywhere in the world, except for CIM, which can be produced under licensing agreement or imported from the manufacturer. The latter is the preferred method for production in Nepal and India.

We estimate that about one million people have already benefited directly from the filtration system. In addition, many people, the authors included, use SONO-filtered water for drinking and cooking. In some places, the filtration system has been scaled up by connecting units in parallel for use by small communities.

Sustainability through Integrated Programs

The sustainability of even a simple technology like SONO requires more than its production and distribution. In most underdeveloped countries, the production and distribution of services to meet humanitarian needs require funding from NGOs and financial subsidies from foreign-aid organizations. But sustainability will require commercialization through further product development.

The filter by itself will not solve the water crisis in Bangladesh. The arsenic crisis will require a sustainable, progressive, integrated program to address the overriding issues of sanitation, education, training and motivation, medical care for arsenicosis patients, social mobilization, the empowerment of women through mothers clubs, and so on (Figure 5). Most NGOs recognize this need and are trying to set up intensive training and cultural programs to motivate people to drink arsenic-free water.

Outlook for the Future

It is now clear that in Bangladesh and many other countries neither the surface water nor the groundwater is potable without treatment and/or filtration. Thus it appears that the development of low-cost filters is one of the best ways to solve the point-of-use drinking-water crisis for Bangladesh and many other countries.

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References

Alauddin, M., A. Hussam, A.H. Khan, M. Habibuddowla, S.B. Rasul, and A.K.M Munir. 2001. Critical Evaluation of a Simple Arsenic Removal Method for Groundwater of Bangladesh. Pp. 439–449 in Arsenic Exposure and Health Effects, edited by W.R. Chappell, C.O. Abernathy, and R.L. Calderon. Proceedings of the Fourth International Conference on Arsenic Exposure and Health Effects, June 18–22, 2000, San Diego, California. Amsterdam: Elsevier Science, B.V.

Altundogan, H.S., S. Altundogan, F. Tumen, and M. Bildik. 2002. Arsenic adsorption from aqueous solution by activated red mud. Waste Management 22(3): 357–363.

BCSIR (Bangladesh Council of Scientific and Industrial Research). 2003. Performance Evaluation and Verification of Five Arsenic Removal Technologies: ETVAM Field Testing and Technology Verification Program. Dhaka, Bagladesh: BCSIR.

Black, R. 2007. World facing 'arsenic timebomb.' BBC News website, August 30. Available online at *http://news.bbc.co.uk/2/hi/science/nature/6968574.stm*.

Chakraborti, D., M.K. Sengupta, M.M. Rahman, S. Ahamed, U.K. Chowdhury, M.A. Hossain, S.C. Mukherjee, S. Pati, K.C. Saha, R.N. Dutta, and Q. Quamruzzaman. 2004. Groundwater arsenic contamination and its health effects in the Ganga-Meghna-Brahmaputra plain. Journal of Environmental Monitoring 6(6): 74N–83N.

Chatterjee, A., D. Das, B.K. Mandal, T.R. Chowdhury, G. Samanta, and D. Chakraborti. 1995. Arsenic in ground water in six districts of West Bengal, India: the biggest arsenic calamity in the world. Part 1. Arsenic species in drinking water and urine of the affected people. Analyst 120(3): 643–650.

Dou, X., Y. Zhang, M. Yang, Y. Pei, X. Huang, T. Takayama, and S. Kato. 2006. Occurrence of arsenic in ground water in the suburbs of Beijing and its removal using an iron-cerium bimetal oxide adsorbent. Water Quality Research Journal of Canada 41(2): 140–146.

Driehaus, W., M. Jekel, and U. Hilderbrandt. 1998. Granular ferric hydroxide—a new adsorbent for the removal of arsenic from natural water. Journal of Water Supply: Research and Technology-Aqua 47(1): 30–35.

Ghosh, U.C., D. Bandhyapadhyay, B. Manna, and M. Mandal. 2006. Hydrous iron(III)–tin(IV) binary mixed oxide: arsenic adsorption behaviour from aqueous solution. Water Quality Research Journal of Canada 41(2): 198–209.

Hussam, A., and A.K.M. Munir. 2007. A simple and effective arsenic filter based on composite iron matrix: development and deployment studies for groundwater of Bangladesh. Journal of Environmental Science and Health Part A 42: 1869–1878. Available online at *http://chemistry.gmu.edu/faculty/hussam/Arsenic%20Filters/ESH%20ARSENIC%20FILTER%20PAPER%202007.pdf*.

IAEA (International Atomic Energy Agency). 2005. Final Report on the Proficiency Test on the Determination of Total Arsenic Concentration in Water. TC Project BGD/08/018. Seibersdorf, Austria: IAEA.

IARC (International Agency for Research on Cancer). 2001. IARC Monographs on the Evaluation of the Carcinogenic Risks to Humans. Lyons, France: IARC. Available online at *http://monographs.iarc.fr/*.

Islam, M.S., A. Siddika, M.N.H. Khan, M.M. Goldar, M.A. Sadique, A.N.M.H. Kabir, A. Huq, and R.R. Colwell. 2001. Microbiological analysis of tube-well water in a rural area of Bangladesh. Applied and Environmental Microbiology 67(7): 3328–3330.

Jang, M., S.H. Min, T.H. Kim, and J.K. Park. 2006. Removal of arsenite and arsenate using hydrous ferric oxide incorporated into naturally occurring porous diatomite. Environmental Science and Technology 40(5): 1636–1643.

Kanel, S.R., B. Manning, L. Charlet, and H. Choi. 2005. Removal of arsenic (III) from ground water by nano-scale zero-valent iron. Environmental Science and Technology 39(5): 1290–1298. Available online at *http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/2005/39/i05/abs/es048991u.html*.

Kanel, S.R., H. Choi, J.Y. Kim, S. Vigneswaran, and W.G. Shim. 2006. Removal of As (III) from groundwater using low cost industrial by-products-blast furnace slag. Water Quality Research Journal of Canada 41(2): 130–139.

Katsoyiannis, I.A., and A.I. Zouboulis. 2002. Removal of arsenic from contaminated water sources by sorption onto iron-oxide-coated polymeric materials. Water Research 36(2): 5141–5155.

Khan, A.H., S.B. Rasul, A.K.M Munir, M. Habibuddowla, M. Alauddin, S.S. Newaz, and A. Hussam. 2000. Appraisal of a simple arsenic removal method for groundwater of Bangladesh. Journal of Environmental Science and Health. Part A, Environmental Science and Engineering and Toxic and Hazardous Substance Control 35(7): 1021–1041.

Khan, A.H. 2007. Centre for Advanced Research in Physical, Chemical, Biological, and Pharmaceutical Sciences, University of Dhaka, Bangladesh. Personal communication, June 2007.

Kuriakose, S., T.S. Singh, and K.K. Pant. 2004. Adsorption of As(III) from aqueous solution onto iron oxide impregnated activated alumina. Water Quality Research Journal of Canada 39(3): 260–268.

Lien, H.-L., and R.T. Wilkin. 2005. High-level arsenite removal from ground water zero-valent iron. Chemosphere 59(3): 377–386.

Lin, T.F., and J.K. Wu. 2001. Adsorption of arsenite and arsenate within activated alumina grains: equilibrium and kinetics. Water Research 35(8): 2049–2057.

Manna, B.R., S. Dey, S. Debnath, and U.C. Ghosh. 2003. Removal of arsenic from ground water using crystalline hydrous ferric oxide (CHFO). Water Quality Research Journal of Canada 38(1): 193–210.

Manna, B.R., M. Dasgupta, and U.C. Ghosh. 2004a. Crystalline hydrous titanium (IV) oxide (CHTO): an arsenic (III) scavenger from natural water. Journal of Water Supply: Research and Technology-Aqua 53(7): 483–495.

Manna, B.R., S. Debnath, J. Hossain, and U.C. Ghosh. 2004b. Trace arsenic-contaminated groundwater upgradation using hydrated zirconium oxide (HZO). Journal of Industrial Pollution Control 20(Part 2): 247–266.

Mukherjee, A., M.K. Sengupta, M.A. Hossain, S. Ahamed, B. Das, B. Nayak, D. Lodh, M.M. Rahman, and D. Chakraborti. 2006. Arsenic contamination in groundwater: a global perspective with special emphasis on the Asian scenario. Special issue on arsenic. Journal of Health, Population, and Nutrition 24(2): 142–163.

NAE (National Academy of Engineering). 2006. Final Report: Evaluation of Grainger Challenge Arsenic Treatment Systems—SONO Filter #29. Prepared by Shaw Environmental Inc. (Shaw PN 118205-03), under EPA Contract No. EP-C-05-056 for the National Academy of Engineering. Washington, D.C.: NAE.

NAE. 2007. 2007 Grainger Challenge Prize Winners. Available online at *http://www.nae.edu/nae/grainger.nsf/weblinks/MKEZ-6XYRHR?OpenDocument*.

Nguyen, T.V., S. Vigenswaran, H.H. Ngo, D. Pokhrel, and T. Viraraghavan. 2006. Ironcoated sponge as effective media to remove arsenic from drinking water. Water Quality Research Journal of Canada 41(2): 164–170.

Pierce, M.L., and C.M. Moore. 1982. Adsorption of arsenite and arsenate on amorphous iron hydroxide. Water Research 16(7): 1247–1253.

Polizzotto, M.L., C.F. Harvey, S.R. Sutton, and S. Fendorf. 2005. Processes conducive to the release and transport of arsenic into aquifers of Bangladesh. Proceedings of the National Academy of Sciences of the USA 102(6): 18819–18823.

Rasul, S.B., Z. Hossain, A.K.M. Munir, M. Alauddin, A.H. Khan, and A. Hussam. 2002. Electrochemical measurement and speciation of inorganic arsenic in groundwater of Bangladesh. Talanta—The International Journal of Pure and Applied Analytical Chemistry 58(1): 33–43.

Raven, K.P., A. Jain, and R.H. Loeppert. 1998. Arsenite and arsenate adsorption on ferrihydrite: kinetics, equilibrium, and adsorption envelopes. Environmental Science and Technology 32(3): 344–349.

Rosenblum E., and D. Clifford. 1984. The Equilibrium Arsenic Capacity of Activated Alumina. Report EPA-600, S2-83-107. Washington, D.C.: Environmental Protection Agency.

Singh, P., T.S. Singh, and K.K. Pant. 2001. Removal of arsenic from drinking water using activated alumina. Research Journal of Chemistry and Environment 5(3): 25–28.

Smith, A.H., E.O. Lingas, and M. Rahman. 2000. Contamination of drinking water of arsenic in Bangladesh: a public health emergency. Bulletin of the World Health Organization 78(9): 1093–1103.

Thirunavukkarasu, O.S., T. Viraraghavan, and K.S. Subramanian. 2003. Arsenic removal from drinking water using iron oxide coated sand. Water, Air, & Soil Pollution 142(1-4): 95–111.

Vaishya, R.C., and S.K. Gupta. 2006. Arsenic (V) removal by sulfate modified iron oxide-coated sand (SMIOCS) in a fixed bed column. Water Quality Research Journal of Canada 41(2): 157–163.

VERC (Village Education Resource Center). 2007. Arsenic Mitigation Pilot Project: Bacteriological Field Test Report, Dhalipara & Doazipara of Muradpur Union in Sitakunda. April 2005–March 2006. B-30, Ekhlas Uddin Khan Road, Anandapur, Savar, Dhaka-1340, Bangladesh.

Wilkie, J.A., and J.G. Hering. 1996. Adsorption of arsenic onto hydrous ferric oxide: effects of adsorbate/adsorbent ratios and co-occurring solutes. Colloids and Surfaces A: Physicochemical and Engineering Aspects 107(20 February): 97–110.

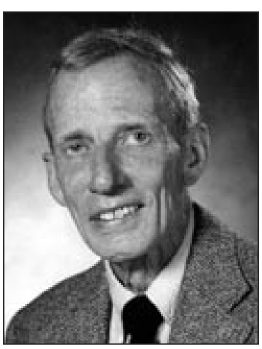
Yuan, C., and H.-L. Lien. 2006. Removal of arsenate from aqueous solution using nano-scale iron particles. Water Quality Research Journal of Canada 41(2): 210–215.

Zeng, L. 2004. Arsenic adsorption from aqueous solution on an Fe(III)–Si binary oxide adsorbent. Water Quality Research Journal of Canada 39(3): 269–277.

Water-resource models have been used to inform decisions about water supplies, ecological restoration, and water management in complex regional systems.

Water Resource Management Models

Daniel P. Loucks



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Water-resources development projects inevitably include economic, environmental, and social considerations, as well as computer-based models that can clarify trade-offs and help identify the plans, designs, and policies that will maximize desired impacts and minimize undesired ones. However, by design, models are simplifications of real systems. Therefore, predictions of how a real system will function under alternative designs and management policies are often controversial and always somewhat uncertain, because they necessarily include assumptions about future events and conditions that are not known. In short, modeling is a necessary part, but only a part, of the information used by decision makers. That said, I am willing to bet that every single major water-resources planning and management activity in the world today, whether focused on flooding problems, reservoir operation, groundwater development, water allocation, or aquatic ecosystem enhancement, includes models.

Thanks in part to advances in computer technology in the past 30 years, the most comprehensive models can now include engineering, economic, ecological, hydrological, and sometimes even institutional and political components of large, complex, multipurpose, water-resources systems. Applications of models to real systems have improved our understanding of how both work. This experience has also taught us the limitations of modeling complex interdependent physical, biochemical, ecological, social, legal, and political water-resource systems. Nevertheless, models are an essential part of the planning process, and models of varying complexity, and thus of varying data requirements, are available, as applicable.

Two major types of computer-based models are simulation models and optimization models. Simulation models address "what if" questions. Given the assumptions for a system design and operation, a simulation model can predict how well it will perform. Optimization models address "what should be" questions, what design and operating policy will best meet the specified objectives. However, the methods (algorithms) used to solve optimization models often limit the amount of detail they can include; thus they are less flexible than simulation models. So, especially for complex systems, optimization may be used first to screen out unsatisfactory alternatives; simulation models can then be used to investigate the remaining more promising alternatives.

Capabilities of Models

Models available today can predict runoff from watersheds due to precipitation and the sediment, nutrient, and other constituent loads in that runoff. Models can predict interactions between groundwater and surface water bodies, as well as flows and their constituents in stream and river channels. These routing models can be based on simple mass balance and advection-dispersion relationships, or they can be based on hydrodynamic computations. They can also include ecological components of aquatic systems. Models can be used to study reservoir operation; to forecast floods and plan flood-control programs; to predict storm surges, embankment erosion, and dam breaks; and to plan for ecosystem restoration.

Federal, state, and local water-resources planning agencies can and do use models for the real-time operation and management of water systems and for assessing water supply availability and reliability, taking into account projections of basin development, administrative and legal requirements, and other constraints related to conveyance and reservoir operations, aquifer pumping, and water demand and distribution. They use models for determining facility-size requirements for water storage and distribution systems given water diversions for domestic, commercial, industrial, rural, irrigation, municipal, energy, and environmental uses. They undertake watershed hydrology studies for improving river and reservoir administration and operation, the conjunctive use of surface water and groundwaters, water banking, and water exchanges and transfers. Many agencies, consultants, and university researchers are also working to improve water-resource analysis tools to meet their modeling and prediction needs.

Models can predict changes in a river bed form and location, including bank erosion, scouring, shoaling associated with construction or changes in the hydraulic regime, and so on. Models involving the transport of sediment have been used for morphological studies in small- and large-scale rivers of all kinds and in all settings, as well in reservoirs. Simulations can cover a few hours to several decades of high runoff events.

Hydrologists increasingly rely on GIS data and standardization to solve a variety of problems on different spatial scales.

Geographical information systems (GIS) are increasingly being included in planning and management models, and hydrologic models can be directly linked to GIS databases. These tools are useful for 2- or 3-dimensional spatial calculations, such as delineating watershed boundaries and stream and river paths, defining drainage areas and the areal extent of any other data layer, and for modeling distributed runoff. In the future, hydrologists will increasingly rely on GIS data and standardized ways of describing them so that they can be used consistently to solve a wide variety of problems at various spatial scales.

Water-resources planning and management activities are often participatory, involving groups of individuals with different interests, goals, and needs, thus requiring negotiation and compromise. So-called "shared-vision models" can be designed to meet the information needs of all stakeholders. The U.S. Army Corps of Engineers Institute for Water Resources has been actively involved in the development and use of such models, especially for planning for droughts and for water-allocation studies (*http://www.svp.iwr.usace.army.mil/*). To be most useful, shared-vision models must provide the right information, and the right amount of information to meet all stakeholder needs. Meeting these requirements can be a challenge to model developers.

Hydroinformatics, a term that originated and was popularized in Europe and was associated at first with computational hydraulic modeling, also recognizes the need to communicate model results in more meaningful ways. Hydroinformatics today emphasizes the use of artificial intelligence techniques (e.g., artificial neural networks, support vector machines, genetic algorithms, and genetic programming). These techniques can also be used for mining large collections of observed data or data generated from physically based models for knowledge discovery.

Models were instrumental in the adaptation of a cooperative regional plan for the Washington, D.C., area.

Examples of Modeling Applications

The three examples below illustrate how models have been and are being used. The first involves the Potomac Basin and describes how modeling helped solve a highly visible and highly political water-supply problem. The next two examples, involving the Everglades region and part of the Great Lakes Basin, are ongoing studies that require much more detailed modeling methods. Although all three examples are in the United States, many others could have been chosen from other parts of the world.

The Water Supply for the Washington, D.C., Metropolitan Area

Since the early 1600s, when humans first settled in the Potomac River Basin, concerns have been raised about the river and how it is used. A main reason for these concerns is the rapidly increasing population, particularly in the Washington, D.C., metropolitan area (WMA), where three water-supply agencies provide water to their customers. Traditionally, these agencies have operated independently, concerned only with satisfying the needs of their own constituents.

However, with a rapidly increasing population, but relatively stable river hydrology, it became apparent in the 1950s that frequent, severe droughts could lead to serious problems. To address these concerns, the U.S. Army Corps of Engineers carried out a number of studies and, in 1963, proposed the construction of 16 new reservoirs in the Potomac Basin. Two were subsequently authorized by Congress, and construction was even begun on one of them in spite of substantial local opposition.

A simulation study in the late 1960s and early 1970s by graduate students at Johns Hopkins University showed how the coordinated use of the water stored in existing reservoirs in the Potomac River Basin during droughts would largely eliminate the need for new reservoirs, at least until 2020. However, they pointed out, the public would have to accept some risk of water restrictions during droughts, and the three utilities would have to cooperate with each other and coordinate their operations.

This was the first time a regional perspective was suggested. The idea had widespread political, legal, social, and environmental dimensions, and the models played a major role in convincing everyone that a cooperative policy would work. In the end, models were instrumental in bringing about a consensus supporting the nonstructural plan (Anon, 1983; Hagen et al., 2005).

On July 2, 1982, at a historic ceremony in the District of Columbia Building, contracts were signed ensuring an adequate water supply for WMA until 2050. The regional water-supply system was expected to cost about $31 million, whereas the federal reservoirs that were originally proposed would have cost about $400 million (McGarry, 1990). The savings far exceeded the money spent up to that time to support research on water-systems modeling.

The original simulation model, now named PRRISM (Potomac Reservoir and River Simulation Model), has undergone several modifications and is currently used to evaluate the response of the system to present and future water demands. PRRISM is also used in drought-management exercises, which are conducted every five years (Hagen et al., 2005; Sheer, 1981). The model is an important tool for the evaluation and development of updated drought-management policies. In this sense, WMA is applying an adaptive-management approach to water-supply planning and management.

Greater Everglades Restoration

Historically, the Greater Everglades in south Florida covered an area of about four million acres. During the last 100 years, approximately half of the Everglades have disappeared as a result of drainage, channelization, and other changes made to allow for increased agricultural

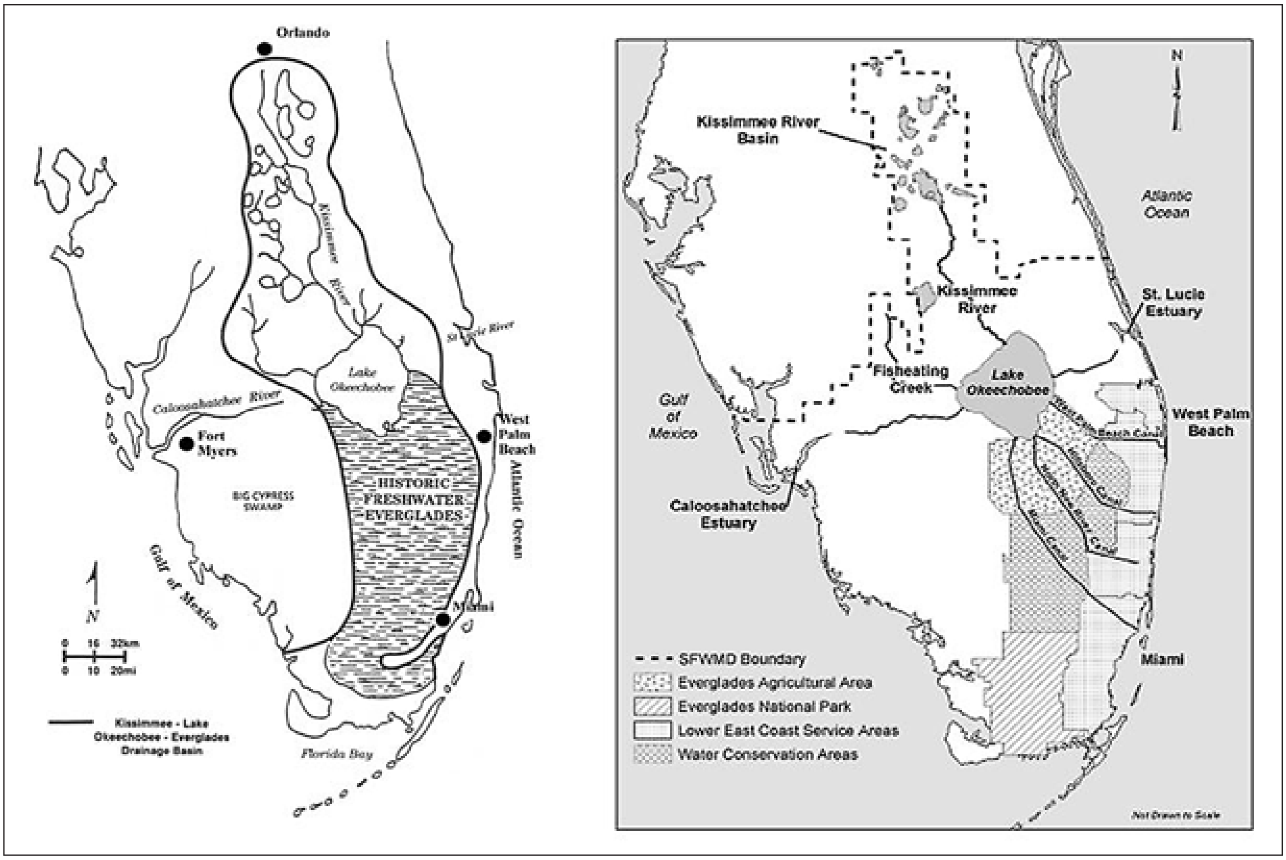

Figure 1 Historic watershed and current features of the Everglades region.

and urban growth. Today the water-management system in south Florida encompasses 18,000 square miles with more than 1,800 miles of levees and canals, about 200 major water-control structures, and nearly 30 pumping stations. However, the Everglades system today (Figure 1) can no longer meet the environmental and water-supply requirements of the current population.

Unprecedented efforts are under way to restore the Greater Everglades ecosystem, involving the creation of more floodplain wetlands (including from some recently purchased land from the sugar industry), improving water quality, reconnecting natural river channels, and improving the habitat of more than 300 species of fish and wildlife—while simultaneously meeting the needs of the urban and agricultural sectors in the region. Restoration is expected to take more than 30 years and to cost more than $10 billion. The Comprehensive Everglades Restoration Plan, which has more than 60 components and has been described as the largest ecosystem restoration effort in the world, is designed to achieve a balance between ecosystem restoration and urban and agricultural water supply.

Computer modeling has been and continues to be a critical component in the development and implementation of the Everglades restoration plan (Tarboton et al., 1999). The Everglades project requires a multidisciplinary modeling approach, as is evident in the models that have been developed and used thus far:

- The Everglades Screening Model (ESM) simulates the major hydrologic features and demands of the south Florida water-resources system. The ESM was used extensively during the screening phase of the Everglades restoration plan.
- The South Florida Water Management Model (SFWMM) simulates the surface and subsurface hydrology under existing and proposed water-management plans in the south Florida region using a fixed grid and climate data for 1965 to 2000. The SFWMM is a premier hydrologic simulation model that has been used for system-wide evaluations of proposed Everglades restoration plans. It is currently being replaced by a finite-volume, variable-grid regional simulation model.

- The Natural System Model (NSM) simulates the hydrologic condition of the Everglades before they were drained. The NSM uses the same climatic inputs, time step, calibrated model parameters, and algorithms as the SFWMM. The NSM has been essential to setting environmental restoration targets for the Everglades restoration plan.
- The Everglades Landscape Model (ELM), which combines hydrologic, water quality, and ecological processes in a single model, predicts spatial and temporal patterns of change in the landscape and interactions and feedback among water, nutrients, soils, and wetland plants.
- The Across Trophic Level System Simulation Model (ATLSSM) simulates the biotic communities of the Everglades/Big Cypress region and the abiotic factors that affect them. The ATLSSM is used to clarify how the biotic communities of south Florida are affected by the hydrologic regime and other, abiotic factors and as a tool for evaluating management alternatives (*http://atlss.org*).
- The River of Grass Evaluation Methodology (ROGEM) predicts the relative quality of habitat responses to Everglades restoration alternatives.

The use of these models for decision making is illustrated in Figure 2 (*www.sfwmd.gov*).

Lake Ontario-St. Lawrence River Study

In April 1999, the International Joint Commission (IJC), which oversees all transboundary waters along the entire Canadian-U.S. border, obtained funds from the governments of Canada and the United States to determine how the management of water levels and outflows in Lake Ontario might be improved in light of public concerns about the environment and adjacent ecosystems and in response to potential climate change. After spending $20 million and taking more than five years to complete a review, the Canadian-U.S. study team submitted three alternative plans to the IJC for consideration (LOSLSB, 2006). The three plans represented different combinations of trade-offs to meet conflicting objectives. The IJC is now in the process of deciding which alternative is "best," but it appears the plan being proposed by the IJC is not the plan many stakeholders wanted (*http://www.greatlakesforall.com/2008/04/ijc-ignores-hea.html*; *http://www.citizenscampaign.org/campaigns/great_lakes.htm*).

Lake Ontario is the most downstream of the Great Lakes, which define part of the boundary between Canada and the United States. The lake receives water from the other four Great Lakes, as well as from the local watershed. Water from the lake is discharged into the St. Lawrence River, which flows northeast past Montreal and Quebec into the Gulf of St. Lawrence and the Atlantic Ocean. Water levels in Lake Ontario and the upper portion of the river, and the flows and water levels in the lower portion of the St. Lawrence River, are regulated, to some extent, by the operation of the Moses Saunders Dam, which separates the upper and lower portions of the river (Figure 3).

Regulation of the Lake Ontario-St. Lawrence River system requires balancing several conflicting water-management objectives, which are inherent in the management of flows and lake levels. For example, alleviating high water levels in Lake Ontario requires releasing more water, which may cause flood-related damage

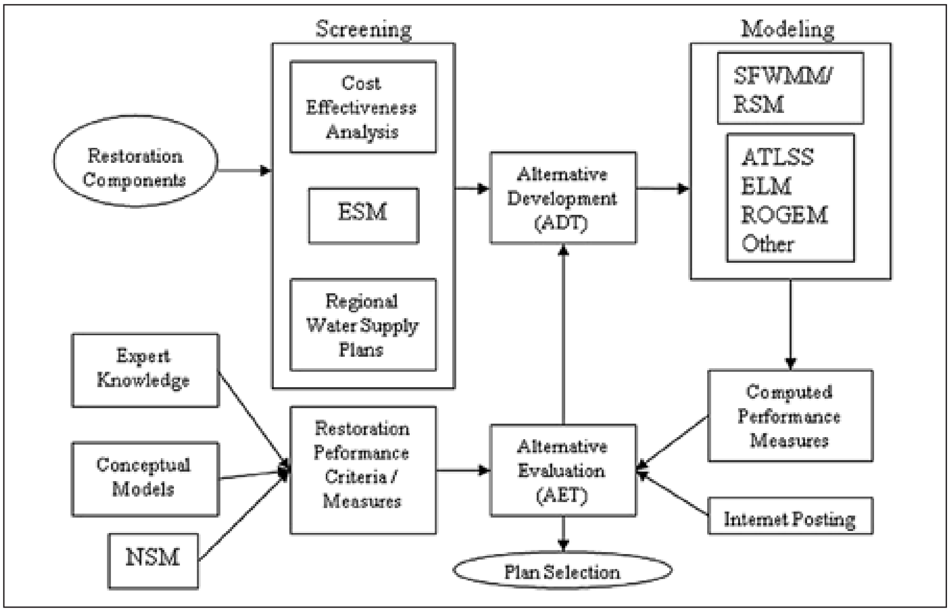

Figure 2 Use of models in the Everglades restoration planning process.

downstream because of high-water conditions in the river. Low water levels in the river can adversely impact shipping, but raising the water levels in the lower river requires releasing water from Lake Ontario, which may cause problems for recreational boaters and municipal water suppliers along the upper river and lake shore. In addition, managing the variability of water levels to accommodate ecosystem needs introduces another level of complexity.

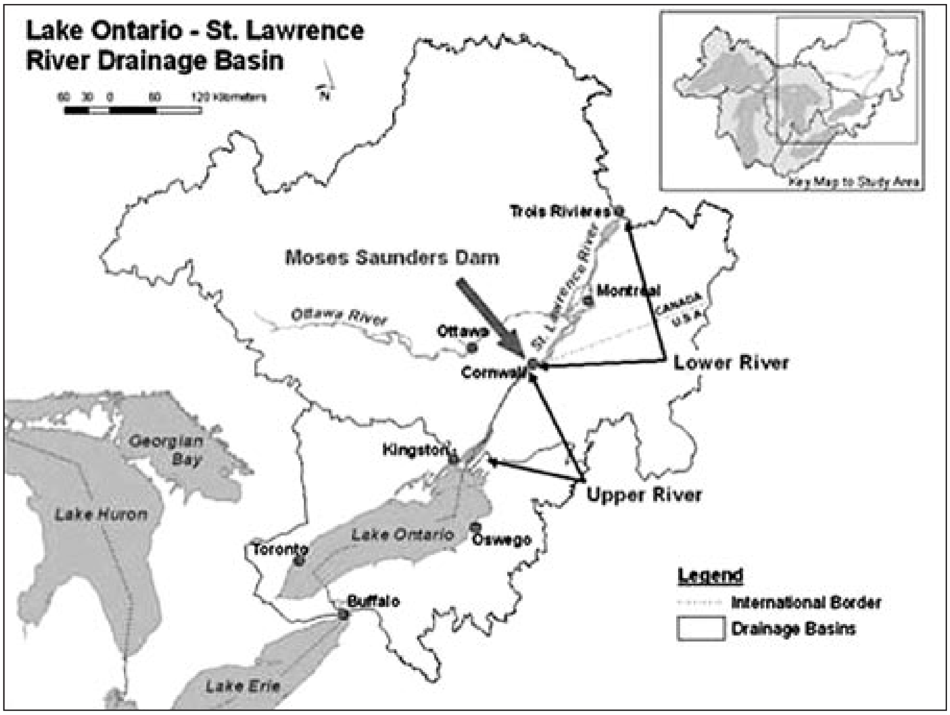

Figure 3 Map of Lake Ontario and the St. Lawrence River and their watersheds.

Uncertainty about future water supplies from the upper Great Lakes and tributaries in the Lake Ontario-St. Lawrence River Basin adds to the difficulty of deciding how much water to release through the dam to balance upstream and downstream needs. For example, if future supplies are unexpectedly low, releases made to alleviate low water levels in the river may drain too much water from Lake Ontario, making it much more difficult to raise river levels later when the impacts may be even worse. Similarly, if future supplies are unexpectedly high, releasing less water to avoid minor downstream flooding may increase damage later, if releases then have to be increased dramatically.

The timing of water availability at different times of year is important, in different ways for different reasons. The level of commercial navigation and recreational boating drops considerably in the winter. The value of energy generated in the summer during periods of peak energy demand can be more than 12 times the value of energy generated in the spring. Larger releases of water from Lake Ontario reduce the water levels of Lake St. Lawrence, which is immediately upstream of the hydropower dam. If too much water is released, the levels in Lake St. Lawrence can be lowered to the point that they become hazardous to navigation and could even cause groundings. On the other hand, high flows can create cross-currents that make it difficult to control vessels. Finally, although more electricity can be generated when a greater volume of water passes through the turbines, this reduces the head (i.e., the level of water in Lake St. Lawrence upstream of the dam), which in turn reduces the amount of electricity generated for each cubic meter of water.

During the five-year study period, considerable physical, economic, environmental, and ecological data were collected, and numerous computer optimization and simulation models were developed and used for economic, environmental, and ecological impact assessments under possible climate-induced changes in regional hydrology. The following list describes models that were developed and used for this study:

- The Flood and Erosion Prediction System (FEPS) Model was developed to assess shoreline erosion rates and damage over time.
- The St. Lawrence River Model was used to estimate the impact of water levels on existing shoreline-protection works, such as structural failures or the need for increased maintenance, and the associated economic costs.
- The Integrated Ecological Response Model (IERM) was used to estimate how different regulation plans would impact plant and animal species in the ecosystems in Lake Ontario and the St. Lawrence River.

- Various policy-generation models, using stochastic optimization as well as simulation, were used to identify and evaluate real-time operation policies and operating policies that could be implemented without periodic modeling. These numerous plans could then be simulated in more detail, using both FEPS and IERM, and an overall shared-vision model.
- Statistical hydrologic models were used to generate alternative time series of inflows to the system, which were then used in policy simulations to ensure the reliability, resilience, and robustness of each policy. Some of these time series, which were as long as 50,000 years, were used to analyze four different climate-change scenarios. Each of the candidate plans was thoroughly tested to ensure that none had fatal flaws that would inhibit its performance under plausible extreme conditions.
- A Shared-Vision Planning Model incorporated the results of all other models; the environmental science, economics, and public responses that had been input into an interactive analytical framework to help the study team and public interest groups explore numerous variations of the plans; operating nuances; and performance impacts. The shared-vision model was developed for stakeholders as well as the study team for use on the Internet via an interactive Excel-based program called the Boardroom (*http://losl.org/boardroom/main_e.php*).

The Lake Ontario-St. Lawrence River study provided a unique opportunity for making changes to the overall system to see if the operation of the system would be improved, and, if so, to determine how. In the opinion of most of the participants, the study succeeded in developing three plans, all of which should perform better than the current operating regime in terms of overall net economic and environmental benefits. Nevertheless, all three plans involve trade-offs, and some stakeholders may have a higher risk of some impacts (e.g., shoreline erosion) than with the current operating policy. In the end, if negatively impacted stakeholders "yell loud enough," they might prevent the adoption of any of the three new plans. This brings us back to the fact that information derived from models is just one factor in the decision-making process.

Conclusions

Water-resources planners and managers are becoming increasingly aware of the importance of establishing an open, participatory decision-making process that requires close coordination among the many institutions that manage water resources and a strong focus on the stakeholders impacted by management decisions. This awareness has increased the use of analytical modeling tools, such as decision-support systems, that can promote consensus building and dispute resolution and the integration of water, energy, and land-use planning.

The situation presents numerous intellectual, analytical, and evaluative challenges for the developers of models, and overcoming these challenges will certainly require research. Unfortunately, funding for such research is a rare commodity in the current climate.

References

Anon. 1983. Water supply. Civil Engineering 53(6): 50–53.

Hagen, E.R., K.J. Holmes, J.E. Kiang, and R.S. Steiner. 2005. Benefits of iterative water supply forecasting in the Washington, D.C., metropolitan area. Journal of the American Water Resources Association 41(6): 1417–1430.

LOSLSB (Lake Ontario–St. Lawrence Study Board). 2006. Options for Managing Lake Ontario and St. Lawrence River Water Levels and Flows. Final report of the International Lake Ontario–St. Lawrence River Study Board. Washington, D.C., and Ottawa, Canada: International Joint Commission.

McGarry, R.S. 1990. Negotiating water supply management agreements for the National Capital Region. Pp. 116–130 in Managing Water-Related Conflicts: The Engineer's Role, edited by W. Viessman and E.T. Smerdon. Washington, D.C.: American Society of Civil Engineers.

Sheer, D.P. 1981. Assuring water supply for the Washington Metropolitan Area—25 years of progress. Pp. 39–66 in A 1980s View of Water Management in the Potomac River Basin. Report of the Committee on Governmental Affairs, U.S. Congress, Senate, 97th Congress, 2d Session, November 12. Washington, D.C.: U.S. Government Printing Office.

Tarboton, K.C., C. Neidrauer, E. Santee, and J. Needle. 1999. Regional Hydrologic Modeling for Planning the Management of South Florida's Water Resources through 2050. Proceedings of the Annual International Meeting of the ASAE, Toronto, Ontario, Canada.

Further Reading

Loucks, D.P., and E. van Beek. 2005. Water Resources Systems Planning and Management: An Introduction to Methods, Models, and Applications. Paris, France: UNESCO Press. Available online at *http://ecommons.library.cornell.edu/handle/1813/2798*.

Water-distribution systems, the last barriers in the water-treatment process, are vital to protecting public health.

Water-Distribution Systems: The Next Frontier

Vanessa Speight is practice leader for distribution-system modeling and master planning for Malcolm Pirnie Inc.

Vanessa Speight

Technologies for treating drinking water have advanced significantly over the past century. Today the availability of abundant, clean, safe drinking water, on demand at every location, is taken for granted in the developed world. However, even this highly treated water is subject to degradations in quality once it leaves the treatment plant and enters the distribution system.

By the time water reaches the consumer, its quality might be very different from what it was when it left the plant. Thus distribution systems, the last barriers in the water-treatment process, are vital to protecting public health. And, because pipes are buried and not subject to the direct control of water utilities, the management of distribution systems has become one of the most difficult challenges to providing safe drinking water.

In the past few decades, researchers have increasingly focused their efforts on water-distribution systems. Maintaining a continuous water supply to customers, providing adequate fire flow (enough pressure to put out fires) to all parts of the system, maintaining water pressure, and ensuring water quality is a difficult balancing act. Because distribution systems must grow as cities grow, they usually are made up of a variety of pipes of different ages, materials, configurations, and quality. In most U.S. systems at least some of the pipes are more than 80 years old (EPA, 2005).

The National Academies recently convened a panel to review the public-health risks from distribution systems (NRC, 2007). The report focused on three areas: physical integrity of the system (i.e., the quality of the pipes); hydraulic efficiency (i.e., the quantity and pressure of delivered water); and water quality (i.e., maintenance of a high level of quality throughout the system). All three of these factors must be addressed to ensure public health. The study panel also identified high-priority areas for risk reduction, including improvements in cross-connections, new and repaired water mains, and water storage (NRC, 2005).

Distribution systems represent the next frontier for the drinking-water industry. In addition to the challenges of managing and replacing infrastructure, the industry is subject to detailed, highly critical scrutiny by the public and the media. Tools are emerging to address these challenges, but considerable work remains to be done.

Aging infrastructure and microbial or chemical contamination are major threats to public health.

The Infrastructure Crisis

It is difficult to calculate the extent of buried infrastructure in the United States, but based on water-industry surveys, there are approximately 1 million miles of piping, 24,000 storage tanks, 6.8 million fire hydrants, and 14.6 million valves in water-distribution systems (AWWA, 2007). The average rate of water-main breaks is estimated to be on the order of 23 to 27 breaks per 100 miles of pipe. More than half of these breaks are attributable to the deterioration of materials in the pipes or fittings. However, one-quarter of them are associated with construction activities, which are generally not under the control of water utilities (AWWA, 2007).

The cost of repairing water mains averages $3,000 per break for the repairs themselves; indirect costs, such as the impact on businesses that lose water service and damage to property, are much higher (American Water Works Service Company, 2002).

Estimates of required infrastructure replacement by several industry groups and the Environmental Protection Agency (EPA) vary. But they all agree that maintaining the current level of service will require a very large investment in drinking-water infrastructure. The *2005 Report Card for America's Infrastructure* prepared by the American Society of Civil Engineers gives drinking-water infrastructure a grade of D–, down from its 2001 rating of D (ASCE, 2005). ASCE estimates that the country faces an annual shortfall of $11 billion, above and beyond the existing investment levels for replacing aging facilities and complying with drinking-water regulations. This report cites the conclusion of the Congressional Budget Office that "current funding from all levels of government and current revenues generated from ratepayers will not be sufficient to meet the nation's future demand for water infrastructure" (CBO, 2003).

The latest *Drinking Water Infrastructure Needs Survey and Assessment* estimates that a total investment of $276.8 billion will be required for drinking-water infrastructure in the next 20 years (EPA, 2005). This total includes both the installation of new infrastructure to meet growing demand and the rehabilitation or replacement of aging infrastructure. Of the $276.8 billion, approximately 75 percent would be related to distribution-system infrastructure: $183.6 billion for piping and $24.8 billion for storage systems.

Rising energy costs adversely affect water utilities, which rely on extensive pumping to maintain pressure and deliver water. Despite some attempts to minimize costs by pumping during off-peak energy times, the majority of these costs cannot be avoided without compromising water-pressure levels and fire protection.

Challenges to Maintaining Water Quality

Microbial contamination in distribution systems is a potential threat to public health (Craun and Calderon, 2001). Pathways for the entry of contaminants into distribution systems include: organisms that survive the treatment process; contaminated groundwater that flows in from outside when pressure in a pipe drops; contamination during the installation or repair of water mains; and backflow from non-potable systems connected to potable plumbing. Chemical contamination can occur in the distribution system as a result of corrosion reactions, the accumulation of contaminated sediments, and the intrusion of chemical compounds into the pipes. Intentional contamination is also a potential threat.

The Centers for Disease Control and Prevention (CDC), which tracks outbreaks of waterborne diseases related to drinking water, found that from 1971 to 2004, 21 of 168 reported outbreaks were attributable to deficiencies in distribution systems. The primary deficiency was cross-connection or back-siphoning from a contaminated water source (Roy, 2007).

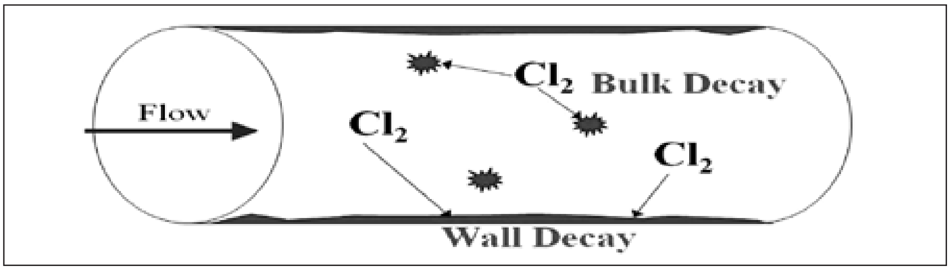

FIGURE 1 Schematic drawing of chlorine decay reactions in a distribution system. Source: Adapted from Speight, 2003.

Degradation of Disinfectant Residual

One key to protecting public health is maintaining a residual amount of disinfectant, typically in the form of free chlorine or chloramine (also known as combined chlorine), in the distribution system. However, as water travels through the pipes, the disinfectant oxidizes material in both the bulk water and on the pipe wall, thereby reducing the amount of disinfectant available to ensure continued disinfection (Figure 1). The decrease in the disinfectant residual can leave water vulnerable to contamination by microbes.

At the pipe wall, chlorine can react with corrosion products, sediments, and biofilm, which forms when bacteria adhere to a surface and excrete slimy, glue-like polymers that form a protective barrier; biofilm is also a site for colonization by a variety of microbes (Montana State University Center for Biofilm Engineering, 2008). Biofilm has been shown to grow on most common pipe materials, but the quantity of attached bacteria is several orders of magnitude higher in unlined cast-iron pipes (Camper et al., 2003).

Drinking-water regulations specify the minimum and maximum amounts of disinfectant allowable in water. Thus the problem of maintaining sufficient disinfectant residual throughout the distribution system cannot be solved by simply adding more chlorine at the treatment plant. In addition, chlorine not only disinfects, but can also produce several classes of harmful disinfection by-products. These compounds, which form when chlorine reacts with natural organic matter present in the water, are suspected carcinogens and have potential reproductive health effects (EPA, 2006).

By-product compounds continue to form in the presence of free chlorine as water travels to the consumer, forcing water utilities to balance the need for disinfection with the need to minimize disinfection by-products. Therefore, it is important that treated water be delivered as quickly as possible to end users to minimize the formation of disinfection by-products and disinfectant decay.

Contamination in Storage Facilities

Water is stored in elevated tanks, ground tanks, and sometimes in the pipes themselves. The design and operation of storage systems varies widely across the country, mostly as a reflection of regional preferences and architectural influences. In addition, the need to provide enough water to maintain fire flow often means that storage tanks must be larger than is optimal for water-quality purposes.

Depending on the design and operation of a storage facility, water might remain in a tank for an extended period of time. The longer the retention time in the tank, the greater the potential for the decay of residual disinfectant, the formation of disinfection by-products, and microbial regrowth. Tanks have also been shown to be the sites of contaminant entry into distribution systems, either through broken hatches or sediment accumulation (Clark et al., 1996). Therefore, the management of storage systems is a critical issue for the operation of distribution systems.

Problems in End-User Systems

Every location where water is available to consumers is connected to a distribution system. Typically a water utility's jurisdiction ends at the customer's meter, and the remaining plumbing is the responsibility of the building owner. All of the reactions that can degrade water quality in a distribution system can also occur in household plumbing. In fact, many incidents that gain media attention, such as the problems with lead in Washington, D.C., in 2004, are linked to household plumbing (EPA, 2007).

New Tools

Because access to distribution systems is extremely limited, the water industry relies on a variety of tools to operate, maintain, and continually improve them. Water quality is sampled daily in a variety of ways to meet regulations and to inform operational decisions.

The traditional sampling method is "grab samples," but the use of continuous (also known as online) monitors is increasing.

Continuous water-quality monitors can measure simple parameters, such as pH and turbidity, or provide more sophisticated analyses, such as the concentration of residual disinfectant and total organic carbon. Considerable research is being done to determine the optimal number and placement of both grab samples and continuous monitors, the best parameters to monitor for different purposes, and the most accurate analytical methods (Speight et al., 2004).

Hydraulic and Water-Quality Models

Along with the collection of continuous data on water quality, data analysis and event detection are emerging fields (Hart et al., 2007). Because each continuous monitor can generate several data points per minute per water-quality parameter, sophisticated techniques must be used to sift through these data to identify meaningful information on the status of the distribution system. Much of the work on data analysis was first done in the security arena, but water utilities are looking for (1) benefits beyond security to justify investing in expensive continuous-monitoring equipment; (2) basic operational information; and (3) indications of contamination, intentional or otherwise (ASCE, 2004).

Hydraulic models, which have been used for decades, provide reliable simulations of flows and pressures when appropriately calibrated to real-world conditions (Ormsbee and Lingireddy, 1997). Newer models can link hydraulic and water-quality parameters in a single simulation. Figure 2 shows the input data required for a hydraulic and water-quality model of a distribution system with chlorine disinfectant.

Accurate modeling of hydraulic and water-quality behavior in distribution systems is heavily dependent on the accuracy of the input data. For water utilities with very old pipes, substantial efforts are necessary just to collect and verify information about pipe diameters, materials, and locations. However, with the advent of geographic information systems (GIS), data required to build a model of a distribution system are becoming more readily available and more accurate (Figure 3). GIS is also a helpful tool for understanding the spatial relationships between water-quality measurements at different locations in the distribution system over time.

A major challenge in hydraulic modeling is determining customer water usage at all points in the distribution system over time. Because meters are generally read on a monthly or quarterly basis, they do not provide real-time data. Innovations in automated meter reading may improve the collection of real-time data, but there are still significant challenges to data management.

Therefore, real-time models today are primarily used for energy management and for detecting situations that differ from the baseline, such as water-main breaks or large fires (Jentgen et al., 2003). The field has not yet advanced to the level of sophistication necessary to fully automate the operation of a water-distribution system, so very few utilities have created real-time models of their systems, which require linking operational data with the model and running repeated simulations.

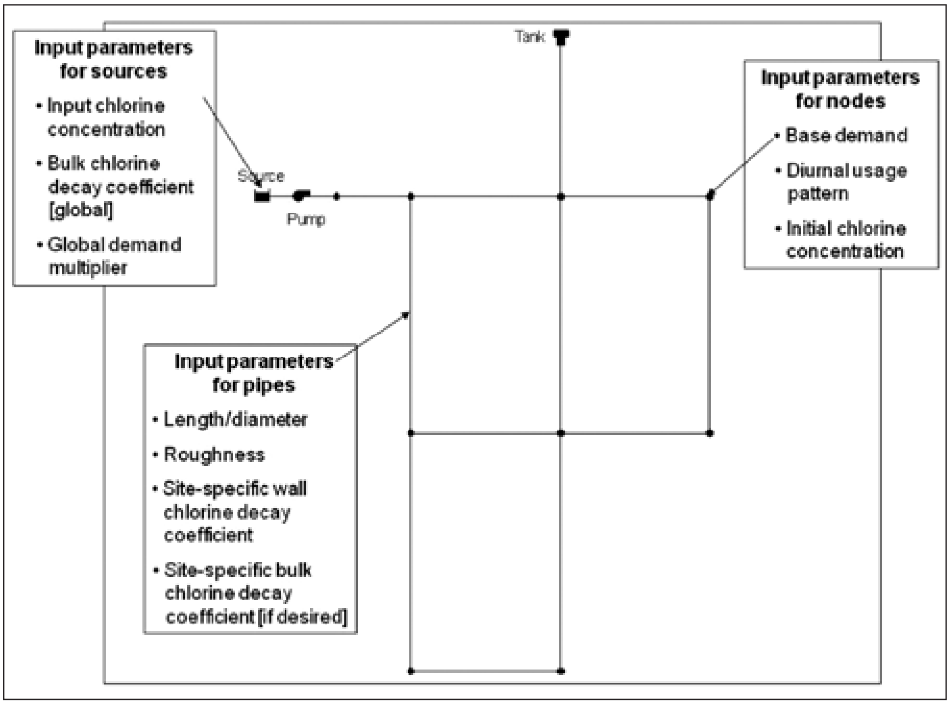

FIGURE 2 Schematic drawing of model-input requirements to simulate chlorine in a distribution system. Source: Adapted from EPA, 2002.

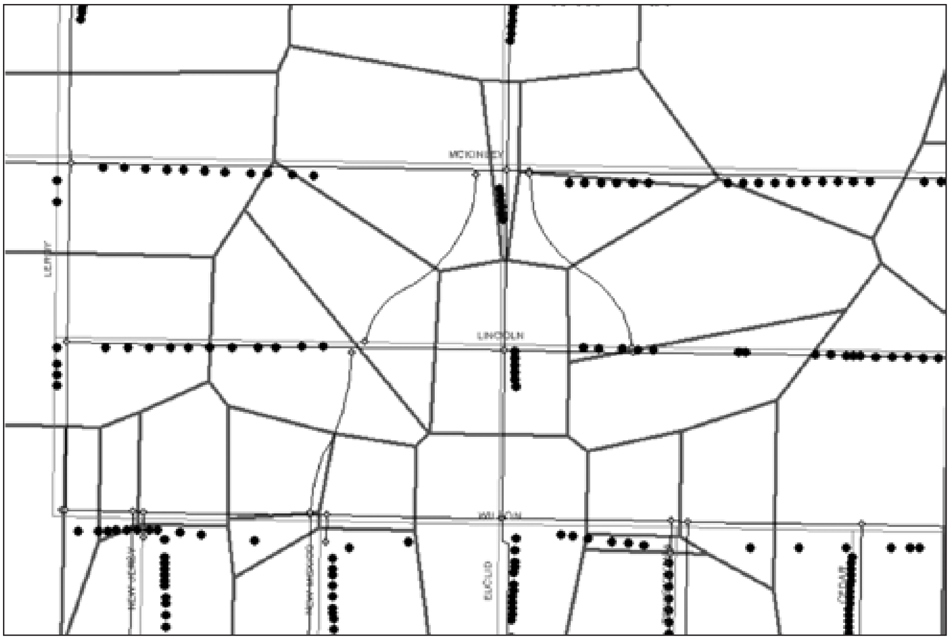

FIGURE 3 Example of a hydraulic model using GIS data.

Even though water-quality models are still considered an emerging technology, they are beginning to be used to inform operational decisions and for developing plans for sampling or system changes. In addition, a relatively simple first-order decay model for chlorine, the most commonly modeled parameter for water quality, has been shown to provide good simulations of field data (Vasconcelos et al., 1997).

Modeling of microbial contaminants in distribution systems is limited by the lack of knowledge about biofilm processes, the attachment and detachment of microbes to particles, growth mechanisms in low-nutrient environments, concentrations of microbes that enter the system via different pathways (e.g., low-pressure transient versus a cross-connection with a sewer), and the presence of pathogens. Particle-transport and deposition modeling are particularly challenging because of the highly variable flow caused by the highly variable use of water by individuals.

Using deterministic models for simulating disinfectant by-products has been even less successful (Speight et al., 2000). However, probabilistic models of water quality look promising because they include mechanistic formulations that can account for uncertainties. However, because probabilistic models are computationally intensive, they are currently limited to research.

Infrastructure Models

Researchers in asset-management are developing tools for modeling the status of infrastructure based on data inputs, such as the age of pipes, the materials used in pipes, soil conditions, and the number of water-main breaks (Davis and Marlow, 2008). Asset-management analyses are used to help prioritize infrastructure investments by balancing the cost of replacing pipes, the likelihood of pipe failure, the consequences associated with failure of a given pipe, and other variables.

The development of reliable, in situ condition-assessment technologies for water mains is an emerging field, as is the development of methods of quickly rehabilitating water mains that are out of service (Deb et al., 2002). Given the large financial burden of replacing the deteriorating water-distribution infrastructure in the United States, cost-effective approaches to asset management, rehabilitation, and replacement will be essential to the integrity of distribution systems in the future.

Alternative Water-Delivery Systems

Alternative water-delivery systems, such as dual-distribution systems that carry potable water and non-potable water separately, are also being investigated. In some areas of the United States where water is scarce, such as Florida and California, the use of reclaimed water (highly treated wastewater effluent) is commonplace, and dual-distribution systems are being installed throughout cities to meet the demand for non-potable water. The challenges associated with dual-distribution systems are parallel to those of current systems; they include the cost of installation, maintaining the integrity of the buried infrastructure, maintaining water quality, and ensuring adequate supplies and pressures. Point-of-use treatment devices are also being considered in areas where water quality at the tap is inconsistent or cannot be guaranteed.

Conclusions

Research on water-distribution systems presents exciting challenges for the engineering community. Solving the problems facing distribution systems will require research in a number of interrelated fields, including infrastructure materials, water treatment, hydraulics, water chemistry and microbiology, data management, computer modeling, human behavior, public health and education, and risk management.

Emerging tools include advanced hydraulic and water-quality modeling software, continuous monitors for water-quality parameters, and data-management systems. In addition, we still need basic data about the physical characteristics of buried infrastructure and fundamental research on water-quality reactions in distribution systems.

Finally, the consequences of the infrastructure crisis are likely to be felt by consumers as water utilities struggle to find economic and political backing to repair, maintain, and replace aging structures.

References

ASCE (American Society of Civil Engineers). 2004. Interim Voluntary Guidelines for Designing an Online Contaminant Monitoring System. Available online at *http://www.asce.org/static/1/wise.cfm*.

ASCE. 2005. Report Card on America's Infrastructure. Available online at *http://www.asce.org/files/pdf/reportcard/2005_Report_Card-Full_Report.pdf*.

AWWA (American Water Works Association). 2007. Distribution System Inventory, Integrity, and Water Quality. Prepared for the Environmental Protection Agency. Available online at *http://www.epa.gov/safewater/disinfection/tcr/pdfs/issuepaper_tcr_ds-inventory.pdf*.

American Water Works Service Company. 2002. Deteriorating Buried Infrastructure, Management Challenges and Strategies. Prepared for the Environmental Protection Agency. Available online at *http://www.epa.gov/safewater/disinfection/tcr/pdfs/whitepaper_tcr_infrastructure.pdf*.

Camper, A.K., K. Brastrup, A. Sandvig, J. Clement, C. Spencer, and A.J. Capuzzi. 2003. The effects of distribution system materials on bacterial regrowth. Journal of the American Water Works Association 95(7): 107–121.

CBO (Congressional Budget Office). 2003. Letter to the Honorable Don Young and James L. Oberstar regarding future spending on water infrastructure. Available online at *http://www.cbo.gov/ftpdocs/40xx/doc4034/01-30-WaterLetter.pdf*.

Clark, R.M., E.E. Geldreich, K.R. Fox, E.W. Rice, C.H. Johnson, J.A. Goodrich, J.A. Barnick, and F. Abdesaken. 1996. Tracking a salmonella serovar typhimurium outbreak in Gideon, Missouri: the role of contaminant propagation modeling. Journal of Water Supply Research and Technology–Aqua 45(4): 171–183.

Craun, G.F., and R.L. Calderon. 2001. Waterborne disease outbreaks caused by distribution system deficiencies. Journal of the American Water Works Association 93(9): 64–75.

Deb, A.K., F.M. Grablutz, Y.J. Hasit, J.K. Snyder, G.V. Loganathan, and N. Agbenowsi. 2002. Prioritizing Water Main Rehabilitation and Replacement. Denver, Colo.: American Water Works Association Research Foundation.

Davis, P., and D. Marlow. 2008. Asset management: quantifying the economic lifetime of large-diameter pipelines. Journal of the American Water Works Association 100(7): 110–119.

EPA (Environmental Protection Agency). 2002. EPANET Program, Examples. Available online at *http://www.epa.gov/nrmrl/wswrd/dw/epanet.html*.

EPA. 2005. Drinking Water Infrastructure Needs Survey and Assessment, 3rd Report to Congress. Washington, D.C.: EPA Office of Water.

EPA. 2006. National Primary Drinking Water Regulations: Stage 2 Disinfectants and Disinfection By-Products Rule; Final Rule. 40 CFR Parts 9, 141 and 142, Federal Register 71:2:388–493. Washington, D.C.: EPA.

EPA. 2007. Lead in DC Drinking Water. Washington, D.C.: EPA.

Hart, D., S. McKenna, K. Klise, V. Cruz, and M. Wilson. 2007. CANARY: A Water Quality Event Detection Algorithm Development Tool. In Proceedings of the World Environmental and Water Resources Congress 2007. CD-ROM. Reston, Va.: American Society of Civil Engineers.

Jentgen, L., S. Conrad, R. Riddle, E.W. Von Sacken, K. Stone, W.M. Grayman, and S. Ranade. 2003. Implementing a Prototype Energy and Water Quality Management System. Denver, Colo.: American Water Works Association Research Foundation.

Montana State University Center for Biofilm Engineering. 2008. Biofilm Basics. Available online at *http://www.erc.montana.edu/CBEssentials-SW/bf-basics-99/bbasics-01.htm*.

NRC (National Research Council). 2005. Drinking Water Distribution Systems: Assessing and Reducing Risks–First Report. Washington, D.C.: National Academies Press.

NRC. 2007. Drinking Water Distribution Systems: Assessing and Reducing Risks. Washington, D.C.: National Academies Press.

Ormsbee, L.E., and S. Lingireddy. 1997. Calibrating hydraulic network models. Journal of the American Water Works Association 89(2): 42–50.

Roy, S. 2007. Waterborne disease and outbreak surveillance. Presented at the EPA TCRDSAC. Available online at *http://www.epa.gov/safewater/disinfection/tcr/pdfs/presentations/presentations_tcrdsac_october2007.pdf*.

Speight, V.L. 2003. Development of a Randomized Sampling Methodology for Characterization of Chlorine Residual in Drinking Water Distribution Systems. Ph.D. dissertation. Department of Environmental Sciences and Engineering, University of North Carolina at Chapel Hill.

Speight, V.L., W.D. Kalsbeek, and F.A. DiGiano. 2004. Randomized stratified sampling methodology for water quality in distribution systems. Journal of Water Resources Planning and Management 130(4): 330–338.

Speight, V.L., J.R. Nuckols, L. Rossman, A.M. Miles, and P.C. Singer. 2000. Disinfection by-product exposure assessment using distribution system modeling. Proceedings of AWWA Water Quality Technology Conference, Salt Lake City, Utah, November 5–9, 2000. Denver, Colo.: American Water Works Association.

Vasconcelos, J.J., L.A. Rossman, W.M. Grayman, P.F. Boulos, and R.M. Clark. 1997. Kinetics of chlorine decay. Journal of the American Water Works Association 89(7): 54–65.

Integrated closed-loop systems for recycling water and waste material can meet consumer demands and satisfy environmental imperatives.

New Approaches and Technologies for Wastewater Management

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In the past decade, practical applications of a variety of new wastewater-treatment technologies, such as membrane filtration systems and advanced oxidation, have led to new ways of managing urban water systems and water resources (Daigger, 2003). These new treatment regimes, especially the integration of urban-water and waste-management systems, promise to dramatically improve the sustainability of our water resources.

These new systems are creating new needs, which are driving further technology development. In this paper, I discuss the circumstances that have necessitated change in urban water and resource management; describe some of the changes that are already being implemented; and describe technological advances that are under development.

The Need for Change

The major driver of change is, quite simply, population growth coupled with a rising global standard of living, a combination that has resulted in resource consumption (including water use) that exceeds the current resources of planet Earth (Daigger, 2007b, 2008a; Wallace, 2005). Let's say the current population of slightly more than 6 billion consumes the resources of one planet Earth. By about 2050, when the population is expected to reach about 9 billion, and if standards of living continue to rise, the amount consumed will be the resources of about three planet Earths. Obviously, this scenario is not sustainable.

When the population of Earth was much smaller (e.g., fewer than 2 billion) and when per capita use of resources was much smaller, our traditional "take, make, waste" pattern of resource consumption was sustainable. Now, however, we need to recycle and reuse all types of resources (including water), and we must increase our use of renewable resources.

Water Stress

In contrast to many other natural resources, water is inherently renewable. Mother Nature has been recycling water since the origin of life on the planet. When the rate of net abstraction and use of water prior to its being returned to the environment exceeds the natural rate of recycling, water stress develops. Water-management practices can add to water stress by reducing the amount of water available, for example by returning water to the environment in a polluted state or by altering land configurations in ways that adversely affect natural water-restoration processes, such as those provided by wetlands.

Water stress currently affects only a modest fraction of the human population, but it is expected to affect 45 percent of the population by 2025 (Daigger, 2007b; WRI, 1996). This situation will be further exacerbated by global climate change, which is altering water-supply and storage patterns in ways that make existing water-management infrastructure less effective.

Recycling technologies can significantly reduce net water abstraction from the environment, but many of those technologies require an increase in the consumption of other resources, especially energy. In our resource-constrained world, increasing the consumption of any resource, even for necessary functions such as water management, must be carefully considered.

A further aspect of water stress caused by urban water-management systems is the increase in the amount of nutrients, especially phosphorus, in the aquatic environment (Steen, 1998; Wilsenach et al., 2003). Mined as phosphate rock, phosphorus is used to manufacture fertilizer, which in turn is used to grow crops that are subsequently consumed by humans. Phosphorus (and other nutrients) then pass through us as we metabolize food and end up in the wastewater stream. When these effluents are discharged to the aquatic environment, the excess nutrients can cause eutrophication. At the current rate of consumption, the supply of phosphate, an essential nutrient with no known replacement, is expected to be exhausted in about 100 years. Thus, there are at least two urgent reasons for us to recover phosphate from the wastewater stream.

Two other factors must be taken into consideration. First, although water service is uniformly provided in the developed world, approximately 1 billion of the people on Earth do not have access to safe drinking water, and more than 2.5 billion do not have access to adequate sanitation. Clearly, we need more efficient urban water management to meet global needs. Second, water and wastewater utilities around the world are hard pressed to find sufficient funding to maintain, let alone extend, their infrastructure to meet growing needs.

Definition of Sustainability

The need for new approaches to urban water and resource management is being driven by the need for sustainability, defined as: (1) access for all to clean water and appropriate sanitation; (2) greater use of local water resources; (3) energy neutrality; (4) more responsible nutrient management; and (5) financially stable utilities.

Taken together, the requirements for sustainable urban-water and resource-management systems are consistent with the "triple bottom line" definition of sustainability (Table 1), which includes social, environmental,

TABLE 1 Triple Bottom Line Urban-Water and Resource-Management Sustainability Goals

Sustainability Area	Goal
Economy	• Financially stable utilities with enough resources to maintain their infrastructure.
Environment	• Locally sustainable water supply (recharge exceeds net withdrawal). • Energy-neutral system (or positive if possible), with minimal chemical consumption. • Responsible nutrient management that minimizes dispersal to the aquatic environment.
Society	• Access to clean water and appropriate sanitation for all.

and economic goals (Daigger and Crawford, 2005). The economic goal is for utilities to provide sufficient value that their users are willing to financially support maintenance (and expansion) of necessary infrastructure. Environmental goals include meeting water needs from locally available water supplies while maintaining energy neutrality, minimal chemical consumption, and responsible nutrient management. The overall social goal is to provide uniform access to clean water and appropriate sanitation for all.

The challenge is to develop and implement approaches to urban water and resource management, and the supporting technologies, to meet all of these goals. If we can do that, we will have sustainable systems today and in the future.

Achieving Sustainability Goals

Meeting the environmental goals outlined above will require that we evolve from the current linear approach to water and resource management to closed-loop systems, with a combination of decentralized and centralized elements, for recycling both water and waste material (Daigger, 2007a, 2008a,b; Daigger and Crawford, 2007). Because of their superior environmental performance, closed-loop systems have the potential to satisfy the social and economic goals of sustainability, as well as the environmental goals.

Figure 1 illustrates one closed-loop system for urban water management. Note that the water supply, both domestic and commercial, is segregated into water for potable uses, such as direct consumption and bathing, and water for non-potable uses, such as toilet flushing, laundry, irrigation, and industrial uses. Overall, the amount of potable water consumed is actually quite small. Thus the amount of water from the environment necessary for this purpose is much smaller than the amount of potable water currently provided. In fact, the demand for potable water can be met either from local water supplies or by importing modest quantities of potable water. By separating potable and non-potable water, the net removal of water from the environment for potable uses can be dramatically reduced.

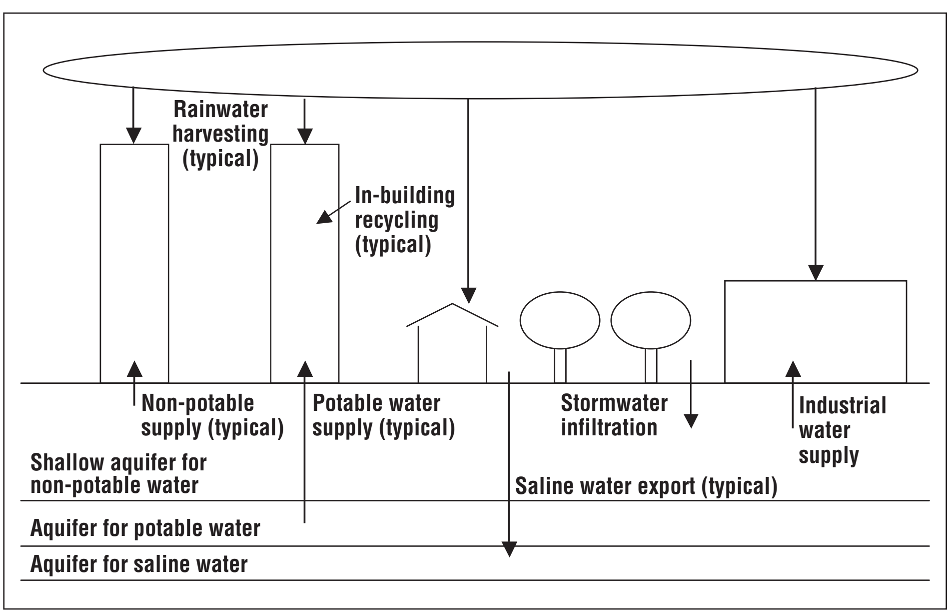


FIGURE 1 Diagram of a decentralized urban water-management system. Source: Daigger, 2008a.

The bulk of the domestic and commercial water supply is non-potable water, which can be supplied from a variety of local sources, including recycled water and captured rainwater. As Figure 1 shows, the storage of non-potable water is a critical component of the system. Non-potable water can be stored either in an aquifer beneath the urban area (as shown in Figure 1) or in a surface storage facility.

The repeated recycling of water may result in the buildup of dissolved solids, including salts, which must be managed to maintain the quality of the water for its intended uses. Reverse osmosis (RO) and other processes can be used to remove the salt, which can then be discharged to a saline-water aquifer (Figure 1) or managed in another way.

Many have asked why water needs cannot be met by increasing the desalination of seawater. Although this is technologically feasible, desalination does not meet the environmental criteria for sustainability because of its significant energy requirements. Even though technological advances continue to reduce these energy requirements, they will always be higher than for treating fresh wastewater, because the solids content of wastewater (1,000 mg/L) is much smaller than of seawater (35,000 mg/L).

TABLE 2 Tools in Centralized and Decentralized Systems

Tools	Centralized Systems	Decentralized Systems
Storm water management and rainwater harvesting		Permeable pavements, green roofs, rain gardens, etc.
Water conservation	New technologies and behavioral changes	
Water reclamation and reuse	Treatment for potable uses and reuse (direct and indirect)	Treatment for potable uses and non-potable reuse
Energy management	Anaerobic digestion, combustion, microbial fuel cells	Capture of heat energy, microbial fuel cells
Nutrient recovery	Land application of biosolids, struvite recovery	
Source separation	Treatment of kitchen, black, and yellow wastewater	Supply potable and non-potable water; treatment of kitchen, black, and yellow wastewater

Technologies for Sustainable Systems

Fortunately tools are available for: (1) more efficient capture and local use of storm water to help conserve local water resources; (2) improved water conservation for reducing water consumption without compromising standards of living; (3) the reclamation and reuse of wastewater; (4) the management and extraction of energy from the wastewater stream; (5) the recovery of nutrients; and (6) the separation of specific wastewater sources. Many technologies are available to facilitate the implementation of systems such as the one shown in Figure 1 and for improving decentralized and centralized water and resource management (Table 2). The goal is to conserve local water resources for meeting a variety of local needs.

Technologies are available for managing storm water, which can be captured and either used directly or treated by natural means and infiltrated into the groundwater for subsequent use (Strecker et al., 2005). These technologies include permeable pavements, green roofs, and rain gardens. In the past decade, as the characterization and understanding of these systems has improved, storm water capture and treatment have become much more reliable and predictable.

Water- and wastewater-treatment technologies are crucial components of urban water systems. Membrane technologies for removing particulate matter (micro- and ultra-filtration) and dissolved substances (nanofiltration and RO) are increasingly being used. When particle-removal membranes are coupled with biological systems, they can create membrane bioreactor (MBR) processes, which are fast becoming an essential water-reclamation process (Daigger et al., 2005; DiGiano et al., 2004). Advanced oxidation processes include combinations of ozone, ultraviolet (UV) light, and hydrogen peroxide to create the highly reactive hydroxyl radical (OH). In addition, activated carbon is still widely used for water reclamation.

Tools That Address Environmental Goals

The remaining tools in the technology tool kit do not necessarily reduce the overall abstraction of water but do contribute significantly to meeting environmental goals, such as energy neutrality and reduced nutrient dispersion. For example, as Figure 2 shows, laundry and bath water (typically referred to as gray water), which contain very few pollutants, constitute the largest component of urban wastewater (Henze and Ledin, 2001; Tchobanoglous, 1981). Because of its low-pollutant content, gray water requires only a modest degree of treatment to become reusable non-potable water. Thus recycling this large volume of wastewater requires less energy, and thus consumes fewer resources, than recycling combined potable and non-potable wastewater. In addition, heat can be transferred to or from the treated gray water stream using specially designed heat exchangers and heat pumps, which represents a significant source of energy.

Organic matter in the several components of the wastewater stream represents a principal source of energy, in addition to the heat value of the water itself. As shown in Figure 2, most of the organic matter (quantified as the five-day biochemical oxygen demand, or BOD_5) is contained in toilet and kitchen waste (typically referred to as black water). The wastewater flow associated with these components is quite small, suggesting that the black-water fraction can be used efficiently for energy production. Energy-producing technologies for organic matter in black water include thermal combustion and anaerobic treatment for producing biogas (Grady et al., 1999), which can be used in combined heat and power systems. The microbial fuel cell is an emerging energy-production technology (Logan et al., 2006).

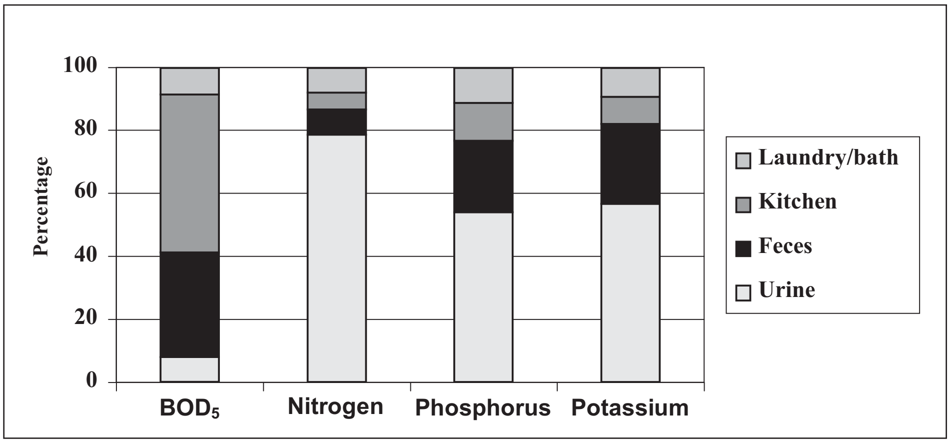


FIGURE 2 Distribution of constituents in domestic wastewater from different sources. Source: Henze and Ledin, 2001.

The majority of nutrients is found in the urine stream (typically referred to as yellow water). When energy management and nutrient recovery are combined with source separation, energy can be efficiently produced and extracted from the wastewater stream, along with nutrient recovery. A variety of technologies are available for nutrient recovery. For example, biosolids containing nitrogen and phosphorus, produced from treatment and nutrient-recovery processes, can be applied directly to agricultural lands as fertilizer. A second approach is to apply phosphate fertilizers, containing either struvite ($MgNH_4PO_4$) or calcium phosphate, produced from the chemical precipitation of phosphorus.

As suggested in Table 2, storm water capture and water-reclamation technologies are most effective at the local (decentralized) level. Water-reclamation technologies result in reduced pumping requirements because the reclaimed water is produced closer to where it is used. By contrast, energy-management and nutrient-recovery technologies are most effective in large-scale centralized systems. Figure 3 shows an integrated system that uses all of these features and indicates the scale at which the various technologies would be applied.

New Technologies

Membrane Filtration Systems

Membrane systems have been critical to the development of advanced water-reclamation systems, and the development of new and improved systems is expected to continue. Immersed micro- and ultra-filtration membranes provide excellent pre-treatment for RO, which can remove a wide range of dissolved constituents. In addition, the development of membrane filtration systems has led to the development of both advanced water-treatment technology and MBRs, which is fast becoming the workhorse of the water-reclamation industry.

With MBRs, biological-solids residence times (SRTs) are increased, making possible more complete biological treatment and the retention of pathogens (including viruses); treatment with MBR produces a highly clarified effluent that can be more easily disinfected. Thus treatment with MBR is ideal for producing non-potable water. For the reclamation of potable water, MBR must be followed by RO and UV treatment (Tao et al., 2005, 2006).

Nanotechnology

Further dramatic improvements are feasible in the near future (Shannon et al., 2008). Nanotechnology concepts are being investigated for higher performing membranes with fewer fouling characteristics, improved hydraulic conductivity, and more selective rejection/transport characteristics. Advances in RO technology include improved membranes and configurations, more efficient pumping and energy-recovery systems, and the development of process technology, such as membrane distillation (Kim et al., 2008).

Microbial Fuel Cells

With microbial fuel cells, a potential breakthrough technology, electrical energy could be extracted directly from organic matter present in the waste stream by using electron transfer to capture the energy produced by microorganisms for metabolic processes (Logan et al., 2006). First, microorganisms are grown as a biofilm on an electrode; the electron donor is separated from the electron acceptor by a proton exchange membrane, which establishes an electrical current. Electrical energy is then generated through the oxidation of organic matter (BOD_5).

Although this technology is still in the early stages of development and significant advances in process efficiency and economics will be necessary, it has the potential to produce electrical energy directly from organic matter in the waste stream.

Natural Treatment Systems

Our fundamental understanding and characterization of processes in natural treatment systems (NTSs) is also improving, enabling us to take advantage of natural processes to improve water quality (Kadlec and Knight, 1996). In NTSs, a variety of physical, chemical, and biological processes function simultaneously to remove a broad range of contaminants.

For example, NTSs are increasingly being used to capture, retain, and treat storm water, thereby converting this "nuisance" into a valuable source of water. These natural systems have the advantage of being able to remove a wide variety of contaminants, including nutrients, pathogens, and micro-constituents (e.g., pharmaceuticals and endocrine-disrupting chemicals). Long proven effective for treatment of potable water, NTSs are increasingly being used for water reclamation.

Urine-Separating Toilets

As shown in Table 2 and illustrated in Figure 3, the development of urine-separating toilets and technologies for treating urine to produce hygienic fertilizer products is a key to managing nutrients with minimal requirements for outside resources, such as additional energy (Larsen et al., 2001; Maurer et al., 2006). Urine-separating toilets have already been developed and continue to be refined, and research on using them for waste management is ongoing. Struvite precipitation and other processes are already available for producing usable fertilizer products from separated urine, and efforts are ongoing to improve the established approaches.

Monitoring and Control Systems

The complex systems illustrated in Figure 3 will require sophisticated monitoring and control systems. The production and consumption of reclaimed water must be balanced so as not to exceed available storage capacity and to take into account variations in supply from rainwater. Water production must also be managed to maintain the integrity of the overall system and, particularly, the efficiency and effectiveness of the barriers that protect public health, such as the separation of potable and non-potable water. In addition, because energy requirements vary diurnally and seasonally, energy consumption also requires active management. Research on a new generation of sensor and system-control technologies is ongoing (Shannon et al., 2008).

Concluding Thoughts

Even though a survey by *BMJ* (formerly *British Medical Journal*) found that modern water supply and sanitation is the most significant contribution to public health in the past 150 years (BMJ, 2007), and the National Academy of Engineering listed modern water-supply

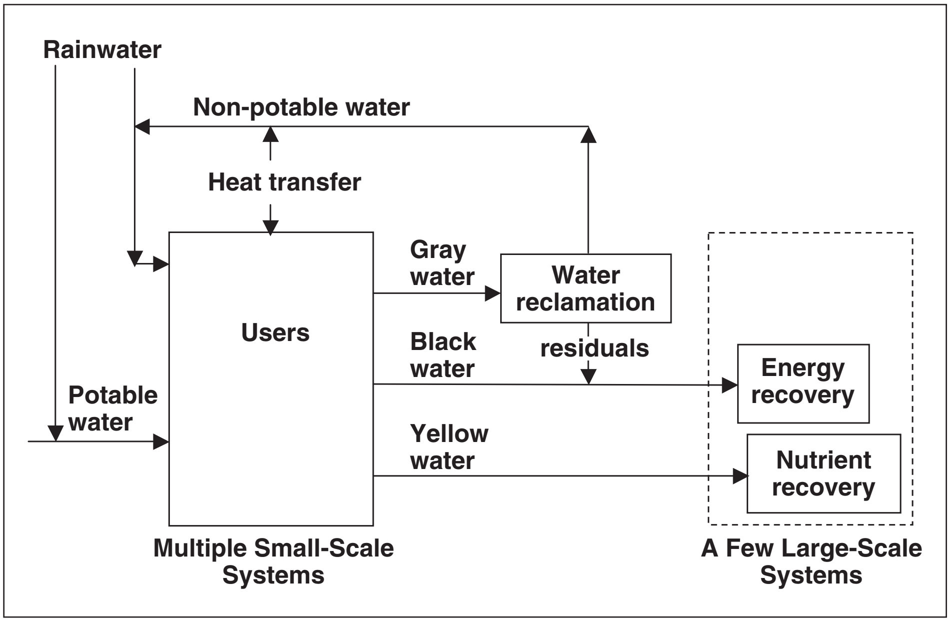


FIGURE 3 Schematic drawing of an integrated urban-water and resource-management system.

and sanitation systems as one of the greatest engineering achievements of the 20th century (Constable and Sommerville, 2003), circumstances have changed, and new approaches to water and sanitation systems are urgently needed. Thus we are faced with many new, interesting, and important challenges.

Fortunately many technologies to meet these challenges already exist, and work is being done on refining them and integrating them into higher performing, more sustainable systems. These are all areas in which engineers excel!

The "companion" challenge will be choosing among available options and developing institutional arrangements for implementing them in the most effective ways (Daigger, 2007a,b; 2008a,b; Daigger and Crawford, 2005). This is where we will need help from other professions.

References

BMJ. 2007. Medical Milestones. BMJ 334: s1–s20.

Constable, G., and B. Sommerville. 2003. A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives. Washington, D.C.: Joseph Henry Press.

Daigger, G.T. 2003. Tools for future success. Water Environment and Technology 15(12): 38–45.

Daigger, G.T. 2007a. Creation of Sustainable Water Resources by Water Reclamation and Reuse. Pp. 79–88 in Proceedings of the 3rd International Conference on Sustainable Water Environment: Integrated Water Resources Management—New Steps. Sapporo, Japan, October 24–25, 2007.

Daigger, G.T. 2007b. Wastewater management in the 21st century. Journal of Environmental Engineering 133(7): 671–680.

Daigger, G.T. 2008a. AEESP Lecture—Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, Resource Recovery. Proceedings of the Water Environment Federation 81st Annual Conference and Exposition. Chicago, Ill., October 19–22, 2008. Available on CD-ROM.

Daigger, G.T. 2008b. Decentralization: A Practitioner's Perspective. Proceedings of the 6th IWA Leading Edge Water and Wastewater Treatment Technology Conference. Zurich, Switzerland, June 1–4, 2008. Available on CD-ROM.

Daigger, G.T., and G.V. Crawford. 2005. Wastewater Treatment Plant of the Future—Decision Analysis Approach for Increased Sustainability. Pp. 361–369 in 2nd IWA Leading-Edge Conference on Water and Wastewater Treatment Technology, Water and Environment Management Series. London, U.K.: IWA Publishing.

Daigger, G.T., and G.V. Crawford. 2007. Enhanced water system security and sustainability by incorporating centralized and decentralized water reclamation and reuse into urban water management systems. Journal of Environmental Engineering and Management 17(1): 1–10.

Daigger, G.T., B.E. Rittmann, S. Adham, and G. Andreottola. 2005. Are membrane bioreactors ready for widespread application? Environmental Science and Technology 39(19): 399A–406A.

DiGiano, F.A., G. Andreottola, S. Adham, C. Buckley, P. Cornel, G.T. Daigger, A.G. Fane, N. Galil, J.G. Jacangelo, A. Pollice, B.E. Rittmann, A. Rozzi, T. Stephenson, and Z. Ujani. 2004. Safe water for everyone. Water Environment and Technology 16(6): 31–35.

Grady, C.P.L. Jr., G.T. Daigger, and H.C. Lim. 1999. Biological Wastewater Treatment. 2nd ed. New York: Marcel Dekker.

Henze, M., and A. Ledin. 2001. Types, Characteristics and Quantities of Classic, Combined Domestic Wastewater. Pp. 57–72 in Decentralised Sanitation and Reuse: Concepts, Systems and Implementation, edited by P. Lens, G. Zeeman, and G. Lettinga. London, U.K.: IWA Publishing.

Kadlec, R.H., and R.L. Knight. 1996. Treatment Wetlands. Boca Raton, Fla.: CRC Lewis Publishers.

Kim, I.S., B.S. Oh, and H.W. Hyun. 2008. Moving Desalination Forward. Proceedings of the Singapore International Water Week Water Convention. Singapore, June 25–26, 2008. Available on CD-ROM.

Larsen, T.A., I. Peters, A. Alder, R. Eggen, and M. Maurer. 2001. Re-engineering the toilet for sustainable wastewater management. Environmental Science and Technology 35(9): 192A–197A.

Logan, B.E., B. Hamelers, R. Rozendal, U. Schroder, J. Keller, S. Freguia, P. Aelterman, W. Verstraete, and K. Rabaey. 2006. Microbial fuel cells: methodology and technology. Environmental Science and Technology 40(17): 5181–5192.

Maurer, M., W. Pronk, and T.A. Larsen. 2006. Treatment processes for source-separated urine. Water Research 40(17): 3151–3166.

Shannon, M.A., P.W. Bohn, M. Elimelech, J.G. Georgladis, B.J. Mariñas, and A.M. Mayes. 2008. Science and technology for water purification in the coming decades. Nature 452(20): 301–310.

Steen, I. 1998. Phosphorus availability in the 21st century: management of a non-renewable resource. Phosphorous and Potassium 217(September-October): 25–31.

Strecker, E., W. Huber, J. Heaney, D. Bodine, J. Sansalone, M. Quigley, M. Leisenring, D. Pankani, and A. Thayumanavan. 2005. Critical Assessment of Stormwater Treatment and

Control Selection Issues. Project No. 02-SW-1. Alexandria, Va.: WERF (Water Environment Research Foundation).

Tao, G.H., K. Kekre, J.J. Qin, M.W. Oo, B. Viswanath, and H. Seah. 2006. MBR-RO for high-grade water (NEWater) production from domestic used water. Water Practice and Technology 1(2): doi: 10.2166/WPT.2006041. Available online at *http://www-32.cis.portlandcs.net/wpt/001/0041/0010041.pdf*.

Tao, G., K. Kekre, W. Zhao, T.C. Lee, B. Viswanath, and H. Seah. 2005. Membrane bioreactors for water reclamation. Water Science and Technology 51(6-7): 431–440.

Tchobanoglous, G. 1981. Wastewater Engineering: Collection and Pumping of Wastewater. New York: McGraw-Hill Book Company.

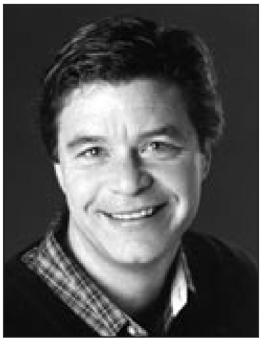
Wallace, B. 2005. Becoming Part of the Solution: The Engineer's Guide to Sustainable Development. Washington, D.C.: American Council of Engineering Companies.

Wilsenach, J.A., M. Maurer, T.A. Larsen, and M.C. van Loosdrecht. 2003. From waste treatment to integrated resource management. Water Science and Technology 48(1): 1–9.

WRI (World Resources Institute). 1996. World Resources 1996–1997. New York: Oxford University Press.

Networks of volunteers working within a common framework to improve water quality can transcend geopolitics.

Living with a Changing Water Environment



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Jerald L. Schnoor

Water, like all things on planet Earth, is changing. But the changes in water resources are attributable primarily to *human activities*, not natural causes. Four major factors profoundly affect access to quality water: population growth and migration; climate change; changes in land use and energy choices; and global poverty. The legacy of these four factors will be not only less water but also more *degraded* water, especially for poor people. Unless we find better ways to protect and improve our water supplies, the future looks dire for billions of people.

Our environment has changed dramatically, even in the past few decades, and the effects are apparent at the local, regional, and even global scale. Arguably, water is our most precious resource, yet we face looming crises in the availability of water for humans, not to mention for fisheries and all aquatic species. The American Society of Civil Engineers estimates that U.S. water and wastewater infrastructure alone will require an investment of $1 trillion over the next 20 years (ASCE, 2005).

What can we do to meet these challenges? First, we must recognize the causes of the problem and seek to *mitigate* them. Second, we must *adapt* or change by altering the way we treat and use water. Third, as engineers and scientists, we must provide appropriate, *sustainable technology* for water infrastructure. Fourth, we must find better ways of monitoring, modeling, and *forecasting* our water future to provide stakeholders and decision makers with better information.

Drivers of Change

Population Growth

Global population has been growing for 1,500 years, except for a brief period in the 1300s when the bubonic plague was rampant (Figure 1). However, it took thousands of years from the dawn of civilization for the population to grow to 1 billion people, in about 1800 A.D. It took only 125 years to reach 2 billion, and then 33 years to reach 3 billion. Since then, the population has grown by about a billion every 13 to 14 years.

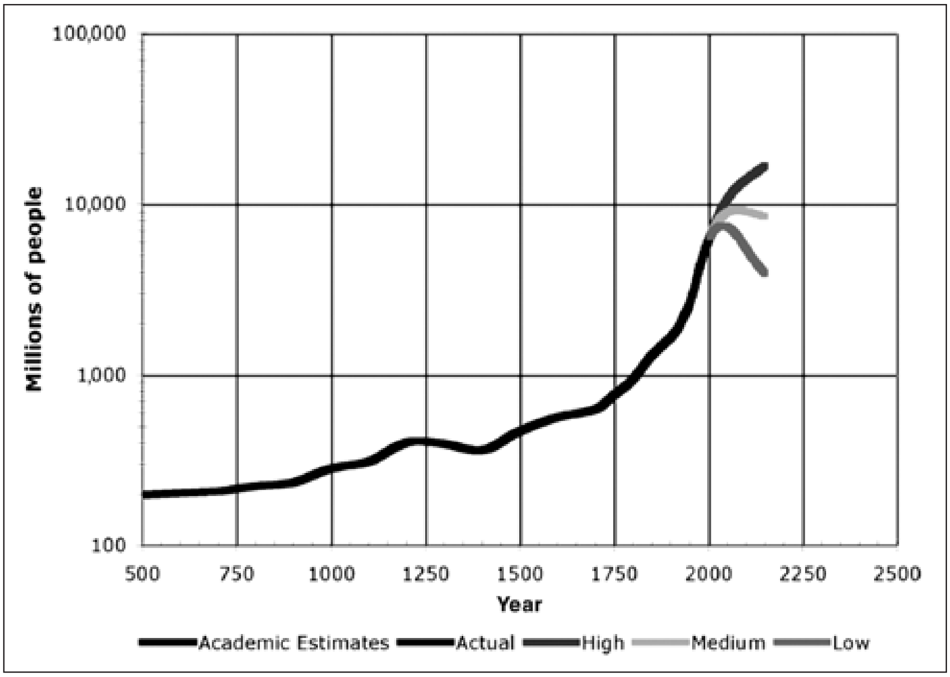


FIGURE 1 Increase in world population from 500 A.D. through today and projected to 2150 with high, medium, and low demographic assumptions. The medium projection reaches a peak population of nearly 10 billion people in 2075 and levels off at 8 to 9 billion. Projections are from mass collaboration at Wikipedia (*http://upload.wikimedia.org/wikipedia/commons/7/79/World-Population-500CE-2150.png*) accessed on July 16, 2008.

The threat of water scarcity is directly related to population density. When population densities are low, the threat of water scarcity is also low. But when population densities are high, any decrease in available water can be disastrous—not necessarily because of a lack of water, but because we lack systems that ensure *access* and *distribution* of precipitation and fresh water. Today, humans use approximately 54 percent of all of the available fresh water on Earth (Postel et al., 1996). Considering the global trend toward growing populations and mass migrations to coastal megacities, many of which are already semi-arid and short of water, the future looks bleak.

The situation is unsustainable, even where adequate distribution systems make inter-basin transfers of water possible; even then increased migration and changing precipitation patterns make future water allocations uncertain. For example, snowmelt water is allocated and conveyed from the Sierra Nevadas (and a portion of the Colorado River) to southern California, which is home to more than 20 million people but only has enough precipitation to provide water for about 1 million people. Because of decreasing snowfalls in the Sierra Nevadas, we have created a situation that precludes further growth in southern California. In fact, even the current population is at risk in times of drought.

Climate Change

In 2007, the United Nations Intergovernmental Panel on Climate Change (IPCC) issued its fourth assessment, a consensus report based on work by hundreds of scientists in dozens of countries (IPCC, 2007). According to the IPCC, our climate is changing, primarily as a result of emissions of greenhouse gases (GHGs) (i.e., human activities). The temperature is already 0.76°C warmer than it was from 1850 to 1899 (Figure 2), and it is likely to increase by 2.0 to 4.5°C (with a best estimate of about 3°C) during the 21st century. In addition, extreme events, such as heat waves, droughts, and increased-precipitation events (floods) will become more frequent.

Increases in precipitation are very likely in high latitudes, while decreases are likely to occur in most subtropical regions, continuing recent trends. This means that regions like the southwestern United States and Mexico, Central America, Brazil, southern Europe and the Mediterranean, northern and southern Africa, the Middle East, and western Australia will receive much less precipitation (10 to 30 percent less than they did from 1980 to 1999). Decreases in precipitation in Africa, Latin America, and southern Asia already threaten billions of poor people who can least afford to respond to the challenges of a warmer, drier world.

We are already experiencing human-induced changes in climate. Arctic ice, permafrost, and continental glaciers are melting rapidly. The Ganges River, which supplies water to 450 million people and is fed by glaciers, is destined for eventual decline. *Stationarity*, the scientific term for when statistics are not changing and conditions are constant, is a thing of the past (Milly et al., 2008). We can no longer count on the mean precipitation or even on traditional annual variability in precipitation.

In such a scenario, it is almost impossible to plan for the future. Most climatologists are less concerned about the increase in mean global temperature and precipitation than they are about the extremes (heat waves, droughts, and floods). We must, somehow, make plans for living in a world with rapidly changing water resources.

Changes in Land Use and Energy Choices

In an effort to develop systems in which citizens can prosper, we convert land to agricultural and industrial uses that require large amounts of water and, in the end, degrade water quality. Every year in the tropics, countries such as Brazil, Malaysia, India, and Indonesia clear huge tracts of forest for agricultural development. Every year in the United States, almost a million acres of land are converted to impervious cover, mostly highways, parking lots, and strip malls, which increases runoff and decimates urban stream ecology. Development is greatest in coastal counties where 53 percent of Americans now live.

In addition, because oil is in short supply and extremely expensive, many countries, such as Brazil, countries in Europe, Malaysia, Japan, China, and the United States, have adopted biofuels as a strategy for reducing, or at least stabilizing, oil imports. "Energy security" and "energy independence" have become the watchwords in these countries. In the United States the emphasis is on ethanol production from corn. In other countries, ethanol is produced from sugar cane and sugar beets, and biodiesel is produced from canola, sunflower, palm, and soybean oils.

However, biofuels are not sustainable, at least not in the way we practice row-crop agriculture today. Far too many nutrients run off the land causing eutrophication of nearby waters, and far too much soil erodes for biofuels to be considered sustainable in the long run. We need a crop system that is perennial, that minimizes (or eliminates) tillage, and that holds soils and nutrients in place.

As Figure 3 shows, ethanol production in the United States depends on intensive, high-input corn as feedstock. The intensive agriculture necessary to supply this corn requires about 8 grams of nitrogen (as N) fertilizer and results in 10 to 20 kilograms of soil loss for every gallon of ethanol produced. All of these nutrients run down the Mississippi River to the Gulf of Mexico where they exacerbate hypoxia (i.e., low concentration of dissolved oxygen), which causes shrimp, crabs, and fish to vacate large sections of the Gulf, 20,000 km^2 in 2007 (Alexander et al., 2008).

Figure 3 also shows that most U.S. ethanol production facilities are located in the rain-fed Midwest (NRC, 2008). But in the high plains of Nebraska, Kansas, and Texas, cornfields are irrigated with

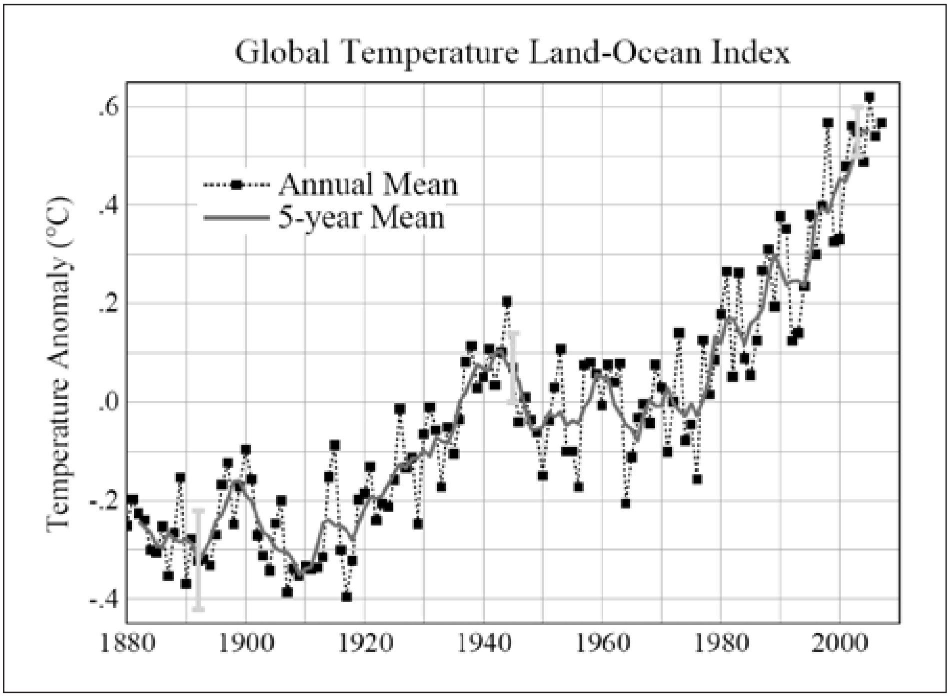


FIGURE 2 Global temperature changes from 1880 to 2005. The annual average temperature (averaged for the entire planet for all seasons) has increased about 0.8°C in the past 125 years. Source: Adapted from Hansen et al., 2007.

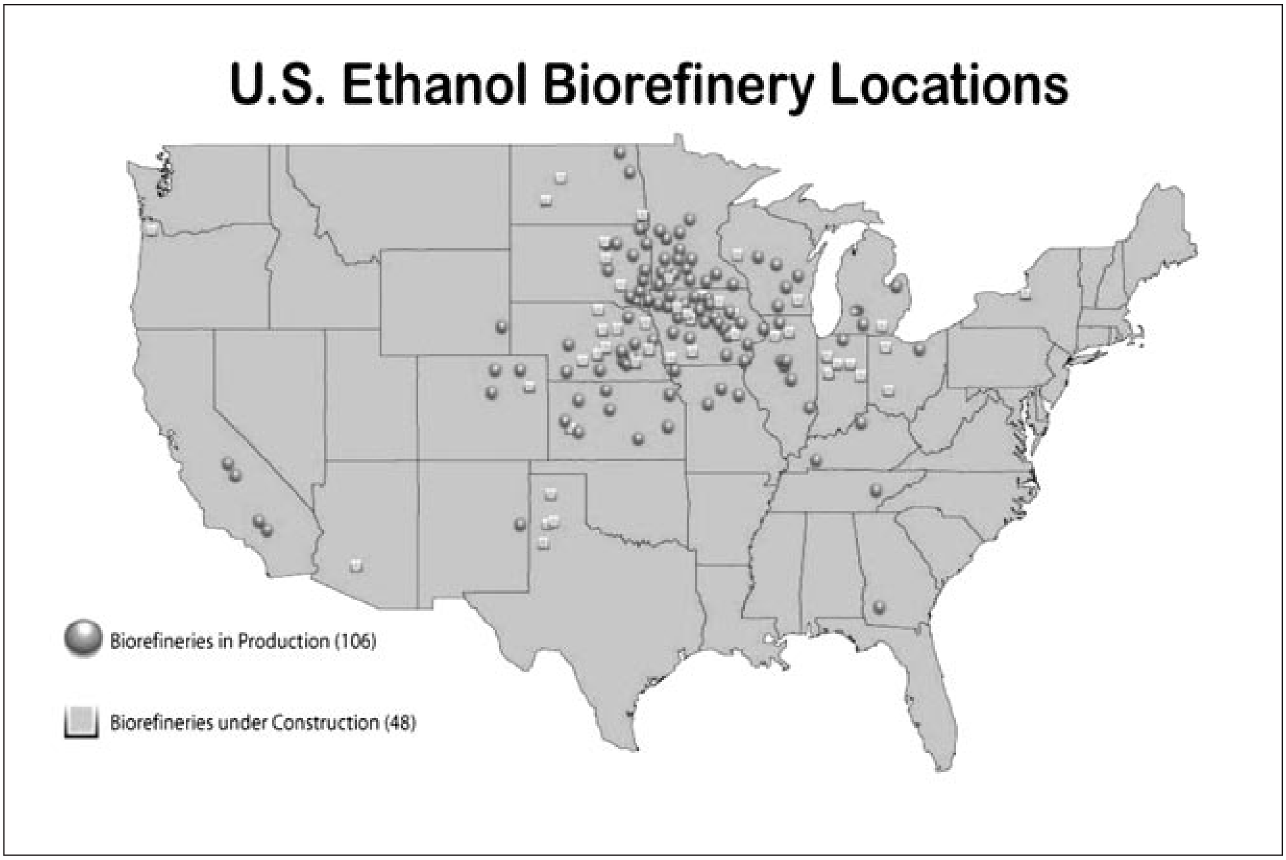


FIGURE 3 Locations of ethanol-production facilities, both existing and under construction in 2007. Source: Renewable Fuels Association, 2008.

water from the Ogallala Aquifer, which is already overdrawn. It takes about 1,000 gallons of water to produce one gallon of ethanol from corn grown with irrigation water. Therefore, it would take the equivalent of the water supply of a city of more than 2 million for a single facility (a single dark circle in Figure 3) to produce 100 million gallons of ethanol per year.

In addition, ethanol production facilities require considerable amounts of water. Each dark circle requires 3 to 4 gallons of water to produce one gallon of ethanol. Thus a facility that produces 100 million gallons per year would use more than 300 million gallons of water, which would come either from surface water or an aquifer. Many aquifers in the Midwest, such as the Cambrian-Ordovician unit in Iowa and Illinois, have already lost more than 100 feet of pressure head through excessive withdrawals.

Most Americans do not realize how far we are from the balance necessary for sustainability. Even if we devoted all of our agricultural land to biofuels, we would still not produce the transportation fuel necessary to supply our 220 million cars and trucks. Americans consume 3 to 4 gallons of petroleum per person per day. We have neither the land nor the water to grow our way out of this problem.

In addition, biofuels policies in Europe and the United States contribute to higher prices for corn and, thus, higher prices for food, which is increasing hunger and poverty around the world. According to life-cycle analyses, biofuels may not even help reduce greenhouse gases.

Perennial prairie grasses or trees would provide cellulosic feedstock for ethanol production far superior to feedstock from corn. Switchgrass, which was once ubiquitous on the Great Plains, could be so again. This would restore bird habitats, improve water quality, and sequester carbon dioxide in the soil.

However, using switchgrass (or agricultural wastes) effectively as a feedstock for ethanol would require a breakthrough in technology, such as the development of enzymes that can break down cellulose into starch and sugars for fermentation or a commercially viable process for the thermochemical conversion of cellulosic materials by gasification. Either of these may take several years.

Global Poverty

One of the UN Millennium Development Goals is the alleviation of global poverty, reflecting a consensus among development professionals that we cannot solve other problems until the issue of global poverty is addressed. More than 2 billion people live on less than $2 per day. As long as 1.1 billion people do not have clean drinking water, and 2.4 billion do not have adequate sanitation, and 1.4 million children die every year from clearly preventable waterborne diseases, no progress can be made on reversing climate change, deforestation, or the loss of species. The developed world must help developing countries solve their pressing problems before they can help us address global issues. Today, however, their children are still dying.

Will there be enough fresh water for 9 to 10 billion people in 2050? We already appropriate 54 percent of fresh water resources (Postel et al., 1996), and the average supply of water per person is decreasing as the number of megacities and coastal development increases and rainfall distributions continue to change. The United Nations estimates that 700 million people suffer from water scarcity today, and as many as 3 billion could face water shortages by 2025 (UN News Service, 2007).

Egypt has the smallest amount of fresh water per capita of any major country, less than 26 cubic meters per year. Survival is possible because Egypt imports "virtual water," that is, liquids from fruits, vegetables, and other products that require a great deal of water where they are grown. In addition, the country has large national agricultural areas in the Nile River Basin and, more recently, in the middle of the desert (e.g., the Toshka project, an oasis where crops are raised using groundwater and drip irrigation) (Martin, 2008). However, as Elie Elhadj, author and water specialist in the Middle East, has said, "You can bring in money and water, and you can make the desert green until either the water runs out or the money" (Martin, 2008). In the long run, this scenario is simply not sustainable.

The Next Steps

Mitigation, Treatment, Action

The first thing we must do is to mitigate the causes of water shortages as much as possible. According to most demographers, population growth will level off sometime in the 21st century. Through education and the empowerment of women, we may be able to limit population at the "medium" projection in Figure 1.

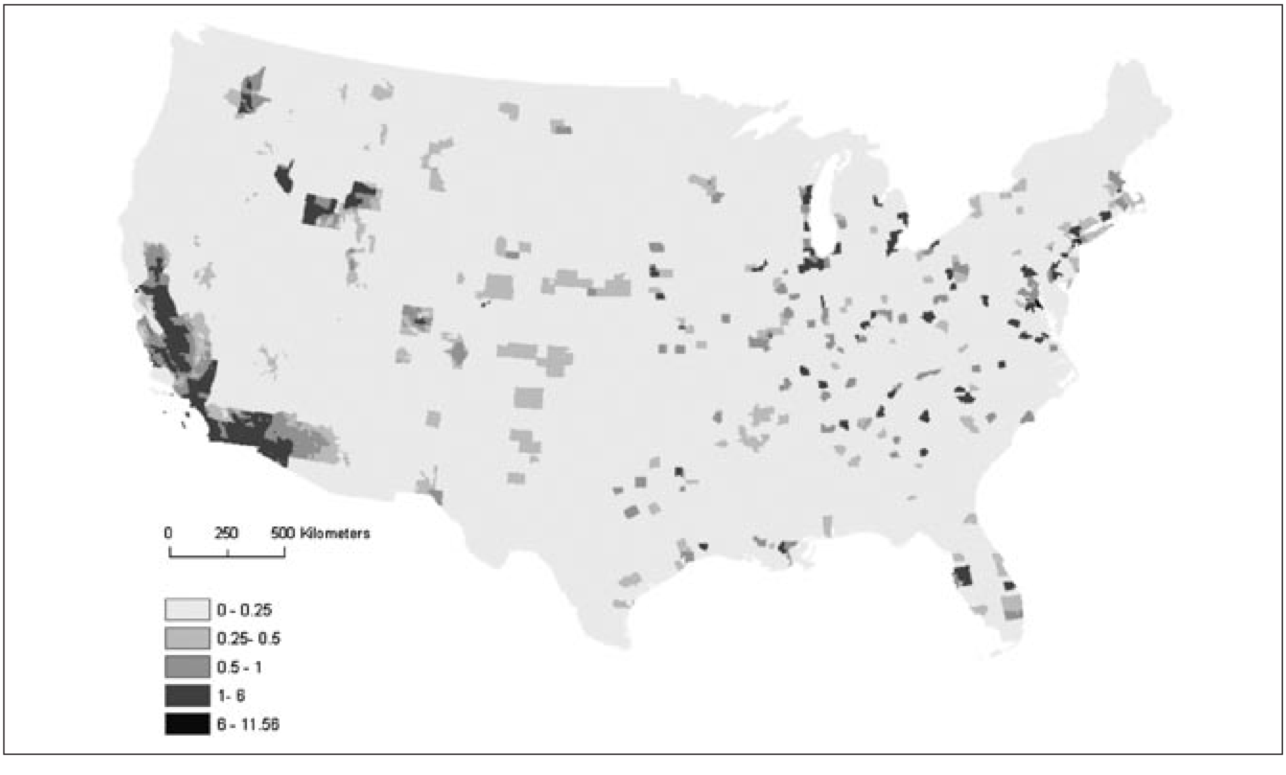


FIGURE 4 Water stress (water withdrawals/annual precipitation) in the contiguous United States. Areas with water stress greater than 1.0 (darkest categories) use more water than falls on that area of the country via precipitation. Source: K.J. Hutchinson, M.S. thesis, University of Iowa, 2008, adapted from PRISM, 2006 and USGS, 2005.

The prospects for mitigating climate change depend on global governmental resolve to decrease emissions of GHGs by 80 percent by the end of the 21st century. At that level the atmospheric concentration of carbon dioxide would be stabilized at approximately 450 parts per million (Hansen et al., 2007; IPCC, 2007). Developed countries would have to take on the heaviest responsibility for early cutbacks in emissions (25 to 40 percent by 2025 and 80 to 95 percent by 2050), and developing countries would be required to follow suit as their economies begin to prosper.

Governments in developed countries must challenge their people to use less energy and encourage a massive conversion to wind power (which is already economical), plug-in hybrid or electric cars refueled by electricity produced from wind energy, and water- and energy-efficient buildings. In the United States, this will require daring changes in policy, such as a revenue-neutral decrease in income taxes and an increase in carbon taxes.

Energy efficiency and renewable technologies can be the engine for economic growth and the creation of green-collar jobs. In Iowa, for example, five new wind-power manufacturers now provide thousands of high-paying manufacturing jobs. The end of the age of fossil fuels will prove to be the turning point of this century. The transition away from dependence on nonrenewable resources will be what Harvard economist Joseph Schumpeter once called "creative destruction," an economic revival that replaces an old system with a better one for the future.

Water Conservation

Water conservation in the United States will be essential. Many people think that water is scarce only in the Southwest, but a large portion of the country is using up its water supplies through the exploitation of aquifers and the degradation of surface waters from non-point source pollution. Figure 4 shows the geographical areas where water is under stress as a result of industrial and agricultural withdrawals from the water supply. We can only hope to address our future water needs through better water-treatment systems, the recharging and reuse

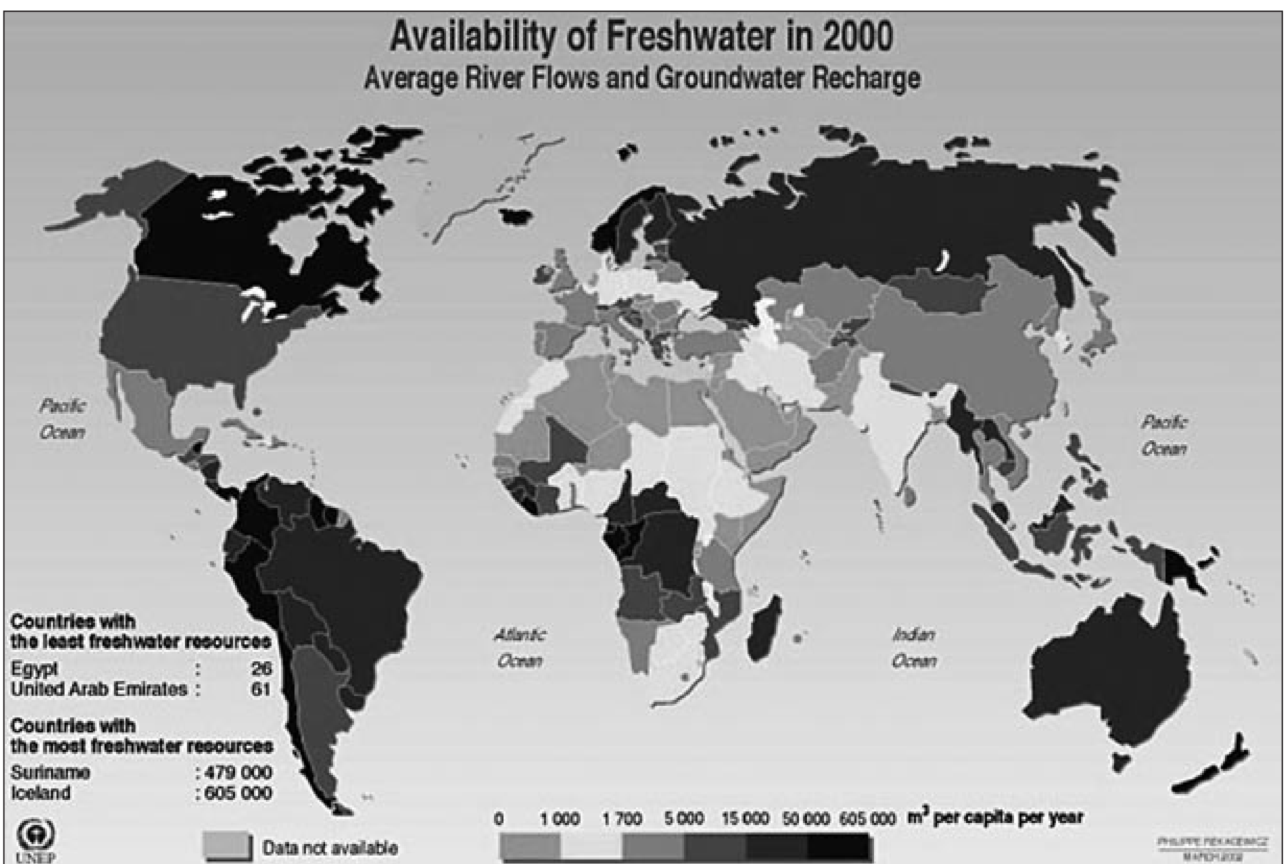


FIGURE 5 Map of global freshwater resources per capita from accessible rivers and groundwater indicating that in many countries less water is available than is recommended (<1700 m^3/capita/year) according to the World Resources Institute and the United Nations Environment Programme. Sources: UNEP, 2002. Reprinted with permission.

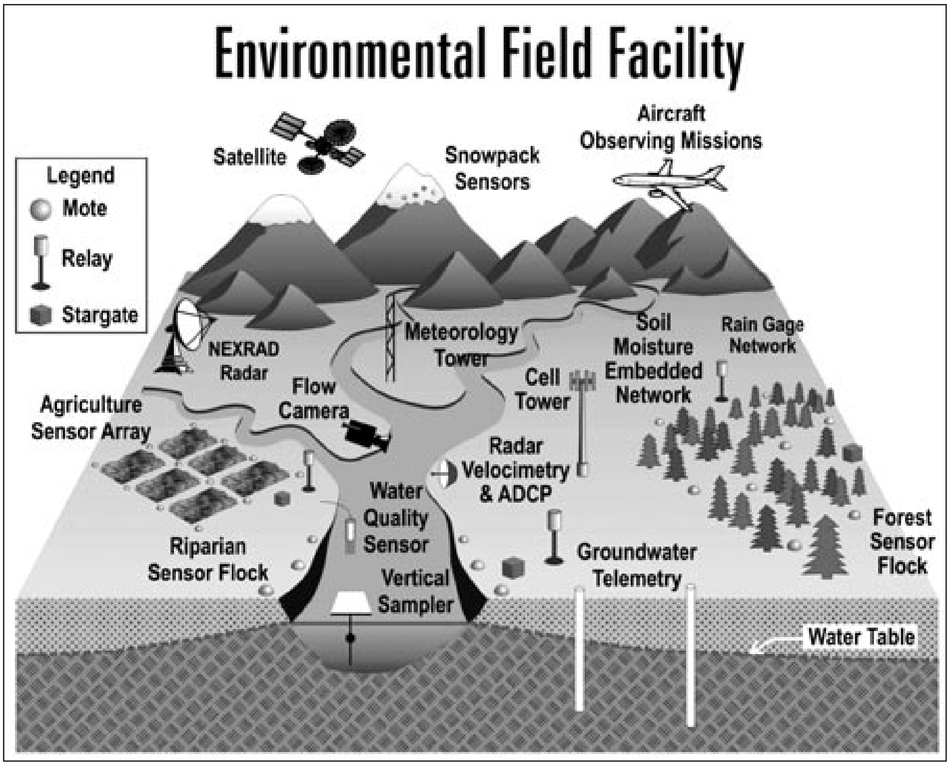


FIGURE 6 An environmental field facility in the proposed WATERS Network. The facility uses breakthrough technologies to predict and forecast capabilities for water-quality constituents (e.g., nutrients, sediments, pathogens, and emerging chemical contaminants).

of aquifers, and water conservation.

Desalination will also be important for meeting future water needs. More than 15,000 desalination plants (mostly using reverse osmosis) are in operation in 125 countries with a total capacity of 32 million cubic meters of water. As the cost of desalination processes come down, capacity will continue to rise (Zimmerman et al., 2008).

Ideally, water reuse, such as flushing toilets with gray water, will become the norm. Aquifer storage and recovery will prevent the evaporation of precious water supplies and help to recharge depleted aquifers. Novel, high-quality treatment regimes will ensure that water is treated appropriately for different uses. Engineers and scientists will find ways to protect watersheds from pathogens, pesticides, and endocrine-disrupting chemicals like hormones and pharmaceuticals, which are now present in both wastewater and drinking water.

Adapting to a Changing World

Some things cannot be changed or mitigated, and for those we must adapt as best we can. The average availability of fresh water from rivers and groundwater (Figure 5) is likely to decrease drastically. Many countries in Africa, the Middle East, and parts of Asia that are particularly short of water also have the largest, fastest growing populations and the highest levels of poverty. It is incumbent on the developed world to help them meet their water-supply and sanitation needs.

Engineers are well suited to make a positive difference. We can teach, we can create appropriate technologies, and we can serve in ways that scientists are sometimes reluctant to undertake. For example, Engineers for a Sustainable World, Engineers without Borders, International Rotary, and many other groups offer people-to-people programs that provide assistance for professional development.

Adapting to a changing world may simply mean working together within a common framework to improve water quality. For example, World Water Monitoring Day (WWMD), sponsored by the Water Environment Federation, was initiated in 2002 as an international outreach program to increase public awareness and involvement in protecting water resources. More than 80,000 participants worldwide are monitoring streams, rivers, lakes, and estuaries in 50 countries for dissolved oxygen, transparency, temperature, and pH. To join, one simply registers a monitoring site, purchases a rudimentary test kit for about $20, monitors during the test period of September 18 through October 18, and enters the results on the organization's website (*www.worldmonitoringday.org*).

Imagine if millions of 5th graders throughout the world were enlisted to monitor water sites. Just suppose that tomorrow at noon every schoolchild walks to a creek, stream, lake, or drinking water source near his or her home and records a scientific observation—the temperature, clarity, pH, or dissolved oxygen in the water at that site. They then file their data via the Internet, and the next day they collectively publish a map of worldwide water quality. We can hope that they will also think, or are taught, about the science behind the results and that they will be motivated to improve the environment. These volunteers would constitute a network of "water watchdogs" for the entire planet. This is the kind of project that can transcend geopolitics.

Modeling, Predicting, and Forecasting

Some engineers are already embracing new technologies that are capable of making a positive difference for the environment. One such effort is the WATERS Network (**Wat**er and **E**nvironmental **R**esearch **S**ystems Network), a $300 million proposal to the National Science Foundation for a capital investment to revolutionize the modeling, predicting, and forecasting of the quantity and quality of water (Montgomery et al., 2007).

Figure 6 is a schematic drawing of a field facility, one node in a national network of sites that span the physiographic characteristics of water resources throughout the country. The facility makes use of breakthroughs in technology, like novel sensors, wireless and broadband technologies, high-performance computing, and real-time data assimilation, to predict and forecast the types and amounts of water constituents (nutrients, sediments, pathogens, and emerging chemical contaminants). Such a system could be used to control or warn of the likelihood of floods, harmful algal blooms, the entry of disease-causing microorganisms into a water supply, or Gulf hypoxia.

This national initiative will use real-time environmental sensing to conduct multi-scale research and experimentation on U.S. water resources. The WATERS Network will integrate, complement, and leverage existing investments in water monitoring operated by various federal and state agencies, as well as river-basin commissions and others.

The goal of the WATERS Network is to improve our understanding of Earth's water resources and related biogeochemical cycles, which could lead to better management of critical water processes that interact with human activities. Through the WATERS Network, hydrologists and environmental engineers will develop skills in predicting water availability and quality, and economists and social scientists will improve forecasts of water availability and provide reliable input for decision makers.

Modern networks like WATERS can provide a way for us to address critical science and engineering questions to mitigate and adapt to the changes threatening our water resources. Data fusion and assimilation techniques that can "bootstrap" model performance, prediction, and forecasting of water quality and quantity throughout the country could lead to more efficient and effective water and wastewater treatment and collection systems. WATERS represents just one initiative that might help us learn to live with a changing water environment.

References

ASCE (American Society of Civil Engineers). 2005. The State of Infrastructure in the United States: The 2005 ASCE Report C. Available online at *http://www.asce.org/reportcard/2005/index.cfm* (accessed July 27, 2008).

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. Environmental Science and Technology 42(3): 822–830.

Hansen, J., M. Sato, R. Ruedy, P. Kharecha, A. Lacis, R. Miller, L. Nazarenko, K. Lo, G.A. Schmidt, G. Russell, I. Aleinov, S. Bauer, E. Baum, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Cohen, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, J. Jonas, M. Kelley, N.Y. Kiang, D. Koch, G. Labow, J. Lerner, S. Menon, T. Novakov, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, R. Schmunk, D. Shindell, P. Stone, S. Sun, D. Streets, N. Tausnev, D. Thresher, N. Unger, M. Yao, and S. Zhang. 2007. Dangerous human-made interference with climate: a GISS modelE study. Atmospheric Chemistry and Physics 7: 2287–2312. Available online at *http://www.atmos-chem-phys.org/7/2287/2007/acp-7-2287-2007.pdf*.

Hutchinson, K.J. 2008. Human Impacted Water Environment Classes. M.S. thesis, University of Iowa, Iowa City.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: The Physical Science Basis: Summary for Policymakers. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press. Available online at *http://www.aaas.org/news/press_room/climate_change/media/4th_spm2feb07.pdf*.

Martin, A. 2008. Mideast Facing Choice Between Crops and Water. New York Times, July 21, 2008, p. A1.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: whither water management? Science 319(5863): 573–574.

Montgomery, J.L., T. Harmon, B. Minsker, J. Schnoor, W. Kaiser, A. Sanderson, C.N. Haas, R. Hooper, N.L. Clesceri, W. Graham, and P. Brezonik. 2007. The WATERS Network: an integrated environmental observatory network for water research. Environmental Science and Technology 41(19): 6642–6647.

NRC (National Research Council). 2008. Water Implications of Biofuels Production in the United States. Washington, D.C.: National Academies Press.

Postel, S.L., G.C. Daily, and P.R. Ehrlich. 1996. Human appropriation of renewable fresh water. Science 271(5250): 785–788.

PRISM. 2006. United States Average Monthly or Annual Precipitation, 1971–2000, 200606. Corvallis, Ore.: The PRISM Group at Oregon State University. Available online at *http://www.prism.oregonstate.edu/*.

Renewable Fuels Association. 2008. U.S. Biorefinery Locations. Available online at: *http://www.ethanolrfa.org/objects/documents/1494/plantmap_janaury_24.pdf*.

UNEP (United Nations Environment Programme). 2002. Vital Water Graphics. Available online at: *http://www.unep.org/dewa/assessments/ecosystems/water/vitalwater/about.htm*.

UN News Service. 2007. UN Marks World Water Day with Calls for Integrated Management of Vital Resources. Available online at: *http://www.un.org/apps/news/printnewsAR.*asp?nid=21951.

USGS (U.S. Geological Survey). 2005. Water Resources of the United States, Estimated Use of Water in the United States, 2000, 200509: National Atlas of the United States. Reston, Va.: USGS.

World Resources Institute. 2000. World Resources 2000–2001: People and Ecosystems: The Fraying Web of Life. Washington, D.C.: United Nations Environment Programme.

Zimmerman, J. B., J.R. Mihelcic, and J. Smith. 2008. Global stressors on water quality and quantity. Environmental Science and Technology 42(12): 4247–4254.

NAE News and Notes

NAE Newsmakers

Two NAE members are among the recipients of the **2008 Visionary Award** from SDForum. **Forest Baskett**, general partner, New Enterprise Associates, and **Irwin M. Jacobs**, chairman, Qualcomm Incorporated, will each be honored as a "leading industry visionary who has fostered the spirit of entrepreneurship and has paved the way for new innovations in technology."

Edmund M. Clarke, FORE Systems Professor of Computer Science, Carnegie Mellon University, was one of three recipients of the **2007 Turing Award** awarded by the Association for Computing Machinery (ACM). The award was presented in June at the ACM Design Automation Conference in Anaheim, California. The Turing Award is given for technical contributions of lasting importance to the computer field. The award was presented to Dr. Clarke, E. Allen Emerson, and Joseph Sifakis "for their roles in developing Model-Checking into a highly effective verification technology, widely adopted in the hardware and software industries."

Texas Instruments Incorporated announced the establishment of the **Engibous Prize**, annual awards totaling $150,000 for engineering students who design the most innovative electronics systems using analog semiconductors. The Engibous Prize, the largest of its kind, will be awarded in three geographical regions—Asia, Europe, and North America. The prize is named in honor of NAE member **Thomas J. Engibous**, retired chairman of Texas Instruments.

Arthur H. Heuer, University Professor and Kyocera Professor of Ceramics, Department of Materials Science and Engineering, Case Western Reserve University, is the 2008 recipient of the **Hovorka Prize**. The prize is awarded to an active or emeritus member of the faculty for exceptional achievement and accomplishments in teaching, research, and scholarly service that have benefited the community, the nation, and the world. The prize was presented to Dr. Heuer at the Case Western Reserve commencement ceremonies on May 18.

Joseph M. DeSimone, W.R. Kenan Jr. Distinguished Professor of Chemistry and Chemical Engineering, Department of Chemistry, University of North Carolina, was named the winner of the Massachusetts Institute of Technology (MIT) **Lemelson Prize**. Dr. DeSimone received the $500,000 cash award in recognition of his diverse contributions in the field of polymers. The MIT Lemelson Prize is an honor bestowed upon an inventor who is in mid-career and rising in his or her field.

Richard M. Karp, senior research scientist, International Computer Science Institute, has been named the **2008 Kyoto Prize Laureate** in the category of Advanced Technology—Computer Science. Dr. Karp will be honored for his NP-completeness theory, which has had a significant impact on society as a whole and on several fields of study, ranging from engineering and computer science to biology and mathematics; other algorithms developed by Dr. Karp have significantly contributed to operations research and bioinformatics. The Kyoto Prize, awarded by the Inamori Foundation, is an international award given in recognition of significant contributions to the scientific, cultural, and spiritual development of humanity. Dr. Karp will receive the award, which includes a diploma, a 20-karat gold medal, and a cash award of $460,000, on November 10 in Kyoto, Japan.

David A. Patterson, professor of computer science, University of California, Berkeley, received the **2008 Eckert-Mauchly Award**, which is jointly sponsored by the Association for Computing Machinery (ACM) and the IEEE Computer Society (IEEE-CS). Dr. Patterson received the award for his leadership in the invention of the reduced instruction set computer (RISC), a microprocessor design that replaces large sets of processor instructions with smaller sets that run faster. Patterson was also cited for his role in the design and implementation of RAID (redundant arrays of independent disks), a computer data-storage system that replaces large storage disks with many small disks that increase reliability and improve performance. The award was presented in June at the International Symposium on Computer Architecture in Beijing, China.

Three NAE members have been named **Distinguished Members of**

the American Society of Civil Engineers (ASCE). Formerly known as honorary membership, the distinguished membership, the highest honor awarded by ASCE, is bestowed on individuals who have achieved eminence in a particular branch of engineering. **Izzat M. Idriss**, Professor Emeritus of Civil Engineering, University of California, Davis, was cited for his major contributions to the understanding of soil behavior during earthquakes and for the development of analysis procedures that are widely used in geotechnical earthquake engineering. **Henry Petroski**, Aleksandar S. Vesic Professor of Civil Engineering and professor of history, Duke University, was honored for significant advances in the practice of civil engineering and education through his work as a renowned educator, author, researcher, and lecturer and for his published works that have greatly improved the public understanding of engineering. **C. Michael Walton**, Ernest H. Cockrell Centennial Chair in Engineering, Department of Civil, Architectural and Environmental Engineering, University of Texas, Austin, received the award for his exemplary career as an educator and researcher in civil engineering and for his extraordinary professional and technical leadership in transportation systems, planning, engineering, financing, operations, and policy analysis.

The American Institute of Chemical Engineers (AIChE) has named **Jerome S. Schultz**, Distinguished Professor and chair, Department of Bioengineering, University of California, Riverside, one of the "**One Hundred Engineers of the Modern Era**." Dr. Schultz was chosen for his contributions to chemical engineering and bioengineering, which have had a major impact on industry, academia, professional societies, and government, and for his research on biosensors, membrane transport, and biotechnology.

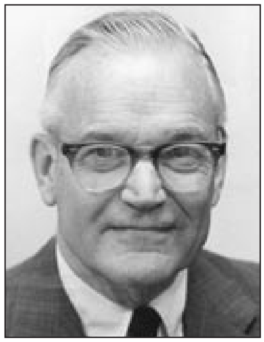
Simon Ramo, cofounder, TRW Inc., received the first University of Southern California **Viterbi School Lifetime Achievement Award** at the 30th annual Viterbi Awards Banquet held May 8, 2008. Dr. Ramo, whose career spans 70 years, has made outstanding contributions in a variety of fields. He conducted pioneering research on microwaves and on the development of the GE electron microscope, was the first director of the Falcon Guided Missile Program for Air Defense, and later was chief scientist for the Intercontinental Ballistic Missile Program.

Chien-Fu Jeff Wu, Coca Cola Professor, Georgia Institute of Technology, recently received three academic awards in a period of 40 days. The **Shewhart Medal**, the highest honor awarded by the American Society for Quality, was presented to Dr. Wu for "seminal contributions to parameter design and quality improvement, as well as his contributions in the education of a generation of quality professionals and professors." The Pan Wen Yuan Foundation selected him as winner of the **2008 Outstanding Research Award** for his research in manufacturing engineering, statistical theory, methodology, and quality control. And he received a **Conference Honoree Medal** for "seminal contributions to statistical theory and methods for quality and productivity." The medal was presented to Dr. Wu at the 2008 American Statistical Association Quality and Productivity Research Conference.

The University of California-Los Angeles (UCLA) presented the **UCLA Medal** to **Charles M. Vest**, President Emeritus and professor of mechanical engineering, Massachusetts Institute of Technology, and president, National Academy of Engineering. The UCLA Medal is presented annually to individuals who have made extraordinary contributions to UCLA or whose significant cultural, political, or humanitarian achievements merit the university's highest recognition. The UCLA Medal was presented at the UCLA Henry Samueli School of Engineering and Applied Science commencement ceremony on June 14, 2008. Dr. Vest also delivered the keynote address at the commencement ceremony.

Remembering Two Past NAE Presidents, Robert C. Seamans Jr. and Courtland D. Perkins

Robert C. Seamans Jr.



Courtland D. Perkins

ROBERT C. SEAMANS JR., president of NAE from May 1973 to December 1974, died on June 28, 2008, at the age of 89. A native of Salem, Massachusetts, he received a B.S. from Harvard University in engineering and an M.S. in aeronautics and Sc.D. in instrumentation, both from Massachusetts Institute of Technology (MIT).

Dr. Seamans had a distinguished career in academia, business, and government. From 1941 to 1955, he held teaching positions at MIT. He then joined the Radio Corporation of America (RCA) in 1955 as manager of the Airborne Systems Laboratory and chief engineer of the Airborne Systems Department; in 1958 he became chief engineer of RCA's Missile Electronics and Controls Division. From 1948 to 1958 he served on numerous technical committees of the National Advisory Committee for Aeronautics, the predecessor organization of the National Aeronautics and Space Administration (NASA). In 1960, he joined NASA as an associate administrator and in 1965 became deputy administrator. His work at NASA led directly to the landing of a man on the moon.

Dr. Seamans was elected to NAE in 1968 "for engineering design and development of airborne systems; technical leadership in the nation's space program." That same year he became a visiting professor at MIT and was appointed to the Jerome Clarke Hunsaker Professorship in the Department of Aeronautics and Astronautics. While at MIT, he continued his association with NASA as consultant to the administrator.

From 1969 to 1973, Dr. Seamans was the ninth secretary of the U.S. Air Force. During his tenure, he oversaw the modernization of weapons systems during a time of budget constraints as the U.S. reduced its involvement in the Vietnam War.

Before his election as NAE president in May 1973, a small but vocal minority of NAE members had been debating the merits of severing ties with the National Academy of Sciences (NAS) and becoming an independent organization. As president, he worked closely with NAE and NAS members and officers to reach favorable agreements regarding the governance, organization, and interactions of the academies and the National Research Council. Thanks to his efforts, the National Academies entered into a period of remarkable cooperation and growth.

In 1974, Dr. Seamans left NAE to become the first administrator of the Energy Research and Development Administration. In 1977, he returned to MIT and in 1978 became dean of the School of Engineering. In 1981 he was elected chair of the Board of Trustees of Aerospace Corporation.

Dr. Seamans is survived by his spouse, Eugenia A. Merrill, as well as five children—Katherine Padulo, Robert C. III, Joseph, May Baldwin, and Daniel—and 12 grandchildren.

An autobiography by Dr. Seamans is available at *http://history.nasa.gov/SP-4106/sp4106.htm*. His tenure as president of NAE is discussed in Chapter 4.

COURTLAND D. PERKINS, president of NAE from 1975 to 1983, died on January 6, 2008, at the age of 95. He was elected to NAE in 1969 "for leadership in the fields of airplane stability and control and airplane dynamics."

A native of Philadelphia, Dr. Perkins received his B.S. from Swarthmore College in mechanical engineering and, in 1941, his M.S. from MIT in aeronautical engineering. By the end of World War II, after working at the Flight Technology Unit of the U.S. Army's Stability and Control Center at Wright-Patterson Air Base, he was a recognized authority on the fundamentals of the science of aeronautics. In 1945, he was appointed to the newly established Aeronautical Engineering Department at Princeton University.

In 1949, he and a colleague, Robert Hage, published *Airplane Performance, Stability and Control*, which soon became the standard text in the field and remains in print to this day. In 1951, he became department chair. Under his direction and supervision, department members constructed a world-class wind tunnel; propulsion laboratories; and a flight-test facility with airplanes, a hanger, and a runway. Professor Perkins was an avid pilot who was known for collecting in-flight data by cleverly rigging airplanes with test equipment.

In 1974, Professor Perkins became associate dean of engineering at Princeton, where he mentored many undergraduate and graduate students who later became leaders in the field of aeronautics and astronautics. In 1975, after becoming Professor of Aerospace and Mechanical Sciences Emeritus, he left Princeton to become president of NAE. Professor Perkins had three main goals as NAE president: to increase NAE membership, to improve NAE's financial resources, and to enhance NAE's position and public visibility.

Prior to his election, NAE rules had restricted membership to actively employed engineers. At his urging, NAE opened its membership to gifted engineers who had retired. By the time of his own retirement from NAE in 1983, NAE membership had doubled, from 550 to 1,100 members. In addition, the first foreign associates had been elected, extending NAE's international reach.

At the time of his election, NAE revenue depended on dues, gifts, and a modest endowment, which together provided 25 percent of the organization's necessary funding. The remaining 75 percent was provided by NAS. Professor Perkins pursued fundraising aggressively, and under his leadership, the NAE endowment was increased to $5.2 million, marking the beginning of the organization's financial independence. His third goal, increasing the public visibility of engineering, was achieved by initiating independent NAE study committees, hosting roundtable talks, and sponsoring reports on technology-related topics relative to important social, environmental, and scientific issues of the day.

Over the course of his career, Dr. Perkins held many public leadership positions: chief scientist and undersecretary of the U.S. Air Force; chief engineer for the U.S. Army; member of the Space Sciences Board of NASA; chairman of the NATO Advisory Group for Aeronautical Research and Development; and president of the American Institute of Aeronautics and Astronautics (AIAA). In 2004 he received the Daniel Guggenheim Medal, which is widely recognized as the highest honor in aviation.

Dr. Perkins married Jean Enfield in 1941, and the couple had two children, William and Anne. After Jean's death in 1980, he married Nancy Wilson, who died in 2004. He is survived by his children, four grandchildren, and three great-grandchildren from his first marriage, as well as three stepchildren and three grandchildren from his second marriage.

2008 German-American Frontiers of Engineering Symposium

On April 25–27, the 2008 German-American Frontiers of Engineering Symposium (GAFOE) was held at the Beckman Center in Irvine, California. **Tresa Pollock**, L.H. and F.E. van Vlack Professor of Materials Science and Engineering at the University of Michigan, co-chaired the symposium with Kai Sundmacher, director of the Max Planck Institute for Dynamics of Complex Technical Systems in Magdeburg, Germany.

Modeled on U.S. Frontiers of Engineering (USFOE) symposia, this bilateral meeting brought together approximately 60 engineers, ages 30 to 45, from German and U.S. companies, universities, and government laboratories. Like USFOE symposia, the goal of the meeting was to bring together emerging engineering leaders in a forum where they could learn about leading-edge developments in various fields of engineering. Bilateral Frontiers symposia not only facilitate the interdisciplinary transfer of knowledge and methodology, but also contribute to the building of cooperative networks that cross national boundaries. GAFOE symposia are organized by NAE, in cooperation with the Alexander von Humboldt Foundation.

The four topics covered at the 2008 meeting were: (1) nanotechnology for medical therapies; (2) micromanufacturing/microprocess engineering; (3) energy harvesting; and (4) advanced imaging technologies. Presentations on each topic were given by two Germans and two Americans. Some of the specific topics were minimally invasive treatments of breast tumors by magnetically induced heating, laboratory chip microreactors, piezoelectric energy harvesting systems, and computational photography. The list of speakers and topics is available online at *www.nae.edu/gafoe*.

On Friday evening, Robert Manning, chief engineer of the Mars Exploration Program at the Jet Propulsion Laboratory, gave an informative and entertaining talk about the challenges of the Mars Rovers missions. He provided valuable insights, based on lessons learned from earlier failures, about managing risk, particularly with regard to the complexity of programs and the critical importance of extensive testing. Other highlights of the meeting were a poster session on the first afternoon that gave all participants a chance to share information about their research or technical work and a poolside dinner on the last evening.

Funding for the 2008 GAFOE Symposium was provided by the National Science Foundation, the Beckman Foundation, the NAE Armstrong Endowment for Young Engineers, and the Alexander von Humboldt Foundation. Plans are under way for the twelfth GAFOE symposium on April 23–25, 2009, in Potsdam, Germany.

USFOE symposia have been held annually since 1995, and GAFOE symposia since 1998. NAE also has bilateral FOE programs with Japan and India. All of the symposia bring together bright, cutting-edge researchers in industry, academe, and government to learn about developments, techniques, and approaches in fields other than their own. Cross-disciplinary exchanges have become increasingly important as engineering has become increasingly interdisciplinary.

For more information about FOE programs, contact Janet Hunziker in the NAE Program Office at 202-334-1571 or by e-mail at *jhunziker@nae.edu*.

Report of the Foreign Secretary

George Bugliarello

Since my last report to you in the Summer 2008 issue of *The Bridge*:

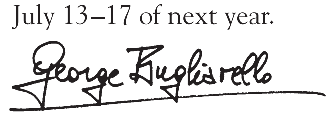
On June 25, **President Charles Vest** addressed the annual meeting, in Beijing, of the Chinese Academy of Engineering.

On June 16–17, I represented NAE at the Annual Meeting of the Canadian Academy of Engineering in Montreal.

On June 25–27, the International Council of Academies of Engineering and Technological Sciences (CAETS) meeting was held in Delft and The Hague, The Netherlands. Hosted by the Netherlands Academy of Technology and Innovation (AcTI-nl), the meeting was attended by delegates from 25 national academies worldwide. **Lance Davis** and I represented NAE. In addition, NAE member **William Lang**, president of the Noise Control Federation, presented a progress report on an international study of traffic noise.

The CAETS meeting was complemented by an international symposium organized by the Netherlands Academy on enabling life in river deltas, where some 70 percent of the world population lives. Broadly defined, river deltas are areas threatened by floods, tsunamis, and changes in sea level. At the end of the symposium a statement was drafted—still being edited—stressing the urgency of the delta problem and identifying international priorities for addressing it.

The next CAETS convocation will be held in Calgary, Canada, on July 13–17 of next year.



Systems Engineers and the Department of Veterans Affairs: Partners in Health Care

Building a Better Delivery System, a joint NAE/Institute of Medicine (IOM) report published in 2005, outlined how a closer partnership between systems engineering and health care delivery could put the ailing U.S. health care system on the road to recovery. Systems design, analysis, and control tools, as well as comprehensive information systems, could potentially improve health care in the same way they have benefited industry.

One of the key recommendations was the creation of interdisciplinary centers dedicated to (1) research on applications of systems engineering tools to health care delivery, (2) demonstrations of those applications in health care settings, and (3) the creation of new and improved system tools tailored to addressing health care problems. The idea of these centers was to provide a mutually productive environment for cooperative action by professionals in engineering and health care. The NAE/IOM report also recommended that health care issues be made an integral component of the engineering curriculum and that the concept of systems engineering be introduced into the medical curriculum.

In response to those recommendations, and after careful study, the Department of Veterans Affairs (VA) announced that it is looking to systems engineers to help improve health care delivery. Drawing on its extensive and unique relationships with medical schools and physicians, the VA has taken a bold step by embracing this opportunity to improve the quality of its care delivery by committing to investing in several health care-engineering centers called Veterans engineering resource centers (VERCs).

Based on unique partnerships between VA hospitals and engineering schools, VERCs will provide operational support for health care delivery systems while providing teaching and research opportunities for engineers and health care professionals, as well as students in both disciplines. The resource centers, which will focus on outpatient, inpatient, and administrative systems, will also have expertise in decision and implementation support, technical assistance, and demonstration projects. Thus they will be in a position to leverage external research funding, contribute to improvements in private health care, and engage in the full range of university teaching.

VERCs, which will be selected by a competitive Request for Proposals (RFP) process, will most likely be located at sites where engineering schools are in close proximity to VA hospitals. Teams of VA professionals, engineers, researchers, and students will be able to direct their efforts toward solving the most pressing, often long-standing operational problems facing the VA health care system (and health care in general). Because VERC teams will work directly with health care staff, engineers and health professionals will learn to understand each other's culture, language, and perspective on patient care. VERC teams are expected to play a major role in addressing national priorities for health care, such as colorectal cancer care, operating room flow, scheduling systems, and hospital patient capacity.

Already a recognized leader in quality health care, the VA system, which cares for more than 6 million patients at 1,300 sites across the nation, is in a unique position to take the lead in improving health care delivery and demonstrating the processes and benefits of system engineering tools to other providers. The VA plans to initiate a national search for the best leader for this initiative, and an RFP with details of the program will be issued in the near future.

For more information, contact Dr. Mike Davies at 605-347-7416 or *michael.davies@va.gov*, or Betsy Geiver, HRM officer, at *betsy.geiver@va.gov*.

Support for the NAE/IOM report was provided by the Robert Wood Johnson Foundation, the National Science Foundation, the National Institutes of Health, and the National Academies.

New NAE Publications

Public Understanding of Engineering

Young people are more likely to consider pursuing careers in engineering if they are reminded of how engineers can make a difference in the world, a message that taps into their optimism and aspirations, rather than of the math and science requirements for engineering courses. This is the overall conclusion of *Changing the Conversation: Messages for Improving Public Understanding of Engineering*, a new NAE report published this summer. The report recommends that the engineering community begin immediately to use tested messages in a coordinated communications strategy to interest young people in engineering careers.

The report describes the qualitative and quantitative research that was done to test the appeal, believability, and relevance of a handful of different messages. One component of the research was an online survey of 3,600 teens and adults, including large numbers of African Americans and Hispanics, who are underrepresented in the engineering profession. The study committee also collected data on the effectiveness of taglines, or slogans.

Released on June 25 at the annual meeting of the American Association for Engineering Education, the report is the product of an 18-month consensus study funded by the National Science Foundation with additional support from the Georgia Institute of Technology. The 10-member study committee was chaired by NAE member **Don Giddens** of Georgia Tech. NAE member **Leah H. Jamieson**, Ransburg Distinguished Professor of Electrical and Computer Engineering and John A. Edwardson Dean of Engineering, Purdue University, was a member of the committee. The report can be viewed and purchased online at *http://www.nap.edu/catalog.php?record_id=12187*.

Information and Communication Technologies and Peacebuilding

Information and communication technologies (ICT) can contribute to peacebuilding efforts around the world. But according to a recent NAE workshop report, *Information and Communication Technology and Peacebuilding: Summary of a Workshop*, ICT may also have some unintended consequences. Simply providing people with more information does not necessarily lead to predictable or positive results, because people who are better informed are sometimes motivated to try to change their circumstances by non-peaceful means. Similarly, as a society accumulates wealth, and as information about disparities in wealth become better known, competition may increase, possibly leading to conflict.

About 30 people from the ICT industry and organizations engaged in peacebuilding and nonviolent conflict resolution participated in the December 2007 workshop. The daylong session featured presentations on specific applications of ICT, such as the use of mobile phones for monitoring elections and for communicating information about events in conflict zones.

The workshop was organized by a five-person steering committee chaired by NAE member **John H. (Jack) Gibbons**, Resource Strategies. NAE members **Vinton G. Cerf**, Google Inc., and **Raj Reddy**, Carnegie Mellon University, also served on the steering committee. The workshop was funded by the U.S. Institute of Peace with additional support from Google Inc. The report can be viewed and purchased online at *http://www.nap.edu/catalog.php?record_id=12255*.

Offshoring of Engineering

The Offshoring of Engineering: Facts, Unknowns, and Potential Implications, a consensus report that includes findings and recommendations, is based on a workshop in October 2006 on the offshoring of engineering. This volume includes commissioned papers on offshoring in six major industries: software engineering, automobile manufacturing, pharmaceuticals, personal computer manufacturing, construction, and semiconductors. Also included are edited talks by NAE president **Charles M. Vest** and NAE members **Robert W. Galvin**, chairman emeritus of Motorola; **Anne L. Stevens**, CEO of Carpenter Technology Corporation; and **Alfred Z. Spector**, former vice president of technology and strategy of IBM Software Group.

Offshoring, the transfer of work from the United States to company facilities abroad or external facilities abroad, has transformed U.S. engineering. In some industries, offshoring has actually contributed to the creation and retention of engineering jobs in the United States. However, the impacts of offshoring in other industries has been all but devastating.

Because of significant gaps in the data on trade in services and employment, the committee found it extremely difficult to assess the net effects of offshoring on the U.S. engineering workforce. The data gaps are partly due to the difficulty of tracking offshoring in specific companies, some of which are reluctant to release information about their offshoring practices. Thus the committee concludes that more study will be necessary to sort out all of the aspects of offshoring and to clarify the long-term implications for U.S. engineering. In the meantime, the committee recommends steps that can be taken to help those who have been adversely affected.

NAE member **William J. Spencer**, chairman emeritus of SEMATECH, chaired the organizing committee. Other NAE members on the committee were **Linda M. Abriola**, dean of engineering at Tufts University; **Peter R. Bridenbaugh**, retired executive vice president, automotive, Aluminum Company of America; **Stephen W. Drew**, Science Partners LLC; **Samuel C. Florman**, chairman, Kreisler Borg Florman General Construction Company; **Susan L. Graham**, professor of computer science, University of California, Berkeley; **Anne L. Stevens**, CEO of Carpenter Technology Corporation; and **George J. Tamaro**, partner, Mueser Rutledge Consulting Engineers.

Calendar of Meetings and Events

September 4	NRC Governing Board/Executive Committee Meeting
September 11	K–12 Engineering Education Standards Committee Meeting
September 18–20	U.S. Frontiers of Engineering Symposium Albuquerque, New Mexico
September 25–26	Workshop on Noise Metrics
October 2–3	Ethics Conference on Engineering, Social Justice, and Sustainable Community Development
October 3	NAE Finance and Budget Committee Meeting
October 3–4	NAE Council Meeting
October 4	NAE Peer Committee Meeting
October 5–6	NAE Annual Meeting
October 6	Annual Meeting Technical Symposium on Grand Challenges for Engineering
October 16	NRC Governing Board/Executive Committee Meeting
October 20	CASEE Advisory Committee Meeting
November 5–7	President's Circle Meeting Irvine, California
November 11–12	NRC Governing Board/Executive Committee Meeting
November 17–19	Japan-America Frontiers of Engineering Symposium Kobe, Japan
December 1–2	NAE Committee on Membership Meeting
December 11	NRC Governing Board/Executive Committee Meeting

All meetings are held in the Academies Building, Washington, D.C., unless otherwise noted.

In Memoriam

ROY G. JOHNSTON, 94, retired vice president, Brandow & Johnston Associates, died on March 13, 2008. Mr. Johnston was elected to NAE in 1981 "for distinguished contributions and service in the field of structural engineering and earthquake-resistant design of buildings."

PHILIP E. LAMOREAUX SR., 88, senior hydrogeologist, P.E. LaMoreaux and Associates Inc., and editor in chief, *Environmental Geology*, died on June 23, 2008. Dr. LaMoreaux was elected to NAE in 1987 "for geological and geotechnical contributions to groundwater resource development and to hazardous waste disposal and management."

A.L. LONDON, 94, Professor Emeritus of Mechanical Engineering, Stanford University, died on March 18, 2008. Mr. London was elected to NAE in 1979 "for contributions to the theory and applications of compact heat exchangers, especially in the gas turbine field."

CHARLES S. MATTHEWS, 88, retired senior petroleum engineering consultant, Shell Oil Company, died on May 8, 2008. Dr. Matthews was elected to NAE in 1985 "for distinguished contributions to petroleum engineering technology and to development of public energy policy in the United States."

JORJ O. OSTERBERG, 93, Stanley F. Pepper Professor of Civil Engineering, Emeritus, Northwestern University, died on June 1, 2008. Dr. Osterberg was elected to NAE in 1975 "for contributions to soils and foundation engineering through research, teaching, practice and professional leadership."

COURTLAND D. PERKINS, 95, past president, National Academy of Engineering, died on January 6, 2008. Dr. Perkins was elected to NAE in 1969 "for leadership in the fields of airplane stability and control and airplane dynamics."

KENNETH J. RICHARDS, 75, retired vice president, Kerr-McGee Corporation, died on May 11, 2008. Dr. Richards was elected to NAE in 2000 "for contributions to the development of advanced copper smelting technology."

ROBERT C. SEAMANS JR., 89, Professor Emeritus in Aeronautics and Astronautics, Massachusetts Institute of Technology, and president of NAE from May 1973 to December 1974, died on June 28, 2008. Dr. Seamans was elected to NAE in 1968 "for engineering design and development of airborne systems; technical leadership in the nation's space program."

MORGAN SPARKS, 91, retired president, Sandia National Laboratories, died on May 3, 2008. Dr. Sparks was elected to NAE in 1973 "for pioneering work in the invention of the grown junction transistor."

BRUNO THURLIMANN, 85, Professor Emeritus of Structural Engineering, Swiss Federal Institute of Technology, died on July 29, 2008. Dr. Thurlimann was elected to NAE in 1978 "for accomplishments in theory, research, and design, and construction of steel, reinforced concrete, and prestressed concrete."

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <*http://www.nap.edu*> or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Setting the Stage for International Spent Nuclear Fuel Storage Facilities: International Workshop Proceedings. In May 2003, the Russian Academy of Sciences and the National Academies organized an international workshop in Moscow to discuss scientific issues relevant to the establishment and operation of an international storage facility in Russia for spent nuclear fuel. Given widespread international interest in this topic, the academies organized a second workshop on issues that had not been on the agenda or that required more discussion. The second workshop focused on international monitoring of the facility, transportation requirements, liability and insurance concerns, and the status of Russian legislation and regulations necessary to determining the location and operation of such a facility. Workshop participants also discussed experiences in Europe, the United States, and Asia related to storing nuclear materials. This volume includes the papers presented at the 2005 workshop sessions, as well as proceedings of the 2003 workshop. Together they provide an overview of the issues and useful background information for organizations and individuals involved in the development of the proposed storage facility.

NAE members on the study committee were **Milton Levenson** (chair), retired vice president, Bechtel International, and consultant, Menlo Park, California; and **John F. Ahearne**, Executive Director Emeritus, Sigma Xi, The Scientific Research Society. Paper, $32.50.

Behavioral Modeling and Simulation: From Individuals to Societies. Military missions no longer involve fighting nation states with conventional weapons. Today, our armed forces are combating insurgents and terrorist networks in a battle space in which military actions primarily influence the attitudes and behavior of civilian noncombatants. To support these new missions, the military services are exploring ways to use models of human behavior, as individuals and in groups of various kinds and sizes. This report provides evaluations of research programs on modeling individual, organizational, and societal (IOS) groups, and identifies the programs and methodologies with the greatest potential for military use. In addition, the study committee provides guidance for designing a research program that would advance the development of IOS models useful to the military. This report will be of most interest to model developers, military users of models, and government decision makers.

NAE member **Andrew P. Sage**, University Professor and First American Bank Professor, Systems Engineering and Operations Research Department, George Mason University, was a member of the study committee. Paper, $69.00.

Science Opportunities Enabled by NASA's Constellation System: Interim Report. To begin implementation of the Vision for Space Exploration (recently renamed "U.S. Space Exploration Policy"), the National Aeronautics and Space Administration (NASA) is developing new launch vehicles and a human-carrying spacecraft, collectively called the Constellation System. In November 2007, NASA asked the National Research Council to evaluate opportunities for using the Constellation System for space-science projects. This interim report provides evaluations of 11 existing "Vision Mission" studies of advanced space-science mission concepts inspired by earlier NASA studies.

NAE member **Spencer R. Titley**, professor of geosciences, University of Arizona, was a member of the study committee. Paper, $21.00.

Ballistic Imaging. The study committee for this new report from the National Research Council concludes that a national database of images of ballistic markings from all new and imported guns sold in the United States should not be created at this time. Instead, the committee recommends specific improvements for an existing database of crime-related ballistic evidence and urges that further research be done on "microstamping."

NAE members on the study committee were **Eugene S. Meieran** (vice chair), senior fellow and director of manufacturing, Strategic Support, Intel Corporation; **Alfred Blumstein**, J. Erik Jonsson Professor of Urban Systems and Operations Research, H. John Heinz III School of Public Policy and Management, Carnegie Mellon University; **Michael R. Stonebraker**, professor of computer science, Massachusetts Institute of Technology; and **Julia R. Weertman**, Walter P. Murphy Professor Emerita of Engineering, Northwestern University. Paper, $59.00.

United States Civil Space Policy: Summary of a Workshop. In 2004, the National Research Council (NRC) released a workshop report about the future of the U.S. civil space program. At the same time, the Bush administration announced the Vision for Space Exploration, and in June 2004, issued a report describing a balanced space program for human and robotic exploration and science. Since then, several NRC reports have noted that the National Aeronautics and Space Administration has not received the resources necessary to carry out this comprehensive program. In light of this and other challenges to the U.S. civil space program, the NRC formed an ad hoc committee of experts to organize a second workshop, held in November 2007, to address the future of the space program. The goal of the workshop was to bring together people with a variety of views and perspectives in hopes of informing discussions by policy makers and the public. This volume provides a summary of the 2007 workshop discussions and presentations.

NAE members **Warren M. Washington**, senior scientist and section head, Climate Change Research Section, Climate and Global Dynamics Division, National Center for Atmospheric Research; and **A. Thomas Young**, Lockheed Martin Corporation (retired), were members of the workshop planning committee. Paper, $15.00.

Fourth Report of the National Academy of Engineering/National Research Council Committee on New Orleans Regional Hurricane Protection Projects: Review of the IPET Volume VIII. In this volume, a committee of experts in relevant disciplines reviews Volume VIII of the report by the Interagency Performance Evaluation Task Force (IPET), which was established in 2005 to evaluate the performance of the New Orleans hurricane protection system during Hurricane Katrina. In Volume VIII, IPET evaluates risk and reliability of the New Orleans hurricane protection system and discusses the likelihood of future flooding in the region. This National Academy of Engineering/National Research Council report finds that the interim draft of Volume VIII is incomplete. Although the risk analysis method appears to be appropriate, further information will be necessary to describe the method in detail and validate the results.

NAE members on the study committee were **G. Wayne Clough** (chair), president, Georgia Institute of Technology; **Rafael L. Bras**, Edward A. Abdun-Nur Professor, Massachusetts Institute of Technology; **John T. Christian**, consulting engineer, Waban, Massachusetts; **Delon Hampton**, chairman of the board, Delon Hampton & Associates Chartered; and **Thomas D. O'Rourke**, Thomas R. Briggs Professor of Engineering, Cornell University. Free PDF.

First Report from the NRC Committee on the Review of the Louisiana Coastal Protection and Restoration (LACPR) Program. In response to the devastation caused by hurricanes Katrina and Rita, Congress requested that the U.S. Army Corps of Engineers (USACE) produce a comprehensive technical report describing a design for a system to protect against future Category 5 hurricanes in southern Louisiana. The report, *Louisiana Coastal Protection and Restoration Technical Report*, describes many alternatives for restoring wetlands, designs for levees and flood walls, and nontechnical measures to provide hurricane protection. In the present National Research Council (NRC) report, a study committee reviews the USACE draft report and recommends how it can be improved. For example, although USACE describes new approaches to protecting this complex ecological and geological environment, it does not prioritize projects by the benefits they would provide. In addition, all three major sections of the report have significant weaknesses. Most significantly the USACE draft report does not show that, given the current and future rates of subsidence, degradation, and sea level rise, the sediment resources necessary to maintain the current coastal configuration will be available.

NAE members on the study committee were **Robert A. Dalrymple** (chair), Willard and Lillian Hackerman Professor of Civil Engineering, Whiting School of Engineering, Johns Hopkins University; and **John T. Christian**, consulting engineer, Waban, Massachusetts. Free PDF.

An Assessment of the SBIR Program at the National Science Foundation. The Small Business Innovation Research (SBIR) Program, founded in 1982, was designed to encourage small businesses to develop new processes and products and to conduct research in support of the many missions of the U.S. government, including health, energy, the environment, and national defense. In response to a request from Congress, the National Research Council has provided assessments of the administration of SBIR by the five federal agencies that account for 96 percent of program expenditures. This volume, focused on the SBIR program at the National Science Foundation, finds that the program is basically sound and effective in practice. The program continues to meet most of the congressional objectives, including stimulating technological innovation, increasing private-sector commercialization of innovations, using small businesses to meet federal research and development needs, and encouraging participation by minority and disadvantaged persons. The review committee suggests some improvements in operating procedures and ways to encourage more private-sector commercialization and more participation by women and minorities.

NAE members on the study committee were **Jacques S. Gansler** (chair), vice president for research, professor, and Roger C. Lipitz Chair in Public Policy and Private Enterprise, School of Public Policy, University of Maryland; **Trevor O. Jones**, chairman and CEO, ElectroSonics Medical Inc.; **Duncan T. Moore**, professor, Institute of Optics, University of Rochester; and **Charles R. Trimble**, chairman, U.S. Global Positioning System Industry Council. Paper, $73.25.

Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft: A Workshop Report. In 2000, the nation's next-generation National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Program anticipated purchasing six satellites for $6.5 billion, with the first launch in 2008. By November 2005, however, it became apparent that NPOESS would overrun its cost estimates by at least 25 percent. In June 2006, the number of spacecraft was reduced to four, the launch of the first spacecraft was delayed until 2013, and several sensor systems were canceled or scaled down in capability. To mitigate the impacts of these changes, particularly for climate research, the National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration asked the National Research Council (NRC) to include this task in its ongoing "decadal survey" of Earth science and applications from space. The sponsors and the NRC then agreed to address the subject separately and to sponsor a major workshop to inform the assessment. This volume provides summaries of workshop discussions on the measurements and sensors originally planned for NPOESS and GOES-R; the generation of climate-data records; and options for mitigating the adverse effects of the changes, including working with international partners; and cross-cutting issues.

NAE member **Thomas H. Vonder Haar**, University Distinguished Professor of Atmospheric Science and director of CIRA, College of Engineering, Colorado State University, was a member of the study committee. Paper, $18.00

Proceedings of a Workshop on Materials State Awareness. The functionality and integrity of military equipment are crucial to effective military operations and the safety of military personnel. For the past several years, the Nondestructive Evaluation Branch at the Air Force Research Laboratory has been working on embedded sensing technologies for real-time monitoring of damage in aircraft, turbine engines, and aerospace structures. These sensing technologies must be capable of operating in environments ranging from normal to extreme conditions, and researchers must have a good understanding of the reliability of materials, wireless telemetry, and signal-processing methods. In addition, the Air Force needs science and technology for sensing material states on the microstructural level, precursor damage at the dislocation level, and fatigue-crack size populations. To address these issues, the National Research Council convened a workshop at which speakers presented personal perspectives on technological approaches to understanding materials states and described potential challenges and advances in technology. This volume includes extended abstracts of the presentations.

NAE members **Edgar A. Starke Jr.**, University Professor and Oglesby Professor of Materials Science, Emeritus, University of Virginia, and **R. Bruce Thompson**, director, Center for Non-destructive Evaluation, Institute for Physical Research and Technology, Iowa State University, were members of the workshop organizing panel. Paper, $21.00.

Inspired by Biology: From Molecules to Materials to Machines. Scientists have long wanted to create synthetic systems that function with the precision and efficiency of biological systems. With new techniques, researchers are now discovering principles that might lead to the creation of synthetic materials that can perform tasks as precisely as biological systems. To assess current research and the potential of the intersection of biology and materials science, the U.S. Department of Energy and the National Science Foundation asked the National Research Council to identify the most compelling questions and opportunities at this interface, suggest strategies for addressing them, and consider their potential applications for health care and economic growth, as well as other national priorities. This volume includes a discussion of the principles governing biomaterial design, a description of advanced materials for selected functions, such as energy and national security, an assessment of biomolecular-materials research tools, and an overview of infrastructure and resources for bridging the biological-materials science interface.

NAE member **Arup K. Chakraborty**, Robert T. Haslam Professor of Chemical Engineering, professor of chemistry, and professor of biological engineering, Department of Chemical Engineering, Massachusetts Institute of Technology, chaired the study committee. Paper, $31.00.

Review and Assessment of Developmental Issues Concerning Metal Parts Treater Design for the Blue Grass Chemical Agent Destruction Pilot Plant. In 1996, Congress mandated that the U.S. Department of Defense demonstrate and select alternatives to incineration at the Blue Grass and Pueblo sites for destroying the chemical weapons stored there. The Assembled Chemical Weapons Alternatives (ACWA) Program was set up to oversee the development of these alternative methods, and pilot plants were established at both sites. New technologies being developed at the Blue Grass pilot plant include metal parts treaters (MPTs) for destroying empty metal munitions cases. Problems that arose during recent testing of MPTs prompted ACWA to request a review by the National Research Council. This report includes a description of the MPT system; an assessment of MPT testing; an analysis of thermal testing, modeling, and predicted throughput; and a discussion of the applicability of munitions-treatment units under development at Pueblo for use at the Blue Grass pilot plant.

NAE member **John R. Howell**, Ernest Cockrell, Jr., Memorial Chair, Department of Mechanical Engineering, University of Texas, was a member of the study committee. Paper, $21.00.

Review of NASA's Human Research Program Evidence Books: A Letter Report. Planning for long-duration space flights requires that strategies be developed for disease prevention, behavioral health, and clinical treatment in case problems arise as a result of hazards in the space environment and limitations on in-mission medical care. These needs prompted the National Aeronautics and Space Administration (NASA) to obtain assessments from both the national and international space-medicine communities and biomedical research communities. In this letter report, a committee of experts reviews NASA's plans to assemble evidence on the risks to human health during space flight and identifies and addresses gaps in research. The committee offers recommendations for improving the content, composition, and dissemination of evidence books, which must be continuously updated as the knowledge base of best evidence increases regarding the risks to human health associated with space flight, particularly beyond low Earth orbit and of long duration. The knowledge base will be essential to mission planners, researchers, and ultimately to the space travelers who accept those risks.

NAE member **Laurence R. Young**, Apollo Program Professor of Astronautics and professor of health sciences and technology, Massachusetts Institute of Technology, was a member of the study committee. Free PDF.

Science and Technology and the Future Development of Societies: International Workshop Proceedings. In June 2006, 17 scientists and educators selected by the National Academies, the Academy of Sciences of Iran, and the Académie des Sciences of France held a workshop at the estate of the Fondation des Treilles in Toutour, France, to discuss the role of science in the development of modern societies. This report includes the workshop presentations and summaries of the discussions that followed. Topics include science and society;

the role of science and engineering in development; obstacles and opportunities for using science and technology in development; scientific thinking of decision makers; managing and using scientific knowledge; and science, society, and education. This volume also provides background information for further interactions between Western scientists and educators and Iranian specialists.

George Bugliarello, President Emeritus and University Professor, Polytechnic Institute of NYU, and NAE foreign secretary, chaired the study committee. Paper, $34.75.

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