The 2005 Clarke Prize Honoree

Menachem Elimelech, Ph.D.

Roberto C. Goizueta Professor of Chemical and Environmental Engineering, Yale University

For the past 16 years, Dr. Menachem Elimelech has made groundbreaking contributions to the basic understanding of the physical and chemical processes for improving drinking-water quality. His research on the fate and transport of colloidal particles and microbial pathogens, like viruses and *Cryptosporidium*, in aquatic environments has proven critical in the removal of such contaminants from water. He has also significantly impacted the areas of water recycling and pollution control through his research on the effective use of membrane technologies for removing contaminants from water. Among his many achievements, he developed a novel process called “forward osmosis” for desalinating brackish and sea waters, which is anticipated to be more cost-effective and efficient than traditional desalination processes.

Dr. Elimelech is the Roberto C. Goizueta Professor of Chemical and Environmental Engineering at Yale University, where he has taught since 1998. He is also the founder and current Director of Yale’s Environmental Engineering Program. An esteemed scholar, he has authored over 110 refereed journal publications and is the principal author of the widely cited book, *Particle Deposition and Aggregation* (1995). He is also a member of the advisory boards of several leading journals in science and engineering, including *Colloids and Surfaces A*, *Desalination*, *Environmental Science & Technology*, *Environmental Engineering Science*, and *Separation Science and Technology*.

Before joining Yale, Dr. Elimelech was a Professor in the Department of Civil and Environmental Engineering at the University of California, Los Angeles, for 9 years. He received a Ph.D. in Environmental Engineering from The Johns Hopkins University and both an M.S. in Environmental Science & Technology and B.S. in Soil & Water Sciences from The Hebrew University of Jerusalem, Israel.

The 2005 Clarke Lecture

The Global Challenge for Adequate and Safe Water

MENACHEM ELIMELECH, PH.D.

Roberto C. Goizueta Professor of Chemical and Environmental Engineering

Yale University

It is now widely accepted that water scarcity and the lack of safe drinking water are the most serious challenges of the twenty-first century. Water — the most vital element for life — is becoming perilously scarce. At present, one-third of the world's population lives in water-stressed countries and, by 2025, this figure is expected to rise to two-thirds. Water scarcity has also the potential to become a major destabilizing force among neighboring countries, particularly in regions with ethnic, territorial, or religious tension. Nowhere is this issue more important than in the Middle East, where water is limited and tensions between countries in the region over this precious resource are high.

In addition to water scarcity, water quality continues to be a major threat to human health and well-being. At present, over 1-billion people lack access to clean water, nearly all of them in developing countries. Unsafe water is the primary cause for the vast majority of diarrheal diseases and is a leading killer of children under the age of five, accounting for 1- to 5-million child deaths per year. Waterborne diseases also inflict significant economic burden through the loss of productivity in the workforce and through increasing national health care costs.

This lecture addresses the global challenge for adequate and safe water through several cases involving water scarcity and quality. The first case exemplifies water scarcity and the harnessing of water quality engineering to extract water from a non-traditional water source — domestic wastewater — to alleviate the problem. As an example, wastewater reclamation for direct potable use in the African nation of Namibia will be described. The second case deals with water scarcity and the implications for national stability and peace, illustrated by Israel and its neighboring countries. The water-stressed country of Israel has turned to wastewater reclamation and seawater desalination to augment its meager water resources. The third discussion is related to water quality, specifically the lack of safe drinking water in the developing world. Simple, yet effective approaches to prevent waterborne diseases and save millions of lives are outlined. Drawing from these cases, the successes and failures of water quality engineering will be highlighted, along with thoughts about our responsibility to ensure that adequate clean water is available to all people.

> *"If we could ever competitively, at a cheap rate, get freshwater from saltwater, that would be in the long-range interest of humanity [and] would dwarf any other scientific accomplishments."*
>
> ~ John F. Kennedy, 1961

Water Scarcity as an Impetus to Extract Water from Nontraditional Sources

Water-stressed countries or regions, with no additional freshwater resources to meet increasing water demands, turn to nontraditional sources to augment their water supplies. Two such sources are domestic wastewater effluent and seawater. The latter option, however, is limited to coastal communities. With existing technologies, domestic wastewater effluent represents a viable source to produce water of any desired quality. Several prominent examples of advanced wastewater reclamation plants for indirect potable use are available, most notably Water Factory 21 in Orange County, California, and the recent NEWater Factory in Singapore. Here, as an example of the complex factors involved, a wastewater reclamation plant for potable use in Namibia will be described. It is notable that this is the only plant in the world that reclaims domestic wastewater for *direct* potable use.

Namibia, located in the southwestern part of Africa, is the most arid country in sub-Saharan

Africa. There are only ephemeral rivers in the interior of the country. The only perennial rivers are on the northern and southern borders of the country, respectively 470 and 560 miles from the capital city, Windhoek.

Drought

With a population of approximately 250,000, Windhoek and other central areas of Namibia have limited water resources. The average annual rainfall in Windhoek is merely 14 inches, while average annual evaporation is 10 times higher, at 140 inches. For most of its water supply, the City relies on three surface reservoirs built on ephemeral rivers that run only after heavy rainfall events. On one of these reservoirs, the Goreangab Dam, a conventional water treatment plant was built in 1958 to treat water from the reservoir to potable standards.

In 1969, the plant was converted to treat not only surface water from the Goreangab Dam, but also secondary effluent from the City's wastewater treatment plant. Thus, the Goreangab Reclamation Plant — the first plant for direct reclamation of wastewater for potable use — was born. The treatment sequence comprised the blending of reservoir water with secondary effluent, coagulation, dissolved air floatation, rapid sand filtration, granular activated carbon adsorption, and chlorination.[1] By blending reclaimed water with local groundwater, the plant was able to deliver 7,500 cubic meters of potable water per day.

Because the whole city lies upstream from and within the catchment of the Goreangab Dam, growth and industrialization introduced pollutants that seriously compromised water quality in the reservoir. Considering that easily accessible natural resources had already been fully exploited, expanded wastewater reclamation was deemed the logical choice to augment the water supply. Thus, the City of Windhoek obtained loans from European financial institutions to construct a new 21,000 cubic meter per day reclamation plant on a site adjacent to the old plant. Completed in 2002, the New Goreangab Reclamation Plant provides 35 percent of the daily potable requirements of the City.

The design approach for the new plant is based on the concept of a multiple barrier system. These barriers — designed to eliminate microbial pathogens and to ensure that the concentrations of substances are within drinking-water standards — are versatile and incorporate non-treatment, operational, and treatment barriers.[1] Non-treatment barriers in the Goreangab Reclamation Plant include:

- Thorough policing and diversion of the City's industrial effluents to a separate treatment plant.
- Complete monitoring at the inlet and outlet of the City's domestic wastewater treatment plant, allowing action to be taken before the treated wastewater reaches the reclamation plant.
- Extensive monitoring of drinking-water quality.
- Blending reclaimed water with other water, so that no more than 35 percent of the delivered drinking water is reclaimed water.

Operational barriers include back-up processes that can be implemented, if needed, to increase the efficiency of the treatment barriers (for instance, a dosing of powdered activated carbon). The treatment barriers are provided by treatment units and processes that comprise coagulation, dissolved air floatation, rapid sand filtration, ozonation, granular activated carbon adsorption, biological activated carbon, membrane ultrafiltration, and chlorination. Note the two new treatment barriers to eliminate microbial pathogens — ozonation and ultrafiltration — which were not present in the old reclamation plant.

"Water should not be judged by its history, but by its quality."

~ Dr. Lucas Van Vuuren
National Institute of Water Research
South Africa

Undoubtedly, the most important aspect of potable reclamation is public acceptance and trust in the quality of the product water. Breaking down the psychological barriers to the idea of direct reuse for potable purposes is not a trivial task. To retain public confidence, water quality at the Goreangab Treatment Plant is monitored routinely through online instrumentation, as well as through the collection of composite water samples after every process step. In case of any quality problem, the plant goes into recycle mode and treated water is not delivered. The final product water is also continuously sampled via online instrumentation and composite sampling, and is analyzed for a full range of physical, chemical, and microbial parameters. The citizens of Windhoek have, over time, become used to the idea that reclaimed water is included in their drinking-water supply. Actually, they have grown to have a genuine pride in the reality that their city leads the world in direct water reclamation.

"When the well is dry, we learn the worth of water."

~ Dr. Benjamin Franklin

Several important points can be highlighted from the example of Windhoek. First, wastewater reclamation represents a viable option to augment water supply in water-stressed regions, even in countries with modest natural and financial resources. Second, with engineering innovations, wastewater can be reclaimed to produce water that is safe for human consumption. Third, we need an integrated approach to wastewater reclamation for indirect or direct potable use that combines several disciplines: engineering, public health, education, and social sciences.

Water Scarcity and National Stability

There is more than a little truth in Mark Twain's saying, "Whiskey is for drinking; water is for fighting over." It is now recognized that water scarcity is a potential source of conflict among countries. A lack of water imperils a country's economy and development. The situation can reach crisis proportions when water resources extend across borders, especially in regions hosting ethnic or territorial conflicts. A few examples of neighboring countries contending over water resources include Egypt, Ethiopia, and Sudan; Malaysia and Singapore; Botswana, Angola, and Namibia; Turkey, Syria, and Iraq; and Israel, Palestine, and Syria.

Water allocation among countries, or even between regions within a country, is a complex issue involving economical, political, legal, and technological considerations. Given that it has taken years of negotiations for California and Nevada to come to an agreement regarding the allocation of Truckee River waters, it is not surprising that it took 9 years for India and Pakistan to agree on the Indus River basin. Water allocation is a problem even among friendly countries. In Europe, for example, the Danube River basin agreement is supervised by a task force of 12 nations, seven international organizations, and four nongovernmental groups.[2]

Nowhere is this problem more urgent than in the arid Middle East. Water has been a most important security matter in the Middle East since antiquity, and the allocation and rights to water in this region are potentially explosive issues. Here, the water scarcity problem and the resulting contention between Israel and its neighbors, particularly Palestine and Syria, are described. The technological solutions implemented by Israel to augment its water supply, namely wastewater reuse and seawater desalination, are presented and discussed to illustrate how water science and technology can serve to alleviate water security problems.

Israel's water supply system relies on three major sources: the Sea of Galilee (Lake Kinneret), the Coastal Aquifer, and the Mountain Aquifer. The upper Jordan River, the source of water for the Sea of Galilee, begins with three tributaries: the Hasbani River, which originates in Syria and has at least part of its outflow in Lebanon, and the Dan and Banias Rivers, originating in the Golan Heights, which were occupied by Israel in the 1967 war. About one-third of the water supply in Israel comes from the Sea of Galilee, and groundwater from the Mountain and Coastal aquifers accounts for the rest. The Mountain Aquifer consists of several basins, one falling almost entirely within the boundaries of Israel proper and several located within the West Bank.
The Coastal Aquifer lies within Israel proper, except for a small portion within the Gaza Strip. The latter, however, is mostly unsuitable for human consumption because of contamination and high salinity levels caused by excessive pumping. The above description of the trans-boundary water resources of Israel clearly shows why water will become a major issue in any peace agreement between Israel and those who share the water resources.
In fact, some historians argue that one of the reasons for the 1967 war between Israel and its neighbors, Jordan and Syria, was for gaining control over the water resources in the region.

Sea of Galilee

The current water resources in Israel are not sufficient to meet the non-agricultural water demand without exceeding the permissible withdrawal from these water sources. Moreover, while the population increases, the quantity of available freshwater is actually shrinking. This is attributable to the deterioration of both the quantity and quality of Israel's water resources. Specifically, the salinity of the Coastal Aquifer, Israel's largest aquifer, has been increasing gradually in numerous sites to levels not acceptable for drinking water. A similar pattern has also begun in the Mountain Aquifer and the Sea of Galilee, albeit to a lesser extent. This grave water deficit problem has prompted the utilization of other non-traditional water resources to augment the country's water supply, specifically via wastewater reuse and seawater desalination. Augmenting the water supply by these means also helps to reduce excessive pumping from the Mountain Aquifer, which is shared by Israel and Palestinians in the West Bank.

The combination of severe water shortage, contamination of water resources, densely populated urban areas, and highly intensive irrigated agriculture has prompted Israel to put wastewater reuse high on its list of national priorities. In fact, Israel ranks first in the world in wastewater reuse per capita and has the highest percentage of wastewater effluents reused for agriculture. Extensive experience has been gathered in this field and state-of-the-art technologies are being practiced and tested.

The Dan Region Treatment and Reclamation Plant, located south of Tel-Aviv, is the largest wastewater treatment plant in Israel.[3] It serves a population of 2.1 million, with an annual flow of 120 million cubic meters per year. It is also the largest reclamation plant for wastewater reuse in Israel and one of the largest in the world. The plant provides advanced biological treatment of wastewater, including the removal of nitrogen and phosphorous. The treated effluent is then recharged into the groundwater aquifer by means of spreading basins for additional polishing and long-term storage. The average storage time within the aquifer is at least 300 days. An array of recovery wells surrounds the spreading sites at distances ranging from 500 to 1,500 meters from the spreading sites. Passage of the effluent through the soil — a process known as soil aquifer treatment — provides significant additional treatment. The water is eventually pumped from the recovery wells and then conveyed to Israel's arid Negev Desert for unrestricted irrigation. Following the recovery wells extraction at the head of the conveyance system, the reclaimed water undergoes chlorination as an extra precaution to eliminate any residual pathogenic micro-organisms. An extensive hydrological and water-quality monitoring program, carried out by a network of observation wells and recovery wells surrounding the recharge basins, has confirmed the high quality of the reclaimed water.

While wastewater reuse has proven to be most successful for irrigation, there is an urgent need for additional potable water. In 2000, Israel launched a desalination master plan to address the country's chronic water resource problems. The plan calls for the construction of several seawater desalination plants along the Mediterranean coast, producing an annual total of 750 million cubic meters of potable water by 2020, mostly for urban consumption. Construction of the first reverse osmosis desalination plant, in the southern city of Ashkelon, began in 2003. Once fully completed, the plant will produce 100 million cubic meters of potable water per year, one of the largest of its kind in the world.[4]

The desalination plant in Ashkelon features many of the recent advancements in reverse osmosis seawater desalination. The facility is designed as two almost entirely self-contained plants, operating autonomously to provide 50 million cubic meters per year of desalinated water. From the pumping station, raw seawater flows to the pretreatment facilities through two separate lines. Pretreatment by filtration is performed in two stages, starting with dual media filters containing quartz sand and anthracite media, followed by cartridge filtration. The filtered water passes to the reverse osmosis membrane modules, equipped with state-of-the-art energy recovery devices. In keeping with the project's general goal to ensure reliability and continuous operation while also providing low cost water, electricity will be provided from two separate sources. A dedicated gas turbine power station, fuelled by natural gas, will be built adjacent to the desalination plant, and an overhead line will also be connected from the national grid. The provision of a dedicated power plant is a major factor in both safeguarding operational reliability and reducing energy costs.

Reverse Osmosis (RO) Desalination

Discussing Israel's technological solutions for its water scarcity brings to light several important points. First, domestic wastewater is a valuable resource in water-starved countries. Wastewater reuse can, at a minimum, provide high-quality water for agricultural and industrial use and, at the same time, be a solution for preventing the contamination of surface water bodies that otherwise would receive discharged effluent. Second, the cost of seawater desalination by reverse osmosis has dropped significantly in the past 10 years, positioning desalination as a key technology for the production of potable water of superior quality from seawater. Lastly, advances in water science and technology leading to reductions in desalination and wastewater reuse costs can help to solve the problem of water scarcity in contending countries, thus contributing to world peace and stability.

Water Quality and the Developing World

In the previous examples, the focus of the discussion was on water scarcity. It was shown that technological solutions, such as wastewater reuse and desalination, can ameliorate the problem to some extent, even in countries with modest economical means. However, the problem of water quality, namely the lack of clean, safe drinking water, even in countries where water is abundant, is one of the most serious challenges of our time. According to the World Health Organization, approximately 1.1-billion people (in other words, one-sixth of the current world's population) lack access to safe water, and 2.4 billion are without adequate sanitation. Over 2-million deaths a year are attributed to unsafe water, mostly due to waterborne diarrheal diseases. Ninety percent of those who die from diarrheal diseases are children in developing countries. Thus, the provision of safe drinking water and proper sanitation will have a dramatic impact on public health and the lives of millions all over the world.

> *"By means of water,*
> *we give life to everything."*
>
> ~ The Koran, 21:30

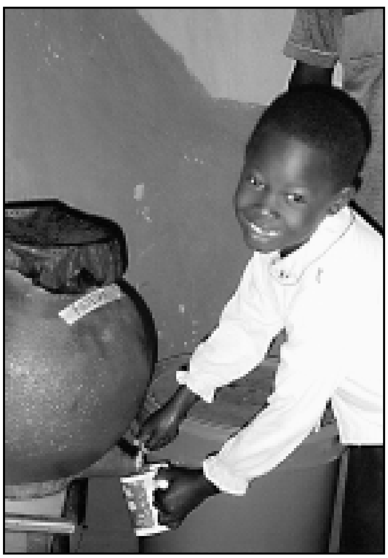
The United Nations General Assembly proclaimed 1981 to 1990 as the International Drinking Water Supply and Sanitation Decade, with the object of full access to water supply and sanitation for all people. During that time, the provision of safe water and sanitation was extended to hundreds of millions, at a cost exceeding $700 billion. Despite the major effort, however, the absolute number of people still lacking access to safe water and sanitation had not changed by much, though slight progress has been made in providing safe water to low-income urban populations, as well as those in rural areas.[5]

Centralized water treatment facilities continue to be an important objective of development agencies. However, for developing countries, providing safe, piped water to remote populations is quite expensive. Furthermore, rapid population growth in urban areas poses problems in planning and constructing new water and sanitary infrastructures. Given the failure to reduce the numbers of people without access to basic water supply and sanitation during the 1990s, it is apparent that current approaches are not satisfactory.[5] Approaches that rely only on centralized solutions will leave hundreds of millions of people without safe water far into the foreseeable future. Alternative interventions to support the impoverished populations in developing countries are called for.

There is growing evidence that simple, "low-tech," low-cost interventions at the household and community level are able to markedly improve the safety of household water, thus reducing diarrheal illness and saving millions of lives. Among these interventions, point-of-use chemical or solar disinfection and safe water storage are most promising. Disinfection by sodium hypochlorite, the active ingredient in commercial laundry bleach solutions, has proved to be the safest, most effective, and least expensive chemical disinfectant for point-of-use treatment. Field data have shown that point-of-use treatment by sodium hypochlorite can reduce diarrheal illness by as much as 85 percent. Similarly, solar radiation can be utilized for the point-of-use inactivation of pathogens in water via the inactivating effect of ultraviolet radiation or the concomitant increase in temperature. For solar inactivation, clear plastic bottles or bags are quite effective. Lastly, household-treated water remains susceptible to the introduction of pathogens during collection, transport, and storage. Replacing unsafe water storage vessels with safer ones has shown to lower the rate of diarrhea in children.

Such point-of-use interventions have been applied, with some success, in several regions in Madagascar, where the lack of safe water and proper sanitation are major contributing factors to high rates of diarrhea and vulnerability to cholera.[6] In 1999, cholera was detected in Madagascar for the first time, after a long hiatus. The cholera outbreak caused more than 37,000 illnesses and 2,200 deaths. The Cooperative for Assistance and Relief Everywhere (CARE) and the Centers for Disease Control and Prevention (CDC) Health Initiative have funded CARE Madagascar to implement a household-based safe water intervention. CARE contracted with Population Services International (PSI) to socially market a Safe Water System. This involved the local production of a 0.5-percent sodium hypochlorite solution stored in a 0.5-liter bottle, an amount sufficient to treat approximately 2,000 liters of water. PSI contracted a local company to produce 20-liter narrow-mouthed plastic jerry cans, which were distributed to residents for safe storage of household water. These measures were found to be effective in reducing cholera and other wasterborne diarrheal diseases associated with the cyclones and resulting flooding that hit Madagascar during that period.

Similar point-of-use interventions involving the use of 1-percent sodium hypochlorite solution, safe storage in clay pots with narrow mouths, and adjustment in behavior were implemented in the rural Nyanza province in Kenya.[7] In that province, 66 percent of the population lacked access to safe water and nearly 50 percent of children younger than 5 years had experienced diarrhea in the preceding 2 weeks. Six months after introducing these interventions, monitoring indicated relatively high adoption rates for chlorine and modified clay pots. The adoption rate for chlorination was substantially higher than rates found in urban projects in other countries. Some of the contributing factors for the success of the project were the perceived need for water treatment to prevent diarrhea, ease in accessing and using the product, and the relatively low cost of the product.



Clay Pot Storage

The experience in Madagascar and Kenya showed that public health interventions must involve behavior changes to achieve significant reductions in the incidence or severity of diarrheal diseases. Such populations have well-established water-handling habits, limited income, and a history of receiving free goods from nongovernmental organizations. The above studies concluded that the process by which new water treatment and storage practices are promoted is as critical as the treatment process itself.

Sufficient Clean Water as a Universal Human Right

Human history has recognized that there is no life on earth without water. Basic survival, built on water, has elevated the element throughout history as being mystical, even God-like. Cultures and religions worldwide have worshipped water, or put it at the center of religious rites and spiritual purifications. Cultural identity is often entwined with relationships with water. Water does more than simply sustain life — it uplifts life, purifies, and renews the spirit. It can also be blamed for taking life, for destroying what has been built up, and for devastation. There is no other natural force quite so powerful, and societies since antiquity have bowed down and revered the forces of water in awe.

For a resource so powerful and vital, it has been overlooked by agreements and constitutions declaring human rights. The right to water exists in the sense that it is an implicit component of other explicit fundamental human rights, yet has not been recognized in international law. Indeed, many world leaders and global and regional organizations have called upon formally naming water as a basic human right.[8] The UN Committee on Economic, Social, and Cultural Rights states:[9] "The human right to water is indispensable for leading a life in human dignity. It is a prerequisite for the realization of other human rights." Former USSR President Mikhail Gorbachev, who is the current President of Green Cross International, further added: "Water is the most important single element needed in order for people to achieve the universal human right to 'a standard of living adequate for the health and well-being of himself and his family' (Article 25, Universal Declaration of Human Rights). Without access to clean water, health and well-being are not only severely jeopardized, they are impossible: people without basic water supplies live greatly reduced and impoverished lives — with little opportunity to create better futures for their children. . . . Let us acknowledge that clean water is a universal human right, and in so doing accept that we have the corresponding universal responsibility to ensure that the forecast of a world where, in 25 years' time, two out of every three persons face water-stress is proven wrong."

In considering the adoption of "water as a basic human right," the practicalities of what this means become complicated. Compare such a right to, for example, the freedoms of thought and association, often considered universal. Such freedoms are not physically given, but rather allowed, nurtured, and protected in society. How then, do we reframe our thinking to allow something physical, like sufficient clean water, to become a right? What would be gained by the declaration of such a right? How do we ensure that each person in the world has this right granted? What local, regional, and international legal structures need to be developed to enforce this? Obviously, a natural question follows: Who pays for this?

Dialogue in this area is growing. The international community is making progress in recognizing the universal importance for sufficient clean water. One day, hopefully, all people in the world will enjoy the right to water as a result of these efforts. There was once a time, in our recent history, when people would have considered voting rights for women or civil rights for marginalized populations to be but a dream. While the fight for civil rights continues, and is a journey rather than an endpoint, significant strides forward have been made thanks to the vision and commitment of many individuals.

We, likewise, can move the struggle for water rights forward. As individuals concerned with water science and technology, we must support these efforts and, in our own circles, push for progress in this area. Treating water and maintaining just distribution does not happen without political will and financial investment. In considering the heavy importance of clean and abundant water for all life, it is not possible to box ourselves into economic considerations of markets demanding continual supplies of water. While safe water surely has a price, this price cannot be considered purely in neoclassical economic terms. The value of water is so much more. Determining the way to ensure safe, sufficient water for all the world's individuals is a huge human challenge and requires the combined charge of many stakeholders from economists and policy analysts, scientists and engineers, to local communities and their politicians.

"All the rivers run into the sea; yet the sea is not full."

~ Ecclesiastes, 1:7

In summary, to be effective, water scientists and engineers must become comfortable traversing both the technical and the complex social terrain. At the bare minimum, we must be sensitive to the inherent ethical, political, and economical environments in which we play a pivotal role and, indeed, we must engage those components to succeed. The preceding discussion emphasizes that solutions to our water scarcity and water quality problems require attention to technology and social structure. At the end of the day, if we are successful, we will have transformed the planet and will need to apply our skills elsewhere, but in the meantime, our most precious resource, water, requires our utmost attention.

Thank You

I am humbled and honored to be the twelfth recipient of the prestigious Clarke

Prize. I am very grateful to Athalie Richardson Irvine Clarke, to her daughter Joan Irvine Smith, and to the National Water Research Institute for establishing the Clarke Prize in recognition of the vital importance of water science and technology. I would like to thank the many individuals who have made this award possible. My mentor Charlie O'Melia — the 2000 Clarke Prize Laureate — who introduced me to the field of water science and technology, and who taught me the value of fundamental research. My graduate students and post-doctoral fellows from whom I have learned so much; I was privileged to work with them — they have done most of the work with which I am associated. My teachers and colleagues at the several institutions with which I have been associated with: Hebrew University, Johns Hopkins, UCLA, and Yale. My mother in Israel, who taught me the importance of hard work. And finally, my wife Karen, my daughter Noa, and my son David, who provided the moral support and motivation for my work.

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