NATIONAL WATER RESEARCH INSTITUTE

presents

The 2014 Clarke Prize Lecture

Delivering the Fourth Water Revolution

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Summary

The complex system developed over the past two millennia to provide cities with water and dispose of wastes is currently under stress from the effects of climate change, population growth, and a confluence of other factors. Urban water systems have responded to these kinds of acute problems three previous times through technological advances and institutional reforms. If water professionals hope to bring about another round of change before our water infrastructure once again reaches a state of crisis, they will need to acknowledge the underlying causes of the problems, develop sound technological solutions, and work within a complex and conservative institutional system to ensure changes are adopted. This lecture draws upon recent experiences in the development and diffusion of water supply technologies to illustrate ways in which water professionals, civic leaders, and members of the public can work together to deliver the fourth revolution in urban water.

A Warm Welcome to the Golden State

Many people make their first trip to Orange County, California, to spend a day at Disneyland – but not everyone. About 20 years ago, my first experience in this community culminated in a windowless room in a hotel near the John Wayne Airport where the Research Advisory Board of the National Water Research Institute (NWRI) interrogated me about a project that NWRI was funding on steroid hormones in recycled water (Huang and Sedlak, 2001). Although my afternoon had moments more harrowing than a ride on Disney's *Space Mountain*, the collective wisdom of the group yielded insights that improved the project and helped me launch a career studying trace organic compounds in recycled water.

During those early years, NWRI's Executive Director, Ronald Linsky, members of the NWRI Research Advisory Board, and leading California water experts educated me on the intricacies of water recycling and the ways in which sound science and professional judgment could be used to provide Southern California with a new source of drinking water. As my research expanded over the next decade to address other problems, including the occurrence of *N*-nitrosodimethylamine (NDMA) in recycled water (Mitch and Sedlak, 2002; Sedlak et al., 2005) and the development of cost-effective treatment technologies for trace amounts of organic chemicals (Gray and Sedlak, 2005; Kolodziej et al., 2003), people started to consider me as one of the experts. Being an expert meant that I gained insight into misconceptions shared by reporters and members of the public. Through these new interactions, I came to appreciate how little most people knew about all the things that happen to water as it makes its way to their faucets.

The need to inform the public about the challenges their water systems are facing eventually inspired me to write a book on urban water for general audiences (Figure 1).

As I conducted background research, I learned a lot about water history and the state of our modern water infrastructure. Perhaps the biggest surprise occurred when I took a step back and reflected on the way change comes to urban water systems. I realized that rather than a constant march toward better technologies and more sophisticated management tools, water systems lurch from crisis to crisis until events galvanize the public's will to break the status quo. Once this happens, many of the good ideas that had previously been rejected as being too expensive or risky suddenly become viable. This observation inspired me to present the history of urban water systems as a series of three revolutions. It also made me much more sanguine about our prospects for solving the range of problems we are currently facing.

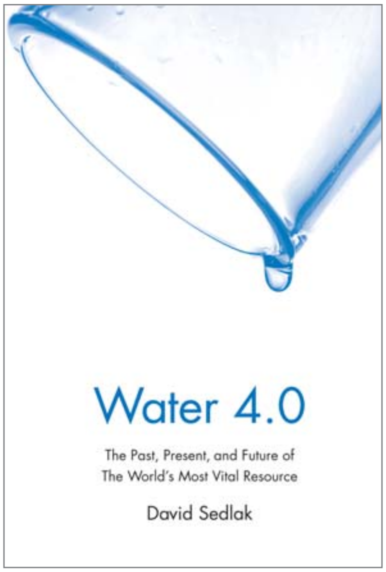

Figure 1: Water 4.0 *is a book I wrote to describe the path to the fourth urban water revolution (Sedlak, 2014).*

Tonight, I will examine an important aspect of the change I see on the horizon. It is a topic that I did not fully address in my book, *Water 4.0* – namely, the actions that water professionals, civic leaders, and members of the public can take to bring about the next water revolution. These groups have the power to solve problems before water systems reach a state of crisis and, by understanding the process through which change occurs, they can take specific actions to bring about the fourth revolution. Along the way, I will highlight some of the emerging technologies and management strategies that may play a major role in the next stage of our urban water voyage.

A System under Stress

Before turning our attention toward solutions, I will review the key factors that are placing stress on urban water systems. Water supply will be the focus of this discussion both because it is particularly relevant for this region of the country and it is also the subject of much of my own research. I suspect that several members of the audience could just as easily provide us with perspectives on stresses associated with water use in agriculture or the threats to cities posed by flooding.

Among the different drivers of the urban water revolution, I consider climate change to be the most important, especially over the long term. It may not be possible to link a specific drought or storm to climate change, but the most credible predictions for the coming decades suggest a future where existing water sources will become less reliable. For example, consider this complicated figure from the chapter of the 2013 Intergovernmental Panel on Climate Change (IPCC) report (Christensen, 2013) that summarizes predictions from the latest models about impacts of climate change on precipitation (Figure 2).

The colors indicate expected changes in annual precipitation by the end of the twenty-first century, scaled to show the percentage increase or decrease for each degree centigrade of warming. The blue and green shading corresponds to places where conditions are expected to become wetter, while the tan and brown shading indicates locations where conditions are expected to become drier. The message of this and other long-term predictions is that wet places are likely to become wetter as dry places become drier. Looking specifically at the Western United States, the models indicate less precipitation in the American Southwest – from California to Texas – as the ocean currents that control much of the region's weather move to the north. Although we cannot tell if it is purely coincidental, this map looks similar to the U.S. Drought Monitor's recent maps for the Western United States (Figure 3). Elsewhere, the models predict drier conditions in the Mediterranean, much of South America, southern Africa, and Australia.

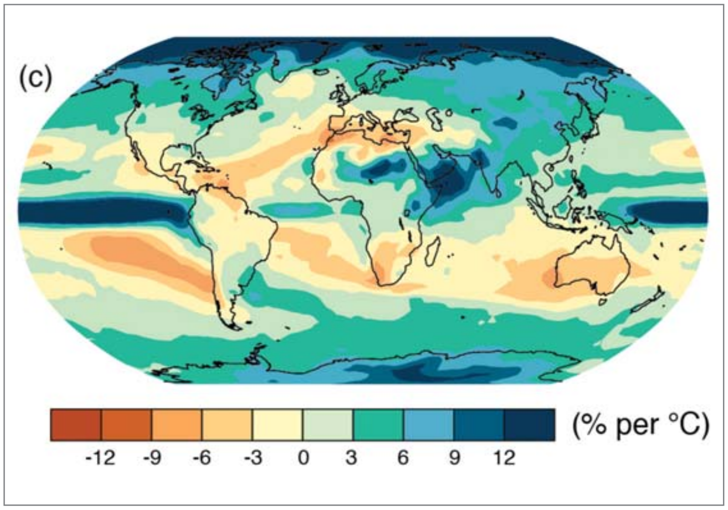

Figure 2: Projected twenty-first century change in annual mean precipitation in % per °C of global mean temperature change (Christensen, 2013).

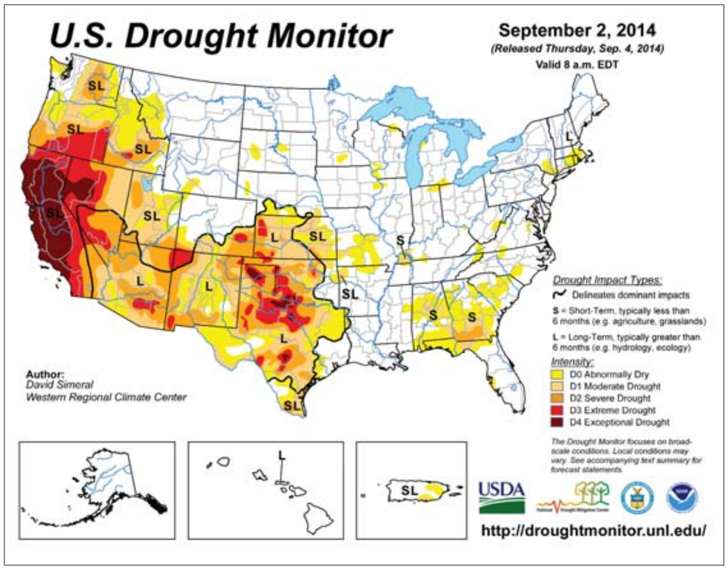

Figure 3: Drought conditions in the United States in September 2014. Source: http://droughtmonitor.unl.edu/.

Precipitation is only part of the climate change story. As Jerry Schnoor eloquently showed in his 2010 Clarke Prize Lecture (Schnoor, 2010), the historic record from the past half-century and global circulation models provide convincing evidence that the planet is warming. Environmental engineers recognize that warmer temperatures mean lower yields from the watersheds that feed our reservoirs, as well as increased demands for water from agriculture and landscaping due to higher rates of evapotranspiration. Thus, even if the models are inaccurate and the amount of precipitation falling on our watersheds remains constant or increases slightly, it is still likely we will no longer have access to the same amount of water that we have had historically.

Warming also poses another major threat to water infrastructure: as more precipitation in the mountains falls as rain, our existing supply systems will capture less water. In places like the Sierra Nevada or Rocky Mountain Ranges, we could compensate for the loss of snowpack through investments in reservoir expansion – an expensive endeavor that is unlikely to be popular with members of the environmental community. However, in places like Bolivia and India, where glaciers play a major role in seasonal water storage, an entirely new infrastructure may be needed to make up for the loss of these important natural storage systems (Guzman, 2013).

The second major factor placing stress on urban water supply is population growth. In the United States, people have been moving to cities with the least secure sources of water for over 40 years. The familiar pattern of migration to the west and the south has been handled with considerable success by water managers, but it is expected they will not be able to keep up with demand in the future. First, consider the 20 largest metropolitan areas in the United States (Figure 4).

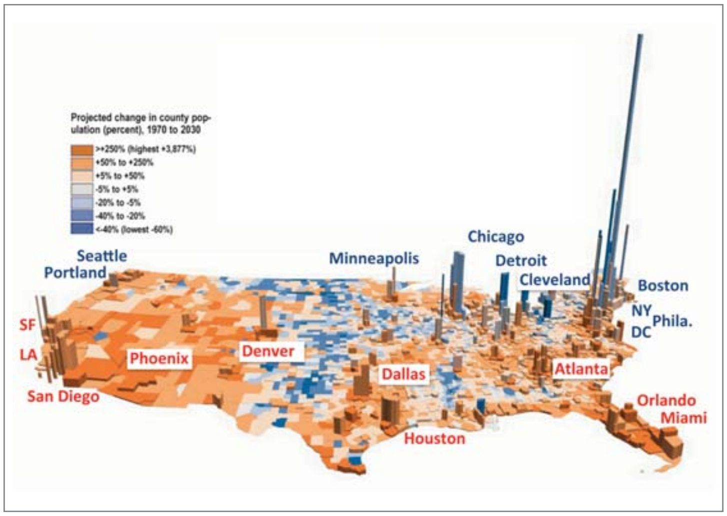

Figure 4: Projected change in county population between 1970 and 2013 (modified from USGCRP, 2000). The names identify the 20 largest metropolitan areas, with those in red facing water supply challenges.

The heights of the bars on the map are proportional to county population, while the colors indicate population growth trends. The areas that have been growing are shown in orange, and those that have been shrinking are shaded in blue. The red labels indicate cities that I believe will face greater water supply challenges in the coming decades, while cities labeled in blue will likely manage using their current water resources. For most of the red-labeled metropolitan regions, the population projections indicate an increase of 20 to 40 percent over the next two decades. Providing new sources of imported water for these growing cities will be extremely difficult because the water rights in most of these water-stressed regions have already been fully allocated. Certainly, water conservation will be part of the story; it is quite likely per capita water demand can be reduced by an amount needed to offset the effects of population growth in cities that have not already tightened the efficiency screws by retrofitting indoor plumbing and providing incentives for people to change the way water is used outdoors. But, as I describe in *Water 4.0*, in cities that have already implemented comprehensive demand management programs, there are signs that a plateau is approaching with respect to how much we can further reduce domestic water use. There are also numerous political reasons why the lawn, or at least some sort of landscaping that requires periodic irrigation, will remain a permanent fixture of American cities for the foreseeable future.

Population growth is also straining urban water supplies in other countries. Notwithstanding Western Europe and Japan (where the population might decrease in the coming century), most of the world's major cities are expected to continue their pattern of rapid growth. What do Mexico City, Sao Paolo, Singapore, Perth, and Delhi have in common? Despite their many superficial and substantive differences, all these big cities are grappling with water supply challenges that have been exacerbated by rapid population growth. The available evidence suggests that the traditional options of expanding imported water supplies, digging more groundwater wells, or focusing on water use efficiency will not solve future water supply challenges in these cities.

Assuming the worst effects of climate change are still decades away and water conservation and efficiency measures will suffice over the near term, we have 20 or 30 years to determine exactly how we will reinvent urban water systems. At first glance, it may seem like enough time. But two or three decades may not be enough to accomplish a full-blown water revolution, considering:

- The remaining research and development needed to advance water technologies to a place where they can be safe bets for the buyers of municipal bonds.
- The need to engage a frequently apathetic public on the "unsexy" topic of treatment plants, pipes, and sewers.
- The long lead times needed to finance, design, and build water infrastructure.

There is no time to waste if we hope to avoid a full-blown water crisis.

Climate Change: Moving Beyond an Inconvenience

For many years, water professionals have been non-committal when it comes to climate change. This attitude may have been a reasonable response when the science was not as well established or when the exact impacts of climate change on a specific region were unclear. Today, I believe that some of the remaining reticence about taking a more aggressive stance on climate change can be traced to the ability of engineers to maintain a pragmatic attitude when faced with controversy. If local politicians find it unpopular to acknowledge the existence of climate change, engineers may be willing to accommodate them by putting their heads down and developing management plans for water resources that explain the need for diversifying a region's water supply solely in terms of accounting for natural climate variability and population growth. Perhaps this is the reason why it is still possible for a team of water resource engineers and hydrologists to write a 300-page plan to manage a state's water supply with only the briefest mention of climate change as an unresolved issue of potential concern that can be addressed after the science is resolved (Texas Water Development Board, 2012).

Although it may be inconvenient, I would like to advocate that engineers, planners, and politicians stop taking the easy way out. If climate change is the defining problem of the first half of the twenty-first century, we need to acknowledge it as a design constraint so we can move on with the task of creating the resilient infrastructure essential to our future. Currently, much of the financial resources and intellectual energy associated with climate change is being directed at understanding how fast it is occurring and where and when the effects will be felt. Resources are also pouring into efforts to mitigate climate change by reducing greenhouse gas emissions. It is only recently that discussions about climate change have turned to the issue of adaptation in a serious way. The momentum associated with worldwide greenhouse gas emissions means that whichever path we take as we solve this problem, we have bought into the reality of a protracted period of climate change. As a result, we will need to adapt our water infrastructure to a different climate, and one of the areas of greatest need will be associated with urban water supply. For water professionals and decision makers, accepting the growing importance of climate change means we have a professional obligation to plan for a future that cannot be predicted from the recent past.

Engineering the Fourth Revolution

From a technological perspective, there is no shortage of great ideas that can be used to make urban water infrastructure more efficient and resilient. In my role as the Deputy Director of the National Science Foundation's Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure (ReNUWIt), I have had the privilege of collaborating with researchers at the University of California Berkeley, Stanford University, Colorado School of Mines, and New Mexico State University to develop technologies for transforming urban water systems. Whether it is wastewater treatment plants that generate more energy than they consume (Scherson and Criddle, 2014), soil aquifer treatment systems outfitted with sensors and actuators to precisely control flow while simultaneously improving water quality (Regnery et al., 2013), or housing developments and office parks that thrive without a connection to a centralized wastewater treatment plant, we are creating blueprints for the next generation of urban water systems. And we are not the only ones actively involved in research and development on urban water infrastructure. Looking around the world, we see no shortage of good ideas for making the fourth revolution a reality (Hering et al., 2013).

If the technological means of realizing our aspirations already exist, why are we not farther along in our quest? Part of the answer to this question can be tied to the fact we are members of what has historically been one of the least innovative professions in the world. As I described in *Water 4.0*, many cities are still investing in new water infrastructure barely distinguishable from projects built 50 years ago. There are a number of reasons why this is the case: the possibility that a new technology might compromise public health; the meager profit margins associated with public sector projects; the long lifetimes of investments in urban water infrastructure; and a host of other social and structural limitations related to our water institutions (Kiparsky et al., 2013). I suspect the only way to quickly change the conservative mentality of urban water institutions would be to wait until our current problems morph into a crisis. But the radical change that happens in response to a crisis may not necessarily be desirable. Instead of dedicating ourselves to the Herculean task of rebuilding our water institutions from the ground up, we may be better served by advocating for incremental reforms and using our knowledge of how change has happened in the past to accelerate the rate at which new ideas are adopted.

The first place where we can have an impact is by focusing on the process through which new technologies diffuse into practice. Looking back at the modest number of new technologies that have recently made this journey, we observe that the process through which change comes to engineering design occurs in stages depicted by an S-shaped curve (Figure 5).

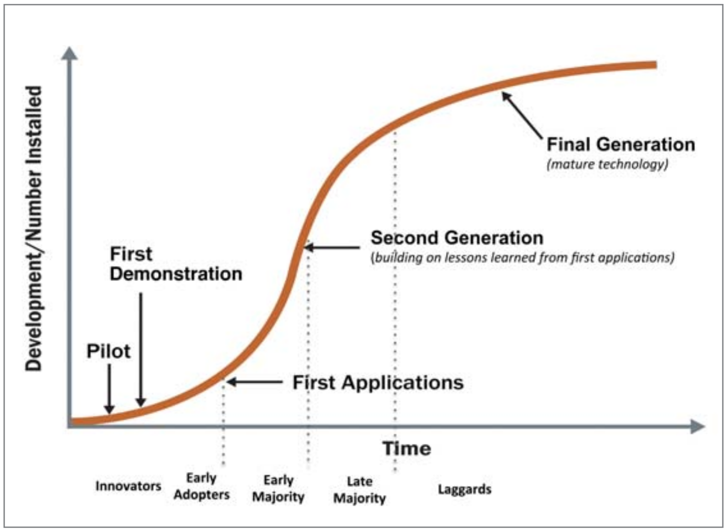

Figure 5: The technology diffusion S-Curve. Figure adapted from Denny Parker and used with permission.

Several years ago, Denny Parker illustrated the process through which nutrient removal technologies have undergone technology diffusion within the municipal wastewater sector (Parker, 2011). He showed it normally takes 25 to 30 years for advanced nutrient removal technologies to move from pilot-scale testing to broad adoption. In all cases, the first step in the S-curve involves a group of developers who take a new invention from the laboratory to the pilot scale. Next, the developers partner with utilities that have a compelling need for the technology – typically, with the motivation coming from the prospect of having to build costly plants if they adopt the existing approach. These utility partners – referred to as "Innovators" – demonstrate the performance of the new technology at full scale. After the demonstration plant operates for several years, engineers and utility leaders from other locations become enthusiastic and adopt the technology when they rebuild their treatment plants. The industry gains experience through the actions of this second group (referred to as "Early Adopters"). The success of Early Adopters encourages a larger group of utilities, referred to as the "Early and Late Majority," to upgrade to the new technology. After a decade of operational experience, the superior technology is no longer considered risky and is even adopted by utilities characterized as technology "Laggards."

At ReNUWIt, we have internalized this model of technology diffusion by establishing a process for supporting our researchers as they navigate the left side of the technology diffusion S-curve. For example, the Coupled Aerobic-Anoxic Nitrous Decomposition Operation (CANDO) process developed by Yaniv Sherson, Craig Criddle, and Brian Cantwell at Stanford University is a new approach for using nitrogen compounds in wastewater to enhance the efficiency of energy generation during biogas combustion (Scherson et al., 2013). To transition this innovative idea from the laboratory to the field, the CANDO team raised funding by winning a business plan competition. They then partnered with members of ReNUWIt's Industrial Advisory Board to create a series of pilot plants in the San Francisco Bay area. The researchers and their Innovator utility partners are now moving toward the construction of a demonstration-scale plant. The CANDO process was the first technology out the gate because it was already under development when we started. Currently, there are about half a dozen other ReNUWIt technologies at earlier stages of development that are starting their trip along the S-curve. Through an active partnership with utilities and with the support of the National Science Foundation, we have created a path for technology diffusion that is reminiscent of those already existing in fields like information technology and medicine. For environmental engineers, these are still fresh and unfamiliar concepts. Therefore, we must constantly nurture the relationships if we want to stay on track. We hope this idea will spread to a new generation of students and water professionals who will adopt the innovation-driven mindset to trim years off of the technology diffusion process.

Unfortunately, the technology diffusion process is often considerably slower when it comes to many innovations essential to our goal of bringing about a revolution in urban water supply. In the case of the more radical ideas, our inability to change the institutional culture of utilities and regulatory authorities is often the biggest impediment. This is particularly evident when it comes to potable water reuse. As part of our research with Bernhard Truffer and Christian Binz of the Swiss Federal Institute of Aquatic Science and Technology (Eawag), we have developed firsthand knowledge of how some Innovators have solved these problems. Specifically, we have investigated the reasons why some potable water reuse projects fail to be accepted by their communities, while others are embraced and even celebrated. Much of our insight into successful projects is drawn from the Orange County Water District in Southern California, where leaders of a renowned potable water reuse project have learned that successful community engagement requires more than a carefully worded web page or glossy brochure (Figure 6). Rather, the water district has found that the community accepted and embraced potable water reuse when the utility transformed itself by internalizing a proactive, transparent, and collaborative response to the management of a new technology (Binz, 2014).

Figure 6: Tasting recycled water at OCWDs Groundwater Replenishment system is important to the creation of legitimacy of a new water technology. Pictures courtesy of Christian Binz.

This approach has many similarities to the process of institutional reform that has accompanied other new and potentially risky technologies, such as air travel. The implication of this idea, which we refer to as the “creation of legitimacy,” is relevant to utilities contemplating investments in direct potable water reuse. Concentrating on the narrow task of creating public acceptance through sophisticated communication strategies (instead of undergoing the more involved process of institutional reform) poses risks to the success of new technologies both from the standpoint of community support and, perhaps, more importantly, from the perspective of creating institutions that better safeguard public health.

Technology diffusion is even more challenging for ideas that are potentially disruptive to the existing paradigm of centralized water management. Many researchers have come to recognize the potential benefits of employing distributed water and wastewater treatment technologies in lieu of further investments in centralized systems (The Johnson Foundation, 2014). Transitioning away from the traditional model of a few centralized water and wastewater treatment plants that serve an entire city by building a network of modular treatment plants has the potential to decrease the amount of energy used to move water through underground pipe networks. Such a network could also increase the resiliency of a water system (by reducing the frequency of interruptions in service) and flexibility of the system (by giving it a means of expanding or contracting in a modular fashion as the city grows or shrinks). Much of the current motivation for developing distributed water systems is driven by problems related to wastewater disposal, such as the need to prevent combined sewer overflows or the failure of onsite treatment systems to protect water quality when septic leach fields can no longer handle all the wastes received. As a result of successes in these areas, utilities are beginning to embrace the creation of networks of satellite treatment plants and membrane bioreactor package plants that serve office buildings and residential developments (San Francisco Public Utilities Commission, 2014). I appreciate these efforts and look forward to the day when distributed treatment technologies are used as alternatives to expanding sewer systems, but I am not certain projects that employ expensive, building-scale wastewater treatment systems to provide recycled water for even more efficient toilets will have much impact on water supply.

Shortly after the ReNUWIt center was launched, we started a project with the hope it would lead to the creation of distributed treatment technologies that would have a big impact on urban water supply. First, we designed a point-of-entry treatment system capable of converting wastewater effluent or water collected from the roof of a building or the water table to a point where it could be consumed without sending it to a centralized drinking water treatment plant. Despite our enthusiasm for the potential impact of this technology, we encountered resistance from our industrial and scientific advisory boards because they believed that concerns over public health risks and the challenges associated with managing hundreds of remote treatment systems would discourage its adoption. Their critique encouraged us to analyze the market more carefully and talk with leading water service providers. Through these inquiries, we concluded that the idea was not yet ready to begin its trip along the technology diffusion S-curve. Recognizing that distributed potable water reuse will require institutional reforms and additional experience in the operation of modular treatment systems before it is ready to be seriously considered, we have channeled our efforts to problems with more mature markets, such as wellhead treatment for contaminated groundwater. As part of one of these projects, Tom Hennebel (a postdoctoral researcher in my group) and James Barazesh (one of my doctoral students) have developed an inexpensive means of using electrochemistry to produce hydrogen peroxide on demand as part of a point-of-entry advanced oxidation system. Our system consumes about as much energy per volume of water treated as the full-scale systems being used at facilities like the Orange County Water District's Groundwater Replenishment System. But, unlike the full-scale systems, it does not require a skilled operator or periodic resupply of chemical reagents. As a result, it is better suited for remote control. We are hopeful developing these devices for existing water treatment application will lead to the creation of knowledge that will ultimately hasten the rate of technology diffusion once the operators of water systems are ready to consider distributed potable water reuse.

Tapping into Ecosystem Services

Environmental scientists and engineers have long recognized the important role natural systems can play in urban water infrastructure. Rivers move water from place to place just as well as aqueducts and pipes do. Lakes and aquifers store water as well as or better than manmade reservoirs can. The passage of water through soil filters out contaminants. And wetlands serve both as a means of storing water and a way of improving water quality. If we are to make urban water more sustainable, we need to determine how to capitalize on the ecosystem services provided by these natural systems as we reinvent urban water infrastructure.

The recent history of the way in which wetlands have been used in urban water systems illustrates an evolution in thinking about how natural systems can be integrated into water infrastructure. After decades of abuse (in which wetlands were thought of as swamps that needed to be drained or were only useful as places where wastes could be dumped), environmental engineers began to put wetlands to work to improve water quality. During the 1960s and 1970s, treatment wetlands were constructed to remove nutrients from agricultural runoff or were employed as a final stage in the municipal wastewater treatment process. Many of these early applications embraced the principle of self-design, an idea derived from ecologists who knew the key to a properly functioning ecosystem is a diversity of habitat types (Odum and Odum, 2003). Employing this principle, wetland ecologists adopted construction methods that allowed natural processes to establish the plant species and flow paths of water in their systems. This approach led to the creation of attractive wetlands that provided excellent habitat and recreational opportunities, but often failed to achieve the full potential of natural systems to purify water.

Environmental engineers who were driven by a need to improve treatment efficiency built the next generation of wetlands (Jasper et al., 2013). In particular, people like Robert Kadlec showed that careful attention to hydraulics could minimize hydraulic short-circuiting and yield better contaminant removal. Other researchers, like my University of California Berkeley colleague Alex Horne, elucidated the role that plants play as substrates for denitrifying bacteria and how active management of the microbial community could make treatment wetlands more efficient and predictable. Through the efforts of these ecological engineers, wetlands became viable options for removing nitrate from wastewater effluent and for the treatment of stormwater and industrial waste.

Treatment wetlands now offer engineers an attractive alternative to conventional pollution control infrastructure. But I believe the greatest potential for employing these natural systems in water infrastructure will come from projects where wetlands do what engineered systems often cannot: treat extremely large volumes of water. My first experience with such a project occurred at the Prado Wetlands, located between the Inland Empire and Orange County in Southern California. This large wetland complex treats about half the base flow of the Santa Ana River (which, for much of the year, consists almost entirely of wastewater effluent from the upstream cities of Riverside, San Bernardino, and Ontario). In the early 1990s, the Orange County Water District started working with Alex Horne to improve the ability of the Prado Wetlands to remove nitrate, which at that time often exceeded the drinking water standard. By rebuilding the wetlands with denser vegetation and paying careful attention to system hydraulics, the water district was able to develop a cost-effective means of meeting the nitrate standard in their downstream drinking water supply.

When I first became interested in the development of approaches for removing steroid hormones from wastewater effluent, I immediately thought of the redesigned Prado Wetlands. In fact, one of my first doctoral students, James Gray, studied the fate of steroidal estrogens in the pilot-scale treatment cells where Alex Horne and his students had conducted their research on nitrate removal. To our surprise, the vegetated wetland cells that had been so effective at removing nitrate were not particularly good at removing hormones (Gray and Sedlak, 2005). Undeterred by the temporary setback, we set out to invent a new type of natural treatment system that could take advantage of the ability of sunlight to transform organic chemicals. The open-water treatment system that we eventually built had a geotextile liner that prevented rooted plants from growing. Our original idea was that exposure to sunlight would result in much more effective treatment of the chemicals so difficult to remove in wastewater treatment plants and vegetated wetlands. Our pilot-scale system in the Town of Discovery Bay, California, was indeed capable of taking advantage of the ability of sunlight to transform contaminants (Jasper and Sedlak, 2013). My colleague Kara Nelson and her students also demonstrated that exposure to sunlight in open water had the added benefit of inactivating waterborne pathogens. But the new ecological system we created provided us with a surprise: the algae and bacteria that grew in a fluffy mat on top of the geotextile liner were capable of breaking down many of the compounds not removed by exposure to sunlight (Jasper et al., 2014). The microbes also removed nitrate on a footprint smaller than that of most existing full-scale vegetated wetlands (Jasper et al., in press). Perhaps the wetland ecologists would have explained our accidental creation of a more effective treatment system for nitrate removal and compounds not amendable to photolysis by invoking the merits of having diverse habitats in natural systems. I know that the second generation ecological engineers appreciated the way in which the simple hydraulics of the open water system created nearly perfect plug-flow conditions.

Our open water treatment cells took the second step in the technology diffusion pathway during the winter of 2013 when our Innovator utility partners at the Orange County Water District built a demonstration-scale open water system in the Prado Wetlands (Figure 7). During the summer and fall of 2014, we demonstrated that the system removes trace organic compounds and nitrate just as well as the pilot-scale system. With some cosmetic surgery to improve the inlet structure and installation of a network of real-time water quality sensors, we are now moving into a phase in which we hope to optimize the performance of the system and collect data on long-term maintenance costs of the open water cells. Our next step will be to identify Early Adopters to help diffuse the technology and provide more experience in the operation of this new type of natural treatment system. Volunteers are welcome.

Wetlands are just one type of natural treatment system that will play a major role in the fourth generation of urban water systems. Although I do not have time to go into the details, similar developments are occurring with respect to natural systems for stormwater treatment (Grebel et al., 2013), engineering of the hyporheic zone of streams to enhance water quality (Lawrence et al., 2013), soil aquifer treatment (Regnery et al., 2013), and other processes that take advantage of our ability to control the activity of microbes in the subsurface.

Figure 7: The open water unit process cell at the Prado Wetlands. Photo courtesy of Scott Nygren, Orange County Water District.

Leveraging the Innovation Ecosystem

Being awarded the 2014 Clarke Prize is, indeed, quite a personal honor. But, as I have tried to illustrate in this lecture, all of my contributions to creating the fourth generation of urban water systems have been part of a team effort. Whether it is research conducted with my students and postdocs or through collaborations with colleagues at the ReNUWIt partner universities, members of our industrial advisory board or our partners in Switzerland, Australia, and Singapore, all the best ideas have come from the collective energy of the group. Furthermore, we would not appreciate the real problems that need to be solved, nor would we have been able to demonstrate the performance of our new technologies at a meaningful scale, without the support of our partner utilities. For me, this award has been given to the entire team, and I am only the person standing up here to accept it on their behalf because we would not all fit at the podium.

More importantly, recognition that the greatest progress is made by teams of people with different skills who share a common goal reinforces my belief in our collective ability to solve our most complex societal problems. My colleagues from the social sciences sometimes refer to the larger community of actors who hope to solve a common problem as an “innovation ecosystem.” With respect to the goal of creating the fourth generation of urban water systems, I am happy to be part of a dynamic and resourceful innovation ecosystem. In California, specifically, I have come to appreciate a spirit of ingenuity and willingness to question long-held assumptions about the way the world works. Much of this attitude can be attributed to a culture that enables water managers to lead, while simultaneously encouraging them to respect the values of the community and recognize the transformative power of technology.

If there is a lesson here for researchers and water professionals, it is that we all need to pay more attention to the innovation ecosystem. Toiling away in the laboratory to create a new technology or studying a treatment plant or wetland with the latest scientific tools is only a small part of the solution. To overcome the many problems facing our water systems, we need to understand their underlying causes, the processes through which change comes about, and the small roles that we all play in improving these remarkable and essential systems.

Acknowledgments

In addition to the efforts of the many colleagues mentioned in this lecture, I would like to acknowledge the efforts and support of several special people. Dick Luthy, who nominated me for this award, and Jörg Drewes, who recently left Colorado for the Technical University of Munich, were my partners in launching ReNUWIt – the adventure that helped me to fully appreciate the merits of interdisciplinary team research. My agent, Andy Ross, and the team at Yale University Press helped turn the idea of *Water 4.0* into an actual book. Kara Nelson, Lisa Alvarez-Cohen, and my colleagues at the Berkeley Water Center have been instrumental to my efforts to spread these ideas into our research and teaching. I thank my family, Meg, Jane, and Adam, for listening to early drafts of this lecture and patiently tolerating me as I collected stories for the book. I would also like to thank the Joan Irvine Smith and Athalie Richardson Clarke Foundation for making the Clarke Prize possible. Finally, I also want to acknowledge the early support of Ron Linsky, the founding Executive Director of NWRI. He believed in me at a time when I did not yet understand the complexity of urban water systems and stood by me when I brought up ideas that were not particularly popular.

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The 2014 Clarke Prize Honoree

DAVID L. SEDLAK, PH.D.

Civil and environmental engineer David L. Sedlak, Ph.D., is the twenty-first recipient of the NWRI Athalie Richardson Irvine Clarke Prize for excellence in water research. Dr. Sedlak is a professor and Co-Director of the Berkeley Water Center, and Deputy Director of the National Science Foundation's Engineering Research Center on Re-Inventing the Nation's Urban Water Infrastructure (ReNUWIt).

Dr. Sedlak was selected as the 2014 recipient because of his pioneering research on advancing the way water resources and urban water infrastructure are managed, including implementing water reuse and reducing the discharge of emerging contaminants (such as pharmaceuticals and personal care products). His work has served as the foundation for major policy and technical initiatives to reduce the effects of these contaminants and protect public health.

Recently, his research has focused on natural system processes, such as using engineered treatment wetlands to remove chemicals from wastewater-impacted waters. His research may change the way wetland treatment systems are enhanced and operated to eliminate micropollutants and improve water quality. As Deputy Director of ReNUWIt, a research center focused on advancing the way urban water is managed, he also has had the opportunity to lay the groundwork for improving water infrastructure, such as expanding water distribution systems, increasing planned water reuse, and reducing the amount of emerging contaminants released into the environment.

Another notable achievement is his newly published book, *Water 4.0: The Past, Present, and Future of The World's Most Vital Resource* (2014), which discusses the evolution of the urban water system over the last two millennia and his perspective on the technologies and advancements needed to remake the system in the near future.

Because of his considerable knowledge and expertise, Dr. Sedlak has been invited to serve on numerous boards and committees throughout the water industry. For instance, he serves on an NWRI Expert Panel to advise the California Department of Public Health on scientific, technical, and public health issues regarding the development of uniform criteria and regulations for advanced treatment water reuse in California.

The
ATHALIE RICHARDSON IRVINE
Clarke Prize
for Outstanding Achievement
in Water Science and Technology

The 2014 Clarke Prize Lecture, *Delivering the Fourth Water Revolution* by David L. Sedlak, Ph.D. of the University of California, Berkeley, was presented on Friday, November 7, 2014, at the Twenty-First Annual Clarke Prize Award Ceremony and Lecture, held at the Hyatt Regency Huntington Beach in Huntington Beach, California.

The National Water Research Institute (NWRI) of Fountain Valley, California, established the Clarke Prize in 1993 to recognize research accomplishments that solve real-world water problems and to highlight the importance of and need to continue funding this type of research. Dr. Sedlak was the twenty-first recipient of the prize, which includes a medallion and $50,000 award.

The Clarke Prize was named after NWRI's co-founder, the late Athalie Richardson Irvine Clarke, who was a dedicated advocate of the careful stewardship and development of our water resources. The Joan Irvine Smith and Athalie R. Clarke Foundation provide funding for this award.

More information about the Clarke Prize can be found at www.CLARKEPRIZE.com.

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