ENVIRONMENTAL ENGINEERING SCIENCE
Volume 30, Number 8, 2013
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DOI: 10.1089/ees.2012.0427

The Innovation Deficit in Urban Water: The Need for an Integrated Perspective on Institutions, Organizations, and Technology

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Received: October 24, 2012 Accepted in revised form: January 27, 2013

Abstract

Interaction between institutional change and technological change poses important constraints on transitions of urban water systems to a state that can meet future needs. Research on urban water and other technology-dependent systems provides insights that are valuable to technology researchers interested in assuring that their efforts will have an impact. In the context of research on institutional change, innovation is the development, application, diffusion, and utilization of new knowledge and technology. This definition is intentionally inclusive: technological innovation will play a key role in reinvention of urban water systems, but is only part of what is necessary. Innovation usually depends on context, such that major changes to infrastructure include not only the technological inventions that drive greater efficiencies and physical transformations of water treatment and delivery systems, but also the political, cultural, social, and economic factors that hinder and enable such changes. On the basis of past and present changes in urban water systems, institutional innovation will be of similar importance to technological innovation in urban water reinvention. To solve current urban water infrastructure challenges, technology-focused researchers need to recognize the intertwined nature of technologies and institutions and the social systems that control change.

Key words: infrastructure; innovation systems; policy: sustainability; urban water

Introduction

There is an innovation deficit in urban water management (Thomas and Ford, 2005; London Economics, 2009; Potts, 2009). Over the past three decades, the engineering community has begun to recognize the need to embrace a suite of new technologies to improve the performance and resiliency of urban water systems (Daigger, 2009, 2011). While compelling visions of reinvented water systems exist, progress has been slow in practice. In this review article, we explore one reason for slow progress: innovation is often conceived in narrow terms that emphasize technological change. A wide variety of institutional constraints, including strategies of incumbent industry actors, block transitions to urban water systems that can meet future needs (Truffer *et al.*, 2012). Considering scholarly research on sociotechnical innovation (*i.e.*, the interrelated change in technologies, firm strategies, and institutional structures) in water and related systems can help ensure that efforts to develop new technologies can be properly targeted to address potential barriers to adoption.

The challenge of innovation is sharpened by inertia in the water industry. There have been modern examples of large-scale, sweeping changes in urban water systems, but such instances have been rare. For example, in the United States, a dramatic increase in the use of improved wastewater treatment technology followed the passage of the Safe Drinking Water Act of 1974 (Dowd, 1984) and the Clean Water Act of 1977 (Andreen, 2003). In the water sector, such examples of rapid change are the exceptions that prove the rule: water management in general has tended to evolve slowly through modern history, particularly in the absence of dramatic regulatory pressure and public funding.

Forces including climate change, increasing urbanization, and the decay of existing infrastructure are already stressing the ability of urban water systems to meet their expectations for performance. Simultaneously, increasing awareness of the environmental impacts of water use is increasing pressure to do more with less. Responding to these stresses will require substantial technological and management changes for which major changes in regulations or funding for operation and maintenance may not be available.

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Novel concepts have been proposed to enable radical changes in urban water systems. In response to these forces, for example, advocates of "soft path" solutions propose a conceptual shift toward a focus on water-related services, rather than absolute quantity of water deliveries, and are conceptually compelling as redefinitions of the technological challenges faced by existing urban water systems (Gleick, 2003). Soft path solutions rely on the decoupling of the productivity and use of water from the amount of water used, and on changes in the technical and institutional methods used to manage water for human and environmental needs. Gleick (2003) suggests that a "transition is under way to a 'soft path' that complements centralized physical infrastructure with lower cost community-scale systems, decentralized and open decision-making, water markets and equitable pricing, application of efficient technology, and environmental protection." However, wholesale soft path solutions have been slow to manifest in practice (Brooks and Holtz, 2009), and arguably most or all of the soft path elements remain the exception rather than the new norm. Consideration of water institutions and the way that they respond to innovation helps explain the challenge of implementing soft path solutions.

Two concepts are crucial to the development of a deeper understanding of the ways in which change can come to urban water systems: *innovation* and *institutions*. *Innovation* can be defined generally as the development, application, diffusion, and utilization of new knowledge (Carlsson and Stankiewicz, 1991; Hekkert *et al.*, 2007). In urban water systems, innovation takes several key forms, including (1) new technologies (*e.g.*, desalination, energy recovery from wastewater); (2) new approaches to management (*e.g.*, regional coordination, rate structures, new business models); and (3) techniques that increase the efficiency of existing systems (*e.g.*, sensors and controls, application of understanding from more precise models).

Institutions can be broadly defined as the rules, norms, and practices that govern decision-making. This definition can include formal institutions, such as regulations and laws, but also acknowledges the multiplicity of factors that shape water systems, such as behavior and cultural factors (Scott, 2001). Thus, water quality regulations, which are designed to protect public health and the environment, career incentives that reward conservative choices within a water utility, and trends toward increasing environmental awareness are all examples of institutional factors that can influence whether a particular technology or practice is implemented. Most importantly, these factors can often outweigh analytical metrics, such as physical or financial efficiency, in actual decision-making. Even where technology with demonstrated potential for improving urban water management is available, institutions may stand in the way of technological diffusion and utilization. *Organizations* are collectively oriented groups that pursue goals linked to an external environment, and are intimately related to institutions.

Institutional and technological aspects of water systems have co-evolved in areas where water stress is the dominant concern to create challenges and opportunities for innovation that merit a distinct analysis. In this article, we focus on examples from water-stressed regions, recognizing that the lessons learned may inform other water management situations. The overarching goals of this review are to (1) characterize literature on innovation and illustrate the degree to which both technological and management innovations are nested within broader institutional context, and (2) present selected examples that highlight the importance of institutions as key hindrances (and potential drivers) of innovation in urban water systems. The importance of the former lies in the insights that emerge from formal conceptualization of innovation systems. The importance of the latter lies in the possibilities for institutional modification and design to increase innovation.

Discussion

Defining and characterizing innovation

The articles in this special issue of *Environmental Engineering Science*, and the field of environmental engineering in general, rightly focus on technological aspects of innovation. Such *hardware technology systems* comprise the material core of urban water services provision, such as sewers, toilets, and water treatment facilities. In contrast, *innovation systems* focus on different, but equally important aspects of innovation, namely, the actors, networks, and institutions that develop new products and technologies. The distinction between the two and the resulting analysis of the importance of context for technological innovation underlie a key concept: technological inventions are necessary, but not sufficient, for innovation, and the success of each is strongly influenced by context.

Invention and *innovation* are related but different (Lemelson-MIT Program, 2004). Invention refers to the process of devising something useful that was not previously known or existing. Innovations provide creative drivers of change in markets and society (Schumpeter, 1947). Innovation includes the products of invention plus their commercialization and introduction into markets and practice. So, while viable polymeric membranes were invented by 1963 (Loeb and Sourirajan, 1963; Lee *et al.*, 2011), they did not become an innovation until the 1990s, when the first large-scale desalination plants began to be built. This example illustrates the distinction between invention and innovation, but also suggests that defining, measuring, tracking, and characterizing innovation can be a long-term process.

Making even coarse comparisons of the importance of different innovations can be challenging. Various classification schemes for innovation have been proposed, but one often-used distinction is made between radical innovation and incremental innovation. Radical innovations can represent "clear departures from existing practice" as opposed to "minor improvements or simple adjustments in current technology" (Dewar and Dutton, 1986). In some cases, the distinction can be made by subjective perception (Dewar and Dutton, 1986), but even extreme examples can present problems due to the existence of multiple simultaneously relevant continuums for most products, such as price, performance, potential for substitution, or functional elements along a value chain (Markard and Truffer, 2006). For example, membrane bioreactors are radical technology in the sense of relying on fundamentally different physical and chemical principles from the filtration systems they can replace (Melin *et al.*, 2006). However, in practice, membrane bioreactors could be considered incremental if retrofitted into existing treatment plants to meet requirements for more effective filtration (Ahn *et al.*, 1999).

A given technology can move in a trajectory from radical to incremental over time. For example, desalination was initially a radical invention as it opened possibilities for entirely new sources of drinking water. Over the past decades, with its increasing acceptance as a potential part of water supply portfolios, desalination has benefitted from incremental technical improvements, to the point where it is a mature and commercially viable technology (Elimelech and Phillip, 2011). Even in the absence of major technological shifts, most water systems are not static, as incremental change comes from production engineers, technicians, and others involved in day-to-day operation. Radical and incremental changes are each important to innovation, and cumulatively both have substantial roles in the evolution of technology over time (Freeman, 1994).

Empirical analyses of technological innovation on the scale of market sectors, such as agriculture (Griliches, 1960; Sunding and Zilberman, 2001) or industry (Fisher and Pry, 1971), suggest that diffusion of new technologies into widespread use follows a predictable conceptual pattern.[1] In a classic technology diffusion framework (Rogers, 1962) (Fig. 1), initial adoption happens slowly as early adopters risk unproven reliability for the promise of novel benefits. Later, the rate of adoption increases as solutions to initial issues arise and acceptance is gained among early and late majority adopters. The rate of adoption then tapers as the sector reaches saturation.

Note that in water resources, both inventors of new technologies and the utilities that adopt them could be considered innovators. That is, adopting a new technology can be an innovative act in itself, as it is a key enabler of diffusion.

Although determining appropriate indicators for assessment of innovation is not always straightforward, diffusion has been measured using total installed capacity, market share, or proxies such as patents, bibliometric indicators, or revealed preferences (Markard and Truffer, 2008). For example, global desalination capacity has grown exponentially since the 1960s (Fig. 2). As technology improves and becomes more energy-efficient and cost-effective, desalination capacity is projected to double over the period from 2008 to 2016 (The Economist, 2008). From the perspective of market share, existing desalination plants in operation account for only 0.5% total global water use as of 2008. However, such metrics are sensitive to how a market is defined. If the market for desalination were segmented further, such as geographically into coastal areas or those with ready sources of brackish groundwater, or by sector, such as for industries requiring high-quality water, such metrics might appear different.

The impact of an innovation depends heavily on how much it disrupts existing modes of operation. The core question is whether established capabilities in a firm are suited to support a technological novelty or whether entirely new capabilities and routines will have to be built up. Disruptiveness can be independent from technological advancement. For example, Christensen (1997) drew a distinction between *sustaining* and *disrupting* innovations, using a case study of the computer disk drive industry. Sustaining innovations continue existing trajectories of product development. For disk drives, sustaining innovations refined performance within an existing format. Disruptive innovations, in contrast, generate new standards and trajectories for performance, perhaps adding additional metrics, enabling new and different uses and creating new markets. Perhaps surprisingly, in the case study of the disk drive industry, disruptive technologies were actually minor technological advances that initially generated quantitatively inferior performance on accepted metrics such as total storage capacity. The key to their disruptive nature was that in each case they enabled new markets and ways of using the products, such as when they reduced in size to enable the development of desktop or laptop computers. Established companies were aggressive and innovative in developing technological advances. However, they did so within existing frameworks, such as mainframe or microcomputer manufacturers. Entrant companies did not contribute to cutting edge engineering. Rather their success as disruptive innovators was based on developing new paradigms for use of disk drives—creating new markets that eventually developed to take over incumbent mainframe and microcomputer business. A potential lesson here for urban water innovators is that entry points for innovation may be found not only through technological refinements of process efficiencies, but also through conceptual disruption of established ways of operating. For example, community or building-scale water and wastewater treatment many create opportunities for new entities, such as private water service providers, to operate under different business models from that of centralized utilities. Similarly, disruptive institutional innovations have begun to shift centralized decision-making through more transparent decision-making and the incorporation of stakeholders in collaborative processes.

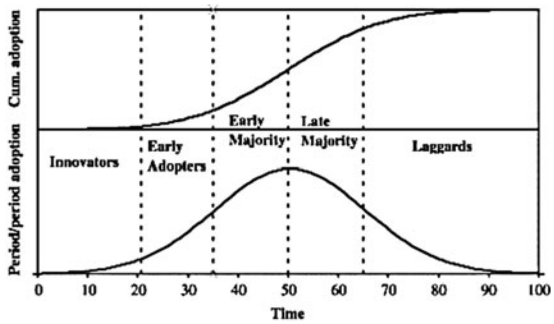

FIG. 1. Stylized diffusion curves. (Reproduced with permission from Meade and Islam, 2006.)

An additional distinction can be made between incremental innovation for specific technologies as described above, and broader transitions to new states. Transition management deals with co-evolution between technological and institutional aspects of new sociotechnical regimes, and often spans time frames of several decades. Both are important for urban water management: incremental technological change is ongoing, but the durable nature of water infrastructure makes other institutional timeframes such as electoral and business cycles less applicable to state changes as broad as those envisioned for holistic reinvention of urban water systems.

To address the problem of a large scale sectoral transformation toward more sustainable future service provision, a whole set of radical technological innovations would have to take place causing disruptive innovations within an industry,

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[1] The simple logistic model described here has been extended in various directions, and diffusion models in general have varying degrees of success in empirical prediction (Meade and Islam, 2006), but the conceptual utility remains powerful (Moore, 2002).

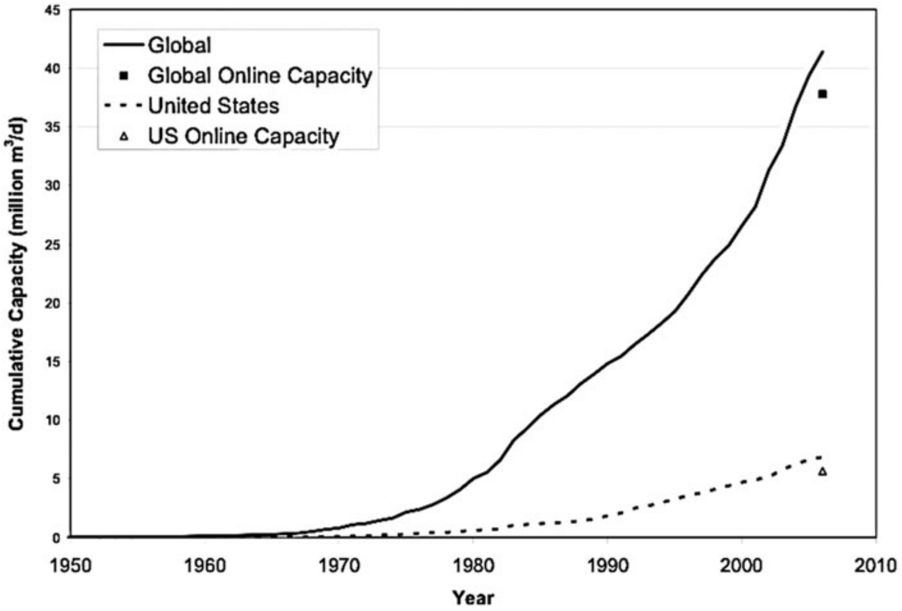

FIG. 2. Cumulative capacity of installed desalination plants. The capacity of desalination plants that are online or presumed online in 2006 is shown as point data. *Source:* NRC (2008).

or even the entry of new industry actors (Tushman and Anderson, 1986) and associated new institutional frameworks. Large-scale, long-term transformation processes (for example, a shift toward an electricity system based largely on renewables) have been analyzed in the recent literature on sustainability transitions (Smith *et al.*, 2010; Van Den Bergh *et al.*, 2011; Markard *et al.*, 2012). One core element of transitions research considers the emergence of new industry structures that provide new products and services, becoming important drivers of the transition processes.

The innovation system literature emphasizes the interplay of different actors (firms, but also research institutes, regulators, associations and other intermediaries, civil society and end users) in diverse network structures (Markard and Truffer, 2008), which is useful for looking both at management of incremental innovation or sectoral transitions. In particular, the approach of *technological innovation systems* enables the identification of necessary conditions for radical innovations to succeed by overcoming barriers stemming from deficiencies in firm capabilities or mismatch in institutional structures between new technologies and incumbent systems (Jacobsson and Bergek, 2011). A technological innovation system can be thought of as "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure […] and involved in the generation, diffusion, and utilization of technology" (Carlsson and Stankiewicz, 1991). It is important to note that the emphasis here is on the actors, networks, and institutions that enable innovation, and not on the nuts and bolts of the hardware itself.[2] This emphasis reflects the importance of these nontechnical elements in the generation of innovation.

In urban water management, transitions research has drawn from innovation studies in analyzing historical transitions (Geels, 2005, 2006) as well as potential pathways toward water sensitive urban design (Brown *et al.*, 2011; Van De Meene *et al.*, 2011). Further, emerging technological innovation systems have been viewed through this lens, include onsite treatment in urban water management (Hegger *et al.*, 2007; Truffer *et al.*, 2012) and the possibility for leapfrogging to new system designs in emerging economies like China (Binz *et al.*, 2012).

Drivers of innovation

In coming decades, increasing stresses on urban systems will influence supply, demand, quality, cost, environmental, economic, and distributive elements of urban water (Gleick, 1993; Zimmerman *et al.*, 2008). The perennial challenges of climate variability will grow in importance for urban water as it is exacerbated by climate change. Historical expectations for surface water (Bates *et al.*, 2008; Kundzewicz *et al.*, 2008) and groundwater (Döll, 2009; Earman and Dettinger, 2011; Treidel *et al.*, 2011) supplies and flooding (Ntelekos *et al.*, 2010) can no longer be relied upon, leading to unanswered questions about future water and stormwater management (Milly *et al.*, 2008; Brown, 2010). Population growth and urbanization trends promise to increase the spatial extent of urban areas as well as their population density (Martine, 2007; Seto *et al.*, 2011), putting pressure on sources of water supply (Vörösmarty *et al.*, 2000; Sun *et al.*, 2008). The energy and greenhouse gas intensity of water and wastewater systems (EPRI, 2002; Klein *et al.*, 2005; Hall *et al.*, 2011) will need to be addressed with both new technologies and decision-making strategies as costs and regulations for emissions increase. Emerging contaminants, such as endocrine disruptors and pharmaceuticals and personal care products, threaten ecological and public health and promise to complicate water treatment (Kolpin *et al.*, 2002; Snyder *et al.*, 2003). Urban water systems are linked to deteriorating environmental quality within cities as well as upstream and downstream of them (Grimm *et al.*, 2008). Increasing societal recognition of the benefits of aquatic ecosystem services (Brauman *et al.*, 2007) puts corresponding pressure for restoring and reducing impacts to aquatic systems. The inexorable deterioration of even long-lived

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[2] The concept of interrelated technological components and that can span over several spatial scales in urban water management is addressed in a distinct literature on *large technical systems* (Hughes, 1989). The overlap in verbiage is unfortunate, but the conceptual distinction is important.

infrastructure suggests impending challenges even absent these stressors (American Society of Civil Engineers [ASCE], 2011). On top of all of these pressures, funding investment and maintenance in urban water systems is increasingly challenged with tightening budgets at all governmental levels (OECD, 2006, 2007; UNESCO/World Water Assessment Program, 2006; Urban Land Institute and Ernst and Young, 2007), and recurring debates about organizational reform in utilities complicate efforts for future planning.

The primary unifying theme of this nonexhaustive list is that of change and uncertainty—the only thing we can say for sure about the future of urban water is that it will look quite different from the past. Water crises are increasingly viewed by the business (World Economic Forum, 2012) and national security (Clapper, 2012) communities as among the greatest social risks of coming years, and urban water systems will be called on to ameliorate these risks.

Existing practices will need to change in ways not yet anticipated, and simply doing more of the same will not be economically efficient or societally acceptable. New ways of doing things—innovation—will be critical to the future of urban water systems.

Can technology promise solutions commensurate to the impending stresses on urban water systems? To some extent it can. Much theoretical room remains for futuristic advances in the efficiency of water-related technologies (Shannon *et al.*, 2008; Elimelech and Phillip, 2011). However, paradigm-shifting concepts promise innovation in all aspects of the urban water cycle (Daigger, 2011). Green infrastructure, distributed water reuse, recovery of energy and nutrients from wastewater (Guest *et al.*, 2009), potable water reuse (NRC, 2012), source separation of wastewater components (Larsen *et al.*, 2009), and other concepts all have potential to change the physical structure and financial outlook for urban water systems. Many of these technologies are the subject of intensive research (www.urbanwatererc.com), and some are reviewed in companion articles in this issue.

However, in spite of much promise, radical technological advances have not been implemented at large scale. While technological inventions are necessary to the future of urban water systems, they are not in and of themselves sufficient. Rather, the potential for innovation depends on a blend of technological and institutional factors that operate in concert.

Processes behind technological innovation

Broad observations of trends in technology change have led to research on *how* and *why* innovation happens. Scholarship on innovation has moved to look inside the "black box" of technology development (Freeman, 1994), paying increased attention to the processes of innovation.

Whether innovation is driven more by the supply of new technological options ("technology-push") or by market demand for solutions to known problems ("demand-pull") has not been explored in depth for water resources, although the question has been explored with some nuance in areas such as renewable energy (Taylor, 2008). Freeman (1994) suggests that the answer depends in part on the stage and type of innovation. For example, there is unlikely to be preexisting market demand for a given radical, early-stage innovation. Some innovators understand this intuitively, as illustrated by the way Steve Jobs eschewed market research while creating a new market category with the Apple iPad, saying, "It's not the consumers' job to know what they want" (Markoff, 2011). Conversely, demand for improvement of existing technologies is more likely to spur incremental innovations. The development of desalination illustrates both points. The initial commercialization of cellulose acetate membranes can be classified as a technology push. Since then, innovations in water permeability and salt rejection of reverse osmosis membranes (Fig. 3) have resulted in gradual improvements in the efficiency of desalination technology (Lee *et al.*, 2011). Over time, a demand for better performing membranes has led to a pull that motivates efforts to increase economic viability of desalination plants.

Distinguishing between technology-push and demand-pull models of innovation may often be a false choice over the lifetime of a technology. Such formulations imply linear models (Freeman, 1994) with smooth, one-way flows of information from research to development to product marketing. Such linear models have been roundly criticized not only as simplistic, but as simply wrong, and replaced by more sophisticated views of innovation process. A progenitor of current models, the "chain linked model" (Kline and Rosenberg, 1986) serves to illustrate the paradigmatic shift. It presents innovation as not a single process driven by scientific discovery, but a chain of innovation activities including market identification, detailed design and testing, production, and so forth. Each element of the chain is connected to the others via feedback loops, and also directly or indirectly to research and knowledge production. The key point emerging from the chain linked model is that a view of innovation that places science as its central driving force is not only simplistic, but potentially misleading. Research is crucial to innovation, but exists only within a larger set of processes.

"Hard" functions (Galli and Teubal, 1997), such as basic and applied research, development and testing of prototypes and products, and the provision of technical services, all of which are core elements of engineering training and practice, are directly involved in development of new technology. However, while technological advances are central to innovation, innovation also includes "soft" functions such as information exchange, policies, financial methods, management strategies, or ways of doing business.[3] Such functions provide essential complements to the "hard" ones more directly related to technology development. For example, Gebauer *et al.* (2012) detail how business networks may need to change dramatically to act on new business opportunities opened by the changing European wastewater industry. They argue that successful development and deployment of novel technical solutions usually cannot be the provenance of a single (technologically focused) firm. Rather, networks with overlapping expertise are required. Understanding how the broad range of innovation activities do, or should, work together for reinvention of urban water systems remains an unanswered challenge.

Innovation in context

Scholarship on *innovation studies* (Fagerberg and Verspagen, 2009) takes as its starting point the premise that

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[3] Note that this use of soft functions is different from the concept of soft path development described above.

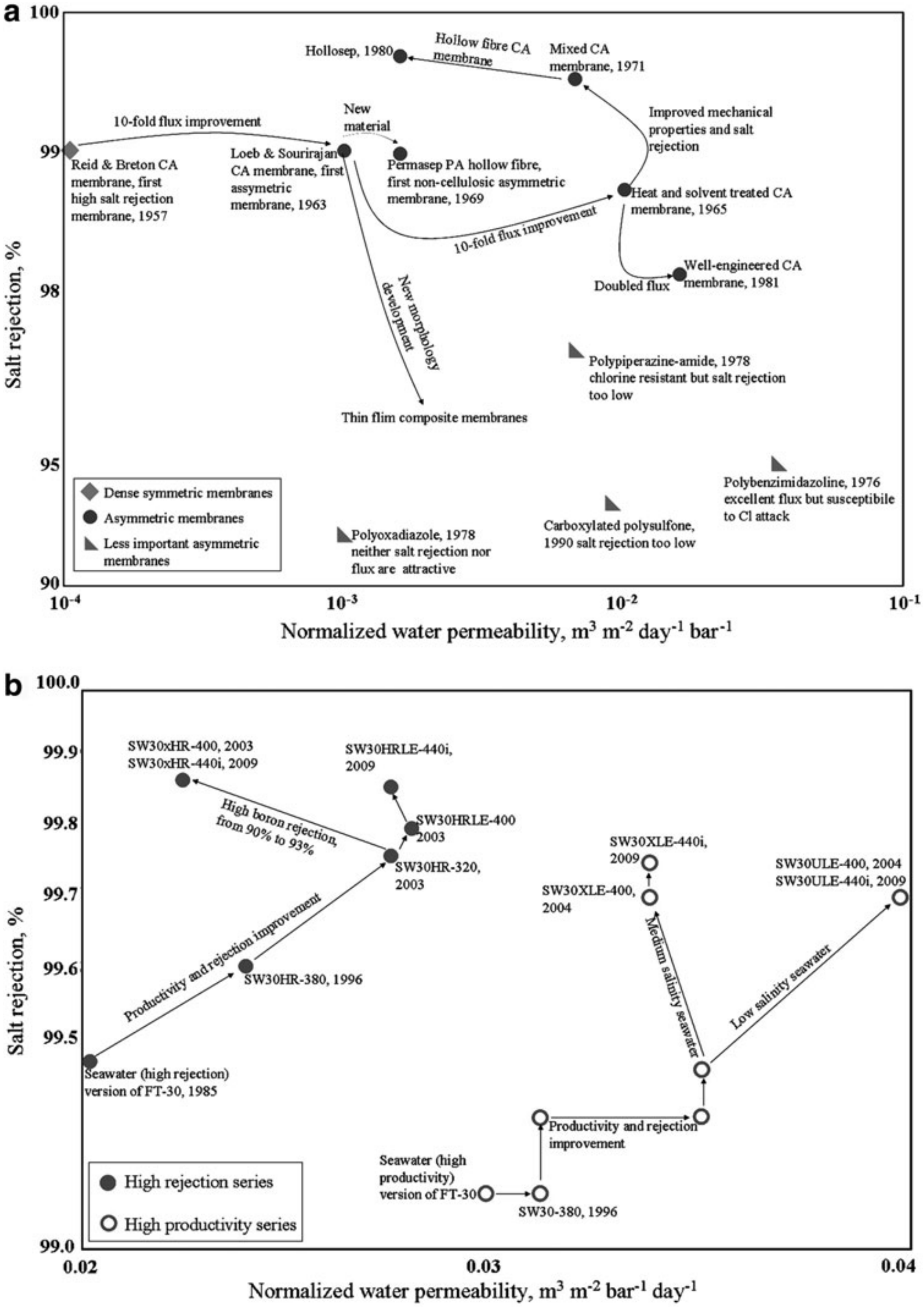

FIG. 3. Incremental innovation in asymmetric reverse osmosis membrane. **(a)** Early developments and **(b)** example of recent increases in efficiency, in Dow membranes. (Reproduced with permission from Lee *et al.,* 2011.)

innovation is determined not only within a given firm or research group, but also by the context in which they are embedded. Myriad elements, including but not limited to technical ones, that influence the potential for successful innovation. A novel technological development alone is not sufficient to disrupt an existing technological regime, nor can it be developed in isolation from the institutional and social context in which its entrepreneurial researchers operate. Innovation results from complex interactions among people and organizations. For example, a collaborative group of firms may combine their offerings into an interrelated package, forming an *innovation ecosystem* (Adner, 2006) that can offer otherwise untenable products, but creating a new set of risks for the now interdependent enterprises. An example would be separate firms making hardware and software for mobile phones. Factors such as this can complicate understanding or forecasting of technological change. They can also lead to insights about what a specific invention needs to consider in order to become a successful innovation.

Technological merits alone cannot explain the ultimate fate of new technologies. A superior but unfamiliar technology needs to overcome the advantages of the ecosystem that develops around an incumbent technology. Existing technologies benefit from knowledge accumulated by users, capital outlays and infrastructure, available skills, and other aspects that collectively support an inertial dominance (Kemp, 1994).

For example, in considering whether to change from sand filtration to membrane filtration, a water system operator could not simply evaluate the decreased risk to public health and space efficiency. In addition, they would need to weigh the potential costs of retraining its workforce and developing a new supply chain. Often, broader effects on interconnected systems would have to be evaluated. For example, while the "theoretical potential for desalination is virtually unlimited," economic, social, environmental, and political complications "are far more important than technological desalination process constraints in limiting the potential for desalination to help meet anticipated water supply needs" (NRC, 2008). Similarly, water organizations have been slow to adopt promising emerging approaches such as in-line energy recovery (Klein *et al.*, 2005; House, 2010) or leak detection and reduction (ECONorthwest, 2011) that promise to plug into existing systems, reducing existing inefficiencies to deliver potentially rapid return on investment. The explanation may stem in part from an inability of the new technology to overcome the advantages of existing technology, or from institutional context, such as lack of familiarity, embedded best management practices, or risk aversion among decision-makers faced with unproven options.

Inertia and path dependency are particularly relevant for water systems. Infrastructure built around the centralized system paradigm can have long design lives, especially compared to other technologies, such as computers, where generation times are orders of magnitude smaller (Christensen, 1997; Christensen *et al.*, 1998). Because of large sunk costs and challenges associated with integrating new technologies into existing systems, wholesale disruptive changes will continue to be rare within established urban cores. Alternatively, urban developments where water efficiency is a design priority may be better venues for radical new approaches. New developments focused on shifting from linear water systems to closed-loop configurations have resulted in 50%–80% reductions in potable water consumption and 70%–100% reductions in discharges to local waterways compared to other regional communities (Apostolidis *et al.*, 2011; Apostolidis, 2012). Such achievements within legacy systems would require dramatic measures, but integrated design can be constructed at similar cost to traditional systems in new developments (Apostolidis *et al.*, 2011). This does not imply that such achievements are easy in new developments. On the contrary, numerous institutional, regulatory, and technical hurdles abound.

One lens through which to view innovation systems is that of evolutionary theory and evolutionary economics. McKelvey (1997, cited in Hekkert *et al.*, 2007) describes the net processes of innovation systems as analogous to biological systems, where necessary elements of evolution include (1) retaining and transmitting information; (2) generation of novelty leading to diversity; and (3) selection among alternatives. Information sharing, policymaking, design and enforcement of patent laws and other related standards, and professional coordination (Galli and Teubal, 1997) are critical to the information functions. An example would be scientific and professional conferences geared toward highlighting new available technology. Generation of technological diversity happens through research and development, manufacturing, and also by end-use. In the context of urban water infrastructure, consulting engineers will often serve the role of information brokers who add value by understanding and presenting a range of technological options that may fit a given utility's needs. Selection among alternatives can happen through the search process where customers look for solutions to existing issues, through allocation of resources for research and development, through exchange of information and vision, and through external facilitation of new market formation.

Other key functions of innovation systems have been enumerated by Hekkert *et al.* (2007). *Entrepreneurial activities* help develop new knowledge, networks, and markets into business opportunities. Presently, support for water entrepreneurs is limited. Water technology entrepreneurs have some access to attention and funding from a small number of environmentally focused venture capital firms, but the capital deployed under the cleantech/greentech umbrella for water resources pales in comparison to that for renewable energy. In 2011, venture capital investments in water technologies totaled about $224 million in 40 deals (Kho, 2012), or about 5% of the $4.3 billion invested in 323 deals in the cleantech sector overall (PwC/NVCA, 2012). Awards for innovative water products (imagineh2o.org, artemistop50.com) provide avenues for increasing entrepreneurial visibility, but there is much room for growth. In part, the lack of entrepreneurial activity is tied to limitations on direct profit potential from water. These include its provision by public agencies rather than for-profit entities, limitations on water markets, and the expense of and limited scope of facilities for bulk storage and conveyance of water that limit the geographic potential of water markets.

Knowledge development can include "learning by doing" and "learning by searching." For example, East Bay Municipal Utilities District (EBMUD) has attempted both approaches to attaining its goal of an energy-positive wastewater treatment facility (Hake *et al.*, 2006). Motivated by California's energy crisis in 2000–2001 as well as the adoption of a Renewable Portfolio Standard by the state, but lacking an accepted set of best management practices for a new goal, EBMUD has had to mix engineering analysis with experimentation to further its efforts in innovative energy management.

Knowledge diffusion often occurs through social and business networks, through learning by interacting or learning by using. Trade organizations such as International Water Association provide forums where industry representatives and public agency representatives can engage through conferences to build networks of knowledge and practice. Regional forums, or groups for those with more specialized needs or specific goals provide more targeted opportunities for knowledge diffusion.

Guidance of search refers to defining and increasing the visibility of demands for new functions among users. In a pull model, innovation producers recognize the need to understand market demands. Goal setting by policymakers is one mechanism for such signaling. For example, recently passed California legislation sends clear signals by requiring 20% reduction in urban water use from year 2000 levels by the year 2020 (State Water Resources Control Board, 2008, 2009). Analysis and communication that incorporates stakeholders can also clarify market demands. Such *boundary work* (Guston, 2001; Cash *et al.*, 2003) recognizes the gaps between producers of and potential consumers of knowledge. Empirical and theoretical studies have shown that the use of knowledge in decision-making in policy contexts is made more effective through early, active, and ongoing collaboration between both groups, and such concepts likely transfer to innovation systems as well. Boundary work can be carried out by boundary organizations that have a defined mission to serve as a bridge between different sectors, and may be most effective when multiple stakeholders are involved in ongoing processes (Jacobs *et al.*, 2010). Research foundations can also serve a boundary role as part of their mission. For example, the Water Research Foundation, the Water Environment Research Federation, and the Water Reuse Foundation not only fund primary research, but also conduct outreach to bridge technology development and science communication. The role of boundary organizations and boundary work is implicit in innovation studies, but new research formally joining the two areas of inquiry could yield useful insights (Taylor, 2008).

The need for *market formation* recognizes that incubation of potentially disruptive new technologies in protected spaces or niche markets can enable them to mature to a point where they have a greater chance of being competitive. In niche markets, actors are willing to accept such teething problems as higher costs and will invest in improvements in a new technology, in order to work toward specific functionalities (Markard and Truffer, 2008). Protected spaces can be developed through policies such as tax regimes and minimal consumption levels. This model has helped enable development of increasingly efficient and cost-competitive renewable energy sources. For example, Germany has become a market leader in photovoltaics over the past two decades (Dewald and Truffer, 2012). The proximate enablers were subsidies in the form of a feed-in tariff providing a protected space. However, the ultimate origin of support for these subsidies can be traced to an evolving range of actors, starting with local pro-solar initiatives and moving across a range including local and state governments and corporations, illustrating the importance of a broad range of actors in a technical innovation system. Closely related to this example, *mobilization of resources* through industry or government funded R&D programs can enable high-risk, early stage actions that would be difficult to fund through market-based means alone.

Creation of legitimacy is also necessary to put a new technology on a policy agenda and break down resistance to disruptive change. One could argue that potable water reuse in the United States appears to be in the midst of a process of legitimacy creation, as technical understanding of its performance grows, and political and social resistance breaks down as nonpotable reuse and potable reuse projects operate for extended periods without adverse health effects (NRC, 2012). Ultimately, all of these functions described by Hekkert *et al.* (2007) are most effective when part of an iterative process.

The scholarship discussed above helps peel away layers of complexity for better conceptual understanding of the ways in which context affects innovation. Translation of such insights into predictive models of innovation systems is in its infancy, and much room remains for further research toward this goal. Arguably, innovation is inherently unpredictable, but attempts have been made to quantitatively model diffusion of new water technologies within multifaceted innovation systems. For example, Kotz and Hiessl (2005) use Agent Based Modeling (ABM) to represent choices and decisions by water suppliers and water consumers within an urban water management system, although with coarsely parameterized and incomplete implementation. Their results show how ABM can reflect feedbacks between agents operating on different timescales and with different incentives and how they complicate system-wide technology adoption, such as where conservation actions by households can impact the economics of sewer system operation. Detailed, citywide ABM representation also holds promise as an integrator of multiple modeling approaches. Galán *et al.* (2009) model technologies for household water conservation, showing that urban population dynamics and other sociogeographic effects influence technology spread in a way that may not be apparent in aggregate modeling. Such efforts highlight the different motivations, different decision frames, and different timescales relevant to water providers, sewerage providers, and water consumers, and how each can affect decisions in a dynamic context. Although ABM in particular has yet to fulfill its promise (Bankes 2002), as the field of innovation studies matures, descriptive and predictive quantification of innovation trajectories will be an important area for further work.

Technological, behavioral, and institutional changes need to be explicitly situated within existing infrastructures and institutions. Recognizing innovation as the product of a multitude of influences and dissecting the different elements that influence innovation promises to help reveal bottlenecks and inform decision-making.

Institutional influences

Institutional context can be a key hindrance or enabler for innovation in urban water systems. Defining *institutions* broadly as the rules, norms, and practices that govern decision-making enables inclusion of the multiplicity of factors that shape water systems. Such factors include public health regulations and laws, but also economic, social, cultural, and other nontechnical aspects. Even where technology with demonstrated potential for improving urban water systems is available, institutional challenges may prove to be the greatest hurdles to cross. Learning how institutional elements enable innovation in urban water will be a key enabler of transforming technological inventions into technological innovations.

In many cases institutions hinder possibilities for innovation, as Roy *et al.* (2008) discuss in the context of sustainable stormwater management. Uncertainties in performance and cost relate provide challenges (Roy *et al.*, 2008). This can be exacerbated by risk aversion and resistance of change by decision-makers who may prefer proven technologies to a potentially better one. Insufficient engineering standards and guidelines (Roy *et al.*, 2008) may apply particularly to radical innovations. Fragmented responsibilities, lack of institutional capacity, and lack of legislative mandate (Roy *et al.*, 2008) all provide challenges for decision-making in water systems that cross existing jurisdictions, and institutional design that can address such challenges presents opportunities for new research. Lack of funding and effective market incentives exacerbate water's dual status as a public and private good (Hanemann, 2006). With the possible exception of performance uncertainties, these are not technical impediments *per se*, but rather institutional challenges that affect the potential for implementation of existing technologies.

In the face of such challenges, there may be the potential to adapt institutions in support of innovation. Edquist and Johnson (1997) suggest that institutions can function in three ways to foster innovation. First, institutions can serve to reduce uncertainty by providing information. Information provision can be required by laws, such as the U.S. National Environmental Protection Act reporting requirements. It can also function through informal means, such a networking among practitioners at industry conferences. Second, institutions can actively manage conflicts and foster cooperation, such as when stakeholder processes allow communities to engage with and develop more durable solutions that take multiple interests into account (Dominguez *et al.*, 2009). Third, institutions can provide incentives for innovation. For example, patent laws generally protect new intellectual property such that entrepreneurs can profit from taking risk on technology development. More specific drivers can be provided by targeted research funding to encourage development in desired areas. Such funding exists from sources including government programs and venture capitalists, but have typically been small for water technologies relative to other natural resources, with U.S. government and private sector investment in water technology lagging renewable energy funding by orders of magnitude in recent years (Moresco, 2009).

Finance, pricing, and innovation

Water systems are capital intensive, but access to capital required for investment in technology faces hurdles related to water's unique characteristics (Hanemann, 2006). Access to capital markets is influenced by agencies' status as public entities or heavily regulated private ones. Privatization of water utilities has yielded mixed results, and it is not clear to what extent market efficiency can be brought to bear without undue risks for consumers. The limited ability of public entities to take financial risks has lead to creative attempts in private sector financing of infrastructure projects. For example, Poseidon Resources' efforts to finance a desalination plant in San Diego represent an attempt to shift risk from the city to outside investors. The Poseidon group has proposed a plan to take on initial capital costs, betting that increases in the price of imported water over the 30-year project lifetime will result in profitable sales of desalinated water to the city (Wilson, 2010). However, the project remains controversial in part because of the lack of overall transparency as well as subsidies attained from other organizations. Thus, even before technological risks are realized in construction and operation, business risk arises from political factors unrelated to technology.

One challenge for water innovation is that costs for innovation and the accrual of benefits can be misaligned. The scale of water problems and solutions often does not coincide with the scale of relevant institutions. For example, distributed, modular methods for water reuse have different costs and benefits at the sub-system level than what aggregates at the whole-system level. In Germany, experience with building-scale water recycling has benefits from reduced water use at multiple scales, but unintended consequences of increased deterioration of pipes because of lower flows and greater concentrations of solids in the waste stream. Short-term infrastructure costs to municipalities thus need to be balanced with long-term public good benefits from decreased water withdrawals. Similarly, reductions in imported water, cost savings from lowering pumping costs, reductions in carbon intensity of water systems, and other benefits often accrue to the water provider in response to conservation, but may be hard to measure and credit (Venkatesh, 2012). Aligning incentives properly at different scales is an ongoing challenge for technocratic, deliberative, participatory, collaborative, and market-based methods.

Culture and governance of organizations

Organizations, including agencies that make and implement decisions about water resources, are particularly important for shaping urban water. Beyond their mandates, their design and culture can have profound effects on whether and how innovation results.

Legal control of water resources often forms a primary constraint on all elements of water management, including supply availability, treatment, and disposal needs. Historical development of water rights has in some areas become out of sync with economic and social priorities, as the latter evolve more quickly than the former (Doremus and Hanemann, 2008). Further, in places with static prioritization systems for water allocation, changing social values may result in misalignment between the best supply sources and the uses with the highest values to society (Sax, 2007). Since urban areas were often settled more recently than the agricultural areas from which their water may be sourced, low priority of use can influence the risk for urban water supply. Further tensions arise where environmental services from in-stream flows have become increasingly valued by society in areas where stream flow is by and large allocated to other uses. All of these factors set the stage and help define the degrees of freedom within which urban managers can make decisions.

The number of organizations with overlapping and fragmented responsibilities in the urban water sector, and the inconsistency in their jurisdictions and methods of decision-making make for complex governance structures (Adler, 2009). Urban water often lies within the domain of organizations at all levels of government, from federal to local. Fragmentation takes multiple forms, categorized by Adler (1995) as "(1) political fragmentation—the overlapping and conflicting division of responsibilities among multiple levels of government and agencies; (2) issue fragmentation—the artificial division of related water issues into separate programs (such as water quality and quantity, land and water use, and surface and groundwater); and (3) gaps in program design and implementation." Further, fragmentation results from spatial mismatch between watershed and political boundaries. Institutional fragmentation is one of the key drivers for the need for coordination and collaboration, which can affect the potential for change. For example, joint management of energy and water could potentially have net benefits for both sectors, financially and environmentally. However, regulatory mismatch between the two closely related sectors can shift a problem previously framed in technical terms into a regulatory challenge, as mechanisms do not exist for valuing costs and benefits across the two sectors and disparate spatial scales.

Organizational capacity and culture also play a role in ability to innovate, and risk aversion is a central facet. Water resource managers are often described as conservative and risk averse (O'Connor *et al.*, 2005; Rayner *et al.*, 2005; Lemos, 2008). It is important to emphasize that for many water managers, such risk aversion is entirely sensible and consistent with the context in which they operate. For example, in civil service, managers can be punished for failure, yet not rewarded for success. This is especially true when the cost of failure is measured in outbreaks of waterborne disease, sewage spills, and flooding of residential properties. Whereas responsibility for increases in efficiency in the corporate world can result in raises, corresponding success in meeting water quality regulations or avoiding supply shortfalls is expected, but where bonuses exist they are rarely substantial. Downside risk, or the risk of bad outcomes, drives conservatism in the public sector, where the negative outcomes are not offset by corresponding rewards for strong upside performance. Decisions involving new technologies will often fall in a particularly tricky category for risk-averse decision-makers because they combined high risk with low data availability. Thus, the reluctance among decision makers to take risks on unproven technologies is unsurprising, since the overall direction of large public works projects is determined by relatively few large and impactful decisions. Reluctance to adopt potable water reuse in spite of the scientific evidence that it can offer safe and cost-effective new supply (NRC, 2012) exemplifies how resistance to change can result from risk aversion. In the aggregate, risk aversion likely slows progress for the water industry as a whole. The role of incentives, organizational culture, and individual behavior in enforcing (or possibly reducing) risk-averse decision-making among water managers represents an opportunity for research.

Capacity for innovative decision-making may be related to the capacity to reflect on future options. Some inertia results from existing infrastructure systems with long design lifetimes, and the entrenched institutions that have evolved to support them. However, water utilities often have not invested in capacity to conduct strategic planning in house. When they explicitly or implicitly relegate strategic planning to consulting engineers, there is greater possibility of restricting the range of technological and organizational options considered (Dominguez *et al.*, 2009), potentially damping innovation by perpetuating established technologies and organizational structures.

Conclusion: How Can Technology and Institutions Interact to Encourage Innovation?

Given the technical and institutional challenges facing urban water, design of future urban water institutions needs to consider innovation. Doing so is nontrivial because of the nature of innovation, which is by definition impossible to predict. While institutional reforms will be critical to fostering future innovation in urban water, a successful, generalizable model has yet to emerge. However, several avenues present promising possibilities or avenues for further research.

From a technological perspective, the observations about risk and risk aversion discussed above may provide additional arguments for the merits of distributed systems. Distributed, modular systems provide the promise of cost-effective ways for new approaches to water and wastewater treatment, but as described above this alone may not be enough to support their adoption and diffusion. However, modular systems could potentially be recognized as a series of experiments, each of which carries less risk to a jurisdiction than a corresponding system-wide change. Development using technology portfolios could spur learning by doing, and pooling such portfolios among multiple agencies could amplify this effect through learning by sharing.

Regulatory changes, supported by data on public health risks and system performance, could favor such risk spreading and risk sharing, to increase the potential for decisions that reduce the magnitude of high-risk experiments. Removing barriers and increasing incentives for more modular systems could increase the effective speed of the technology life cycle, enabling competition and iterative solutions and creating technology portfolios within urban jurisdictions. Such observations might change the perception of investing in this kind of technology development are currently perceived as too expensive or risky. The key would lie in the recognition that individual large-scale risk-taking at is not necessarily prudent from the perspective of an individual decision maker, but increasing collective risk taking by the water industry as a whole has the potential to spur innovation, and thus should be encouraged (Potts, 2009).

Novel processes for decision support and decision-making hold promise. Building flexibility into decision-making through discursive approaches to planning including strategic planning (Dominguez *et al.*, 2009, 2011) and collaborative processes are increasingly cited as a way to bring additional viewpoints and generate more durable solutions (Innes and Booher, 2010). Increasing the capacity for strategic planning in order to improve consideration of multiple concerns, acknowledging that such capacity will take different forms depending on specific organizational needs and goals. Information transfer, in multiple directions, needs to be facilitated. The role of boundary organizations to help increase linkages between producers of knowledge and its potential consumers is expanding in some areas of water management, and we anticipate an acceleration of this concept in practice in coming years.

Frameworks have been proposed that explicitly incorporate multiple aspects of the urban water cycle. They include the soft path concept (Gleick, 2003), Integrated Water Resources Management (Biswas, 2004), and anticipatory governance (Quay, 2010). In locations where water is clearly perceived as a priority, motivating such changes in thinking about water though novel planning processes may prove productive.

In some cases, indirect pathways have the potential to motivate for new ways of addressing water. Green building and green infrastructure often have water efficiency as components, suggesting possible avenues for leveraging the price premiums they command in the marketplace. However, a focus on water efficiency from such measures may involve generating new standards, or targeting existing ones more heavily toward water efficiency: while LEED certification for green building includes water efficiency, it is limited to five among 69 total possible points (Starr and Nicolow, 2007).

Another indirect lever could be found in the energy-water nexus. Increasing attention to the fact that it takes energy to manage water supplies, and takes water to produce energy, has motivated an increase in attention to the interactions between the two resources (Klein *et al.*, 2005; Hightower and Pierce, 2008; Schnoor, 2011). The potential to draw linkages between water (which arguably is undervalued and has low exposure to market forces) and energy (for which markets exist and future prices are projected to increase) may provide opportunities to gain additional leverage for water efficiency efforts, and to motivate further rethinking of energy resource opportunities that already exist in wastewater treatment. The potential to value greenhouse gas emissions reductions has related implications. Many challenges exist for integrating two regulatory sectors that are each fragmented already, and exploration of the technical and practical opportunities will require technical and policy focused research.

The perception of acute crisis can often be the key to rapid change. The creeping nature of the stressors projected to impact urban water systems makes it challenging to directly leverage such future projections. Drought, however, has effectively focused the public's attention on regional water issues, including in recent years in Australia and Spain (Kallis, 2008; Tal, 2011). Waiting for a drought to make anticipated changes in management is at best inefficient, but preparations for climate variability that goes beyond weathering a given particular event to anticipating the opportunity for focused policy attention may be politically prudent water management and a key driver of meaningful climate adaptation (Kiparsky *et al.*, 2012).

To achieve the sort of truly integrative solutions that may represent the ultimate in innovative reinvention for urban water, rethinking institutional forms at the same depth as rethinking the hydrological, biological, and infrastructure systems may be appropriate. Increasing the diversity of organizational forms in water providers to reflect the disparate sets of challenges faced by individual utilities (Dominguez *et al.*, 2009) is a first step. From the perspective of technologists, engaging or partnering early in the technology life cycle with stakeholders including business and investors may help to develop networks and target nascent technology more directly toward viable niches (Gebauer *et al.*, 2012). More radically, considering reorganization of utilities to consolidate multiple services could parallel efforts to rethink the physical structure and function of utilities (Camci *et al.*, 2012).

Most generally, technologists could increase their power to affect change by thinking more broadly about innovation. Not only will institutional innovation be of similar importance to technological innovation, achieving it will present similar levels of difficulty. Intertwined technological and institutional barriers will require joint consideration to enable development of viable solutions for the next generation of urban water management challenges.

Acknowledgments

We are grateful to two reviewers for providing comments on an earlier version of the manuscript. The authors were partially supported by NSF Grant 28139880-50542-C.

Author Disclosure Statement

No competing financial interests exist.

References

Adler, R.W. (1995). Addressing barriers to watershed protection. *Environ. L.* 25, 973.

Adler, R.W. (2009). Institutions affecting the urban water environment. In L.A. Baker, Ed., *The Water Environment of Cities*. New York: Springer.

Adner, R. (2006). Match your innovation strategy to your innovation ecosystem. *Harvard Bus. Rev.* 84, 98.

Ahn, K.H., Cha, H.Y., and Song, K.G. (1999). Retrofitting municipal sewage treatment plants using an innovative membrane-bioreactor system. *Desalination* 124, 279.

American Society of Civil Engineers [ASCE]. (2011). *Failure to Act: The Economic Impact of Current Investment Trends in Water and Wastewater Treatment Infrastructure*. Washington, DC: ASCE.

Andreen, W.L. (2003). Water quality today—Has the clean water act been a success. *Ala. L. Rev.* 55, 537.

Apostolidis, N. (2012). *Integrated Water Management: Good Adaptation Strategy for Climate Change.* Presentation to East Bay Municipal Utilities District. Oakland, CA.

Apostolidis, N., Hertle, C., and Young, R. (2011). Water recycling in Australia. *Water* 3, 869.

Bankes, S.C. (2002). Agent-based modeling: A revolution? *Proc. Natl. Acad. Sci. USA* 99 Suppl 3, 7199.

Bates, B.C., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P. (Eds.) (2008). *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Secretariat.

Binz, C., Truffer, B., Li, L., Shi, Y., and Lu, Y. (2012). Conceptualizing leapfrogging with spatially coupled innovation systems: The case of onsite wastewater treatment in China. *Technol. Forecast. Soc. Change.* 79, 155.

Biswas, A.K. (2004). Integrated water resources management: A reassessment. *Water Int.* 29, 248.

Brauman, K.A., Daily, G.C., Duarte, T., and Mooney, H.A. (2007). The nature and value of ecosystem services: An overview highlighting hydrologic services. *Annu. Rev. Environ. Resour.* 32, 67.

Brooks, D.B., and Holtz, S. (2009). Water soft path analysis: From principles to practice. *Water Int.* 34, 158.

Brown, C. (2010). The end of reliability. *J. Water Resour. Plann. Manage.* 136, 143.

Brown, R., Ashley, R., and Farrelly, M. (2011). Political and professional agency entrapment: An agenda for urban water research. *Water Resour. Manage.* 25, 4037.

Camci, F., Ulanicki, B., Boxall, J., Chitchyan, R., Varga, L., and Karaca, F. (2012). Rethinking future of utilities: Supplying all services through one sustainable utility infrastructure. *Environ. Sci. Technol.* 46, 5271.

Carlsson, B., and Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *J. Evol. Econ.* 1, 93.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jager, J., and Mitchell, R.B. (2003). Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. USA* 100, 8086.

Christensen, C.M. (1997). *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Cambridge, MA: Harvard Business Press.

Christensen, C.M., Suarez, F.F., and Utterback, J.M. (1998). Strategies for survival in fast-changing industries. *Manage. Sci.* 44, S207.

Clapper, J. (2012). *Unclassified Statement for the Record on the Worldwide Threat Assessment of the US Intelligence Community for the Senate Select Commitee on Intelligence*. Washington, DC: Office of the Department of National Intelligence.

Daigger, G.T. (2009). Evolving urban water and residuals management paradigms: Water reclamation and reuse, decentralization, and resource recovery. *Water Environ. Res.* 81, 809.

Daigger, G.T. (2011). *Sustainable Urban Water and Resource Management.* Washington, DC: National Academy of Engineering.

Dewald, U., and Truffer, B. (2012). The local sources of market formation: Explaining regional growth differentials in German photovoltaic markets. *Eur. Plann. Stud.* 20, 397.

Dewar, R.D., and Dutton, J.E. (1986). The adoption of radical and incremental innovations: An empirical analysis. *Manage. Sci.* 32, 1422.

Döll, P. (2009). Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. *Environ. Res. Lett.* 4, 035006.

Dominguez, D., Truffer, B., and Gujer, W. (2011). Tackling uncertainties in infrastructure sectors through strategic planning: The contribution of discursive approaches in the urban water sector. *Water Policy* 13, 299.

Dominguez, D., Worch, H., Markard, J., Truffer, B., and Gujer, W. (2009). Closing the credibility gap: Strategic planning for the infrastructure sector. *Calif. Manage. Rev.* 51, 30.

Doremus, H., and Hanemann, M. (2008). The challenges of dynamic water management in the American West. *UCLA J. Envn. L. Policy* 26, 55.

Dowd, R. (1984). Safe drinking water act. *Environ. Sci. Technol.* 18, 340.

Earman, S., and Dettinger, M. (2011). Potential impacts of climate change on groundwater resources-a global review. *J. Water Clim. Change* 2, 213.

ECONorthwest. (2011). *Embedded Energy in Water Pilot Programs Impact Evaluation: Final Report*. Prepared for the California Public Utilities Commission Energy Division. Portland, OR: ECONorthwest.

Edquist, C., and Johnson, B. (1997). Institutions and organisations in systems of innovation. In C. Edquist, Ed., *Systems of Innovation*. London: Pinter, p. 342.

Elimelech, M., and Phillip, W.A. (2011). The future of seawater desalination: Energy, technology, and the environment. *Science* 333, 712.

Electric Power Research Institute (EPRI). (2002). *Water and Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply and Treatment—The Next Half Century*. Palo Alto, CA: EPRI.

Fagerberg, J., and Verspagen, B. (2009). Innovation studies—The emerging structure of a new scientific field. *Res. Policy* 38, 218.

Fisher, J.C., and Pry, R.H. (1971). A simple substitution model of technological change. *Technol. Forecast. Soc. Change* 3, 75.

Freeman, C. (1994). The economics of technical change. *Cambridge J. Econ.* 18, 463.

Galán, J.M., López-Paredes, A., and del Olmo, R. (2009). An agent-based model for domestic water management in Valladolid metropolitan area. *Water Resour. Res.* 45, W05401.

Galli, R., and Teubal, M. (1997). Paradigmatic shifts in national innovation systems. In C. Edquist, Ed., *Systems of Innovation*. London: Pinter, p. 342.

Gebauer, H., Truffer, B., Binz, C., and Störmer, E. (2012). Capability perspective on business network formation: Empirical evidence from the wastewater treatment industry. *Eur. Bus. Rev.* 24, 169.

Geels, F. (2005). Co-evolution of technology and society: The transition in water supply and personal hygiene in The Netherlands (1850–1930)—A case study in multi-level perspective. *Technol. Soc.* 27, 363.

Geels, F.W. (2006). The hygienic transition from cesspools to sewer systems (1840–1930): The dynamics of regime transformation. *Res. Policy* 35, 1069.

Gleick, P.H. (1993). *Water in Crisis: A Guide to the World's Fresh Water Resources*. Oxford, United Kingdom: Oxford University Press.

Gleick, P.H. (2003). Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302, 1524.

Griliches, Z. (1960). Hybrid corn and the economics of innovation. *Science* 132, 275.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., and Briggs, J.M. (2008). Global change and the ecology of cities. *Science* 319, 756.

Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., MacPherson, L., Mihelcic, J.R., Pramanik, A., Raskin, L., Van Loosdrecht, M.C.M., Yeh, D., and Love, N.G. (2009). A new planning and design paradigm to achieve sustainable resource recovery from wastewater1. *Environ Sci. Technol.* 43, 6126.

Guston, D.H. (2001). Boundary organizations in environmental policy and science: An introduction. *Sci. Technol. Human Values* 26, 399.

Hake, J., Cohn, A., Gray, D., and Ramanathan, M. (2006). Get more juice out of that lemon: EBMUD's search for energy in wastewater. *Proceedings of the Water Environment Federation, WEFTEC 2006*, 2536.

Hall, M.R., West, J., Sherman, B., Lane, J., and de Haas, D. (2011). Long-term trends and opportunities for managing regional water supply and wastewater greenhouse gas emissions. *Environ. Sci. Technol.* 45, 5434.

Hanemann, W.M. (2006). The economic conception of water. In P.P. Rogers, M.R. Llamas, and L. Martinez Cortina, Eds., *Water Crisis: Myth or Reality?* London: Taylor & Francis, p. 61.

Hegger, D.L.T., Van Vliet, J., and Van Vliet, B.J.M. (2007). Niche management and its contribution to regime change: The case of innovation in sanitation. *Technol. Anal. Strategic Manage.* 19, 729.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., and Smit, R.E.H.M. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technol. Forecast. Social Change* 74, 413.

Hightower, M., and Pierce, S.A. (2008). The energy challenge. *Nature* 452, 285.

House, L.W. (2010). *Order Instituting Rulemaking Regarding Policies, Procedures and Rules for the California Solar Initiative, The Self Generation Incentive Program and Other Distributed Generation Issues: Association Of California Water Agencies Comments On Staff Proposal: Pressure Reducing In-Conduit Hydroelectric Generation*. San Francisco, CA: Public Utilities Commission of the State of California. Rulemaking 10-05-004.

Hughes, T.P. (1989). The evolution of large technological systems. In W.E. Bijker, T.P. Hughes, and T. Pinch, Eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge, MA: MIT Press, p. 51.

Innes, J.E., and Booher, D.E. (2010). *Planning with Complexity: An Introduction to Collaborative Rationality for Public Policy*. London: Taylor & Francis.

Jacobs, K., Lebel, L., Buizer, J., Addams, L., Matson, P., McCullough, E., Garden, P., Saliba, G., and Finan, T. (2010). Knowledge systems for sustainable development special feature sackler colloquium: Linking knowledge with action in the pursuit of sustainable water-resources management. *Proc. Natl. Acad. Sci. USA* 2010 Jun 29 [Epub ahead of print]; DOI: 10.1073/pnas.0813125107.

Jacobsson, S., and Bergek, A. (2011). Innovation system analyses and sustainability transitions: Contributions and suggestions for research. *Environ. Innov. Soc. Transit.* 1, 41.

Kallis, G. (2008). Droughts. *Annu. Rev. Environ. Resour.* 33, 85.

Kemp, R. (1994). Technology and the transition to environmental sustainability: The problem of technological regime shifts. *Futures* 26, 1023.

Kho, J. (2012). *Water Acquisitions Rise: Will Venture Capital Follow? Forbes*. Available at: www.forbes.com/sites/jenniferkho/2012/02/28/water-acquisitions-rise-will-venture-capital-follow (accessed August 1, 2012).

Kiparsky, M., Milman, A., and Vicuna, S. (2012). Climate and water: From knowledge of impacts to action on adaptation. *Annu. Rev. Environ. Resour*. 37, 163.

Klein, G., Krebs, M., Hall, V., O'Brien, T., and Blevins, B.B. (2005). *California's Water–Energy Relationship*. Sacramento, CA: California Public Utilities Commission.

Kline, S., and Rosenberg, N. (1986). An overview of innovation. In R.L.N. Rosenberg, Ed., *The Positive Sum Strategy: Harnessing Technology for Economic Growth.* Washington, DC: National Academy Press, p. 275.

Kolpin, D.W., Furlong, E.T., Meyer, M.T., Thurman, E.M., Zaugg, S.D., Barber, L.B., and Buxton, H.T. (2002). Pharmaceuticals, hormones, and other organic wastewater contaminants in US streams, 1999–2000: A national reconnaissance. *Environ. Sci. Technol.* 36, 1202.

Kotz, C., and Hiessl, H. (2005). Analysis of system innovation in urban water infrastructure systems: An agent-based modelling approach. *Water Sci. Technol. Water Supply* 5, 135.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Jimenez, B., Miller, K., Oki, T., Şen, Z., and Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management. *Hydrol. Sci. J.* 53, 3.

Larsen, T.A., Alder, A.C., Eggen, R.I.L., Maurer, M., and Lienert, J. (2009). Source separation: Will we see a paradigm shift in wastewater handling? *Environ. Sci. Technol.* 43, 6121.

Lee, K.P., Arnot, T.C., and Mattia, D., (2011). A review of reverse osmosis membrane materials for desalination—Development to date and future potential. *J. Membr. Sci.* 370, 1.

Lemelson-MIT Program. (2004). *Invention: Enhancing Inventiveness for Quality of Life, Competitiveness, and Sustainability, Report of the Committee for the Study of Invention*. Cambridge, MA: MIT Press.

Lemos, M.C. (2008). What influences innovation adoption by water managers? Climate information use in Brazil and the United States. *J. Am. Water Resour. Assoc.* 44, 1388.

Loeb, S., and Sourirajan, S. (1963). Sea water demineralization by means of an osmotic membrane. *Adv. Chem. Ser.* 38, 117.

London Economics. (2009). *Innovation in the Water Industry in England and Wales: Final Report, Cave Review of Competition and Innovation in Water Markets.* London: London Economics.

Markard, J., Raven, R., and Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Res. Policy* 41, 955.

Markard, J., and Truffer, B. (2006). Innovation processes in large technical systems: Market liberalization as a driver for radical change? *Res. Policy* 35, 609.

Markard, J., and Truffer, B. (2008). Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Res. Policy* 37, 596.

Markoff, J. (2011, October 5). Apple's visionary redefined digital age. *The New York Times*, p. A1.

Martine, G. (2007). *The State of World Populaton 2007*. New York: United Nations Population Fund.

McKelvey, M. (1997). Using evolutionary theory to define systems of innovation. In C. Edquist, Ed., *Systems of Innovation*. London: Pinter, p. 342.

Meade, N. and Islam, T. (2006). Modelling and forecasting the diffusion of innovation—A 25-year review. *Int. J. Forecast.* 22, 519.

Melin, T., Jefferson, B., Bixio, D., Thoeye, C., De Wilde, W., De Koning, J., van der Graaf, J., and Wintgens, T. (2006). Membrane bioreactor technology for wastewater treatment and reuse. *Desalination* 187, 271.

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

Moore, G.A. (2002). Crossing the chasm: Marketing and selling high-tech products to mainstream customers. New York: HarperBusiness.

Moresco, J. (2009). *A Rising Tide for Water Power Funding?* Available at: www.renewableenergyworld.com/rea/news/article/2009/07/a-rising-tide-for-water-power-funding (accessed July 10, 2012).

National Research Council (NRC). (2008). *Desalination: A National Perspective.* Washington, DC: The National Academies Press, p. 316.

NRC. (2012). *Water Reuse: Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater*. Washington, DC: National Research Council.

Ntelekos, A.A., Oppenheimer, M., Smith, J.A., and Miller, A.J. (2010). Urbanization, climate change and flood policy in the United States. *Clim. Change* 103, 597.

O'Connor, R.E., Yarnal, B., Dow, K., Jocoy, C.L., and Carbone, G.J. (2005). Feeling at risk matters: Water managers and the decision to use forecasts. *Risk Anal.* 25, 1265.

Organisation for Economic Co-operation and Development (OECD). (2006). *Infrastructure to 2030: Telecom, Land Transport, Water and Electricity*. Paris: OECD Publishing.

OECD. (2007). *Infrastructure to 2030 (Volume 2): Mapping Policy for Electricity, Water and Transport.* Paris: OECD Publishing.

Potts, J. (2009). The innovation deficit in public services: The curious problem of too much efficiency and not enough waste and failure. *Innov. Manage. Policy Pract.* 11, 34.

Pricewaterhouse Coopers and the National Venture Capital Association (PwC/NVCA). (2012). Annual venture investment dollars increase 22% over prior year, according to the *MoneyTree Report.* PwC/NVCA *MoneyTree™ Report* based on data from Thomson Reuters. Available at: www.pwc.com/us/en/press-releases/2012/annual-venture-investment-dollars.jhtml (accessed July 23, 2013).

Quay, R. (2010). Anticipatory governance. *J. Am. Plann. Assoc.* 76, 496.

Rayner, S., Lach, D., and Ingram, H. (2005). Weather forecasts are for wimps: Why water resource managers do not use climate forecasts. *Clim. Change* 69, 197.

Rogers, E.M. (1962). *Diffusion of Innovation*. New York: Free Press.

Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Thurston, H.W., and Brown, R.R. (2008). Impediments and solutions to sustainable, watershed-scale urban stormwater management: Lessons from Australia and the United States. *Environ. Manage.* 42, 344.

Sax, J.L. (2007). Reflections on Western water law. *Ecol. L. Q.* 34, 299.

Schnoor, J.L. (2011). Water-energy nexus. *Environ Sci. Technol* 45, 5065.

Schumpeter, J.A. (1947). *Capitalism, Socialism, and Democracy*. New York: Harper and Brothers.

Scott, W.R. (2001). *Institutions and Organizations*. Thousand Oaks, CA: Sage Publications.

Seto, K.C., Fragkias, M. Güneral, B., and Reilly, M.K. (2011). A meta-analysis of global urban land expansion. *PLoS One* 6, e23777.

Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Marinas, B.J., and Mayes, A.M. (2008). Science and technology for water purification in the coming decades. *Nature* 452, 301.

Smith, A., Voß, J.-P., and Grin, J. (2010). Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. *Res. Policy* 39, 435.

Snyder, S.A., Westerhoff, P., Yoon, Y., and Sedlak, D.L. (2003). Pharmaceuticals, personal care products, and endocrine disruptors in water: Implications for the water industry. *Environ. Eng. Sci.* 20, 449.

Starr, J., and Nicolow, J. (2007). *How Water Works For LEED.* Available at: www.facilitiesnet.com/green/article/How-Water-Works-for-LEED-7545

State Water Resources Control Board. (2008). *20×2020 Water Conservation Plan Draft Final Report, Public Draft Technical Memorandum Task 2–Determining Conservation Targets*. Sacramento, CA: California Environmental Protection Agency.

State Water Resources Control Board. (2009). *20×2020 Water Conservation Plan Draft Final Report*. Sacramento, CA: California Environmental Protection Agency.

Sun, G., McNulty, S.G., Myers, J.A.M., and Cohen, E.C. (2008). Impacts of climate change, population growth, land use change, and groundwater availability on water supply and demand across the conterminous U.S. *AWRA Watershed Update* 6, 2.1.

Sunding, D., and Zilberman, D. (2001). The agricultural innovation process: Research and technology adoption in a changing agricultural sector. *Handb. Agric. Econ.* 1, 207.

Tal, A. (2011). The desalination debate—Lessons learned thus far. *Environ. Sci. Policy Sustain. Dev.* 53, 34.

Taylor, M. (2008). Beyond technology-push and demand-pull: Lessons from California's solar policy. *Energy Econ.* 30, 2829.

The Economist. (2008). *Tapping the Oceans*. London: The Economist.

Thomas, D., and Ford, R. (2005). *The Crisis of Innovation in Water and Wastewater.* Cheltenham, United Kingdom: Edward Elgar.

Treidel, H., Martin-Bordes, J.L., and Gurdak, J.J. (2011). *Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations.* IAH—International Contributions to Hydrogeology Series. London: CRC Press, p. 414.

Truffer, B., Binz, C., Gebauer, H., and Störmer, E. (2012). Market success of on-site treatment: A systemic innovation problem. In T.A. Larsen, K.M. Udert, and J. Lienert, Eds., *Wastewater Treatment: Source Separation and Decentralisation*. London: IWA Publishing, p. 209.

Tushman, M.L., and Anderson, P. (1986). Technological discontinuities and organizational environments. *Admin. Sci. Q.* 31, 439.

UNESCO/World Water Assessment Program (2006). *Water: A Shared Responsibility. The United Nations World Water Development Report 2.* Paris and New York: UNESCO Publishing and Berghahn Books.

Urban Land Institute and Ernst and Young. (2007). *Infrastructure 2007: A Global Perspective*. Washington, DC: The Urban Land Institute.

van de Meene, S.J., Brown, R.R., and Farrelly, M.A. (2011). Towards understanding governance for sustainable urban water management. *Global Environ. Change* 21, 1117.

van den Bergh, J.C.J.M., Truffer, B., and Kallis, G. (2011). Environmental innovation and societal transitions: Introduction and overview. *Environ. Innov. Soc. Transit.* 1, 1.

Venkatesh, G. (2012). Cost-benefit analysis—Leakage reduction by rehabilitating old water pipelines: Case study of Oslo (Norway). *Urban Water J.* 9, 1.

Vörösmarty, C.J., Green, P., Salisbury, J., and Lammers, R.B. (2000). Global water resources: Vulnerability from climate change acid population growth. *Science* 289, 284.

Wilson, J. (2010). *Poseidon's Desalinization Plant: Dream Water Supply or Draining the Pacific and Taxpayers?* Washington, DC: DC Bureau, Public Education Center. www.dcbureau.org/20100511749/natural-resources-news-service/poseidons-desalinzation-plant-dream-solution-for-californias-water-woes-or-a-taxpayer-and-environmental-nightmare.html (accessed July 23, 2013).

World Economic Forum. (2012). *Global Risks 2012*. Geneva: World Economic Forum.

Zimmerman, J.B., Mihelcic, J.R., and Smith, J. (2008). Global stressors on water quality and quantity. *Environ. Sci. Technol.* 42, 4247.