Environ. Sci. Technol. **2009,** *43,* 6126–6130

Environmental Science & Technology
Feature

A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater[1]

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[1] *Editor's Note: To our delight at* ES&T, *we have started to receive Features and Viewpoints by independent author(s) coincidentally overlapping both in topic and review schedule. This manuscript was accepted just as another on the "paradigm shift" needed for sustainable water infrastructure design was being readied for production. The choice was thus made to present both manuscripts in the same issue (August 15, 2009; 43, 16). Readers of this piece by Guest* et al. *are therefore encouraged to read that by Larsen* et al. (DOI 10.1021/es803001r), *which also appears herein as reference (8).*

To employ technologies that sustainably harvest resources from wastewater (for example struvite granules shown here), new perceptions and infrastructure planning and design processes are required.

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Water and wastewater system decisions have been traditionally driven by considerations of function, safety, and cost–benefit analysis. The emphasis on costs and benefits would be acceptable if all relevant factors could be included in the analysis, but unfortunately many relevant factors are routinely excluded. Coupled with failures to fully engage the public in decision-making processes, this can impede progress toward achieving sustainable solutions. Ignoring broader social issues that impact the adoption of sustainable solutions prolongs not only global environmental and ecological problems, but also unjust public health and social conditions in the developing world.

Within the water and wastewater management industry, discussions of sustainable development have often focused on water stress (*1*, *2*): a hazard that is exacerbated by other global stressors such as climate change, demographic and land use changes, increasing population, and urbanization (*2*). In addition to water stress, water and wastewater management practices contribute to nutrient imbalances and a host of environmental detriments such as eutrophication (*3*), discharge of pharmaceuticals and other emerging contaminants (*4*), and a loss of biodiversity in receiving streams (*5*). Efforts to address these issues across regional and global scales are hindered by the historical disconnect between the water quality and water quantity factions of the water profession. Although our understanding of sustainability is constantly evolving, the water and wastewater design process retains its foundation in engineering traditions established in the early 20th century (*6*). As we chart a path in the 21st century, we contend that wastewater contains resources worthy of recovering and that the development of

10.1021/es9010515

Published on Web 07/14/2009

technologies, practices, and policies that enable cost-effective recovery will have broad geopolitical implications.

The primary problem we face is not the availability of technology for resource recovery, but the lack of a socio-technological planning and design methodology to identify and deploy the most sustainable solution in a given geographic and cultural context. We acknowledge that the most sustainable solution may not result in maximum, or any, recovery of resources from wastewater. Instead a sustainable water and wastewater decision-making process considers environmental, economic, and social ramifications of decisions across spatial and temporal scales to achieve the best balance identified by the project stakeholders. A central element of sustainability is that *stakeholders* are defined broadly to include utility managers, operators, regulators, local government officials, end-users, public interest groups, and other parties impacted by the project. The objective of this paper is to identify elements of such a decision-making methodology that can provide all stakeholders with the tools needed to advance sustainability, as well as to suggest a set of guiding principles for resource recovery systems in the water industry.

Wastewater as a Renewable Resource

Sustainability demands that we acknowledge wastewater as a renewable resource from which water (*7*), materials (e.g., fertilizers (*8*), bioplastics (*9*)), and energy (*7*) can be recovered. By shifting away from today's paradigm, which focuses on what must be *removed* from wastewater, to a new paradigm focusing on what can be *recovered*, sanitation systems may begin to be described as resource recovery systems (RRS)—a conceptual transformation that could allow the perceived impact of wastewater on communities to become a net positive (*5*).

Water Recovery. Water reclamation and reuse (or water recycling) can provide additional water resources in water stressed areas. Successful examples include the Orange County Water District (California) and the Upper Occoquan Sewage Authority (Virginia), which have each been achieving indirect potable reuse for over 30 years. A large "systems-level" example of reuse can be seen in Singapore's "four national taps" strategy. Singapore has a diverse water portfolio which includes (1) imported water from Malaysia, (2) local water supplies, (3) desalination, and (4) indirect potable and direct non-potable reuse of reclaimed water (NEWater). In fact, with the opening of the Changi plant in 2010, NEWater will meet 30% of Singapore's drinking water demand (*10*). A successful example of *direct potable* reuse is found in Windhoek, Namibia, where water resources are particularly sparse (*11*).

Energy Recovery. The most common form of energy recovery from wastewater is methane (CH_4)-containing biogas produced during the anaerobic treatment of wastewater and the digestion of solids collected and generated. Anaerobic reactors are in use throughout the world, producing CH_4 that can be (1) combusted on-site for heat or electricity generation, (2) cleaned and sold to a local natural gas provider, or (3) cleaned and used as fuel for vehicles. Other examples of wastewater energy recovery include microbial fuel cells (*12*) and the extraction of latent heat for buildings' heating and cooling (*13*).

Material Recovery. The use of biosolids as fertilizer is a well-documented application that is becoming increasingly common in the U.S. (*14*) and the U.K. (*15*). There have also been recent developments in the harvesting of struvite ($MgNH_4PO_4 \cdot 6H_2O$) from solids treatment processes (*16*) as well as the recovery of nutrients from source-separated urine (*8*). For instance, a significant portion of the vegetables consumed in Kampala, Uganda, are produced in backyard gardens using storage-sterilized, source-separated urine (*17*).

Resource Recovery Systems (RRS). Water, energy, and materials recovery from wastewater can all be achieved with existing technologies, and new technological approaches are on the horizon (*6*). Despite such advances, our observation is that wastewater systems contribute to a greater proportion of negative impact on regional hydrological cycles than on energy and materials consumption. Indeed, is the recent, heavy focus by the water industry on energy sustainability *causing us to miss the major point of water sustainability?* We propose a reorientation of stakeholders' thinking toward addressing the impact of wastewater technologies on regional and global hydrological cycles first, then assess whether these approaches are negatively impacting global energy, climate, and/or material(s) sustainability. By utilizing this approach, our planning and design processes will evolve toward applying available technologies that have the maximal benefit for regional and global goals for water resource quality and availability, while simultaneously reducing negative impacts on other aspects of sustainability when possible. Note that although an RRS may not include energy or material recovery in a specific instance, what matters most is that decisions in the water industry do not significantly impede regional or global action plans for energy and/or material sustainability (which are unlikely to include the water industry to a significant degree in the foreseeable future). Once we understand which technologies best contribute to sustainability from this regional and global perspective, we must strive to learn how best to implement these technologies in a manner that is socially acceptable from the local perspective.

Barriers to the Successful Implementation of RRS. Given the availability of technologies to recover resources from wastewater, *why don't we use them more often*? Reasons include a lack of agreed-upon sustainability goals and targets (see *18*) and the absence of a holistic design methodology capable of including sociological factors. The importance of sociological factors is illustrated by San Diego, CA (*19*), a coastal city with a semi-arid climate and population >1.3 million. The city relies on the importation of water a distance of 390 and 715 km from the Colorado River and Sacramento-San Joaquin Delta, respectively. In recent years, imported water (containing discharge from >200 wastewater treatment plants) has constituted up to 90% of San Diego's water supply. To provide more water from local sources, two reclamation plants were constructed with the capacity to recycle just >25% of the local water demand. In an attempt to encourage reuse, the U.S. EPA mandated that one of the plants would operate at 75% capacity and produce water for non-potable reuse. However, public rejection of the plan has resulted in returning 73% of the water produced by this plant to the sewer for treatment at the local wastewater treatment plant before discharge to the ocean. Despite having technology *in place* to recover a major fraction of wastewater, the failure to simply use it demonstrates the need to include social sustainability factors in the planning and design process.

The San Diego example teaches us that there is more to sustainability than economics and process performance. Public and political pressures coupled with opposition from the media have significantly restricted the use of reclaimed water (*20*) and not just in San Diego: also Toowoomba, Australia (*21*), and the California locales of San Ramon-Dublin (*22*) and Los Angeles (*22*). The reclamation of water is a volatile issue that challenges cultural and historical notions of water, resulting in perceived risks that engineers and scientists often believe to be unjustified (*21, 23*). To engage successfully with the public it is important that engineers and decision makers understand the socio-political context of stakeholders' existence (*24*) including: forms of relevant experience, past relations with expert and decision-making bodies, and the distinctive forms and styles through which diverse publics make sense of expert knowledge—concerns nicely captured by Jasanoff's notion of *civic epistemology* (*25*). Beyond the challenge of understanding civic epistemology, additional barriers to the advancement of water and wastewater systems may include the lack of political will (*26, 27*) and the absence of an enabling environment (policies, legislative frameworks, financing, and modes of public discourse) (*24, 27, 28*).

To date, the water industry has been poorly equipped to address factors outside of the traditional engineering scope. We believe that this can be traced to the long-standing and narrowly defined approaches that are used to train water industry professionals. This shortcoming—as well as the institutional compartmentalization that impedes integrated water resource management (*6, 29*)—must be remedied to make progress in developing and deploying sustainable water management strategies.

The Pursuit of Sustainability in Water Management

Since sustainability does not exist at a single project level, our overall goal must be to harmonize RRS design at the local level with the goal of *global* sustainability. Guiding principles at the local level that impact the global sustainability goals of the water industry are provided in Table S1 of the Supporting Information (SI). Following all these principles simultaneously is usually impossible in a given project and therefore we require context-specific assessment techniques to evaluate alternatives and a means to resolve trade-offs among them. Representative methods to evaluate project alternatives from the sustainability perspective are described in the following paragraphs.

Environmental and Ecological Assessment. Life cycle assessment (LCA) is a tool traditionally used to elucidate the environmental and ecological impacts of products or processes throughout their life cycle. For instance, Sydney Water (Australia) in collaboration with the University of New South Wales produced a comprehensive LCA of their integrated water and wastewater infrastructure to forecast environmental and ecological impacts through 2021 (*30*). While this approach provides guidance on the impact of specific emissions expected from design choices, it can only serve as an input to a broader stakeholder decision-making process which must resolve the trade-offs that inevitably emerge: (1) between different environmental and ecological impacts, (2) across spatial and temporal scales, and (3) across the categories of guiding principles listed in Table S1 that also include considerations of economics, societal acceptance and equity, and functional performance.

Economic Assessment. Life cycle costing (LCC) can start to address the economic dimension of sustainability by estimating capital, operational, and maintenance costs, as well as costs from upstream and downstream processes (*31*). The absence of LCC approaches has led to implementation failures in both industrialized (*32*) and developing countries (*33*). Although LCC could improve the economic sustainability of a given project, neither it nor other economic assessment techniques are appropriate for the evaluation of other sustainability dimensions. Recent progress has been made in the use of environmental valuation—a tool that monetizes environmental and ecological impacts—but the monetization of externalities (including social impacts such as morbidity and mortality effects) has met with a number of criticisms (see *34*). Ultimately, if the objective of the assessment is to evaluate a project's sustainability characteristics, the monetization of nonmarket impacts is inappropriate since it forces a value mapping by the decision makers which, even if it could be done "correctly", eliminates the independence of environmental and social dimension bases; an outcome that is contrary to the sustainable development principle of balancing considerations across all three categories (*35*). Instead LCC should be used along with other assessment tools such as LCA for the environmental and ecological dimensions, and new tools should be developed to help assess the social dimension(s) (*36*).

Social Assessment. Ideally social dimensions could be included in an LCA framework but this has proven difficult (*35*). One of the great challenges associated with social life cycle evaluations is the existence of several hundred indicators (*37*). Although risk assessments have been used to quantify potential impacts on public health, few methods have been developed for the water industry to incorporate a broader set of social indicators into the planning and design process (e.g., those listed in Table S1). Recent work includes that of Hunkeler (*37*) using employment as a midpoint variable and Ashley et al. evaluating stakeholder perception and understanding (*38*).

Resolving Trade-Offs in Decision-Making. After the assessment of project alternatives in each dimension of sustainability, decision makers must resolve the trade-offs that will inevitably exist. One tool that can provide a framework for comparative sustainability assessments is multicriteria decision analysis (MCDA): a class of formal approaches to decision-making that allow stakeholders to take explicit account of multiple criteria (*39*). Of particular value to sustainability decision-making is MCDA's ability to resolve trade-offs among qualitative and quantitative metrics, and for the process to evolve as stakeholder preferences are articulated (*39*).

Stakeholder participation is a vital component of sustainability that has not been universally applied in the planning and design of water systems (*40*). The importance of appropriately timed stakeholder participation in decision-making is not unique to the water industry and has been acknowledged as a key component of socio-technological planning and design methodologies in natural resource management (*39*) and sustainability projects (*41*).

Box 1: Decision-making in a developing world context

In a development setting, beneficiaries are often poor and reside in under-developed communities. The word *project* encompasses more than the physical structure that is designed and constructed. Projects must account for the local social and cultural setting and include input from the people who will ultimately operate, manage, and benefit from the whole endeavor (*42*). Therefore project designers must establish the appropriate ownership, skills, and management capacity to support the effort while at the same time designing the physical structure. In addition to environmental and economic sustainability elements, designers should consider the following social factors: socio-cultural respect, community participation, gender roles, and political cohesion (*43*).

Challenges and the Path Forward

As we pursue a more sustainable water industry, management strategies must evolve to address the broad set of challenges listed in Table S2. Our water systems must become integrated RRS that (1) match water supply with demand (both in location and level of treatment), (2) enable the efficient recovery of resources, and (3) acknowledge the significance of environmental, economic, and social aspects of sustainability throughout the planning and design process.

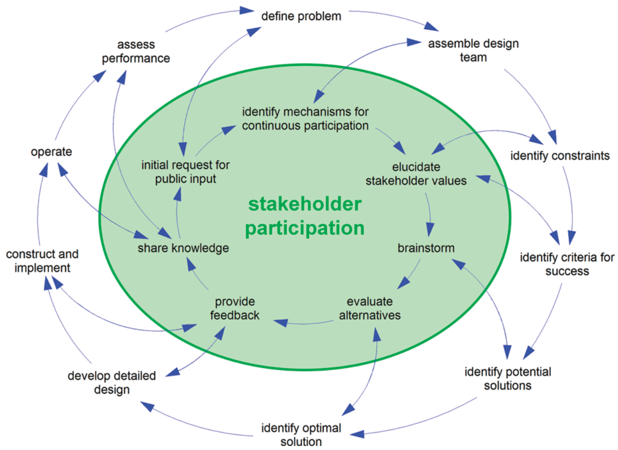

FIGURE 1. Example of a suggested planning and design process that connects engineering (outer loop) with sustained stakeholder participation (inner loop). Double-headed arrows connecting the technical design process with stakeholder participation represent workshops held throughout the planning and design of a water system. This depiction bears resemblance to the *Framework for Environmental Health Risk Management* (*44*) in that the technical decision-making process relies on stakeholder participation throughout.

Stakeholder Participation in Planning and Design. The successful implementation of more sustainable solutions requires that the social dimension of technology be acknowledged via both assessment techniques (*38, 41*) and participatory planning (*21, 38, 40, 41*). Through the respectful inclusion of stakeholders in the decision-making process, project managers can facilitate positive social learning, minimize and resolve conflicts, elicit and use local knowledge, and achieve greater public and stakeholder acceptance of water management decisions (*40*). The sustained participation of stakeholders can be achieved through regular workshops that are designed to facilitate meaningful contributions and build trust among participants (Figure 1).

A more thorough discussion of stakeholder participation in water industry projects may be found elsewhere (*24, 38–40*). These articles discuss the importance of community values and mechanisms for their inclusion in planning and design. The next step is for these approaches to be extended to RRS in pursuit of sustainable water systems as a critical element of global sustainability.

The Transition toward Sustainability. For over 100 years, drinking water and wastewater treatment have existed for the protection of human health. Although successful, we now rely on infrastructure and management strategies that are not sustainable in the 21st century. Envisioning wastewater as a renewable resource offers exciting opportunities for the water industry to contribute to global sustainability through the recovery of water, energy, and materials. Achieving this objective will require coordination and cooperation among the different sectors of water and wastewater management to set achievable sustainability targets for the water industry.

After the identification of industry-wide targets, a research and implementation strategy will be necessary to identify and support their pursuit, recognizing that water recovery may be the most important strategic focus due to the disproportionate impact of water and wastewater systems on the sustainability of water resources (as compared to energy and materials resources). Next, place-based definitions of sustainability will need to be developed using a socio-technological planning and design methodology. Finally, through both industry-wide leadership and locality-based initiatives, it will then become possible to identify the best practices that promote sustainable resource recovery systems in water and wastewater management.

This will not be a "one size fits all" endeavor. Methods for evaluating the sustainability of alternatives in a local (or place-based) context are needed, along with an inherently subjective process for resolving trade-offs across spatial scales, temporal scales, and sustainability dimensions (social, environmental, and economic). Furthermore, the pursuit of sustainable systems must not take place in a vacuum among only experts. The planning and design process will require collaboration across stakeholder sectors building on the expertise of a broad set of disciplines. The importance of undertaking this challenge cannot be understated. As the water industry discovers new technological solutions contributing to environmental protection, public health, and global sustainability, it must be recognized that these solutions will not be adopted unless greater attention is given to stakeholder interests as a central element of a sustainable planning and design paradigm.

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Acknowledgments

We acknowledge financial support from the Graham Environmental Sustainability Institute at the University of Michigan which facilitated a workshop on this topic and provided partial funding for the lead author. We thank the anonymous reviewers of this manuscript for their constructive comments.

Note Added after ASAP Publication

The Supporting Information was revised in the version of this article published ASAP July 14, 2009; the corrected version published ASAP July 23, 2009.

Supporting Information Available

Tables S1 and S2. This information is available free of charge via the Internet at http://pubs.acs.org.

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ES9010515