Distributed optimal technology networks: a concept and strategy for potable water sustainability

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Abstract Viable strategies for ensuring adequate supplies of potable water are essential to long-term societal sustainability. The steadily increasing necessity for multiple reuse of water in urban societies is even now taxing our technical and financial abilities to meet ongoing needs for water suitable for human consumption. As a consequence, the current practice of treating the entire water demands of urban communities to the increasingly stringent standards required for drinking water is becoming an unsustainable practice, and thus a questionable strategy for planning and development of urban water systems. An innovative technology-based concept for implementation of a more sustainable strategy and practice for potable water is developed here. The concept is predicated on the inherent advantages of flexibility and responsiveness associated with decentralization of complex functions and operations. Specifically, it calls for strategic dispersal of flexible advanced treatment and control technologies throughout urban water transport and storage networks. This is in direct contradistinction to current strategies and practices of centralized and inflexible monolithic facilities. By integrating use-related satellite systems with critical components of existing systems and infrastructures, the concept can enable and facilitate optimal cost-effective applications of highly sophisticated advanced treatment and on-line monitoring and control technologies to in-place infrastructures in a holistic and sustainable manner.

Keywords Drinking water; infrastructures; innovative strategies; treatment technologies

Introduction

The global dimensions of diminishing quantities and qualities of water available for sustenance of humankind have been detailed in a number of authoritative reports over the past decade. It takes but a casual reading of any one of these reports to quickly appreciate the scope and magnitude of water supply problems throughout the world. The problems are not abstract or obscure; they are large, evident, and extremely serious. They are, moreover, not problems pending tomorrow; they are with us now, and they will only worsen until we devise and implement changes in water supply strategies and practices to resolve them.

The increasing necessity for society’s multiple reuse of water is central to global freshwater problems. Human water demands now so far exceed nature’s ability to replenish fresh water that it must be used and reused many times during each period between its extraction from and return to Earth’s natural hydrologic cycle. A recent report from a workshop sponsored by the National Science Foundation, titled “Environmental Engineering Research Frontiers Workshop,” identified “safe, adequate, and sustainable water supplies” as the foremost challenge to achievement of environmental sustainability (Logan and Rittmann, 1998). Regarding ongoing and increasing needs for multiple water reuse, the report called upon the policy and technology sectors to “...address the consequent realities of water quality and water quality demands and use by developing and applying new technologies that can transform any specific water supply to a level of quality required for a particular use.” The net effect of constantly increasing water use, and of the correspondingly increased frequency with which the intrinsic hydrologic cycle of Earth is thereby short-circuit, is that distinctions between natural waters, water supplies and wastewaters from municipal, agricultural, and industrial sources are becoming increasingly artificial. These are not new issues, nor are
the views expressed new. They are the same views as those articulated by some on the same issues as long as three decades ago (Weber, 1972). The issues, however, are now much more broadly evident and increasingly urgent, and the views are thus now even more appropriate, and are more widely accepted (Asano, 1998; National Research Council, 1998; Water Environment Research Foundation, 1999; Weber and LeBoeuf, 1999; Weber, 2000).

In recognition of the need to consider appropriately treated wastewater as an integral component of Earth’s fresh water resource, the Water Environment Research Foundation in 1998 conducted a workshop designed to identify associated research needs (Water Environment Research Foundation, 1999). Two major recommendations of that workshop are paraphrased here: i) devise means to harness new and incipient technologies for this purpose; and, ii) consider means to address the associated public concerns. I reiterate a position stated often regarding enduring solutions to the global water crisis, and the two essential features those solutions must embrace. First, they must incorporate sophisticated treatment and control technologies that can accomplish essentially complete restoration of fresh water qualities in any reasonable source of water. Second, they must operate under policies and within infrastructures designed to facilitate optimal use of those advanced technologies in ways compatible with urban values and social mores (Water Environment Research Foundation, 2000).

The distributed optimal technology (DOT-NET) concept described here envisions a revolutionary approach to infrastructures employed for potable water supplies, an approach designed specifically to capture the two “essential features” identified above. The concept applies to both new urban developments and existing urban environments. For implementation in existing urban communities, it is designed to lever in-place water treatment and distribution infrastructures. This is an important feature of the concept, given the reality that complete replacement of such infrastructures will, even under the best of circumstances, be highly disruptive and costly. A recent report by the American Society of Civil Engineers on America’s infrastructure estimates that there will be at least an $11 billion annual shortfall in funds available in the U.S. to adequately address the country’s obsolescent drinking water infrastructure (American Society of Civil Engineers, 2001). That projection was made in the context of in-kind replacement of current infrastructures, a strategy I maintain we cannot afford to pursue.

Requisite upgrading of potable water supplies in existing urban environments is in most cases a more difficult problem than providing adequate supply systems in new urban developments. Thus, existing urban infrastructures will serve as the focal point for this presentation. Extension of the concept and its implementation in new urban developments should then be logically and readily apparent. For existing urban systems the DOT-NET concept engages in-place central treatment facilities and distribution networks in innovative ways that make it cost effective to employ the most highly advanced technologies for potable water of the highest possible quality.

**Infrastructures**

Extant infrastructures are critical considerations in any plan to upgrade an existing urban water system to improve and sustain potable water. A schematic characterization of the major infrastructure components of traditional systems for providing water and collecting water-borne waste from urban population centers is presented in Figure 1. Appropriate integration in any particular system-specific schematic of storm water collection and agricultural use components not specifically depicted in Figure 1 would not alter the basic DOT-NET concepts advanced here.

The code numbers in the diamond shaped boxes shown in Figure 1 are defined in Table 1. They reference qualitative characterizations of water at different production, propagation, and use stages within the infrastructure illustrated. The class designations and other descriptors are arbitrary, and intended here simply to suggest relative differences in water quality at different points in a typical urban water system.

Traditional strategies of public water supply and wastewater treatment and disposal are
inherently fixed by the huge centralized and function-dedicated water and wastewater treatment plants and endless miles of high capacity distribution and collection networks depicted in Figure 1. Attempts to upgrade water quality in such systems are thus frustrated by the inherent inflexibility of the infrastructures involved, and by the enormous efforts and costs required to rehabilitate or rebuild those infrastructures. The distribution and collection networks are particularly problematic because they are generally buried beneath buildings, roadways, and other superstructures. The magnitude of the problem is evident in the sizes of the water production, propagation, collection, treatment and disposal systems of large urban cities, most of which have been built to process many millions, and even billions, of cubic metres of product per day.

The current dilemma for potable water supply practice is that the qualities of available sources of water are steadily declining under the influence of increasing pollution burdens, while use-related standards are increasing as concentration levels of contaminant detectability and regulatory concern are lowered. It is further likely that, in the context of present infrastructures, increasingly advanced levels of treatment will have to be accomplished using more or less traditional technologies. It is further likely that we will be able to advance those technologies only marginally in unit effectiveness and efficiency through ongoing research and development activities. In other words, no economically feasible “silver-bullet” technology is evident on the immediate horizon, at least not in the context of implementation in traditional infrastructure format.

**Technologies**

The need for increased reuse of water cited earlier significantly impacts both source-water quality and product water value. This raises formidable challenges to our ability to ensure potable water of higher and higher chemical and microbiological quality in response to legitimate societal demands. Fortunately we have been able to meet many water quality
challenges successfully through research and development of various types of highly competent physicochemical and biologically based treatments. In this regard, anyone actively engaged in water treatment technology can readily demonstrate that perfectly acceptable drinking water can be produced from contaminated source waters using relatively simple one-stage treatments (e.g. distillation, reverse osmosis). There are in fact existing single-unit, full-scale treatment processes of these types that can reduce high source levels of contaminants to the most stringent of existing use-based standards.

We are, therefore, not necessarily and specifically constrained by technology per se. Rather, the overriding problem is providing high quality water from low quality sources cost effectively, for processes of the type cited above would generally involve prohibitive costs for full-scale, stand-alone use. We are even now in water supply practice usually faced with selecting combinations of unit operations that provide required levels of treatment at total costs that are less per unit volume of water treated than the perceived “value(s)” of the water produced. Time and space constraints here do not allow detailed discussion of “true” vis-à-vis perceived and adopted costs and values, but that subject is in itself one of the keys to viable future water supply strategies and practices (National Water Research Institute, 1999; Weber and LeBoeuf, 1999; Weber, 2000). In the context of existing water infrastructures, multi-stage arrangements of processes usually involve complex multiple-unit, large central processing systems, and correspondingly large associated construction times, efforts, costs, and amortization periods. Such systems seldom can be implemented in a timely manner to meet evolving treatment needs and, once built, be flexible enough to respond to needs other than those for which they were specifically designed and constructed.

Logic
Given the deteriorating quality of our urban raw water sources, and the escalating technology requirements to meet increased product water quality, it no longer seems reasonable to believe we can afford to treat all of the water we use to the level of quality we desire for drinking and other personal uses; i.e., for uses that involve regular long-term exposure by ingestion and/or inhalation. It seems pointless, moreover, to even attempt this in the context of typical in-place urban water supply infrastructures (e.g. Figure 1). Such large volumes of high quality water produced at correspondingly large costs would, in all likelihood in most cases, be degraded in quality while transversing deteriorated distribution networks between central treatment plants and users’ taps. It may eventually become technically possible, and even economically feasible, to upgrade our massive central plants to produce water of the quality we desire for drinking and personal use. I have serious reservations, however, about whether it will ever be technically possible and economically feasible to replace all of our existing distribution networks with systems having both comparable hydraulic capacities and the enduring ability to maintain the integrity of that water quality.

Concept
DOT-NET is proposed here as an alternative strategy for potable water supply. It suggests bold departures from traditional visions and charter practices of current urban water supply institutions. Figure 2 is a schematic characterization of the DOT-NET concept: designations of water quality are again as defined in Table 1. It is to be specifically noted that the concept levers existing infrastructures in an innovative manner that allows cost-effective implementation of the most sophisticated optimal technologies exactly where and when they are required: i.e. for production of “personal” potable water of markedly and consistently higher quality. Key elements of the proposed concept include two different types of pluralized satellite or point of use/discharge treatment systems designed for advanced water treatment (AWT) and black water treatment (BWT).
The satellite AWT systems would process relatively low flows and would employ off-the-shelf treatment technologies of the most advanced nature (e.g. supra-selective foul-resistant membrane separations, customized polymeric adsorbents and molecular sieves, supercritical water oxidation, etc.). In essence, technologies that would not be affordable for application to the processing of all water distributed in typical urban systems. These processes would further be monitored regularly and controlled by micro electrical-mechanical systems, capable of wireless on-line data interpretation and real-time feedback control. Such systems are even now under development through joint efforts between the Environmental and Water Resources Engineering Program and the Center for Wireless Integrated Microsystems at the University of Michigan, among other places.

Self-contained black water treatment (BWT) systems are not as routinely available in off-the-shelf mode, nor do they at this time lend themselves as readily to automatic operation and control. Significant advances are, nonetheless, being made every day in such applicable areas as advanced oxidation technologies, membrane separations, and integrated bio-membrane systems. The major purpose of separate black water treatment is to reduce the disproportionate water quality burden this material imposes on the much larger volumes of less contaminated waters collected and routed to existing central treatment systems. Where possible, it would also be desirable in processing it in satellite systems to recover some of its energy and nutrient value(s), a potential cost reduction/recovery measure that is much more difficult once discharged to a large collection network. In reality, BWT may in most cases be less a technology-limited issue than an issue of publicly acceptable/attractive alternatives for on-site collection and use/reuse. Factors relating to this issue have been discussed in a recent publication edited by Lens et al. (2001).

The distribution and strategic placement of relatively small and highly effective treatment systems at specific locations in existing water supply and collection networks is a signature element of DOT-NET. The satellite AWT and BWT systems would be strategically located to serve the water use and waste elimination needs of population clusters such as housing subdivisions, apartment and condominium complexes, commercial districts, etc. Smaller scale point-of-use systems could serve individual households or individual buildings for rural populations that are dependent upon individually developed and maintained water systems. In both cases technologies of similar levels of sophistication and placement would also address major issues and problems associated with the collection, treatment, and “disposal” of what is traditionally viewed as “wastewater,” but which in the proposed scheme becomes a “raw” water source of reasonable quality.

**Closure**

The need for rethinking our approaches to potable water collection, processing, and distribution...
is evident. Concepts that have served us well in the past must be reexamined with respect to their appropriateness now and in the future. We have markedly improved the competency of our processing technologies over the past few decades. It is necessary for us now to raise the performance bars applied to our means for collection, storage and distribution to the same levels.

Can we afford to do this? Not unless we are creative in our thinking. Simply forging ahead with business as usual will not get us where we want to be with respect to potable water sustainability. In addition to the issues and concepts discussed above, we must, from an affordability point of view, begin to think about turning some of our “cost centers” into “profit centers.” This means, among other things, reconsideration and appropriate adjustment of product values and redistribution of roles between public utilities and for-profit supply and research institutions.

Many of the physical components of the system concept described above should lend themselves to: i) standardized and modularized design and construction; and ii) privatized vendor installation, maintenance, and operation. These features are not unlike those offered in commercially available water softener services today. The potential for technology innovation and commercialization of public drinking water products and services is beginning to be recognized broadly, even in developing countries (see, for example, Binder, 1998; Burton, 1998). This realization is evolving from compelling evidence that consumers of water who traditionally rebel at public water rates of approximately one U.S. dollar per thousand liters delivered to their tap are, at the same time, apparently more than willing to travel to the supermarket for a gallon of bottled water costing as much as one U.S. dollar or so per liter to use as drinking water; i.e. a cost, and apparent value, multiple of three orders of magnitude. Water is clearly becoming a tradable commodity of significant market value, and it will continue to grow as a major factor in international industry, commerce, and policy in the years ahead.

In summary, we can be confident of our abilities to use current technologies more effectively and develop more effective and demand-responsive technologies as necessary for producing enough potable water to meet our needs and demands. To do so, however, will require that we devise new and innovative infrastructures within which such technologies can be implemented more sensibly, effectively, and affordably. The DOT-NET concept provides a potentially fruitful first step in that direction.

References
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