Water: New Technologies for Managing and Ensuring Future Water Availability

Technology Innovation Program
National Institute of Standards and Technology
Gaithersburg, MD 20899

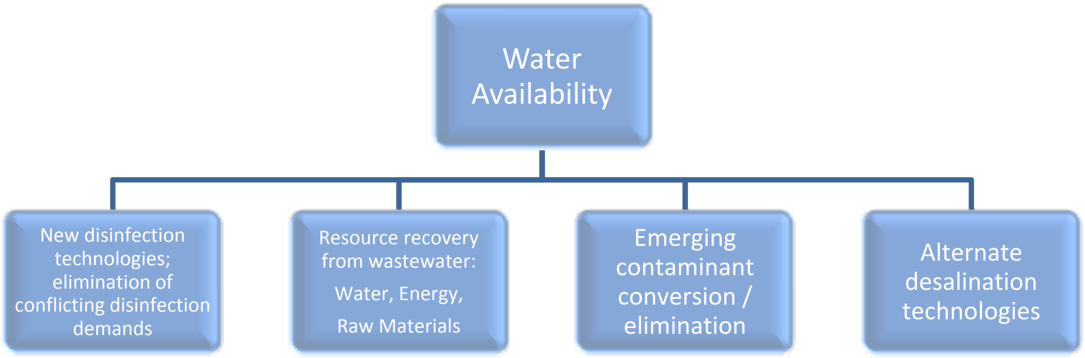
The Technology Innovation Program (TIP) [1] at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting U.S. businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions, to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of critical national need. Areas of critical national need are those areas that justify government attention because the magnitude of the problem is large and societal challenges that can be overcome with technology are not being sufficiently addressed.

TIP seeks to support accelerating high-risk, transformative research targeted to address key societal challenges. Funding selections will be merit-based, and may be provided to industry (small and medium-sized businesses), universities, and consortia. The primary mechanism for this support is cost-shared cooperative agreements awarded on the basis of merit competitions.

AN AREA OF CRITICAL NATIONAL NEED

The topic: “New Technologies for Managing and Ensuring Future Water Availability” is within the proposed critical national need area of water. This area of interest was selected from a larger field of areas where transformative research could be expected to have large societal impact. Input regarding potential areas of critical national need was obtained from government agencies and advisory bodies (such as the National Research Council, the National Academy of Sciences, the National Academy of Engineering and the Institute of Medicine), and the Science and Technology Policy Institute (STPI). Input was obtained from the Environmental Protection Agency, the American Water Works Association research organization and other industry organizations, and leading researchers from academic institutions.

Water supply is a complicated matter. Freshwater quantity at any particular location and at any particular time depends on climate and the dynamics of the movement of water through the hydrosphere. The ability to predict climate variation and the dynamics of the hydrosphere has long been the subject of Federally sponsored research, on the order of a billion dollars per year currently and in the foreseeable future. Freshwater quality depends on many factors both natural and anthropogenic. Some aspects of freshwater quality research have been well supported; however, there remain several societal challenges that are not being addressed.
The figure below shows the relation between several technology areas where investment would improve the cost-efficiency of water supply and thereby affect the critical national need of water availability.



The desired outcome is to have improved means for better managing the quality and quantity of delivered-water supplies and for protecting the public from waterborne-disease sources. Better tools are required: for environmentally benign disposition of brines and waste streams from desalination and water reclamation projects; for low-cost methods for removal of emerging contaminants from wastewater streams and from water distribution systems; for resource recovery from wastewater; and for transformative improvements in the energy costs of producing water from non-freshwater sources. Environmental issues of concentrated brine discharge from reverse osmosis plants limit deployment as permitting is a major constituent of the fixed costs of current desalination projects. The energy costs of new means of producing water and also for treating wastewater must be reduced to decouple water prices from energy prices and to provide cost-effective availability.

The need for advanced technologies for better managing water quality is both *national* and *critical* because every citizen in the nation needs clean water for life itself; every municipality and state in the nation has a responsibility for assuring the supply of safe water; and the economy depends on water supply. Just as energy prices enter into national economic pressures, so will water prices as security and scarceness affect the cost of delivered water.

Magnitude of the Problem

It is easy to take our supply of clean water for granted. Widely-available, publicly-supplied water that is purified and disinfected is a fairly recent historical development. Prior to 1900, the primary treatment method for publicly-supplied water, if any was used at all, was simple sand filtration. The first application of chemical water disinfection in the United States was in 1908 for the water supply of cattle in the stockyards of Chicago. The same year saw the first continuous chemical disinfection treatment of a community water supply – the East Jersey Water Company applied chlorination to meet contractual water quality commitments for Jersey City, against the objections of the city's commissioners. The first U.S. water standard was imposed by the Treasury department in 1914 (2 coliforms per 100 ml of water) and affected only interstate water transfers. In 1925, standards for lead, zinc, and copper were added. Disinfection of water became sufficiently widespread to nearly eradicate cholera and typhoid epidemics from the United States only as recently as the 1920s and 1930s. Our current versions of water treatment, combining disinfection and decontamination, therefore, are only about eighty years old. Wastewater treatment is also fairly recent; as late as 1924 more than 88 percent of communities of over 100,000 residents discharged their sewage directly (untreated) into waterways; those that didn't discharge sewage directly into waterways used the sewage in agricultural fields as fertilizer.

Water is essential to the quality of life. The consumer uses water directly, from the household tap, and also indirectly. Large supplies of water are used in agriculture and can affect directly the quality of agricultural products ranging from ready-to-eat organic produce to meat products. Freshwater is also consumed in large quantities in manufacturing and energy production. Altogether, the nation consumes roughly 210 billion gallons of water every day for all uses other than energy production.

There are several different types of freshwater sources and several different types of water usages. Public water facilities supply more than 43 billion gallons of water per day and households self-supply another 3.6 billion gallons daily from privately owned wells. Irrigation, much of which is crop irrigation, consumes 137 billion gallons of water per day. Also drawing on freshwater supplies are industrial usages of 18 billion gallons per day. [2] Supplying freshwater are the public water systems that comprise 53,000 community water systems, and 21,400 not-for-profit, non-community systems. In addition to the community systems, large numbers of Americans have privately-owned wells drawing on groundwater, as do farmers for irrigation and businesses for industrial use. [3] The variety of water sources and uses presents challenges to technological solutions to rising problems of supplying sufficient high-quality water.

As the nation's population and economy grow, more freshwater is required. As weather and climate changes continuously, water stands to become scarcer in some areas, either temporarily or permanently. Increasing demands on water supplies have led to contention between communities and between states. As an example, the states of Alabama, Georgia, and Florida have been fighting over the Apalachicola-Chattahoochee-Flint and the Alabama-Caloosa-Tallapoosa river systems for thirty years and have embroiled the Federal government in litigation for almost twenty years in these matters. As another example, regional population increases coupled with a multi-year drought in the Western states is leading to concern over potential renegotiation of the 1922 Colorado River Compact. The Colorado River is particularly illustrative of the problems associated with scarce water supplies. Before it reaches its geographical end at the Sea of Cortez, the Colorado is often sucked dry by upriver consumption leaving only a dry riverbed.

Other areas not thought of as drought-stricken or as arid deserts--communities in Maryland and Massachusetts--have had to institute temporary building moratoria due to water scarcity. Communities in non-arid areas, seeking adequate water supplies, are turning to desalination as the means of augmenting their freshwater supplies. The town of Brockton Massachusetts, after reducing water consumption from 11 million gallons per day to 9 million gallons per day, has opened a 4 million-gallon-per-day filtration-desalination plant. The Tampa Bay area now supplies approximately 10% of its water supply from a single 28 million-gallon-per-day reverse osmosis desalination facility. These join other desalination plants in Texas, Florida, and California.

In some ways, the situation with water is similar to that of petroleum. As demand for petroleum-based products outstrips supply of sweet crude oil, producers and refiners are forced to process lower quality crude oils and other nontraditional sources like tar sands. The higher costs of processing the lower quality crudes translate into higher costs for energy products and petrochemicals, which then ripple through the economy. The same model is applicable to water; as water demands increase, more expensive means of recovering fresh water from lower quality waters are employed, the costs of which will have to be passed into the economy.

In addition to the growing need for larger quantities of freshwater, delivery of sanitary freshwater faces expanding challenges for maintaining and/or improving the quality of the delivered water. Mandatory reductions in contaminant levels, concerns over emerging contaminants, and the means of monitoring water quality across an entire water-delivery system, in order to protect system wide water quality, will drive upwards the cost of the water supply unless technology can transform the means for better management of delivered water supplies.

Finally, any address of water's societal challenges must be cognizant of the water-energy nexus. Energy is required to produce consumable water – and copious amounts of water are used in the generation of energy. The interlinking of energy and water has the potential to produce positive feedback loops in the economics of producing energy and consumable water. There are many consequences to this nexus.

- The energy cost of producing and distributing consumable water comprises both a direct economic cost and a cost in greenhouse gas production. If water standards are increased, energy consumption to achieve the standard must inevitably increase, using current technologies.
- Often, the economics of producing consumable water from marginal supplies, and municipal water pricing, are calculated on a presumed energy cost per gallon of water produced. As energy costs fluctuate, projects not economical one year may become economical the next year, and vice versa.
- Wastewater is a rich, and unaccessed, energy source. Currently, energy is expended treating waste and little or no resource recovery is achieved. Wastewater and sludge solids are rich in phosphorus, energy, and other resources. With phosphate rock reserves declining the United States has approximately 40 years of reserve at current production levels (USGS 2008).

MAPPING TO NATIONAL OBJECTIVES

The focus upon New Technologies for Managing and Ensuring Future Water Availability as a Critical National Need maps well upon national objectives, Administration guidance, Congressional testimony, and NIST's core competencies.

The National Science and Technology Council identified several challenges of meeting future U.S. demands for water. Among those challenges, the Council wrote “The United States should develop methods that will allow expansion of fresh water supplies while using existing supplies more efficiently.” The proposed critical national need aligns well with the Council’s assessment: “Expanding the water supply should be accomplished through technological means by making poor-quality water usable.”[2]

As a representative of the Administration, the EPA Administrator, Lisa P. Jackson, has spoken at length regarding the need to bring innovation to bear on emerging contaminant problems and their removal from water supplies, specifically in the need to accelerate development and adoption of treatment technologies [3]. The Administration has also initiated a water census project through the U.S. Geological Survey, a recognition of pressing water quantity issues.

Congressional committees are focusing more attention on issues of water quality, recently holding hearings on emerging contaminants [4] and water availability [5].

NIST conducts research and facilitates efforts with consensus determinations of water quality for different processes and uses. Research at the intersections of water supply with nanomanufacturing or with energy reduction research also capitalize on NIST’s strengths in nanotechnology and thermodynamics.

MEETING TIMELY NEEDS NOT MET BY OTHERS

The Federal government’s expenditures for research in monitoring and predicting climate variability are large and increasing—involving most, if not all, of the research budget of the National Oceanic and Atmospheric Agency, and also a significant portion of the research budget of the U.S. Geological Survey.

Federal research on desalination technologies, be they for purification of seawater, brackish water, or waste streams, is accomplished primarily by earmarked-funding of projects. Additionally, some states also sponsor research on desalination. Most of these projects are improvements or scale-ups of reverse-osmosis projects, but do also include basic and applied research through some Federally funded research centers. There appears to be very little federal funding of new technologies (non-membrane technologies) that could provide the dramatic reduction of energy consumption like that observed when reverse-osmosis technologies disrupted thermal desalination technology.

National Science Foundation funding support of water purification methods is aimed primarily at basic research, does not generally fund for-profit research organizations, and does not appear to address the high-risk, high-reward research necessary to provide technologies on a scale applicable to meeting societal needs.

Other funding sources, e.g., the Environmental Protection Agency, the Water Environment Research Fund, and the American Water Works Association's Research Fund, are directed at shorter time-frame issues many of which affect regulatory compliance.

Timely needs include, but are not limited to:

- Next generation water purification that can provide an energy reduction from that required for reverse-osmosis technologies analogous to the energy reduction that reverse osmosis technologies achieved over that for thermal desalination technologies.
- Next generation contaminant removal/conversion for emerging contaminants.
- Means to cost efficiently produce large quantities of membranes with embedded nanochannels, suitable for deployment in large-scale, water purification facilities.
- Harvesting energy carriers and other resources from solid waste and wastewater discharge. Higher efficiency energy recovery, higher quality materials recovery, e.g. high efficiency phosphate recovery with low heavy metal contamination.

Societal Challenges

Societal challenges are defined as problems or issues confronted by society that when not addressed could negatively affect the overall function and quality of life of the nation, and as such justify government attention. Without a supply of freshwater, all other issues of water quality are moot. Freshwater is the nation's primary source of water for domestic and industrial uses and for irrigation. In many locations, the available supply of freshwater varies over time. Droughts, which can exist in patterns of many years, can affect freshwater availability in many areas of the country. Large population shifts into arid regions can push demand for freshwater beyond available supply. Water managers, however, have little ability to forecast long-term water supply availability, which depends on long-term weather prediction, predicted future water-use patterns, and predicted population fluxes.

Many regions affected by vagaries in natural freshwater supplies have access to non-freshwater supplies. The naturally occurring freshwater supplies could be augmented by converting non-freshwater supplies, e.g. seawater, brackish water, or wastewater streams, through purification technologies. Although there are currently technologies for accomplishing purification of many of these non-freshwater sources, transformative research would improve the economics of capturing these water supplies, yielding significant benefits to communities in regions whose water costs stand in peril.

We consider the following societal challenges to maintaining the water supply necessary for the nation.

Water Quality

Disinfection / Decontamination – Disinfection and decontamination of water prior to distribution are essential to meet current and future water-quality standards. However, as the list of regulated substances grows, and/or as regulated contaminant levels drop, current disinfection and decontamination technologies face serious challenges. As one example of these challenges, as bacterial and viral pathogens become easier to detect, regulations for their removal appear and also challenge current chemical disinfection methods – e.g. cryptosporidium parvum and mycobacterium avium are somewhat resistant to chlorine disinfection. Ozone disinfection, which is highly efficient for viruses and protozoan parasites, however, forms carcinogenic bromate ions in waters containing naturally occurring bromide. UV disinfection is capable of sanitizing water of most pathogens at a single point, with exceptions like adenovirus, but provides no residual disinfection capability against pathogens that may be found harboring in the biofilms that line the water delivery systems. As a further challenge, changing disinfection strategies changes the chemistry of the water in delivery systems that are decades old. The changed disinfection chemistry can result in unpredicted effects on the scales formed over decades on the interior of the water pipes, which may release deposited harmful materials into the delivered water streams. Real-life experiences in the Washington, D.C., water system showed abrupt rises in dissolved lead levels at home faucets after the disinfecting agent was switched to chloramine, in order to reduce the concentration of chlorinated disinfection by-products.

Decontamination of water from emerging contaminants will also be an increasing societal challenge. Chemical reactions of contaminants with disinfectants may produce new contaminants with unknown health effects. Removal of contaminants like arsenic, heavy metals, and distillates from water supplies will produce hazardous waste streams at each municipal treatment plant and at each well. Conversion of contaminants to harmless forms may compete with contaminant removal in a cost-benefit analysis. Yet, there is insufficient knowledge regarding any of these matters.

Waterborne diseases. A common problem in the public consciousness is contamination of drinking water or agricultural products with waterborne microorganisms or chemical toxins. Either of these situations can lead to waterborne disease outbreaks. The minimum floor on waterborne disease outbreaks is established through data voluntarily reported for inclusion in the CDC's Surveillance for Water-borne Diseases. [6] Exact numbers of water-borne disease outbreaks are not known because 1) the current reporting system is voluntary; and 2) the data, being epidemiological, may not observe small outbreaks within large populations. The number of water-borne disease outbreaks remains on the order of 15 per year. However, the percentage of outbreaks from community water systems that were due to main breaks and pipe replacements grew from 1990 to 2002. [7] Main breaks are projected to continue to increase due to the aging of many urban water delivery systems, and as such the numbers of waterborne-disease outbreaks may be expected to increase in the future. The changing demographics of the population compounds the problem of the damages caused by waterborne-disease outbreaks because microorganism-based waterborne diseases generally cause the most acute health effects in the elderly and those with compromised immune systems. As the percentage of the population in the upper age brackets increases, the damages from waterborne disease outbreaks can be expected to increase proportionately. More difficult to track than waterborne diseases from water-systems are disease outbreaks from microorganisms in agricultural products. Many of these outbreaks trace back to contaminated water at some point in the agricultural process, contamination that could have been introduced by either irrigation water or by water used in cleaning and processing foods, particularly ready-to-eat produce.

There are several problems that arise in the detection of harmful microorganisms in the water supply system. The life cycle of many parasites or harmful organisms involve an oocyst or spore. This stage is very hardy and can survive for extended periods of time. Methods for quantitative detection of microorganisms or spores, such as using fluorescent antibody staining, following collection and immunomagnetic separation, require fairly expensive equipment, trained personnel, and give only spot determinations, as opposed to continuous and autonomous monitoring of water at many points throughout the water-supply system. The cost burden of the current technology is quite significant for smaller municipal water systems. Contaminated irrigation water faces the same constraints–-it is not plausible to maintain an immuno-fluorescence facility in every tomato, lettuce, and spinach field in the nation, nor in every produce processing plant. Further complicating the detection problem for irrigation water and agricultural products is the presence of innocuous microorganisms that present no public-health threat. Any detection method destined for widespread deployment that can determine and identify harmful microorganisms on agricultural products or in irrigation and wash waters would have to distinguish between harmful and harmless microorganisms.

Emerging contaminants. Emerging contaminants are currently unregulated materials that can now be measured in water sources due to advances in analytical chemistry or are new materials with only a recent history of release into the environment. These substances include household products, naturally occurring elements such as arsenic, and other chemicals, for example, methyl-t-butyl ether, a gasoline additive. One example is considered here, methyl-t-butyl ether. MTBE: Methyl-t-butyl ether (MTBE) is an additive that has been added to gasoline since 1992 in response to Clean Air Act amendments. MTBE, over long periods of time, corrodes underground storage tanks and has contaminated surface and ground waters in several states. At 5 micrograms per liter of water, it imparts an unpleasant kerosene taste to water that makes the water unpotable. Cleanup of MTBE is complicated due to its high solubility in water. Estimates for cleanup costs vary widely; an AWWA study places the costs at $25 billion or higher. These costs are multifaceted, including removal of all MTBE from ground water and municipally supplied water, removal of leaking storage tanks, and other costs. There is substantial evidence of microbial attenuation of MTBE in the environment. Research on microbial remediation could make order of magnitude reductions in the costs of MTBE cleanup. This example is only representative of one of the future challenges faced in decontamination of water supplies. New treatment methods that are flexible so as to adapt to changing future water regulations are essential.

Energy Recovery

Harvesting resources from wastewater. Treatment of municipal waste discharge is viewed as a necessary burden. This perception is a result of the technologies available for handling municipal wastes, in which energy is consumed to filter, coagulate, settle, and dry a sludge waste from the contained sewer system. Currently, most biosolids obtained from sewage sludge are treated as refuse and disposed in landfills, composted, or spread as a soil amendment.

The reality, however, is that municipal waste contains significant unrecovered energy and chemical resources. The energy content of dewatered sludge is an order of magnitude greater than the energy required to operate the treatment facility that produces it. New technologies are needed to cost effectively derive from the waste biosolids an energy stream, such as hydrogen, natural gas, or some other energy carrier. Previous trial efforts have yielded megawatt capacities from waste treatment facilities.

Better technologies are needed for recovery of phosphorus from both the discharged water from municipal waste treatment facilities and the solids portion of the waste stream. Phosphorus, a key agricultural input, is a limited resource. The United States has a reserve of phosphorus rock that is sufficient to meet demands for only the next 40 to 100 years at current usage rates. Increases in phosphorus rock prices in 2008 passed directly into fertilizer prices and agricultural commodity prices. Driving the price increases in 2008 were sharp demand increases with a limited capacity to supply those demands as well as energy commodity prices. Cost-effective means to recover phosphorus from waste streams has multiple benefits: it is a source of supply that extends reserves and increases supply, and removal of phosphorus from wastewater released into the environment reduces algal blooms, which damage ecosystems. A particular challenge for phosphorus recycling technologies is removal of heavy metals from the produced phosphorus product. Ultimately, municipal waste treatment could become an economic resource.

Water Quantity

Reclaimed Water / Desalination. As water demand grows and also as regions undergo long-term climate changes, there is an increasing societal challenge of insufficient freshwater sources. There are at least three means related to relieving pressure on local water supplies; conservation, reclamation of wastewater, and desalination of brackish water or sea water. Conservation is well enough supported by other venues. Here, reclamation of wastewater refers to the processes by which treated wastewater is used to augment the water supply, rather than being released back into the environment.[1] Current municipal water reclamation projects supply water for non-

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[1] Although treated wastewater released into the environment is also referred to as reclaimed water (reclamation), for the purposes of this document, water reclamation is used to describe water removed from the wastewater stream and supplied for usage rather than simply released back into the environment.

domestic consumption, for example, irrigation of golf courses. Many industrial concerns, ranging from chemical manufacturing to carwashes, reclaim and/or recycle their water. Ultrafiltration and reverse osmosis technology currently exists for reclaiming wastewater with a quality that meets or exceeds current EPA drinking water standards.[2] The economics of water reclamation, however, are currently prohibitive for widespread usage as a supplement to domestic water supplies. [8] The economics of water reclamation depend not only on the water purification technology but also on the disposition of the residual material left after water removal. Vast differences in economics could be envisioned dependent on whether the residual material must be treated as a separate waste stream or whether a commercial end-use for the processed waste could be developed.

Because reclamation of wastewater and conservation both depend on an initial supply of water, which may decline or disappear for some communities, desalination of brackish water or sea water must also be considered for communities whose future water supply needs are projected to exceed projected available freshwater supplies. Desalination is, in fact, practiced in many locations throughout the world. Desalination of brackish water or sea water is achieved by either reverse osmosis or some form of thermal distillation, whether by multistage flash distillation or multi-effect distillation. The marginal costs of water produced from either reverse osmosis or distillation are coupled to energy prices. The energy demands of reverse osmosis purification depend directly on the pressure required to effect separation, which depends directly on the total dissolved solids concentration (TDS) in the feedwater. Conversely, the energy requirement for distillation is essentially independent of TDS concentration. Both thermal distillation and reverse osmosis desalination are relatively mature technologies. For reverse osmosis desalination, membrane costs and energy recovery efficiencies have been improved significantly in the last ten years. Current energy consumption in the process is approximately twice the thermodynamic limit. For comparison purposes, the energy costs for desalination of seawater at a modern test-bed facility in Southern California have reached par with the energy costs of water delivered to Southern California via the California Aqueduct.[3] Recently, a multi-staged nanofiltration technology for desalination has been demonstrated also. The multistage process lowers the highest pressures required in the system, thereby lowering some of the energy costs of a single-stage desalination process. A significant barrier to desalination deployment is the uncertainty regarding the environmental impacts of the concentrated brines that result from desalination. Also of concern is the potential for aquatic biota to be harmed by water intakes. The Chair of the Committee on Advancing Desalination Technology (of the National Research Council) is quoted as saying; “Uncertainties about desalination’s environmental impacts are currently a significant barrier to its wider

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[2] Water is reclaimed by passing the wastewater stream through low-pressure membrane filters, passing the filtrate through a reverse-osmosis purification step, and then disinfecting the purified water stream for distribution.

[3] The California Aqueduct moves water from Northern California to Southern California. Water must be pumped over several geographical rises, including a nearly 2,000 foot rise through the Tehachapi Mountains. Geographical rises are followed by descents. In cases where descents are steep there is a partial recovery of the pumping energy through hydroelectric generation.

use, and research on these effects – and ways to lessen them – should be the top priority.”[9]

Although basic research in nanotechnology has pointed to means of increased membrane efficiencies for high-efficiency filtration and perhaps for desalination, e.g. use of carbon nanotubes as membrane pores or molecular combs attached to pore entries, most of these projects have been conducted without an eye to the economics of deployment. For example, although there is great interest in the insertion of carbon nanotubes in a polymeric membrane, accomplishable in a laboratory a square millimeter at a time, there seems to be far less interest in devising how one would make millions of square meters of such a membrane at a sufficiently low cost that water does not become so expensive as to be unattainable. Here the confluence of nanomanufacturing with water applications is a greatly fertile area.

Most federal and state funding for desalination is earmarked for specific projects. Industrial research is aimed at membrane improvements compatible with existing reverse-osmosis or nanofiltration technologies, energy recovery devices, and other incremental research. There appears to be little to no funding for methods that are an alternative to membrane technologies for water desalination that could ultimately provide better energy cost-efficiencies for water purification.

These societal challenges require transformative, multidisplinary research at the intersections of the traditional research areas of water and energy science and of water and manufacturing of new nano-structured materials and of water and green/sustainable chemical processing.

Summary

The societal challenges–needed improvements in providing sufficient quantities, quality, and security of water supplies; reducing the energy consumption for water systems; and recovery of resources from wastewater–can potentially be resolved with better and more cost-effective technologies. There is not a coherent pattern to funding the research required to ensure low-cost, high-quality water systems for population use. Most federal funding on water research, billions of dollars, is involved in modeling the hydrosphere, with very little spent on advanced solutions that provide delivery of public water supplies adequate for future population growth.

New transformative research could lead to:

- New decontamination technologies for current and emerging contaminants
- New disinfection technologies and less expensive means for dealing with water-borne microorganisms
- Recovery of energy and other resources from the wastewater stream
- Providing new means for desalination of brackish and sea waters; means for environmentally benign disposition of the concentrated streams from desalination processes.

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