NTSC COMMITTEE ON TECHNOLOGY
SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

Nanotechnology Signature Initiative

Water Sustainability through Nanotechnology:

Nanoscale Solutions for a Global-Scale Challenge

Collaborating Agencies:[1] *DOC/NIST, DOE, EPA, NASA, NSF, USDA/NIFA*

March 22, 2016

National Need Addressed

Water is essential to all life, and its significance bridges many critical areas for society: food, energy, security, and the environment. Projected population growth in the coming decades and associated increases in demands for water exacerbate the mounting pressure to address water sustainability. Yet, only 2.5% of the world's water is fresh water, and some of the most severe impacts of climate change are on our country's water resources. For example, in 2012, droughts affected about two-thirds of the continental United States, impacting water supplies, tourism, transportation, energy, and fisheries – costing the agricultural sector alone $30 billion. In addition, the ground water in many of the Nation's aquifers is being depleted at unsustainable rates, which necessitates drilling ever deeper to tap groundwater resources. Finally, water infrastructure is a critically important but sometimes overlooked aspect of water treatment and distribution. Both technological and sociopolitical solutions are required to address these problems.

The small size and unique properties of engineered nanomaterials (ENMs) are particularly promising for addressing the pressing technical challenges related to water quality and quantity. For example, the increased surface area and reactivity of ENMs can be exploited to create precious-metal-free catalysts for water purification, and the enhanced strength-to-weight properties of nanocomposites can be used to make stronger, lighter, and more durable piping systems and components. The goal of the *Water Sustainability through Nanotechnology* Signature Initiative (the "Water NSI") is to take advantage of the unique properties of engineered nanomaterials to generate significant breakthroughs in addressing our Nation's water challenges. This initiative is designed to aid in the development of technological solutions that can alleviate current stresses on the water supply and provide methods to sustainably utilize water resources in the future. The three specific thrusts of the Water NSI are as follows:

1. Increase water availability using nanotechnology.
2. Improve the efficiency of water delivery and use with nanotechnology.
3. Enable next-generation water monitoring systems with nanotechnology.

This white paper highlights key technical challenges for each thrust, identifies key objectives to overcome those challenges, and notes promising areas of research and development where nanotechnology promises to provide the needed solutions. By shining a spotlight on these areas, this NSI will increase Federal coordination and collaboration, including with public and private stakeholders, which is vital to making progress in these areas. The additional focus and associated collective efforts will advance stewardship of water resources to support the essential food, energy, security, and environment needs of all stakeholders.

[1] Please note that "collaborating agencies" is meant in the broadest sense and does not necessarily imply that agencies provide additional funds or incur obligation to do so. Agencies are listed in alphabetical order.

Technical Program

The *Water Sustainability through Nanotechnology* Signature Initiative has thrusts on increasing water availability (Thrust 1) and on improving the water and energy efficiencies associated with moving and delivering water (Thrust 2). The third thrust on next-generation water monitoring systems will enable smart water management in pursuit of the goals laid out in Thrusts 1 and 2. The agencies participating in the Water NSI have identified several key objectives under each of the three thrusts that can be uniquely pursued through the targeted interagency collaboration that is supported by this NSI. In addition to tackling the technical challenges of applying nanotechnology to water issues, the safety of nanotechnologies used in water treatment and distribution systems must be ensured; as such, environmental, health, and safety issues are central to all of the thrust areas, as described below.

Thrust 1: Increase Water Availability Using Nanotechnology

Population growth, urban migration, and the effects of extreme events associated with climate change make water availability an increasingly pressing issue. The Third National Climate Assessment finds that water demand in the United States is projected to increase over the next several decades, possibly rising by as much as 34% over 2005 levels by 2060 [*1*]. Couple this increased demand with the fact that many of the Nation's aquifers are being depleted at unsustainable rates (Figure 1; [*2*]), and water managers may face increased challenges in locating appropriate water sources in the future. Use of "nontraditional waters"[2] in major water-using sectors has the potential to mitigate freshwater shortages and to provide other benefits to agriculture, energy, and industrial end-users. These nontraditional uses, however, are often hampered by technological barriers and high costs that currently prohibit most communities from turning nontraditional water sources into fresh water. However, technologies are being developed, for instance, to improve recycling of waste water and sewage treatment, so that water can be used for nonpersonal uses such as irrigation or industrial purposes. Recycled water resupplies some critical aquifers, but outreach may be needed to educate the public about the advantages, disadvantages, and consequences of water recycling [*3*].

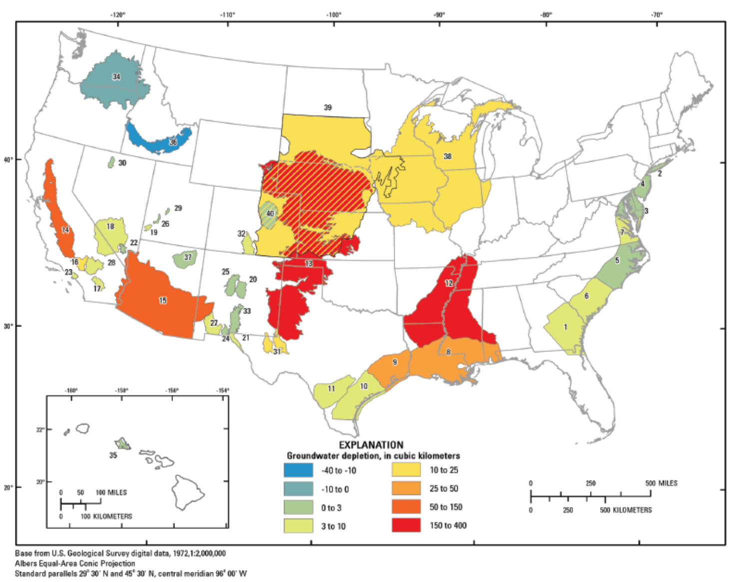

Figure 1. Map of the United States (excluding Alaska) showing cumulative volume of groundwater depletion, 1900 through 2008, in 40 assessed aquifer systems or subareas [*2*].

Nanomaterials have unique size-dependent properties, such as high surface area and reactivity, that make them ideal for treating nontraditional water sources, and these properties can enable the development of novel nanotechnology-based solutions for more efficient utilization of drinking water, nontraditional water sources, and wastewater treatment processes. Indeed, there are many nanotechnology-enabled approaches

[2] In this document, the term *nontraditional waters* is used broadly to describe all waters not traditionally used by the energy, industry, and agricultural sectors that could displace traditional sources of fresh water and potable water. This category includes saline waters, brackish or impaired ground water, municipal waste water effluent, produced waters from oil and gas wells, agricultural return flows, and onsite grey water and rain water recovery, as well as other sources. This definition is based in part on the 2012 National Research Council Report on Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater.

that could be applied during key steps in the water treatment process [*4*, *5*]. For example, membranes can be designed with nanoscale pores that remove specific pollutants while allowing water molecules and important nutrients to pass through, and the antimicrobial properties of silver nanoparticles can be utilized for point-of-use water disinfection. Given the broad application space for nanotechnology-enabled water treatment, the agencies participating in the Water NSI have identified the following key objectives where interagency coordination can lead to nanotechnology-enabled improvements in water purification technologies to increase water availability:

- Use nanotechnology to double the throughput and halve the cost of **filtration and membrane separation systems** within 5 years.
- Demonstrate **nanotechnology-enabled alternatives to reverse osmosis for desalination** within 5 years. Within 10 years facilitate the transfer of these technologies from demonstration to market.
- Develop **nanoscale catalysts** for use in water treatment that can completely replace precious-metal–based catalysts within 10 years.

Filter- and membrane-based water purification and disinfection technologies are critically important for a wide variety of applications, including food processing, wastewater treatment, medical applications such as artificial kidneys, and environmental protection. The incorporation of nanoscale features and nanomaterials into membranes and filters offers several compelling opportunities, such as high selectivity and antifouling functionality. For instance, in the case of membranes, the feature sizes of nanostructured surfaces allows fine-tuning of flux, selectivity, and strength to optimize performance [*6*, *7*]. More advanced developments in atomically precise membranes could separate greenhouse gases from air and pure water from salt water. Alternatively, the introduction of carbon nanomaterials such as nanotubes and graphene offers a unique combination of robustness, precise control, and ease of functionalization to create desirable membrane characteristics [*8*]. Both of these approaches also show promise in reducing fouling—perhaps the key challenge in the cost-effective deployment of advanced membrane systems [*9*, *10*].

In the case of filters, nanoscale morphology provides a high surface area for adsorbing pollutant molecules. Further functionalization or decoration of surface groups or inclusion of metal clusters as adsorption sites can enhance the adsorption capacity and selectivity. For example, photocatalytically active silver–titanium dioxide nanofibers [*11*] could be used in a filter with chromate-absorbing iron oxide nanofibers [*12*] to treat water contaminated by agrochemicals and other impurities that are common in rural areas. However, the ability to regenerate nanoscale sorbents for reuse remains a challenge. Additional improvements in nanotechnology-enabled filters may be available through broadening the range of materials used for sorbents, the types of pollutants they can treat, and the types of membranes whose capabilities they can enhance. Further, long-term technology improvements may result in systems that require less pressure and are more resistant to biofouling and scaling.

Over 96% of the water on earth is sea water, and desalination offers an opportunity to convert previously unusable saline water to fresh water. Reverse osmosis (RO), often in combination with nanofiltration pretreatment, has emerged as the predominant technology used in desalination operations in the United States. However, sea water that is treated with current commercial RO systems is significantly higher in cost than water from traditional sources. Moreover, alternatives to RO may offer opportunities for cost, energy, and carbon emissions reductions, as well as smaller infrastructure requirements. Technologies such as forward osmosis, multi-effect distillation, multistage flash distillation, membrane distillation, freeze separation, and capacitive deionization potentially can be used in commercial desalination of both brackish water and sea water, but these technologies will require research advances to achieve “pipe parity” or achieve costs equal to those of current processes for delivering fresh water. The research needs for these technologies are wide-ranging, but nanotechnology could enable several potential “game-changing” advances. For example, nanotechnology-enabled working fluids have the potential to boost heat-carrying capacity, which would be advantageous for technologies that employ heat exchange (e.g., multi-effect distillation, multistage flash distillation, membrane distillation, and dew vaporization), particularly if the nanoparticle-enhanced fluids are low-cost. Nanoengineered surfaces can also reduce fouling, biofilm formation, and scaling [*13*], effectively reducing efficiency losses and improving component lifetimes in the technologies that employ heated fluids. As described above, nanotechnology offers many potential improvements over current membrane technologies, and these improvements would also be beneficial for alternatives to RO that utilize membranes, such as forward osmosis and membrane distillation. Finally, novel electrodes are needed for capacitive deionization; nanostructured electrodes may improve the efficiency of this process due to their high surface areas and, depending on the nanomaterial, favorable electronic properties [*14, 15*].

In contrast to the technologies above which separate and exclude contaminants, catalysis is used to destroy or inactivate organic pollutants and pathogens. Catalysis could be used, for example, to replace chemical biocides that can have unintended consequences, such as production of carcinogenic by-products [*4*]. Precious metals such as gold, silver, palladium, and platinum have excellent catalytic activity, but these materials are rare and expensive. In addition to reducing costs by eliminating expensive precious metals, the increased surface area of nanoscale catalysts could also improve reactivity. Furthermore, the electronic properties of nanoscale catalysts can be tuned by precisely controlling the size and spatial arrangement of homogeneous, subnanometer clusters, and the application of a nanomaterials-by-design approach could enable nanoscale catalysts that are more selective, treat a broader range of contaminants, and have longer lifetimes.

Thrust 2: Improve the Efficiency of Water Delivery and Use with Nanotechnology

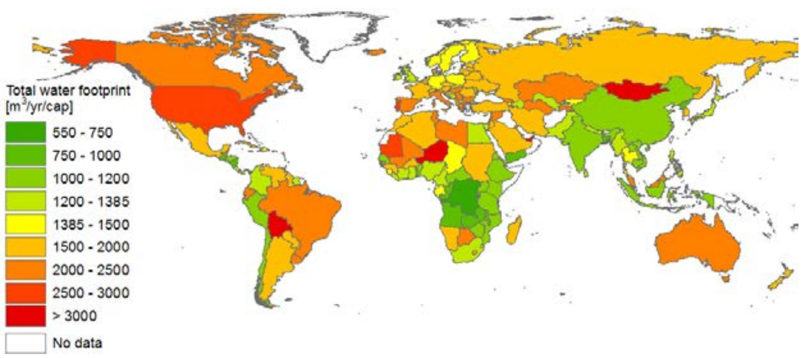

Figure 2. The total water footprint of consumption per country in the period 1996–2005 (m^3/year per capita) [*16*].

The per-capita water footprint in the United States between 1996 and 2005 was approximately twice the global average and 1.5 times that of other industrialized nations (see Figure 2; [*16*]). By continuing to support the efforts of businesses, industries, and communities to efficiently deliver and use water—especially in water-stressed regions—and through better management practices and new technologies, the country's water usage could potentially be reduced by 33% [*17*]. This reduction would bring U.S. consumption levels in line with those of other industrialized nations and could reduce the Nation's total CO_2 emissions by about 1.5% annually [*18, 19*].

There are many promising avenues for increasing the efficiency of water delivery and use—from consumers implementing water-saving behaviors at home, to manufacturers repairing leaks and modifying inefficient processes—so a holistic approach is needed. However, nanotechnology is uniquely poised to enable significant gains in water efficiency and to reduce energy needs associated with transporting and using water. For example, self-healing nanoscale coatings could be used to repair leaky pipes, and new nanomaterials could enable low-water-withdrawal cooling technologies for thermoelectric power generation. In addition, nanotechnology can reduce water use in other parts of the energy system. Nanotechnology-enhanced fluids can replace fresh water in hydraulic fracturing, geothermal operations, and power cycles, and nanoparticle-enhanced fluids have also shown promise as working fluids for heat exchangers [*20*]. The agencies participating in the Water NSI have identified several objectives where nanotechnology can improve the efficiency of water delivery and use and that can be uniquely advanced through interagency coordination:

- Develop within 5 years nanotechnology-enabled coatings that **reduce the amount of energy needed to transport water through pipes** by reducing friction loss by 50%.
- Develop within 10 years **nanotechnology-enabled piping systems and components** that are lighter, stronger, and longer-lasting; that eliminate or greatly reduce the development of biofilms, corrosion, and scaling; and that cost less than currently used technologies.
- Within 5 years, develop low-cost photonic nanostructures to **enable the use of solar thermal energy for industrial heat processes**, including water purification, food processing, and enhanced oil recovery.
- Develop within 10 years low-cost, long-lived nanotechnology-enabled liquids, coatings, and materials to **improve water and energy efficiency of heating and cooling** by at least a factor of five while dramatically reducing maintenance needs and costs.

Pumping water can be one of the most energy-intensive parts of water treatment and delivery, but the energy required to transport water could be reduced through the use of nanotechnology. For example nanotechnology-enabled coatings could decrease friction and increase the flow rate. In fact, coatings formed by infusing a nanoporous substrate with a lubricating liquid can provide a self-healing hydrophobic layer that reduces drag by 7% [*21*]. Coatings may also be engineered to provide antifouling, anticorrosion, and antiscaling properties. The benefits, including energy and cost savings, provided by these types of improvements are highly desirable for irrigation systems, public and industrial water distribution systems, and even future space flights. Nanotechnology-enabled coatings are also attractive because they can be applied to existing pipes and other water distribution components as a cost-effective means of improving functionality without replacing infrastructure, and they may also extend infrastructure lifetimes by reducing corrosion.

While nanotechnology-enabled coatings can be applied to existing infrastructure in the short term, nanocomposites could potentially revolutionize piping systems and components in the midterm. Nanocomposites are already employed in industries from aerospace to sporting goods, and the properties that make nanocomposites attractive for these applications, namely high strength-to-weight ratios and durability, are also desirable traits for piping systems and components. While the development of nanocomposites for advanced pipes, flanges, pumps, radiators, and other related equipment can build on the knowledge developed in other sectors, water distribution systems have unique challenges that warrant further research. For example, piping systems and components are subject to processes such as biofouling, corrosion, and scaling that increase flow resistance and reduce lifetimes. The formation of biofilms is particularly problematic because traditional treatments use aggressive chemicals. If a nanocomposite or other surface could be designed with intrinsic biofouling resistance, for example, with nanoscale structures that prevent bacterial adhesion, it could reduce or eliminate treatment requirements while simultaneously minimizing potentially environmentally deleterious waste discharges.

Heating and cooling are critical processes in a wide variety of applications and settings, from climate control in commercial and residential buildings to thermal management in manufacturing and power generation. Yet, heating and cooling can require large amounts of energy and heat-transfer medium, which is often water. The distinctive, size-dependent properties of nanomaterials can be exploited to conserve both the energy and water used for heating and cooling. For example, coating a condensation tube with hydrophobic graphene has been shown to enhance heat transfer by a factor of four [*22*]. Additionally, these graphene coatings are more robust than traditional polymeric hydrophobic coatings when exposed to power plant operating conditions (e.g., high temperature and humidity). Another promising area is the application of nanotechnology to increase radiative cooling capabilities. Innovations in nanotechnology-enabled dry cooling can support the development of low-water-withdrawal technologies for thermoelectric power plants, which is particularly desirable because these plants account for a large percentage of total water withdrawals in the United States—45% in 2010 [*23*]. ARPA-E's Advanced Research in Dry cooling (ARID) program funds research in transformative new power plant cooling technologies with zero net water dissipation. For example, the Electric Power Research Institute is investigating indirect dry cooling using nanoscale additives for enhanced thermal conductivity of the heat-transfer medium [*24*]. Furthermore, nanoscale coatings applied to condensing heat exchangers may extend life and performance by sustaining hydrophilic properties and providing lasting antifouling and antimicrobial functionality.

In addition to heating and cooling system improvements, nanomaterials can also enable low-cost solar thermal process heat. For instance, photonic nanostructures are able to guide light over a wide range of incident angles, and this phenomenon could be used to eliminate expensive sunlight-tracking mechanisms in solar thermal energy systems. According to a 2015 report from the National Renewable Energy Laboratory (NREL), if the installed cost of a solar field for industrial process heat falls to $200/m^2 or less, solar thermal energy would be cost-competitive with natural gas for steam generation in a wide range of water-relevant sectors, including food, paper, petroleum, chemicals, and primary metals [*25*]. Further, solar thermal process heat can be used for large-scale water purification. At a pilot solar desalination demonstration plant in California's Central Valley, the thermal energy provided for evaporation and distillation of the brackish/agricultural waste water has been shown to desalinate 14,000 gallons/day [*26*].

Thrust 3: Enable Next-Generation Water Monitoring Systems with Nanotechnology

The development of next-generation water monitoring systems is an essential element of increasing water availability (Thrust 1) and of improving water delivery and use efficiency (Thrust 2). In support of Thrust 1, detailed measurement and tracking of water quantities and contaminant levels underpins informed decision making and water management at all levels of the government and in the private sector. Water monitoring and analytics are used to assess quantity and availability of water for specific uses, to identify causes of contamination, and to evaluate potential remediation strategies. Yet, currently, less than 30% of the Nation's surface water bodies are assessed by EPA, States, or tribes, partly because of the high cost of traditional fixed-station water quality monitoring [*27*]. Additionally, the development of affordable, autonomous, and real-time sensors would allow for proactive management of potential problems. For example, before a storm, municipalities and water utilities could evaluate water storage levels and adjust reserves as necessary to prevent overflow events that deposit raw sewage into natural waterways. In support of Thrust 2, improved sensor networks and metering technologies can enable better management of water distribution networks and identify leaks and system inefficiencies that currently result in average losses of about 16% of clean and treated water in public water systems, thereby allowing for preventative and rapid response to water-infrastructure problems [*28*].

Innovative technologies are needed to build next-generation water monitoring systems, and nanotechnology is particularly promising for the development of affordable sensors with high sensitivity, accuracy, selectivity, and fast response. For example, nanomaterials such as carbon nanotubes (CNTs) and inorganic nanowires offer a very high surface-to-volume ratio and can produce a large, measureable signal, even for a small concentration of target analytes, and in some cases, even for single molecules [*29*, *30*]. Theoretical studies estimate that the sensitivity of nanosensors may be three to four orders of magnitude greater than the sensitivity of comparable thin-film-based sensors [*7*]. Further, nanoscale detection elements, with sizes comparable to those of the corresponding recognition elements, can provide high signal-to-noise ratios to provide sufficient total detection, and nanosensors have shown promise for multifunctional sensing [*31*, *32*]. Finally, nanosensors can be designed for improved sample collection and preprocessing and to aid development of portable, rapid-turnaround sensor devices, which would be particularly relevant for environmental water quality monitoring. Recognizing the potential for nanosensors to revolutionize water monitoring systems, the agencies participating in the Water NSI have identified the following high-priority objectives for targeted interagency collaboration:

- Within 5 years, develop a suite of nanotechnology-enabled sensors for **continuous, real-time measurement of water quality** that are more sensitive, more reliable, easier to use remotely, last longer, analyze more pollutants, and cost less than currently used sensors.

- Within 5 years, develop nanotechnology-enabled sensors and sensor networks to monitor and optimize the targeted delivery of water, nutrients, and pesticides for **precision agricultural applications** to minimize production inputs.
- Within 10 years, create a complete water contaminant detection and analysis system that is enabled by nanotechnology and designed for the **space environment**.

The agencies participating in the Water NSI will also focus on developing the infrastructure required to distribute and power the sensors, as well as the tools needed to analyze the data. These nanotechnology-enabled elements will be designed to augment and integrate with existing infrastructure. The *Water Sustainability through Nanotechnology* Signature Initiative will collaborate with the *Nanotechnology for Sensors and Sensors for Nanotechnology* Signature Initiative (Sensors NSI) in pursuit of these objectives. This partnership will build on the knowledge and the community that have developed under the Sensors NSI since its establishment in 2012, in addition to facilitating regular dialogue and information exchange between the nanosensing and water sustainability communities.

The need for broadly applicable nanotechnology-enabled sensors for continuous, real-time measurement of water quality is described above, but the motivation for specifically focusing on the application areas of agriculture and space warrants further description. First, irrigation accounted for 38% of total freshwater withdrawals in the United States in 2010 [*23*], and the Food and Agriculture Organization of the United Nations estimates that 70% of water withdrawals worldwide are for agricultural uses [*33*]. Yet, some experts estimate that as much as 50% of water used for irrigation is wasted due to evaporation, wind, or runoff caused by inefficient irrigation methods and systems [*34*]. Nanotechnology-enabled sensors could combat these inefficiencies by collecting data on, for example, water and nutrient levels, sunlight, and soil composition, effectively enabling the application of water, nutrients, and pesticides only where and when needed [*35*]. In addition to the substantial potential for conserving water, the use of precision agriculture can improve water quality by reducing the quantity of fertilizer and pesticides applied, thus minimizing runoff.

Second, with respect to space applications, NASA must balance its instrumentation needs with the requirements for space flight. For example, the International Space Station could use water contaminant and detection systems for monitoring the environment inside the station, as well as within the wastewater processing systems; yet, monitoring the habitable environment of crewed spacecraft currently relies primarily on sample return and subsequent ground analysis [*36*]. Deploying water monitoring systems in space is necessary for missions beyond Low Earth Orbit to eliminate the dependency on ground sample return, but these systems must also meet the requirements for space flight, including low power consumption, light weight, small volume, and high reliability. Not only can nanotechnology improve the sensitivity of sensors used in space, but the scale of nanotechnology lends itself to miniaturizing current state-of-the-art technologies. Sensor miniaturization is a priority for several agencies participating in the Water NSI because it would allow for the incorporation of multiple types of sensors (multianalyte detection) in the same instrument footprint for an overall reduction in size and therefore cost.

Agency Contributions

The agencies participating in the *Water Sustainability through Nanotechnology* NSI chose to focus on the thrusts and objectives outlined above because these topics offer substantial potential improvements over current technologies, are of interest to multiple agencies, and can be uniquely pursued through targeted interagency collaboration. The Water NSI will leverage Federal agencies' existing and emerging efforts to create the necessary technical breakthroughs. These efforts include DOE's Water-Energy Tech Team; the Innovations at the Food-Energy-Water Nexus activity at NSF and USDA/NIFA; and EPA's 2014 Water Technology Innovation Blueprint, Promoting Technology Innovation for Clean and Safe Water. Where appropriate, the Water NSI will also interface with other interagency Federal activities such as the Sensors NSI and the Administration's Open Water Data Initiative to build and share cross-community expertise and to collaboratively address key challenges that span multiple groups. For example, preliminary discussions have been initiated between the agencies participating the Water NSI and the Sensors NSI to explore potential collaborations on water monitoring technologies.

The existing and retired NSIs have successfully employed a number of mechanisms for building and engaging with the scientific and stakeholder communities in a specific field, assessing the state of science and commercialization in that field, and sharing resources. These mechanisms include hosting public webinars and workshops, releasing a Request for Information, and creating resource portals on nano.gov. The Water NSI will explore the opportunities available for advancing its goals and implement those that meaningfully can impact the field. Given the fragmented nature of the water treatment and distribution ecosystem, it is particularly important to engage with stakeholders from industry, academia, nonprofit organizations, government, and public works and utilities to understand their needs, leverage expertise, and share successes.

The expertise and perspectives that each agency will bring to this effort are described below.

DOC/NIST

The NIST laboratories are at the forefront of developing and disseminating robust measurement techniques, test methods, and protocols for the detection and characterization of nanomaterials in diverse environments. These tools are needed to perform robust risk assessments of nanomaterials and nanotechnology-enabled products. NIST will continue to focus on the detection, separation, and quantification of specific nanoparticles that are relevant to consumer and industry stakeholders. NIST is also committed to ensuring that the United States has the necessary tools to effectively manage its water resources. In support of this effort, NIST is developing advanced broad-spectrum organic, inorganic, and biological measurement capabilities for assessing water quality. The development of nanosensors for real-time, *in situ* measurement of both conventional pollutants and emerging contaminants is a key component of this commitment. Additionally, NIST is pursuing the development of standard reference materials incorporating nanomaterials for the validation of the accuracy and reliability of sensors. In the area of water distribution research, NIST is interested in developing new test methods and protocols that will enable pipeline designers to make better-informed material selections and life cycle analyses.

DOE

The water-energy nexus is a high priority area for DOE. In 2014, the Water-Energy Tech Team (WETT) prepared a report—The Water-Energy Nexus: Challenges and Opportunities[3]—that frames an integrated challenge and opportunity space around the water-energy nexus for DOE and its partners, laying the foundation for future efforts. Priorities for DOE include desalination[4], advanced cooling technologies[5], and energy-positive water resource recovery[6]. Related to the latter, the DOE is also interested in the production of biofuels and bioproducts from organic waste waters[7], as well as novel technologies to extract energy value from these feedstocks[8]. Nanoscale solutions may offer innovative possibilities in all of these areas.

[3] www.energy.gov/downloads/water-energy-nexus-challenges-and-opportunities

[4] energy.gov/eere/amo/downloads/energy-optimized-desalination-technology-development-workshop-november-5-6-2015

[5] arpa-e.energy.gov/?q=arpa-e-programs/arid

[6] www.energy.gov/eere/bioenergy/downloads/energy-positive-water-resource-recovery-workshop-report

[7] energy.gov/eere/bioenergy/downloads/waste-energy-workshop-summary-report

[8] energy.gov/eere/fuelcells/downloads/wet-waste-energy-bioenergy-technologies-office

EPA

The EPA Office of Water (OW) has developed a Water Technology Innovation Blueprint[9] that identifies ten areas of need for technology development and commercialization. In the EPA Office of Research and Development (ORD), the Safe and Sustainable Water Resources[10] research program provides innovative scientific and technological solutions for drinking water, post-use water, storm water, and ecosystems that ensure clean, adequate, and equitable supplies of water to protect human health and to protect and restore watersheds and aquatic ecosystems. The ORD Chemical Safety and Sustainability research program's efforts are focused on the impacts of nanoparticles on environmental health and safety. EPA's SBIR Program[11] has included water, sensor, and nanotechnology-based topics in its annual solicitations and has funded nanotechnology-based projects. Its recent water topics have been based on the needs identified in the OW Blueprint.

NASA

NASA has unique water needs in space that have analogous applications on Earth. NASA's wastewater collection differs from systems used on Earth in that it is highly concentrated with respect to urine, uses minimal flush water, is separated from solid wastes, and contains highly acidic and toxic pretreatment chemicals. NASA is interested in recovery of potable water from waste water, low toxicity residual disinfection, antifouling treatments for plumbing lines and tanks, and miniaturized sensors and monitoring systems for contaminants in potable water and waste water. NASA's goal is zero-discharge water treatment, targeting 100% water recycling and reuse. Spacecraft traveling away from Earth require the capability of a fully functional water analysis laboratory, including identification and quantification of known and unknown inorganic ions, organics, and microbes, as well as pH, conductivity, and other typical measurements. Spacecraft Water Exposure Guidelines (SWEGs)[12] have been published for selected contaminants. For potential future bioregenerative life support applications involving growth of crop plants for production of food, process water may include agricultural waste waters, and there may be interest in separation of sodium chloride, nitrogen, and other nutrients from waste water for reuse in plant growth systems. Nanotechnology may offer solutions in all of these application areas.

NSF

The priority of NSF in the area of nanotechnology and water is to support fundamental scientific exploration of techniques and technologies to improve water quantity and enhance water quality. NSF is receptive to research in numerous areas across multiple disciplines, programs, and research directorates. NSF is also receptive to research that, for example, employs nanotechnology to develop novel materials useful for enabling anti-fouling capabilities in membranes; for creating materials that permit water infrastructure improvements (e.g., energy reduction, tensile strength, intelligent sensing); for enabling more efficient heat transfer; for developing techniques for more efficient irrigation; and for developing modular, portable water treatment and remediation technologies.

USDA/NIFA

The USDA National Institute of Food and Agriculture Water for Agriculture Challenge Area[13] program will award grants totaling greater than $50 million over five years to (1) ensure the water security of surface and ground water needed to produce agricultural goods and services; (2) improve nutrient management in agricultural landscapes focused on nitrogen and phosphorous; and (3) reduce impacts of chemicals and the

[9] www.epa.gov/sites/production/files/2014-04/documents/clean_water_blueprint_final.pdf

[10] www.epa.gov/sites/production/files/2014-06/documents/sswr-strap.pdf

[11] www.epa.gov/sbir

[12] www.nasa.gov/feature/exposure-guidelines-smacs-swegs

[13] nifa.usda.gov/program/afri-water-agriculture-challenge-area

presence and movement of environmental pathogens in the Nation's fresh and nontraditional water supplies. NIFA is interested in the development of inline, real-time smart sensors for identifying pathogens, chemicals, and contaminants in agriculture production systems, including water, plants, and soil. NIFA is also interested in technologies and systems for recycling nontraditional water for agricultural uses and the use of precision agriculture technologies to improve water use efficiency and reduce water demand. USDA is studying the use of nanoparticles to remediate chlorinated solvents and heavy metals in soils. USDA agencies are also investigating the various health effects and risks of engineered nanoparticles as contaminants introduced into water sources.

References

1. J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., *Climate Change Impacts in the United States: The Third National Climate Assessment* (U.S. Global Change Research Program, Washington, District of Columbia, 2014, s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1).
2. L. F. Konikow, *Groundwater Depletion in the United States (1900−2008)* (USGS Scientific Investigations Report 2013−5079, U.S. Geological Survey, Reston, Virginia, 2013, pubs.usgs.gov/sir/2013/5079/SIR2013-5079.pdf).
3. B. E. Cain, I. Hui, *Overcoming Psychological Resistance toward Using Recycled Water as a Solution to California's Climate Change Challenge* (The Bill Lane Center for the American West at Stanford University, Palo Alto, California, 2016, west.stanford.edu/sites/default/files/Recycled_AgriWater Hui_Cain.pdf).
4. A. Street, R. Sustich, J. S. Duncan, N. Savage, Eds., *Nanotechnology Applications for Clean Water: Nanotechnology Solutions for Improving Water Quality* (William Andrew Publishing, Oxford, UK, ed. 2, 2014).
5. X. Qu, P. J. J. Alvarez, Q. Li, Applications of nanotechnology in water and wastewater treatment. *Nanotechnol. Water Wastewater Treat.* **47**, 3931–3946 (2013).
6. S. Qi *et al.*, Influence of the properties of layer-by-layer active layers on forward osmosis performance. *J. Membr. Sci.* **423–424**, 536–542 (2012).
7. Y. Liao, R. Wang, M. Tian, C. Qiu, A. G. Fane, Fabrication of polyvinylidene fluoride (PVDF) nanofiber membranes by electro-spinning for direct contact membrane distillation. *J. Membr. Sci.* **425–426**, 30–39 (2013).
8. L. Dumée *et al.*, Fabrication of thin film composite poly(amide)-carbon-nanotube supported membranes for enhanced performance in osmotically driven desalination systems. *J. Membr. Sci.* **427**, 422–430 (2013).
9. X. Jin, Q. She, X. Ang, C. Y. Tang, Removal of boron and arsenic by forward osmosis membrane: Influence of membrane orientation and organic fouling. *J. Membr. Sci.* **389**, 182–187 (2012).
10. Y. Liu, B. Mi, Combined fouling of forward osmosis membranes: Synergistic foulant interaction and direct observation of fouling layer formation. *J. Membr. Sci.* **407–408**, 136–144 (2012).
11. M. J. Nalbandian *et al.*, Synthesis and optimization of Ag–TiO_2 composite nanofibers for photocatalytic treatment of impaired water sources. *J. Hazard. Mater.* **299**, 141–148 (2015).
12. M. J. Nalbandian *et al.*, Synthesis and optimization of Fe_2O_3 nanofibers for chromate adsorption from contaminated water sources. *Chemosphere* **144**, 975–981 (2016).
13. A. Al-Janabi, M. R. Malayeri, Nano-coated surfaces to mitigate fouling in thermal water services. *Desalination Water Treat.* **55**, 2909–2917 (2015).
14. M. S. Gaikwad, C. Balomajumder, Capacitive deionization for desalination using nanostructured electrodes. *Anal. Lett.*, doi: 10.1080/00032719.2015.1118485 (2016).
15. T. Humplik *et al.*, Nanostructured materials for water desalination. *Nanotechnology* **22**, 292001 (2011).

16. M. M. Mekonnen, A. Y. Hoekstra, *National Water Footprint Accounts: The Green, Blue and Grey Water Footprint of Production and Consumption* (Value of Water Research Report Series 50, UNESCO Institute for Water Education, Delft, the Netherlands, 2011; waterfootprint.org/media/downloads/Report50-NationalWaterFootprints-Vol1.pdf).
17. A. Zaidi, Changing the Game on Water Supply, https://www.whitehouse.gov/blog/2015/12/15/changing-game-water-supply; accessed 26 February 2016.
18. B. Griffiths-Sattenspiel, W. Wilson, *The Carbon Footprint of Water* (River Network, Portland, Oregon, 2009; https://www.csu.edu/cerc/researchreports/documents/CarbonFootprintofWater-RiverNetwork-2009.pdf).
19. U.S. Environmental Protection Agency, *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* (U.S. Environmental Protection Agency, Washington, District of Columbia, 2016; www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html).
20. S. Kim *et al.*, The study of heat transfer for nanofluid with carbon nano particle in an exhaust gas recirculation (EGR) cooler. *Heat Mass Transf.* **49**, 1051–1055 (2013).
21. Y. Wang, H. Zhang, X. Liu, Z. Zhou, Slippery liquid-infused substrates: a versatile preparation, unique anti-wetting and drag-reduction effect on water. *J. Mater. Chem. A* **4**, 2524–2529 (2016).
22. D. J. Preston, D. L. Mafra, N. Miljkovic, J. Kong, E. N. Wang, Scalable graphene coatings for enhanced condensation heat transfer. *Nano Lett.* **15**, 2902–2909 (2015).
23. M. A. Maupin *et al.*, *Estimated Use of Water in the United States in 2010* (Circular 1405, U.S. Geological Survey, Reston, Virginia, 2014, pubs.usgs.gov/circ/1405/pdf/circ1405.pdf).
24. J. Shi, Indirect Dry Cooling using Recirculating Encapsulated Phase Change Materials, presented at the 2016 ARPA-E Energy Innovation Summit, 29 March 2016, www.arpae-summit.com/paperclip/exhibitor_docs/16AE/Electric_Power_Research_Institute_Inc._EPRI__458.pdf.
25. P. Kurup, C. Turchi, *Initial Investigations in the Potential of CSP Industrial Process Heat for the Southwest United States* (NREL/TP-6A20-64709, National Renewable Energy Laboratory, Golden, Colorado, 2015, www.nrel.gov/docs/fy16osti/64709.pdf).
26. K. Fagan, "California drought: Solar desalination plant shows promise," *San Franc. Chron.* (March 18, 2014), www.sfgate.com/science/article/California-droughtSolar-desalination-plant-5326024.php#photo-6028210; accessed 26 February 2016.
27. The White House, *Water Resource Challenges and Opportunities for Water Technology Innovation* (The White House, Washington, District of Columbia, 2015, https://www.whitehouse.gov/sites/whitehouse.gov/files/documents/Water_Resource_Challenges_and_Technology_Innovation_12_14.pdf).
28. J. Thornton, R. Sturm, G. Kunkel, *Water Loss Control* (McGraw-Hill, New York, New York, ed. 2, 2008).
29. Y. Cui, Q. Wei, H. Park, C. M. Lieber, Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species. *Science* **293**, 1289–1292 (2001).
30. P. E. Sheehan, L. J. Whitman, Detection limits for nanoscale biosensors. *Nano Lett.* **5**, 803–807 (2005).
31. E. Rand *et al.*, A carbon nanofiber based biosensor for simultaneous detection of dopamine and serotonin in the presence of ascorbic acid. *Biosens. Bioelectron.* **42**, 434–438 (2013).
32. J. Li *et al.*, "Nanotechnology based cell-all phone-sensors for extended network chemical sensing," in *Sensors, 2012 IEEE, 28-31 Oct. 2012* (2012), pp. 1–4.
33. Food and Agriculture Organization of the United Nations, AQUASTAT: Water Uses, www.fao.org/nr/water/aquastat/water_use/index.stm; accessed 26 February 2016.
34. U.S. Environmental Protection Agency, WaterSense: Outdoor Water Use in the United States, www3.epa.gov/watersense/pubs/outdoor.html; accessed 26 February 2016.

35. G. V. Lowry *et al.*, *Role of Nanotechnology in Achieving Sustainability at the Food-Energy-Water-Nexus* (NSF Workshop Report, December 15, 2015, faculty.ce.cmu.edu/lowry/files/2016/02/NSF-FEW-WorkshopReport-final-dec-2015.pdf).
36. National Aeronautics and Space Administration, *NASA Technology Roadmaps, TA 6: Human Health, Life Support, and Habitation Systems* (National Aeronautics and Space Administration, Draft, May 2015, www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_6_human_health_life_support_habitation.pdf).