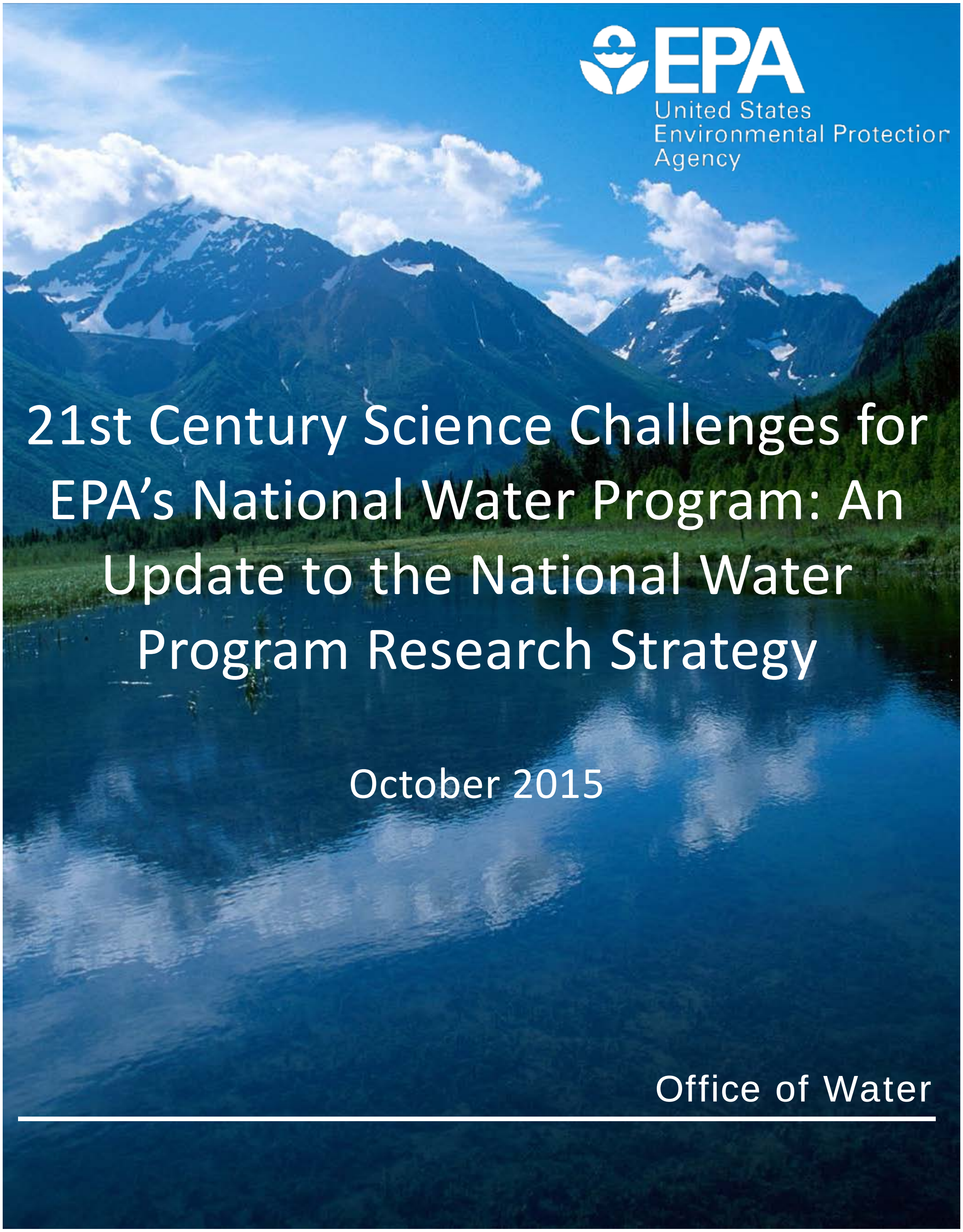

United States Environmental Protection Agency

# 21st Century Science Challenges for EPA's National Water Program: An Update to the National Water Program Research Strategy

October 2015

Office of Water

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This *Water Research Strategy Update* is available online at:
http://www.epa.gov/water-research/national-water-program-research-strategy.

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# DISCLAIMER

This *Update to the National Water Program Research Strategy (Update)* captures the most current research needed for EPA's National Water Program to successfully achieve its statutory and regulatory obligations, and its strategic targets and goals. To the extent the document mentions or discusses statutory or regulatory authority, it does so for information purposes only. The document does not substitute for those statutes or regulations, and readers should consult the statutes or regulations themselves to learn what they require. Neither this document, nor any part of it, is itself a rule or a regulation. Thus, it cannot change or impose legally binding requirements on EPA, states, the public, or the regulated community. The use of words such as "should," "could," "would," "will," "intend," "may," "might," "encourage," "expect," and "can," in this document means solely that something is intended, suggested or recommended, and not that it is legally required. Any expressed intention, suggestion or recommendation does not impose legally binding requirements on EPA, states, the public, or the regulated community. Agency decision makers remain free to exercise their discretion in choosing to implement the actions described in this *Update*.

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# FOREWORD

On September 30, 2009, the National Water Program (NWP) published its first Research Strategy. The goal of the 2009-2014 National Water Program Research Strategy (*Strategy*) was three fold: (1) to ensure the NWP's research, science, and technology needs were identified and documented in a comprehensive plan that reflected collaborative corporate planning, prioritization, and research management, (2) to expand partnerships and collaborations across the United States Environmental Protection Agency (EPA) and the federal research family, and (3) to engage the broader research community in the investigation of water research needs.

Our objective was to bring a broader diversity of relevant and appropriately vetted science to the NWP's regulatory and non-regulatory tools and water management decisions. In the end, we wanted to increase program credibility, expedite the production of needed tools, and achieve water quality environmental outcomes faster and with better quantification.

It is now 2015 and I am very pleased when I look back at the impact the *Strategy* has had on the NWP's collaborations with EPA's Office of Research and Development (ORD) as it realigned its research programs from 15 independent to 6 integrated, multidisciplinary research programs and created cross-cutting research roadmaps to promote that integration and meet program science needs. I also see expanded engagement of NWP scientists and staff with other federal agency environmental programs for example, the US Geological Survey and Department of Agriculture; with environmental agencies in other countries, such as Environment Canada; and with scientists and research organizations including the Water Environment Research Foundation, the Water Research Foundation, and the Water ReUse Research Foundation.

Writing and publishing the *Strategy* established a culture of collaboration and communication within and across the NWP to advance our science. In very recent years, the NWP has developed a variety of project- and program-specific strategies, action plans, and science plans for emerging and priority water challenges. This *Update* to the *Strategy* captures the science priorities emerging from these activities, bringing the substance of these approaches under a single cover to highlight the science questions and capture the interconnections. The *Update* is brief by design and connects the reader to the full documents through links and references. I believe that this *Update* will help us continue and enhance the collaboration which has been fostered by our initial *Strategy.*

As always, we invite those researchers who are conducting or considering conducting investigations in the areas identified in the *Strategy* or in this *Update* to let us know about their work so we can improve our communications.

Michael H. Shapiro
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Office of Water

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# Table of Contents

## Tables

## Table of Acronyms

| Acronym | Term |
|---|---|
| ACE | Air, Climate, and Energy |
| ADAF | Age-Dependent Adjustment Factors |
| ANS | Aquatic Nuisance Species |
| AOP | Adverse Outcome Pathway |
| ASDWA | Association of State Drinking Water Administrators |
| AR | Androgen Receptor |
| AUV | Autonomous Underwater Vehicle |
| AWQC | Ambient Water Quality Criteria |
| BAF | Bioaccumulation Factor |
| BCF | Bioconcentration Factor |
| BMP | Best Management Practices |
| BOD | Biological Oxygen Demand |
| CAFO | Confined Animal Feedlot Operations |
| CAS | Chemical Abstracts Service |
| CBR | Chemical, Biological, and Radiological |
| CCL | Contaminant Candidate List |
| CCLCP | Contaminant Candidate List Classification Protocol |
| CDC | Centers for Disease Control |
| CEC | Contaminants of Emerging Concern |
| CNT | Carbon Nanotubes |
| COD | Chemical Oxygen Demand |
| CSOs | Combined Sewer Overflows |
| CRWU | Climate Ready Water Utilities |
| CSS | Chemical Safety for Sustainability |
| CWA | Clean Water Act |
| CWT | Centralized Waste Treatment Facility |
| DBPs | Disinfection Byproducts |
| DO | Dissolved Oxygen |
| DOC | Dissolved Organic Carbon |
| EDCs | Endocrine Disrupting Chemicals |
| EGS | Ecosystem Goods and Services |
| EIA | Energy Information Agency |
| ENMs | Engineered Nanomaterials |
| EPA | United States Environmental Protection Agency |
| ETV | Environmental Technology Verification |
| FDA | Food and Drug Administration |
| FEGS-CS | Final Ecosystem Goods and Services Classification System |
| FIB | Fecal Indicator Bacteria |
| GAC | Granular Activated Carbon |
| GHG | Green House Gas |

| Acronym | Term |
|---|---|
| GI | Green Infrastructure |
| GOM | Gulf of Mexico |
| GWPC | Ground Water Protection Council |
| $H_2O_2$ | Hydrogen Peroxide |
| HAB | Harmful Algal Blooms |
| HAP | Hazardous Air Pollutant |
| HF | Hydraulic Fracturing |
| HFDWA | Hydraulic Fracturing Drinking Water Assessment |
| HH-AWQC | Human Health Ambient Water Quality Criteria |
| HWP | Healthy Watersheds Program |
| IPCC | Intergovernmental Panel on Climate Change |
| IWRM | Integrated Water Resources Management |
| LID | Low Impact Development |
| LOD | Limit of Detection |
| LOQ | Limit of Quantitation |
| LTCPs | Long-Term Control Plans |
| MABR | Membrane Aerated Biofilm Reactor |
| MBR | Membrane Bioreactors |
| MIB | 2-methylisoborneol |
| MS4s | Municipal Separate Storm Sewer Systems |
| MRB | Mississippi River Basin |
| MTBE | Methyl tert-butyl ether |
| NAAQS | National Ambient Air Quality Standards |
| NCOD | National Contaminant Occurrence Database |
| NERL | National Exposure Risk Laboratory |
| NIH | National Institutes of Health |
| NIOSH | National Institute for Occupational Safety and Health |
| NNI | National Nanotechnology Initiative |
| NORMs | Naturally Occurring Radioactive Materials |
| NPDWR | National Primary Drinking Water Regulation |
| Nr | Reactive Nitrogen |
| NRC | National Research Council |
| NWP | National Water Program |
| $O_3$ | Ozone |
| OAR | Office of Air and Radiation |
| OECD | Organization for Economic Cooperation and Development |
| OGWDW | Office of Ground Water and Drinking Water |
| ORD | Office of Research and Development |
| OSHA | Occupational Safety and Health Administration |
| OST | Office of Science and Technology |
| OW | Office of Water |
| OWOW | Office of Wetlands, Oceans, and Watersheds |

| Acronym | Term |
|---|---|
| POE | Point of Entry |
| POTW | Publicly Owned Treatment Works |
| POU | Point of Use |
| PPCPs | Pharmaceutical and Personal Care Products |
| PWS | Public Water System |
| qPCR | Quantitative Polymerase Chain Reaction |
| RfD | Reference Dose |
| RICP | Distribution System Research and Information Collection Partnership |
| RSC | Relative Source Contribution |
| SCADA | Supervisory Control And Data Acquisition |
| SDWA | Safe Drinking Water Act |
| SETAC | Society of Environmental Toxicology and Chemistry |
| SHC | Sustainable and Healthy Communities |
| SSOs | Sanitary Sewer Overflows |
| SSWR | Safe and Sustainable Water Resources |
| StRAP | Strategic Research Action Plan |
| SWC | Stormwater Calculator |
| SWMM | Storm Water Management Model |
| $TiO_2$ | Titanium Dioxide |
| TSCA | Toxic Substances Control Act |
| TDS | Total Dissolved Solids |
| TMDL | Total Maximum Daily Load |
| UCM | Unregulated Contaminant Monitoring |
| UIC | Underground Injection Control |
| USGS | United States Geological Survey |
| USGCRP | U.S. Global Change Research Program |
| UV | Ultraviolet |
| VOCs | Volatile Organic Compounds |
| WERF | Water Environment Research Foundation |
| WQS | Water Quality Standards |
| WWTF | Waste Water Treatment Facilities |
| WWTP | Waste Water Treatment Plant |

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# 21ST CENTURY SCIENCE CHALLENGES FOR EPA'S NATIONAL WATER PROGRAM: AN UPDATE TO THE NATIONAL WATER PROGRAM RESEARCH STRATEGY

## Introduction

The United States Environmental Protection Agency (EPA) is engaged in an ongoing effort to strengthen science and promote more effective coordination and integration of scientific research within the agency. As one facet of this effort, in 2006 Mike Shapiro, EPA's Principal Deputy Assistant Administrator of the Office of Water (OW) charged the National Water Program (NWP)[1] to ". . . develop a common approach for identifying and articulating each office's research needs and priorities within the context of an overall OW strategic research plan." The plan would also capture research needs beyond those included in the Office of Research and Development's (ORD's) plans and promote improved coordination of water-related research among federal and non-federal partners and strengthen and expand those research partnerships.

In response to this call to action, the NWP produced the *National Water Program Research Strategy (Strategy)* in September 2009 (US EPA, 2009). The strategy described and ranked the projected research needs for 2009-2014. The goals of that strategy and this Update continue to be to:

- Ensure the NWP's research, science, and technology needs are identified and documented in a comprehensive plan that supports EPA's commitment to collaborative corporate planning, prioritization, and research management to meet the environmental goals of the NWP.
- Expand partnerships and collaborations across EPA and the federal research family.
- Engage the broader research community in the investigation of water research needs.

The *Strategy* summarized a range of research topics under four major topical themes that aligned with OW's core mission areas and statutes:

- Theme A: Healthy Watersheds and Coastal Waters Research Needs;
- Theme B: Safe Drinking Water Research Needs;
- Theme C: Sustainable Water Infrastructure Research Needs; and
- Theme D: Water Security Research Needs.

[1] The NWP is comprised of the OW major offices: Office of Ground Water and Drinking Water; Office of Science and Technology; Office of Wastewater Management; and Office of Wetlands, Oceans, and Watersheds, as well as the ten EPA regional offices.

In 2011, EPA asked the National Research Council (NRC) to independently assess the overall capabilities of the EPA to "develop, obtain and use the best available scientific and technologic information and tools to meet the persistent, emerging and future mission challenges and opportunities" (NRC, 2012). In its findings, the NRC identified three key features of persistent and future environment challenges:

- Understanding the effects of low-level exposures to numerous stressors as opposed to high-level exposures to individual stressors,
- Understanding social, economic and environmental drivers, and
- Using "Systems Thinking" to devise optimal solutions.

NRC advised EPA to rely on robust approaches to acquiring data, modelling that data and developing knowledge. Particularly, that discovery-driven research may yield many important insights that hypothesis-driven research does not. NRC also suggested that EPA rely on "Systems Thinking"[2] to assess the implications of decisions. To further this approach, NRC advised that EPA develop and apply systems-level tools and expertise and also integrate methods for tracking and assessing the outcomes of actions. The NRC found that EPA needs more effective coordination and integration of science efforts within the agency. Efforts to strengthen EPA science should incorporate the resources, expertise, and scientific and nonscientific perspectives of both the program and fields offices. The efforts should:

- Support the integration of both existing and new science throughout the agency,
- Avoid duplication or, worse, contradictory efforts,
- Respect different sets of priorities and timeframes, and
- Advance common goals.

The NWP and the ORD have collaborated on the design of ORD's Strategic Research Action Plans (StRAPs) for 2016-2019 and Cross-Cutting Roadmaps which were prepared, in part, to be responsive to the NRC and other research program reviewers. The StRAPs and Roadmaps take up many of the research needs of the NWP and are limited only by the resources available to the Agency. The *Strategy* and this *Update* have been prepared to outline the full range of research that will help inform water quality policy and decision making even where those needs go beyond what can be performed in-house and will require collaboration with other institutions.

To update the *Strategy* with consideration for the core themes that had been explored in the intervening years, as well as the NRC analysis, the NWP has developed this *Update* to present the following eight research priority areas to be addressed in the next 5 to 10 years to meet the human health, drinking water, and ecological water challenges ahead.

[2] As an example, a systems approach recognizes that watersheds are best understood in the context of the dynamic linkages between landscapes and aquatic ecosystems. A variety of factors can affect the integrity of a watershed including: stormwater and wastewater discharges; water withdrawals; nutrient and sediment runoff; habitat fragmentation from development; and other stressors such as climate change, air deposition, and invasive species.

- Chapter 1 – Nutrient Pollution and Harmful Algal Blooms.
- Chapter 2 – Hydraulic Fracturing.
- Chapter 3 – Next Generation Water and Wastewater Treatment Technologies.
- Chapter 4 – Wet Weather Pollution Management.
- Chapter 5 – Actionable Information on Chemical and Microbial Contaminants of Emerging Concern.
- Chapter 6 – Systems Approach to Protecting Watersheds.
- Chapter 7 – Ecosystem Services.
- Chapter 8 – Climate Change Impacts.

The remainder of this document is divided into chapters addressing each of these research priority areas, including background, key ongoing or recently completed research projects, and research needs. Many research needs are applicable to two or more priority areas, reflecting the emphasis on integration and system thinking.

The background, discussion, and research needs for each chapter have been pulled from a variety of existing OW publications, action plans, strategy documents, and research needs compilations and analyses as well as ORD StRAPs and Roadmaps. The citations for the reference documents are provided at the end of each chapter. Readers are encouraged to also review the ORD StRAPs for *Safe and Sustainable Water*; *Sustainable and Healthy Communities*; *Air, Climate, and Energy*; *Human Health Risk Assessment*; *Chemical Safety and Sustainability*; *Homeland Security* as well as the Cross-Cutting Roadmaps for *Nitrogen and Co-Pollutants* and *Climate* for more discussion of in-house research supporting water programs that is underway or planned: http://www2.epa.gov/research/strategic-research-action-plans.

## References

National Research Council. 2012. *Science for Environmental Protection: The Road Ahead.* National Academy of Sciences.

US EPA. 2009*. National Water Program Research Strategy. 2009-2014*. Office of Water (4304T). EPA 822-R-09-012. September 2009. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/strategy.pdf.

# Chapter 1. Nutrient Pollution and Harmful Algal Blooms

The objective of the Clean Water Act (CWA) is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (33 U.S.C. Sec. 1251(a), CWA Sec 101(a)). Nutrient enrichment, a direct result of excess nitrogen and phosphorus in the air and water, is among the top five causes of surface water impairment in the United States, along with pathogens, mercury, other metals and sediment (US EPA, 2009).

Nitrogen and phosphorus are essential biological elements that support algae and aquatic plant growth, which in turn provide food and habitat for fish and other aquatic species. Nutrients come primarily from urban, rural, and agricultural environments, along with discharges from wastewater treatment facilities (WWTF) and air deposition. Excess nutrients in surface waters can result in the formation of dense algal blooms, which adversely impact streams, rivers, lakes, bays, and coastal waters, threatening the environment, human health, and the economy. Nutrient dynamics and their impacts on aquatic species and water quality may vary based on in-stream conditions, such as temperature, flow, and the size and distribution of aquatic organism populations (Moss et al., 2011). These conditions are influenced by changes in climate, such as storm surges or flooding that increase nutrient runoff and loading (Moss et al., 2011).

Other noticeable effects of nutrient pollution can include: toxin-producing harmful algal blooms (HABs), hypoxia (lack of oxygen), decreased biodiversity, reduced transparency, and taste and odor issues in drinking water (Carpenter et al., 1998). HABs that contain cyanobacteria can produce toxins at levels capable of negatively affecting the health of humans, domestic animals, and wildlife that come in contact with affected waters. According to the Centers for Disease Control (CDC), cyanotoxins are responsible for almost half of the recreational water disease outbreaks in the United States (CDC, 2014). All algae blooms, hazardous or not, block sunlight from penetrating the water column resulting in a decrease of natural aquatic vegetation. The proliferation of blooms may be further exacerbated by climate change impacts, such as warmer water temperatures, increased ocean acidification and surface stratification, higher atmospheric concentrations of carbon dioxide, increased nutrients in runoff due to heavier precipitation events, and changes in local nutrient upwelling (Hallegraeff, 2010).

As blooms die, the decomposing cyanobacteria rob the water of the oxygen needed by aquatic animals resulting in dead zones. Algal blooms can have an unpleasant odor, prohibit recreational swimming and boating uses, decrease local housing prices, and negatively impact tourism (Bricker et al., 2007). Treating drinking water to remove algae and nutrients can be challenging and costly (e.g., Conry, 2010). In the summer of 2014, the Toledo, Ohio drinking water plant was affected by a toxin producing algal bloom at the source intake, putting approximately 500,000 people under a "do not drink" order for several days, requiring the purchase and delivery of water for consumption, cooking, and other domestic purposes, and forcing industries that used city water to slow or stop production (Baker, 2014).

Addressing nutrient pollution requires a myriad of approaches to reduce point and nonpoint source excess nutrients in order to protect or restore designated uses. To complement the United States Environmental Protection Agency (EPA) and the states' traditional regulatory programs, such as numeric criteria, standards, total maximum daily loads (TMDLs) and permitting, a recent review of the state-of-the-science of the socio-economic components of environmental decision making indicate that the use of an ecosystem services approach, which evaluates the costs and benefits of nitrogen mitigation, enables decision makers to advance integrated nutrient policy and management programs that may have stalled over concerns of treatment and removal costs and technology availability (Compton et al., 2011).

### Types of Nutrient Pollution

Urban and suburban nutrient pollution from wastewater discharge point sources and stormwater.

Rural impacts from septic systems.

Agricultural impacts primarily from fertilizer; manure runoff; field drainage and infiltration, including pastures; and volatilization/ deposition.

The National Water Program (NWP) alone and in conjunction with the Office of Research and Development (ORD) is undertaking specific research to inform decision-making on nutrient pollutant reduction strategies to protect aquatic ecosystems and enable recovery and restoration of impacted waters, as follows:

- 1.1 Update Water Quality Criteria for Nutrients.
- 1.2 Explore Innovative, Sustainable, and Cost-Effective Solutions.
- 1.3 Address Impacts from Urban, Rural, and Agricultural Environments.
- 1.4 Address Impacts from Air Deposition of Reactive Nitrogen (Nr).

Each of these areas is presented in separate subsections below. Research needs related to the impacts of climate change on nutrient pollution are addressed in Chapter 8.

## 1.1 Update Water Quality Criteria for Nutrients

### Background

In the past decade, science has significantly advanced our understanding of nutrient dynamics. Recent research has led to a better understanding of methods that can be used to derive scientifically-defensible numeric nutrient criteria, such as the stressor-response (US EPA, 2010) and reference-condition approaches, mechanistic modeling, and the use of remote sensing data.

In response to the growing incidence of HABs, EPA's OW collaborated with Health Canada to develop human health criteria for up two cyanotoxins (microcystin-LR, cylindrospermopsin), which were published on June 15, 2015 (US EPA, 2015). OW is also coordinating with ORD on treatment and analytical methods (US EPA, 2012; US EPA, 2013b).

## Future Research Areas

To continue building upon the NWP's understanding of nutrient dynamics, further research is needed to improve nutrient indicator development in a variety of water body types and over a variety of time and space scales to support condition assessment, relating exposure and response, and to inform regulatory actions.

- **Obtain sufficient field data (biological indicator, causal, and response parameters).** Data are needed to calculate numeric nutrient criteria.
- **Evaluate the effectiveness of emerging technologies.** These include genomics and bioinformatics to characterize aquatic life.
- **Evaluate the effectiveness of new monitoring technologies.** These include devices for identifying waters that are degraded or at risk for nutrient pollution such as in-stream sensors for water body health status, continuous monitoring devices, satellites with remote sensing, aircraft, autonomous underwater vehicle (AUV), or photographic or video technologies.
- **Evaluate nutrient indicators.** Indicators should be evaluated for different regions of the United States and for different water body types, for example west coast estuaries, artificial reservoirs, different stream orders, black-water or turbid streams.
- **Evaluate indicator responses across temporal and spatial scales.**
- **Determine the endpoints and indicators associated with nutrient-enhanced coastal acidification.**

The NWP also needs to understand the relationships among nutrient sources, transport and exposure, and responses at the source and downstream in order to evaluate nutrient management options.

- **Develop ecosystem and watershed-scale multi-media models**. Develop ecosystem and watershed-scale multi-media models to evaluate management options and inform decisions.
- **Evaluate flow.** Ensure numeric nutrient criteria are protective under varying flow conditions.
- **Implement protective nutrient trading approaches***.* Develop monitoring methods, models, and guidance so that nutrient trading approaches can be investigated and implemented.
- **Investigate cyanobacteria toxins.** Determine the conditions under which cyanobacteria produce toxins. Development of analytical methods is needed to determine if a cyanobacteria species is producing toxins and, if so, what type and variant. Design sensors that identify burgeoning HAB/cyanobacteria conditions.
- **Establish human health risks.** Investigate the risks to human health associated with long-term low-level exposure to cyanobacteria HABs in drinking water.

To learn more about how these future research needs relate to the other research priorities, see Table 1-1.

## 1.2 Explore Innovative, Sustainable, and Cost-Effective Solutions

### Background

Addressing nutrient pollution requires a multi-barrier approach that incorporates source reduction, Best Management Practices (BMPs), sustainable treatment technologies, and recovery. Reducing impacts from permitted dischargers and nonpoint sources will be critical to protecting downstream water bodies. To accomplish this, many dischargers may need to reduce current loading rates which means developing innovative, sustainable, and cost-effective technologies to achieve loading rates that will protect designated uses while minimizing the carbon footprint of the dischargers.

Removing nutrients can be costly; however, significant advancements have been made in wastewater treatment (US EPA, 2013a) to reduce costs and recover and repurpose what was once considered waste. A wide range of nitrogen and phosphorus removal technologies and tools exist ranging from nitrogen management techniques for upstream sources (e.g., urine separation, pre-treatment and recovery) to various wastewater treatment technologies (e.g., conventional nitrification-denitrification, nitritation-denitritation or nitrite shunt, and deammonification or partial nitritation-anammox). Technologies for phosphorus removal have a similar range of technologies and options. While significant progress has been made, more research and demonstrations are needed to understand and overcome the barriers to adopting new technologies. These emerging technologies should be capable of reliable deployment, wider use for various treatment objectives, and accommodating rapidly changing climate conditions. Research in some of these areas is in progress by a number of researchers and collaboration with stakeholders is critical to ensure that research gaps are addressed in to order to expedite the development and wide deployment of these technologies.

In addition, innovative management of the chemical oxygen demand (COD) in wastewater can reduce the facility's greenhouse gas footprint as well as optimize nutrient management processes. For example, carbon from wastewater can be captured upstream and sent to anaerobic digesters to generate energy while minimizing aeration treatment and costs. This could also benefit nutrient removal processes such as nitrite shunt, deammonification, and other processes. Developing and demonstrating approaches to sustainably manage wastewater carbon under various plant configurations and conditions is an emerging research area which could be significant in developing sustainable nutrient management strategies for publicly owned treatment works (POTWs).

Nutrient recovery technologies have also been developed which reduce loading to and costs of biological nutrient removal and solids treatment processes and in some cases can generate sufficient revenue to offset the costs of implementation. Cost-effective phosphorus recovery processes are available and can have, in many cases, additional benefits such as reducing struvite blockages in pipes and creating nutrient rich fertilizers. While some nitrogen recovery processes are available, more research is needed on cost effective methods and approaches to recover nitrogen.

## Future Research Areas

Research is needed to further develop cost-effective and sustainable solutions that allow for nutrient removal and recovery, and reuse to achieve designated uses, while minimizing energy and chemical use. Future research should:

- **Advance sustainable nutrient removal technologies.** Develop improved technologies capable of reducing nutrient pollution to achieve designated uses while minimizing the costs, energy consumption, and chemical consumption.
- **Advance sustainable technologies for low carbon footprint biological oxygen demand (BOD) removal.** Further develop anaerobic and low dissolved oxygen wastewater treatment processes for reliable and improved performance, particularly in cold climates.
- **Advance innovative low energy membrane processes.** Continue development of membrane processes to reliably meet secondary and advanced wastewater treatment requirements under various operating conditions and climates and reduce energy requirements. An example of a significant area is further developing and demonstrating anaerobic membrane bioreactors to reliably meet secondary treatment requirements under various climate conditions and discharge limit requirements. Another example is development of the membrane aerated biofilm reactor (MABR) which diffuses oxygen through the membrane into the biofilm providing near complete oxygen transfer efficiency and significantly reducing aeration requirements and greenhouse gas conditions.
- **Further develop and demonstrate short-cut nitrogen removal processes including nitritation-denitritation and deammonification processes.** Further evaluate stable operating conditions, determine optimal configurations, and determine whether combinations with other processes are needed for process reliability in meeting various treatment targets under various wastewater conditions.
- **Improve analytical methods.** Evaluate the need to develop more sensitive analytical methods to measure low levels of phosphorus.
- **Further develop innovative wastewater resource technologies and management approaches.** Further develop research recovery technologies including recovery of nutrients (particularly nitrogen), carbon, and water from various types of wastewater. Assess and advance scientific and societal research needed for practical deployment of sustainable management approaches such as gray water, black water, and urine diversion in appropriate settings. Develop sensor technology for system management and optimization.

To learn more about how these future research needs relate to the other research priorities, see Table 1-2.

## 1.3 Address Impacts from Urban, Rural, and Agricultural Environments

### Background

Nutrient loading from various sources, such as residential use of fertilizers in urban areas, shallow wells in rural regions, and agricultural practices is another important research area. Loading may increase due to higher ambient temperatures and changes in precipitation due to climate change, which affect runoff patterns (Whitehead and Crossman, 2011). Currently the NWP is coordinating cross agency (Office of Wetlands, Oceans, and Watersheds (OWOW); Office of Science and Technology (OST); and ORD) research and involving key stakeholders to understand evolving coastal acidification science, such as the role of land-based sources (e.g., nutrient runoff), to better inform water quality-related decisions (US EPA, 2014a). ORD is currently modeling the linkage of discharge and nutrients from the Mississippi River Basin (MRB) to the Gulf of Mexico (GOM), to assess management and policy scenarios of nutrient change and climate change (US EPA, 2014b). The nutrient-related hypoxia and HABs in the GOM at the mouth of the Mississippi, and in Chesapeake Bay are prime examples of the downstream impacts of nutrient pollution (Boesch et al., 2001, Rabalais et al., 2002). Importantly, while these may represent the most well-known hypoxic “dead zones” in the country, there are an estimated 166 documented “dead zones” along our nation’s coastlines (Diaz and Rosenberg, 2008), and 65% of the country’s major estuaries displayed symptoms of nutrient pollution in 2004 (Bricker et al., 2007). Other research investigates nutrient loading with the potential to cause adverse impacts to both local and downstream water bodies. However, conditions such as limited light availability (Cloern, 1999), a high proportion of grazers in the macroinvertebrate community (Rosemond et al., 1993, Riseng et al., 2004), and the presence of zebra mussels (Dzialowski and Jessie, 2009), can all mask or delay local nutrient pollution impacts.

In addition to environmental impacts, nutrient pollution causes measurable economic impacts (Hoagland and Scatasta, 2006). A recently completed comprehensive study on the economic impact of nutrients and algae on a central Texas drinking water supply evaluated the watershed nutrient impacts on algal blooms and consequent economic costs and benefits of treating source water (US EPA, 2014a). OW is also collaborating with ORD’s Sustainable and Healthy Communities Research (SHC) Program’s research program in the area of nutrients and economics.

### Future Research Areas

Research to address these environmental and economic impacts should:

- **Model effects on downstream regions.** Model decision alternatives for regions such the Middle Savannah River Basin and the GOM to provide a framework for assessing and mitigating these widely varying sources and impacts.
- **Identify and understand best practices for communicating alternative practices.**

To learn more about how these future research needs relate to the other research priorities, see Table 1-3.

## 1.4 Address Impacts from Air Deposition of Reactive Nitrogen (Nr)

### Background

Deposition of nitrogen from the atmosphere generates a series of effects, including acidification of soils and water bodies and inadvertent fertilization of trees and grasslands. This leads to excessive growth rates and nutrient imbalances. Reactive nitrogen (Nr) leaches out of the soils and can make ground and surface waters unfit for human consumption (Woods Hole Research Center, 2014). As all but a small portion of Nr produced comes from agricultural and industrial sources (US EPA, 2011), the problem of addressing deposition must be approached holistically to prevent pollution from being shifted from one medium to another. Focusing on the overabundance of nitrogen at the air-water interface should allow environmental laws to coordinate and form an interlocking barrier rather than a loose sieve. To reach this goal, the NWP, Office of Air and Radiation (OAR), and ORD's Safe and Sustainable Water Resources (SSWR); SHC; and Air, Climate, and Energy (ACE) research programs have been discussing how to best collaborate to reduce Nr and address the overall threat of nutrient pollution.

### Future Research Areas

Future research should (US EPA, 2014c):

- **Develop integrated air and water sensor technology.** This type of technology would be helpful for the bullets below.
- **Improve the understanding of the air-water interface of reactive nitrogen.** Target chemical forms that have been less studied.
- **Build from the "Nitrogen and Co-pollutant Research Roadmap".** Explore both air deposition and volatilization, especially in areas where aerial, aquatic, and terrestrial environments are impaired.
- **Locate impaired waters and airways.** Identify the pollutants causing the impairments and the relative contributions from air deposition and volatilization to the impairments defined. Such data would help provide the scientific basis for national ambient air quality standards (NAAQS) and hazardous air pollutants (HAPs) standard revisions, as well as provide support for future rulemakings and for the identification of additional research needs.
- **Complete a systematic review of science on the air-water interface.** Study the cascade effects from air deposition and volatilization from land and water to air to support potential revision of secondary NAAQS and HAPs standards. A full understanding of existing science will enable EPA to use limited research dollars and resources more efficiently.
- **Establish a common base of understanding.** Strengthen new regulatory and voluntary efforts, clearing up confusion stemming, for example, from lags in the nitrogen cycle or indirect effects from ecosystem structure and function changes.

- **Support potential regulatory changes and new voluntary programs.** Develop load-response functions and conduct policy analyses and cost-benefit analyses that consider ecosystem services to validate NAAQS revisions.
- **Complete research on areas suitable for new voluntary programs.** Assess the effectiveness of different interventions, such as updates to POTWs and green infrastructure solutions.

To learn more about how these future research needs relate to the other research priorities, see Table 1-4.

## 1.5 Nutrient Pollution and Harmful Algal Blooms Crosswalk with Other Research Priority Areas

**Table 1-1. Update Water Quality Criteria for Nutrients – Future Research Needs**

| Future Research Need | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Obtain sufficient field data to calculate numeric criteria. | | | | | X | | |
| Evaluate effectiveness of emerging technologies for characterization of aquatic life. | | | | | X | X | |
| Evaluate effectiveness of new monitoring technologies for identifying degraded or at risk waters for nutrient pollution. | | X | | | X | | |
| Evaluate nutrient indicators for different regions and water body types. | | | | | X | X | X |
| Evaluate indicator responses across temporal and spatial scales. | | | | | X | X | X |
| Determine endpoints/indicators for nutrient-enhanced coastal acidification. | | | | | X | X | X |
| Develop ecosystem and watershed-scale multi-media models to evaluate management options and inform decisions. | | | | | X | X | X |
| Ensure numeric nutrient criteria are protective under varying flow conditions. | | | X | | X | X | X |
| Implement protective nutrient trading approaches by developing monitoring methods, models, and guidance. | | | | | X | X | X |
| Investigate conditions under which cyanobacteria produce toxins, and develop tools to help with that assessment (analytical methods, sensors). | | | | X | X | | X |

| Future Research Need | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Investigate risks to human health associated with long-term, low-level exposure to cyanobacteria HABs in drinking water. | | | | X | | | X |

**Table 1-2. Explore Innovative, Sustainable, and Cost-Effective Solutions – Future Research Needs**

| Future Research Need | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Advance sustainable nutrient removal technologies. | | X | | | | | |
| Advance sustainable technologies for BOD removal and low dissolved oxygen wastewater treatment processes. | | X | | | | | |
| Advance innovative low energy membrane processes. | | X | | | | | |
| Further develop short-cut nitrogen removal processes. | | X | | | | | |
| Improve analytical methods to detect low-levels of phosphorus. | | X | | | | | |
| Further develop wastewater resource technologies and management approaches. | | X | | | | | |

**Table 1-3. Address Impacts from Urban, Rural, and Agricultural Environments – Future Research Needs**

| Future Research Need | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Model the environmental and economic effects of runoff on downstream regions. | | | X | X | X | X | X |
| Identify and understand best practices for communicating alternative practices. | | | | | X | X | |

**Table 1-4. Address Impacts from Air Deposition of Reactive Nitrogen (Nr) – Future Research Needs**

| Future Research Need | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Develop integrated air and water sensor technology. | | X | | | X | X | |
| Improve the understanding of the air-water interface of Nr. | | | | | X | X | |
| Explore Nr air deposition and volatilization. | | | | | X | X | |
| Locate impaired waters and airways. | | | | | X | | |
| Review the state-of-the-science on the air-water interface. | | | | | X | | |
| Establish a common base of understanding to support regulatory change and voluntary programs. | | | | | X | X | |
| Support potential regulatory changes and new voluntary programs. | | | | | X | X | |
| Assess effectiveness of interventions such as GI. | | X | | | X | X | |

## 1.6 References


Baker, M. 2014. “Dealing with an array of challenges: Algal toxins to diesel oil spills.” ASDWA Twenty-Ninth Annual Conference.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. *Journal of Environmental Quality*. 30:303-320.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of nutrient enrichment in the nation's estuaries: a decade of change. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. http://ian.umces.edu/neea/.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*. 8:559-568.

Centers for Disease Control. 2014. Recreational water-associated disease outbreaks—United States, 2009-2010. *Morbidity and Mortality Weekly Report (MMWR)*. 2014. 63:6-10.

Cloern, J.E. 1999. The relative importance of light and nutrient limitation of phytoplankton growth: a simple index of coastal ecosystem sensitivity to nutrient enrichment. *Aquatic Ecology*. 33:3-16. http://ic.ucsc.edu/~kudela/OS130/Readings/Cloern,1999.pdf.

Compton, J.E., J.A. Harrison, R.L. Dennis, T.L. Greaver, B.H. Hill, S.J. Jordan, H. Walker and H. V. Campbell. 2011. Ecosystem services altered by human changes in the nitrogen cycle: A new perspective for U.S. decision making. *Ecology Letters.* 14:804–815.

Conry, T.M. 2010. Lake Waco comprehensive study: Background and overview. *Lake and Reservoir Management.* 26:74-79.

Diaz, R.J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science.* 321:926-929.

Dzialowski, A.R., and W. Jessie. 2009. Zebra mussels negate or mask the increasing effects of nutrient enrichment on algal biomass: A preliminary mesocosm study. *Journal of Plankton Research.* 31(11):1437-1440.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology.* 46:220-235.

Hoagland P., and S. Scatasta. 2006. The economic effects of harmful algal blooms. In: E. Graneli and J. Turner, eds., *Ecology of Harmful Algae*. Ecology Studies Series. Dordrecht, The Netherlands: Springer-Verlag, Chap. 29.

Moss, B., S. Kosten, M. Meerhoff, R.W. Battarbee, E. Jeppesen, N. Mazzeo, K. Havens, G. Lacerot, Z. Liu, L. De Meester, H. Paerl, and M. Scheffer. 2011. Allied attack: Climate change and eutrophication. *Inland Waters.* 1:101-105.

Rabalais, N.N., R.E. Turner, and W.J. Wiseman. 2002. Gulf of Mexico hypoxia, a.k.a. "the dead zone." *Annual Review of Ecology and Systematics.* 33:235-263.

Riseng, C.M., M.J. Wiley, and R.J. Stevenson. 2004. Hydrologic disturbance and nutrient effects on benthic community structure in Midwestern U.S. streams: A covariance structure analysis. *Journal of the North American Benthological Society.* 23(2):309-326. http://www.owrb.ok.gov/quality/standards/pdf_standards/scenicrivers/Riseng,%20Wiley%20and%20Stevenson%202004.pdf.

Rosemond, A.D., P.J. Mulholland, and J.W. Elwood. 1993. Top-down and bottom-up control of stream periphyton: Effects of nutrients and herbivores. *Ecology.* 74(4):1264-1280. http://www.uvm.edu/~ngotelli/Bio%20264/Rosemond.pdf.

US EPA, 2009. *TMDL Program Results Analysis Fact Sheet.* US EPA Office of Water, July 17, 2009. http://www.epa.gov/owow/tmdl/results/pdf/aug_7_introduction_to_clean.pdf.

US EPA. 2010. *Using Stressor-response Relationships to Derive Numeric Nutrient Criteria. US EPA, Office of Water, Office of Science and Technology*. EPA-820-S-10-001. November 2010. http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/upload/Using-Stressor-response-Relationships-to-Derive-Numeric-Nutrient-Criteria-PDF.pdf.

US EPA. 2011. Reactive nitrogen in the United States: An analysis of inputs, flows, consequences, and management options. A report of the EPA Science Advisory Board (EPA-SAB-11-013). http://yosemite.epa.gov/sab/sabproduct.nsf/WebBOARD/INCSupplemental.

US EPA. 2012. *Safe and Sustainable Water Resources: Strategic Research Action Plan 2012-2016. Office of Research and Development*. EPA 601-R-12-004. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/sswr-strap.pdf.

US EPA. 2013a. *Emerging Technologies for Wastewater Treatment and In-Plant Wet Weather Management*. Office of Water, Office of Wastewater Management. EPA 832-R-12-011. March 2013. http://water.epa.gov/scitech/wastetech/upload/Emerging-Technologies-Report-2.pdf.

US EPA. 2013b. Nitrogen and co-pollutant research roadmap: Implementation plan. Draft. August 26, 2013.

US EPA. 2014a. The economic impact of nutrients and algae on a central texas drinking water supply. May 2014.

US EPA. 2014b. *FINAL DRAFT - 2014 Workplan for the national water program 2012 strategy: Response to climate change*. April 2014. http://water.epa.gov/scitech/climatechange/2012-National-Water-Program-Strategy.cfm.

US EPA. 2014c. *Summary of research gaps - N and Co-pollutant research*. Draft Final. May 2, 2014.

US EPA. 2015. *Drinking water health advisory for the cyanobacterial microcystin toxins*. Office of Water. EPA 820-R-15-100. June 15, 2015. http://www2.epa.gov/sites/production/files/2015-06/documents/microcystins-report-2015.pdf.

Whitehead, P.G., and J. Crossman. 2011. Macronutrient cycles and climate change: Key science areas and an international perspective. *Science of the Total Environment.* 434:13-17.

Woods Hole Research Center. 2014. Reactive nitrogen in the environment: Too much or too little of a good thing. http://whrc.org/global/nitrogen/index.html#sthash.6Tl976Ie.dpuf.

# Chapter 2. Hydraulic Fracturing

The United States has extensive reserves of natural gas and oil that are now commercially viable as a result of recent advances in horizontal drilling and hydraulic fracturing (HF) technologies. HF is a production stimulation technique used to increase the production or oil and gas since the late 1940s. Historically, HF was mainly used in conventional hydrocarbon reservoirs and continues to be used in these settings. However, technological advancements reached in the early 2000s have enabled the widespread use of modern HF in unconventional (low permeability) reservoirs such as shale, tight sands, and coalbeds. The Energy Information Agency (EIA) projects that over the next 30 years, the majority of domestic natural gas production will come from unconventional resources where HF is used (EIA, 2013). With the increased use and projections of a continued expansion of HF, concerns have increased about its potential human health and environmental impacts, especially those on the quantity and quality of drinking water. These concerns are particularly relevant in the context of climate change. Changes in precipitation patterns can degrade water quality in some locations with, for example, increased contaminant loadings due to more intense precipitation events or increase water scarcity and stress in other locations under drier or drought conditions (Melillo et al., 2014).

HF involves the injection of specially engineered fluids under high pressure great enough to fracture the oil- and gas-bearing rock formations. The resulting fractures are propped open using “proppants,” such as sand or ceramic beads, allowing oil and gas to flow to the production well. The injected HF fluids typically consist of about 90% water, 9% sand, and 1% or less of chemicals (King, 2012; GWPC and ALL Consulting, 2009; US EPA, 2015a). HF wells can range from 600 feet to more than 13,000 feet in depth (GWPC and ALL Consulting, 2009; NETL, 2013), and they may include deviated (angled) or horizontal sections extending thousands of feet (Hyne, 2012; Miskimins, 2008). Once the injection process is completed, the natural pressure in the deep formation causes fluid, along with the oil and/or gas, to flow to the well and through the well to the surface. These fluids consist of some portion of the injected HF fluids (sometimes referred to as “flowback”) along with native formation water (“produced water”). The flowback and produced water are sometimes referred to as HF wastewater.

The United States Environmental Protection Agency (EPA) is conducting extensive research regarding many aspects of the potential impacts to drinking water resources from HF operations. In response to a request from Congress (US House of Representatives, 2009), EPA is conducting research on HF that includes approximately 20 research projects (US EPA, 2011; US EPA, 2012). Results from some of these projects served as a source of information for the recent draft publication of "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources" or National HF Assessment (US EPA, 2015b). The National HF Assessment also includes state-of-the-science literature reviews and other research regarding HF and drinking water resources. This multifaceted EPA national study is designed around five stages of the HF water cycle with each stage associated with a fundamental research question, as follows:

- **Water Acquisition:** What are the potential impacts of large volume water withdrawals from ground and surface waters on drinking water resources?
- **Chemical Mixing:** What are the possible impacts of surface spills of HF fluids on or near well pads on drinking water resources?
- **Well Injection:** What are the possible impacts of the injection and fracturing process on drinking water resources?
- **Flowback and Produced Water:** What are the possible impacts of surface spills of flowback and produced water on or near well pads on drinking water resources?
- **Wastewater Treatment and Waste Disposal:** What are the possible impacts of inadequate treatment of HF wastewaters on drinking water resources and aquatic life?

The National Water Program (NWP) is also interested in understanding the potential impacts of HF operations, waste products, and spills on human health, aquatic life, and ecosystems and their services, with the goal of informing decisions on potential policy and rulemaking. The remainder of this chapter summarizes on-going research and additional needs in the context of the five stages of the HF water cycle.

## 2.1 Water Acquisition

### Background

To develop and produce natural gas and/or oil from an unconventional shale reservoir, a HF well typically uses between 1 million and 2 million gallons of water. The amount ranges from less than 1 million to more than 5 million gallons per well due to geologic and operational factors (US EPA, 2015a). Most of the water used is fresh water obtained from local surface or ground water sources. Although the use of reused and lower quality water for HF injection is on the rise (USGAO, 2012; Rassenfoss, 2011; US EPA, 2015b), fresh water is currently the predominant type of water used in HF operations (FracFocus, 2014; GWPC and ALL Consulting 2009; Nicot et al., 2012; US EPA, 2015b).

EPA's ongoing research is aimed at answering the following questions related to water acquisition:

- How much water is obtained and used in HF operations, and what are the sources of this water?
- How might withdrawals of water for HF affect short- and long-term water availability in an area with significant and possibly growing HF activity?

- What are the possible impacts of water withdrawals for HF operations on local water quality?

To begin addressing these questions, EPA has reviewed data from state websites, numerous peer-reviewed publications, and nearly 40,000 HF well records from the publicly-accessible FracFocus website[3] to gain a better understanding of the amount of water used for HF operations in different regions. In addition, EPA has reviewed HF water use at the county level and used watershed models to identify potential drinking water resource impacts in two river basins – one in a semi-arid and one in a humid region) caused by the withdrawal of water for HF operations. This modeling study also evaluated the potential impacts of water withdrawal on the hydrology of stream headwaters.

## Future Research Areas

Given the diverse and extensive geography in which HF operations are conducted, additional research is needed to:

- **Understand water withdrawal on a wider geographic scale.** Determine the applicability of the first and second phase of EPA basin modeling studies to other areas and regions.
- **Study the seasonal impact on water withdrawal.** Assess the potential impacts of water withdrawal during different seasons and other water quantity-impacting conditions like drought. Determine the geographic areas where water quantity and quality may be vulnerable to seasonal effects.

Changes in water quantity can impact the hydrology and water quality of a watershed, which in turn can affect the watershed's ecological integrity and the capacity of water bodies to support aquatic life. In watersheds where HF water withdrawals occur, there is a need to:

- **Understand water withdrawal impacts on ecological integrity and ecosystem services.** Research water withdrawal impacts on the health and abundance of aquatic life as well as fishing and other recreational uses. For example, research may provide information to support actions to protect watersheds from potential impacts (e.g., protecting minimum instream flow needs).
- **Determine potential impacts of flow modification practices.** Address whether diversions and other flow modifications are being used by well operators for water acquisition and whether, individually or cumulatively, these affect watershed hydrology and water quality.

To learn more about how these future research needs relate to the other research priorities, see Table 2-1.

[3] FracFocus is a national registry for chemicals used in HF. This registry was jointly developed by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission. EPA developed and analyzed a database using wells records submitted to FracFocus between January 1, 2011 and February 28, 2013.

## 2.2 Chemical Mixing

### Background

Chemicals are transported to the well pad and are mixed on site with water and proppant to prepare the HF fluids. Chemicals are added to water to change its properties (e.g., viscosity, pH) to optimize the production-enhancing performance of the fluid when injected into the oil- and gas-bearing formations. Although hundreds of different chemicals are used as HF fluid additives by different operators in different reservoirs across the United States (US House of Representatives, 2011), the estimated median number of chemicals used per well is 14 based on EPA's analysis of the FracFocus data (US EPA, 2015a). With chemical additives comprising approximately 1% of the injected HF fluids, there is an estimated 10,000 gallons of HF chemical additives handled at a site for a well that injects 1 million gallons of HF fluid. In general, this quantity of chemicals is hauled to and temporarily stored on the well site until it is injected into the subsurface as part of the HF process. Onsite storage, mixing, and pumping of HF fluids may result in accidental releases, such as spills or leaks. These released fluids can flow into nearby surface water bodies or infiltrate into the soil and near-surface ground water, potentially reaching drinking water resources.

As part of the National HF studies, EPA evaluated data from spill databases on the frequency, causes, and volumes of spills of hydraulic fluids for several states and the National Response Center. Hydraulic fracturing-related spill rates are estimated to range from 0.4 to 12.2 per 100 wells based on data available from Pennsylvania and Colorado (US EPA, 2015b), although these numbers may not be representative of national spill rates or rates in other regions. The median volume of spilled hydraulic fracturing fluid was 420 gallons (US EPA, 2015b; US EPA, 2015c). EPA has analyzed data from the FracFocus website related to the types and quantities of chemicals mixed on well pads and used in the hydraulic fluids injected into these wells (US EPA, 2015a) and has compiled available physicochemical properties and toxicity information for chemicals used in HF fluids (US EPA, 2015b).

### Future Research Areas

Beyond this fundamental research, the NWP needs additional information to:

- **Understand risk from surface spills.** Determine if a significant risk exists from surface spills during chemical mixing that: (1) migrate from well pads to the ground surface and reach shallow ground water; (2) migrate from well pads to surface water bodies; or, (3) migrate to surface water bodies that are hydrologically connected with shallow ground water. This research is also relevant in the context of releases from HF flowback and produced water impoundments.

- **Identify factors that affect spill-related risks.** Identify factors that increase or prevent spill-related risks to water quality. For example: (1) if certain surface and subsurface conditions are useful for assessing potential risks; (2) if data on existing spills indicate types of chemicals or site factors that could be used to develop preventative measures; or, (3) whether effective measures could be applied to the diverse localities at which HF is conducted.

- **Determine how to protect drinking water resources and aquatic life.** Determine how information on surface spills can be used by the Source Water Protection Program to safeguard drinking water resources and aquatic life.
- **Assess cumulative impacts from spills at multiple well pads.** Assess potential cumulative impacts from spills at multiple well pads located throughout a watershed that may introduce and elevate pollutant levels, and degrade the ecosystem integrity and related ecosystem services for a given watershed. These types of impacts have the potential to occur in watersheds with a high number and density of wells, well pads, and well operation-support activities.

To learn more about how these future research needs relate to the other research priorities, see Table 2-2.

## 2.3 Well Injection

### Background

To perform HF, the HF fluid is pumped down the production well at pressures great enough to fracture the oil- and/or gas-bearing rock formation. The section of the well that is located within the oil- and/or gas-bearing production zone can be horizontal, deviated, or vertical in orientation. The induced fractures provide the pathways for the oil and/or gas in the hydrocarbon reservoir to flow to the production well. The fracturing process is designed to create fractures that will remain in the targeted zone within the reservoir to optimize production. Impacts on drinking water resources may occur when fluids in or around the production reservoir or along the wellbore move into ground water resources. Proper well construction is critical to maintaining the structural integrity of the well, keeping oil and gas in the well and formation fluids out of the well and wellbore.

EPA research evaluated well design and construction using information and data provided by well operators (US EPA, 2015d). Research conducted for the HFDWA identified two subsurface mechanisms by which the injection of fluid and the creation of fractures can potentially impact drinking water resources: (1) the unintended movement of gases or liquids out of the production well or along the outside of the production well and (2) the unintended movement of gas or liquids from the production zone through subsurface geologic formations (US EPA, 2015b). Some of EPA's HF research is using computer models to evaluate scenarios of potential migration of subsurface gas and fluids from deep shales to overlying aquifers through a deficient well or induced fractures that intersect possible flow pathways (e.g., other wells or existing fractures) (Rutqvist et al., 2013 and 2015). The modeling and other research projects are also assessing how HF fluids and the native fluids encountered may change due to subsurface geochemical interactions. This fate and transport research can also identify if minerals or metals can be mobilized from the geologic formations through which the fluids are flowing. Another aspect of the study involves evaluations provided by well operators regarding well performance data on the effectiveness of current well construction and operational practices.

### Future Research Areas

The NWP is interested in understanding subsurface fluid movement through additional research to:

- **Determine potential impacts on ground water.** Continue modeling studies to assess if the movement of HF-related fluid through the wellbore or induced fractures can impact deep or shallow ground water resources, and if so, the potential human health, aquatic life, or ecosystem services risks.
- **Assess potential water quality impacts associated with surface water-groundwater interactions in the context of HF-related contamination.** Determine the potential risks to both surface water and ground water due to surface water-groundwater interactions if one or the other is affected by the fracturing process. Determine the potential risks that such contamination would pose to human health, aquatic life, or ecosystem services.

To learn more about how these future research needs relate to the other research priorities, see Table 2-3.

## 2.4 Flowback and Produced Water

### Background

Once the HF injection process is completed and the pressure on the well is released, the natural pressure in the targeted production reservoir causes fluid (along with the oil and/or gas) to flow to the well and through the well to the surface. This fluid includes some portion of the injected HF fluid ("flowback"), with subsequent flow of native formation water ("produced water") as the well enters the production phase of its life cycle.[4] The mineralogy and geochemistry of the production reservoir influences the composition of the flowback and the produced water (US EPA, 2015b). The flowback and produced water may contain some chemicals from the injected HF fluid during the flowback phase, plus naturally-occurring constituents such as salts, metals, radionuclides, and hydrocarbons. Flowback and produced water from unconventional oil and gas operations is characteristically high in total dissolved solids (TDS). Reported median TDS values range from 100,000 mg/L in the Marcellus shale play in Pennsylvania (Barbot et al., 2013) to 32,000 mg/L in Western shale basins (Benko and Drewes, 2008). HF flowback and produced water can have high concentrations of major ions (e.g., calcium, magnesium, sodium, chloride, and sulfate), hardness, iron, and strontium as well as bromide, radium, and other naturally occurring radioactive materials (NORMs) (Vidic, 2010; Hayes, 2009; URS, 2011; US EPA 2015b). Limited data are available on the concentrations, persistence, or transformations of the fracturing fluid additives in the HF flowback water, with even less known about proprietary fluid additives.

EPA's National HF Assessment has been evaluating:

- The current knowledge regarding the frequency, severity, and causes of spills of flowback and produced water.
- The current state of information on the composition of HF flowback and produced water and what factors influence composition.

[4] Collectively, flowback and produced water may be referred to as hydraulic fracturing wastewater or simply as produced water.

- The chemicals associated with HF flowback and produced water in terms of their physicochemical and toxicological properties.
- How surface spills of HF flowback and produced water might contaminate drinking water resources.

### Future Research Areas

The NWP is interested in characterizing the composition of HF wastewater to enable assessments of their potential impacts to surface water that serves as drinking water sources as well as potential impacts to ecological integrity and aquatic life. Specific research is needed to:

- **Characterize HF flowback and produced water constituents.** Continued efforts are needed to better characterize the constituents in HF flowback and produced water from the various major oil and gas basins. Data are needed on a broad suite of analytes, especially with respect to organic constituents and radionuclides. This would provide data to understand geochemical variation in HF flowback and produced water among reservoirs and/or operational practices.
- **Identify indicators or tracers and sensor technology to detect them.** Identify possible indicators or tracers, such as chloride and TDS, that can indicate if HF fluids may have been released to surface water or shallow ground water. Identify monitoring and sampling strategies that include timing, sample locations, and sampling parameters (i.e., indicators or tracers) or sensors that will increase the likelihood of identifying potential impacts from flowback or produced waters.

The NWP is also interested in studying the impacts of potential releases of HF flowback and produced water on human health, aquatic life, and ecological integrity. Additional research is needed to:

- **Assess additive or synergistic effects of HF flowback and produced water.** Develop an approach to assess the additive and synergistic effects of the chemical constituents of HF flowback and produced water on human health and the ecological integrity and aquatic life of watersheds, for example, considering the toxicity equivalent factor or Biotic Ligand Model.

To learn more about how these future research needs relate to the other research priorities, see Table 2-4.

## 2.5 Wastewater Treatment and Waste Disposal

### Background

Hydraulically fractured oil and gas production wells can generate several hundred thousand gallons or more of flowback and produced water with generated volumes varying significantly and dependent on the type of hydrocarbon being produced, the geology of the reservoir, and well operational details (Boschee, 2014; USGAO, 2012; US EPA, 2015a; US EPA, 2015b). Hydraulic fracturing wastewater encompasses flowback and produced water that is managed using any of a number of practices, including treatment and discharge, reuse, or injection into disposal wells. HF wastewater is generally transported to and injected into deep Underground Injection Control (UIC) Class II disposal wells, but in some regions the wastewater is processed by wastewater treatment facilities and either discharged or sent for reuse as base fluid for new fracturing jobs (US EPA, 2012; USGAO, 2012; US EPA, 2015b). Wastewaters may also be reused with minimal or no treatment other than dilution, or they may be used for other beneficial uses, e.g., irrigation, if water quality is suitable.

If HF wastewater is not managed properly, chemicals of concern can present a risk to water quality, which in turn may also place a burden on wastewater and drinking water treatment facilities. Effluent containing inadequately treated HF wastewater can impact surfaces waters where wastewater treatment plants discharge or if spills from trucks or impoundments occur.

EPA's National HF Assessment (US EPA, 2015b) and other EPA research efforts (US EPA, 2015e, f, g, and h) have been evaluating:

- Common wastewater management methods, including UIC Class II disposal wells, treatment, and reuse, and where these methods are practiced.
- The potential impacts from surface water disposal of treated HF wastewater on drinking water treatment facilities.
- Analytical methods for select chemicals found in HF fluids or wastewater, especially in the context of high TDS.
- Whether HF wastewater may contribute to disinfection byproducts (DBPs) formation during drinking water treatment processes, with particular focus on brominated DBPs.

In addition, the NWP is updating the aquatic life criteria for chloride, and developing new sulfate criteria and a conductivity method which can be used by states to develop HF wastewater discharge permits and for monitoring surface waters near HF pads.

## Future Research Areas

Additional research is needed to:

- **Identify which wastewater management choices are most appropriate for different regions**. Consider which wastewater management options are appropriate in different regions depending upon wastewater quality, quality of the aquatic ecosystem potentially receiving (treated) wastewater discharges, available infrastructure, possible beneficial uses, availability of Class II disposal wells, state and local regulations, and other factors. This may be particularly important on a local level if disposal into UIC Class II disposal wells becomes limited for any reason, e.g., capacity, induced seismicity.
- **Continue to identify new or more sensitive analytical methods.** Analytical methods are needed that can identify and quantify chemical additives in HF fluids and the chemical constituents anticipated in HF wastewater. The methods need to be effective in high-TDS waters.
- **Evaluate wastewater treatment capabilities.** Assess whether wastewater treatment facilities can adequately treat and keep pace with the possible changes in composition and/or quantities of HF wastewater.

- **Evaluate Class II well operations.** Determine whether the availability and capacity of Class II disposal wells are adequate and appropriate for HF wastewater quantities anticipated in areas where HF activity is expected to increase. Assess whether regulations and operations of Class II disposal wells are appropriate for the chemical constituents in HF wastewaters, e.g., radionuclides.

Research is also needed on HF wastewater recycling, reuse, and disposal to:

- **Assess on-site pre-treatment/treatment of wastewater practices.** Assess current and develop new on-site pre-treatment or treatment techniques for HF wastewater. These treatment techniques may allow for greater reuse and recycling, and reduce transportation and disposal of waste off-site. Also clarify settings and conditions in which on-site reuse with minimal to no treatment is feasible.
- **Define pre-treatment/treatment levels for agricultural use.** Clarify the necessary water quality and levels of pre-treatment or treatment needed for agricultural or other beneficial uses. This information will assist permit writers in developing discharge permits that meet downstream designated uses and water quality standards.
- **Expand research on the impact of disposal practices on drinking water treatment systems.** Assess disposal practices that minimize potential impacts of wastewater discharges on downstream water facilities. Also assess the most effective pre-treatment and treatment technologies to optimize treatment of HF wastewater.

To learn more about how these future research needs relate to the other research priorities, see Table 2-5.

## 2.6 Hydraulic Fracturing Crosswalk with Other Research Priority Areas

**Table 2-1. Water Acquisition – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Understand water withdrawal on a wider geographic scale. | | | | | X | X | X |
| Study seasonal impacts of water withdrawal. | | | | | X | X | X |
| Research ecological impacts of water withdrawal. | | | | | X | X | X |
| Research impacts of flow modification practices. | | | | | X | X | X |

**Table 2-2. Chemical Mixing – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Understand risk from spills during chemical mixing. | | | | X | X | | |
| Identify factors that affect spill-related risks. | | | | X | X | | |
| Determine how information on surface spills can be used to protect source waters and aquatic life. | | | | X | X | X | |
| Assess cumulative impacts of spills at multiple well pads within a watershed. | | | | X | X | X | |

**Table 2-3. Well Injection – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Model potential impacts to ground water and potential human health, aquatic life, or ecosystem risks. | | | | X | X | X | |
| Assess potential water quality impacts from surface water-ground water interactions and potential human health, aquatic life, or ecosystem risks. | | | | X | X | X | |

**Table 2-4. Flowback and Produced Water – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Better characterize HF flowback and produced water constituents. | | | | X | | | |
| Identify HF indicators or tracers and sensor technology to detect them. | | X | | X | | | |
| Assess additive or synergistic effects of HF flowback and produced water. | | | | X | X | | |

**Table 2-5. Wastewater Treatment and Waste Disposal – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Identify regionally appropriate wastewater management options. | | X | | | X | | |
| Identify new or more sensitive analytical methods. | | X | | X | | | |
| Evaluate wastewater treatment capabilities for HF wastewater. | | X | | X | | | |
| Evaluate Class II well operations for handling HF wastewater. | | X | | | | | |
| Assess on-site wastewater treatment practices for HF wastewater. | | X | | X | | | |
| Define treatment levels for agricultural use. | | X | | X | | | |
| Expand research on impacts of disposal practices on drinking water treatment. | | X | | X | X | X | |

## 2.7 References


Barbot, E., N.S. Vidic, K.B. Gregory, and R.D. Vidic. 2013. Spatial and temporal correlation of water quality parameters of produced waters from devonian-age shale following hydraulic fracturing. *Environmental Science and Technology.* 47(6):2562-2569.

Benko, K.L. and J.E. Drewes. 2008. Produced water in the western United States: Geographical distribution, occurrence, and composition. *Environmental Engineering Science.* 25(2):239-246.

Boschee, P. 2014. Produced and flowback water recycling and reuse: Economics, limitations, and technology. *Oil and Gas Facilities*. 3:16-22.

EIA. 2013. *Annual energy outlook 2013*. April. DOE/EIA-0383(2013). http://www.eia.gov/forecasts/archive/aeo13/pdf/0383(2013).pdf.

FracFocus. 2014. Available at https://www.fracfocusdata.org/. Accessed July 2, 2014.

GWPC and ALL Consulting. 2009. Modern shale gas development in the U.S.: A primer. Ground Water Protection Council and ALL Consulting for U.S. Department of Energy. http://energy.gov/sites/prod/files/2013/03/f0/ShaleGasPrimer_Online_4-2009.pdf. Accessed July 28, 2015.

Hayes, T. 2009. Sampling and analysis of water streams associated with the development of Marcellus shale gas. Des Plaines, IL: Marcellus Shale Coalition. http://eidmarcellus.org/wp-content/uploads/2012/11/MSCommission-Report.pdf. Accessed July 28, 2015.

Hyne, N.J. 2012. *Nontechnical guide to petroleum geology, exploration, drilling and production* (Third Edition). Tulsa, OK: PennWell Corporation.

King, G.E., 2012. “Hydraulic fracturing 101: What every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells.” Society of Petroleum Engineers 2012 Hydraulic Fracturing Technology Conf., The Woodlands, TX. http://dx.doi.org/10.2118/152596-MS.

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014. *Climate change impacts in the United States: The third national climate assessment.* U.S. Global Change Research Program.

Miskimins, S.L. 2008. “Design and lifecycle considerations for unconventional reservoir wells.” SPE Unconventional Reservoir Conference.

NETL. 2013. *Modern shale gas development in the United States: An update*. National Energy Technology Laboratory. September 2013.

Nicot, J.P., R.C. Reedy, R.A. Costley, and Y. Huang. 2012. *Oil & gas water use in Texas: Update to the 2011 mining water use report*. September 2012. https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830939_2012Update_MiningWaterUse.pdf.

Rassenfoss, S. 2011. From flowback to fracturing: Water recycling grows in the Marcellus Shale. *Journal of Petroleum Technology*. July 2011: 48-51.

Rutqvist, J., A.P. Rinaldi, F. Cappa, and G.J. Moridis. 2013. Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs. *Journal of Petroleum Science and Engineering*. 107:31-44. http://dx.doi.org/10.1016/j.petrol.2013.04.023.

Rutqvist, J., A.P. Rinaldi, F. Cappa, and G.J. Moridis. 2015. Modeling of fault activation and seismicity by injection directly into a fault zone associated with hydraulic fracturing of shale-gas reservoirs. *Journal of Petroleum Science and Engineering.* 127:377-386. http://dx.doi.org/10.1016/j.petrol.2015.01.019.

US EPA. 2011. *Plan to study the potential impacts of hydraulic fracturing on drinking water resources.* Office of Research and Development. EPA 600-R-11-122. November 2011. http://www2.epa.gov/sites/production/files/documents/hf_study_plan_110211_final_508.pdf.

US EPA. 2012. *Study of the potential impacts of hydraulic fracturing on drinking water resources: Progress report*. Office of Research and Development. EPA 601-R-12-011. December 2012. http://www2.epa.gov/sites/production/files/documents/hf-report20121214.pdf.

US EPA. 2015a. *Analysis of hydraulic fracturing fluid data from the FracFocus chemical disclosure registry 1.0*. Office of Research and Development. EPA 601-R-14-003.March 2015. http://www2.epa.gov/hfstudy/analysis-hydraulic-fracturing-fluid-data-fracfocus-chemical-disclosure-registry-1-pdf.

US EPA. 2015b. *Assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources – External review draft (undergoing peer review)*. Office of Research and Development. EPA 600-R-15-047. June 2015. http://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=244651.

US EPA. 2015c. *Review of state and industry spill data: Characterization of hydraulic fracturing-related spills*. Office of Research and Development. EPA 601-R-14-001. May 2015. http://www2.epa.gov/sites/production/files/2015-05/documents/hf_spills_report_final_5-12-15_508_km_sb.pdf.

US EPA. 2015d. *Review of well operator files for hydraulically fractured oil and gas production wells: Well design and construction*. Office of Research and Development. May 2015. EPA 601-R-14-002. http://www2.epa.gov/sites/production/files/2015-05/documents/wfr_1_final_5-8-15_508_km_5-13-15_sb.pdf.

US EPA. 2015e. DMR spreadsheet Pennsylvania wastewater treatment plants per Region 3 Information Request. Data provided by request. US EPA Region 3.

US EPA. 2015f. Effluent data from Pennsylvania wastewater treatment plants per Region 3 Information Request. Data provided by request. US EPA Region 3.

US EPA. 2015g. *Sources contributing inorganic species to drinking water intakes during low flow conditions on the Allegheny River in western Pennsylvania*. Office of Research and Development. EPA 600-R-14-430. May 2015.

US EPA. 2015h. Technical development document for proposed effluent limitation guildelines and standards for oil and gas extraction. Office of Water. EPA 821-R-15-003. March 2015. http://water.epa.gov/scitech/wastetech/guide/oilandgas/upload/UOG-Proposal-TDD-2015.pdf.

USGAO. 2012. *Energy-water nexus: Information on the quantity, quality, and management of water produced during oil and gas production*. U.S. Government Accountability Office. GAO-12-156. January 2012. http://www.gao.gov/assets/590/587522.pdf.

U.S. House of Representatives. 2009. *Appropriations committee report for the department of the interior, environment, and related agencies appropriations bill, HR 2996*. http://www.gpo.gov/fdsys/pkg/CRPT-111hrpt180/pdf/CRPT-111hrpt180.pdf.

U.S. House of Representatives. 2011. *Chemicals used in hydraulic fracturing*. Available at http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic-Fracturing-Chemicals-2011-4-18.pdf.

URS Corporation. 2011. Water-related issues associated with gas production in the Marcellus Shale. Prepared for New York State Energy Research and Development Authority. March 25, 2011.

Vidic, R.D. 2010. “Sustainable water management for marcellus shale development.” Marcellus shale natural gas stewardship: Understanding the Environmental Impact summit at Temple University, March 2010.

# Chapter 3. Next Generation Water and Wastewater Treatment Technologies

Over the last 40 years, government and private sector efforts to implement the wastewater and drinking water treatment requirements of the Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA) have resulted in tremendous progress in protecting the nations' water resources, meeting water quality standards, and achieving public health protection goals. This progress had been aided by improvements in drinking water and wastewater treatments over the past 20 years to optimize process design and develop appropriate advanced treatment technologies.

Despite these advances, rapid population growth and land development, rising energy prices, and the emergence of new contaminants of concern place increased stress on current wastewater and water treatment systems. In addition, aging infrastructure, dwindling water supplies, increased treatment needs from high contaminant levels may necessitate novel approaches that improve NWP's ability to anticipate and address these issues proactively. Innovative treatment approaches and technologies, known as "next generation" technologies, must be developed to address the effect of these growing stressors on water and wastewater systems. New technologies are also needed to enable states, local governments, and municipalities to continue providing clean and safe drinking water and managing water and wastewater in a sustainable manner. To meet these goals, research is needed to:

- 3.1 Improve Performance of Existing Drinking Water and Wastewater Technologies.
- 3.2 Promote Infrastructure Sustainability.
- 3.3 Develop Innovative Methods to Address Nutrient Pollutants.
- 3.4 Tailor Technologies to Address Contaminants of Emerging Concern.

Research needs related to the impacts of climate change on water and wastewater treatment technologies as well as to the development of sustainable technologies for climate change mitigation are addressed in Chapter 8.

## 3.1 Improve Performance of Existing Drinking Water and Wastewater Technologies

### Background

Research is underway to improve the performance of existing drinking water and wastewater technologies. For drinking water treatment, the use of expanded membrane filtration technologies[5] and advanced oxidation processes[6] alone or with conventional processes, such as granular activated carbon (GAC) filtration, have been shown to cost-effectively remove multiple contaminants and allow for the use of low quality raw water sources, especially those affected by drought.

For centralized wastewater treatment, the use of membrane bioreactors (MBRs), integrated membrane systems, and advanced oxidation/biofiltration processes have been used to reduce levels of solids, nutrients, trace organics, and emerging contaminants of concern in effluent to meet more stringent treatment requirements and allow for water reuse (Brueck et al., 2012). On-site septic systems are recognized as a major source of ground water contamination; however, newer technologies that combine primary treatment with biological treatment have been verified to substantially reduce nitrogen levels (US EPA, 2007). High-volume decentralized wastewater treatment system technologies that use a combination of biological treatment, filtration, and ultraviolet (UV) treatment have been shown to effectively reduce pollutant loads and produce a high quality effluent that can be recycled for landscape irrigation uses (US EPA, 2011b). Improvements in energy efficiency and recovery using combustion engines, microturbine, and fuel cell technologies to generate energy at the point of use, and waste-to-energy technologies involving anaerobic digesters have all been evaluated at full-scale (US EPA, 2006; US EPA, 2009b).

In smaller communities, point-of-use (POU) and point-of-entry (POE) treatment technologies are becoming more technologically and economically feasible, and may be viable options for treatment (Means, 2008; Maxwell, 2010; Brueck et al., 2012). Small systems are of particular concern because these systems are often affected to a greater extent than larger systems by new regulatory developments and by environmental and anthropological stresses for reasons including limited financial and technical resources, aging infrastructure, and costs of scale (US EPA, 2014a). More than 94% of drinking water systems are considered small, i.e., serving fewer than 10,000 individuals (US EPA, 2014b). Very small drinking water systems that serve fewer than 500 individuals have the highest rate of health-based violations. In April 2014, EPA awarded $12.7 million for small water systems to maintain compliance with SDWA requirements and conduct research on improving financial and managerial

[5] Membrane technologies that include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis can provide an effective barrier against microbes, pathogens, and some chemical contaminants.

[6] Advanced oxidative processes can be used to remove taste- and odor-causing compounds and will oxidize many organic and inorganic contaminants, including disinfectant by-products and difficult to treat compounds such as methyl tert-butyl ether (MTBE) and perchlorate (Kavanaugh et al., 2003; Jo et al., 2011; Lamsal et al., 2011; Sarathy et al., 2012; Lehman and Subramani, 2011). Advanced oxidative processes include ozone and hydrogen peroxide ($O_3/H_2O_2$ or $H_2O_2/O_3$), UV radiation and ozone ($UV/O_3$), and UV radiation and hydrogen peroxide ($UV/H_2O_2$).

capabilities, and to small publicly owned treatment works (POTWs) and decentralized wastewater systems to improve their operational performance (US EPA, 2014c). Although plans have been developed for small systems to achieve greater efficiency through management-focused initiatives (US EPA, 2013a), technological limitations still exist.

Tools, such as "smart sensor" technology, which is widely deployed for air quality monitoring, could be expanded to provide real-time and continuous water quality data in drinking water distribution systems, wastewater systems, and stormwater systems. This information would help plant managers make decisions regarding needed adjustments to their treatment operations.

### Future Research Areas

While many of these technologies are already in use or under development, additional research is needed to:

- **Meet future challenges by improving the efficiency of existing processes.** Develop processes at water or wastewater systems to remove current and contaminants of emerging concern (CECs), treat wastewater from hydraulic fracturing (HF) operations, keep pace with increased volumes of pollutants (e.g., nutrients), reduce energy consumption, and increase flexibility in accounting for changing hydrologic conditions due to climate change.
- **Develop new technologies for small systems.** Develop technologies that allow these systems to meet demand and required water and wastewater quality standards while simultaneously improving water and energy efficiency in a sustainable manner.
- **Improve and implement automated "smart sensor" remote monitoring capabilities.** Improve sensor quality and reliability and broaden its use to assist with optimizing drinking water and wastewater plant operations by remotely monitoring water quality in drinking water distribution systems, wastewater systems, and stormwater systems in real time (US EPA, 2012).

To learn more about how these future research needs relate to the other research priorities, see Table 3-1.

## 3.2 Promote Infrastructure Sustainability

### Background

Conventional treatment technologies are designed to perform efficiently under a certain set of conditions. Due to challenges presented by population increases, climate change, and changing land use practices, the performance of current infrastructure must be improved to keep pace with the growing demand for safe drinking water as well as wastewater treatment services. Infrastructure updates can be in the form of repair or replacement of failed infrastructure or improvements in the efficiency and performance of infrastructure. For 2011, the United States Environmental Protection Agency (EPA) estimated that drinking water systems would need to invest $384 billion in drinking water infrastructure repairs or upgrades to ensure they can continue to provide the same or improved services to communities, $64.5 billion of which represent small system investment costs (US EPA, 2014c). EPA also estimated wastewater infrastructure costs to be $298 billion as of 2008 (US EPA, 2014c). However, repair and replacement of existing infrastructure is not an adequate approach for systems that are faced with the challenge of balancing growing demand with their limited resources and manpower.

The National Water Program (NWP), through its drinking water and wastewater systems research, aims to evaluate the sustainability of existing drinking water and wastewater systems and to identify next generation technologies that will promote future infrastructure sustainability (US EPA, 2015b). Current condition assessments can be costly and involve excavation and service interruptions (Davis et al., 2013). Next generation infrastructure assessment technologies are needed that are cost-effective and provide real-time data on the condition of water and wastewater systems, such that systems can detect problems as they arise and can act promptly to avert severe infrastructure failures and reactive maintenance costs (Davis et al., 2013; US EPA, 2008).

The Distribution System Research and Information Collection Partnership (RICP), whose members include EPA and the Water Research Foundation, leads a Steering Committee focused on prioritizing and promoting research and information collection activities related to distribution system issues (e.g., cross connections and backflow, biofilm and microbial growth, etc.). The RICP began in 2009 and developed a list of priority distribution system research needs (US EPA, 2010). Currently, the RICP is reviewing new information since the priority list was developed and will provide recommendations for future research needs in 2016.

## Future Research Areas

Specific research needs include:

- **Adapt Supervisory Control and Data Acquisition (SCADA) systems for condition assessments.** Further adapt SCADA systems for condition assessments. SCADA systems are already in use for real-time monitoring to provide a warning when water or wastewater quality parameters are not within an expected range (Spellman, 2013).
- **Further development, testing, and commercialization of other technologies.** Further pilot test and commercialize new technologies to allow their use by utilities. Such technologies include:
    - Permanent digital noise logging for automated leak and burst detection,
    - Flow monitoring to infer blockages in sewers,
    - Surface-based resistivity to monitor corrosion,
    - Optical fiber monitoring for structural condition, and
    - Pressure transient monitoring to detect internal deterioration (Davis et al., 2013).

To learn more about how these future research needs relate to the other research priorities, see Table 3-2.

## 3.3 Develop Innovative Methods to Address Nutrient Pollutants

### Background

Approximately 14,000 water bodies are affected by nutrient-related impairment from both point and nonpoint sources (US EPA, 2011a). Nutrient over-enrichment, a direct result of excess nitrogen and phosphorus in the air and water, is among the top five causes of surface water impairment in the United States, along with pathogens, mercury, other metals and sediment (US EPA, 2009a). Climate change conditions, such as increased water temperatures, changes in streamflow, and increased acidification, are expected to worsen the impacts of nutrient loading and to increase the proliferation of harmful algae blooms (HABs; Moss et al., 2011; Hallegraeff, 2010).

Impaired water bodies often serve as source waters for water systems that must implement treatment to ensure that their drinking water quality meets National Primary Drinking Water Regulation (NPDWR) standards. Research is needed to develop next generation technologies that will effectively and reliably remove nutrients from wastewaters and source waters to allow the use of nutrient-enriched freshwater to be used as drinking water sources.

Removal of nutrients from wastewater effluent is a major challenge in water reclamation and reuse for designated downstream uses, such as drinking and irrigation. Several technologies show promise for effective nutrient removal and recovery including nitrition-dinitrition, deammonification, and low input ammonia stripping and recovery. Many nutrient technologies are still in the emerging phase where they are tested at laboratory or pilot demonstration scale, such as ammonia recovery analyzer, or are in the research and development phase and tested at the laboratory or bench scale (US EPA, 2008; US EPA, 2013b).

### Future Research Areas

Further research is needed to:

- **Develop improved and cost-effective wastewater treatment technologies.** Develop improved technologies to reduce nutrient pollution levels in wastewater to achieve designated uses while obtaining a minimal carbon footprint.
- **Assess performance and reliability of technologies.** Assess the performance and reliability of new wastewater technologies before making them available to wastewater facilities.

To learn more about how these future research needs relate to the other research priorities, see Table 3-3.

## 3.4 Tailor Technologies to Address Contaminants of Emerging Concern

### Background

EPA regulates microorganisms, organic and inorganic chemicals, disinfectants and disinfection byproducts (DBPs), and radionuclides through its NPWDRs. In addition, through the Unregulated Contaminant Monitoring (UCM) program (as required by the Unregulated Contaminant Monitoring Regulation (UCMR)), EPA gathers data on the occurrence of contaminants suspected to be in drinking water, but which do not have NPDWRs. With the advancement in detection technologies, additional new CECs have been identified in drinking water. Furthermore, changing climate conditions (such as ambient temperatures and streamflow patterns) may lead to the emergence of new CECs or affect the fate, transport, and toxicity of others (Noyes et al., 2009). CECs include endocrine disrupting chemicals (EDCs), pharmaceutical and personal care Products (PPCPs), and other chemicals and constituents identified through EPA's Contaminant Candidate List (CCL) and Regulatory Determinations process, such as microcystins.

Another group of CECs that EPA is investigating are engineered nanomaterials (ENMs), a potential emerging industrial wastewater pollutant category. According to the Nanotechnology Consumer Product Inventory, ENMs are currently used in over 800 consumer products in the United States (US EPA, 2015a). However, the environmental and human health risks associated with these materials are largely unknown.

Next generation water and wastewater treatment technologies must have the capability to remove currently regulated contaminants as well as CECs and groups of contaminants, and control pathogens in drinking water and wastewater without formation of DBPs.

### Future Research Areas

Research therefore, is needed to:

- **Assess the effectiveness of current drinking water technologies.** Evaluate current drinking water treatment technologies to identify areas for improved or new treatment technologies. This process may be guided by EPA's ongoing efforts to identify CECs and to understand their physical and chemical characteristics and fate and transport in water. For example, nanomaterials[7] are used in novel water-treatment approaches (e.g., ceramic water filters coated with nanosilver) (Lubick et al., 2008 as cited in Luoma, 2008), but there is concern about their health effects and fate in the environment (US EPA, 2013c).
- **Assess the effects of emerging contaminants.** Assess the effects of CECs, including ENMs and various cyanotoxins, on water systems and POTWs and the abilities of these materials to pass

[7] Nanomaterials are defined as "a diverse class of small-scale substances that have structural components smaller than 1 micrometer (1000 nanometers (nm)) in at least one dimension" (USEPA, 2010).

through treatment processes. This includes identifying the facilities, production volumes, and wastewaters generated and disposed of from manufacturing and processing ENMs. In addition, the fate, transformation, and treatment of ENMs in industrial wastewaters should be characterized.

To learn more about how these future research needs relate to the other research priorities, see Table 3-4.

## 3.5 Next Generation Water and Wastewater Treatment Technology Crosswalk with Other Research Priority Areas

**Table 3-1. Improve Performance of Existing Drinking Water and Wastewater Technologies – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Improve the efficiency of CEC and nutrient removal processes at water or wastewater systems. | X | | X | X | | | X |
| Develop new technologies for small water and wastewater systems. | X | | X | X | | | |
| Expand the use of sensor monitoring technologies to monitor drinking water distribution systems, wastewater systems, and stormwater systems. | X | X | X | X | X | | X |

**Table 3-2. Promote Infrastructure Sustainability – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Adapt SCADA systems for condition assessments. | | | | | | | X |
| Conduct pilot tests and commercialize other technologies that allow monitoring of flow, leaks bursts, corrosion, and structural condition. | | | X | | | | X |

**Table 3-3. Develop Innovative Methods to Address Nutrient Pollutants – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Further develop wastewater treatment technologies to reduce nutrient pollution. | X | | | | | | |
| Assess technology performance and reliability of new wastewater technologies. | X | | | | | | |

**Table 3-4. Tailor Technologies to Address Contaminants of Emerging Concern – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Assess the effectiveness of current drinking water technologies to remove CECs. | | | | X | X | | |
| Assess the effects of CECs on water systems, POTWs, and treatment capabilities. | | | | X | X | | |

## 3.6 References

Brueck, T., D. O'Berry, L. Blakenship, and P. Brink. 2012. *Forecasting the Future: Progress, Change, and Predictions in the Water Sector. Trend White Papers: Environmental, Technology, Economic/Business, Societal/Political*. Project #4232. Water Research Foundation. Denver, CO.

Chang Hyun, J., A. Dietrich, J. Tanko. 2011. Simultaneous degradation of disinfection byproducts and earthy-musty odorants by the UV/$H_2O_2$ advanced oxidation process. *Water Research*. 45:2507-2516.

Davis, P., E. Sullivan, D. Marlow, and D. Marney. 2013. A selection framework for infrastructure condition monitoring technologies in water and wastewater networks. *Expert Systems with Applications.* 40(6):1947-1958.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology.* 46:220-235.

Kavanaugh, M., G. Amy, Z. Chowdhury, Cooper, N. Corin, J. Crouè, S. Kommineni, S. Liang, J. Min, M. Nickelsen, E. Simon, and W. P. Tornatore, 2003. *Removal of MTBE with advanced oxidation processes*. AWWA Research Foundation.

Lamsal, R., M. Walsh, and G. Gagnon. 2011. Comparison of advanced oxidation processes for the removal of natural organic matter. *Water Research*. 45:3263-3269.

Lehman, S.G. and A. Subramani. 2011. *State-of-science on perchlorate treatment technologies and regulations*. Water Research Foundation: Denver, CO.

Lubick, N. 2008. Ceramic filter makes water treatment easy. *Environmental Science and Technology.* 42:649-650. (As cited in Luoma, 2008).

Luoma, S.N. 2008. *Silver nanotechnologies and the environment: Old problems or new challenges.* Project on Environmental Nanotechnologies 15, September, 2008. Available online at: http://www.nanotechproject.org/process/assets/files/7036/nano_pen_15_final.pdf. Accessed June 12, 2014.

Maxwell, S. 2010. A look at the challenges and opportunities in the world water market. *Journal of the American Water Works Association*. 102:5.

Means, E.G., L. Ospina, N. West, and R. Patrick. 2008. *A strategic assessment of the future of water utilities.* Water Research Foundation: Denver, CO.

Moss, B., S. Kosten, M. Meerhoff, R.W. Battarbee, E. Jeppesen, N. Mazzeo, K. Havens, G. Lacerot, Z. Liu, L. De Meester, H. Paerl, and M. Scheffer. 2011. Allied attack: Climate change and eutrophication. *Inland Waters.* 1: 101-105.

Noyes, P.D., M.K. McElwee, H.D. Miller, B.W. Clark, L.A. Van Tiem, K.C. Walcott, K.N. Erwin, and E.D. Levin. 2009. The toxicology of climate change: Environmental contaminants in a warming world. *Environment International.* 35(6): 971-986.

Sarathy, S., M. Stofan, A. Royce, and M. Mohseni. 2012. Pilot-scale UV/$H_2O_2$ advanced oxidation process for surface water treatment: effects on natural organic matter characteristics and DBP formation potential. *Environmental Technology*. 32(15): 1709-1718.

Spellman, F.R. 2013. *Water & wastewateriInfrastructure: Energy efficiency and sustainability.* CRC Press: Boca Raton, FL.

US EPA. 2006. *ETV and energy. Tech brief*. US Environmental Protection Agency. Environmental Technology Verification Program. EPA 600-F-06-015. October 2006 (updated June 2009).

US EPA. 2007. *Residential Nutrient Reduction*. Environmental Technology Verification Program. EPA 600-S-07-004. January 2007.

US EPA. 2008. *Emerging technologies for wastewater treatment and in-plant wet weather management.* EPA 832-R-12-011. March 2013. water.epa.gov/scitech/wastetech/upload/Emerging-Technologies-Report-2.pdf.

US EPA, 2009a. *Total maximum daily load (TMDL) program results analysis fact sheet*. US EPA Office of Water, July 17, 2009. http://www.epa.gov/owow/tmdl/results/pdf/aug_7_introduction_to_clean.pdf.

US EPA. 2009b*. National water program research strategy. 2009-2014*. Office of Water (4304T). EPA 822-R-09-012. September 2009. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/strategy.pdf.

US EPA. 2010. *Priorities of the distribution system research and information collection partnership.* April 2010. http://www.epa.gov/safewater/disinfection/tcr/pdfs/tcrdsac/finpridsricp051010.pdf.

US EPA. 2011a. "Working Partnership with States to Address Phosphorus and Nitrogen Pollution through the Use of a Framework for State Nutrient Reductions." Issued by Nancy Stoner in March 2011.

US EPA. 2011b. *Environmental Technology Verification (ETV) program case studies. Demonstrating program outcomes. Volume 3*. Office of Research and Development, National Risk Management Research Laboratory. EPA 600-R-10-119. September 2010. www.epa.gov/ord.

US EPA. 2012. *Office of Water technology innovation priority list*. Revised Working Draft. September 27, 2012.

US EPA. 2013a. *Rural and small systems guidebook to sustainable utility management.* October 2013. http://water.epa.gov/infrastructure/sustain/upload/SUSTAINABLE-MANAGEMENT-OF-RURAL-AND-SMALL-SYSTEMS-GUIDE-FINAL-10-24-13.pdf.

US EPA. 2013b. *Addendum: Emerging technologies for wastewater treatment and in-plant wet weather management.* Addendum to EPA 832-R-12-011. August 2013. http://water.epa.gov/scitech/wastetech/upload/2013-Addendum-Emerging-Technologies-for-Wastewater-Treatment.pdf.

US EPA. 2013c. Nanomaterials EPA is assessing. http://www.epa.gov/nanoscience/quickfinder/nanomaterials.htm. Accessed June 6, 2014.

US EPA. 2014a. Climate ready water utilities. http://water.epa.gov/infrastructure/watersecurity/climate/index.cfm. Accessed June 5, 2014.

US EPA. 2014b. Climate change and water: Infrastructure. http://water.epa.gov/scitech/climatechange/Infrastructure.cfm. Accessed June 6, 2014.

US EPA. 2014c. *Promoting technology innovation for clean and safe water. Water technology innovation blueprint – version 2*. EPA 820-R-14-006. April 2014. http://www2.epa.gov/sites/production/files/2014-04/documents/clean_water_blueprint_final.pdf.

US EPA. 2015a. *Engineered nanomaterials in industrial wastewater: Literature review and implications for 304m.* Memorandum from Eva Knoth and Kim Wagoner, ERG, to William Swietlik, US EPA, EAD. January 23, 2015.

US EPA. 2015b. Drinking water and wastewater systems research. http://www2.epa.gov/water-research/drinking-water-and-wastewater-systems-research. Accessed August 18, 2015.

# Chapter 4. Wet Weather Pollution Management

Wet weather flows include nonpoint source runoff from land surfaces directly into receiving waters as well as point source discharges from municipal separate storm sewer systems (MS4s), combined sewer overflows (CSOs), and sanitary sewer overflows (SSOs). Municipal water supplies and precipitation contribute heavily to wet weather flows (Marsalek et. al., 2006).

The EPA 2000 National Water Quality Inventory (US EPA, 2002) identified stormwater runoff as a prime cause of water quality impairment in the United States. Although agricultural lands contribute contaminants such as nutrients, pesticides, and microbial constituents to receiving waters, wet weather flows in urban areas receive particular attention because impervious areas (e.g., paved roads, sidewalks) increase runoff, which contributes a wide array of pollutants to water bodies. As the population increases, land use shifts to more urban uses, and climate changes contribute to high impact storms, management of wet weather flows continues to be a priority for the National Water Program (NWP) to maintain the health of water bodies, the quality of drinking water, and the quality of recreational water.

Watershed managers need to understand how various control measures function, their effectiveness and limitations, how they may be improved, and the associated costs. Wet weather flow management has traditionally been handled by end-of-pipe Best Management Practices (BMPs) designed to rapidly convey runoff to receiving waters or to treatment plants. However, many of these BMPs are developed using design storms[8] that assume static climate conditions, which is no longer a valid assumption (Milly et al., 2008). As climate change causes alterations in precipitation patterns, current methods for managing wet weather flows may be less effective, and new approaches may be needed. While traditional “gray infrastructure” [9] features will continue to be important in managing wet weather flows, increased use of green infrastructure (GI) that is designed with changing precipitation patterns in mind will offer municipalities new options. The following key research areas are discussed in this chapter:

- 4.1 Improve Treatment of Wet Weather Flows.
- 4.2 Assess the Effectiveness of Stormwater Best Management Practices (BMPs).

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[8] A mathematical representation of a precipitation event that reflects conditions in a given area for design of infrastructure.

[9] Gray infrastructure refers to traditional practices for stormwater management and wastewater treatment, such as pipes and sewers http://www.epa.gov/nrmrl/wswrd/wq/stormwater/green.html.

- 4.3 Evaluate Green Infrastructure (GI) and Implementation at a Watershed Scale.
- 4.4 Set Standards for Stormwater Reuse.

Research needs related to the impacts of climate change on wet weather management are addressed in Chapter 8.

## 4.1 Improve Treatment of Wet Weather Flows

### Background

Wet weather flows can contain high levels of microbes, including fecal indicator bacteria and pathogens. CSOs and SSOs pose a particular risk because they may contain untreated sewage. In CSOs, densities of microbes can be up to two orders of magnitude greater than in stormwater (Marsalek and Rochfort, 2004). In the United States, over 770 communities (serving about 40 million people) have combined sewer systems. Direct discharges of CSO and SSO effluents create an obvious public health risk to those using beaches, rivers, or lakes recreationally. It also places an added burden of treatment on drinking water systems that draw from affected water bodies.

The United States Environmental Protection Agency (EPA) guidance on development of long-term control plans (LTCPs) for CSOs notes the need for treatment and disinfection of CSO effluents (US EPA, 1995). This may take place at a wastewater treatment plant (WWTP) if the water is subsequently pumped to the publicly owned treatment works (POTW), or in CSO storage structures equipped with disinfection capabilities. Appropriate removal of dissolved organics and disinfection of peak flows, however, can be difficult. The quality and quantity of the flows are site-specific and temporally variable, and thus, present challenges in adjusting the level of treatment to meet water quality requirements for biological oxygen demand (BOD) and indicator bacteria.

Traditionally, chlorine has been used as a disinfectant for wet weather flows, but can cause the formation of disinfection byproducts (DBPs). A 2005 Water Environment Research Foundation (WERF) demonstration study (Moffa and LaGorga, 2005) found that chlorination, chlorine dioxide, ozonation, and ultraviolet (UV) radiation could all achieve a guideline criteria for fecal indicator bacteria,[10] but that residual chlorine from chlorination and chlorine dioxide disinfection constitutes a contaminant of potential concern for aquatic health. In addition, gram negative fecal indicator bacteria may not necessarily indicate effective treatment of viruses and other pathogen groups, including protozoa.

Although not widely used for stormwater and CSOs/SSOs, UV disinfection has been studied in pilot settings, and UV disinfection units are commercially available. However, the high suspended solids content in wet weather flows presents a technical challenge to UV efficiency due to the association of microorganisms with particles, potentially shielding them from disinfection.

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[10] The study used a bacterial criterion for fecal coliform of 200 CFU/100mL that was established under a consent order.

### Future Research Areas

Research into wet weather flow disinfection should:

- **Address pre-disinfection settling and biological treatment in WWTPs.** Include an assessment of the influence of the effectiveness of disinfection (e.g., how additional coagulation helps remove high suspended solids).
- **Assess the performance of disinfection technologies.** Investigate how these technologies perform in combination with high-rate liquid/solid separation technologies.
- **Explore the effects of dilution.** Investigate whether dilution in the receiving water will keep chlorine or chlorine dioxide DBP concentrations acceptably low in a given receiving water.
- **Investigate optimization of UV, ozone, and advanced disinfection processes for average and peak wet weather flows for various pathogens.** Include an assessment of how suspended solids affect disinfection treatment efficiency. In addition, guidance is needed on how to weigh the relative costs and benefits of the disinfection options. For example, UV disinfection is likely to be more expensive than chlorine and chlorine dioxide; however, it would avoid the development of DBPs and their associated treatment/health costs.[11]
- **Investigate technologies to allow adequate treatment of viruses and protozoa in stormwater using UV.** Explore whether UV can adequately treat viruses and protozoa that can occur in stormwater and the need for additional pre-treatments to improve UV effectiveness.

To learn more about how these future research needs relate to the other research priorities, see Table 4-1.

## 4.2 Assess the Effectiveness of Stormwater Best Management Practices (BMPs)

### Background

Stormwater structural BMPs (e.g., detention basins, wet ponds, stormwater wetlands) provide control for flooding, peak flows, and improve and protect water quality. Heavy precipitation events due to climate change may produce larger volumes of stormwater that exceed the current capacity of structural BMPs (Melillo et al., 2014). Combined sewer systems, which capture both sewage and stormwater, may be overwhelmed by greater volumes of runoff, causing them to overflow and release untreated wastewater (including contaminants) into local source waters (Melillo et al., 2014). Moreover, sea level rise can impair the capacity of inland urban stormwater drainage systems that are designed to discharge into oceans (Melillo et al., 2014). Thus, an accurate evaluation of BMP performance, both for

[11] A 2005 Water Environment Research Foundation (WERF) study partially funded by EPA and entitled *Disinfection of Wastewater Effluent: Comparison of Alternative Technologies* compared advantages and disadvantages of disinfection alternatives and identified research gaps in the collective knowledge on each of the disinfection alternatives.

water quality and quantity, is an ongoing and crucial area of study. The International Stormwater BMP Database (http://www.bmpdatabase.org/), supported by a coalition that includes EPA, contains voluntarily submitted data from performance studies of BMPs. Key issues include difficulties in obtaining representative samples and the numerous drawbacks to evaluating water treatment by percent removal of contaminants (Jones et al., 2008).

### Future Research Areas

The NWP needs information on how to best design and target BMPs, and thus, future research should:

- **Find sources for representative samples of BMP influent and effluent.** Once determined, use these representative samples in monitoring studies.
- **Discover how to optimally characterize BMP influent**. Include as part of the characterization, solids to which many pollutants are associated.
- **Investigate how to optimally design BMPs.** Focus on BMPs that rely on sedimentation for pollutant removal.
- **Determine the lowest achievable pollutant concentrations.** Determine the levels in discharges for each BMP along with how this varies for different pollutants.
- **Investigate site-specific factors.** Assess how site-specific factors, which may be influenced by climate change, affect BMP performance and translate into decisions on selection, design, placement, and maintenance of BMPs.

To learn more about how these future research needs relate to the other research priorities, see Table 4-2.

## 4.3 Evaluate Green Infrastructure (GI) and Implementation at a Watershed Scale

### Background

GI refers to sustainable pollution reducing practices that also provide other ecosystem services such as reduced greenhouse gas emissions or increased flood control (US EPA, 2014). GI is becoming an increasingly attractive option to reduce stormwater runoff volumes and attenuate peak flows. GI may provide opportunities for ecosystem restoration, while buffering coastal areas and infrastructure from floods, storm surges, and sea-level rise, all of which are expected to occur due to climate change (Foster et al., 2011; Melillo et al., 2014). It also offers a potentially powerful approach to reduce CSOs and to mitigate the high costs associated with addressing them through traditional gray infrastructure. To a lesser extent, the burden on SSOs (Three Rivers, 2012a) and MS4s (Three Rivers, 2012b) can be relieved through GI BMPs. GI and low-impact development (LID) BMPs such as rain gardens, permeable pavement, vegetated swales, and urban reforestation cost-effectively reduce stormwater runoff by means of infiltration, reuse, and evapotranspiration on site. Unlike conventional hard-piped stormwater management infrastructure, GI allows a decentralized, flexible approach to stormwater management.

EPA is promoting the increased use of GI. EPA's website (http://water.epa.gov/infrastructure/greeninfrastructure/) provides a range of information on GI and LID, including the results of research, case studies of municipalities across the United States, and links to models, guides, and other resources. Organizations such as the Low Impact Development (LID) Center also conduct research and provide pertinent technical information. EPA's Green Infrastructure Partnership, established in 2007 to promote GI, includes the Natural Resources Defense Council, National Association of Clean Water Agencies, the LID Center, EPA, and the Association of Clean Water Administrators. A number of municipalities, most notably Philadelphia, have embraced GI as an approach to reducing CSOs and have developed extensive and sophisticated programs. GI approaches are also estimated to reduce carbon emissions, which contribute to climate change. For example, New York City estimates that every fully vegetated acre of GI would provide annual savings of $166 in reduced carbon dioxide emissions (Foster et al., 2011).

Technical and institutional barriers to implementation of GI BMPs still remain that include negative perception regarding their effectiveness and expense (e.g., Clifton and Weinstein, 2012). Because GI BMPs are decentralized, evaluating their combined effects and costs at a watershed-, city-wide-, or even neighborhood-wide-scale remains challenging. Other barriers include regulatory issues such as conflicting or restrictive local, state and federal rules.

One example of ongoing research to promote the use of GI is EPA's Storm Water Management Model (SWMM) (http://www2.epa.gov/water-research/storm-water-management-model-swmm). This model is used to simulate runoff quantity and quality from primarily urban areas and now includes a module to model LID BMPs. Research is underway to validate the performance of this module. In addition, a new tool prepared by EPA, called the National Stormwater Calculator (SWC) (http://www2.epa.gov/water-research/national-stormwater-calculator), is aimed toward city planners, developers, and property owners to assess GI scenarios. These tools are works in progress and may be considered an initial step in understanding how a suite of GI BMPs will operate in a city or watershed.

## Future Research Areas

Research going forward should:

- **Build on the SWMM module.** Validate the performance of the SWMM. As SWMM's GI capabilities are refined, SWMM will become an increasingly valuable way to explore scenarios for implementation of GI BMPs.
- **Continue refining and updating the SWC.** Continue improving the methodologies behind the SWC. This would benefit planners, property owners, and watershed managers.
- **Identify best metrics.** Develop metrics to assess GI program performance (as opposed to individual BMPs) and reliable data procurement.
- **Evaluate the effectiveness of GI.** Assess the effectiveness of GI in urbanized areas.
- **Gather information on costs and benefits of GI.** Collect information that also includes maintenance and costs savings compared to traditional gray infrastructure.

- **Gather information on long-term performance and maintenance needs.** Include information on different climates and soil types.
- **Determine costs to develop and maintain a clearinghouse.** Include GI performance and cost information from municipalities and researchers.
- **Assess GI implementation at a watershed level.** Consider selection, sizing, and placement of BMPs, as further detailed in the *Watershed Systems Approach* chapter.

To learn more about how these future research needs relate to the other research priorities, see Table 4-3.

## 4.4 Set Standards for Stormwater Reuse

### Background

Stormwater harvesting can be done on various scales, from rain barrels to cisterns to larger reuse systems. In arid areas, stormwater reuse can help cope with the scarcity of water. In areas with greater rainfall, storage and reuse can manage the volume of runoff that would otherwise add burden to MS4s. In addition, reused stormwater can be used in place of water of drinking quality for non-potable applications such as landscape irrigation and toilets. Further, stormwater reuse may help alleviate the increased stress on existing water resources in regions facing droughts or with the increased flooding in other regions due to climate change.

Stormwater reuse requires suitable water quality for the intended use (Emmons, 2013). Currently no federal regulations govern water reuse (Pitt et al., 2012). Some states have regulations and guidelines, though these are generally more applicable to treated wastewater. Some recommended water quality criteria are geared primarily towards heavy metal concentrations (Pitt et al., 2012). Roof runoff can be a good source of water for reuse, although it can contain metals (especially zinc from galvanized metal roofs) as well as nutrients and bacteria.

Decisions on required treatment will depend on water quality and intended use. For example, water for potable needs will require more extensive treatment, including disinfection. Other considerations include proper storage and delivery of water (e.g., to irrigation areas).

### Future Research Areas

Stormwater reuse research is needed to:

- **Understand the water quality needs and treatments.** Assess how the needs and treatments may vary by the intended use.
- **Evaluate rainwater harvesting treatment systems.** Assess the effectiveness of various rainwater harvesting treatment systems.
- **Assess the design of treatment systems.** Consider those that would be inexpensive and suitable for small decentralized storage vessels such as cisterns.

- **Determine storage needs for best volume control.** Determine the amount of storage needed for the volume of water desired for reuse and how to properly store and effectively deliver water based on its intended use (e.g., to irrigation areas).
- **Develop water quality metrics for stormwater reuse.** EPA does not have federal reuse requirements. Develop metrics for different types of stormwater reuse (e.g., drinking water, irrigation).

To learn more about how these future research needs relate to the other research priorities, see Table 4-4.

## 4.5 Wet Weather Pollution Management Crosswalk with Other Research Priority Areas

**Table 4-1. Improve Treatment of Wet Weather Flows – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Address pre-disinfection settling and biological treatment in WWTPs. | X | | X | X | | | |
| Evaluate disinfection technology performance. | X | | X | X | | | |
| Explore the effects of dilution in receiving waters on chlorine or chlorine DBP concentrations. | | | X | | X | | |
| Optimize UV, ozone, and advanced disinfection for wet weather flows. | | | X | X | | | |
| Investigate UV treatment of stormwater for pathogen and virus removal. | | | X | X | | | |

**Table 4-2. Assess the Effectiveness of Stormwater Best Management Practices (BMPs) – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Find representative samples for BMP influent/ effluent for monitoring. | X | | | | X | | |
| Evaluate optimal characterization of BMP influent. | X | | | | X | | |
| Investigate optimal BMP design with a focus on sedimentation or pollutant removal. | X | | X | | | | |
| Determine lowest achievable pollutant levels for each BMP. | X | | X | | | | |

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Assess impacts of site-specific factors, including local effects of climate change, on BMP performance. | X | | | X | X | | X |

**Table 4-3. Evaluate Green Infrastructure (GI) and Implementation at a Watershed Scale – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Build on and validate the SWMM module. | | | | | X | | X |
| Refine and update the SWC. | | | | | X | | X |
| Develop metrics to assess GI performance. | X | | X | | X | | |
| Evaluate the effectiveness of GI in urbanized areas. | X | | X | | X | | |
| Evaluate GI costs/benefits compared to gray infrastructure. | | | | | X | | |
| Evaluate GI long-term performance and maintenance needs for different climates and soil types. | X | | X | | X | | X |
| Develop a clearinghouse of information on GI performance and costs. | | | X | | | | |
| Assess GI implementation at the watershed scale. | | | X | | X | | X |

**Table 4-4. Set Standards for Stormwater Reuse – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Assess stormwater quality needs and treatments by intended reuse. | X | | | X | X | | |
| Evaluate rainwater harvesting treatment systems. | | | X | | X | | |
| Assess treatment system design including those for small decentralized storage vessels. | | | X | | X | | X |
| Determine storage needs for volume control and access to and delivery of stored water. | | | X | | X | | X |
| Develop stormwater reuse water quality metrics. | X | | X | | X | | |

## 4.6 References

Clifton, E. and N. Weinstein. 2012. *Tools for evaluating the benefits of green infrastructure for urban water management*. Water Environment Research Foundation INFR5SG09b.

Emmons, B.H. 2013. “Stormwater reuse – retrofitting last century systems for the future.” Presented at 2013 International LID Symposium, St. Paul, Minnesota, August 18-21, 2013.

Foster, J., A. Lowe, and S. Winkelman. 2011. *The value of green infrastructure for urban climate adaptation*. Center for Clean Air Policy. http://ccap.org/assets/The-Value-of-Green-Infrastructure-for-Urban-Climate-Adaptation_CCAP-Feb-2011.pdf.

Jones, J., J. Clary, E. Strecker, and M. Quigley. 2008. 15 Reasons you should think twice before using percent removal to assess BMP performance. *Stormwater*. January/February 2008.

Marsalek, J, B.E. Jiménez-Cisneros, P.A. Malmquist, M. Karamouz, J. Goldenfum and B. Chocat. 2006. *Urban water cycle processes and interactions*. IHP-VI Technical Documents in Hydrology No. 78, UNESCO, Paris.

Marsalek, J. and Q. Rochfort. 2004. Urban wet-weather flows: Sources of fecal contamination impacting on recreational waters and threatening drinking-water sources. *Journal of Toxicology and Environmental Health, Part A: Current Issues*. 67(20-22):1765-1777.

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014. *Climate change impacts in the United States: The Third national climate assessment.* U.S. Global Change Research Program.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science.* 319:573-574.

Moffa, P. and J. LaGorga. 2005. Identifying technologies and communicating the benefits and risks of disinfecting wet weather flows. Water Environment Research Foundation 00-HHE-6.

Pitt, R., L. Talebi, R. Bean, and S. Clark. 2012. *Stormwater non-potable beneficial uses and effects on urban infrastructure*. Water Environment Research Foundation INFR3SG09.

Three Rivers Wet Weather. 2012a. Inflow, infiltration and overflows. http://www.3riverswetweather.org/about-wet-weather-issue/understanding-sewer-collection-system/inflow-infiltration-overflow. Accessed June 2014.

Three Rivers Wet Weather. 2012b. Municipal separate storm sewer systems. http://www.3riverswetweather.org/storm-water-green-solutions/municipal-separate-storm-sewer-systems. Accessed June 2014.

US EPA. 1995. *Combined sewer overflows guidance for long-term control plan*. Office of Water. EPA 832-B-95-002. September 1995.

US EPA. 2002. *National water quality inventory 2000 report*. EPA-841-R-02-001.

US EPA. 2014. Green infrastructure research. http://www2.epa.gov/water-research/green-infrastructure-research. Updated June 26, 2014.

# Chapter 5. Actionable Information on Chemical and Microbial Contaminants of Emerging Concern

Under the statutory authority of the Safe Drinking Water Act (SDWA), the United States Environmental Protection Agency (EPA) sets national drinking water standards to ensure the safety of water provided by public water systems (PWSs). EPA evaluates unregulated chemical and pathogenic contaminants as candidates for regulation under the Contaminant Candidate List (CCL) and Regulatory Determinations programs, establishes new standards as warranted, or revises existing standards for regulated contaminants under the Six-Year Review process as new data become available. EPA also identifies research priorities for protecting source water including underground sources of drinking water as new threats from contaminants of emerging concern (CECs), such as those found in hydraulic fracturing (HF) fluids, are identified. Similarly, under the authority of the Clean Water Act (CWA), EPA promotes activities to manage, protect, and restore the Nation's fresh and marine water resources and associated aquatic ecosystems, including state development of allowable standards for pollutants in impaired water bodies. Through these programs, EPA identifies significant information gaps, including needs for improved analytical methods, occurrence data, and information on human health effects, as well as long-term research needs for protecting drinking water and ambient water quality from risks posed by CECs.

CECs are unregulated chemicals and microbes that become recognized as potential threats to human or ecological health through their potential presence in the environment. To protect human and ecological health from CECs, EPA's Office of Water (OW) assesses the need for regulation to control many chemical and pathogenic contaminants. If peer-reviewed scientific data support a regulation, the Agency proceeds with developing rules to protect human health from harmful chemical and pathogenic contaminants. However, contaminants that are regulated, or are under study by EPA and stakeholders, are a small fraction of the potential contaminants in the environment. As of March 2015, over 93 million organic and inorganic substances were indexed by the American Chemical Society's Chemical Abstracts Service (CAS) in their CAS Registry; of those, 312,000 are regulated around the world (CAS, 2015).

Every year, hundreds of new chemicals are introduced into commercial use. EPA receives on average 1,000 new chemical notices annually under the Toxic Substances Control Act (TSCA; US EPA, 2011a). Some of these chemicals are intentionally released into the environment (i.e., pesticides) and others (e.g., pharmaceuticals and personal care products, or PPCPs) have the potential to be released to the environment even when used as intended. Given changing environmental conditions and the increasing attention to water reuse, especially in the context of adaptation to climate change and regional water scarcity, attention must be paid to emerging microbes, including viruses that can be transmitted via human sewage. Furthermore, extreme weather events that cause changes in high flows and increased runoff may carry chemicals and pathogens from urban and agricultural lands into source waters (Melillo et al., 2014). Heavy precipitation may further trigger CSOs, increasing the potential for emerging contaminants, which are not otherwise removed in the treatment process, to occur in drinking water (Melillo et al., 2014). Though new chemicals may provide an obvious focus for research into CECs, concerns about chemicals that have been in commerce for years or naturally-occurring compounds can "emerge" or "remerge" as new information becomes available regarding toxicity, mode of action (e.g., endocrine disruption), or routes of exposure. New information also may become available regarding pathogens as they evolve new pathogenic properties and strains (such as with *E.coli* 0157), and as previously unrecognized pathogenic threats are discovered (e.g., prions).

Often chemicals and microbes become contaminants of concern because they are detected in drinking water, in the environment (e.g., water, air, sediments), or in humans or other living organisms. Advances in analytical measurement capabilities have allowed the detection of new classes of chemical and microbiological contaminants in water and related environmental media as well as the ability to detect and report more conventional contaminants (e.g., Volatile Organic Compounds (VOCs)) at lower concentrations.

To continue to meet the requirements of the SDWA and CWA, the National Water Program (NWP) must conduct research to:

- 5.1 Assess Effects of CECs on Ecological and Human Health Effects.
- 5.2 Develop New Analytical Detection Methods.
- 5.3 Study the Occurrence of and Exposure to CECs.
- 5.4 Develop Cost-Effective Treatment and Mitigation Options.
- 5.5 Characterize and Prioritize Contaminants for Future Research.

Research needs related to the impacts of climate change on CECs are addressed in Chapter 8.

## 5.1 Assess Effects of CECs on Ecological and Human Health Effects

### Background

While human health assessment methods have traditionally studied the effects of one chemical at a time, there is a growing interest in the health effects of contaminant combinations. More comprehensive assays that are capable of screening samples for multiple biological pathways are proving to be powerful tools for water quality evaluation. New case studies indicate that the monitoring paradigm is shifting from a single chemical analysis towards an effect-based, multi-chemical screening approach (Doyle et al., 2014). The NWP's most recent Drinking Water Strategy (US EPA, 2010) calls for consideration of regulating contaminants as groups, further highlighting the need to understand interactions among contaminants.

Evaluating interactions among CECs is particularly challenging, as well as characterizing the effects of exposure to low CEC doses over long periods (NRC, 2012). Effect-based monitoring is providing a way to monitor CEC impacts on human health (Escher et al., 2014), ecosystems (Ekman et al., 2013) and aquatic life (US EPA, 2015b). EPA and USGS are collaborating to study the presence, concentrations, and persistence of estrogenic activity in source and treated drinking waters of the United States using in vitro assays (Evans et al., 2015).

Additional shortcomings in contaminant monitoring and health assessment methods have been identified. For example, human health concerns related to pathogens in drinking water and ambient waters currently rely on fecal bacteria as indicators of contamination. However, a growing body of science demonstrates that fecal bacteria are not effective indicators of all potential human pathogens, including some enteroviruses and protozoa. Partly in response to recommendations by the National Academy of Sciences (e.g., NRC, 2012), EPA has also been working to modernize dose-response analyses (US EPA, 2012b).

EPA is collaborating with partners to address health and risk assessment challenges. EPA's Chemical Safety for Sustainability (CSS) program is coordinating with the National Nanotechnology Initiative (NNI) and Organization for Economic Cooperation and Development to identify specific properties of nanomaterials that are relevant to toxicity. CSS is also working with the National Institutes of Health (NIH) and the Food and Drug Administration to develop and use new toxicological methods, including computational toxicology methods[12], for toxicity testing and risk assessment (US EPA, 2012a).

An additional challenge is incorporating these novel risk assessment tools into regulatory processes. EPA has made some progress towards understanding the use of effect-based tools at the regulatory stage. An example is the adverse outcome pathway (AOP), a conceptual framework that links existing knowledge of chemicals from a molecular initiating event (i.e., chemical interaction) to an adverse health outcome (e.g. cancer; Ankley et al., 2010). AOPs incorporate results from these novel test methods and enable those results to be available for regulatory decision-making (Tollefsen et al, 2014). An AOP Wiki webpage has been established to help the scientific community recognize and build AOPs (AOPKB, 2015). The Endocrine Disruptor Screening Program is the first EPA regulatory program to implement these new testing methods; results from this program will highlight the benefits and challenges of integrating effects-based data interpretation into the regulatory framework.

## Future Research Areas

To promote improved assessment of CEC effects on ecological and human health, the following research is needed:

- **Develop and validate methods to evaluate human health risk.** Develop methods to assess health risks posed by chemical mixtures found in environmental media (US EPA, 2009a; US EPA,

[12] Computational toxicology methods apply mathematical and computer models and molecular biological approaches to predict chemical hazards and risks to human health and the environment.

2012c) and by groups of related contaminants per the National Water Program Research Strategy.

- **Identify factors that can influence the human health effects of exposure to chemicals.** Assess the chemical, biological, and physical characteristics of agents; genetic and behavioral attributes of host; and the physical and social characteristics of environment. All of these factors contribute to human health effects (NRC, 2012).
- **Establish health endpoints.** Determine appropriate toxicological data and health endpoints to evaluate emerging contaminants, such as pharmaceuticals, prions, and nanomaterials to allow for a better understanding of the range of health effects (US EPA, 2008).
- **Develop risk assessment methods.** Develop high-throughput toxicity testing and risk assessment methods for CECs (US EPA, 2012a). For example, techniques for increasing sample concentration, such as ultrafiltration, continuous filtration, and new types of filters, are needed for improving the recovery and for automated extraction of nucleic acids. This reduces risk of contamination, reduces inhibition, and allows a more rapid throughput approach (Hill et al. 2005; Srinivasan et al. 2011 as cited in NRC, 2012). EPA human health research should also continue to incorporate "omics" data (from genomics, proteomics, and metabolomics) into risk assessments (NRC, 2012).
- **Investigate metagenomics and bioinformatics approaches to assessing risks.** Microbiomes play an important role in modulating health risks through environmental exposures. Ongoing research is developing methods and generating data to identify the presence of specific microorganisms. However, their viability and functional activity are not known. Genomic data may be used to inform microbial risk assessment, as well as bioinformatics for more sophisticated data interpretation and modeling (NRC, 2012).
- **Develop robust computational toxicology techniques.** Establish the validity of the in vitro techniques (computational toxicology), and to find ways to efficiently use both in vivo and in vitro testing to produce robust results while in vitro methods are being validated and ramped up (NRC, 2012). Toxicokinetic and physiologically-based pharmacokinetic models are needed in the computational toxicology program. Studies to assess these extraneous factors that compound the human health effects of exposure to chemicals are needed. These tools are being applied to the development of new approaches to assess and predict toxicity in vitro (NRC, 2012).
- **Reduce uncertainty in extrapolation from animals to humans and from high to low doses for chemicals and pathogens** (US EPA, 2009a). Research is needed to reduce the uncertainty in assessing human risk to chemical and pathogens based on animal studies or in assessing their impacts at lower doses based on studies involving higher dosages.

- **Improve endocrine disruption testing protocols.** Develop and validate high-throughput screening and computational models in collaboration with partners in the Tox21 Consortium[13] (US EPA, 2012a).
- **Assess the impact of CECs on aquatic life health and ecosystem function.** Such research can inform new water quality criteria, including bacteriophage in the near term and viral pathogens in the longer term (US EPA, 2009a).
- **Investigate risks posed by biosolid application.** Conduct additional field studies to determine whether contaminants in biosolids pose a public health and aquatic life risk even when they are being applied in compliance with current regulations (US EPA, 2009a; US EPA, 2014a).

To learn more about how these future research needs relate to the other research priorities, see Table 5-1.

## 5.2 Develop New Analytical Detection Methods

### Background

Before chemical or microbiological contaminants can be monitored in water and other media, analytical methods to detect and quantify the contaminants must be developed and validated. Media of interest may include drinking water (including distribution systems and biofilms), surface and ground waters, and other media, such as wastewaters and biosolids that contribute to water contamination. EPA Office of Research and Development's (ORD's) Exposure Research Program and the Office of Ground Water and Drinking Water's (OGWDW's) Technical Support Center both develop analytical methods for compliance monitoring and for detection and analysis of unregulated contaminants.[14] These methods are approved under SDWA.[15] EPA also approves analytical methods and test procedures used by industries and municipalities to analyze constituents in other wastewater samples.[16] As new CECs emerge or as technology improves, new analytical methods may be necessary or existing methods may need fine tuning to detect and quantify contaminant levels in water and other media. Depending on the specific purpose for which they are employed, analytical methods may need to meet standards for accuracy, precision, speed, and cost-effectiveness (US EPA, 2008; US EPA, 2009b).

Other potential emerging industrial wastewater pollutants are engineered nanomaterials (ENMs), manmade materials composed of primary particles with sizes less than 100 nanometers (nm) (US EPA, 2013a). Recent research presented at the Society of Environmental Toxicology and Chemistry (SETAC) North America 33rd Annual Meeting in November 2012 indicates that ENMs may impact human health and the environment. In its Final 2010 Effluent Guidelines Program Plan, EPA solicited data and

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[13] The Tox21 Consortium is a federal collaboration between the NIH, EPA, and the FDA that aims to develop better toxicity assessment methods.
[14] http://water.epa.gov/scitech/drinkingwater/labcert/analyticalmethods_ogwdw.cfm and http://www.epa.gov/nerlcwww/ordmeth.htm.
[15] http://water.epa.gov/scitech/drinkingwater/labcert/analyticalmethods_ogwdw.cfm.
[16] http://water.epa.gov/scitech/methods/cwa/index.cfm.

information for future annual reviews on the manufacture, use, and environmental release of silver materials, including nanosilver, due to their anti-microbial activity and potential to create a source of silver in associated industrial wastewater discharges (US EPA, 2011b). Methods for detecting, quantifying, and characterizing nanomaterials in any aqueous media—let alone a complex, high-strength medium such as industrial wastewater—are not fully developed. EPA has not approved standardized methods for sampling, detecting, monitoring, quantifying, or characterizing nanomaterials in aqueous media. This is a critical area of research because the ability to detect and characterize nanomaterials is essential to understanding the implications of their release into the environment. EPA approved methods are also needed to support any future potential regulatory structure for industrial discharges of ENMs.

## Future Research Areas

The increasingly wide and diverse array of CECs poses a challenge for the NWP. Specific research needs include the following:

- **Develop and improve viral fecal indicator methods.** These include the lytic method for coliphages, the culturable method and other potentially fast methods.
- **Develop and improve analytical methods.** Develop or improve the sensitivity of analytical methods to detect, identify, and quantify chemicals and pathogens, including both individual contaminants and contaminant groups, listed on the CCL as contaminants of possible concern in drinking water. One area of focus is on disinfection byproduct (DBP) mixtures in drinking water and distribution systems. In addition, standard methods and sampling techniques to detect and characterize nanomaterials and ENMs in industrial wastewater are needed. (US EPA, 2008; Ekman et al., 2015).
- **Develop cost effective test methods for CECs.** Test methods for pathogens, nanoparticles, and trace organics (including PPCPs and endocrine disrupting chemicals (EDCs)) in wastewater, surface water, biosolids, and residual manure and runoff from animal feeding operations to inform risk assessment and potential future wastewater treatment regulations. Particularly useful will be methods that can address multiple chemicals with common modes of action (US EPA, 2008; US EPA, 2009a).
- **Finalize development of qPCR techniques.** Finalize the development of quantitative polymerase chain reaction (qPCR) techniques to quantify *E. coli* and develop limit of detection/limit of quantitation (LOD/LOQ) for use in quantifying enterococci and *E. coli* using qPCR.
- **Develop digital qPCR techniques.** This technique will enable quantification at very low concentrations and analysis for multiple indicator organisms at the same time.
- **Develop and validate molecular microbial source tracking tools.** Build on efforts to develop and validate molecular microbial source tracking for application to ambient water criteria development and surface water quality protection (US EPA, 2005; US EPA, 2009a; NRC, 2012). Continue research on source apportionment for fecal indicator bacteria (enterococci and *E. coli*) using microbial source tracking genetic markers (US EPA, 2015b).

- **Develop bioactivity measures.** These measures would be used for monitoring and development of ambient water quality criteria.
- **Improve the accuracy of Canary.** Improve the accuracy of Canary, a software tool that analyzes water quality data and identifies anomalous conditions in distribution systems that require further investigation (US EPA, 2008; US EPA, 2009a).
- **Improve CBR detection capabilities to promote drinking water security.** Address data gaps in detection capabilities for chemical, biological, and radiological (CBR) contaminants (including biological toxins) considered priorities from a water security standpoint (US EPA, 2008; US EPA, 2009a).

To learn more about how these future research needs relate to the other research priorities, see Table 5-2.

## 5.3 Study the Occurrence of and Exposure to CECs

### Background

The NWP, states, the regulated drinking water community, and other parties monitor for chemical and microbial contaminants and use the analytical results to identify threats to water quality and public health from CECs. The NWP uses occurrence data to prioritize research and regulatory efforts. To satisfy the statutory requirements of the SDWA, EPA collects data for the National Contaminant Occurrence Database (NCOD), which contains occurrence data from PWSs and other sources, such as the United States Geological Survey's (USGS) National Water Information System. The Unregulated Contaminant Monitoring (UCM) program gathers occurrence data on contaminants in PWSs that do not currently have set health-based standards under the SDWA; these data are used to support the regulatory development process and are included in the NCOD.

EPA is also investigating ENMs as a potential emerging industrial wastewater pollutant category. Currently, human health effects of exposure to ENMs in any environmental medium are not fully understood (US EPA, 2015a). There have been recent efforts to minimize airborne exposure to ENMs in the workplace, due to concern for inhalation hazards. In 2013, the National Institute for Occupational Safety and Health (NIOSH) published guidelines to minimize workplace exposure to ENMs (NIOSH, 2013). In addition, the Occupational Safety and Health Administration (OSHA) published recommended best practices and exposure limits for airborne carbon nanotubes (CNTs) and titanium dioxide ($TiO_2$) ENMs (OSHA, 2013). Other research suggests that aquatic ecosystems may be at risk from exposure to silver and $TiO_2$ ENMs released into the environment, though they do not clearly distinguish between potential inputs from releases to wastewater from manufacturing, processing, and end use. Current information indicates that human health risks are low, but there is ongoing research into the physiological responses and human health outcomes from exposure to these and other types of ENMs.

## Future Research Areas

To better understand the occurrence and potential exposure of humans to CECs, specific research is needed to:

- **Provide wider deployment of microbial source tracking.** Identify the source of pathogens, to aid in the development and implementation of ambient water quality criteria.
- **Survey the occurrence of PPCPs and other CECs in drinking water** (US EPA, 2009a).
- **Evaluate ENM toxicity and potential exposure from industrial wastewater.** This should take into consideration relevant forms and concentrations of ENMs (Ekman et al., 2015).
- **Assess the entry of pathogens, PPCPs and EDCs into the environment.** Assess the various routes through which these contaminants can enter the environment, including wastewater and application of biosolids and manure to land (US EPA, 2008). Develop biosolid metrics that can identify potential sources of enteroviruses and pathogenic protozoa to surface and ground waters.
- **Assess the impact of CECs on underground sources of drinking water.** Assess: (1) activities and waste management associated with oil and gas production, (2) underground carbon sequestration, (3) brines and residuals injected into shallow Underground Injection Control (UIC) Class V wells, and (4) coal fly ash injected into UIC Class V mine backfill wells (US EPA, 2009a).
- **Select appropriate pathogens and indicators to assess sewage sludge quality** (US EPA, 2009a).
- **Study and monitor pathogens, PPCPs, and other CECs in waste streams and wet weather flows.** Track and monitor pathogens, PPCPs, and CECs in publicly owned treatment works (POTWs) and decentralized system waste streams, as well as in municipal, industrial, and construction wet weather flows that do not pass through POTWs, to better characterize the threats those waste streams pose to water quality (US EPA, 2008).
- **Adopt new technologies to monitor surface water.** Expand the use of "smart sensor" water quality monitoring technology and remote sensing (satellite imagery) to supplement traditional labor-intensive techniques for monitoring the nation's surface water bodies (US EPA, 2013b; NRC, 2012).
- **Develop techniques to assess the vulnerabilities of drinking water sources to contamination.** (US EPA, 2009a).
- **Identify concentrations of nanomaterials of concern in environmental media.** Detect and quantify nanomaterials in air, soil, water, and biological systems (US EPA, 2012a), including in land-applied biosolids (US EPA, 2009a).

- **Develop methods to identify priority contaminants.** Develop methods to capture the risk of consumer exposure to contaminants prioritized under the CCL and monitored under the Unregulated Contaminant Monitoring (UCM) program (US EPA, 2009a).

To learn more about how these future research needs relate to the other research priorities, see Table 5-3.

## 5.4 Develop Cost-Effective Treatment and Mitigation Options

### Background

Protection of ecosystems and human health begins with preventative measures, to keep harmful chemicals and pathogens from entering surface and ground water. It also depends on the availability of technologies to remove or deactivate chemicals and pathogens, whether at their source (for anthropogenic compounds), in situ in the environment, in the drinking water treatment plant, or in the distribution system. Widely available and cost-effective treatment options are a prerequisite for regulation of a contaminant in drinking water under the NWP.

EPA conducts research on the efficacy of existing technologies at removing CECs. For example, ORD's National Exposure Risk Laboratory (NERL) is currently partnering with the USGS on a multi-phase study to determine the presence of CECs in both treated and untreated drinking water at 30 drinking water treatment plants in the United States whose receiving waters are affected by waste releases from municipalities, septic systems, and livestock. As CECs become more prevalent in drinking water, more focused technologies will be necessary to target the removal of these contaminants.

### Future Research Areas

Research needs include the following:

- **Develop cost effective management and treatment options for risk management.** Develop treatment options for trace organics, nanoparticles, pathogens, and other CECs in wastewater, surface water, animal wastes, and biosolids. This information can inform risk assessment and potential future wastewater treatment regulations (US EPA, 2008; US EPA, 2009a).

- **Determine performance capabilities and reliability of decentralized wastewater system treatment technologies.** Conduct this assessment for EDCs, PPCPs, and difficult-to-treat pathogens (US EPA, 2008).

- **Assess removal of CECs and DBPs.** Determine the effectiveness of treatment processes that are used for high-end treatment and water reuse at removing CECs and DBPs.
- **Develop risk models for alternative water disinfection strategies**.

- **Investigate transformations of water treatment chemicals.** Assess the transformations of source water contaminants during water treatment (chlorination and chloramination) process.

- **Design methods to control pollutants in runoff.** Develop new methods to control pollutants in runoff from various sources, activities, and materials, such as source reduction and pollution prevention programs, as well as innovative stormwater treatment at hot spots (US EPA, 2008).

- **Identify technologies appropriate for radiological contamination.** Identify technologies that can decontaminate systems in the event of intentional or accidental microbial or radiological contamination (US EPA, 2009a).

- **Assess new technologies that address nonpoint sources of pollution** (US EPA, 2013b).

- **Identify and develop technologies to improve wastewater from hydraulic fracturing.** Technological improvements are needed that can help ameliorate the poor quality of wastewater generated by shale gas production (US EPA, 2013b).

- **Investigate antimicrobial resistance in wastewater streams.** Include an assessment of the impact this may have on POTW treatment processes (US EPA, 2008).

- **Minimize mobilization of CECs.** Investigate technologies to minimize mobilization of geologic chemicals/radionuclides and the formation of drinking water contaminants during aquifer storage and recovery (US EPA, 2012d).

To learn more about how these future research needs relate to the other research priorities, see Table 5-4.

## 5.5 Characterize and Prioritize Contaminants for Future Research

### Background

Limited resources and time are available to study health effects and risk, to develop analytical methods and treatment technologies, and to monitor contaminants in the environment. The NWP has developed a systematic method for prioritizing chemicals for research and regulatory action as drinking water contaminants. This methodology, called the CCL Classification Protocol (CCLCP), was used to narrow an initial list of thousands of chemical contaminants down to approximately 100 priority contaminants on the third CCL (74 FR 51850; US EPA, 2009b). Empirical data on occurrence and health effects were used where possible in CCLCP, but reliable occurrence and health effects data are available for only a fraction of chemical contaminants. For other contaminants, data on fate and transport and physical and chemical properties were used in surrogate roles when available. Information about fate and transport and properties is more widely available than health effects and occurrence data, and easier to generate. However, the availability of this information is still insufficient for most contaminants, and methodologies for predicting occurrence and health effects based on fate and transport and physical and chemical properties could be further refined.

The NWP is developing an equivalent methodology to prioritize contaminants for research and regulatory action under the CWA. The NWP has made progress in developing a pollutant-screening tool to identify pollutants that may accumulate in biosolids, and has identified a need to develop a comprehensive risk-based process for prioritizing chemicals for ambient water quality criteria development (US EPA, 2014a).

## Future Research Areas

Research needs include the following:

- **Understand fate and transport of CECs.** Improve the understanding of the fate and transport of trace organics (including pharmaceuticals), nanoparticles, pathogens, and other CECs in wastewater, surface water, and biosolids (US EPA, 2008; US EPA, 2009a; US EPA, 2012c). This is needed on both national and international scales (NRC, 2012). Current advances in remote sensing continue to improve understanding of contaminant sources, fate, and transport. Such approaches can, for example, monitor the distribution of aerosols in the atmosphere, releases of VOCs from landfills, and other diffuse or dispersed sources (NRC, 2012).
- **Solidify understanding on antibiotic resistance.** Investigate whether antibiotics discharged into the environment in low doses can contribute to antibiotic resistance in microbes and humans. Explore the extent this encourages horizontal gene transfer of androgen receptor (AR) genes within the broader microbial community, and determine if this hastens the functional obsolescence of antibiotics (US EPA, 2008).
- **Examine interplay among treatment processes, nanoparticles, and antimicrobial resistance.** Assess the effect that nanoparticles and antimicrobial resistance have on treatment processes and conversely, how treatment processes may impact nanoparticles and antimicrobial resistance (US EPA, 2009a).
- **Investigate behavior of microbial and radiological contaminants.** Determine the fate and transport of microbial and radiological contaminants in drinking water, and develop a surrogate/simulant database to provide a resource/reference for contaminant modeling (US EPA, 2009a).
- **Develop tools for prioritizing groups of contaminants.** Occurrence of multiple contaminants may modify expected behavior and health effects. Tools are needed to examine and prioritize groups of contaminants, whereas previously only individual contaminants were considered, as in the current CCL process.
- **Develop a risk-based framework to select microbial contaminants for development of new or revised water quality criteria.** Research is also needed to further refine and improve EPA's quantitative microbial risk-assessment framework for estimating human health risk for exposure to ambient and drinking waters (NRC, 2012).
- **Develop and improve pathogen dose responses.** This includes understanding the occurrence and prevalence of pathogens from various sources, along with treatment efficacy for all pathogen groups (US EPA, 2014b).

To learn more about how these future research needs relate to the other research priorities, see Table 5-5.

## 5.6 Actionable Information on Chemical and Microbiological CEC's Crosswalk with Other Research Priority Areas

**Table 5-1. Assess Effects of CECs on Ecological and Human Health Effects – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Develop methods to assess human health risks posed by chemical mixtures in the environment. | | | X | | | | |
| Identify factors that influence human health effects from chemical exposure. | | | | | | | X |
| Establish health endpoints for CECs. | | | | | | | |
| Develop risk assessment methods. | | | X | | | | |
| Investigate metagenomics and bioinformatics for risk assessment. | | | | | | | |
| Develop computational toxicology techniques to assess human health. | | | | | | | |
| Reduce uncertainty in extrapolating chemical and pathogen data to assess human health risks to chemicals and pathogens. | | | | | | | |
| Assess impacts of CECs on aquatic life and ecosystems function. | | | | X | X | X | |
| Improve endocrine disruption testing protocols. | | | | | | | |
| Investigate risks from biosolids application. | X | | | X | X | | |

**Table 5-2. Develop New Analytical Detection Methods – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Improve viral fecal indicator methods. | | | | X | | | |
| Improve analytical method sensitivity for individual contaminants and contaminant groups. | | | | | | | |
| Develop cost effective CEC test methods for performing risk evaluations. | | | | X | | | |
| Finalize development of qPCR techniques. | | | | X | | | |
| Develop digital qPCR techniques. | | | | X | | | |
| Develop microbial source tracking tools. | | | | X | X | | |
| Develop bioactivity measures. | | | | | X | | |
| Improve the accuracy of Canary for analyzing water quality data in distribution systems. | | | | | | | |
| Improve CBR detection capabilities. | | | | | | | |

**Table 5-3. Study the Occurrence of and Exposure to CECs – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Employ microbial source tracking more widely. | | | | X | X | | |
| Survey PPCPs and other CEC occurrence in drinking water. | | X | X | X | | | |
| Evaluate ENM toxicity and exposure from industrial wastewater. | | | X | X | X | | |
| Assess pathogen, PPCP, and EDC transport to the environment. | | | X | X | X | | |
| Assess CEC impact on underground sources of drinking water. | | X | X | X | X | X | |

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Identify indicators of sewage sludge quality. | | | X | X | | | |
| Survey CECs in waste streams and wet weather flows. | | X | X | X | | | |
| Expand the use of sensors and remote sensing technologies for surface water monitoring. | | | | X | X | X | |
| Develop technologies to assess drinking water source vulnerability. | | X | X | | X | | |
| Determine levels of nanomaterials in various media. | | | X | X | X | | |
| Develop methods to identify priority contaminants. | | X | X | X | | | |

**Table 5-4. Develop Cost-Effective Treatment and Mitigation Options – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Develop cost-effective management and treatment options for risk management. | | | X | X | X | | |
| Determine performance of decentralized wastewater treatment technologies. | | | X | | X | | |
| Assess removal effectiveness of CECs and DBPs for processes used for high-end treatment and water reuse. | | X | X | | X | | |
| Develop risk models for alternative disinfection strategies. | | | X | | | | |
| Investigate transformations of contaminants during treatment processes. | | | X | | X | | |
| Develop methods to control pollutants in runoff. | | | X | X | X | | |
| Identify radiological decontamination technologies. | | | X | | | | |

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Assess new technologies to address nonpoint pollution sources. | | | X | X | | | |
| Develop technologies to improve HF wastewater quality. | | X | X | X | | | |
| Investigate antimicrobial resistance in wastewater. | | | X | | | | |
| Investigate technologies to minimize CEC mobilization during aquifer storage and recovery. | | X | X | X | | | |

**Table 5-5. Characterize and Prioritize Contaminants for Future Research – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Research CEC fate and transport in wastewater, surface water, and biosolids. | | X | | X | | | |
| Research antimicrobial resistance. | | | | | | | |
| Examine interplay among nanoparticles, antimicrobial resistance, and treatment processes. | | | X | | | | |
| Investigate behavior of microbial and radiological contaminants. | | | | | | | |
| Develop tools to prioritize groups of contaminants. | | X | | | | | |
| Develop a risk-based framework for microbial water quality criteria development. | | | | | X | | |
| Understand efficacy of pathogen treatment. | X | | X | X | | | |

## 5.7 References

Ankley, G.T., R.S. Bennett, R.J. Erickson, D.J. Hoff, M.W. Hornung, R.D. Johnson, D.R. Mount, J.W. Nichols, C.L. Russom, P.K. Schmieder, J.A. Serrrano, J.E. Tietge, and D.L. Villeneuve. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. *Environmental Science and Technology*. (3):730-741.

AOPKB. 2015. Adverse outcome pathway wiki. https://aopkb.org/aopwiki/index.php/AOP_List. Accessed April 28, 2015.

CAS. 2015. CAS Databases. http://www.cas.org/content/cas-databases. Accessed March 23, 2015.

Doyle, E., A. Biales, M. Focazio, D. Griffin, K. Loftin, and V. Wilson. 2014. Effect-based screening methods for water quality characterization will augment conventional analyte-by-analyte chemical methods in research as well as regulatory monitoring. *Environmental Science and Technology*. Dec 18, 2014 [epub ahead of print].

Ekman, D.R., G.T. Ankley, V.S. Blazer, T.W. Collette, N. Garcia-Reyero, L.R. Iwanowicz, Z.G. Jorgenson, K.E. Lee, P.M. Mazik, D.H. Miller, E.J. Perkins, E.T. Smith, J.E. Tietge, and D.L. Villeneuve. 2013. Biological effects-based tools for monitoring impacted surface waters in the Great Lakes: A multiagency program in support of the Great Lakes. *Environmental Practice*. (15):409-426.

Ekman D.R., D.M. Skelton, J.M. Davis, D.L. Villeneuve, J.E. Cavallin, A. Schroeder, K.M. Jensen, G.T. Ankley, and T.W. Collette. 2015. Metabolite profiling of fish skin mucus: A novel approach for minimally-invasive environmental exposure monitoring and surveillance. *Environ. Sci. Technol.*, 49(5): 3091–3100.

Escher B.I., M. Allinson, R. Altenburger, P.A. Bain, P. Balaguer, W. Busch, J. Crago, N.D. Denslow, E. Dopp, K. Hilscherova, A.R. Humpage, A. Kumar, M. Grimaldi, B.S. Jayasinghe, B. Jarosova, A. Jia, S. Makarov, K.A. Maruya, A. Medvedev, A.C. Mehinto, J.E. Mendez, A. Poulsen, E. Prochazka, J. Richard, A. Schifferli, D. Schlenk, S. Scholz, F. Shiraishi, S. Snyder, G. Su, J.Y. Tang, B. van der Burg, S.C. van der Linden, I. Werner, S.D. Westerheide, C.K. Wong, M. Yang, B.H. Yeung, X. Zhang, and F.D. Leusch. 2014. Benchmarking organic micropollutants in wastewater, recycled water and drinking water with in vitro bioassays. *Environmental Science and Technology*. (3):1940-1956.

Evans, N., K. Schenck, H. Mash, L., Rosenblum, S. Glassmeyer, E. Furlong, D. Kolpin, and V. Wilson. 2015. Using an in vitro cell line to assess source and treated drinking water extracts for estrogenic activity (abstract). Society of Toxicology (SOT) Annual Meeting, San Diego, CA, March 22 - 26, 2015. http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=307678&subject=Water%20Research& showCriteria=0&searchAll=water%20and%20(water%20quality%20or%20water%20contaminants%20or%20water%20treatment%20or%20ground%20water%20or%20drinking%20water%20or%20wastewater%20or%20microbial%20or%20waterborne%20illness%20or%20waterborne%20virus)&sortBy=revisionD ate&dateBeginPublishedPresented=01%2F01%2F2010.

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014. *Climate change impacts in the United States: The third national climate assessment.* U.S. Global Change Research Program.

NRC. 2012. *Science for environmental protection: The road ahead*. National Research Council. Washington, D.C.: The National Academies Press. http://www.nap.edu/catalog.php?record_id=13510.

NIOSH. 2013. *Current strategies for engineering controls in nanomaterial production and downstream handling processes*. U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health. Cincinnati, OH. November, 2013. DHHS (NIOSH) Publication No. 2014–102.

OSHA. 2013. *OSHA fact sheet: Working safely with nanomaterials*. U.S. Department of Labor, Occupational Safety and Health Administration. April, 2013. https://www.osha.gov/Publications/OSHA_FS-3634.pdf.

Tollefsen, K.E., S. Scholz, M.T. Cronin, S.W. Edwards, J. de Knecht, K. Crofton, N. Garcia-Reyero, T. Hartung, A. Worth, and G. Patlewicz. 2014. Applying Adverse Outcome Pathways (AOPs) to support Integrated Approaches to Testing and Assessment (IATA). *Regulatory Toxicology and Pharmacology*. (3):629-640.

US EPA. 2005. *Microbial source tracking guide document*. EPA-600-R-05-064. Office of Research and Development. June 2005. http://www.ces.purdue.edu/waterquality/resources/MSTGuide.pdf.

US EPA. 2008. *National water program research compendium, 2009-2014*. Office of Water, Washington, DC. EPA 822-R-08-015.September 30, 2008. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/compendium.pdf.

US EPA. 2009a*. National water program research strategy. 2009-2014*. Office of Water (4304T). EPA 822-R-09-012. September 2009. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/strategy.pdf.

US EPA. 2009b. Drinking water Contaminant Candidate List 3-Final, *Federal Register* 74:51850ff, October 8, 2009.

US EPA. 2010. *A new approach to protecting drinking water and public health*. Office of Water. EPA 815-F-10-001. March 2010. http://water.epa.gov/lawsregs/rulesregs/sdwa/dwstrategy/upload/Drinking_Water_Strategyfs.pdf.

US EPA. 2011a. EPA moves to electronic reporting of new chemical notices. April 6, 2011. http://yosemite.epa.gov/opa/admpress.nsf/bd4379a92ceceeac8525735900400c27/65c135180da8e53a8525786a004f219c!OpenDocument.

US EPA. 2011b. *Final 2010 effluent guidelines program plan*. Washington, D.C. EPA-HQ-OW-2008-0517-0575.

US EPA. 2012a. *Chemical safety for sustainability: Strategic research action plan 2012-2016.* EPA 601-R-12006. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/css-strap.pdf.

US EPA. 2012b. *Human health risk assessment: Strategic research action plan 2012-2016.* EPA 601-R-12-007. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/hhra-strap.pdf.

US EPA. 2012c. *Safe and sustainable water resources: Strategic research action plan 2012-2016*. EPA 601-R-12-004. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/sswr-strap.pdf.

US EPA. 2012d. *EPA national water program 2012 strategy: Response to climate change. December 2012.* http://water.epa.gov/scitech/climatechange/upload/epa_2012_climate_water_strategy_full_report_final.pdf.

US EPA. 2013a. Research in action: Engineered nanomaterials in the environment. http://www.epa.gov/athens/research/nano.html. Accessed July 28, 2015.

US EPA. 2013b. *Blueprint for integrating technology innovation into the national water program (Version 1.0 - March 27, 2013).* http://water.epa.gov/upload/blueprint.pdf.

US EPA. 2014a. Integrating 21st century science into ambient water quality criteria development: A strategy and action plan for FY 2014 – 2019. Health and Ecological Criteria Division, Office of Science and Technology. June 29, 2014.

US EPA. 2014b. Microbiological risk assessment (MRA) tools, methods, and approaches for water media. EPA-820-R-14-009. December 2014.

US EPA. 2015a. Engineered nanomaterials in industrial wastewater: Literature review and implications for 304m. Memorandum from Eva Knoth and Kim Wagoner, ERG, to William Swietlik, US EPA, EAD. January 23, 2015.

US EPA. 2015b. Enterococcus and Escherichia coli fecal source apportionment with microbial source tracking genetic markers - is it feasible? http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=262661. Accessed March 26, 2015.

# Chapter 6. Systems Approach to Protecting Watersheds

The objective of the Clean Water Act (CWA) is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (33 U.S.C. Sec. 1251(a), CWA Sec 101(a)). Since enactment of the CWA, federal and state water quality regulations have reduced pollutant levels in many lakes, rivers, and streams. Impaired aquatic ecosystems have been successfully restored through considerable federal, state, and local actions. Despite these efforts, however, the United States Environmental Protection Agency's (EPA) recently published *2008-2009 National Rivers and Stream Assessment* indicates that more than half – 55% – of the nation's stream miles do not support healthy populations of aquatic life (US EPA, 2009). Changes in streamflow, runoff, drought, flood flows, and storms due to climate change are predicted to further affect watersheds across the country. In urban watersheds, for instance, population growth has led to an increased demand for land for development and sustenance, resulting in destruction of natural features, such as wetlands, that are critical to buffering the impact of storm surges due to climate change (US EPA, 2012a).

Achieving the objective of the CWA by protecting healthy watersheds and restoring degraded ones hinges on the National Water Program (NWP) and states embracing the systems approach to watershed management. This chapter outlines priority areas and research needs to effectively implement a systems approach to protecting watersheds, as described in the Introduction. The NWP has identified research needs to effectively implement a systems approach to protecting watersheds as follows:

- 6.1 Identify and Protect Healthy Watersheds.
- 6.2 Modernize Water Quality Criteria and Establish Restoration Targets.
- 6.3 Address Contaminants of Emerging Concern.
- 6.4 Inform Waters of the U.S. Policy.
- 6.5 Develop Biological Criteria for the Protection of Aquatic Life.

Research needs related to the impacts of climate change on watershed protection are addressed in Chapter 8.

## 6.1 Identify and Protect Healthy Watersheds

### Background

Identifying and protecting healthy watersheds through a comprehensive, systems approach protects critical habitat, maintains ecosystem services, and protects local, downstream, and coastal water quality. Restoring and protecting the integrity and beneficial uses of aquatic systems is the primary goal of the CWA (US EPA, 2012a). The Office of Water's (OW) Healthy Watersheds Program (HWP) (US EPA, 2013) promotes a holistic approach to protecting intact watersheds based on integrated assessments of habitat, biological communities, water chemistry, and watershed processes such as hydrology, fluvial geomorphology, and natural disturbance regimes. OW's HWP is providing states with technical support to complete integrated assessments of watershed health on an individual river basin scale as well as statewide.

To protect watersheds, a detailed understanding is needed of the physical, chemical, and biological processes that support healthy aquatic ecosystems, the ways that anthropogenic stressors impact these processes, and the pathways to degraded ecosystem structure and function. The ability to quickly identify degrading system health is also critical. The beneficial uses of many watershed aquatic ecosystems are threatened by a complex array of pressures and stressors, including nutrient and sediment loading, habitat alteration, introduction of invasive species, toxic pollutants, and hydrologic alteration (US EPA, 2012b). Furthermore, it is important to specifically examine the interaction of climate change with such stressors and the cumulative impact on the watershed.

Further research on the effectiveness of various tools and methods used to identify and protect healthy watersheds will support implementation of the HWP. For example, part of protecting watersheds from degradation involves preserving natural land cover and wetlands to maintain hydrologic and geomorphic processes within their natural range of variation. Such efforts could be strengthened through research to better understand how the green infrastructure (GI) concepts of Benedict and McMahon (2006), which highlight a strategically planned network of wilderness, parks, and other green space to sustain natural resources, can be targeted to maximize benefits to healthy watersheds.

To better monitor and protect watersheds, the NWP is also interested in expanding the use of "smart sensor" technology beyond its traditional use for monitoring air quality to provide real-time and continuous water quality data in source waters and their tributaries. Sensors can monitor basic water chemistry (e.g., pH, dissolved oxygen, conductivity, turbidity, and temperature), as well as dissolved anions and ions, including nutrients (Mukhopadhyay and Mason, 2013). Sudden changes in dissolved oxygen and nitrates detected by the sensor, for example, may indicate the presence of sewage or agricultural and urban runoff. Extreme changes in pH may be an indication of a chemical or sewage spill. Gradual changes in dissolved oxygen levels may be an indication of algal blooms. These indicators of degrading system health can supply data needed to aid quick investigation into situations that may degrade watersheds.

### Future Research Areas

Additional research is needed to:

- **Assess the use of GI and wetland preservation.** The ecological and economic benefits and costs of GI and wetland preservation will assist in local, state, and EPA decision-making processes when establishing priorities and allocating resources for drinking water and recreational water protection.
- **Investigate the interactions of watershed-scale controls.** In the future, watersheds will best be understood and managed as complex ecological systems (US EPA, 2012b). Climate and human drivers control the key watershed processes that are observed as fluxes of water, sediment and organic matter, heat and light, invasive species, and nutrients and chemicals.
- **Identify and more fully characterize a healthy watershed**. The ability to readily access and synthesize available data on aquatic ecosystem conditions and watershed characteristics will facilitate the identification of healthy watersheds to focus protection efforts and tracking of trends in watershed health over time.
- **Expand the use of "smart sensor" technology to monitor source waters.** Deploying remote sensors in source waters and their tributaries will facilitate detection of water quality changes in real time.

To learn more about how these future research needs relate to the other research priorities, see Table 6-1.

## 6.2 Modernize Water Quality Criteria and Establish Restoration Targets

### Background

Science-based water quality standards are essential to protecting surface water and ground water resources, including public and private drinking water systems and recreational waters. Water quality standards are the foundation for tools to safeguard human health such as advisories for beaches, fish consumption, and drinking water, as well as to protect aquatic life. Periodic revisions to water quality criteria are needed to ensure that the protective thresholds are based on the latest research and scientific knowledge. For example, OW recently revised water quality criteria for total coliform in drinking water, and for enterococci and *E coli* in recreational waters and is developing conductivity, copper, selenium and other criteria for the protection of aquatic life. OW is also currently developing a risk-based prioritization process for chemicals; modernizing the methodologies for deriving aquatic life criteria for toxics, human health criteria for chemicals and microbes, and for nutrient criteria. Efforts are also ongoing to update the biological evaluation methods for endangered species and the screening and risk assessment methods for biosolids pollutants.

Water quality standards can be used to identify impaired water bodies and establish restoration strategies. Recognizing that restoration is resource-intensive, EPA has developed a Recovery Potential Screening website to assist states and water resource managers in prioritizing waters based on relative restorability (http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/recovery). Applying the Recovery Potential Screening process is helping numerous states. In the absence of a water quality standard, ecological thresholds can be used to define target endpoints for water body condition.

## Future Research Areas

To improve water quality and restore degraded systems, future research should:

- **Support protection of source waters for drinking water.** Understand bioactivity for assessing chemical mixtures and developing effects-based data interpretation, such as Adverse Outcome Pathways (AOPs).
- **Develop new science to inform OW's Human Health Ambient Water Quality Criteria (HH-AWQC) Methods Update**. This new science would include:
  - Relative Source Contribution (RSC)[17] and Bioaccumulation Factor/Bioconcentration Factor (BAF/BCF)[18] determinations, including trophic level BAF data for applicable fish,
  - Methods for adding inhalation and dermal exposures to the RSC process,
  - Evaluation of the available software/updates for EpiSuite[19].
  - Use of exposure data to support application of Age-Dependent Adjustment Factors (ADAF) concepts in determining lifetime HH-AWQC for carcinogens,
  - Research on analytical methods, treatment technologies, and BAF values for new chemicals being released to ambient water by industry, waste water treatment plants, and drinking water treatment plants,
  - Development of probabilistic methods for human health criteria and distributional techniques to evaluate exposure based on appropriate populations,

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[17] The RSC represents the portion of an individual's daily exposure to a contaminant that can be attributed to a particular route to exposure, such as consumption of drinking water. Individuals can be exposed to a contaminant through sources other than drinking water, such as food or air, and these other contributions are accounted for when calculating the maximum contaminant level goal by incorporating the RSC into the calculation (USEPA, 2015).

[18] The BAF is the ratio of the contaminant in an organism to the concentration in the ambient environment at a steady state, where the organism can take in the contaminant through ingestion with its food as well as through direct contact. It is analogous to the BCF, but applies to field measurements or to laboratory measurements with multiple exposure routes. The BCF is the ratio of contaminant concentration measured in biota in the field (or under multiple exposure conditions) to the concentration measured in the surrounding water. The BCF measures the extent to which pollutants concentrate from water into aquatic organisms such as fish. The extent of such concentration is given by the ratio of the pollutant concentration in fish to that in water (USGS, 2014).

[19] EpiSuite is a Windows®-based suite of physical/chemical property and environmental fate estimation programs that may be used in estimating BAFs (http://www.epa.gov/opptintr/exposure/pubs/episuite.htm).

- Integration of information using a reference dose (RfD) approach (http://www.epa.gov/iris/rfd.htm) to consider the effects of multiple systems and multiple effects (cancer and noncancer), and
- Assessment of the cumulative risks for non-CCL nitrosamines, carcinogenic VOCs, and perfluorinated compounds.

- **Support development and improvement of HH-AWQC for microbial contaminants.** Research predictive modeling, human health risks, and characterization of fecal indicators and pathogens in fresh and marine waters.
- **Support modernizing the methodology for deriving aquatic life AWQC for chemicals.** There are a number of areas open to new science: toxicity test data requirements, extrapolation methods for estimating toxicity values and linear carbon chain radicals such as HC5s, routes of exposure, bioavailability, addressing mixtures, population modeling and community metrics, application of ecosystem data, and development of uncertainty analysis/statistical methods.
- **Define ecological thresholds.** These thresholds are needed to better develop science-based ecological restoration targets for impaired water bodies. More research in this area will also help guide water body restoration and management efforts.

To learn more about how these future research needs relate to the other research priorities, see Table 6-2.

## 6.3 Address Contaminants of Emerging Concern

### Background

Recent technological innovations have assisted in identifying chemicals in water that were previously not detected. Referred to as contaminants of emerging concern (CECs), their source and frequency of occurrence, which affect their risk to human health and the environment, are often not known. For example, a limited base of research suggests detrimental impacts from certain pharmaceuticals on aquatic organisms, but there is minimal understanding of the potential short- and long-term impacts of such compounds on human health.

### Future Research Areas

In support of OW's risk-based process for selecting chemicals for water quality criteria derivation, further research is needed to:

- **Identify and characterize these contaminants.** Evaluate waters, effluents, sediments for CECs and develop an understanding of their fate, transport, exposure, potential risks to human health and aquatic life, and potential management/treatment options and technologies.
- **Understand the effectiveness of CEC degradation and removal.** Evaluate existing practices, such as BMP plans and collection systems, as well as conventional and innovative stormwater

and wastewater treatment technologies for their effectiveness and efficiency of removal and degradation.

To learn more about how these future research needs relate to the other research priorities, see Table 6-3.

## 6.4 Inform Waters of the U.S. Policy

### Background

Surface waters of the U.S. are protected under the CWA. However, not all surface waters are legally defined as "waters of the U.S." and several court rulings have led to ambiguities about which waters and wetlands remain federally protected. Virtually all waters are connected to differing degrees within the hydrologic cycle. EPA regulatory and enforcement staff members need a standardized and scientifically sound method to determine if a headwater stream, adjacent wetland, or isolated wetland significantly affects the biological and chemical integrity of a navigable water body or has relatively permanent flow/connections. This information will assist in setting priorities and developing science-based tools to improve program implementation consistency and enforcement clarity.

### Future Research Areas

Future research should (US EPA, 2012b):

- **Determine aggregated effects of multiple geographically isolated waters on downstream systems.** Determine whether thresholds should be defined beyond which geographically isolated waters affect downstream waters.
- **Assess indicators.** Assess usefulness of indicators, such as a common species, in evaluating the existence (or lack thereof) of biological, chemical, and physical connectivity between isolated and downstream waters.
- **Determine effects of pollutants in different systems.** Assess the direct and indirect effects of filling or discharging pollutants into an intermittent or ephemeral stream on a perennial downstream system. Also, the spatial and temporal scale of these impacts should be observed.
- **Develop nationally consistent indicators.** Consider ecoregion-based, field or remotely sensed indicators and approaches to classify streams as ephemeral, intermittent, or perennial.

To learn more about how these future research needs relate to the other research priorities, see Table 6-4.

## 6.5 Develop Biological Criteria for the Protection of Aquatic Life

### Background

Biological criteria have been used by states and tribes in support of CWA goals and objectives for over two decades (US EPA, 2011). Accurately characterizing aquatic life is fundamental to the further development and application of biocriteria. Ideally, aquatic life would be characterized based on a full and precise accounting of either all of the species that occur in a water body (including their abundances and ecological functions) or a subset of those species that are representative of the entire ecological community (Carignan and Villard 2002). However, several technical challenges currently limit how robustly aquatic life can be characterized, thus limiting assessment of the degree to which water bodies support the biological integrity goals of the CWA.

## Future Research Areas

In order to establish robust biocriteria and accurately characterize the biological status of water bodies, additional research is needed to:

- **Reduce and quantify uncertainty and bias associated with site-specific estimates of aquatic life.** Emerging DNA-based approaches are needed to produce more complete characterizations of aquatic life conditions and deliver standard and consistent descriptions of the aquatic life present (or expected) at a site with potentially very low sample uncertainty. This will require investment in the production of standard field and laboratory protocols to ensure consistency and comparability of sampled biota; creation of a national library of DNA sequences associated with known or surrogate species that will serve as the standard catalog of taxa used in assessments; and training and technical assistance to allow states and tribes to properly implement and interpret DNA-based assessments.
- **Improve the accuracy, consistency, and resolution of taxonomic identifications.** Methods should be developed and applied that permit consistent reporting of the taxa that occur in a water body at a level of taxonomic resolution that allows protection and restoration of aquatic life consistent with the goals of the CWA. This includes clarifying use of species and higher-level taxonomic identification in assessments, providing tools for consistent identification of diatom taxa and advancing metagenomic technology.
- **Improve how comprehensively aquatic life conditions are characterized**. This includes evaluating whether currently used biological endpoints adequately characterize aquatic life given the advances in ecological knowledge in the last 40 years, developing or refining techniques for more comprehensively characterizing aquatic life condition, and resolving whether biological criteria based on a single assemblage are protective of other components of aquatic life. A thorough assessment of how to most effectively and meaningfully combine information from multiple assemblages is needed, along with refinement and further development of a national database that links specific taxa to empirically derive stressor-specific sensitivity values and other ecological traits.
- **Understand the larger-scale context that influences aquatic life.** This includes individual water bodies and developing landscape-scale measures of both biological condition and the habitat attributes needed to support healthy ecosystems. Further evaluation of existing approaches and development of new methods for integrating site-level and regional assessments are needed to increase the overall utility of biological assessments. Further work is needed to understand the significance of changes in beta diversity to landscape-scale ecological function and the

protection and restoration of regional biotas. Aspects of watershed integrity relevant to biocriteria should be assessed with a variety of existing spatial analyses and remote sensing tools. A general framework for understanding and quantifying watershed integrity is needed to guide these efforts as is developing consensus on how to most meaningfully detect thresholds of important biological change in response to stressors.

To learn more about how these future research needs relate to the other research priorities, see Table 6-5.

## 6.6 Systems Approach to Protecting Watersheds Crosswalk with Other Research Priority Areas

**Table 6-1. Identify and Protect Healthy Watersheds – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Assess the use of GI and wetland preservation. | X | | | X | | X | X |
| Investigate interactions of watershed-scale controls. | X | | | X | X | X | X |
| Identify and more fully characterize healthy watersheds. | | | | | | X | X |
| Implement sensor technologies for remote and continuous water quality monitoring. | X | X | | X | X | X | X |

**Table 6-2. Modernize Water Quality Criteria and Establish Restoration Targets – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Support protection of source waters for drinking water. | X | X | | X | X | X | X |
| Develop new science to inform OW's HH-AWQC Methods Update. | | X | | | X | X | X |
| Support development and improvement of human health AWQC for microbial contaminants. | | X | | | X | X | X |
| Support modernizing the methodology for deriving aquatic life AWQC for chemicals. | X | | | | | X | X |
| Define ecological thresholds. | X | | | | | X | X |

**Table 6-3. Address Contaminants of Emerging Concern – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Characterize the potential risk of CECs to human and aquatic life. | | X | | X | X | | |
| Understand the effectiveness of CEC degradation and removal. | | X | X | X | X | | X |

**Table 6-4. Inform Waters of the U.S. Policy – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Determine aggregated effects of geographically isolated waters on downstream systems. | X | | | | X | X | |
| Research connections between isolated waters and downstream systems. | X | | | | X | X | |
| Assess effects of filling or discharging pollutants into intermittent/ephemeral streams on perennial downstream systems. | | | | | X | X | X |
| Develop nationally consistent indicators to classify streams as ephemeral, intermittent, or perennial. | | | | | | X | X |

**Table 6-5. Develop Biological Criteria for the Protection of Aquatic Life – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 7: Ecosystem Services | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Reduce uncertainty and bias with site-specific aquatic life estimates. | X | | | | | X | |
| Improve accuracy, consistency, and resolution of taxa reporting. | | | | | | X | |
| Improve aquatic life condition characterization. | X | | | | | X | X |
| Understand larger-scale influences of aquatic life. | | | | | | X | X |

## 6.7 References

Benedict, M. A. and E.T. McMahon. 2006. *Green infrastructure: linking landscapes and communities*. Washington, D.C., Island Press.

Carignan, V. and M.A. Villard. 2002. Selecting indicator species to monitor ecological integrity: A review. *Environmental Monitoring and Assessment*. 78:45-61.

Mukhopadhyay, S. C. and A. Mason (eds). 2013. *Smart sensors for real-time water quality monitoring*. Springer-Verlag, Berlin, Heidelberg.

US EPA. 2009. TMDL program results analysis fact sheet. Office of Water, July 17, 2009. http://www.epa.gov/owow/tmdl/results/pdf/aug_7_introduction_to_clean.pdf.

US EPA. 2011. *A primer on using biological assessments to support water quality management*. Office of Science and Technology, Office of Water, Washington, D.C. EPA 810-R-11-01,

US EPA. 2012a. *National water program 2012 strategy: Response to climate change.* December 2012. http://water.epa.gov/scitech/climatechange/upload/epa_2012_climate_water_strategy_full_report_final.pdf.

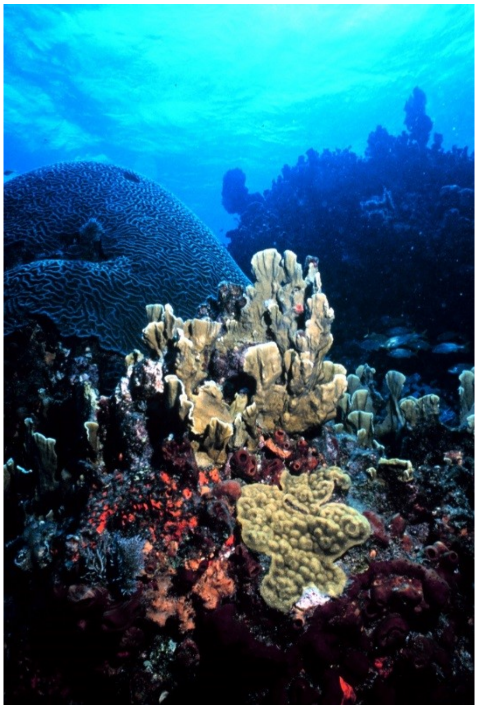
US EPA. 2012b. Safe and sustainable water resources: Strategic research action plan 2012-2016. June 2012. EPA 601-R-12-004. http://www2.epa.gov/sites/production/files/2014-06/documents/sswr-strap.pdf.

US EPA. 2013. Healthy watersheds initiative: National framework and action plan 2011. http://water.epa.gov/polwaste/nps/watershed/hwi_action.cfm.

US EPA. 2015. What is the relative source contribution with regard to development of drinking water standards? http://safewater.supportportal.com/link/portal/23002/23015/Article/20103/What-is-the-relative-source-contribution-RSC-with-regard-to-development-of-drinking-water-standards. Accessed July 21, 2015.

USGS. 2014. Environmental health, toxics, bioaccumulation definitions. http://toxics.usgs.gov/definitions/bioaccumulation.html. Accessed July 21, 2015.

# Chapter 7. Ecosystem Services



Ecosystem services are the benefits provided naturally by our environment. Because they are perceived as free and occur without human assistance, they are often taken for granted. These ecosystem services, however, are essential to human health and well-being. They provide benefits such as water filtration, ground water and surface flow regulation, flood and surge impact reduction, erosion control, stream bank stabilization, as well as recreational and economic benefits (e.g., fishing and tourism). Despite these benefits, anthropogenic (human) activities and climate change have negatively impacted these services. For example, natural ecosystems may be threatened by storm surges, sea-level rise, wildfires (when extremely dry conditions prevail), all of which may affect their ability to provide beneficial services (Melillo et al., 2014).

The value that society places on the benefits provided by ecosystem services should be an essential part of making decisions that affect ecosystems. Although a number of regulatory authorities call for the use of this valuation in decision-making, including Executive Order 12866 and the National Environmental Policy Act, value estimates do not exist for many ecosystem services, primarily due to a lack of information about those services. Approaches and methodologies to establish a valuation for ecosystem services are not coordinated across all elements (US EPA, 2008). Further, conventional decision-making often does not adequately characterize the complex interactions among human health, ecosystem services, economic vitality, and social equity (US EPA, 2011a).

The National Water Program (NWP) has identified research needs to protect and restore ecosystem services, as follows:

- 7.1 Incorporate Ecosystem Services into Decision-Making Using Tools and Models.
- 7.2 Incorporate Ecosystem Services into Pollution-Control Strategies.
- 7.3 Protect and Manage Water Resources Using Ecosystem Services.
- 7.4 Protect Against Nonnative Aquatic Nuisance Species.
- 7.5 Manage Reactive Nitrogen (Nr).
- 7.6 Inform Wetlands and Coral Reef Services Evaluations and Decisions.
- 7.7 Inform Decisions for Altered Waters, Including Ditches.

Research needs related to the impacts of climate change on ecosystem services are addressed in Chapter 8.

## 7.1 Incorporate Ecosystem Services into Decision-Making Using Tools and Models

### Background

The NWP is developing user-friendly tools to allow decision-makers to more easily incorporate ecosystem service considerations into their strategies. These tools include costs and benefits accounting methods (e.g., total resource impacts and outcomes), websites (e.g., Northeastern Lakes Ecosystem Services), databases (e.g., National Ecosystem Goods and Services Classification System), and models (e.g., Ecosystems Goods and Services (EGS) Production and Benefit Function) (US EPA, 2012a; US EPA, 2012b; US EPA, 2014). ORD's Sustainable and Healthy Communities Research Program's (SHC) research program is developing a collection of interactive tools and resources to allow users to view and analyze multiple ecosystem services in a specific region (US EPA, 2014). These tools, including EnvironAtlas and the Eco Services Model Library, will advance decision making by providing consistency and standardization for quantifying ecosystem goods and services to facilitate resource conservation through trading, environmental markets, and other policies or incentives, as well as allow for tracking changes, following performance, and quantifying goods and services (US EPA, 2014).

### Future Research Areas

Research into tools and models to incorporate ecosystem services into decision-making processes should:

- **Create and add to online decision-support.** This would allow users to integrate programs and information; visualize outcomes of their decisions; generate alternative decision options; and understand how management decisions and social norms affect the sustainability of ecosystem services, their value, and human well-being.
- **Evaluate costs and benefits.** Evaluate the full costs and benefits to ecosystem services and human well-being of different communities' actions and inactions.
- **Understand how education and outreach best impacts decision making.**
- **Examine the added benefits of ecosystem service restoration and protection.** Consider the benefits of the sustained recreational use of a lake that may include: increased revenue from a rise in tourism; reduced nutrient and sediment loadings; improved sources of drinking water/less expensive drinking water treatment; and, increased property values.
- **Determine methods and metrics.** Determine appropriate "yardsticks" to measure impacts on environmental, economic, social equity, and interacting conditions.
- **Measure progress toward sustainability.**

To learn more about how these future research needs relate to the other research priorities, see Table 7-1.

## 7.2 Incorporate Ecosystem Services into Pollution-Control Strategies

### Background

The United States Environmental Protection Agency (EPA) has developed an analytic framework (US EPA, 2011b) to assist policymakers in evaluating alternative nutrient- and sediment-control strategies that incorporate both the cost-effectiveness and ecosystem service impacts associated with individual pollution-control projects. It accounts for both targeted pollutant reductions and ancillary societal benefits (referred to as "bonus" ecosystem services) provided by certain pollution-control projects.

EPA has applied the framework to the Chesapeake Bay Watershed to illustrate how it can be used to answer: (1) what mix of pollution-control projects provide the least costly approach for achieving water quality goals in an impaired watershed, and (2) how does the consideration of bonus ecosystem services affect the desired mix of projects (US EPA, 2011b).

### Future Research Areas

Additional research is needed to:

- **Strengthen and broaden the existing analytic framework.** Include additional pollutant-control methods and technologies; regional- or state-level load-reduction targets; additional ecosystem service effects; examination of the broader economic and ecological impacts of the modeled changes; and application of the framework to other watersheds.

To learn more about how these future research needs relate to the other research priorities, see Table 7-2.

## 7.3 Protect and Manage Water Resources Using Ecosystem Services

### Background

Previous research has shown that gradual degradation of water quality results in a loss of opportunity for future generations, which inversely impacts economic growth (US EPA, 2012c). Research in the fields of natural resource economics and ecological economics seeks to prevent such market failures through explicit valuation of natural resources. One research area focuses on the use of natural and engineered water infrastructure. Specifically, water infrastructure management approaches are needed that optimize the use of water conservation, wastewater (and gray water) reuse, groundwater recharge by stormwater and reclaimed water, green infrastructure, and energy conservation and resource recovery. The Safe and Sustainable Water Resources (SSWR) Program identified synergistic use of natural ecosystem services and built infrastructure to achieve well characterized and safe public and ecosystem health as a priority (US EPA, 2012c).

Most research on the role of ecosystems services in water resource management has been conducted on the watershed scale (US EPA, 2014). (See also Chapter 6.) This research has sought to quantify watershed management effects on water quality and ecosystem services, with a focus on informing management actions and allowing decision makers to predict and evaluate how specific actions may improve or alter water quality and ecosystem services in their watersheds. While most of this has focused on a regulatory context, newer research is seeking to develop products that support decision making in the more general context of ecosystem services, such as the Eco Services Model Library (US EPA, 2011b; US EPA, 2014). Some of this research has involved evaluating the interrelationship of human well-being with ecosystems, which the Eco-Health Relationship Browser is continuing to incorporate (US EPA, 2013). Other decision-making tools are living documents that are continually modified with new data, such as the Final Ecosystem Goods and Services Classification System (FEGS-CS) Website (US EPA, 2014).

### Future Research Areas

Continuing and additional research is needed to (US EPA, 2008):

- **Quantify watershed management.** Include the effects on water quality and ecosystem services to allow decision-makers to predict and evaluate how specific actions may improve or alter water quality and ecosystem services in their watersheds.
- **Identify effective and sustainable approaches beyond the watershed level.** Identify approaches that maximize maintaining and improving the natural and engineered water system in a manner that effectively protects the quantity and quality of water. This research will use systems analysis tools at various scales and for different regions of the United States to take full advantage of the use of natural ecosystem services and the built environment to protect and manage water resources.

To learn more about how these future research needs relate to the other research priorities, see Table 7-3.

## 7.4 Protect Against Nonnative Aquatic Nuisance Species

### Background

The introduction of nonnative aquatic nuisance species (ANS) via ballast water discharge can cause significant economic and ecological damage to United States water bodies. In addition to ecological and water quality impacts, it has been estimated that non-indigenous invasive species may cost the United States over one hundred billion dollars per year (Miller et al., 2011). Other information puts the costs of major environmental damages and losses due to invading alien species in the United States at almost $120 billion per year (Pimentel et al., 2005). In the absence of robust scientifically-based risk assessment and verification methodologies, it is difficult to determine the most appropriate discharge standards to address this risk.

United States and international rules have been proposed to reduce the risks associated with invasive aquatic organisms by requiring that ships' ballast water be treated to kill or remove living organisms and achieve certain standards before being discharged. A document entitled, "Generic Protocol for the Verification of Ballast Water Treatment Technology" was published in 2010 resulting from a joint effort between the U.S. Coast Guard and EPA under ORD's Environmental Technology Verification Program. This document will be revised to take into consideration available commercial ballast water treatment systems and current testing procedures used to verify technology performance. A shipboard technology verification protocol is also needed to augment the environmental technology verification (ETV) land-based protocol and provide data on the operation and maintenance requirements of ballast water technology installed in ships over an extended period of time.

Based on preliminary assessment of available alternatives to meet the verification requirements of an enforcement system for implementing updated ballast water regulations, the most promising path forward involves indirect measures of ballast water characteristics using sensors, rather than mandatory reporting and inspection of ballast water treatment system equipment or direct ballast water sampling and analysis. This and other enforcement should be features of an overall compliance program to allow ballast water regulations to meet their goals at the lowest possible cost to ship operators and the general public.

To date, numeric concentration-based discharge limits have not generally been based upon a thorough application of risk-assessment methodologies. Future refinement of ballast water discharge standards will benefit from activity by the scientific community to improve and develop more precise risk-assessment methodologies. Rigorous and consistent sampling protocols are necessary for an effective ballast water management program. Without standardized sampling protocols, the outcome of a regional ballast management program will vary considerably depending on the particular sampling protocol that is adopted.

### Future Research Areas

To better protect against ANS, additional research is needed to:

- **Gather data on the operation and maintenance requirements of ballast water technology.** This particularly applies to technology installed in ships over an extended period of time. A shipboard technology verification protocol is also needed to augment the ETV land-based protocol.
- **Develop indirect measures of ballast water characteristics.** Potentially use sensors to develop this information.
- **Improve and develop more precise risk-assessment methodologies.** This information is needed to further refine ballast water discharge standards.

To learn more about how these future research needs relate to the other research priorities, see Table 7-4.

## 7.5 Manage Reactive Nitrogen (Nr)

### Background

Nitrogen can result in eutrophication of significant ecosystems (e.g., Chesapeake Bay), hypoxia or "dead zones" (e.g., Gulf of Mexico,), toxic algal blooms, acid rain, contributions to global warming, and associated human health effects due to drinking water contamination. Currently, EPA research programs have active research projects related to understanding and reducing nitrogen and co-pollutant loadings, including:

- The SSWR water, air, land, and ocean simulation modeling of nitrogen and phosphorus sources, fates, and impacts on ecological condition and ecosystem services (US EPA, 2013).
- The SHC's synthesis of information on nitrogen impacts on ecosystem services for air and water that identifies opportunities within the nitrogen cascade where management actions could yield the greatest benefits (US EPA, 2013).

The intensification of nitrogen release to the environment is affecting essential ecosystem services such as the provision of clean air and water, recreation, fisheries, forest products, aesthetics, and biodiversity. Reactive nitrogen (Nr) needs to be evaluated in terms of ecosystem services and their overall value (Compton et al, 2011).

## Future Research Areas

In order to better understand and define how Nr affects ecosystem services, research is needed to:

- **Connect ecological processes to a complete range of ecosystem services and human benefits.** Use quantitative rather than qualitative or anecdotal data.
- **Estimate costs associated with nitrogen damage.** Defensibly attach value to the damage costs per unit of N and the costs of abatement, restoration, or replacement.
- **Create monitoring and inventory methods.** Develop methods and sensor technology that rapidly and defensibly track the status of ecosystem services in air, land and water.
- **Study interaction of nitrogen effects.** Conduct studies to assess how nitrogen effects will interact with other projected changes such as land use, human populations and climate change.
- **Identify best practices for informed decision making.** Understand how regulatory and non-regulatory decisions regarding nitrogen pollution are made and the socio-economic aspects that facilitate them.

To learn more about how these future research needs relate to the other research priorities, see Table 7-5.

## 7.6 Inform Wetlands and Coral Reef Services Evaluations and Decisions

### Background

Wetlands and coral reefs are unique aquatic ecosystems, and each provides valuable services. Therefore, providing a scientifically defensible research approach to support policy and management actions that protect, enhance, and restore these ecosystems and their goods and services would have far reaching effects.

Conceptual and qualitative links among wetland condition, function, and services are well-known, but research is still needed to quantify those links at multiple scales. Further research also is needed to demonstrate the ability of wetlands to provide services under different future scenarios (US EPA, 2008). For example, coastal wetlands and similar ecosystems, including mangroves, sea grasses and salt marshes, can sequester greenhouse gases, such as carbon (as known as “blue carbon”).

Coral reefs provide many services, including protection to coastal communities from storm surge; habitat for fisheries; carbon sequestration; lucrative recreational and tourism opportunties; and extraction of chemical compounds for cancer and other medical uses (US EPA, 2012d). Methods to measure the value of coral reef services have evolved over the last two decades. However, the mechanisms through which a number of these ecosystem services are produced are complex, and most reef services have not been quantitatively linked to the reef attributes that provide them.

### Future Research Areas

For both wetlands and coral reefs, EPA will explore how surveys of condition can be used to estimate the delivery of ecosystem services and characterize the relationships between ecological function and delivery of services. NWP research should:

- **Assess inventory and characterize the services provided by wetlands and coral reefs.** For example, quantify the blue carbon potential of coastal wetlands, or its ability to sequester greenhouse gases, and develop market-based strategies for funding protection of natural wetlands and construction of artificial wetlands. Expand research on coral reefs, which are critical indicators of climate change through ocean acidification, coastal hydrology, nutrient pollution.
- **Assess how natural and anthropogenic activities impact those services.** Quantify adverse and beneficial agents of change.
- **Forecast the outlook for sustained services under alternative future scenarios.**

To learn more about how these future research needs relate to the other research priorities, see Table 7-6.

## 7.7 Inform Decisions for Altered Waters, Including Ditches

### Background

Altered waters present an ongoing challenge for decision-makers that need to take ecosystem services into consideration. For example, in evaluating the role of ecosystem services in the Chesapeake Bay restoration (US EPA, 2011b), researchers found that the method used to define waters for the analysis did not identify key features in the watershed, such as man-made ditches constructed to drain hydric soils for agriculture and silviculture. The omission caused an underestimation of the agricultural acreage suitable and available for riparian buffer installation and likely also led to an understatement of the costs of buffers required for nutrient control in areas with high densities of drainage ditches.

### Future Research Areas

Research is needed to provide program priority-setting management tools that will allow Clean Water Act managers to address the following issues regarding altered waters, including ditches and related ecosystem services (US EPA, 2012e):

- **Evaluate the hydrology and ecosystem functions of drainage.** Develop tools to examine how drainage functions in an ecosystem and how flows through ditches compare with natural streams and channelized streams. Variations caused by type of ditch, its location in the landscape, etc., should also be evaluated.
- **Investigate the role of wetland fringes.** Develop tools to determine whether wetland fringes along ditches perform ecological services of value to the downstream waters.

To learn more about how these future research needs relate to the other research priorities, see Table 7-7.

## 7.8 Ecosystem Services Crosswalk with Other Research Priority Areas

**Table 7-1. Incorporate Ecosystem Services into Decision-Making Using Tools and Models – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Create and add to online decision support. | | | | | | X | |
| Evaluate costs and benefits of community actions/inactions on ecosystems and human well-being. | X | | | | | X | X |
| Understand how education and outreach best impact decision making. | X | X | X | X | X | X | X |
| Evaluate benefits of restoring and protecting ecosystem services. | X | | | | | X | X |
| Determine methods and metrics for measuring impacts on ecosystem services. | X | | | | | X | X |
| Measure progress toward sustainability. | X | | | | | X | X |

**Table 7-2. Incorporate Ecosystem Services into Pollution-Control Strategies – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Strengthen the existing analytical framework for incorporating ecosystem services into pollution-control strategies. | X | X | X | X | X | X | X |

**Table 7-3. Protect and Manage Water Resources Using Ecosystem Services – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Quantify watershed management. | | | | | | X | X |
| Identify effective approaches beyond the watershed scale. | | | | | | X | |

**Table 7-4. Protect and Manage Water Resources Using Ecosystem Services – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Gather data on ballast water technology. | | | | | | | |
| Develop indirect measures of ballast water characteristics. | | | | | | | |
| Develop more precise risk-assessment methods. | | | | | | X | |

**Table 7-5. Manage Reactive Nitrogen (Nr) – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Connect ecological processes, ecosystem services, and human benefits using quantitative data. | X | | | | | X | |
| Estimate costs associated with nitrogen damage. | X | | | | | X | |
| Create monitoring and inventory methods including sensor technology. | X | | | | | X | |

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Study interaction of nitrogen effects with projected changes (e.g., land use, human population, and climate change). | X | | | | | X | X |
| Identify best practices for decision making regarding nitrogen pollution and the influence of socio-economic aspects. | X | | | | | X | |

**Table 7-6. Inform Wetlands and Coral Reef Services Evaluations and Decisions – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Characterize ecosystem services from wetlands and coral reefs including the potential to sequester GHG. | X | | | | | X | X |
| Evaluate natural and anthropogenic impacts on wetland and coral reef services. | X | | | | X | X | X |
| Forecast the outlook for sustained services. | | | | | | X | X |

**Table 7-7. Inform Decisions for Altered Waters, Including Ditches – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 8: Climate Change |
|---|---|---|---|---|---|---|---|
| Evaluate the hydrology and ecosystem functions of drainage. | | | | X | | X | X |
| Investigate the role of wetland fringes and their potential value to downstream waters. | | | | | | X | X |

## 7.9 References


Compton, J.E., J.A. Harrison, R.L. Dennis, T.L. Greaver, B.H. Hill, S.J. Jordan, H. Walker and H. V. Campbell. 2011. Ecosystem services altered by human changes in the nitrogen cycle: A new perspective for U.S. decision making. *Ecology Letters*. 14:804–815.

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014. *Climate change impacts in the United States: The third national climate assessment.* U.S. Global Change Research Program.

Miller, A.W., T. Huber, M.S. Minton, and G.M. Ruiz. 2011. Status and trends of ballast water management in the United States: Fourth biennial report of the National Ballast Information Clearinghouse. Smithsonian Environmental Research Center, submitted to the United States Coast Guard. September 1, 2011.

Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics*. 52:273-288.

US EPA. 2008. *National water program research compendium, 2009-2014*. Office of Water, Washington, DC. EPA 822-R-08-015.September 30, 2008. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/compendium.pdf.

US EPA. 2011a. *Sustainable and healthy communities research*. Office of Research and Development. April 2011. http://nepis.epa.gov/Exe/ZyPDF.cgi/P100B5BG.PDF?Dockey=P100B5BG.PDF.

US EPA. 2011b. *An optimization approach to evaluate the role ecosystem services in Chesapeake Bay restoration*. Office of Research and Development. EPA/600/R-11/001. October 2011. http://www2.epa.gov/sites/production/files/2014-03/documents/chesapeake-bay-pilot-report.pdf.

US EPA. 2012a. Coastal and marine ecological classification standard receives federal approval. June 2012. http://www2.epa.gov/sites/production/files/2013-09/documents/cmecs-federal-approval.pdf.

US EPA. 2012b. Lake ecosystem services. http://www.epa.gov/aed/lakesecoservices/. Accessed May 2, 2014.

US EPA. 2012c. *Safe and sustainable water resources: Strategic research action plan 2012-2016*. EPA 601-R-12-004. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/sswr-strap.pdf.

US EPA 2012d. EPA priorities for oceans and coasts. Draft. OWOW. December 4, 2012.

US EPA. 2012e. Research needed to inform clean water act policymaking and implementation. August 2012.

US EPA. 2013. Nitrogen and co-pollutant research roadmap: Implementation plan. Draft. August 26, 2013.

US EPA. 2014. Ecosystem Research. http://www2.epa.gov/eco-research/ecosystems-services. Accessed May 1, 2014.

# Chapter 8. Climate Change Impacts

Global climate change affects environmental and human health world over. Defensible data prove that climate patterns are changing as a result of human activities, primarily those producing greenhouse gases (GHGs) (IPCC, 2013; Melillo et al., 2014). Predictions indicate temperatures will increase by 2-4°F in the United States over the next few decades (Melillo et al., 2014). Precipitation patterns are also predicted to change, with dry areas generally becoming drier while wetter areas become wetter (Melillo et al., 2014). However, impacts are proceeding at different paces and vary by region, and the full scope and timing of impacts are difficult to project.

Climate change may occur gradually over time or in the form of sudden, extreme events. Gradual changes include global warming, sea level rise, ocean acidification, and incidence and growth of drought conditions, among others (Melillo et al., 2014). Extreme changes include storms (winter storms, hurricanes, and thunderstorms), heat waves, and floods, among others (Melillo et al., 2014). These types of changes could affect the availability and quality of water resources, thereby affecting drinking water and wastewater systems (Melillo et al., 2014). Groundwater and surface water resources may be adversely affected by declining runoff, changes in the timing of peak streamflow, changes in lake levels, reduced recharge, saltwater intrusion, precipitation changing from snow to rain and early melting of snowpack and glaciers (Melillo et al., 2014; Parry et al., 2007).

Water and wastewater systems that are already vulnerable, such as those with aging infrastructure, dwindling water supplies, and increased treatment needs from high levels of contamination, could be heavily affected by climate change (NACWA and AMWA, 2009). Extreme events could damage critical infrastructure at drinking water and wastewater facilities, thereby disrupting treatment and distribution and endangering public health and safety (NACWA and AMWA, 2009). Such events may cause breaking points, which can be difficult to predict, within human and natural ecosystems (Melillo et al., 2014). Improving systems and developing tools that can help communities anticipate such breaking points is valuable in mitigating and adapting to climate change (Melillo et al., 2014).

Furthermore, with increasing population pressure, drinking water and wastewater systems will be stressed as they strive to provide the same quality and efficiency of services to society as they do today (Parry et al., 2007). Smaller treatment systems without the financial and operational resources of larger systems may, in particular, be unable to cope with such pressures. In addition, utilities themselves contribute to climate change by releasing GHGs, either by their use of energy or as a byproduct of treatment.

Responses to climate change fall into two types of actions: mitigation and adaptation (Melillo et al., 2014). Mitigation entails taking steps to reduce future GHG emissions that contribute to climate change (Melillo et al., 2014). Adaptation entails improving a community's ability to cope with climate change by avoiding or minimizing impacts, or by improving ability to recover (Melillo et al., 2014). EPA plans to address climate change through both mitigation and adaptation by "reducing GHG emissions and taking actions that help communities and ecosystems become more resilient to the effects of climate change" (US EPA, 2010).

Climate change affects EPA's ability to achieve its mission (US EPA, 2015a). The Agency's strategic plan for Fiscal Years 2014-2018 identifies addressing climate change by reducing GHG emissions and taking actions to protect human health and become resilient to climate change impacts as one of the Agency's strategic goals (US EPA, 2014a). EPA is one of 13 federal departments and agencies that contributes to climate change research under the U.S. Global Change Research Program (USGCRP), which emphasizes the key role played by sound science and high quality research in understanding the impacts of global climate change (US EPA, 2015a). There are seven key research areas in EPA's climate change science research program: water quality and aquatic ecosystems; air quality; human health; ecosystems and land; mitigation and associated environmental impacts; social system influences; and uncertainty (US EPA, 2015a). These last two research areas (i.e., social system influences and uncertainty) reflect two related science challenges that affect all other research areas: (1) incorporating social considerations into analyses, and (2) improving our understanding uncertainties related to climate impacts and responses. Within each of the seven priority areas, the National Water Program (NWP) has identified the following research needs to prepare for and adapt to climate change:

- 8.1 Address Climate Change Impacts on Nutrient Pollution.
- 8.2 Assess Climate Change Impacts of Hydraulic Fracturing.
- 8.3 Use Next Generation Technologies to Address Climate Change Impacts on Infrastructure.
- 8.4 Develop Wet Weather Flow Management Approaches.
- 8.5 Address Climate Change Impacts on Chemicals and Microbial Contaminants of Emerging Concern.
- 8.6 Develop Resilience in Watersheds.
- 8.7 Examine Impacts of Climate Change on Ecosystem Services.
- 8.8 Assess Social System Responses to Climate Change Issues.

The research needs presented under each of the priority areas below are aligned with the research needs presented in the individual chapters on these priority areas. In addition, this chapter includes research needs related to uncertainties in the social system response to climate change. These research needs also reflect climate-related research needs identified by EPA Office of Research and Development (ORD).

## 8.1 Address Climate Change Impacts on Nutrient Pollution

### Background

Nutrient dynamics and associated impacts to aquatic ecosystems can vary significantly depending on in-stream conditions such as temperature, flow, and aquatic organism populations and distribution. Each of these factors is profoundly influenced by climate changes such as warming temperatures and fluctuations in precipitation intensity and variability. For example, storm surges and flooding may increase nutrient runoff to surface and ground waters from agricultural and urban areas. In addition, the adverse impacts of eutrophication may be exacerbated by warmer temperatures (Moss et al., 2011). Higher ambient temperatures and changes in precipitation due to climate change can change runoff patterns and greatly affect nutrient dynamics and transport mechanisms (Whitehead and Crossman, 2011).

Increased nutrient loading, coupled with other factors such as the availability of light and warmth, may lead to rapid growth of harmful algal blooms (HABs), which negatively affect aquatic environments by blocking out sunlight, depleting oxygen, and, in some cases, releasing toxins (National Ocean Service, 2011). Proliferation of HABs may be intensified under climate change scenarios due to warmer water temperatures, increased ocean acidification and surface stratification, higher atmospheric concentrations of carbon dioxide, increased nutrient in runoff due to heavier precipitation events, and changes in local nutrient upwelling (Hallegraeff, 2010). Some studies that examine nutrient impacts under climate change are underway. EPA's research assesses the impacts of climate change on nutrient flows and on critical environmental endpoints, including hypoxia in the Gulf of Mexico (US EPA, 2015a). For example, in a 2013 study, EPA examined the effects of projected land cover and climate changes on simulated nitrate and organic nitrogen levels in two watersheds within the Neuse River Basin in North Carolina (US EPA, 2014b).

### Future Research Areas

Methods and models are needed to evaluate the effects of various temperature and precipitation regimes on nutrient pollution in different ecosystems across the country. Protecting our nation's water resources from the impacts of climate change must involve a multi-faceted and collaborative approach (US EPA, 2012a). This research should:

- **Incorporate climate change into models predicting environmental impacts of future nutrient loads.** Develop predictive models to account for impacts on water quality impairments due to changes in the hydrologic cycle, temperature, and coastal acidification (US EPA, 2015a). Additional studies are needed to develop a deeper understanding of nutrient pollution under climate change scenarios and to develop strategies to reduce impacts to aquatic ecosystems and source water. Further studies should also evaluate the performance of Best Management

Practices (BMPs) under future temperature and precipitation scenarios, particularly on estuarine and coastal waters.

- **Develop innovative and cost-effective nutrient removal technologies.** Develop new technologies that are able to reduce nutrient pollution, in light of the anticipated increase in eutrophication due to climate change. These technologies should have a minimal carbon footprint. Wastewater treatment plants (WWTPs) need affordable and effective nutrient removal technologies to meet the challenges of increased loadings, the need to reduce loadings to achieve designated uses, and limited resources.
- **Prioritize watersheds for nutrient load reductions.** Provide information to assist states in prioritizing watersheds for nutrient load reduction (US EPA, 2011a). Prioritization is meant to take into account receiving water problems, public and private drinking water supply impacts, nutrient loadings, opportunity to address high-risk nutrient problems, among other factors. Regional- and local-scaled projections of changes in streamflow (as a result of change in precipitation) and temperature, which can affect nutrient loadings, could help inform prioritization.

To learn more about how these future research needs relate to the other research priorities, see Table 8-1.

## 8.2 Assess Climate Change Impacts of Hydraulic Fracturing

### Background

Hydraulic fracturing (HF) is an oil and natural gas production stimulation technique that involves the injection of specially engineered fluids under pressure great enough to fracture oil-and gas-bearing formations. The created fractures enable or enhance the flow of oil and gas to the production well. To develop and produce natural gas and/or oil from an unconventional reservoir in a shale basin, several million gallons of water are needed for the HF well and that water is typically obtained from local (and usually fresh) surface or ground water sources.

The interaction between climate change and HF relates primarily to potential water quantity and quality concerns from HF water use and competition between HF and other water-using activities in geographic areas with current or future water scarcity or water quality concerns. EPA is conducting extensive research regarding many aspects of the potential impacts on drinking water resources from hydraulic fracturing operations (US EPA, 2011b; US EPA, 2012b; US EPA, 2015b; US EPA, 2015c).

### Future Research Areas

Further research efforts are needed to address the interplay of HF and climate change on groundwater and surface water resources. Specifically, these efforts should:

- **Investigate opportunities for reuse and beneficial use of water from HF operations.** In regions where HF activity is likely to continue or grow, evaluate the risk of climate-induced water scarcity (Melillo et al., 2014) and the opportunities for reuse of HF wastewater. Evaluate the potential for sustainable onsite technologies for pre-treatment or treatment of HF wastewater for reuse for subsequent HF injection. Evaluate the potential for pre-treatment and reuse of HF wastewater for agricultural and other uses. Potential reuse can substitute for, and decrease the demand for, local fresh water.

- **Evaluate potential impacts of climate change on HF wastewater management.** Drinking water systems that rely on a limited number of source waters may be more susceptible to water quality issues if potential spills or discharges of contaminated HF fluids or wastewater are exacerbated by climate change effects. In regions where HF activity is likely, evaluate possible impacts due to inappropriate wastewater management in the context of effects from climate change such as the changes in the amount or timing of precipitation.

- **Evaluate effects of HF disposal practices on drinking water treatment systems.** In regions where HF activity is likely, examine how wastewater treatment plant effluent quality and quantity can potentially affect receiving water bodies under scenarios of increased or decreased water volumes due to short- and long-term changes in precipitation under climate change. Examine the ability of centralized waste treatment facilities (CWTs) to adequately treat constituents (including radionuclides) that can be found in HF wastewater. Concentration reductions by a range of treatment systems, including state-of-the-art systems, should be evaluated and, the effectiveness of drinking water treatments and the costs to install, operate, and maintain them should be examined.

To learn more about how these future research needs relate to the other research priorities, see Table 8-2.

## 8.3 Use Next Generation Technologies to Address Climate Change Impacts on Infrastructure

### Background

Climate changes, both gradual (e.g., sea level rise, drought) and extreme (e.g., intense storms, heat waves), may damage water and wastewater infrastructure and reduce the availability and quality of water resources. Systems with aging infrastructure, dwindling water supplies, increased treatment needs from high contaminant levels, or located in coastal or low-lying places are more vulnerable to the impacts of climate change.

Through its Climate Ready Water Utilities (CRWU) initiative, EPA assists utilities in becoming "climate ready" by providing tools and resources to develop more resilient systems (US EPA, 2014c). The initiative promotes the adoption of new technologies that enable systems to physically meet their changing demands as a means of adapting to climate change (US EPA, 2015d).

## Future Research Areas

Research is needed on new technologies that improve water and wastewater treatment processes to account for climate change impacts that will (Elliot et al., 2011):

- **Enable diversification of water supply, including a plan for backup supplies.** Given the possibility of increased regional droughts, develop guidelines for quality assessments of alternative sources, such as seawater (through desalination), rainwater (using harvesting methods), wastewater (through recycling), and produced water (formed during oil and gas exploration). Include the development of technologies that enable provision of water during climate conditions when primary supplies cannot be used (e.g., wells).
- **Promote ground water recharge.** Include the development of technologies that facilitate the reclamation of wastewater to augment underground sources of drinking water.
- **Improve resilience of water resources.** Using scaled-down climate projections, develop technologies to enable the identification of watersheds in which community water systems may be at risk of long-term shortfalls as well as technologies to control water quality degradation (e.g., household water treatment options). Research in these areas should include methods for planning, designing and operating infrastructure that will be resilient to threats such as sea level rise, flooding, wind, and drought. Water reuse technology will need to be adapted so small systems can treat multiple chemicals and pathogens.
- **Conserve water or improve water use efficiency.** Continue to develop lower-cost and more water-efficient products (faucets, toilets, washing machines) and technologies that enable leakage management. Such products and technologies would alleviate the burden on utilities by reducing the volume of water to be treated and distributed.

Drinking water and wastewater systems can also help mitigate climate change impacts by reducing GHG emissions through the use of Next Generation Technologies (Elliot et al., 2011; US EPA, 2014d). Many of these sustainable next generation technologies are still in the research and development phase. Also, to make these sustainable next generation technologies cost-effective and viable for use by water and wastewater systems, additional research is needed to develop or improve on technologies that can:

- **Enable energy conservation.** Assess how to effectively incorporate energy-efficient fixtures into utility operations, which reduces the consumption of energy purchased from the grid. This allows a system to become “net-zero,” or self-sufficient in terms of energy consumption.
- **Increase reliance on renewable energy**. Explore the use of renewable sources, such as wind and solar power at water and wastewater utilities.
- **Modify system design to increase self-sufficiency.** Design innovative conservation practices and energy self-sufficiency, which will help ensure continued functionality under conditions of climate stress (e.g., severe storms that disrupt power grids). Technologies need to be developed for small systems, particularly those facing new stringent regulatory requirements. Many of these facilities face problems with the reliability of their energy resources, so improved backup systems are needed.

- **Advance waste-to-energy technologies at wastewater treatment plants**. This would generate energy at the point of use and develop methods for cost-effectively promoting adoption in communities.
- **Enable use of local water resources.** Evaluate the use of new technologies (e.g., desalination for sea water) to promote use of existing local water resources that may be currently untapped. This may reduce the need for activities, such as transportation and distribution of water or wastewater over large distances, that otherwise contribute significantly to the release of GHG emissions.
- **Identify alternative and nonconventional drinking water sources and protect existing ones**. This is necessary to relieve pressure on already stressed freshwater sources and allow for sustainable water use.
- **Develop real-time control systems.** Develop innovative approaches to reduce collection system infiltration and inflow and other causes of sanitary sewer overflows (SSOs), combined sewer overflows (CSOs), and treatment system bypass. For CSOs, work is needed to compare the effectiveness of different approaches used in long-term control plans. This includes maximized use of collection systems, and maximized performance of treatment systems (e.g., real-time control and alternative in-plant processes for treating storm flow; NWP, 2008).
- **Develop real time system management capability.** Develop remote sensing systems (sensors, satellites, etc.) that monitor ambient conditions and inform the management of the system based on ambient condition and system performance on a real time basis.
- **Improve reuse or recovery of resources from system outputs or byproducts.** As an example, develop technologies that recover phosphorus from wastewater to be used in fertilizer and recovery of methane gas from treatment plants to be used as fuel. In addition, WWTP design should minimize aeration and GHG emissions, while allowing for recovery of resources such as nutrients, carbon, and water, including at the source.

To learn more about how these future research needs relate to the other research priorities, see Table 8-3.

## 8.4 Develop Wet Weather Flow Management Approaches

### Background

Wet weather flows include non-point and point-source runoff, including stormwater discharges and sewer overflows, a primary cause of impairment of water bodies in the United States (US EPA, 2002). Stormwater management has been historically planned using design storms[20] which assume static climate conditions based on past observational data. However, as climate changes, these assumptions

[20] A mathematical representation of a precipitation event that reflects conditions in a given area for design of infrastructure.

may be no longer be valid (Milly et al., 2008). Under future climate change scenarios, wet weather flows will increase in intensity and complexity and related BMPs, both structural and non-structural, will need to evolve to accommodate these changes. The Intergovernmental Panel on Climate Change (IPCC) has found that the frequency and/or intensity of heavy precipitation events in North American and Europe has likely increased in recent decades (IPCC, 2013), and Karl and Wright (1998) have described increased and disproportionately severe precipitation changes in the United States since 1910. The 100-year storm may become the new 10-year storm (Watt et al., 2003) and the design storm as previously used will become unreliable. Best Management Practices (BMP) performance evaluation is already complex and dynamic; climate change will add yet another layer of complexity.

Some stormwater BMPs (e.g., wet ponds) may not be sufficient to handle larger predicted storms. However, decisions about BMP design (or alteration) and placement must be made in the face of uncertainty since climate change science and modeling cannot provide reliable predictions at a scale that is useful for local stormwater management. Green infrastructure (GI) may offer a way for municipalities to adapt to changing precipitation patterns. GI BMPs can potentially be resized or retrofitted into a landscape, which may be less costly than investing in gray infrastructure to handle extra loads during extreme events.

## Future Research Areas

Developing GI BMPs, assessing the vulnerability of gray infrastructure, and identifying the most resilient combination of gray and GIs will improve wet weather flow management in the long-term. Evaluation is needed of the existing and planned gray infrastructure, along with its vulnerability to breakage due to drying soils, capacity under increased precipitation scenarios, loss of treated drinking water through leakage, and infiltration causing overflows. Research needs in this area should:

- **Estimate the performance of existing BMPs.** Assess future scenarios in terms of resizing BMPs or adding new BMPs. For example, additional research is needed to evaluate the impacts of wildfires, due to climate change, on the functioning of GI (US EPA, 2015a).
- **Assess the anticipated performance and costs of GI.** Include a comparison of GI costs to traditional gray infrastructure, or a combination of green and gray, under future climate change scenarios.
- **Compare and contrast large versus small BMPs.** Assess whether larger, centralized BMPs or smaller and more numerous, distributed BMPs are a better solution for their community (USGS, 2013). Also create and implement watershed level designs.
- **Assess and develop a comprehensive list of all and most technologically advanced available BMPs.** Categorize BMPs and their appropriate scale to provide example and guidance on how specific BMPs or combination of BMPs can be implemented with quantitative results.
- **Determine how to phase in control measures to properly respond to future conditions.**

- **Research pathogen removal and reduction of Biological Oxygen Demand***.* Evaluate performance of removal processes and develop innovative technologies to handle wet weather flows.

To learn more about how these future research needs relate to the other research priorities, see Table 8-4.

## 8.5 Address Climate Change Impacts on Chemicals and Microbial Contaminants of Emerging Concern

### Background

Climate change, changing land use practices and activities (e.g., HF and carbon sequestration), and emerging industries (e.g., nanotechnologies) are likely to introduce contaminants of emerging concern (CECs) into the environment and raise the profile of others, creating new challenges for protection of the environment and public health. CECs include endocrine disrupting chemicals (EDCs), pharmaceutical and personal care products (PPCPs), pathogens, and other chemicals and constituents. Industrial and commercial innovations are sources of some CECs; others are long-established contaminants that emerge to higher priority as circumstances change. Under climate change, water sources may be more vulnerable to emerging contaminants that are not monitored and for which detection and treatment technologies may not yet exist.

From an analysis of trends, the NWP can take steps to prepare for the challenges that will be posed by likely CECs in the coming decades (US EPA, 2008; US EPA, 2012b). Anticipating, detecting, and managing the threat posed by these contaminants requires development of expanded monitoring and treatment capabilities, occurrence surveys, risk modeling, and more. For example, ORD is finalizing the development of quantitative polymerase chain reaction (qPCR) techniques for quantification of *E. coli* and the development of thresholds for use in quantifying enterococci and *E. coli* using qPCR. Such methods will improve monitoring and reporting on the status of these pathogens in coastal waters, which is of increasing importance as environmental conditions change due to climate change.

Some research is already underway to assess changes in CEC occurrence under climate change. EPA Region 2 has been conducting water quality monitoring in the aftermath of Hurricane Sandy, to determine the longer-term effects of Sandy on levels of contaminants in sediments and receiving waters of specific coastal waters of New Jersey and New York, with a focus on areas affected by combined sewer overflows, sanitary sewer overflows, bypassing of wastewater treatment plants, and runoff or discharge from hazardous waste sites (US EPA, 2014b).

## Future Research Areas

Further research is needed in this area to:

- **Anticipate emergence of CEC-related challenges.** Analyze possible and likely climate change scenarios to anticipate overarching CEC challenges in the coming decades (US EPA, 2008; US EPA, 2012c).
- **Investigate harmful algal blooms (HABs).** Identify impacts of and expected changes in HABs under warmer water temperatures expected as a result of climate change, including changes in HAB dynamics, composition, and toxicity (US EPA, 2015a). The National Research Council (NRC, 2012) identifies HABs, caused by agricultural runoff and nutrient pollution, as an emerging challenge for the NWP.
- **Investigate the consequences of extreme precipitation events.** Identify the effects of extreme precipitation events (as a projected consequence of climate change) for sediment loading or scouring, nutrient, pathogen, and toxic contaminant loads to water bodies (US EPA, 2012b).
- **Examine emerging compliance challenges for drinking water and surface water quality standards.** Determine the consequences of warmer water on pathogen control and drinking water standard compliance to protect drinking water. Research should address the following specific concerns: the need to model the effect of warmer water temperatures on pathogen survival and proliferation and consequently on treatment requirements (both at drinking water and sanitary wastewater treatment plants); the need to identify pathogens that may be of greatest concern under conditions of increased or decreased precipitation or ground water scarcity; and the possible need to revise exposure factors and assessment methods. Pathogens from point sources should be distinguished from naturally occurring pathogens like *vibrios* bacteria and *Naegleria fowleri*, both of which have important linkages to climate change effects (US EPA, 2012a; US EPA, 2008).
- **Evaluate treatment technology readiness.** Investigate the capability of existing treatment technologies in wastewater and drinking water treatment facilities to control and treat the types and populations of pathogens associated with the warmer water temperatures expected to result from a changing climate (US EPA, 2015a). Research on water reuse systems and energy-efficient nutrient removal systems, to account for anticipated increases in nutrient loading, is also necessary (US EPA, 2015a).
- **Conduct research on fate and transport of emerging contaminants.** Investigate the fate and transport of contaminants under future climate change conditions. For example, increased precipitation will result in changes in streamflow, runoff, and drainage, which may affect the dilution and sediment loading of certain contaminants. Research on specific types of CECs can also be valuable. Identify nanomaterials of concern and determine what forms are most likely to result in environmental exposure (US EPA, 2012a).

To learn more about how these future research needs relate to the other research priorities, see Table 8-5.

## 8.6 Develop Resilience in Watersheds

### Background

Climate change will have a myriad of impacts on our nation's water resources. Many of these impacts, such as increased occurrence of floods and droughts, present challenges to achieving the goals of the Clean Water Act (CWA) and Safe Drinking Water Act (SDWA) through surface water and source water protection regulations. Environmental stressors, such as nutrient loading, population growth, and climate change contribute to watershed degradation. With predicted changes in precipitation under future climate scenarios, streamflow, runoff, drought, flood flows, and extreme storm events will affect watersheds all over the country.

A key strategy for increasing watershed resilience in the face of threats such as climate change, is protecting ecosystems, such as wetlands, which serve as natural buffers against storm surges and extreme weather events (US EPA, 2012a). Methods need to be developed to target wetlands for protection and recovery; to quantify the ability of wetlands to store and sequester carbon (see also Section 7.6); and to quantify benefits of wetlands mitigating coastal impacts from storm surges and contributing to watershed resilience. Also, the projected impacts of changes in sea levels and storm surges on coastal wetland area and function should be evaluated in terms of which wetlands and associated ecosystem services are at risk, and at what rate the ecosystems might be predicted to degrade.

In addition to improving watershed resilience in the face of climate change, embracing the Integrated Water Resources Management (IWRM) approach will allow for better short- and long-term protection of water resources. The IWRM approach provides a holistic framework for managing water resources that cross jurisdictional boundaries, and mitigating impacts from climate change and other stressors.

### Future Research Areas

To improve watershed resilience and protect healthy watersheds, research is needed to:

- **Monitor climate impacts and build resilience to climate change within watersheds**. Identify and monitor specific parameters or indicators to understand the impacts of climate change on watersheds. Indicators should assess changes in water temperature and estuarine and coastal acidification, to establish a baseline for measurement of long-term trends that account for climate change (US EPA, 2015a). Other parameters would include pH, total alkalinity, partial pressure of carbon dioxide (PCO2), dissolved inorganic carbon, dissolved organic carbon (DOC), and dissolved oxygen (DO). Methods to identify tipping points and thresholds will also be needed (US EPA, 2015a). Better estimates of precipitation frequency, duration, and intensity, and low-flow and no-flow conditions in rivers and streams, as well as developing bioactivity/bioassay measures for monitoring chemical contaminants at the watershed-scale, are needed (US EPA, 2015a). Such data can support screening assessments and criteria development based on adverse outcome pathways.

- **Support methods for identifying recoverable watersheds**. Methods need to be developed to target wetlands for protection and recovery; to quantify the ability of wetlands, especially coastal wetlands, to store and sequester carbon; and to quantify benefits of wetlands to reduce coastal impacts and to build resilience. Also, the projected impacts of changes in sea levels and storm surges on coastal wetland area and function should be evaluated in terms of which wetlands are at risk, what ecosystem services they provide, and at what rate they might be predicted to degrade. It is also important to understand the response of aquatic ecosystems to precipitation changes, temperature changes, sea-level rise, and storm surges (US EPA, 2015a).
- **Promote integrated wastewater management approaches for small systems**. Internationally, integrated water and wastewater management at the community level is recognized as a best practice for increasing resilience to climate change (UNESCAP, 2014). Decentralized wastewater management and small wastewater systems may provide a balance between treatment and environmental protection, productivity (e.g. agriculture, aquaculture), and resource recovery (e.g. water, nutrients). NWP should investigate the applicability of these practices to wastewater management in the United States, including assessing the capacity to properly maintain these systems and whether they are adequately designed to be resilient to climate change.
- **Develop hydrodynamic process models, including fate and transport, for chemicals and pathogens**. Such models facilitate application of measures to downstream critical control points to assess and mitigate the impacts of climate change on surface water quality. These critical control points can include land application of by-products of municipal wastewater and confined animal feedlot operations (CAFO) wastewater.
- **Evaluate acidification in coastal waters**. Transfer of carbon dioxide from the atmosphere to the ocean surface causes ocean acidification (IPCC, 2013). Research is needed to understand the scope, regional differences (e.g., geographic natural variability and upwelling events versus river inputs), sources (e.g., anthropogenic versus natural, atmospheric versus land-based), and the biological responses across different taxa from acidification in coastal waters.
- **Assess the effects of wildfires on drinking water management and ecosystem services**. Wildfires can have both short- and long-term effects on drinking water quality, quantity, availability, and treatability. Via changes in patterns of temperature and precipitation, climate change can affect the frequency and severity of wildfires and the time required for burn sites to regenerate and return to pre-fire erosion rates (Sham et al., 2014). As more frequent wildfires are expected under climate change, a firmer understanding of how wildfires in upland areas above contaminated sites may reduce ground cover, leading to sudden increases in runoff and wide-scale flooding that causes contamination of source waters (US EPA, 2015a). Research should identify the relative costs, benefits, and effectiveness of pre- and post-forest management approaches to reducing the risk of wildfire or mitigating its effects on drinking water treatment processes.
- **Examine emerging compliance challenges for ambient water quality standards.** For protection of ambient water quality, one concern is the vulnerability of designated uses to warmer temperatures and lower streamflows. In addition, there is a need to assess what scenarios may

increase water temperature or lower streamflows such that they no longer support attainment of water quality standards (WQSs).

- **Promote research on wetland contributions to watershed resilience and blue carbon.** Research is needed to better predict the buffer capacity of wetlands in the face of climate change, and more accurately quantify the ability of coastal wetlands to sequester GHGs. Further, there is a need to identify circumstances when coastal wetlands become sources rather than sinks for GHGs. This includes monitoring impacts of climate change on coastal wetlands and developing methods for facilitating wetland migration and preserving ecosystems services as sea level rises. Additional work is needed to develop market-based strategies to fund preservation and construction of coastal wetlands based on its value for sequestering GHGs in coastal wetlands as well as the benefits for reducing the impacts of climate change.
- **Determine 10-Year Low Flow Conditions to Set Discharge Limits.** Methods are needed to estimate lowest 7-day average flow that occurs over a 10-year period, as this determines the low flow for the purpose of setting discharge limits (US EPA, 2015).

To learn more about how these future research needs relate to the other research priorities, see Table 8-6.

## 8.7 Examine Impacts of Climate Change on Ecosystem Services

### Background

Ecosystem services are the benefits of natural ecosystems that are available to humans for sustenance, recreation, and economic use. Climate change affects biodiversity and structural elements (e.g., biomass) of ecosystems, which has an impact on human communities that rely on these systems for economic, biophysical, cultural, social, and recreational resources (Staudinger et al., 2012). An example of ecosystem services directly affected by climate change impacts would be precipitation-induced flooding of land that is used for residential, commercial, or agricultural purposes. Temperature changes that are a characteristic of global climate change could affect flora and fauna that provide recreational value to our society. Wetlands that provide percolation for groundwater recharge and flood and surge reduction may be degraded, as previously noted. Aquatic ecosystems may be adversely affected by the growth of HABs and nutrient loading.

### Future Research Areas

Research is needed to develop tools and strategies to better protect ecosystem services against climate change impact. Specific research should:

- **Identify specific impacts of climate change on ecosystem services.** Build on research that identifies the effects of climate change on ecosystem services to include additional research on the monetary and social implications of the loss of ecosystem services. This will allow for more effective adaptation strategies.

- **Develop decision-making tools that integrate data on ecosystem system services and climate change.** Standardize the quantification of ecosystem goods and services and improve the ability to assign a value to them. As an add-on, tools that integrate climate data, such as future projections of precipitation and temperature changes, with information on ecosystem services are needed to assist in planning and policy decisions on how to prioritize and protect specific services.
- **Identify effective methods for protecting ecosystem services that affect water quantity and quality.** Develop systems analysis tools at various scales and for different regions of the United States to identify natural ecosystem services that are capable of mitigating climate change impacts on water quantity and quality under climate change.
- **Protect natural features that provide protection from climate change threats.** Prioritize ecosystem features that specifically provide protection against climate change impacts on human communities. For example, wetlands are a known buffer to coastal flooding, which may result due to climate change, and therefore, are critical for protection against sea level rise and storm surges (US EPA, 2012a).
- **Complete more defined research on coral reefs.** Research should be focused particularly on coral reefs as they are directly linked to climate change and are critical indicators of change (e.g., ocean acidification, coastal hydrology, nutrient pollution, etc.).

To learn more about how these future research needs relate to the other research priorities, see Table 8-7.

## 8.8 Assess Social System Responses to Climate Change Issues

### Background

According to EPA's Climate Change Roadmap (US EPA, 2015a), significant research is needed to understand how social systems may respond and adapt to climate change. Research in this area has been largely focused on economics, behavioral, and decision science, but examining social impacts of climate change is also necessary to develop appropriate adaptation and response actions (US EPA, 2015a).

### Future Research Areas

Research should target social and behavioral sciences that assess the effects of climate change impacts on human communities. Although the following research needs reflect EPA-wide needs that are not limited to those that will be addressed by the NWP, incorporating such research considerations into the NWP's other research needs can provide a meaningful way of accounting for social system resilience to climate change. The NWP's research needs in this area include:

- **Improve capacity of communities to address harmful environmental impacts.** The growing emphasis on supporting community decisions requires approaches to develop data and information at those same scales. Although the current climate research does account for appropriate scales, it is important to adapt the results of climate change-related analyses into easily accessible information to aid decision-makers in understanding the magnitude, timing, and uncertainties of expected changes.

- **Understand interactions among social, behavior, environmental, and biological factors.** Social systems analysis of this nature includes: assessing impacts of climate change on cultural resources; understanding organizational structures and dynamics and how these might change during climate stress; and evaluating community relationships to build appropriate response actions (US EPA, 2015a). Particular emphasis should be placed on environmental justice and tribal communities that are disproportionately affected by climate change.

To learn more about how these future research needs relate to the other research priorities, see Table 8-8.

## 8.9 Climate Change Impacts Crosswalk with Other Research Priority Areas

**Table 8-1. Address Climate Change Impacts on Nutrient Pollution – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Incorporate climate change into nutrient models. | X | | | | | X | X |
| Further develop nutrient removal technologies. | X | | X | | | | |
| Prioritize watersheds for nutrient load reductions. | X | | | X | | X | |

**Table 8-2. Assess Climate Change Impacts of Hydraulic Fracturing– Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Investigate reuse of HF wastewater. | | X | X | | X | | |
| Evaluate climate change impacts on HF wastewater management. | | X | | | X | | |
| Evaluate effects of HF wastewater disposal on drinking water systems. | | X | X | | X | | |

**Table 8-3. Use Next Generation Technologies to Address Climate Change Impacts on Infrastructure – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Develop guidelines for quality assessments of alternative water sources, including backup water supplies. | | X | X | | | | |
| Develop technologies to promote ground water recharge. | | | X | | | | |
| Improve resilience of water resources. | X | | X | | X | X | |
| Improve water use efficiency. | | | X | | | | |
| Incorporate energy conservation at utilities. | | | | | | | |
| Increase water and wastewater utility reliance on renewable energy. | | | | | | | |
| Increase system energy self-sufficiency including those for small systems. | | | | | | | |
| Advance waste-to-energy technologies at wastewater treatment plants. | | | X | | | | |
| Promote the use of existing local water resources. | | | X | | | | |
| Identify alternative and nonconventional water supplies and protect existing ones. | | | | | | X | |
| Develop real-time control systems. | | | X | X | | | |
| Develop remote sensing systems for system management. | | | X | | | X | |
| Improve resource reuse from system outputs and byproducts. | X | | X | | | | |

**Table 8-4. Develop Wet Weather Flow Management Approaches – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Evaluate existing BMP performance. | | | X | X | | X | |
| Evaluate GI performance and costs. | | | X | X | | X | |
| Compare efficacy of BMPs in terms of size and distribution and at a watershed level. | | | X | X | | X | |
| Prepare a list of the most technologically advanced BMPs. | | | X | X | | X | |
| Determine how to phase in control measures to respond to future conditions. | | | | X | | | |
| Research pathogen and biological oxygen demand reduction performance. | | | X | X | X | X | |

**Table 8-5. Address Climate Change Impacts on Chemicals and Microbial Contaminants of Emerging Concern – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Analyze possible and likely climate change scenarios to anticipate overarching CEC challenges. | | X | | | X | | |
| Investigate impacts of warmer water temperature on HABs. | X | | | | X | X | |
| Investigate consequences of extreme precipitation. | X | | | X | X | X | X |
| Examine challenges with standards compliance for pathogen control in warmer water. | X | | X | X | X | | |

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Evaluate treatment technology readiness for pathogens and anticipated increased nutrient loading associated with climate change. | X | | X | | X | | |
| Research CEC fate and transport. | | | | X | X | | |

**Table 8-6. Develop Resilience in Watersheds – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Monitor climate change impacts and promote watershed resilience in the face of climate change. | | | | X | | X | X |
| Protect healthy and recoverable watersheds. | | | | X | | X | X |
| Promote integrated wastewater management for small systems. | X | | X | | | X | |
| Develop hydrodynamic process models for chemical and pathogens. | X | | | | X | X | |
| Evaluate factors influencing coastal water acidification. | | | | | | X | X |
| Assess effects of wildfires on drinking water management and ecosystem services. | X | | | X | X | X | X |
| Examine emerging compliance challenges associated with ambient water quality standards due to climate change. | X | | | | | X | X |
| Promote research on wetland contributions to watershed resilience and blue carbon. | | | | | | X | X |
| Determine the value of 10-year low flow conditions to use in setting discharge limits. | | | | | | X | |

**Table 8-7. Examine Impacts of Climate Change on Ecosystem Services – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Examine climate change impacts to ecosystem services. | | | | | | X | X |
| Develop tools that integrate ecosystem services and climate change. | | | | | | X | X |
| Protect ecosystem services that affect water quantity/quality. | X | | | | | X | X |
| Protect natural features that protect against climate change impacts. | X | | | | | X | X |
| Research coral reefs as climate change indicators. | X | | | | | | X |

**Table 8-8. Assess Social System Responses to Climate Change Issues – Future Research Needs**

| Future Research Need | Ch 1: Nutrients and HABs | Ch 2: Hydraulic Fracturing | Ch 3: Next Gen Water/Wastewater Technologies | Ch 4: Wet Weather Pollution | Ch 5: Chemical/ Microbial CECs | Ch 6: Protecting Watersheds | Ch 7: Ecosystem Services |
|---|---|---|---|---|---|---|---|
| Improve community capacity to address environmental impacts. | X | X | | | X | X | |
| Understand how social systems respond to climate change. | | | | | | | |

## 8.10 References

Elliot, M., A. Armstrong, J. Lobuglio, and J. Bartram. 2011. *Technologies for climate change adaptation—The water sector.* T. De Lopez (Ed.). Roskilde: UNEP Risoe Centre.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology.* 46:220-235.

IPCC. 2013. Climate change 2013: The physical science basis. http://www.ipcc.ch/report/ar5/wg1/.

Karl, T.R. and R.W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the USA. *Bulletin of the American Meteorological Society.* 79:231-241. http://journals.ametsoc.org/doi/abs/10.1175/1520-0477%281998%29079%3C0231%3ASTOPAF%3E2.0.CO%3B2.

Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014. *Climate change impacts in the United States: The third national climate assessment.* U.S. Global Change Research Program.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science.* 319:573-574.

Moss, B., S. Kosten, M. Meerhoff, R.W.Battarbee, E. Jeppesen, N. Mazzeo, K. Havens, G. Lacerot, Z. Liu, L. De Meester, H. Paerl, and M. Scheffer. 2011. Allied attack: Climate change and eutrophication. *Inland Waters.* 1:101-105.

National Association of Clean Water Agencies (NACWA) and American Water Works Association (AMWA). 2009. *Confronting climate change: An early analysis of water and wastewater adaptation costs.* October 2009. http://www.amwa.net/galleries/climate-change/ConfrontingClimateChangeOct09.pdf.

National Ocean Service. 2011. Overview of harmful algal blooms. http://www.cop.noaa.gov/stressors/extremeevents/hab/. Accessed March 24, 2015.

NRC. 2012. *Science for environmental protection: The road ahead*. Washington, DC: The National Academies Press, 2012. http://www.nap.edu/catalog.php?record_id=13510.

NWP. 2008. *National water program (NWP) research compendium 2009-2014*. EPA 822-R-08-015. September 2008. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/compendium.pdf.

Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, eds. 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html.

Sham, C.H., M.E. Tuccillo and J. Rooke. 2014. Effects of wildfire on drinking water utilities and best practices for wildfire risk reduction and mitigation. Sponsored by WRF and US EPA. http://www.waterrf.org/PublicReportLibrary/4482.pdf.

Staudinger, M.D., N.B. Grimm, A. Staudt, S.L. Carter, F.S. Chapin III, P. Kareiva, M. Ruckelhaus, and B.A. Stein. 2012. *Impacts of climate change on biodiversity, ecosystems, and ecosystem services: Technical input to the 2013 National Climate Assessment.* July 2012. http://downloads.globalchange.gov/nca/technical_inputs/Biodiversity-Ecosystems-and-Ecosystem-Services-Technical-Input.pdf.

UNESCAP. 2014. *Application of community-based integrated water supply and wastewater treatment systems to improve resilience to climate change.* June 4, 2014. http://www.unescap.org/resources/application-community-based-integrated-water-supply-and-wastewater-treatment-systems.

US EPA. 2002. *National water quality inventory 2000 report*. EPA 841-R-02-001.

US EPA. 2008. *National water program research compendium, 2009-2014*. Office of Water, Washington, DC. EPA 822-R-08-015.September 30, 2008. http://water.epa.gov/scitech/research-riskassess/researchstrategy/upload/compendium.pdf.

US EPA. 2010. *EPA strategic plan FY 2011-2015*. September 30, 2010. http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1008YOS.PDF.

US EPA. 2011a. Working partnership with states to address phosphorus and nitrogen pollution through the use of a framework for state nutrient reductions. Memorandum from Nancy K. Stoner, Acting Assistant Administrator to Regional Administrators, Regions 1-10. March 16, 2011. http://www2.epa.gov/sites/production/files/documents/memo_nitrogen_framework.pdf.

US EPA. 2011b. *Plan to study the potential impacts of hydraulic fracturing on drinking water resources.* Office of Research and Development. November 2011. EPA 600-R-11-122. http://www2.epa.gov/sites/production/files/documents/hf_study_plan_110211_final_508.pdf.

US EPA. 2012a. *National water program 2012 strategy: Response to climate change.* December 2012. http://water.epa.gov/scitech/climatechange/upload/epa_2012_climate_water_strategy_full_report_final.pdf.

US EPA. 2012b. *Chemical safety for sustainability: Strategic research action plan 2012-2016*. EPA 601-R-12-006. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/css-strap.pdf.

US EPA. 2012c. *Safe and sustainable water resources: Strategic research action plan 2012-2016*. EPA 601-R-12-004. June 2012. http://www2.epa.gov/sites/production/files/2014-06/documents/sswr-strap.pdf.

US EPA. 2014a. *EPA strategic plan FY 2014-2018*. April 10, 2014. http://www2.epa.gov/sites/production/files/2014-09/documents/epa_strategic_plan_fy14-18.pdf.

US EPA. 2014b. 2013 *Highlights of progress: Responses to climate change by the National Water Program.* April 24, 2014. http://water.epa.gov/scitech/climatechange/upload/Final-2013-NWP-Climate-Highlights-Report.pdf.

US EPA. 2014c. *Climate ready water utilities*. http://water.epa.gov/infrastructure/watersecurity/climate/index.cfm. Accessed June 5, 2014.

US EPA. 2014d. Climate change and water: Infrastructure. http://water.epa.gov/scitech/climatechange/Infrastructure.cfm. Accessed June 6, 2014.

US EPA. 2015a. *Climate change research roadmap: Cross-cutting roadmap, preliminary draft, July 2, 2014*. http://yosemite.epa.gov/sab/sabproduct.nsf/0/337ECE7064DEE1F185257CF3005F5367/$File/draft-climate-change-cross-cutting-roadmap-20140702.pdf. Accessed May 8, 2015.

US EPA. 2015b. *Analysis of hydraulic fracturing fluid data from the FracFocus chemical disclosure registry 1.0*. Office of Research and Development. EPA 601-R-14-003. March 2015. http://www2.epa.gov/hfstudy/analysis-hydraulic-fracturing-fluid-data-fracfocus-chemical-disclosure-registry-1-pdf

US EPA. 2015c. *Assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources-draft (undergoing peer review)*. Office of Research and Development. June 2015. EPA 600-R-15-047. http://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=244651.

US EPA. 2015d. Climate Ready Water Utilities (CRWU). http://water.epa.gov/infrastructure/watersecurity/climate/index.cfm. Accessed August 20, 2015.

USGS. 2013. How do you estimate Best Management Practices effectiveness? Available at http://egsc.usgs.gov/5-effective_bmp.html.

Water Research Foundation, 2009. Changes in storm intensity and frequency. Climate Change Clearinghouse. http://www.theclimatechangeclearinghouse.org/ClimateChangeImpacts/ChangesStormIntensityFrequency/Pages/default.aspx

Watt, W.E., D. Waters, and R. McLean. 2003. *Climate change and urban stormwater infrastructure in Canada: Context and case studies*. Toronto-Niagara Region Study on Atmospheric Change, Report and Working Paper Series.

Whitehead, P.G. and J. Crossman. 2011. Macronutrient cycles and climate change: Key science areas and an international perspective. *Science of the Total Environment.* 434:13-17.

# Appendix - List of Contributors

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