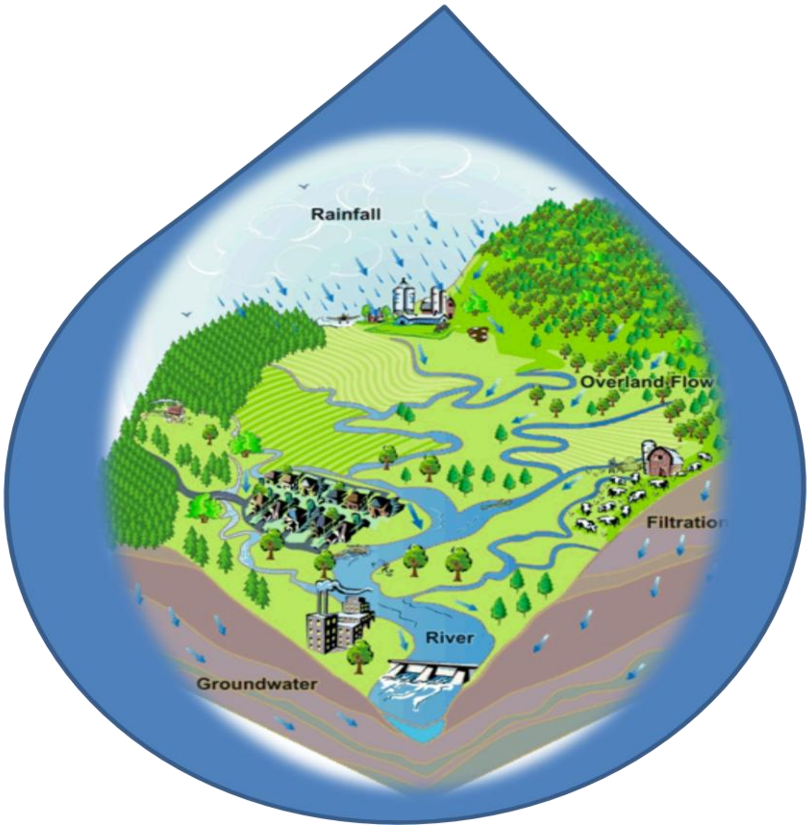
Framework for an EPA
Safe and Sustainable Water Resources
Research Program



Office of Research and Development
Office of Water
Region VI
US Environmental Protection Agency

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EPA Contributors

Rochelle Araujo, NERL
Karma Anderson, Region 10
Nicholas Ashbolt, NERL
Adam Biales, NERL
Andrea Bolks, Region 5
Randy Bruins, NERL
Eric Burneson, OGWDW
Gelena Constantine, ORMA
Ellen Cooter, NERL
John Darling, NERL
Tom Davenport, Region 5
Robin Dennis, NERL
Maura Donohue, NERL
Chris Faulkner, OWOW
*Joseph Fiksel, NRMRL**
Thomas Fontaine, NHEERL
Alice Gilliland, NRMRL
Susan Glassmeyer, NERL
Heather Golden, NERL
Rick Greene, NHEERL
Dale Hoff, NHEERL
Virginia Houk, NHEERL
Chris Impellitteri, NRMRL
Marjorie Jones, OW; ORD
David Jewett, NRMRL
Brent Johnson, NERL
Tammy Jones-Lepp, NERL
Jack Kelly, NHEERL
Ron Landy, Region 3
Chuck Lane, NERL
Michael McDonald, ORD
Jennifer Meints, Region 8
Jatin Mistry, Region 6
Bruce Mintz, NERL
Marirosa Molina, ORD
Chris Moore, OWM
Ardra Morgan, ORD
Walt Nelson, NHEERL
Edward Ohanian, OW
Jennifer Orme-Zavaleta, ORD
Margaret Osbourne, Region 6
Mike Overbay, Region 6
Roberta Parry, OW
Jim Pendergast, OWOW
Sean Porse, OGWDW
Stig Regli, OGWDW
Mary Reiley, OST
William Russo, NHEERL
Thomas Speth, NRMRL
John Stoddard, NHEERL
Robert Todd, Region 6
Eric Villegas, NERL
Phil Zahreddine, OWM

***** and Ohio State University

External Stakeholders

Jose Aguto, National Congress of American Indians
Charles Bott, Hampton Roads Sanitation District
Erica Brown, Association of Metropolitan Water Agencies
Gary Burlingame, Philadelphia Water Department
Mary Busby, Merck
Vic D'Amato, Tetra Tech
Josh Dickinson, Water Reuse Foundation
Cynthia Finley, National Association of Clean Water Agencies
Suzy Friedman, Environmental Defense
Paul Gruber, National Ground Water Association
Clif McClellan, National Sanitation Foundation

Eileen McClellan, Environmental Defense
Sudhir Murthy, DC Water
Valerie Nelson, Water Alliance
Darrell Osterhoudt, National Association of State Drinking Water Administrators
Chris Rayburn, Water Research Foundation
Christine Reimer, National Ground Water Association
Glenn Reinhardt, Water Environment Research Foundation
Rob Renner, Water Research Foundation
Barbara Sattler, University of Maryland School of Nursing
Perry Schafer, Brown and Caldwell
Udah Singh, CH2MHill
Paul Schwartz, Clean Water Action
Leslie Shoemaker, Tetra Tech
Chi Chung Tang, LA County Sanitation Districts
Ed Thomas, National Rural Water Association
Laurens Van der Tak, CH2MHill
Steve Via, American Water Works Association
Jane Wilson, National Sanitation Foundation
Dan Woltering, Water Environment research Foundation
Doug Yoder, Miami-Dade Water and Sewer Department

List of Acronyms

ACE	Air Climate and Energy
CAFO	Concentrated Animal Feedlot Operation
CCL	Candidate Contaminant List
CDCP	Centers for Disease Control and Prevention
CoE	Corps of Engineers
CSO	Combined Sewer Overflow
CSS	Chemical Safety for Sustainability
DoE	Department of Energy
DW	Drinking Water
HABs	Harmful Algal Bloom
HH	Human Health
HHRA	Human Health Risk Assessment
ITR	Integrated Transdisciplinary Research
LAE	Large Aquatic Ecosystems
NARS	National Aquatic Resource Survey
NERL	National Exposure Research Laboratory
NHEERL	National Health and Environmental Effects Research Laboratory
NIH	National Institutes of Health
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory
OGWDW	Office of Ground Water and Drinking Water
ORD	Office of Research and Development
ORMA	Office of Resources Management and Administration
OST	Office of Science and Technology
OW	Office of Water
OWM	Office of Wastewater Management
OWOW	Office of Wetlands, Oceans and Watersheds
PH	Public Health
POTW	Public Owned Treatment Works
PPCP	Pharmaceuticals and Personal Care Products
SHC	Sustainable and Healthy Communities
SSO	Sanitary Sewer Ocerflow
SSWR	Safe and Sustainable Water Resources
UAA	Use Attainability Analysis
UCMR	Unregulated Contaminant Monitoring Rule
UIC	Underground Injection Control
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WQ	Water Quality

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Aquatic-dependent wildlife – organisms (including plants) that live on or in the water for some portion of their life-cycle, or for which a significant portion of their diet is made up of those that do, or that are dependent on, at least occasionally, water-inundated habitat for survival, growth, and reproduction.

Contaminant – a contaminant is defined by the Safe Drinking Water Act (SDWA) as "any physical, chemical, biological, or radiological substance or matter in water" (U.S. Senate, 2002; 40 CFR 141.2). This broad definition of contaminant includes every substance that may be found dissolved or suspended in water—everything but the water molecule itself. Therefore, the presence of a contaminant in water does not necessarily mean that there is a human health concern.

Ecosystem Services – benefits supplied to human societies by the natural environment. These services are represented by processes by which the environment produces resources such as clean water, timber, habitat for fisheries, and pollination of native and agricultural plants.

Greenhouse Gas Mitigation – practices to reduce net concentration of greenhouse gases in the atmosphere through, for example, reduced energy use, water use, geological or biological or chemical sequestration of carbon dioxide, or by producing alternative low-emission energies and fuels.

Infrastructure:

Built Infrastructure: use of grey infrastructure, i.e., pipes and conveyances that do not make use of natural systems

Green Infrastructure: engineered systems that make use of natural waterways and other natural systems that complement traditional systems to manage land use impacts on hydrology

Natural green infrastructure: natural ecosystem components that function to capture and retain water, and remove some level of natural and anthropogenic substances from the water

Natural Infrastructure: natural environment, not engineered or manipulated by human design

Integrated Water Resource Management - a voluntary collaboration of state, interstate, local, and tribal governments and among water sectors to manage the quality and quantity of water resources sustainably within watersheds and underlying aquifers.

***Life Cycle Analysis* (LCA)** – a systematic approach to the identification of a product's total impacts on the environment, accounting for all the inputs and outputs throughout the life cycle of that product from its genesis (including design, raw material extraction, material production, production of its parts, and assembly) through its use and final disposal.

Pollutant - as defined in Clean Water Act Sec. 502(6), a pollutant means dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt, and industrial, municipal, and agricultural waste discharged into water.

Resilience – the capacity of a system to survive, adapt, and flourish in the face of turbulent change.

Return on Investment (ROI) – a performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. The ROI is calculated by dividing the benefit of an investment by the cost of the investment; the result is expressed as a percentage or ratio.

Sustainability — adaptation of Brundtland Commission definition: attaining a society and environment that can meet its current needs while preserving the ability of future generations to meet their needs.

Sustainable solution - a system intervention that offers measurable improvements in an integrated set of *sustainability indicators* (economic, social, and environmental) such that the projected outcomes are valued by stakeholders in the affected system or systems.

Water resources - a general term encompassing all water types that may include groundwater, lakes, streams, rivers, wetlands, drinking water, estuaries, coastal waters, and marine waters.

Watershed – a topographically delimited area, scale independent, which drains surface and subsurface water to a common outlet. The hydrological system within a watershed is comprised of precipitation inputs, surface water (e.g., streams, rivers, lakes), soil water, and groundwater; vegetation and land use greatly affect these processes.

Healthy Watershed – a well-functioning watershed that has a high integrity (see definition below) and is resilient to stress (see definition below).

Watershed integrity - refers to the overall biological, physical, and chemical condition of the watershed being unimpaired, interconnected, and stable.

Watershed resiliency - refers to a watershed's ability to maintain its structure and function in the presence of stress.

I. Executive Summary

Increasing demands are being placed on finite water resources to supply drinking water, water for other societal needs (including energy, agriculture, and industry), and the water necessary to support healthy aquatic ecosystems. Having adequate water of sufficient quality underpins the Nation's health, economy, security, and ecology. It is the responsibility of the US Environmental Protection Agency (EPA) to conduct research and analyses that will ensure that our Nation's water resources are safe for use and can be sustained for future generations.

To this end, EPA's Office of Research and Development (ORD) is realigning its current Drinking Water and Water Quality research programs into a single research program called Safe and Sustainable Water Resources (SSWR). The SSWR research program will strive to develop sustainable solutions to 21st century water resource problems by integrating research on social, environmental, and economic outcomes to provide lasting solutions.

SSWR will tackle two major challenges:

1. Provide the best science in a timely manner to allow faster, smarter management decisions on our existing problems; and
2. Get our science out in front of tomorrow's problems by developing and applying new approaches that better inform and guide environmentally sustainable behavior.

Increasing demands for sources of clean water, combined with changing land use practices, population growth, aging infrastructure, and climate change and variability, pose significant threats to our Nation's water resources. Failure to manage our Nation's waters in an integrated, sustainable manner will limit economic prosperity and jeopardize both human and aquatic ecosystem health. The SSWR research program seeks to develop sustainable solutions to these complex water issues and to proactively develop solutions to emerging and future problems, ensuring that clean, adequate and equitable supplies of water are available to support human well-being and resilient aquatic ecosystems, now and in the future.

A series of seminars, webinars, and science meetings have been conducted to develop the goals, science questions, objectives and outputs that form the basis for SSWR's Research Framework in support of the Agency's mission. This process involved scientists and managers from EPA's Office of Water and other programs offices, its Office of Research and Development, and stakeholders from Water Associations, Water Research Foundations, utilities, environmental groups, Tribes, industry, and State Agencies. The input from these groups was invaluable in identifying the key research elements that will result in timely, relevant, and sustainable solutions.

In a water-connected world, sustainable solutions will require a systems approach. We propose using two broad, interrelated research themes as the framework for a research program that will inform the decisions and policies needed to manage our Nation's water in a sustainable manner: 1) **Sustainable Water Resources** and 2) **Sustainable Water Infrastructure Systems**. The goals of these thematic research areas are:

> **Research Theme 1 – Sustainable Water Resources:** *Ensure safe and sustainable water quality and availability to protect human and ecosystem health by integrating social, economic and environmental research for use in protecting and restoring water resources and their designated uses (e.g., drinking water, aquatic life, recreation, industrial processes, and other designated uses) on a watershed scale.*
>
> **Research Theme 2 –Sustainable Water Infrastructure Systems:** *Ensure the sustainability of critical water resources using systems-integrated water resource management where the natural, green and built water infrastructure is capable of producing, storing and delivering safe and high-quality drinking water, and providing transport and use-specific treatment of wastewater and stormwater.*

EPA and its stakeholders have evaluated and prioritized the key science questions needed to address each research theme. This document articulates the research framework, defining the science questions, research objectives and outputs that the research projects will be designed to answer. The specific research solutions to address the framework research objectives will be set forth in the SSWR Research Action Plan (RAP). The combination of the Framework and the RAP will constitute the SSRW Research Program, which EPA will implement beginning in FY2012.

II. Introduction

a. What is the Environmental Problem?

Adequate and safe water underpins the Nation's health, economy, security, and ecology (NRC, 2004). It is the responsibility of the US EPA to conduct research and analyses that will ensure that our Nation's water resources are safe for use and can be sustained for future generations. In EPA's 40 year history, significant advances have been made in protecting America's waters through the effective control of pathogens and the control of point-source contamination. This has resulted in better protected and improved human and ecosystem health through reductions in waterborne disease organisms and chemicals.

Despite the advances made over the past 40 years, there are 21st century challenges that continue to threaten our Nation's water supplies. Our Nation's wastewater and drinking water systems are stretched to serve an increasing population, and they suffer from inadequate, outdated, and/or neglected technology, resulting in over 240,000 water-main breaks a year (Kirmeyer et al., 1994), losing trillions of gallons of water each year at a cost more than $2.5 billion. In addition, there are as many as 75,000 sanitary sewer overflows per year, which discharge billions of gallons of untreated wastewater into our water resources and contribute to more than 5,000 annual illnesses from contaminated recreational waters (US EPA, 2004). Waterborne disease continues to threaten drinking water supplies as well, with *Legionella* and viruses the more common pathogens attributed to disease incidences (Yoder et al., 2008).

The controls on point sources of pollution will no longer suffice to sustain our Nation's water quality, as nonpoint sources in watersheds are often the main pollutant contributors. An example is nutrient pollution (nitrogen and phosphorous), described as OW's water issue of the decade. The events that cascade from nutrient pollution are not simply a pervasive problem for aquatic ecosystems; they also create public health problems. Both of these will likely be exacerbated by climate variability/change, and changes in water quantity. Nutrients enter the hydrologic cycle either directly or from other media (air, land) to impact fresh surface water, groundwater, estuaries, and marine systems. Based on CWA 303d listings of impaired waters, excessive nutrient loads are responsible for poor biological condition in over 30% of the nation's stream miles (U.S. EPA, 2006) and about 20% of the nation's lakes and reservoirs (USEPA, 2009b). In addition, these loads raise public health concerns associated with toxic cyanobacterial blooms, nitrate pollution and the formation of disinfection by-products in drinking water supplies. Solving the nutrient pollution problem and ensuring sustainable, safe water resources will require expertise from the industrial (e.g., energy, agriculture), social (e.g., public health, cultural), and environmental (e.g., wastewater treatment, natural green infrastructure, recreation) sectors.

> Problems cannot be solved using the same level of awareness that created them. Albert Einstein

Another challenge not often associated with EPA but integral to EPA's responsibilities in managing water quality and meeting our designated uses is water quantity. The US Geological Survey (USGS) evaluates the withdrawal of water for different uses, as well as water that is used for consumptive purposes. The USGS (2000) estimated that more than 85% of the withdrawals in the US were from freshwater, with 80% of that coming from surface waters. The 340 billion gallon per day withdrawals of freshwater support primarily irrigation and livestock (85%), industrial and mining processes (4%), and thermal electric power (3%).

Thus, the increasing demands for sources of clean water, combined with changing land use practices, growth, aging infrastructure, increasing energy and food demands, increasing chemicals in commerce and climate variability and change, pose significant threats to our Nation's water resources. Specific effects from these pressures on drinking-water quality or aquatic ecosystem condition are more difficult to define, and current assessments are not sufficient to meet the information needs of most water resource managers. These demands and uses are creating diffuse and widespread stressors on our finite water resources, and these stressors cannot be accommodated by conventional 20th century approaches. As a result, we find that the rate of listed impaired waters exceeds the rate in which waters are restored (USEPA, 2011: *Coming Together for Clean Water*). Without new and better approaches to inform and manage the implications of our Nation's changing water condition, we will continue to slip backwards from our earlier progress towards clean water, and this will limit economic prosperity and jeopardize both human and aquatic ecosystem health.

To address these challenges, EPA is integrating its Drinking Water and Water Quality research programs to establish a Safe and Sustainable Water Resources (SSWR) Research Program. The goal of this program is to seek sustainable solutions to the 21st century problems facing our Nation's water resources. This document represents a framework to guide EPA's research actions, alone and in partnership with the broader Federal, industry, and scientific research community. The following are a Problem Statement and Vision for the program developed by scientists and managers from EPA's Office of Water and other programs offices, Office of Research and Development, and Regions, as well as stakeholders from Water Associations, Water Research Foundations, utilities, environmental groups, Tribes, industry, and State Agencies:

> ***Problem Statement****: Increasing demands for sources of clean water, combined with changing land use practices, growth, aging infrastructure, and climate change and variability, pose significant threats to our Nation's water resources. Failure to manage our Nation's waters in an integrated, sustainable manner will limit economic prosperity and jeopardize both human and aquatic ecosystem health.*

> ***Vision***: *SSWR uses an integrated, systems approach to research for the identification and development of the scientific, technological and behavioral innovations needed to ensure clean and adequate and equitable supplies of water that support human well-being and resilient aquatic ecosystems.*

The overarching and actionable goals for SSWR research stem from EPA's mandate and the needs for EPA's National Water Program to:

- protect public health and the environment;
- protect and restore water sustainably to ensure that drinking water is safe and that aquatic ecosystems sustain fish, plants, and wildlife, and to meet societal, economic and environmental needs; and
- manage water resources in a sustainable manner that integrates wastewater, stormwater, drinking water, and reclaimed water; maximizes the recovery of energy, nutrients, materials, and water; and incorporates comprehensive water planning (such as low-impact development and smart growth) and optimum combinations of built, green and natural infrastructure.

What is meant by safe and sustainable waters?

Considering the types of challenges facing our water resources, we developed the following comparison of current and desired state (Table 1) to illustrate our research goals for achieving safe and sustainable water resources.

Table 1. Aspirational desired state to achieve safe and sustainable water resources.

Current State	Desired State
Not all communities receive high quality drinking water	All US communities receive high quality drinking water
Human health and aquatic life are challenged by known and emerging contaminants in our water resources	Human health and aquatic ecosystems are proactively protected
Lack of resilience to climate change or other destructive forces	Resilient, climate ready, flexible, efficient, and adaptive systems
Failure of aging water infrastructure outstrips resources to repair, replace, and restore function and uncharacterized public and ecosystem health impacts	Synergistic use of natural ecosystem services and built infrastructure to achieve well characterized and safe public and ecosystem health
Many water bodies are impaired by excessive nutrients	Nutrient levels are in balance with natural water systems and associated safe public and ecosystem health
Watershed integrity is compromised by unsustainable land use practices	Watershed/ basin hydrology has been restored to maintain integrity
Increased urbanization and land development threaten healthy watersheds	Environmental stewardship is incorporated into our societal fabric and land use planning, resulting in an increase in healthy watersheds
Unsustainable practices threaten water resources and water treatment capacity is often insufficient for existing loads	Water availability and quality is consistently maintained in an affordable manner to support human and ecological needs
Potable water demand is increasing in populated areas	Potable water demand is safely met by local sources while maintaining ecological needs

To meet the desired state, our research will seek to

- develop water systems that decrease energy demands, recover resources, and restore the environment through affordable and public health promoting means; and

- utilize effective tools for various scales and tiers of application to undertake systems analysis of water resources by addressing health/societal needs, economic and ecosystem concerns.

b. Why is EPA investing in this research?

EPA is responsible for protecting America's water resources under the Clean Water Act and for ensuring that the Nation's drinking water is safe under the Safe Drinking Water Act. Further, it is the responsibility of EPA to conduct research and analyses to inform decisions ensuring that our Nation's water resources are safe for use and can be sustained for future generations.

Building on EPA's statutory responsibilities, EPA's FY 2011-2015 Strategic Plan (US EPA 2011b) highlights *Protecting America's Waters* as one of 5 key goals for the Agency. Under this goal, EPA will strive to

> "*protect and restore our waters to ensure that drinking water is safe, and that aquatic ecosystems sustain fish, plants, and wildlife, and economic, recreational, and subsistence activities.*"

SSWR is well positioned to support this goal and the two specific objectives of protecting human health and protecting and restoring watersheds and aquatic ecosystems. By focusing on sustainable solutions and integrating the historical drinking water and water quality research into one holistic program, EPA will be able to leverage expertise and capabilities to address not only manifestations of water problems (such as poor water quality), but also the root causes of problems related to increased urbanization, population demographics and non-point source pollution as a means towards achieving sustainable solutions. In addition, research under this program will benefit other strategic goals (e.g., *Taking Action on Climate Change and Improving Air Quality, Cleaning Up Communities and Advancing Sustainable Development, and Ensuring the Safety of Chemicals and Preventing Pollution*) through the intersection of SSWR with each of the other ORD research programs (see Figure 1).

c. How is this research program designed?

The realignment of EPA's water program along with other research programs in the Office of Research and Development (ORD) is designed to draw upon its proven internal capabilities and expertise in air, water, land, health, and ecosystem sciences -- as well as its success in supporting external researchers with additional expertise -- to better plan and conduct the transdisciplinary research needed by EPA. Where feasible, the ORD research programs will use an integrated, transdisciplinary approach to address existing high-priority research needs. Integrated Transdisciplinary Research (ITR) brings together people from different disciplines, perspectives, and experiences and develops synergistic approaches to define problems, conduct research, and deliver products and outcomes. This ITR approach is designed to ensure that the realigned research program provides innovative science and engages end users of its research from the initial research planning stages through product delivery and application, and across the full spectrum of environmental research.

Existing science and technologies can advance EPA's mission only so far. The Nation's environmental challenges and opportunities cut across, and go beyond, traditional environmental science disciplines to include human and behavioral sciences—they are *transdisciplinary*. Thus, to ensure that we are providing a sustainable future for our children, we must develop new science approaches to find solutions to our 21st century environmental challenges. To help lead the U.S. toward an environmentally sustainable future, EPA faces two major challenges:

1. Guided by sound science, EPA must make faster, smarter management decisions on our existing problems; and
2. EPA must get its science out in front of tomorrow's problems by identifying and applying approaches that better inform and guide environmentally sustainable policy and behavior.

To that end, ORD is realigning its current research areas into four programs:

- Air, Climate, and Energy (ACE)
- Safe and Sustainable Water Resources (SSWR)
- Sustainable and Healthy Communities (SHC)
- Chemical Safety for Sustainability (CSS)

The ORD research portfolio will be rounded out by the existing programs of Human Health Risk Assessment (HHRA) and Homeland Security, which will integrate findings from these new transdisciplinary programs into assessments that inform decisions.

Figure 1 represents the realigned ORD research programs that are interrelated and fit within larger EPA and stakeholder contexts. To provide scientific information and tools that advance environmental sustainability, the four new national program areas must contribute to and reinforce one another, and jointly work with decision makers both inside and outside EPA. To fully address all of the issues that fall within the SSWR research program, ORD recognizes that, where possible, issues related to water resources must be integrated with other ORD programs.

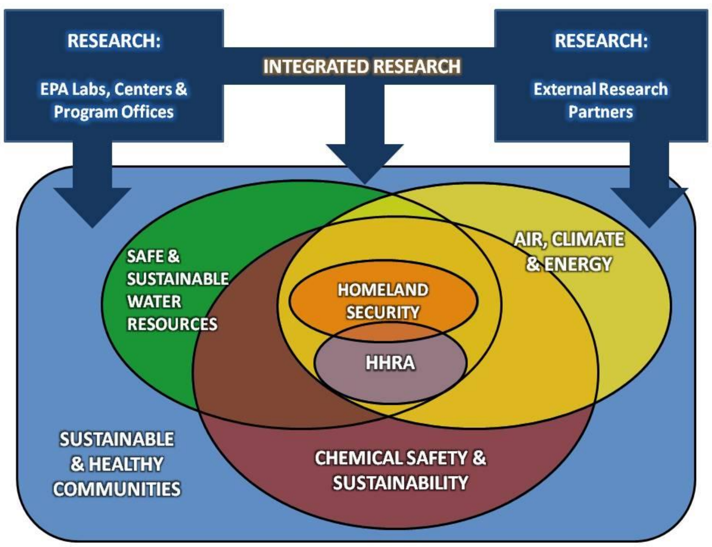

Figure 1. Integrated ORD Research Programs within EPA with Non-EPA Partner and Stakeholder Contexts

The SSWR Research Program builds on the Office of Water's (OW's) National Water Program Research Strategy (EPA, 2009a). It ensures that the necessary research, science, and technology are in place to meet the needs of the National Water Program, and it engages its federal partners and the broader water community in the identification and investigation of the most pressing current and future water research needs. SSWR will help ensure that the EPA's National Water Program successfully achieves its statutory and regulatory obligations, while also developing the research approaches needed for the emerging 21st century problems. Both the OW's Research

Strategy and SSWR's research are designed to address EPA's Strategic Goals and Sub-objectives.

SSWR's integrated research approach adds a transformative component to EPA's existing water research portfolio in striving for sustainable solutions by integrating research on social, environmental, and economic outcomes in solving water resource problems. This research will leverage the diverse capabilities of the Agency, as well as our partner's scientists, engineers, economists, social scientists, and policy makers. This integrated approach to developing scientific, technological and behavioral innovations will help ensure that waterbodies within the context of their watersheds meet their designated uses, and that clean, adequate and equitable supplies of surface, ground, and drinking water are available to support human needs and resilient aquatic ecosystems.

The rationale for realigning the Drinking Water and Water Quality research programs into one program is simple: water is all one resource. The SSWR research program will begin addressing key issues, such as comprehensive water resource management, water sustainability metrics, infrastructure life-cycle assessments, and economic, effective management of multiple stressors (e.g., nutrients, sediments, pathogens and other contaminants).

Historically, EPA's Drinking Water and Water Quality research programs conducted research in support of EPA's Office of Water and Regional Offices. The Drinking Water program provided methodologies, data, tools, models, and technologies in support of regulatory decisions, health risk assessments and other needs pertaining to the Safe Drinking Water Act's statutory requirements. Drinking Water research has been targeted at reliable delivery of safe drinking water, as well as developing approaches to improve water infrastructure, promoting high-quality water sources, and implementing regulatory decisions, along with addressing simultaneous compliance issues.

The Water Quality research program, on the other hand, was designed to support the Clean Water Act (CWA). It does so by providing scientific information and tools to help protect and restore the designated uses of water bodies that sustain human health and aquatic life. Water Quality research has focused on the development and application of water quality criteria, the implementation of effective watershed management approaches, and the application of effective treatment and management alternatives to restore and protect water bodies.

Through this realignment, ORD will be able to improve responsiveness to the Agency Program and Regional Offices and leverage partnerships with many of our outside stakeholders (e.g., federal, tribal, state and local governments, non-governmental organizations, industry, and communities affected by environmental problems), and thereby better identify the most important environmental problems facing the Nation. These interactions have occurred at the earliest planning stages for this new program and will continue through research implementation, ultimate product delivery, and subsequent technical support.

Many of the water issues addressed by this research program are not unique to SSWR and will require close coordination and collaboration with the other ORD research programs. For example, energy-related issues (such as the impacts of hydraulic fracturing and mineral extraction on drinking water resources, surface mining, and carbon capture sequestration) will be closely coordinated with the ACE program. Similarly, the impacts of climate change and variability on water resources will be addressed under SSWR and also coordinated with the ACE program. In addition to climate, nitrogen is another cross-cutting issue for all the research programs and will be managed out of SSWR, but closely integrated with each of the other programs as appropriate. The CSS and SSWR programs will work together to address the drinking water program research needs concerning the Contaminant Candidate List, and SSWR and the SHC research program will work together on research focusing on green infrastructure. In addition to coordination within ORD, research addressed by the SSWR program will be coordinated with other Federal research organizations concerned with water resources, such as the USGS, NOAA, USFWS, USDA, and DoE, and external stakeholder groups such as the Water Environment Research Foundation, Water Research Foundation, National Groundwater Research Foundation and Water Reuse Research Foundation.

III. Research Themes

Central to the development of the SSWR Program was an understanding of the problems and issues facing EPA's Office of Water and Regions, States and other stakeholders over the next decade. This section first presents six programmatic challenges that have been articulated by EPA's Office of Water and the EPA Regions. Following this are brief descriptions of six focal problems that contribute to those and other challenges. Finally, these have been integrated into two Research Themes that address the major issues and also capture the targeted research and technical assistance needed to support current and future obligations.

The six key programmatic challenges identified by EPA's Office of Water and Regions are:

1. The National Water Program and the States need to be fully implementing cost-effective nutrient pollutant reduction strategies that protect aquatic ecosystems from nutrient pollution and enable recovery/restoration of impacted waters.
   - High priority ecological focal areas include the Mississippi River Basin, Gulf of Mexico, Chesapeake Bay, and Florida.
   - Associated human health issues stem from cyanobacterial blooms in fresh, estuarine and marine waters related to nutrient pollution.

2. The National Water Program needs to be more efficient and effective in managing and/or regulating both known and emerging chemicals of concern (e.g., pharmaceutical and personal care products, or PPCP).
   - Critical needs include cumulative risk impacts, water quality criteria and methods, nonpoint source introductions, and impacts on susceptible populations.

3. The National Water Program and States need to fully implement regulatory strategies to protect human health from new and emerging pathogens.
   - Critical needs include microbial source tracking, quantitative cumulative microbial risk, criteria and methods, and pathogen level reduction.

4. The National Water Program needs to provide States, local governments, and municipalities with the tools, technology, and approaches for sustainable water infrastructure that ensures public health protection.
   - High priority areas include drinking water and wastewater infrastructure sustainability, new treatment technology, stormwater management, cost effective and energy efficient solutions, and pollutant source reduction.

5. The National Water Program and States need to fully embrace systems approaches to protect watersheds in order to better maintain, protect, and restore water resources, including groundwater, to ensure they are sustainable now and in the future
   - High priority areas include climate change impacts and adaptation, green infrastructure and water reuse, wetlands, alternative fuels impacts minimization, watershed best management practices, futures/alternatives analysis, monitoring, modeling, and analysis for water quality/quantity trends and decision making for freshwater and estuarine ecosystems.

6. The National Water Program needs to understand and address the impacts of climate change on water management programs. It is necessary to understand how to modify tools and approaches to set water quality criteria and standards.

EPA's regional offices expressed further needs addressing issues such as the development of water quality criteria, cost effective tools and technologies, and cumulative risk.

From these programmatic challenges, EPA focused on seven topics impacting water resources that build the foundation for developing an integrated transdisciplinary research approach across ORD's National Research Programs:

- nitrogen and phosphorous pollution (see Appendix A),
- agricultural uses of water (see Appendix B),
- energy/mineral extraction and injection (see Appendix C),
- protecting aquatic ecosystems and their supporting watersheds (see Appendix D),
- contaminants and industrial processes (see Appendix E),
- built infrastructure (see Appendix F), and
- climate.

The specific issues and research questions associated with each of these areas are described in the appendices to this framework. Research issues associated with climate change and variability and water resources are summarized in EPA's *National Water Program Strategy – Response to Climate Change* (US EPA, 2011) and will not be individually discussed here.

To place these topics into context, EPA's research historically has focused on manifestations of the problems in the water environment. These include issues such as physical processes, (including temperature, flow and degraded habitat), and concentrations for nutrients, pathogens, chemicals and sediments. Additional stressors related to increasing demands on our water supply and climate change and variability exacerbate water quality problems. In order to solve these problems, EPA's research needs to also address the origins of the problems associated with increased urbanization, which includes land use management and industrial processes; changing population demographics and the pressures placed on aging drinking water and wastewater infrastructure; and non-point sources of pollution that includes agricultural practices (Figure 2). Only by considering both the root causes and the manifestations of the problems can we seek the sustainable solutions.

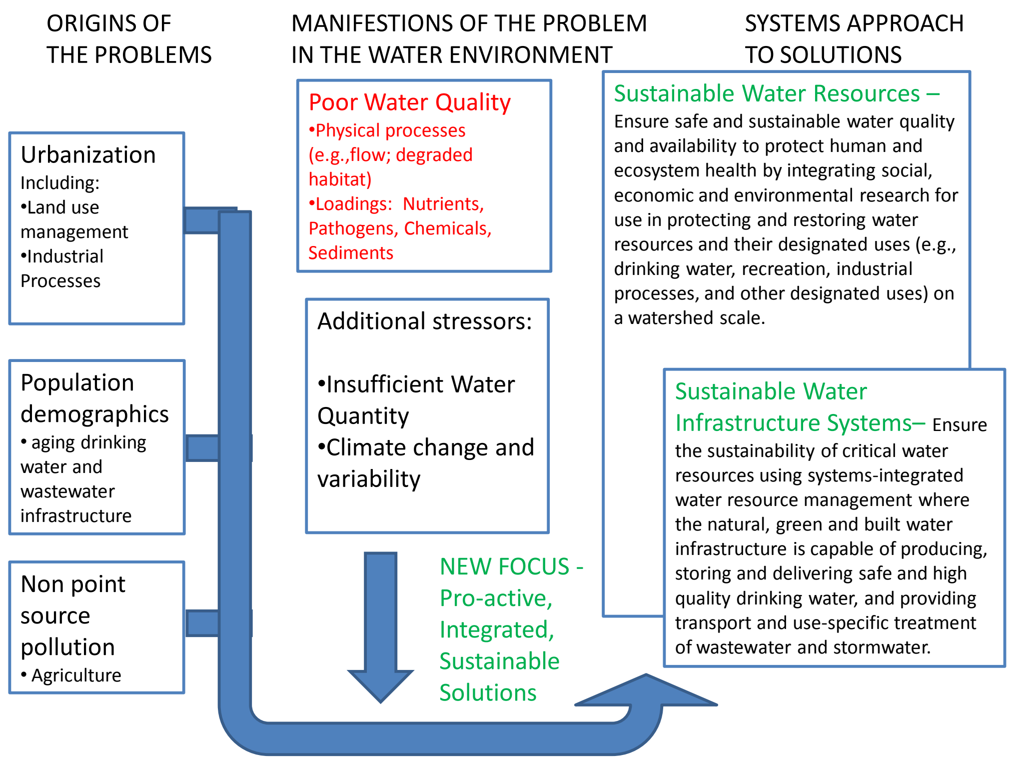

Figure 2. SSWR Research Program to address both the origins and manifestations of problems in the water environment

Conceptual Model

To investigate the sustainability of water resources, it is necessary to consider three basic attributes of human well being: the environment, the economy, and society (including public health). In essence, sustainability can be defined as the continued assurance of human health and well being, environmental resource protection, and economic prosperity—today and for generations to come. Sustainability challenges cannot be addressed in isolation, because most problems are highly interdependent and most solutions have hidden consequences. For example, the research community has recognized the close linkage between water and energy resources: we need water to generate energy and energy to convey water. A systems approach is needed to understand these complex, systemic relationships and to develop sound environmental policies that lead to sustainable development.

When addressing sustainability challenges, the development of "solutions" requires a balancing of the three aspects of sustainability. A preferred solution or management intervention will improve the environmental dimension of the system in question without degrading the economic and social dimensions, and ideally will improve all three. However, in some cases, trade-offs will be necessary. For example, initial financial investments may be required to reverse environmental degradation. In practice, there will be a need for finer resolution of the three dimensions (e.g., short-term vs. long-term, workers vs. consumers, etc.) and careful definition of the system scale and boundaries (e.g., supply chain, urban community, ecosystem). To explore sustainable solutions, the SSWR research framework utilizes an overarching conceptual model (Figure 3) that depicts the linkages and flows of value among economic, social, and environmental systems (Fiksel et al., 2011). Environmental systems provide critical ecosystem services, including water resources, which provide value to both industrial and societal systems. Human communities consume products and services supplied by the industrial economy, and they generate waste that may be recycled into industrial systems or deposited into the environment. In addition, communities benefit from the recreational and cultural amenities provided by water resources. Economic growth may be adversely impacted when markets fail to account for economic externalities such as gradual degradation of water quality; the result is a loss of opportunity for future generations, sometimes called an "inter-temporal market failure" (Binswanger and Chakraboty, 2000). Research in the fields of natural resource economics and ecological economics seeks to prevent such market failures through explicit valuation of natural resources.

As stated earlier, the goal of SSWR is to ensure that clean and adequate supplies of water are available to support human well-being and resilient aquatic ecosystems, now and in the future. Based on our overarching conceptual model, also known as the Triple Value Model, two interrelated research themes emerge: Sustainable Water Resources and Sustainable Water Infrastructure Systems. These inter-related themes and their intended outcomes provide the framework for an integrated research program that will inform decisions and policies regarding water resource management.

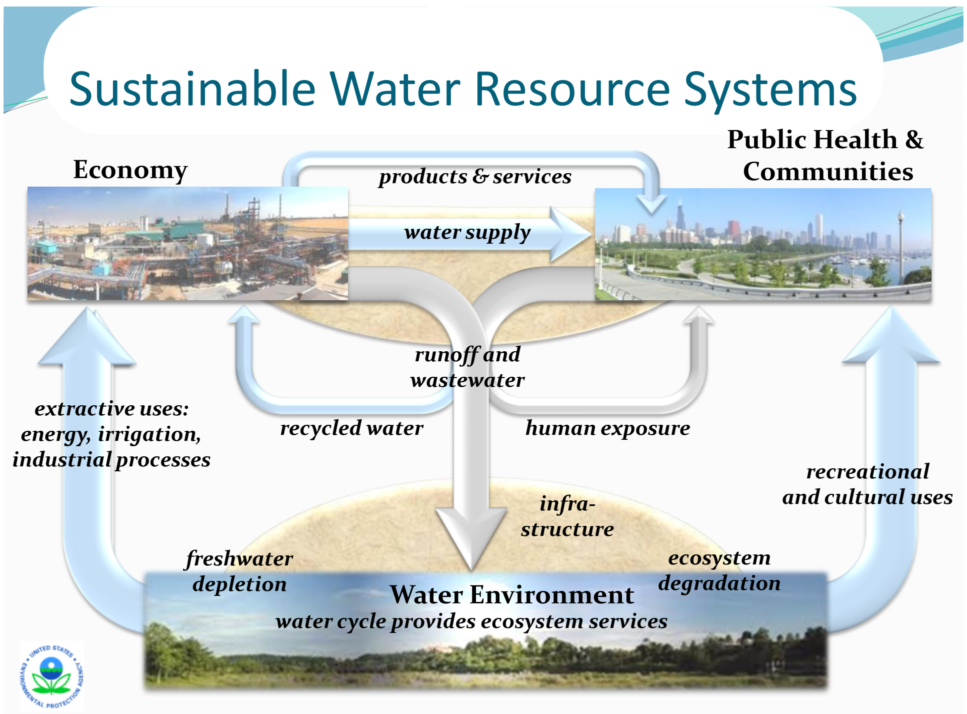

Figure 3. Conceptual Model: Organization of SSWR's goal of sustainable water resource systems

Theme 1 is a subset of this organizing construct that focuses on the flow and uses of water in the system (Figure 4). *The goal of Theme 1 is to ensure safe and sustainable water quality and availability to protect human and ecosystem health by integrating social, economic and environmental research for use in protecting and restoring water resources and their designated uses (e.g., drinking water, aquatic life, recreation, industrial processes) on a watershed scale.*

Theme 1 focuses primarily on the research to inform the protection and restoration of the quality of water in order to sustainably provide safe drinking and recreational waters for humans, to maintain healthy aquatic life and aquatic-dependent wildlife and ecosystems, and to provide adequate water for any other state-designated uses. Integral to this theme is the need to have sufficient availability of quality water to achieve sustainable societies, ecosystems and economies. Research into the protection and maintenance of the chemical, physical, and biological integrity of the nation's waters cannot be successful without some consideration of both the sufficient quantity and quality of water, particularly in the face of increasing and competing uses associated with increased housing, food and energy production, and economic development, which are compounded by climate variability and change. Developing a more complete understanding of the complex interplay of water resources and their desired uses is a key, necessary aspect of sustaining healthy people, ecosystems and economies into the future.

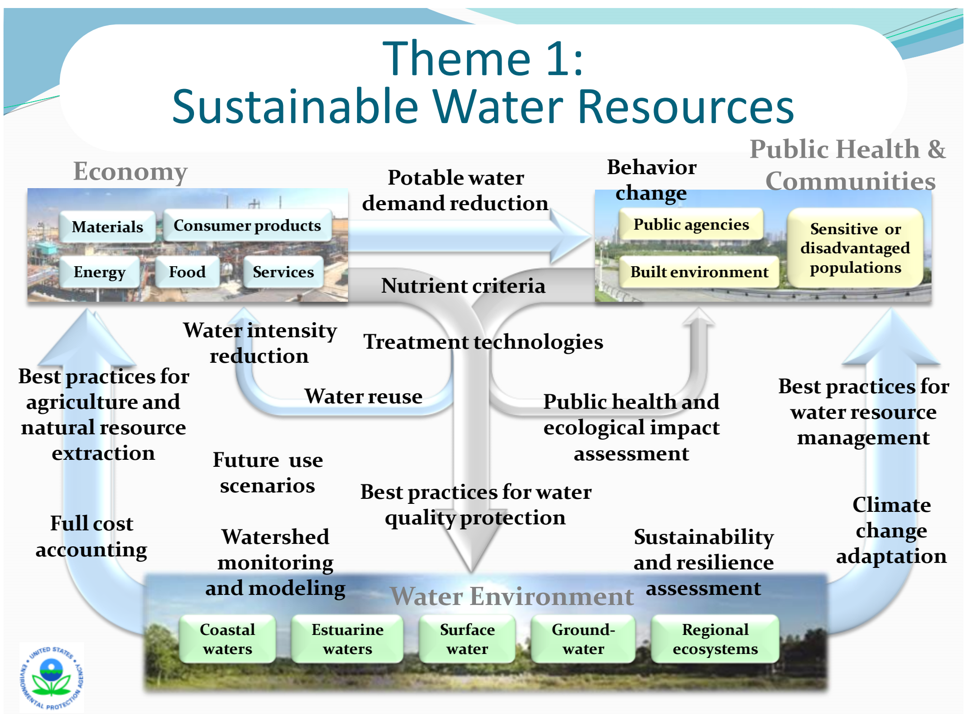

Figure 4. Conceptual Model: Theme 1- Sustainable Water Resources

Water quality is affected by naturally occurring contaminants and anthropogenic activities. Currently, the rate at which waterborne contaminants are assessed cannot keep pace with the rate at which new contaminants are introduced into the environment, potentially impacting human and ecological health. The lack of environmental and public health assessment data, analytical sensitivity, and understanding of the properties and fate and transport for new contaminants challenges our ability to evaluate and prioritize contaminant risk and, consequently, our ability to effectively regulate and manage these new contaminants. Theme 1 research focuses on: better approaches to identify, assess and prioritize contaminant risks; developing new approaches to minimize the impacts of these contaminants on water resources; and considering the impacts of climate change and variability -- as well as increased population and changing human demographics -- on water resources.

Research under Theme 1 will also provide the models, tools, and an understanding of the interconnections to develop a systems approach to protect and restore the ecological integrity of water resources within watersheds. An important component must be integrated assessments that can establish the health of watersheds and capture the dynamic spatio-temporal context of aquatic ecosystems and the role of water interconnectivity in the landscape. Assessments will require water-use data and models of stream flows and lake levels for hydrologic classes across the country. Water quality gains over the last several decades are not sustainable without a better understanding of aquatic systems and pollutant fate and effects, along with improved technology and decision analysis tools.

The science questions to be addressed under this theme include:

1. What factors are most significant and effective in ensuring the sustainability and integrity of water resources?
   This research will focus on keystone factors that promote sustainable water resources, as well as the anthropogenic activities and natural contamination that threaten the sustainable quality and quantity of water resources

2. What approaches are most effective in minimizing the environmental impacts of naturally occurring contaminants and different land use practices (e.g., energy production, mineral extraction and injection (EMEI) activities, agriculture, urbanization) leading to the sustainability of surface and subsurface water resources?
   This research will describe current and future best and cost-effective management practices that minimize impacts to water resources. Research will also include the evaluation of contaminant risk.

3. What are the impacts of climate variability and changing human demographics on water quality and availability in freshwater, estuarine, coastal aquatic ecosystems? What approaches are needed to mitigate these impacts?
   This research will provide sentinel indicators and models to identify trends or changes in water quality and availability associated with climatic and demographic variation across the US.

The relationship between these questions and the program needs is shown in Table 2. Research questions from each of the seven water topics, as well as the input received from a meeting of scientists from ORD, OW and the Regions, were used in developing the 3 integrated questions and research objectives under Theme 1.

Specific objectives, research products and how they will meet the Agency's needs are summarized in Table 3 (located on page 26, following the References). The research conducted under Theme 1 will fully implement a systems approach to protect and restore the ecological integrity of freshwater, groundwater, and coastal waters, watersheds, and wetlands, and to provide sustainable drinking water and aquatic ecosystems. Such capability is required to protect aquatic ecosystems and human health while addressing a broad range of 21st century challenges that include: hydraulic fracturing, geologic sequestration, climate change adaptation, alternative fuels impacts, and mountain-top coal mining. Solutions will require integrated approaches involving improvements to green infrastructure and water reuse, watershed best management practices, futures analysis of water use alternatives, as well as monitoring, modeling, and analysis for water quality and drinking water quality, trends in quality, trading for mitigation and improved decision making tools. In addition, this research will fully implement regulatory strategies to protect human health and aquatic ecosystems from pathogens, both known and emerging chemical contaminants, and nutrient/sediment pollutants, and to enable recovery and restoration of impacted waters.

Figure 5 illustrates the extraction of freshwater resources from the environment to support economic activities, the provision of water to communities, the discharge of wastewater and runoff into the environment, and the infrastructure systems that are needed to manage these flows. The diagram enables consideration of industrial and agricultural demands for water, management practices in the treatment of drinking water and wastewater, efficiency considerations in water utilization, and potential initiatives for protection and restoration of water resources. In addition, it supports identification of relevant ecosystem services such as recreational amenities, filtration of stormwater run-off, and flood regulation. As the research program evolves, the value and scope of both existing and new projects can be explored using this model. For example, a new research project might investigate the following hypothesis: "Investment in green infrastructure, harnessing existing ecological resources rather than building traditional water treatment systems, can reduce the adverse effects of sewer overflows while simultaneously creating valuable public amenities."

Table 2. Program Needs addressed by Theme 1 Research

Research Theme	Program Needs					
	Nutrient/Sediment Reduction Strategies	Efficient/Effective Regulation known/emerging chemicals DW Strategy	Strategies to Protect HH from Pathogens	Tools & Tech for HH Protection: Infrastructure	Systems Approach to Watershed Protection	Impact of climate change on water mgmt prgms
Theme 1 - Sustainable Water Resources						
1. What factors are most significant and effective in ensuring the sustainability and integrity of water resources?	x	x	x		x	x
What approaches are most effective in minimizing the environmental impacts of naturally occurring contaminants and different land use practices (e.g., energy production, mineral extraction and injection (EMEI) activities, agriculture, urbanization) leading to the sustainability of surface and subsurface water resources?	x	x	x	x	x	x
What are the impacts of climate variability and changing human demographics on water quality and availability in freshwater, estuarine, and coastal aquatic ecosystem? What approaches are needed to mitigate their impacts?	x	x	x	x	x	x

The focus of Theme 2 is on the use of natural and engineered water infrastructure (delivery, treatment, and reuse of water). *The goal of Theme 2 is to ensure that water of sufficient quality is available to meet human uses and needs and to maintain resilient aquatic ecosystems.* Specifically, water infrastructure management approaches are needed that optimize the use of water conservation, wastewater (and grey water) reuse, groundwater recharge by stormwater and reclaimed water, green infrastructure, and energy conservation and recovery.

The research conducted under Theme 2 focuses on topics that include design, treatment, life cycle analysis, best management practices, watershed management, systems, and integration of water resource management. The results of this research will allow States, local governments, and municipalities to protect human health and ecosystem condition, while providing them with the tools and technology for sustainable drinking water and wastewater infrastructure management, for water re-use, to address the impacts of wet-weather discharges, and to reduce the sources of pathogens and water pollutants (including invasive species).

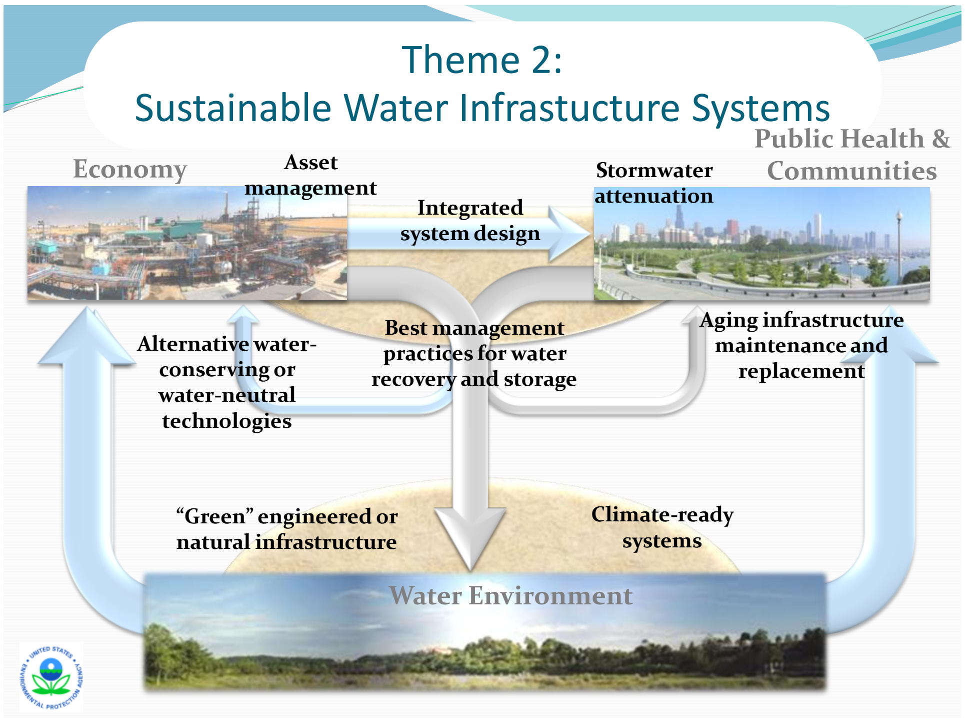

Figure 5. Conceptual Model: Theme 2-Sustainable Water Infrastructure Systems

The science questions to be addressed under this theme are:

1. What are the most effective and sustainable approaches for 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 US to take full advantage of the use of natural ecosystem services and the built environment to protect and manage water resources.

2. How do we effectively manage water infrastructure to produce safe and sustainable water resources from source to drinking water tap to receiving waters?
   This research will focus on developing the next generation of water infrastructure to promote sustainable water resources from watersheds to piped systems to receiving waters.

3. What effective systems-based approaches can be used to identify and manage causes of degraded water resources to promote protection and recovery?
   This research will synthesize research and approaches across the two themes to develop a systems approach aimed at protecting high quality and restoring degraded water resources.

Table 4 summarizes how research under Theme 2 addresses the six program needs. Specific objectives, research products and how they will meet the Agency's needs are summarized in Table 5 (located on page 36, following the References). Like Theme 1, the science questions and objectives under Theme 2 were developed from the detailed research for all seven water topics and the input received from a meeting of scientists from ORD, OW and the Regions.

In summary, having adequate water supplies of sufficient quality is critical to support human health and aquatic ecosystems, and it underpins the Nation's health, economy, security, and ecology. Increasing demands are being placed on our finite water resources, and the choices being made influence the sustainability of these precious resources. The development of management solutions to sustain water resources requires the balancing of water needs for human health, economic and societal health, and environmental health. To do this requires sustainable solutions and an appreciation that all forms of water are inter-related and connected; it is all one resource. SSWR's research embraces this concept from the overarching conceptual diagram to the interconnection of our Themes of Sustainable Water Resources and Sustainable Water Infrastructure Systems, to the interconnections of our Science Questions. This holistic approach to research on water resources will provide the science necessary to inform the societal choices about maintaining clean, adequate and equitable supplies of water to support human well-being and resilient aquatic ecosystems, now and in the future.

Table 4. Program Needs addressed by Theme 2 Research

Research Theme	Program Needs					
	Nutrient/ Sediment Reduction Strategies	Efficient/Effective Regulation known/emerging chemicals DW Strategy	Strategies to Protect HH from Pathogens	Tools & Tech for HH Protection: Infrastructure	Systems Approach to Watershed Protection	Impact of climate change on water mgmt programs
Theme 2 - Sustainable Water Infrastructure Systems						
What are the most effective and sustainable approaches that maintain and improve the natural and engineered water system in a manner that effectively protects the quantity and quality of water?	X	X	X	X	X	X
How do we effectively manage water infrastructure to produce safe and sustainable water resources from source to drinking water tap to receiving waters?	X	X	X	X	X	X
What effective systems-based approaches can be used to identify and manage causes of degraded water resources?	X	X	X	X	X	X

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Table 3: Theme 1 science questions, objectives, outputs and outcomes

Theme 1: Sustainable Water Resources: Ensure safe and sustainable water quality and availability to protect human and ecosystem health by integrating social, economic and environmental research for use in protecting and restoring water resources and their designated uses (e.g. drinking water, recreation, industrial processes, and other designated uses) on a watershed scale.

Science Questions	Research Objective	Outputs	Outcome	Comments
1. What factors are most significant and effective in ensuring the sustainability and integrity of water resources?	a. Establish metrics of water resources and watershed resiliency (including coastal and other receiving waters). Regions, OWOW, OST	1) Biological, chemical, and physical indices that are characteristic attributes of integrity necessary for sustaining water quality and quantity within a watershed including downstream users, and identifying stressors (including non-indigenous species) from headwaters to coastal systems. 2) Quantify anthropogenic impacts on water resources and watershed integrity, including methods to detect and identify pathogens in wastewater, biosolids, and animal wastes. 3) Watershed classification to improve application and effectiveness of monitoring and modeling approaches to multiple watersheds; processes at various scales.	Supports NARs; Criteria Derivation; Standards Implementation; Healthy Watersheds Initiative; Waters of the US; Mountaintop Mining; Gulf Hypoxia, future guidance on developing numeric nutrient criteria, Vessel General Permit, CAFO Rule.	Link to ACE, SHC, HS, CSS

Science Questions	Research Objective	Outputs	Outcome	Comments
	b. Develop more effective monitoring methods and models to inform integrated assessments of watershed health including downstream estuaries and other receiving waters (i.e., establish baseline and follow over time). Regions, OWOW, OWM	1) Biological, chemical, and physical indices that are characteristic attributes of integrity necessary for sustaining water quality and quantity within the watershed from headwaters (including wetlands) to downstream users and identifying stressors from headwaters to coastal systems. 2) Watershed classification to improve application and effectiveness of monitoring and modeling approaches to multiple watersheds. 3) Monitoring methods and models to integrate the indices for decision making. 4) Assessment tools for sustainability.	Supports Healthy Watersheds Initiative, Waters of the US, Mountaintop Mining, Gulf Hypoxia	Link to SHC
	c. Update existing water quality models for nutrients and other parameters, Regions, OWM, OST	1) Develop updated water quality models that accurately depict the role of hydrolysis, refractory compounds, and nutrient bioavailability.	Supports OW nutrient program implementation, permitting decisions, Standards Implementation, Gulf Hypoxia, Chesapeake Bay Executive Strategy, Healthy Watersheds Initiative, and Nutrient Guidance Oct 2011.	Link to ACE, SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
	d. Develop metrics and models to link water system parameters with land use, economic indicators, and demographics. Regions, OWOW	1) Establish effectiveness, placement, and cost of BMPs including those used to reduce natural and anthropogenic nonpoint source pollution. 2) Metrics for watershed resiliency (including coastal and other receiving waters). 3) Models for linking the metrics.	Gulf Hypoxia, Healthy Watersheds Initiative, Mountaintop Mining	Link to SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
2. What approaches are most effective in assessing and minimizing the environmental impacts of natural and anthropogenic contaminants and different land use practices (e.g., energy production, mineral extraction and injection (EMEI) activities, agriculture, urbanization) leading to the sustainability of surface and subsurface water resources and public health protection?	a. Determine the public health and ecological impacts of natural and anthropogenic contaminants and the different stressors that result from land use practices including: energy extraction, carbon sequestration, and surface mining, agricultural practices including animal waste management, industrial effluents, and urbanization on water quality. Regions, OST, OGWDW, OWM	1) Improved diagnostics and metrics to inform contaminant occurrence and demonstrating public health and ecological condition improvement relative to established baselines associated with water quality improvements. 2) Methods to evaluate emerging, legacy and multi-contaminant (including chemicals and pathogens) risk to human health (including sensitive subpopulations) and aquatic species. 3) Innovative methods to evaluate, assess, and manage emerging, legacy and groups of contaminants (chemical, biological, and radiological).	Supports CCL, UCMR, Reg-Det, Drinking water strategy, Six year review, Drinking Water Standards Development and/or Revision, criteria derivation and standards implementation (N&P, pathogens, toxics, pH, sediment), Healthy Watersheds Initiative, Large Aquatic Ecosystems (LAE) priority, Peak Flows Policy, SSO rule, SW rule, 503 regulations	Link to ACE, SHC, CSS, HHRA
	b. Determine vulnerabilities of water resources to natural and anthropogenic contaminants and to stressors associated with different land use practices. Regions, OGWDW, OST, OWM	1) Innovative approaches for determining sustainable and implementable nutrient criteria that are protective of various downstream water bodies (including ways to link response variables such as chlorophyll A back to WQS)	Supports UIC, N&P, pesticides, pathogens, sediment (chemical, biological, physical vulnerabilities) , Healthy Watersheds Initiative, Gulf Hypoxia, NPDES Guidance and Permitting	Link to SHC, ACE

Science Questions	Research Objective	Outputs	Outcome	Comments
	c. Develop methods and guidance for constructing water balances and assessing the state of water resources across watersheds that include water availability (quality and quantity) and potential land use (present and future) impacts. Regions, OST, OWOW, OWM	1) Stressor-response models of land use practices on water quality and quantity in gradient of watersheds including models of parameter specific surrogates (e.g. relationship between multiple pollutants related to stormwater and surrogate measures such as % impervious surface) and generalized gradients (e.g. the biological condition gradient, disturbance gradients).	Supports Standards Implementation, Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia, Large Aquatic Ecosystems, nutrient guidance, New Source Rule	Link to SHC, ACE
	d. Determine alternative future states for land use practices (EMEI, agriculture, industry, etc) in a watershed and the potential resultant impacts on surface and subsurface water resources (quality and quantity). Regions, OST, OWOW, OWM, OGWDW	1) Innovative approaches for determining sustainable and implementable nutrient standards that are protective of various downstream water bodies. 2) Predictive models for estimating changes in spatial and temporal extent of different land use on the quality of surface and subsurface water resources (e.g., total dissolved solids, mixed wastes, cumulative impacts or multiple stressors, and environmental justice). 3) Scenario evaluations examining trade-offs between social and economic conditions with the quality and availability of water resources leading to sustainability.	Supports UIC, N&P, pesticides, pathogens, sediment (chemical, biological, physical vulnerabilities), Healthy Watersheds Initiative, Mountaintop Mining, Hypoxia, HABs, LAE, Derivation and Standards Implementation	Link to SHC, ACE

Science Questions	Research Objective	Outputs	Outcome	Comments
	e. Determine most effective best management practices to mitigate the production of stressors by different land use practices. Regions, OWOW, OST, OWM	1) Innovative methods to evaluate, assess, and manage contaminants (chemical, biological, and radiological). 2) Innovative Best Management Practices (BMPs), and improved placement that minimizes the production of aquatic stressors from anthropogenic uses of land in watersheds.	Criteria derivation and standards implementation, Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia, LAE, Biosolids, TMDLs, CAFO rule, Stormwater rule Sept 2011, Guidance for POTW's accepting shale wastewater, VGP, 503 Regulations	Link to CSS, SHC
	f. Examine the predominant flows of value (e.g., materials, energy, investment) and impact (benefit and harm) in environmental, economic and social systems related to key land use practices (EMEI, agriculture, industry, etc) to identify opportunities to improve system sustainability. Regions, OST, OWOW, OWM, OGWDW	1) Full cost assessment for land use activities on water resources. 2) Scenario evaluations examining trade-offs between social and economic conditions with the quality and availability of water resources leading to sustainability.	UIC, Support criteria derivation and standards implementation (UAAs) Healthy Watersheds Initiative Mountaintop mining Gulf Hypoxia	Link to ACE, SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
	g. Develop full cost accounting for the impacts of different land use practices on water resources. Regions, OGWDW	1) Full cost assessment for land use activities on water resources. 2) Scenario evaluations examining trade-offs between social and economic conditions with the quality and availability of water resources leading to sustainability.	Supports UIC	Link to SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
3. What are the impacts of climate change/variability and changing human demographics on water quality and sufficient quantity in freshwater, estuarine, coastal aquatic ecosystems, and drinking water? What approaches are needed to mitigate these impacts? (link to ACE & SHC)	a. Determine impacts of climate change/variability, human demographics and behaviors, on water quality and demand. Regions, OGWDW, OST	1) Better predictive models of expected demand and availability of water with changing/variable climate and human demographics for use by Federal, State and Local decision makers. 2) Full cost accounting for population and climate change/variability impact on water resources.	Supports Six Year Review, Standards Implementation	Link to ACE, SHC
	b. Determine how changes in water quality, availability and demand impact vulnerable and sensitive human populations and aquatic dependent wildlife. Regions, OWOW, OST, OGWDW, OWM	1) Improved assessment and management strategies to protect human and ecological health in response to changes in water quality and quantity associated with a changing/variable climate.	Supports Six year review, CCL, Reg-Det, Drinking Water Standards Development and/or Revision, Standards Implementation	Link to ACE, SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
	c. Determine impacts of climate change/variability (including temporal and extreme events) on watershed integrity. Regions, OWOW, OST	1) Better predictive models of expected demand and availability of water with changing/variable climate and human demographics for use by Federal, State and Local decision makers. 2) Full cost accounting for population and climate change /variability impact on water resources.	Standards Implementation, Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia.	Link to ACE
	d. Determine impacts of climate change/variation on the functioning of built, green, and natural infrastructure on water quality and availability. Regions, OGWDW, OWM, OWOW	1) Innovative drinking water and wastewater treatment technologies and management approaches that address emerging water quality challenges, including changing/variable climate and changes in human populations. 2) Improved assessment and management strategies to protect human and ecological health in response to changes in water quality and quantity associated with a changing climate.	Supports Six year review, Drinking Water Strategy, Drinking Water Standards Development and/or Revision, Standards Implementation, Healthy Watersheds Initiative, Gulf Hypoxia	Link to ACE, SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
	e. Identify vulnerable/sensitive human populations at risk for adverse health outcomes due to climate change/variability and other impacts on water quality, water demand, and availability. Regions, OGWDW, OST, OWM	1) Improved assessment and management strategies to protect human and ecological health in response to changes in water quality and quantity associated with a changing/variable climate.	Supports CCL, Reg-Det, Drinking Water Standards, Six Year Review, WQ Standards Implementation, Biosolids, Healthy Watersheds Initiative, Gulf Hypoxia, LAE	Link to ACE
	f. Determine the most effective management practices that mitigate these impacts. Regions, OGWDW, OWM, OST, OWOW	1) Innovative drinking water and wastewater treatment technologies and management approaches that address emerging water quality challenges including emerging contaminants, changing/variable climate and human populations. 2) Better communication and education tools promoting desired public behaviors in water use and protection in the face of climate change/variation and increasing populations in watersheds.	Supports Drinking Water Strategy, Drinking Water Standards Development and/or Revision, Standards Implementation, Biosolids, Healthy Watersheds Initiative, Gulf Hypoxia	Link to SHC

Table 5: Theme 2 science questions, objectives, outputs and outcomes

Theme 2: Sustainable Infrastructure Systems – Ensure the sustainability of critical water resources using systems-integrated water resource management where the natural, green, and built water infrastructure is capable of producing, storing, and delivering safe, high quality drinking water, preserving ecological functioning, and providing transport and use-specific treatment of wastewater and stormwater.

Science Questions	Research Objective	Outputs	Outcome	Comments
1. What are the most effective and sustainable approaches which maintain and improve the natural and engineered water system in a manner that effectively protects the quantity and quality of water?	a. Develop and promote water management approaches that integrate wastewater, stormwater, drinking water, reclaimed water; maximizes energy, nutrients, materials, and water recovery; minimizes DBP precursor formation and incorporates comprehensive water planning (such as low impact development and smart growth) and optimum combinations of built, gray, and natural infrastructure. Regions, OWM, OST, OGWDW	1) Innovative BMPs for water reuse, recycling, and storage, including research on satellite systems. 2) Advanced technologies for energy efficiency and recovery at drinking water treatment and wastewater facilities (e.g., for wastewater facilities, improved economics of advanced combined heat and power processes). 3) Management options for sustainable water quality and availability for communities at the watershed scale. 4) Optimized water treatment approaches and technologies for removal of contaminants. 5) Optimized climate ready designs for water management systems.	Supports CCL, UCMR, Drinking Water Strategy, Six Year Review, Standards Implementation, Sustainable and Integrated Infrastructure, Nutrient Policy Implementation, Climate Change Mitigation	Link to SHC, ACE

Science Questions	Research Objective	Outputs	Outcome	Comments
	b. Determine the public and ecological health risks of waters impacted by different contaminants, including those from water reuse and fluid injection. Regions, OGWDW, OWOW, OST	1) Develop exposure and risk assessments of contaminants related to different water uses (e.g. water reuse options such as indirect potable reuse), fluid injection (e.g. supercritical CO_2) or industrial produced fluids.	Supports CCL, Reg-Det, Drinking Water Strategy, Six Year Review, UIC, Drinking Water Standards Development, Implementation, and/or Revision, Standards Implementation	Link to SHC, HHRA, CSS
	c. Provide long-term innovative water quality solutions to small and disadvantaged communities that take into consideration their technical, administrative, and financial capacity and maximizes economic and environmental benefits. Regions, OGWDW, OWM	1) Optimized water and wastewater treatment approaches and technologies. 2)Innovative technologies and approaches for small systems including those that combine pollution prevention, water reuse, resource recovery (including N&P, biosolids) and potential economic advantages with low capital, operations and maintenance costs. 3) Management options for sustainable water availability for communities at the watershed scale. 4) Optimized climate ready designs for water management systems.	Supports Drinking Water Strategy, Six Year Review, Drinking Water Standards Development and/or Revision, Alaskan Native Village and Mexican Border Programs, Standards Implementation, Decentralized Wastewater Program, Sustainable Infrastructure, Chesapeake Bay Executive Order Implementation, Healthy Watersheds Initiative, Climate Change Adaptation and Mitigation	Link to SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
	d. Determine critical interactions and management issues for urban and rural communities in sustaining their water supplies. Regions, OGWDW, OWM	1) Better groundwater and surface water monitoring methods and models, including the costs/benefits of water quality trading and assigning trading credits. 2) Innovative technologies and approaches for small systems including those that combine pollution prevention, water reuse, resource recovery (including N&P, biosolids) and potential economic advantages with low capital, operations and maintenance costs. 3) Management options for sustainable water quality and availability for communities at the watershed scale. 4) Develop sustainable processes for point source and nonpoint source contaminant (e.g., nutrients) removal below current limit of technology that minimizes costs, energy consumption and associated greenhouse gases and chemical consumption. 5) Optimized climate ready designs for water management systems.	Supports Drinking Water Strategy, Six Year Review, UCMR, Drinking Water Standards Development and/or Revision, New Source Rule, NPDES Program Implementation, Alaskan Native Village and Mexican Border Programs, Standards Implementation, Decentralized Wastewater Program, Sustainable Infrastructure, Chesapeake Bay Executive Order Implementation, Healthy Watersheds Initiative, Gulf Hypoxia, Climate Change Adaptation and Mitigation	Link to SHC, ACE

Science Questions	Research Objective	Outputs	Outcome	Comments
	e. Determine use of natural green infrastructure, engineered green infrastructure, and grey infrastructure for waste and drinking water treatment and management of water. Regions, OWM, OGWDW, OWOW	1) Innovative BMPs for water reuse, recycling, storage, and water treatment. 2) Natural green infrastructure is effectively characterized and integrated into water management at the watershed scale. 3) Watershed and community specific guidelines to determine optimum sustainable combinations of green and grey infrastructure, with methods to compare costs/benefits of green and grey infrastructure. 4) Develop sustainable processes for point source and nonpoint source contaminant (e.g., nutrients) removal below current limit of technology that minimizes costs, energy consumption and associated greenhouse gases and chemical consumption. 5) Optimized climate ready designs for water management systems.	Supports Drinking Water Standards Development and/or Revision, Standards Implementation, Sustainable and Integrated Infrastructure, Climate Change Mitigation, Stormwater Rule and subsequent guidance, peak flows policy and SSO rule, Chesapeake Bay Exec Order Implementation, Healthy Watersheds Initiative, Gulf Hypoxia	Link to SHC, ACE

Science Questions	Research Objective	Outputs	Outcome	Comments
	f. Develop innovative and cost effective technologies to manage and treat waste streams produced by different land use practices. Regions, OWM, OGWDW	1) Innovative BMPs for stormwater management, water reuse, recycling, and storage, and manure management. 2) Innovative technologies and approaches for small systems including those that combine pollution prevention, water treatment, water reuse, resource recovery and potential economic advantages with low capital, operations and maintenance costs. 3) Develop sustainable processes for point source and nonpoint source contaminant (e.g., nutrient) removal below current limit of technology that minimizes costs, energy consumption and associated greenhouse gases and chemical consumption. 4) Optimized water treatment approaches and technologies to treat contaminated drinking water source waters and to reduce residuals.	Drinking Water Strategy, Six Year Review, Drinking Water Standards Development and/or Revision, Standards Implementation, Sustainable Infrastructure, Biosolids, Chesapeake Bay Executive Order Implementation, Healthy Watersheds Initiative, Gulf Hypoxia, Stormwater Rule	**Link to SHC**

Science Questions	Research Objective	Outputs	Outcome	Comments
	g. Determine the new and innovative technologies and approaches that can be used to mitigate or replace the current aging infrastructure for water treatment and conveyance including drinking water, wastewater, stormwater, and water reuse. Regions, OGWDW, OWM	1) Improved water conveyance technologies and innovative approaches to replace aging water infrastructure. 2) Optimized water and wastewater treatment approaches and technologies 3) Management options for sustainable water quality and availability for communities at the watershed scale. 4) Optimized climate ready designs for water management systems.	Supports Drinking Water Strategy, Six Year Review, Drinking Water Standards Development and/or Revision, Standards and Permitting and Enforcement Implementation, Sustainable Infrastructure, Peak Flow policy and SSO Rule, Stormwater Rule	Link to SHC, ACE

Science Questions	**Research Objective**	**Outputs**	**Outcome**	**Comments**
2. How do we effectively manage water infrastructure to produce safe and sustainable water resources from source to drinking water tap to receiving waters? (link to SHC)	a. Determine human and ecological health effects of existing, improved, or novel treatment technologies, processes, and approaches. Regions, OGWDW, OWM, OWOW, OST	1) Assessments of human and ecological health consequences of new treatment technologies and processes including for biosolids and disinfection byproducts. 2) Models and metrics that predict public health impacts and benefits from changing infrastructure conditions (drinking water, wastewater treatment and conveyance systems). 3) Identification of assessment methods for sources, fate, transport, toxicity, and cumulative effects for legacy and emerging contaminants. 4) Innovative models and approaches to treat, transport, and monitor water. 5) Designation of water quality for different uses. 6) Improved monitoring and modeling tools to assess progress towards reaching sustainability goals.	Supports Drinking Water Strategy, Six Year Review, Drinking Water Standards Development and/or Revision, Criteria Derivation, Standards Implementation, Healthy Watersheds Initiative, Gulf Hypoxia, LAE, Biosolids, Peak Flows Policy, SSO Rule	Link to SHC, CSS

Science Questions	Research Objective	Outputs	Outcome	Comments
	b. Determine most cost effective intervention (centralized, decentralized and combinations) to reduce formation of, and introduction of, contaminants into all water resources (including surface, ground, and coastal waters). Regions, OGWDW, OWM, OWOW	1) N&P recycling, reuse, reduction, and removal strategies that also address biosolids. 2) Innovative models and approaches to treat, transport, and monitor water. 3) Community education and communication tools.	Supports Drinking Water Strategy, Drinking Water Standards Development and/or Revision, Healthy Watersheds Initiative, Gulf Hypoxia, Biosolids, standards and Permitting Implementation	Link to SHC, ACE
	c. Determine new land use (EMEI, agriculture, urban) systems, technologies, and practices that lead to sustainable water resources. Regions, OGWDW, OWM, OWOW	1) Innovative methods , integrated environmental models, and technologies to assess and manage groups of contaminants (both chemical and biological) 2)N&P recycling, reuse, reduction, and removal strategies including biosolids 3) Identification and assessment methods on sources, fate and transport and toxicity for emerging contaminants, as well as options for product substitution.	Supports CCL, Reg-Det, Six Year Review, Drinking Water Strategy, Drinking Water Standards Development and/or Revision, Support Standards and UAAs, Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia, LAE, Biosolids Supports Standards and permitting Implementation Sustainable Infrastructure, Biosolids Risk Management, Chesapeake Bay Executive Order Implementation	Link to SHC, ACE, CSS

Science Questions	**Research Objective**	**Outputs**	**Outcome**	**Comments**
	d. Determine optimal watershed composition and structure to prevent or decrease pollution in waterbodies. Regions, OWM, OWOW	1) N&P recycling, reuse, reduction, and removal strategies; strategies and technologies for management and treatment of municipal, industrial and construction waste streams. 2) Optimized, climate ready design of water management systems.	Supports Regional Short-term Need, Supports Nutrient Accountability Framework, Criteria derivation, Standards Implementation, Healthy Watersheds Initiative Mountaintop Mining, Gulf Hypoxia, LAE, Peak Flow policy and SSO Rule, Climate Change Adaptation and Mitigation	Link to SHC, ACE, CSS
	e. Develop innovative valuation tools to assess sustainability of water resource management options. Regions, OGWDW, OWOW, OWM	1) Innovative economic valuation tools. 2) Metrics for triple bottom line sustainability that considers feedback from stakeholders, quantifies environmental and societal impacts, and adequately addresses tradeoffs between environmental and economic costs. 3) Community education and communication tools.	Supports Six Year Review, Drinking Water Strategy, Drinking Water Standards Development and/or Revision, Healthy Watersheds Initiative, Gulf Hypoxia, Sustainable Infrastructure, EPA Sustainability Objectives	Link to SHC

Science Questions	Research Objective	Outputs	Outcome	Comments
	f. Determine Life Cycle Analysis (LCA) for complete public and ecological health impacts. Regions, OWM, OWOW	1) Designation of water quality for different uses. 2) Metrics for triple bottom line sustainability that considers feedback from stakeholders, quantifies environmental and societal impacts, and adequately addresses tradeoffs between environmental and economic costs. 3) Improved monitoring and modeling tools to assess progress towards reaching sustainability goals.	Supports Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia, Biosolids, Sustainable Infrastructure, EPA Sustainability Objectives	Link to SHC
	g. Determine assessment methodologies and technology options for drinking water and wastewater treatment plants with other sources and sinks. Regions, OGWDW, OWM, OST	1) Improved monitoring and modeling tools to assess progress towards reaching sustainability goals. 2) Identification of assessment methods for sources, fate, transport, toxicity, and cumulative effects for legacy and emerging contaminants.	Supports CCL, Reg-Det, Drinking Water Strategy, UCMR, Six Year Review, Drinking Water Standards Development and/or Revision, Standards Implementation and UAAs, Criteria Derivation, Healthy Watersheds Initiative, Gulf Hypoxia, LAE, Sustainable Infrastructure, Biosolids Risk Management, Chesapeake Bay Executive Order Implementation	Link to SHC, CSS, HHRA

Science Questions	Research Objective	Outputs	Outcome	Comments
	h. Determine effective climate ready designs for multi-use systems for drinking water, wastewater, stormwater, and water reuse. Regions, OGWDW, OWM, OST	1) Optimized, climate ready design of water management and treatment systems.	Supports Drinking Water Strategy, Drinking Water Standards Development and/or Revision, Standards Implementation, Nutrient Accountability Framework, Climate Change Adaptation and Mitigation	Link to SHC, ACE

Science Questions	Research Objective	Outputs	Outcome	Comments
3. What effective systems-based approaches can be used to identify and manage causes of degraded water resources to promote protection and recovery?	a. Develop innovative, integrated cost-effective approaches to watershed protection, intervention, and restoration for the protection of drinking water sources and to maintain the natural systems ability to assimilate waste. Regions, OGWDW, OWM, OWOW	1) Develop better approaches to identify primary causes of impairment of degraded water resources. 2) Develop improved source water protection strategies that result in decreased chemical costs for treating drinking water. 3) Innovative and cost-effective mitigation approaches are available to restore degraded water resources by watershed types. 4) Develop sustainability assessment methods for restoration and protection of water resources that include return on investment evaluations (ROI). 5) Develop better management strategies that effectively use natural systems to assimilate waste without overload.	Supports Standards Implementation, Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia, Peak Flows Policy, SSO Rule, Source Water Protection Program	Link to SHC

Science Questions	**Research Objective**	**Outputs**	**Outcome**	**Comments**
	b. Identify metrics and approaches to support decision-making and land use/property rights (e.g., when/how to apply eminent domain to protect (sustainably use) resource for public benefit). Regions	1) Develop better approaches to identify primary causes of impairment of degraded water resources. 2) Demonstrate use of metrics and decision support tools in land use decision-making.	Standards Implementation, Healthy Watersheds Initiative	Link to SHC
	c. Develop social and communication tools and practices for use in Federal, State and Local programs. Regions	1) Develop sustainability assessment methods for restoration and protection of water resources that include return on investment evaluations (ROI). 2) Communication and public education tools have successfully lead to source water protection and waste reduction within the watershed.	Supports Six Year Review, Standards Implementation, Healthy Watersheds Initiative, Mountaintop Mining, Gulf Hypoxia, LAE, Biosolids	Link to SHC

Appendix A

Nitrogen and Phosphorus Pollution

I. Problem Statement

Water quality problems resulting from N and P pollution have been recognized for decades. A National Academy of Sciences 1969 report noted "[t]he pollution problem is critical because of increased population, industrial growth, intensification of agricultural production, river-basin development, recreational use of waters, and domestic and industrial exploitation of shore properties. [Eutrophication] causes changes in plant and animal life – changes that often interfere with use of water, detract from natural beauty, and reduce property values."

Despite some early successes from landmark legislation such as the Clean Water Act, which provided regulatory authorities statutory power to address point-source pollution nearly 40 years ago, N and P pollution remains a critical environmental concern today. For example, progress made over the last few decades in managing municipal wastewater discharges is being overcome by wastewater plant ageing, infrastructure degradation, combined sewer overflows, and undersized wastewater plants, where improvements have failed to match local population increases. Further, combustion of fossil fuels, land development, creation and use of synthetic fertilizers, industrial and agricultural infrastructure, reactive nitrogen fixation by legumes, and increased erosion from surface soils are among an even longer list of factors contributing to elevated non-point source N and P loading to rivers, streams, lakes, reservoirs, and estuaries and coastal marine waters, as well as groundwater resources.

Excess loading of various forms of N and P, plus pathogen contamination, are among the most prevalent causes of water quality impairment in the United States: water quality impairments totaled 6,950 surface waters for nutrients, 6,511 surface waters for organic enrichment/oxygen depletion and 10,956 surface waters for pathogens per the 2010 CWA Sec. 303(d) List. Excess N and P in waterbodies comes from many point and nonpoint sources, which can be grouped into six general categories: 1) urban and suburban stormwater runoff associated with residential and commercial land development, 2) municipal and industrial waste water discharges, 3) row crop agriculture and fertilizer use, 4) livestock production and manure management practices, 5) atmospheric deposition resulting from nitrogen oxide emissions from fossil fuel combustion and ammonia emissions from row crop agriculture and livestock production, and 6) legacy nutrient pollution, often due to contamination of groundwater. Furthermore, land use and land cover in watersheds across much of the nation has been altered such that a higher fraction of the N and P applied to the landscape will reach surface and groundwater resources and impact aquatic life uses, human health and economic prosperity.

Hydrologic modifications also affect water quality by changing the magnitude and timing of pollutant transport across the landscape. Similar changes are expected in association with climate change, which may increase or decrease flows, and severe weather events, which cause large pulsed inputs of water and pollutant loads. These may overwhelm wastewater systems and hydrologic control infrastructure, increasing inputs of nutrients, sediments, and waterborne pathogens to surface waters. Although storm events have always occurred, their interaction with anthropogenic pollutant sources and modification of the landscape threaten human health, aquatic life and ecological services provided by ecosystems.

N and P pollution creates significant and ever-growing water quality concerns across the nation. Often the most immediate effects are economic, since contaminated water sources can no longer be used and must be replaced with new water sources that are safe to use. This can be especially challenging where limited water resources are already tightly managed and heavily utilized. Human health impacts and threats to aquatic life are shown to occur as both a direct and indirect consequence of nutrient pollution.

In terms of public health, direct effects from N and P pollution result from contamination of surface and groundwater with nitrates. Serious adverse health effects are associated with nitrate-contaminated water consumed by susceptible individuals such as infants, pregnant women, and those with certain chronic diseases (e.g., pulmonary disease). Populations exposed for years to contaminated water are at higher risk for developing neoplasias, such as cancers of the digestive tract and bladder. Indirect effects are generally caused initially by the primary ecological response to increased nutrients, which is increased production of organic matter. High organic matter in water sources can lead to increased production of disinfection byproducts when disinfectants such as chlorine or bromine are used to treat drinking water. Disinfection byproducts, in turn, have been linked to increased rates of certain cancers and increased reproductive health risks.

Human health may also be affected by algal blooms, some of which produce potent toxins. Human toxin exposure may occur by consuming contaminated drinking water, via recreational activities on or near contaminated waterways, or even from incidental exposure to aerosols resulting from algal blooms (e.g., red tides). Human and animal exposures to algal toxins are associated with adverse liver, kidney, and nervous system effects; cell death; liver cancer; reproductive impairment; and, in cases of acute exposure to high doses, sudden death. Non-toxic algae present their own problems, such as taste and odor problems, requiring additional water treatment costs, and the value of waters as recreational resources may decrease as a result of excessive algal growth.

The same primary ecological response to N and P pollution (i.e., excess organic matter production) that threatens human health also poses an equal or even greater threat to aquatic life and the ecological services provided to humans by aquatic ecosystems. Nutrient pollution degrades waterbodies via a variety of mechanisms. Nutrient pollution may shift the species composition of algal communities, leading to blooms of algal species that are unpalatable to algal grazers, thereby degrading a key pathway contributing to productivity of food webs. Healthy grazing food chains may be replaced with increased metabolism by bacterial decomposition, accompanied by reduced productivity of desirable fish and shellfish. Responses to N and P pollution may also include low dissolved oxygen (resulting from bacterial metabolism) and loss of vegetated habitats, both of which further reduce the ecological integrity of ecosystems. Low dissolved oxygen or "hypoxia" occurs widely as a secondary response to nutrient pollution. Hypoxia causes substantial ecological effects, including fish kills, avian botulism outbreaks and effects that may persist after hypoxia has abated, due to persistent changes in the composition of aquatic ecosystems.

Existing regulatory and non-regulatory efforts to control N and P pollution have not, in most cases, kept pace with the growth of N and P sources. Absent a change in approach, N and P pollution will likely continue to increase in the future. Moreover, climate change has the potential to exacerbate impacts due to N and P pollution by changing the magnitude, timing, and variability of rainfall and by increasing temperature. Climate change could contribute to further increases in N and P loading to the nation's waters, particularly where rainfall is expected to increase, and may also change the response to nutrients. To optimize sustainable production of ecosystem services, a better understanding of multiple interacting stressors is essential. Sustainable management will require new, more effective and more efficient approaches to manage and regulate human use of land and water resources.

II. Solutions

Innovative and integrated scientific, management and regulatory approaches are needed to provide sustainable solutions to reduce N and P pollution, while providing the greatest opportunity to enjoy long-term economic prosperity, ecosystem health and human well being. Accelerating efforts to collect and assemble adequate monitoring data, conducting research to improve mechanistic understanding of the impacts of N and P pollution, and developing modeling tools to support sustainable solutions to nutrient pollution will provide a stronger technical foundation for sustainable water resource management. However, scientific and technological advances alone will not be sufficient. Sustainable and innovative solutions will require better utilization of existing regulatory tools for point and non-point source control, as well as new approaches that leverage regulatory controls along with non-regulatory, incentive-based tools. A national framework must be developed that fosters environmental accountability for all polluters and regulators, while harnessing the creativity of communities and other stakeholders to identify beneficial and cost-effective solutions. Such a framework should incorporate a comprehensive understanding of sources, fate and effects of nutrients across multiple media (air, freshwaters, groundwater, coastal waters), as well as multiple metrics quantifying future costs and benefits (e.g., ecological services, economic considerations) associated with different economic and environmental policy options.

Sustainable solutions to these problems will require an improved focus on several key challenges. These include: i) reducing release of N and P, as well as associated pollutants such as pathogens and sediments, into the environment; ii) maximizing the benefit obtained per unit of new N and P used (i.e., maximizing efficiency and/or recycling); iii) protecting and restoring the ability of watersheds and receiving waters to process N and P inputs without loss of proper ecosystem function and associated services; and iv) identifying communities and associated aquatic systems where the greatest increase in ecological services may be obtained at the least cost and, conversely, those sensitive and most valuable ecosystems where a large loss of services either has occurred or will likely occur without an effective strategy to protect the resource.

Research to address N and P pollution within SSWR will address two broad, desired outcomes. The first focuses on identifying numeric nutrient criteria and science-based interpretations of narrative nutrient standards for the nation's waters. Numeric criteria and narrative interpretations establish quantitative targets for protection and restoration of designated uses in aquatic systems and provide the basis for nutrient management decisions across the landscape. But numeric criteria development and narrative standards interpretation provide only a goal, not a path to achieving a sustainable solution to nutrient pollution. Thus, the second desired outcome within SSWR addresses watershed-level components of the nutrient problem, which involve improving our ability to understand and predict how alternative scenarios for future watershed management and development will impact N and P loading, fate and transport of nutrients within watersheds and downstream receiving waters, and the physical, chemical and biological integrity of aquatic ecosystems. This understanding, ideally captured within an array of practical decision-support tools, will help achieve the desired outcome, which is reducing or eliminating human and aquatic life impacts resulting from nutrient pollution (e.g., as indicated by attainment of criteria and narrative standards), while securing cultural and economic benefits of water resources for the present and future generations.

- **Timely Science to Support Development and Implementation of Numeric Nitrogen and Phosphorus Criteria:** Numeric N and P criteria and science-based interpretations of narrative standards are limits on N and P and their related response variables that, if met, provide an expectation that designated uses established by states and tribes (e.g., fishable, swimmable, recreation, drinking water source water, etc.) will be protected. Numeric criteria and interpreted narrative standards are important because they provide an effective basis for implementation of the CWA. For example, criteria guide NPDES water quality-based permit limits for point source dischargers, as well development of Total Maximum Daily Loads (TMDLs) for impaired waters. Numeric criteria and interpreted narrative standards significantly improve prospects for identifying and managing impairments in downstream waters resulting from sources upstream, which is predominantly nonpoint source pollution in the case of N and P. Since development of numeric criteria or interpretation of a narrative standard is a key first step in implementing CWA protections, criteria development and narrative interpretation are receiving a high priority in many states and at EPA. Yet, the task is enormously complex and technically challenging. Rapid progress is needed to provide timely scientific guidance and tools for new and ongoing efforts, while sustained progress on a longer term basis will remain important because criteria development and narrative interpretation, evaluation, and revision will likely continue indefinitely, incorporating new evidence and information as envisioned under the CWA.

Because of the scope and complexity of the problem, new approaches are needed that can be applied across a range of spatial and temporal scales to inform development and implementation of numeric criteria and interpreted narrative standards. Criteria and interpreted narrative standards are needed that can function well as part of ecosystem-based, sustainable management approaches. For example, rather than specific criteria values, some criteria or interpreted narrative standards could be developed so as to provide a scientific foundation for N and P trading as part of a nutrient management strategy. Approaches for nutrient criteria development and interpreted narrative standards developed under SSWR should consider all relevant literature on N and P pollution, nutrient sources and sinks, and new technological developments. For example, ambitious application of new or rapidly evolving technologies such as satellite remote sensing, automated environmental monitoring, geographic information systems, and simulation modeling could help address some of the challenges associated with numeric criteria development, interpreted narrative standards, and related watershed management. Nutrient effects must be understood in the context of exposure and effects expressed across a range of spatial and temporal scales and modulated by a range of local site-specific factors. Ecological change due to nutrient pollution can be subtle and gradual over the short term, with dramatic and fundamental ecological changes becoming apparent over time, resulting in significant losses of ecological function. Characterizing and predicting likely trajectories of long-term ecological change (and alternatives associated with policy options) is a key challenge that could be embraced under SSWR.

- **Science to Support Integrated Watershed Management:** The goal of scientific research to inform sustainable solutions should be to optimize a range of best management practices that provides integrated watershed management systems to deal with issues arising from agriculture, forestry, animal husbandry, urban stormwater and wastewater through protecting the natural environment with its abilities to trap, recycle and remove nutrients. An important output of this research will include sustainable solutions that clearly reflect the capacity of specific classes or groups of watersheds to integrate the targeted management practices, which will increase the potential for a positive outcome. A key element of innovative and sustainable solutions is identifying nutrient reduction goals (or limits) and developing management practices that result in the most effective and most beneficial health and environmental outcomes for the lowest possible cost. In this regard, sustainable solutions will encompass the most efficient and cost-effective actions to reduce pollution with new approaches that consider the environmental, economic and social sector ramifications of nutrient use, water use, land use, wastewater management, manure management, energy planning and climate change.

III. Research Needs

To achieve the desired outcomes for the research program, a range of research needs are evident. Research elements broadly fall within the themes of Effective Decision Support and Improving Assessments in order to support Safe and Sustainable Water Resources. Principal research elements, objectives, representative key questions and outputs are described below.

Effective Decision Support for Sustainable Waters

1) Development of Numeric Nutrient Criteria and Science-Based Interpretation of Narrative Standards for Inland Waters and Downstream Estuarine and Coastal Waters: Numeric water quality criteria and interpreted narrative standards are the cornerstone of effective water quality management. Numeric nutrient criteria and interpreted narrative standards establish the targets for protection of waters, as well as for restoration of waters already listed as impaired by nutrients or nutrient-related causes. Numeric nutrient water quality standards and interpreted narrative standards will drive water quality assessments and watershed management, support improved development of nutrient TMDLs, help create state- and community-developed environmental baselines that fosters more effective environmental management, measures of progress, and broader partnerships based on nutrient trading, BMPs, land stewardship, voluntary collaboration, and urban storm water runoff control strategies.

Nutrient criteria are defined herein, consistent with OW's National Nutrient Program, to include both causal (N and P) and some suite of response (chlorophyll, water clarity, dissolved oxygen, etc) variables for all waters of the U.S. The approaches to numeric nutrient criteria development are generally well described in numerous OW technical guidance documents and scientific publications. However, improvements, demonstrations and applications of these approaches across different scales (e.g., site-specific, state-wide, regional) and waterbody types will inform the decision process and facilitate adoption and implementation of numeric criteria. Many states have narrative nutrient standards rather than numeric. Science-based interpretation of narrative nutrient standards is critical to accomplishing the same goals listed above for numeric criteria, and research is needed to make the narrative standards viable.

Objective: Advance the approaches and decision tools needed to establish and implement numeric nutrient criteria and interpreted narrative standards protective of human and aquatic life uses for surface waters, downstream receiving waters and groundwater that foster sustainable solutions to nutrient management across the nation.

Questions

- What classification approaches are useful in developing numeric nutrient criteria and interpreted narrative standards for different waterbody types and different spatial scales?
- What are the exposure-effect or stressor-response relationships (or other approaches) to protect different uses and waterbody type?
- What models and information are needed to establish upstream thresholds (criteria and interpreted narrative standards) to protect downstream uses?
- What technological improvements (e.g., optimizing best management practices) are available or needed for nutrient management?
- What are the socioeconomic cost and benefits for successful nutrient management?
- What data and information are needed to establish a foundation for nutrient trading as part of a nutrient management strategy?
- What data and information is needed to better utilize existing regulatory tools for point and non-point source control of N and P, as well as to develop innovative new

approaches that leverage regulatory controls along with non-regulatory, incentive-based tools?

Outputs and Timelines

- Short-Term (5 yr): Provide technically-sound data products and models that effectively quantify watershed nutrient loads and biological response endpoints in coupled watershed-receiving water ecosystems at local, state or regional scales.
- Short-term (5 yr): Provide technically-sound data products and models that quantify watershed N and P inputs, instream N and P losses and demonstrate approaches to establish stream nutrient criteria that protect downstream waters.
- Long-term (10-20 yr): Provide a framework that links nutrient criteria and interpreted narrative standards to nutrient trading as a part of a comprehensive and sustainable nutrient management strategy.

2) Development of Water Quality Simulation Modeling for Managing N and P Pollution:
Water quality simulation models (WQMs) are commonly used for both research and management questions involving N and P pollution and other water quality problems in all types of water bodies. Improving WQMs is a key element of ensuring safe and sustainable water resources in general and management of N and P pollution, specifically. In the past 30 years, multimedia WQM frameworks have been developed that link simulations of airsheds, watersheds and coastal receiving waters. Over the past decade, application of WQMs has been greatly facilitated by advancements in information technology and computational resources, resulting in enhanced process descriptions, improved model skill and expanded application. It is now reasonable to envision more capable large-scale and linked models with enhanced and/or more complete systems descriptions that can support much broader, integrated applications. Such large-scale and linked models would collectively address sustainable management of N and P at a regional scale through simulation of atmospheric, hydrologic and biogeochemical processes and the alteration of these processes due to land-use and climate change. However, simply expanding the scope of WQMs will not be adequate to address important needs. Other important objectives include: promoting critical evaluation and improvement of model representation of environmental processes without sacrificing computational efficiency; extending the system-

wide scope of models by improving the ability of models to simulate endpoints of concern (e.g., population- and community-level biological responses to N and P that are reflective of designated uses); addressing model uncertainty; expanding utilization of WQMs among a broader trans-disciplinary cross-section of scientists and environmental professionals, social scientists and economists which will ultimately improve communication of models and model results to decision makers and the public; identifying appropriate models for the scale and focus of specific management questions. These WQMs should be linked to economic and decision support models in order to illustrate the costs and benefits for human health and ecosystems.

Decisions on the appropriate mix of built and green infrastructure, the optimization of water treatment technologies, and the quantity and quality of water required for human society and natural ecosystems must be made in the face of accelerating change engendered by complex interactions among climate variability and change, population growth and land use alterations. The development of the suite of modeling tools needed to adequately integrate multiple sources of ecosystem change while providing forecasts with acceptable uncertainties to support management decisions is a critical research need.

Objective: Advance regional and watershed-scale simulations of linked atmospheric, hydrologic and biogeochemical processes and the alteration of these processes by BMPs, land use, and climate change to support management of anthropogenic N and P to meet water quality goals or numeric criteria and interpreted narrative standards.

Questions

- What are the physical, chemical, and biological processes for which improved understanding and quantification would most improve water quality models (WQMs)?
- What conceptual or technological advances will improve the science linking airshed and watershed fate and transport models of N and P to aquatic biological endpoints and at what spatial and temporal scales will these models be appropriate?
- What advances in large-scale modeling are needed to address those effects of climate change on water quality relevant to improving nutrient management? What are the

impacts of climate change, human demographics, behaviors and new technologies on water quality?

- What advances in large-scale modeling are needed to incorporate systems thinking to model N and P from an Earth Systems perspective to address water quality sustainability?
- What is needed to incorporate process-based modeling outputs into water quality decision support frameworks?
- What models and other tools will enable more rapid, effective and economical approaches to reducing and phosphorus in our water resources at a watershed, state-wide or regional scale to better protect and sustain human health and aquatic ecosystems?
- How well can available or developing models predict the aquatic ecosystem response to changing levels of watershed N and P loadings resulting from best management practices, climate change, and land cover change?

Outputs and Timelines

- Short-Term (5 yr): Provide a linked modeling system(s) of atmospheric, hydrologic and watershed biogeochemistry capable of addressing land-use and climate change. System will connect to dynamically-downscaled meteorology based on climate model simulations capable of modeling conterminous U.S.
- Long-Term (10-20 yr): Provide a modeling system(s) that links simulation of N and P watershed biogeochemical processing to aquatic biological endpoints at the population and community levels.
- Long-Term (10-20 yr): Provide a coupled modeling system(s) incorporating Earth Systems thinking to simulate aquatic biological endpoints at the population and community levels to address analyses of integrated and sustainable management.
- Long-Term (10-20 yr): Provide a process-based coupled modeling system(s) incorporated into decision support frameworks for integrated management and transdisciplinary analyses.

3) Ecological Processes Affecting Water Quality: Water quality simulation models (WQMs) have become critical decision support tools for assessment and management of N and P pollution, in large part because these models are so well-suited to addressing key policy-related questions. For example, WQMs can directly address how increasing or decreasing a point source of N and P will impact key water quality indicators in the receiving water body, such as chlorophyll-a concentrations. Similarly, watershed models can predict nutrient concentrations and loading in streams and potential changes in response to land use changes. Given the importance of WQMs as decision support tools, it is important to decrease uncertainty by continually testing and improving model performance as well as the mechanistic ecological processes that underlying them. In addition, future applications of WQMs will likely require that they can address more complex questions. For example, to simulate the effect of implementing BMPs such as riparian buffers, watershed models may require more spatially-explicit treatment of the landscape. BMP type and placement will need to be optimized simultaneously for multiple endpoints. In addition, information will be needed for newer types of stormwater BMPs being promoted under proposed post-construction stormwater guidelines to increase onsite infiltration to determine their effectiveness in removing dissolved inorganic nitrogen. Adequate studies of ecosystem processes are needed to inform model development. Similarly, improved performance of estuary models may require a better understanding of which processes are important for addressing which questions and how to best represent those target processes in the WQM. Process data such as rates of primary production and plankton metabolism may be useful to better validate models. Depending on the management questions, it may be necessary to improve simulation of water quality effects associated with sediment processes or seagrass or marsh processes. Long term success will depend on integrating monitoring, process-oriented research, and development of decision support tools such as WQMs.

> ***Objective:*** Advance current understanding of terrestrial and aquatic ecological processes and rates of these processes, including controls on the rates of these processes, to improve simulation of the effects of N and P pollution and management on aquatic ecosystems.

Questions

- What are effective approaches for evaluating WQM sensitivity and uncertainty and how can this information be used to prioritize research designed to improve model skill?
- What new data and information related to ecological processes would be most useful for improving WQMs used in regulatory and other nutrient management decision making. How does this differ by region, basin or state?
- What will be the net effect of changes in the number, location and type of nutrient management BMPs?

Outputs and Timelines

- Short-term (5 yr): Identify ways to evaluate model skill, uncertainty, and sensitivity to different model inputs and parameters. Apply these approaches in selected applications.
- Short-term (5 yr): Establish a research planning process incorporating a cycle of identifying information needed to improve models, and utilizing that the information in models in order to demonstrate improvements in model skill.
- Long-term (10-20 yr): Develop community modeling support products to improve the quality and accessibility of modeling as a decision support tool.
- Long-term (10-20 yr): Improve the scope of WQMs to support environmental planning and decision making more broader. Ecosystem simulations should be able to address a range of biological community responses and should consider interactions with habitat quality and a range of environmental stressors.

4) Develop Optimized Decision Processes for Integrated Watershed Management: The implementation of Integrated Watershed Management requires being able to select and incorporate an optimized selection of best management practices (BMPs) to achieve the management objectives for any given watershed. It is important that selected BMPs work together in an integrated systems approach that spans the range of activities in a watershed (e.g. agriculture, forestry, animal husbandry, urban stormwater management, wastewater removal, mineral extraction). This work should develop approaches that account for the social, environmental and economic costs and benefits associated with practices in order to determine the most efficient and cost-effective means by which to reduce the adverse impacts of N and P loads. Interdisciplinary human dimensions and policy research should examine successful existing programs in the U.S. and elsewhere to determine the factors and processes that contribute to successful N and P reduction. Especially of interest will be the identification of successful N and P reduction programs that are responsive to the pressures on water quality and aquatic ecosystems. Decision processes should also integrate adaptive management practices. As more studies and information become available concerning N and P management, a means of assessing feedbacks associated with updated management practices (e.g, monitoring and efficient inventory /tracking of BMPs) will be needed.

Objective: Develop optimized decision systems to support application of integrated and adaptive watershed management systems at a scale responsive to the needs of communities, regulators and managers.

Questions

- What existing programs have successfully reduced N and P pollution and its impacts? Is it possible to identify scientific, policy, and socioeconomic structural characteristics that have contributed to their success?
- What is the state of the science linking watershed fate and transport models of N and P to aquatic biological endpoints at the population and community levels, and at what spatial and temporal scales are available models appropriate? What are the needs in this area of modeling research?
- What watershed or multimedia modeling tools can best be applied to assess hydrologic, nutrient sediment and pathogen responses to BMPs?
- What are the innovative approaches to verify the efficacy of new treatment technologies or pollution prevention approaches which will protect human and aquatic ecosystems from diffuse sources of aquatic pollution?
- What tools, models, policies or other innovative approaches are needed to determine the effect of best management practices on nutrient yields to surface and groundwater?
- What tools can be applied to quantify and track the effectiveness of nutrient BMPs and regulatory actions on aquatic systems?

- What methods are needed to rapidly assess a watershed's capacity (physical, biogeochemical, anthropogenic) to integrate best management practices?
- What are the best modeling approaches to understand the influence of physical, chemical, and biological processes in estuaries that influence the response to management practices implemented in the upland drainage areas?
- What decision support tools are needed to evaluate the effectiveness of watershed management and nutrient reduction strategies?

Outputs and Timelines

- Short-term (5 yr): Provide a conceptual framework including modeling methods that integrate and assess the effects of N and P management practices on nutrient loading, ecosystem health, and social and economic outcomes.
- Long-term (10-20 yr): Provide modeling systems that integrates and assesses the effects of N and P management practices on nutrient loading, ecosystem health, and social and economic outcomes.

<u>Improving Assessments for Sustainable Water</u>

1) Refine and Improve Assessment of Water Resources and Biological Response Indicators: In spite of considerable research efforts, a key issue for protecting waterbodies from N and P pollution remains the effective demonstration of stressor-response measures for biological response indicators. Currently chlorophyll *a* is the biological response indicator that is most often monitored in waterbodies to assess N and P effects. Biological assessment endpoints or response indicators should relate to the valued ecosystem characteristics to be protected and should provide a conceptual linkage to the designated uses and water quality goals established by the States. Monitoring of biological response indicators should be able to track improvements in watershed condition following restoration or implementation of nutrient reduction goals. To develop additional nutrient-related biological response indicators that meet these goals, however, improvements are needed in the approaches used to quantify stressor-response relationships and to identify the appropriate targets for biological endpoints and the designated uses they protect.

Objective: Advance the approaches and indicators needed to quantify biological responses to N and P pollution and link biological endpoints to ecosystem condition, water quality, human health, and designated uses.

Questions

- What data and information are needed to improve assessments of the effects nutrient pollution on biological response indicators, aquatic populations and communities and human health?
- What data and information are necessary to improve linkages between biological assessment endpoints or response indicators, the valued ecosystem attributes to be protected, the designated uses of different waterbody types?
- What innovative technologies (e.g., omics) can improve identification of biological responses to nutrient pollution and inform assessment approaches?

Outputs and Timelines

- Short-term (5 yr): Provide biological indicators and models that demonstrate quantitative responses to N and P loads and concentrations at multiple temporal and spatial scales.
- Long-term (10-20 yr): Provide models and tools that enable States to track progress and improvements in water quality, biological condition, and attainment of designated uses following watershed restoration or implementation of nutrient-reduction programs.

2) Improve Monitoring Approaches for Compliance and Watershed Condition: Improved methods for efficiently and effectively monitoring biological communities in the context of biological responses to N and P are also important, addressing the need to link N and P with attainment of aquatic life uses. Regardless of the data that are collected, improvements in management and sharing of data will be essential to facilitate implementation of research, modeling and management solutions for N and P. Monitoring is also imperative for adaptive management, as new science and information is gained, changes in management must be evaluated to assess the consequent outcomes. Central databases, web-based tools, and decision support systems that provide spatial and temporal information on N and P pollution sources and sinks, along with uncertainties, should be accessible to a wide range of users. In this regard, more effective use of computing technology, systems thinking and life cycle assessments will also greatly enhance efforts to evaluate management and policy alternatives for the most effective and efficient approaches to N & P management.

Objective: Advance monitoring tools and technologies to assess the effects of N and P on aquatic resources and to more effectively evaluate the impacts of watershed management policies, including implementation of N and P water quality standards and nutrient reduction strategies.

Questions

- What advances will improve the development and management of national data sets of monitoring data relevant to nutrient management?
- What data and information are needed for cross ecosystem and watershed comparisons?
- What approaches are needed for monitoring compliance to water quality standards that can address variability associated with climate change?
- What monitoring information is most critical for assessing short and long-term changes in watershed condition in response to management (including adaptive management practices)?
- What are the best and most efficient approaches for classifying watersheds in order to transfer the knowledge gained on linkages between N and P sources, fate, and watershed conditions to unassessed watersheds?

Outputs and Timelines

- Short-term (5 yr): Provide comprehensive and adaptive monitoring tools to assess biological responses to N and P pollution.
- Short-term (5 yr): Provide a web-based system that links to existing databases of N and P sources, effects, and outcomes in a variety of multi-scale watershed systems.
- Long-term (10 -20 yr): Provide web-based decision support tools to facilitate the efficient exchange of monitoring data among water quality managers and to evaluate the effects of N and P management strategies on aquatic resources.

Appendix B

Agricultural Uses of Water

I. Problem Statement

Agriculture harnesses the productive capacities of soil, water, and climate to provide food, fiber, and energy. The transformations of land and water that occur in this process, however, pose a potential threat to the sustainability of water resources (Table 1) and can adversely affect aquatic systems and human well being.

Agricultural production of crops and livestock significantly alters soils, surface and ground water quality, hydrology, biodiversity, and landscapes. Crop production can expose soil to erosion, requires addition of nutrients (chemical fertilizers, manure, biosolids) and pesticides, and can physically alter hydrology (i.e., drainage of croplands, draining or filling of wetlands, removal of riparian areas, channelization of headwater and stream environments, soil compaction, and construction of levees), resulting in the direct physical and chemical alteration of surface water and ground water. Irrigation, where used, alters water availability, flow, and chemistry in streams, rivers, soils and ground water. Livestock production adds another set of concerns. In some areas of the country, it is concentrated in areas without adequate cropland/pasture to appropriately utilize the nutrients in the manure. Inappropriate application of livestock waste to crops or pasture causes the manure to runoff to water. Hormones, antibiotics, and heavy metals added to feed end up in both the manure and the water. Pastured cows with access to streams physically alter riparian areas by compacting soils, contributing to streambank instability, increasing surface runoff, and reducing riparian vegetation cover. These changes destroy riparian and instream habitat and reduce the buffering ability that riparian areas provide. In addition, pastured cows directly deposit manure in streams, increasing ambient nutrient and pathogen levels. Air quality and climate can also be adversely impacted by crop and livestock production. The severity of the impacts can vary dramatically depending on site-specific factors such as climate, soils, hydrology, topography, cropping systems and environmental management systems.

Table 1. The overall relationship between agriculture and water resources management, summarized here as Drivers, Pressures, State, Impacts and Responses, is the context within which research priorities should be determined. This listing is not intended to be comprehensive.

DRIVERS of change/ trends for US agriculture	Related PRESSURES on waters/ aquatic systems	Attributable STATE of waters/ aquatic systems	Attributable societal IMPACTS of water resources state	Policy RESPONSES, current or potential
↑ high commodity prices, resulting from: ↑ global grain demand ↑ corn grain ethanol demand ↑ DDGs in feed ↑ cellulosic demand (expected) ↑ mechanization, biotech ↑ economies of scale (farm, AFO size) ↑ commodification of land (vs stewardship ethic) • urban squeeze drives land market • corporate farms • rent vs. owner-farmer ↑ demand for environ. regulation and protection (WHO, EU as well as US public) ↑ food safety concerns ↑ water shortages, conflicts ↑ farmer acceptance of conservation practices (tillage, buffers) ↑ influence of environ. markets (e.g., carbon) ↑ education and stewardship ethic improved technologies with lower impact	tillage loss of soil carbon ↑ continuous corn drainage AFO production areas nutrient use (fertilizer, manure, biosolids) exceeding or not timed with crop needs pesticide use ↑ runoff: • volume • N, P • sediment • pesticides • hormones • pathogens • heavy metals (arsenic, copper) ammonia /$N_2$0 emissions channelization/drainage management destruction of riparian structure removal of shade trampling of bed/bank water withdrawal for irrigation introduction of invasive plants	Streams, Rivers, Reservoirs headwater ecosystem loss wetland loss instream habitat loss flashy hydrology low/no flow bank erosion turbidity sedimentation ↓ WQ: solids, N, P, pesticides, hormones, pathogens, antibiotic resistance eutrophication ↑ temperature biodiversity loss toxic algae blooms Aquifers N, pesticides drawdown Coastal Waters eutrophication toxic algae blooms biodiversity loss reduced fish and invertebrate production presence of pathogens	↓ cultural, aesthetic and existence values assoc. w/ degradation and reduced biodiversity in streams, rivers, reservoirs, coastal zones ↓ recreational values assoc. w/ degradation and reduced biodiversity (sport fishing, hunting, wildlife watching, boating, water contact) human illness (NO_3, pathogens) ↑drinking water treatment costs, taste/odor issues ↓ reservoir volumes dredging costs, drainage capacity maintenance flooding damage and loss of life	Cost-effective targeting of conservation systems within watersheds development and tech transfer of improved methods/ technologies (conservation practices, manure management, ecosystem restoration) ag conservation program investments education/extension to improve BMP adoption promulgation of nutrient criteria, standards promulgation of drinking water standards TMDLs for nutrients, sediments, pathogens, temperature development of environmental markets (C, water quality, flood prevention, temperature, wildlife habitat) development of improved irrigation technologies water rights/pricing reforms development of cellulosic ethanol; revision of RFS

The direct effects of agriculture on the stream environment have many impacts in aquatic systems. Potential adverse effects include degraded surface and ground water quality, flashy stream flows, increased sediment loads, blooms of toxic algae, and the loss of many aquatic habitats necessary to support healthy communities of aquatic plants, invertebrates, fish and wildlife. Increases in coarser sediments alter stream morphology and resultant aquatic habitat. Biological losses reduce the cultural and recreational values associated with healthy streams, lakes and fish and wildlife, both within farming regions themselves and beyond those regions (as, for example, when migratory wildlife are adversely impacted). Pesticides, nitrates, fine sediments, hormones, antibiotics and pathogens in surface- and ground-water sources of drinking water increase the costs of drinking water treatment. Such contaminants can harm wildlife and pose a threat to human health. The use of drainage systems, which quickly remove water from production areas, and levees, which protect production areas located in flood plains, results in higher flood flows during rainy periods and increased risks of loss of life and property. Irrigation may reduce stream flows, affecting water quality and fish and wildlife habitat, deplete aquifers, and compete with other uses. As surface waters polluted with nitrogen, phosphorus, sediments, and pathogens reach coastal waters, eutrophication, harmful algal blooms and reduced biological diversity may occur. Coastal fish and invertebrates, including many that are important for commercial or recreational harvest, may be reduced in abundance or contaminated.

A large variety of conservation practices, systems, and technologies have been developed to limit the impacts of agriculture on water, as well as to provide other benefits of nature to society (often referred to as ecosystem services). Although substantial public resources have been invested in providing farmers with financial and/or technical assistance in implementing these systems, many factors, such as cost, labor needs, farmer familiarity, and ease of implementation, limit the use or effectiveness of these improvements. The implementation and maintenance of conservation practices in many environmentally sensitive areas still needs to be improved. Furthermore, some problems resist solution because they reflect difficulties with overall system design, not just inadequate practices. For example, much of the livestock and poultry production in the U.S. is geographically concentrated. Improved manure management practices alone cannot compensate for the long-term importation of nutrients, via animal feeds, into a limited area, far in excess of local crop requirements. Similarly, improvements in irrigation system efficiency may be insufficient to compensate for structural problems in water law or pricing that facilitate overuse, and floodplain management policies focused narrowly on levee improvement may miss opportunities for achieving other important benefits to society.

Complexity also poses a challenge to the development of sustainable agricultural systems. While biofuel production reduces fossil fuel use, the feeding of ethanol production byproducts to cattle increases phosphorus levels in manure, and residue removal from fields as a biofuel feedstock can increase soil erosion. Conversely, some changes aimed at improving water quality have the potential to increase pollutant movements to the atmosphere. Thus, a change in any agricultural process that addresses one problem can have unintended impacts on other environmental resources. While water quality management in agricultural areas receives a lot of attention, many adverse impacts to which agriculture may contribute (bank erosion, sedimentation and increased downstream flooding) are due to impaired hydrology and need to be examined at a systems level.

In addition to these existing problems, current and anticipated trends must be addressed. Grain demand is increasing in response to both global economic development and biofuel demand, encouraging continuous corn production (thereby reducing the benefits of crop rotation) and discouraging retirement of marginal farmland for conservation. The increasing proportion of land that is rented, rather than owner-farmed, may reduce the adoption and maintenance of conservation practices. Agricultural production systems, including conservation practices or systems, have not been designed to account for a changing climate. The addition of cellulosic ethanol to corn ethanol production will lead to use of new energy crops, many with substantial potential for ecological benefit but in some cases with potential for spreading invasive species that may harm wetlands or waterways.

II. Solutions

Improvements to agricultural practice generally occur in response to the combined influence of improved knowledge about adverse environmental and public health impacts, development of new technologies and management practices, and policies to encourage or require their implementation. This complex process is depicted as a simplified cycle in Figure 1. Research plays a key role at many steps in this process.

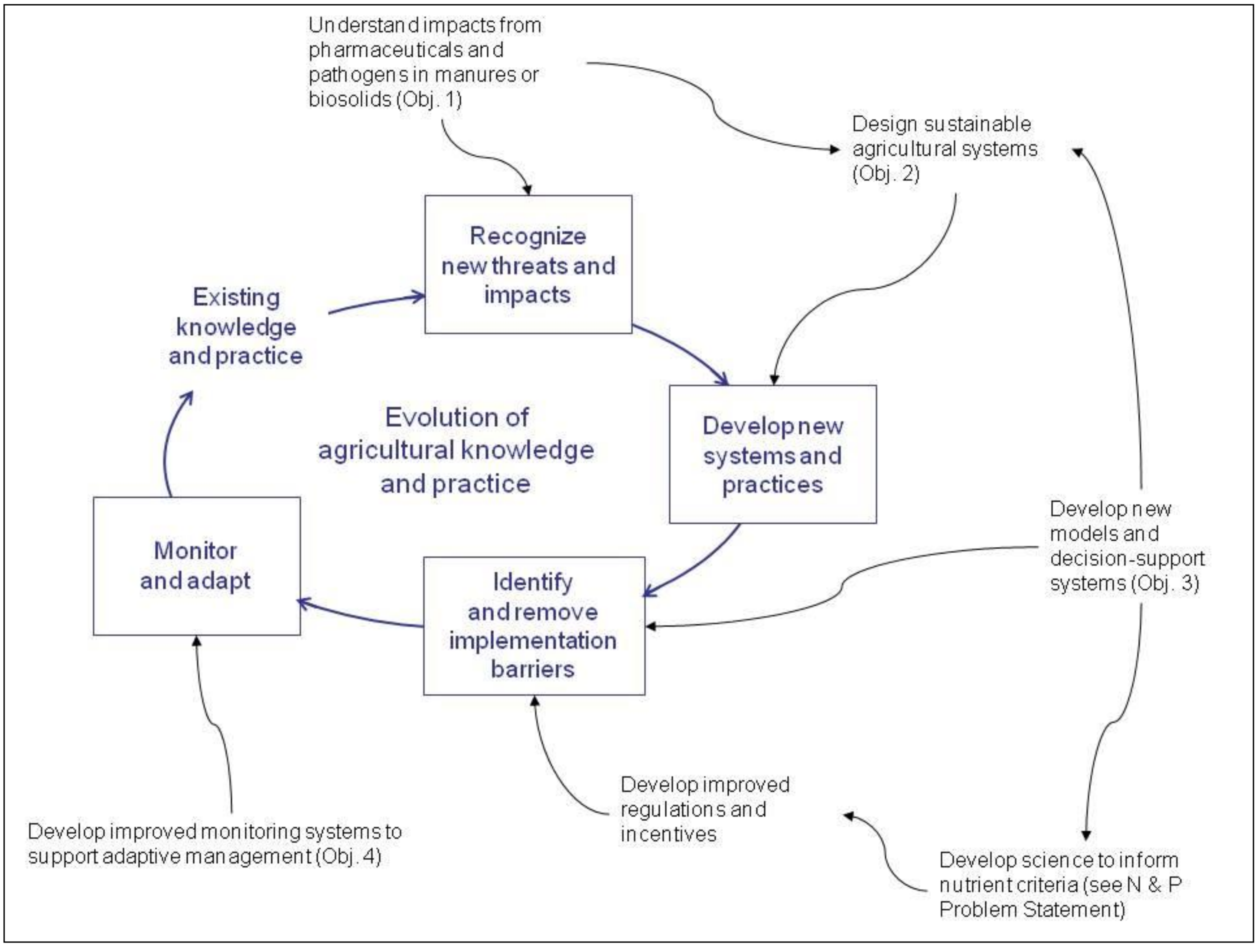

Figure 1. Roles for research in addressing the impacts of agriculture on water resources. Numbers in parentheses refer to research objectives described in Section III.

➢ **Recognition of threats and impacts posed by existing and new agricultural practices:** While some impacts of agriculture on water resources are relatively well understood, others are still being uncovered, and more information is needed before they can be effectively addressed. For example, an understanding of the environmental effects of feed additives – including hormonal effects on fish, and development of antibiotic-resistant strains of pathogens – is still emerging. Overland and in-stream transport of antibiotic-resistant bacteria into water systems as a result of manure applications, biosolids applications, or shedding from grazing animals is poorly understood. The ecological impacts of new cropping systems – such as the use of new corn varieties to allow expansion of corn production into new areas, and the production of new bioenergy crops – are only beginning to be explored. Such agricultural threats must be better understood and resolved if sustainability is to be achieved.

- **Continued development of improved agricultural systems, technologies and practices:** Agricultural technologies must be improved so as to take into account environmental and economic impacts. Most importantly, improvements at a systems level need to take place, where the flows of resources and materials among interacting agricultural, ecological and economic systems are examined in order to identify and correct any underlying causes of environmental problems (such as the examples of nutrient concentration and water use described above). Continued improvements are also needed in specific practices (e.g., tillage, cropping, manure management, drainage management, range management), by finding new and cost-effective ways to improve or maintain production while reducing erosion, increasing soil organic matter, utilizing nutrients, reducing reliance on added chemicals, improving water-use efficiency, and restoring the essential structure, function and biological diversity of aquatic systems, including wetlands, riparian areas and headwater stream channels. Equally important to the development of these improved systems and technologies are the social factors that encourage or retard their adoption; these are addressed in a later section.

- **Identification and removal of barriers to the implementation of improved agricultural systems and practices:** Technological improvements often face barriers to adoption that must be recognized and removed before improvements are realized. Some barriers are informational. One important contributor to agricultural sustainability will be the availability of modeling systems capable of linking agricultural practices to socially relevant environmental and health outcomes, in a spatially explicit fashion. These systems must be continually updated so as to model newly developing practices, including conservation practices, ecological restoration techniques and new bioenergy production systems. They must be able to examine how the location of these practices influences their effectiveness, so that optimal placements and alternative landscape designs can be explored. They must predict a variety of endpoints, at scales relevant to different stakeholders. At local scales important to farmers and their communities, important endpoints include contamination of drinking water and corresponding costs of drinking water treatment, the condition of streams, reservoirs, fish, wildlife, and related recreation, and the frequency of local flooding. Over broader scales, impacts on distant communities, estuaries and migratory wildlife must be considered. In each case, the capability to tie these various outcomes to localized goals, such as edge-of-field goals for farmers in a given area, is a necessary step for encouraging local implementation. The ability to show trade-offs among production and multiple quality-of-life goals, in interactive formats suited to different stakeholders, is essential to good decision-making. And while various modeling tools will adapt best to different needs, modelers must harmonize their efforts so that best estimates can be clearly identified in each case, to ensure that differences among models do not derail conservation efforts.

In addition to the informational tools just described, a combination of regulatory and other incentives to the implementation of best systems and practices are needed as well. Additional regulatory approaches have an important role to play, including the development of nutrient water quality standards, various TMDLs (nutrients, temperature, pathogens, or sediments), and CAFO regulations. Cost-effective implementation of TMDLs can be aided by the use of modeling tools described above, to guide the type and placement of practices, to emphasize those practices providing multiple benefits, and to assist the development of water quality trading programs. Financial incentives, including USDA conservation program investments, environmental markets, water law and pricing reforms, can also be better coordinated by means of modeling simulations, especially simulations of alternative futures done at regional scales, and examining tradeoffs among multiple objectives.

Incentive programs must be aligned not only with environmental models, but also with understanding or modeling of key social or institutional factors leading to system adoption. This requires not only improved understanding of how different kinds of farmers, across different regions, decide what practices to use, but recognition of other key decision-makers in the food or bioenergy production system. For example, some commodities are produced under contract to food processers or buyers, whose contracts often specify production practices. Outreach focused on the interests of those stakeholders could have disproportionately larger influence than other programmatic investments.

➢ **Monitoring approaches providing more rapid and cost-effective feedback on environmental threats and on the effectiveness of improved practices:** Incentive programs require the support of strong and cost-effective monitoring programs capable of verifying practices put in place, long term maintenance, and the effectiveness of those actions. In the case of water quality monitoring, for example, weather variability (including the disproportionate influence of high-flow events) complicates the verification of practice effectiveness, increasing time, costs and statistical complexity involved. To improve their practicality, monitoring programs need cost-effective improvements in instrumentation and remote sensing, as well clear guidance about what level of verification is possible.

III. Research Needs

This section develops a set of research objectives and subobjectives based on the solutions described in the previous section, and it focuses on how EPA and partner agencies can collaborate to address these questions. Because EPA often has limited authority or research funding compared to partner agencies or land grant universities, ORD's effectiveness will critically depend on developing effective research collaborations.

The outline below is organized hierarchically by Research Objectives [Obj], Research Subobjectives [SObj], Actionable Research Questions [Q] and Outputs [Out]. Outputs begin with the year in which they should be accomplished, and represent sequential accomplishments needed to answer the Actionable Research Question and help fulfill the Subobjective. Metrics are with Subobjectives rather than research questions, because ideally they track the accomplishment of objectives more so than completion of specific research efforts (though these will tend to be related). Metrics are intended to be quantifiable.

1. [Obj] **Minimize adverse public health and ecosystem impacts associated with pharmaceuticals and pathogens in manures or biosolids associated with agriculture (in collaboration with USGS)**

EPA should collaborate closely with USGS in the detection of emerging threats to water resources associated with pharmaceuticals and pathogens from agricultural sources. Detection methods need to be improved. Models should be used to improve our understanding of the behavior of pathogens and indicator organisms originating in agricultural lands as they move from source-to-receptor through land and water. These investigative models should employ source allocation techniques (microbial source tracking markers, chemical source indicators, etc.) to determine sources of contamination to downstream locations, and they should link transport modeling outputs with quantitative microbial risk assessment approaches, to estimate the risk of illness based on varying sources of the agricultural contamination.

[SObj] ***Understand and quantify aquatic ecosystem exposures and risks from hormones and antibiotics in animal manures*** [linkage to CSS]

Metrics:

- *Number of feed-additive pharmaceuticals for which analytical methods have been developed*
- *Number of EPA Regions in which concentrations of hormones and antibiotics in manures, biosolids and affected environmental media have been surveyed*

[Q] How do different kinds or combinations of livestock production contribute to releases of pharmaceuticals?

[Out] By FY15, quantified stressor loadings and established risk estimates associated with differing livestock types and management systems.

[Q] What analytical methods are needed to quantify pharmaceuticals in manures, AFO effluents, biosolids, surface waters and aquatic organisms?

[Out] By FY15, prioritized list of veterinarian pharmaceuticals for analysis development

[Out] By FY20, chemical extraction, detection and quantification methods for veterinary pharmaceuticals in manures, biosolids, and aquatic organisms

[Q] What biomarkers can provide sensitive indicators of exposure, and/or correlation to effects?

[Out] By FY15, prioritized list, including groupings of pharmaceuticals with similar structures and modes of action for biomarker development

[Out] By FY20, field tested biomarkers for exposure with linkages to known toxicity and metabolic pathways for highest priority contaminants

[Out] By FY25, characterized biomarker performance in varying environmental conditions and mixture exposures

[Q] How do these pharmaceuticals affect aquatic ecosystems, at individual, population and system levels?

[Out] By FY15, generated spatial map on watershed scale overlaying predicted and measured occurrence of priority contaminants, individual level responses and population and community level effects.

[Out] By FY20, generated adverse outcome models integrating data from chemical quantification, biological detection (biomarkers) and known adverse health effects to predict impacts at higher biological levels (population, community)

[SObj] ***Understand and quantify human exposures and health risks associated with pathogens in animal manures manures*** [linkage to HHRA]

Metrics:

- *For each major category of manure-release scenario (related to manure type and kind of use or release), number of watersheds for which the concentration of pathogens has been documented*
- *Number of watersheds where risk assessments (QMRA or others) have been performed to determine the risks associated with manure-derived pathogens.*

[Q] What is the pathogen fate and transport in soils, surface waters and drinking water systems in environments impacted by agricultural practices and systems?

[Out] By FY 16, Identify methodologies with more accurate detection and quantification of a wide spectrum of pathogens including parasites, viruses and bacterial pathogens.

[Out] By FY21, Use quantifiable pathogen information to model the fate and transport of pathogens in a variety of environmental matrices.

[Q] Are manure-derived pathogens impacting drinking water systems?

[Out] By FY14, Identify the risk of exposure of drinking water systems to manure-contaminated waters.

[Out] By FY21, Offer solution scenarios to protect drinking water systems from manure contaminated waters.

[Q] What are the human exposure and risks of infection in waters impacted by different types of animal manures?

[Out] By FY15, Identify survival rates, concentrations and types of pathogens present in various types of animal manures in most important or widespread agricultural practices.

[Out] By FY21, apply quantitative microbial risk assessment models to a variety of recreational and drinking water scenarios to determine the risk of infection and level of exposure to humans in contact with waters impacted by agricultural practices.

[Q] What modeling system needs to be developed and applied to advance our understanding of exposure and risk to waters impacted by manure-derived pathogens?

[Out] By FY15, identify a suite of models that can be used to best describe the fate and transport of pathogenic organisms derived from agricultural sources in a variety of environmental and drinking water systems.

[Out] By FY18, integrate information from microbial source tracking markers, field monitoring studies and laboratory process work with models on microbial fate and transport to model and allocate sources of contamination in agricultural watersheds.

[Out] By FY21, provide a generic modeling framework that can be used in watersheds nationwide to integrate information on overland transport, in-stream transport, exposure and risk to estimate health risks for a variety of surface and drinking waters.

2. [Obj] **Design sustainable agricultural systems (in collaboration with USDA, DOE, USGS, the Corps of Engineers and stakeholder groups)**

Any evaluation of the sustainability of agriculture and food systems must examine system-level flows of materials, energy and value, and examine long-term viability in terms of appropriate social, economic and ecological endpoints, including endpoints related to water resources and aquatic ecosystems. USDA and the land grant universities should continue to lead in the development of new systems and technologies. However, EPA should collaborate with USDA, DOE, USGS and the Corps of Engineers and stakeholder groups in defining agricultural and ecological system sustainability goals and indicators, and in the application of system-level assessments (e.g., life cycle analyses) to agriculture. EPA should also collaborate with USDA in evaluations of the environmental performance of new technologies, and should conduct research to fill in key gaps related to ecosystem services. For example, EPA should work with USDA to quantify the ecosystem services provided by constructed wetlands on tile drain or drainage ditch outlets. While USDA plays the leading role in social and economic research related to agricultural systems, EPA should collaborate with USDA and DOE in defining macro-level sustainability goals and indicators, as mentioned above, and collaborate in identifying systemic barriers to achieving sustainability.

[SObj] ***Design sustainable approaches to concentrated animal production***

Metrics:

- *Number of animal production system constituents important to the protection of water resources (e.g., water use, nitrogen, carbon) for which sufficient LCA methods and data libraries are available and in use*
- *Number of impact categories, including water-related ecosystem services (e.g., water quality, water supply, flood regulation, aquatic-related habitat), incorporated into LCA metrics and animal production industry-adopted sustainability metrics*
- *Fraction of US animal production to which scientifically defensible LCA methods, including a broad array of impact metrics, have been applied*

[Q] What are an appropriate, stakeholder-agreed set of multi-objective sustainability metrics and criteria for concentrated animal production systems that include the long-term protection of water resources?

[Out] By FY14, For the most important types of animal production systems, identify the predominant flows of value (e.g., materials, energy, investment) and impact (benefit and harm) within the related environmental, economic and social systems, including sensitive environmental processes and functions that are critical to achieving sustainable water resources.

[Out] By FY16, Provide data that helps stakeholders to identify sustainability metrics and criteria for animal production systems that ensure sustainability of water resources.

[Out] By FY21, provide an integrated multipollutant multimedia model that quantifies the environmental and economic feedbacks that influence sensitive ecosystem processes or functions critical to sustainable water resources.

[Q] What changes in system design, technology or practice would enhance the sustainability of concentrated animal production systems?

[Out] By FY14, For the most important animal production areas and systems, identify the predominant flows of value (e.g., materials, energy, investment) and impact (benefit and harm) within the related environmental, economic and social systems, including sensitive environmental processes and functions that are critical to achieving sustainable water resources.

[Out] By FY16, Provide data that helps stakeholders to identify sustainability metrics and criteria for animal production areas and systems that ensure sustainability of water resources .

[Q] What safe, cost-effective and nutrient-recovering solutions can be applied to deal with animal waste legacy issues, including abandoned manure lagoons and soils saturated with phosphorus, which endanger ground and surface water resources?

[SObj] ***Design sustainable approaches to biofuel feedstock production and supply chains***

Metrics:

- *Number of biofuel production constituents important to the protection of water resources (e.g., water use, nitrogen, carbon) for which sufficient LCA methods and data libraries are available and in use*
- *Number of impact categories, including water-related ecosystem services (e.g., water quality, water supply, flood regulation, aquatic-related habitat), incorporated into LCA metrics and bioenergy industry-adopted sustainability metrics*
- *Fraction of US biomass supply to which scientifically defensible LCA methods, including a broad array of impact metrics, have been applied*

[Q] What are an appropriate, stakeholder-agreed set of multi-objective sustainability metrics and criteria for biofuel feedstock production and supply chains that include the long-term protection of water resources?

[Out] By FY14, For the most important biofuel production supply chains, identify the predominant flows of value (e.g., materials, energy, investment) and impact (benefit and harm) within the related environmental, economic and social systems, including sensitive environmental processes and functions that are critical to achieving sustainable water resources.

[Out] By FY16, Provide data that helps stakeholders to identify sustainability metrics and criteria for biofuel production supply chains that ensure sustainability of water resources.

[Q] What changes in system design, technology or practice would enhance the sustainability of biofuel feedstock production systems?

[Out] By FY21, provide an integrated multipollutant multimedia model capable of exploring existing and new engineering solutions for biofuel feedstock production and quantifying the implications of those solutions for sustainable water resources.

[SObj] ***Design sustainable approaches to hydrology management in agriculturally-dominated watersheds***

Metrics:

- *Characterization of effect of agricultural practices impacting hydrology on ecosystem services at the watershed scale.*
- *Stakeholder engagement on issues and problems related to hydrologic management of agricultural systems*
- *Presentations to stakeholders of framework for agricultural hydrologic sustainability*

[Q] How do agricultural land, water, stream-channel and floodplain management practices affect stream, river and groundwater hydrology over a range of catchment scales, and what are the impacts (benefits and harms) in related environmental, economic and social systems?

[Out] By FY14, produce a catalog of ecosystem services that contribute to, or are impacted by, agricultural land, water, drainage, stream-channel and floodplain management practices, and identify watershed processes and functions that compete for water resources.

[Out] By FY16, elucidate the influence of agriculture (including cropping and animal production systems, roads/trails, drainage and channelization) on hydrology and sediment flux at watershed scales, including adverse impacts (e.g., flooding, low-flow, siltation), for typical and best agricultural practices.

[Out] By FY21, provide a multi-scale life cycle analysis model of land, water, stream-channel and floodplain management practices.

[Q] What are an appropriate, stakeholder-agreed set of sustainability metrics and criteria related to the hydrology of agriculturally-dominated watersheds?

[Out] By FY16, quantify ecosystem service changes associated with landuse change in agriculturally-dominated watersheds.

[Out] By FY18, provide guidance to stakeholders on social, economic and environmental impacts of agricultural land-use and management practices affecting watershed-level hydrology, and a framework for identifying related sustainability metrics.

[Q] What are the potential future effects of climate change and land-use change on meteorology and watershed hydrology? **[Linkage to ACE]**

[Out] By FY18, provide an integrated multimedia, multipollutant model that quantifies ecosystem service response to landuse and land management (adaptation) changes in response to climate change that will support sustainable water resources.

[Q] What changes in system design, technology or practice would enhance the sustainability of agriculturally-dominated watersheds?

[Out] By FY21, provide an integrated, multipollutant, multimedia model capable of quantifying the costs and benefits of existing and emerging engineering water management solutions for sustainable water resources.

3. [Obj] **Inform agricultural policy- and decision-making about the environmental, social and economic trade-offs associated with current and improved agricultural systems and practices (in collaboration with USDA, USGS and DOE)**

EPA should play both a leading and a collaborative/catalytic role in the development of the needed modeling and decision support systems. Key water quality modeling resources, utilizing different modeling approaches, exist in USDA and USGS. EPA should collaborate in integrating these approaches and implementing them within modeling systems that include biological outcomes and the associated societal benefits (i.e., ecosystem services). EPA/OW's HAWQS (Hydrologic and Water Quality System) and EPA/ORD's FML (Future Midwestern Landscapes) Study should be key elements of this effort. HAWQS needs to be integrated with climate and air models to develop a national integrated environmental modeling system (NIEMS). The FML Study is using the ReVA (Regional Vulnerability Assessment) approach to develop an online

Environmental Decision Toolkit to visualize ecosystem services for alternative futures in the Midwestern United States.

Much of the information needed for the integrated modeling of agriculture, watersheds and ecosystem services has been generated by USDA's Conservation Effects Assessment Project (CEAP) but has not yet been compiled into the tools needed by, e.g., states, watershed planners, and stakeholders engaged in TMDL implementation or the development of environmental markets. USGS is collaborating with CEAP to develop an Integrated Landscape Monitoring (ILM) framework to better observe, monitor, understand, and predict landscape changes and their ecological implications. EPA can help increase the usefulness of CEAP data by collaborating with USGS to construct the needed ecosystem service modeling and decision-support frameworks and working with CEAP scientists to synthesize the needed information. Similarly, EPA should help DOE to link their models of bioenergy cropping systems to multiple ecosystem service endpoints.

Efforts to model agricultural impacts on water resources should also address the potential effects of climate change and land-use change on meteorology and water balance. For example, EPA has an important collaboration with climate modelers at the University of Washington, DOE and the National Center for Atmospheric Research to harmonize meteorological, water quantity and water quality models; a key element in this effort is Variable Infiltration Capacity (VIC) model which examines land-surface water balance.

[SObj] ***Achieve agreement among modelers across various agencies (USGS, USDA, CoE, EPA) about the best uses and interpretations of various hydrologic and water quality modeling tools being developed for or applied to agricultural systems and landscapes***

Metrics:

- *Evidence of interagency agreement regarding the appropriate application of hydrologic models to the characterization of agricultural pollutants and other impacts*

[Q] How well do different hydrologic models inform questions about agricultural impacts on water resources, and how should differences between those models be interpreted?

[Out] By FY2015, provide joint guidance (with hydrologic modelers in USDA/ARS, USDA/NRCS, USGS and CoE) on the comparative application of various hydrologic models (SWAT, SPARROW, HAWQS, RHYME^{2}S and VIC) in agricultural landscapes, to better interpret inter-model differences in results (e.g., nutrient loadings, sediment loadings, flows).

[SObj] ***Develop decision-support tools that convey understandable information about the full range of environmental, social and economic trade-offs associated with agricultural decisions, using terminology and spatio-temporal scales that are meaningful for decision-makers at different levels (i.e., farm, watershed, national-policy)***

Metrics:

- *Number of water resource related ecosystem services that are included in widely-used decision support tools at each spatial scale (i.e., farm, watershed, national-policy)*
- *Number of EPA Regions in which farm- and watershed-scale decision support tools are being used*

[Q] What is the impact of agriculturally derived contaminant loadings on drinking water treatment processes, effectiveness and costs?

[Out] By FY14, Literature survey and synthesis of agricultural impacts on drinking water treatment processes and costs

[Out] By FY17, Integration of pollutant-specific drinking water treatment cost curves with hydrologic models of pollutant loading

[Q] What forms of information about the ancillary ecological benefits of agricultural conservation practices (e.g., improved hunting or fishing, cleaner water, environmental markets, new rural economic development opportunities, etc.) are most meaningful to farmers and rural communities? How can decision-support systems be adapted accordingly? **[Linkage to SHC]**

[Out] By FY14, literature survey and synthesis on farm, ranch and rural community values regarding benefits from nature (e.g., improved hunting or fishing, cleaner water, environmental markets, new rural economic development opportunities, etc.), including those that are water-related.

[Out] By FY16, value hierarchies for farm, ranch and rural community values regarding benefits from nature, including those that are water-related.

[Q] What are the most effective modeling methods for characterizing multiple endpoints – including ecological, health and social impacts – for current and future agricultural landscapes, including biofuels and conservation practices (building on ORD's FML and ReVA, incorporating results of USDA's CEAP and USGS's ILM)? **[Linkage to SHC, ACE]**

[Out] By FY14, Interagency workshop on ecosystem service estimation methods for alternative future agricultural landscapes.

[Out] By FY16, Interagency state-of-the-science report (i.e., workshop report) on ecosystem service estimation methods for alternative future agricultural landscapes.

[Q] How can models addressing multiple endpoints be incorporated into decision support systems illustrating trade-offs at scales appropriate for different kinds of decision-makers (e.g., conservation policy design vs. local watershed protection)? (collaborating with USDA/FSA, USDA/ARS, USDA/NRCS) **[Linkage to SHC]**

[Out] By FY16, Interagency workshop on decision support tools for sustainability of alternative future agricultural landscapes, addressing three scales of decision-making (farmer, watershed manager, national policy-maker).

[Out] By FY18, Interagency state-of-the-science report (i.e., workshop report) on decision support tools for sustainability of alternative future agricultural landscapes, addressing three scales of decision-making (farmer, watershed manager, national policy-maker).

[Out] By FY21, provide an integrated multimedia, multipollutant model that quantifies ecosystem service response to agricultural management policies.

[Out] By FY21, provide an integrated multimedia, multipollutant model that quantifies ecosystem service response to climate change.

[Out] By FY26, provide reduced form integrated multi-pollutant multimedia models that quantify ecosystem responses to management policies and climate change.

[Q] What kinds of decision support systems can assist the development of environmental markets for benefits including water quality, temperature, flooding risk? **[Linkage to SHC]**

[Out] By FY18, provide applications of ecosystem service models specific to the needs of, and supporting the development of, environmental market mechanisms, such as water quality trading, while illustrating trade-offs among a range of ecosystem services.

4. [Obj] **Adaptively implement new agricultural systems and practices through improved monitoring (in collaboration with USDA and USGS)**

EPA should collaborate with USGS and USDA in the development of remote sensing approaches for mapping and verifying the use of conservation practices. This work should be linked to EPA/ORD's ongoing efforts to develop an Ecosystem Services Atlas for the United States. EPA should also collaborate with USGS and USDA in the improvement of water quality monitoring technologies and data systems for cost-effective verification of pollutant reductions, and for the rapid detection and tracking of pathogens.

[SObj] ***Develop and implement cost-effective approaches for monitoring the implementation, maintenance and effectiveness of improved agricultural practices***

Metrics:

- *Cost-reductions in the verification of BMP installation and maintenance*
- *Cost-reductions in the verification of BMP effectiveness in reducing sediment and nutrient pollution*

[Q] What cost-effective approaches (including remote sensing technologies) could be used to identify locations where agricultural best management practices (BMPs) have been implemented?

[Out] By FY18, cost-effective technology and methods for verifying the **establishment** of conservation practices, BMPs or aquatic habitat restoration, including wetlands.

[Out] By FY20, tested protocols for the appropriate application of practice-**establishment** verification methods.

[Q] What cost-effective approaches (including remote sensing technologies) could be used to document the effectiveness of agricultural best management practices (BMPs) in protecting water resources (i.e., water quality, aquatic habitat, aquatic communities)?

[Out] By FY18, cost-effective technology and methods for verifying the effectiveness of conservation practices, BMPs or aquatic habitat restoration.

[Out] By FY20, tested protocols for the appropriate application of practice-**effectiveness** verification methods.

Appendix C

Energy/Mineral Extraction and Injection

I. Problem Statement

Energy and minerals production in the United States already have an enormous impact on surface and subsurface water resources; future impacts can be expected to be greater and more diverse. Increasing demands for energy and mineral resources, the desire to supply a greater fraction of energy and mineral demands from domestic sources, and the need to mitigate the production and release of greenhouse gases all argue for greater diversification of energy and mineral production. Scientifically rigorous information and assessment techniques will be needed to assist society in making sound choices for a more sustainable energy future. The nation's energy portfolio will likely span such diverse activities as enhanced recovery of unconventional fossil fuels sources, geothermal, wind and wave, solar, and possibly nuclear energy, all of which exert differing pressures on water resources. The assessment and mitigation tools of the future must not only be able to accommodate this divergence of impacts, but must be able to account for cumulative impacts of mixtures of such activities in differing proportions in differing geographic and climactic regions.

Currently, agriculture and energy together account for nearly 80% of the freshwater withdrawals in the United States (Fig 1). Agriculture, primarily in the form of irrigation, accounts for the largest consumptive use; generation of thermoelectric power accounts for the majority of the non-consumptive use. When impacts on water beyond withdrawals/consumption - e.g. water quality impacts associated with runoff, land disturbance, waste disposal/injection, etc - are considered, it becomes clear that no holistic view of the water resource can fail to address the magnitude and nature of the interconnections between energy, agriculture and water.

Moreover, as the nation looks to diversify its energy sources, including the exploitation of nonconventional fossil fuels, and to mitigate its greenhouse gas impacts, the future holds enormous shifts in energy sources and technologies. The demands that such emerging energy technologies (Fig. 2) put on the water resource are often difficult to discern and quantify, promulgating from a cascade of primary and secondary impacts.

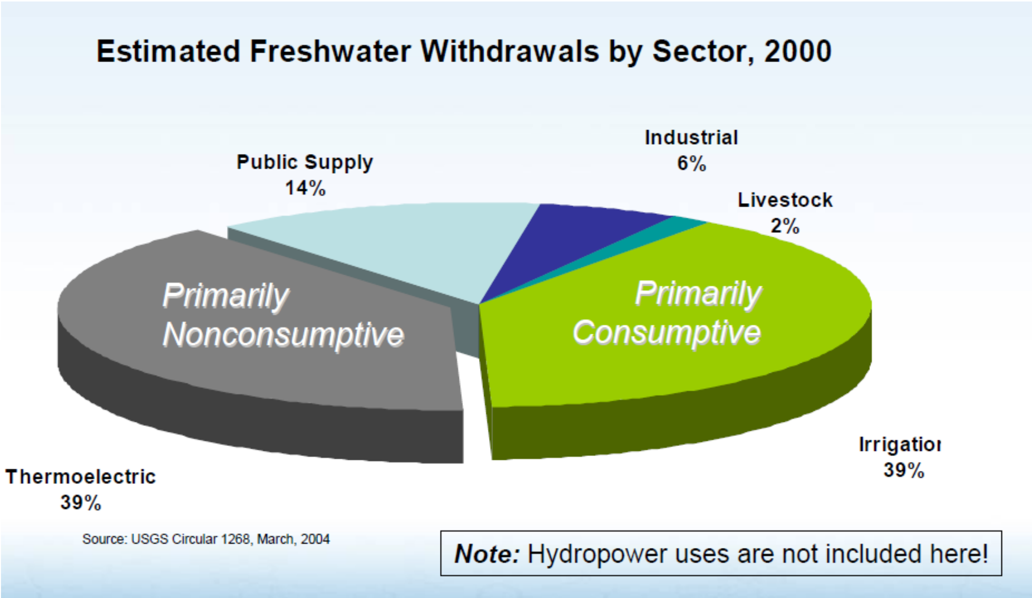

Figure 1 – Estimated freshwater withdrawals by sector; total withdrawals = 345 Bgal/day (Hutson et al., 2004).

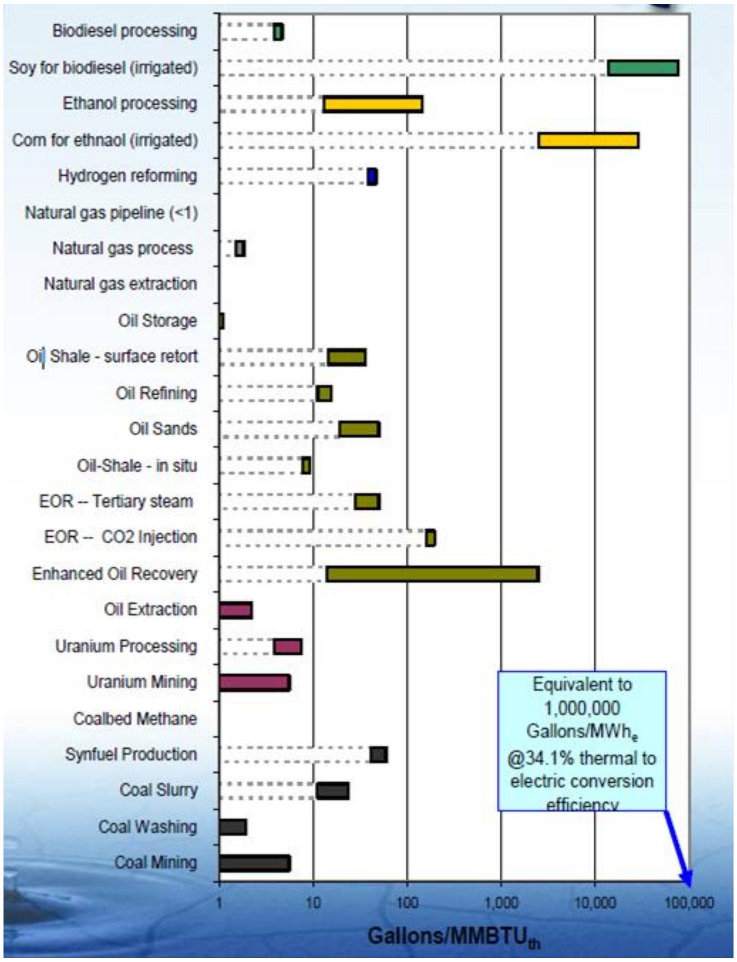

Figure 2 – Demands of energy technologies, current and emerging, on water resources (in volume of water used per unit energy produced, gal/MMBTU) (U.S. Department of Energy, 2006).

A systems-based framework is needed to identify unintended consequences, evaluate trade-offs, and promote a sustainable use of the water resource in light of a shifting and intensifying energy and mineral exploration and production future.

The operations associated with the exploitation of energy (fossil fuel, nuclear, renewable) and mineral resources, and their related waste products and emissions, have significant potential impacts on the Nation's water resources, both on the surface and in the subsurface. Extraction activities that involve removal of quantities of overburden disturb the landscape integrity of watersheds and may involve the intentional or unintentional discharge of materials to streams, including stream burial. Extraction activities that are predominantly subterranean, as well as subsurface injection of waste materials, may introduce contaminants to underground sources of drinking water and/or facilitate the movement of naturally occurring or anthropogenic contaminants between hydrogeologic units. Moreover, extraction and processing activities may require large quantities of water, potentially in competition with other water uses and/or with significant water quality consequences.

Key Science Questions

- What are the demands of a given energy/mining technology for water withdrawals? Quantity, timing, surface/subsurface?
- What information is necessary to assess the demands, and ultimate sustainability, of an energy/mineral extraction activity?
- What are the competing demands for water in the region?
- What is the full suite of activities associated with a given energy/mining technology? (Life-cycle perspective)
- Which stages of activities generate stressors? Chemicals? Surface/land disturbances? Alterations of subsurface environments?
- What are the water-mediated exposure pathways that pose risks to humans, domestic animals, wildlife, and adjacent ecosystems?
- What is the fate of discharged materials?
- Which environments are most vulnerable to energy/mining activities?

- What are the true costs on water resources (water availability and quality) of energy/mining activities?
- How can cumulative impacts of multiple instances of diverse types of energy/mining activities be accounted for?
- How can likelihood of accidents, failures be accounted for in a sustainability framework?
- How can recovery processes be accounted for, enhanced in the post-activity phase?
- What technologies/practices can most effectively mitigate the impacts of mining/energy activities on water resources?
- What human behaviors can be influenced to reduce the need for energy and mineral resources (and thus the need for energy/mineral extraction activities) and minimize harm to human health and ecosystem services?
- What technologies and management practices can be developed or advanced to increase efficiency of, and reduce the need for, energy/mineral extraction activities?

II. Solutions

Assessment of the full suite of impacts of Energy/Mineral Extraction and Injection (EMEI) activities on water resources requires a life-cycle view of the extraction and injection processes, from exploration, exploitation, transportation, processing, consumer use, and treatment and disposal of waste products. Both water quantity and quality effects must be considered, including consumptive and nonconsumptive uses and contaminant discharges, as they impact the ability of the water resources to support human and ecological uses.

Solving this problem requires: 1) constructing a life-cycle view of sequence of activities entailed in exploration, extraction, transport, processing, and managing the wastes associated with the mining of minerals, fossil fuels, radioactive ore, and others, as well as reclamation and post-extraction environmental restoration; 2) constructing local and regional (dynamic) water budgets at the appropriate scales that reflect both water quantity and quality and the salient interconnections between surface and subsurface systems; 3) identifying the potential points of contact, or exposures, between 1) and 2); and 4) characterizing the risks – human and ecological – arising from those exposures.

Moreover, both the life-cycle view of the EMEI activities and the dynamic water budget must be constructed to reflect the key elements of sustainability – social, economic and environmental – and their interactions, as captured in a systems model. Such a model is not only useful for identifying intersections of potential risk, but also for expanding the opportunities for risk mitigation and innovative solutions.

By its integrative nature, such an approach offers opportunities for complementarity among sustainability-oriented research elements and programs. Societal decisions to utilize extracted materials as energy sources in addition to, or as an alternative to, agriculturally-derived energy sources such as biofuels (a separate element of the Safe and Sustainable Water Resources, SSWR, action plan) depends on availability of comparable information about the social, economic, and environmental consequences. This program performs such analyses primarily through the lens of the water resources – but that view must be incorporated into the fuller view developed by the Air, Climate, and Energy (ACE) program to ultimately inform national decisions and policies for energy and climate. For example, the potential ACE goal of stabilizing atmospheric concentrations of anthropogenic greenhouse gases linked to global climate change, such as carbon dioxide (CO_2), and the emerging technology of carbon capture and storage (CCS) through deep injection and geologic sequestration (GS) of emissions from coal and natural gas power plants, has a potential impact on underground sources of drinking water (USDW).

Similarly, the risks associated with the EMEI materials – both the extractive materials, secondary chemicals used in their extraction and processing, and any resultant wastes – derive from their physical, chemical, and biological properties. While this program would investigate the fate, transport, and impacts of potential contaminants of concern in surface and ground water systems, it is not the intention of this program to conduct hazard analyses; rather, it will depend on the capabilities of the Chemical Safety and Sustainability (CSS) program for the conduct of EMEI risk assessments.

Finally, the ultimate decision of the community to accept the trade-offs, risk, and sustainability consequences of EMEI activities will depend on a suite of considerations well beyond the range of this program: cumulative health impacts, jobs creation, valuation of ecological resources, etc.

The expectation is that the outputs of this program will, in addition to responding to the policy and regulatory needs of the Agency, be available to serve as inputs into a community-based sustainability assessment as developed by Sustainable and Healthy Communities (SHC) program and others.

III. Research Needs

The goal of this research program is to produce a framework for decision-making and the requisite populating science to enable assessment of water impacts of energy production and energy and mineral extraction, processing, and injection activities from a full sustainability perspective. Development of the framework and the body of science will advance through strategic engagement with current and emerging issues as exemplars of the more general problem type. Thus, the program will prioritize research to meet both objectives: the solution of current problems and the extent to which the research contributes to the development of a robust framework for evaluating and managing our changing energy and mineral future as it impacts water resources. Hydraulic fracturing, geologic sequestration, and soft- and hard-rock mining, represent both intensive, present problems and, together, a spectrum of interactions with surface and subsurface water resources, having water quantity and quality implications.
Hydraulic fracturing, geologic sequestration of carbon dioxide, and mining (surface mining, mountaintop mining and mining megasites) practices, if poorly managed and executed, can cause significant impacts to health and the environment. The Agency is currently evaluating these EMEI activities and the concerns that have been raised.

ORD is conducting integrated, transdisciplinary research to better understand the scientific and technical aspects and challenges of these EMEI activities and their potential impacts to the environment. ORD needs to evaluate what innovative strategies and management practices are available to promote a sustainable future, with energy and mineral resource extraction being a potential land use, while minimizing negative impacts to human health and the environment. Key science questions and the research needed to address these questions are provided below, categorized by EMEI activity.

1. Hydraulic Fracturing

Hydraulic fracturing (HF) is a process used by natural gas producers to stimulate wells and recover natural gas from sources such as coalbeds, tight sands, and shale gas formations (U.S. EPA, 2011a). HF is also used in other applications, including oil recovery. Over the past few years, several key technical, economic, and energy policy developments have spurred increased use of HF for gas extraction over a wider diversity of geographic regions and geologic formations. In particular, the advancement of horizontal drilling techniques has improved access to major shale gas plays (e.g., the Marcellus Shale, the Barnett Shale). Along with the expansion of HF, there have been increasing concerns about its potential impacts on drinking water resources, public health, and environmental impacts in the vicinity of HF operations.

Questions

- How might large volume water withdrawals from ground and surface water impact drinking water resources?
- What are the possible impacts of accidental releases of hydraulic fracturing fluids on drinking water resources?
- What are the possible impacts of the injection and fracturing process on drinking water resources?
- What are the possible impacts of accidental releases of flowback and produced water on surface and subsurface sources of drinking water?
- What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources?

Outputs and Timelines

The highly complex nature of the problems to be studied will require a broad range of scientific expertise in areas such as environmental and petroleum engineering, groundwater hydrology, fate and transport modeling, and toxicology as well as many others. As such, a transdisciplinary research approach that brings together various types of expertise from inside and outside the Agency in an integrated manner will be necessary (U.S. EPA, 2011b). This approach will include analysis of existing data, retrospective and prospective case studies investigations, laboratory experiments, and scenario evaluations using numerical modeling to address these key questions.

In cooperation with the US Army Corps of Engineers, the US Geological Survey, state environmental agencies, state oil and gas associations, river basin commissions, and others, existing data on water use and water quality in areas impacted by hydraulic fracturing will be compiled. Simple water balance and geospatial information system (GIS) analysis will be conducted using the existing data. A critical analysis of trends in water flows and water usage patterns will be conducted to determine whether water withdrawals in areas subject to hydraulic fracturing activities alter ground water levels and movement and surface water flows. Data collection will support the assessment of the impacts of hydraulic fracturing on water availability at various spatial scales (e.g., site, watershed, basin, and play) and temporal scales (e.g., days, months, and years). Water quality trends will also be evaluated to determine the potential for using routine monitoring data in identifying water resource vulnerabilities. Industry-provided data on the composition and variability of hydraulic fracturing fluids, flowback water, and produced water will be used to identify individual chemicals and classes of chemicals of potential concern. Armed with this information on chemicals or classes of chemicals of concern, existing literature will be reviewed for appropriate analytical methods, fate and transport properties, known impacts to human health, and existing or emerging water treatment technologies. In addition to improving our understanding of hydraulic fracturing fluids, flowback waters, produced waters, and their impacts to drinking water, an analysis of existing data will help to identify knowledge gaps, which in turn will help to prioritize needs and target further research.

Retrospective case studies will focus on investigating reported instances of drinking water resource contamination or other impacts in areas where hydraulic fracturing has already occurred. Retrospective case studies will take place at several sites across the United States that have potential drinking water impacts from hydraulic fracturing. The sites will be illustrative of the types of problems that have been reported to EPA during stakeholder outreach meetings, and will provide EPA with information regarding key factors that may be associated with drinking water contamination. These studies will use existing data, field investigations and/or parallel laboratory investigations, and numerical modeling to determine the likelihood that reported impacts are due to hydraulic fracturing activities. Prospective case studies will involve sites where hydraulic fracturing will occur after the research is initiated. These case studies will allow sampling and characterization of the site prior to, during, and after water extraction, drilling, hydraulic fracturing fluid injection, flowback, and gas production. EPA, with industry and other stakeholders, will conduct several prospective case studies in different regions of the United States. The data collected during prospective case studies will allow EPA to gain an understanding of hydraulic fracturing practices, evaluate changes in water quality over time, and assess the fate and transport of potential chemical contaminants.

Laboratory investigations will be conducted to evaluate which characteristics of gas-bearing formations and fracturing conditions (e.g., temperature and pressure) are most important in determining the potential impact of hydraulic fracturing on drinking water resources. Laboratory studies will also help to identify possible components in flowback and produced water. Once identified, these components can be used to identify or develop analytical methods needed for detecting these compounds. Results from laboratory studies on possible flowback and produced water components can be used to assess the toxicity and human health effects of naturally occurring substances that may be released during hydraulic fracturing operations. Bench-scale laboratory studies will also be conducted to investigate if hydraulic fracturing fluid additives, naturally occurring constituents mobilized during the fracturing process, or degradation products of fracturing fluid additives are precursors to disinfection by-products (such as trihalomethanes, haloacetic acids, or nitrosamines). Laboratory research will also be conducted to evaluate whether other constituents, such as elevated chloride concentrations, result in unintended problems such as increased drinking water distribution system corrosion.

Generalized scenario evaluations will allow EPA to explore hypothetical scenarios relating to hydraulic fracturing activities, and to identify scenarios under which drinking water resources may be adversely impacted by hydraulic fracturing based on current understanding and available data. Computer models will be designed based on physical and chemical aspects of natural systems, incorporating data from actual case studies and laboratory experiments. Once constructed, the models will be used to explore the influence of pressure response and contaminant transport under fracture stimulation conditions. Well-failure scenarios (for example, failures of the well casing or cement) can be safely evaluated using models. Models can also be used to evaluate the impact of abandoned wells and natural fractures and fault zones as a potential pathway for fracturing fluids to migrate beyond the intended injection zone. Computer models can also be used to evaluate the potential for fracturing to unintentionally extend outside of the target zone and create new pathways for pressure and fluid leakage.

Data and results provided by scenario evaluations will allow EPA to identify and predict the area of evaluation (AOE) around a hydraulic fracturing site. The AOE includes the subsurface zone that is potentially impacted by hydraulic fracturing activities and is projected as an area at the land surface. Estimated AOEs for multiple injection operations can be overlain on regional maps to evaluate cumulative impacts, and, when compared to regional maps of underground sources of drinking water, be used to evaluate regional vulnerability.

Computer modeling can also provide a scientific approach for testing the potential impacts of hydraulic fracturing flowback and produced water on drinking water resources. The conceptual model for representative geology remains the same as in the case of injected fluids, but the reservoir production and engineering changes from injection to extraction. An important exposure pathway to consider is the long-term movement of injected chemicals, formation fluids, and/or transformation products of the mixture up an improperly cemented section of the borehole or casing. Again, it will be informative to compare the typical management practices to unexpected situations that may lead to impacts of flowback and produced water on drinking water resources.

EPA's current research on hydraulic fracturing focuses on impacts drinking water resources as directed by the congressional appropriations conference committee. Initial results from these research activities have been requested over the short term (by the end of 2012 and 2014). However, hydraulic fracturing process also has other potential environmental impacts. Based on preliminary data and feedback from stakeholders, EPA is aware of potential impacts to air quality and terrestrial and aquatic ecosystems, as well as potential seismic risks, occupational risks, and economic impacts. Future work (over the next 5-10 years) encompassing these research areas should be integrated with results of current research to provide a holistic view of the impacts of hydraulic fracturing on human health and the environment. Environmental justice concerns and cumulative changes to the quality of life in areas of dense oil/gas activities should also be evaluated as part of this research effort (in conjunction with immediate to intermediate-term research efforts). Future long term activities should include developing decision support tools to enable regions, states, local governments to utilize the vast, complex data being generated and develop management options. Developing alternative futures and visioning tools for determining long-term socioeconomic impacts, trade-offs, and impacts of lost ecosystem services should also be conducted as part of any future research strategy.

2. Geologic Sequestration

In December 2010, EPA published a new rule under authority of the Safe Drinking Water Act that created a new class of injection well, Class VI, for regulating geologic sequestration (GS). GS is the process of injecting carbon dioxide (CO_2), captured from an industrial or energy-related source, into deep subsurface rock formations for long-term storage, potentially offsetting global CO_2 emissions (U.S. EPA, 2010a). Even with the large physical separation and presence of sealing layers between subsurface storage reservoirs and surficial environments, there remains concern that CO_2 stored in reservoirs may eventually leak back to the surface through improperly sealed abandoned wells or along geological features such as faults. Leakage would reduce the effectiveness of carbon capture and sequestration, may lead to human health and ecological impacts at the ground surface, and possibly endanger both surface water and underground sources of drinking water (U.S. EPA, 2010b). Inherently, as GS is a developing technology, with a goal for 6-10 commercial-scale projects by 2016 (Interagency CCS Task Force, 2010), there are unidentified gaps of research that still need to be explored to fully understand the effects of CO_2 in the subsurface. Some of these goals are outlined below, however, others, such as the effects of multiple commercial scale GS projects on a community and environment, will not be available for research until further commercialization of GS occurs.

Questions

- What risk profiles can be made from data to ensure the protection of USDWs?
- What are the expected time periods for permanent CO_2 trapping through geologic sequestration and what is the potential for CO_2 leakage during injection and post-injection time frames?
- What monitoring methods are best at detecting soil gases and ground water movement related to CO_2 injection?
- How does underground injection of large volumes of CO_2 impact ground water chemistry and microbiology (that is, what are the CO_2/water/rock interactions, geochemical/biogeochemical impacts, contaminant mobilization consequences)?
- What methods are best to test mechanical integrity of wells accepting large volumes of supercritical CO_2 for deep underground injection?
- What is the capability of existing models to evaluate hydrologic and geologic factors in defining the area of potential endangerment, or area of review for UIC Class VI CO_2 injection wells?
- What is the capability of models to evaluate potential leakage within the area of potential endangerment, including the impact of displaced native saline waters, the cumulative effects of multiple injections, and the presence of fractures/faults?
- How do we best account for the cumulative physical and chemical effects of CO_2 injection when calculating area of review for GS projects obtaining a UIC permit under Class VI?
- What is the capability of existing models to evaluate hydrologic and geologic factors in the area of review for CO_2 injection, and what is their capability to predict potential leakage?
- Are monitoring and modeling methods adequate to monitor/assess/predict long-term (100–1,000 years) performance efficacy?
- Is geologic sequestration of CO_2 sustainable with the inclusion of the economic costs/benefits and societal impacts involving water resources?

Outputs and Timelines

In order to address these questions, ORD has taken an integrated, multidisciplinary approach: conducting internal research, developing research collaborations with other federal researchers, and funding academic research through the STAR grant program. Ongoing and newly initiated research activities should build upon : 1) developing methods to predict and verify capacity, injectivity, and effectiveness of CO_2 storage in subsurface environments; 2) designing efficient and cost-effective direct monitoring schemes (e.g., ground-water monitoring) to track plume migration and detect leaks; 3) developing area of review modeling tools to assist permitting authorities in evaluating a potential GS site; 4) characterizing and managing risks (potential microbiological and geochemical impacts) associated with the release of CO_2 to deep and shallow subsurface environments (e.g., USDWs); 5) developing tools to identify artificial penetrations (usually existing and abandoned wells) in the proximity of GS injection sites, especially in the permitted Area of Review; and 6) extending concepts and methods for defining the area of potential endangerment, including dynamic evaluations of potential displacement of native brines through boreholes connecting the injection reservoir with the USDW.

While the oil and gas industry has much experience in using CO_2 for oil and gas production activities, injecting CO_2 for the exclusive purpose of storage presents new challenges. One critical area of continuing research involves the area of review of a GS project, or the region surrounding a GS project where USDWs may be endangered by the injection activity. Within the area of review, CO_2 will have both chemical and physical effects on the geochemistry and subsurface pressures. These changes may in turn affect a variety of factors including subsurface formations, microbiology, and geochemistry of the area of review. Building on existing efforts to directly quantify this area of review through comprehensive modeling, research should continue through all future research time frames from immediate (i.e. within 5 years) to long term (i.e. 10-20 years) to help more accurately refine codes, assumptions, and models used. This research can include a large number of entities, including but not limited to academia, Federal partners as well as internal and external laboratory collaboration. An emphasis should be placed on strengthening collaboration with other Federal laboratories (e.g., DOE) as well as relevant academic universities.

The biogeochemical interactions with CO_2 in the subsurface are not well understood. Research should emphasize in-situ testing of CO_2 saturated waters with various microbiological communities to test the effects on aqueous geochemical factors and ultimately investigate the potential to endanger USDWs. Internal laboratories have started this research and should continue to do so in collaboration with other Federal partners over a long term time frame. Because operational data from commercial CO_2 injection will not be available for at least a decade, this time frame allows methodologies to be developed to study the associated biogeochemical reactions within the subsurface between biological communities and CO_2. An emphasis should also be placed on integrating both laboratory and field research in order to test not only idealized scenarios, but more realistic conditions where GS may occur commercially in the future (e.g., the Illinois Basin). Given their expertise, ORD scientists should provide technical assistance to regional staff regarding the understanding of potential impacts of CO_2t injection on USDWs and the permitting of injection activities.

In order to properly test the construction of GS wells, mechanical integrity tests, and other physical well properties as they relate to CO_2, site access issues should be addressed in an immediate time frame within a few years. It is strongly encouraged that ORD laboratories work with Federal partners, as well as state agencies, to gain site access to GS pilot projects or developing commercial projects. Obtaining access through an academic research facility may also help to solve previous site access issues. By solving site access issues, research at these sites can begin quickly as site access allows and should focus on understanding if existing tests for mechanical integrity can properly account for the unique properties of large volumes of CO_2 in the subsurface on well components. One related area of research that may be best conducted through academic STAR grant funding is cement composition research. There has been previous work at a number of academic universities on the suitability of certain grades of cement for long-term exposure to CO_2, but further clarifications should be made as to new compositions that may work well when interacting with CO_2. Overall, research universities may be in the best position to conduct this research, and it is encouraged that funding continue through academic STAR grants in the short term.

Another short term goal should be the close collaboration with other relevant ORD Integrated Research Frameworks, such as Air, Climate and Energy (ACE). Like EMEI, ACE works with a number of cross cutting issues, and GS in particular may have potential effects on water, air, and energy needs. Discussions between both groups will be important to foster unique goals for each group, while keeping in mind the link between the two research outlooks.

Future long term needs can include research on maintenance and assessment of mechanical integrity of injection and existing wells due to long-term exposure to injected fluids, testing of models used for definition of the area of potential endangerment with data coming from demonstrations of commercial scale injection, potential health and ecological impacts associated with changes in water quality associated with injected fluids and mobilized contaminants, and socioeconomic considerations in the benefit/cost and life cycle analysis of GS.

Additionally, long term OW program goals should include an integrated approach to permitting such Class VI wells through a process that can be informed from ORD research. Tools can be developed that evaluate the cumulative impact on an environment, including local populations with environmental justice considerations, where multiple energy extraction and injection activities are occurring, such as GS, hydraulic fracturing, or in-situ solution mining. By evaluating these effects holistically, OW and ORD can ensure that energy activity permits are issued appropriately as to not endanger human health and the environment, including drinking water resources.

EPA research will be tightly coordinated with the DOE NETL research program in the CCS arena, with future research continuing to cultivate academic and federal partner collaboration.

3. Mining

Mineral resources also are important for the continued economic prosperity of society, and mining practices (whether extant, extinct, or future; surface or subsurface) have impacts on human health and environmental resources. Surface mining is a type of mining operation used when mineral deposits are located near the earth's surface, where overburden (soil and rock overlying a mineral deposit) is removed to gain access to the deposit. Mountaintop mining is a surface mining practice involving the removal of mountaintops to expose coal seams, and then disposing of the associated overburden in adjacent valleys (U.S. EPA, 2010c). Mining megasites are abandoned hardrock mining areas located throughout the United States, particularly in western states, that are extensive, expensive, complex, and controversial to clean up (NRC, 2005). Mining operations can produce several negative environmental impacts, such as acid rock drainage, large scale changes to surface hydrology, mobilization of naturally occurring contaminants (metals and metalloids) to adjacent water bodies, and excessive loading of sediments and/or dissolved solids to surface waters, and burying of streams in valley fill areas.

Questions

- What are the human health and environmental impacts of current, and future, mining practices on water resources?
- What new, innovative approaches are needed to assess impacts from mining activities?
- What are the individual and cumulative impacts of elevated concentrations of potential chemicals of concern (such as heavy metals, selenium, and TDS), and what is an acceptable level of these chemicals of concern in surface waters receiving mine discharges?
- What are the ecological effects in streams and rivers affected by valley fills and excessive sediment loads, and what are the impacts at the landscape level?
- What is the relationship between mining impacts in headwater streams and downstream water quality, and what are the cumulative risks of multiple, headwater mining operations within a watershed?
- What important water-rock interactions (geochemical and biogeochemical reactions) occur as water infiltrates mine waste materials and percolates to ground water, and what is the resulting influence on water quality?

- What geochemical and microbiological reactions predominate in surface and near-surface environments (ground water-surface water mixing zones), which reactions facilitate the attenuation of dissolved contaminants, and what is the stability of the immobilized contaminants?
- What treatment technologies and strategies can be used to protect surface and ground water resources and provide acceptable drinking water in areas impacted by surface mining?
- Which sites or ecological resources have the greatest ecosystem effect, either through their loss or preservation, and should receive priority in regards to protecting water resources?
- What new or better best management practices would minimize environmental impacts of mining?
- What societal practices (such as recycling or reuse) reduce the need for mining?

Outputs and Timelines

Through internal research and assessment projects, collaborative studies with other federal partners, and the STAR grant program, ORD is currently investigating biological, physical, and chemical processes that influence the generation of acid-rock drainage and facilitate the mobilization of contaminants in ground and surface waters. Current short-term research (over the next 2-5 years) should investigate the ability of the natural environment to attenuate potential contaminants of concern at the ground water – surface water interface, as well as evaluate the speciation and stability of the immobilized contaminants. More research (over the short to intermediate term) is needed to investigate the impact of excessive sediment and TDS loads on the ecological health of receiving waters with the goal of developing protective water quality criteria. Methods and tools are needed to rapidly, and reliably, assess toxicity in the field, and research is needed to better understand the correlation between the empirically-based field data and results derived from standard laboratory studies. We need to understand the connectiveness between mining activities in headwater streams and the resulting downgradient water quality. We also need to better understand cumulative risks and develop methods to conduct cumulative risk assessments in watersheds. Research on headwater and downstream connectiveness and cumulative risks in watersheds needs to be conducted over the intermediate to long term. ORD needs to work with partners and stakeholders to identify best management practices that optimize the sustainability of mining operations, thereby minimizing health and environmental risks. Where risks are unacceptable, we need to develop technologies and strategies that restore water resources to acceptable standards.

4. Impending Issues

Even though hydraulic fracturing, carbon capture and storage, and mountain-top mining are high priority issues in the Agency and will continue to be focus areas for ORD research, the Agency needs to keep an eye on future energy and mineral resource exploration and production issues and be proactive in understanding potential adverse environmental impacts in order to limit potential threats to health and the environment. As current energy and mineral reserves are depleted, new reserves will be identified and developed. The Agency needs to assure exploration and production activities do not impact sensitive ecosystems or vulnerable populations. The Agency needs to work with federal and state partners, tribes, communities, and industry to promote more efficient and environmental-friendly extraction technologies and strategies while at the same time assure these extraction activities are conducted with minimal harm human health or the environment. The Agency and its partners also need to develop and evaluate options for reducing and reusing waste materials and options for future land use after extraction activities have been completed, thereby minimizing post-extraction impacts associated with current and future resource extraction practices.

Society also has to make a conscious effort to reduce energy and mineral resource consumption. The Agency can play a major role here as well. The Agency needs to educate the public on the true cost of energy and mineral extraction activities. The Agency also needs to educate the public about options available to help minimize resource consumption (reuse, recycle, reduce). Providing sound information on the advantages and impacts of extraction practices, options to minimize consumption, and true costs will allow the public to make informed decisions about their future.

ORD needs to be proactive with its future research efforts on EMEI issues to assure safe and sustainable water resources. ORD needs to look to revolutionary approaches and innovative solutions for addressing EMEI issues, such as developing watershed-based permitting strategies and novel approaches to assess EMEI practices and potential vulnerabilities. ORD can work with Agency partners to develop watershed-based permitting strategies that take into account all water resources in a basin (both surface and ground water), current land use practices and risks, and future considerations and implications. Another area where ORD should concentrate is in developing innovative approaches to evaluating EMEI issues. One such idea is the combination of life cycle analysis and landscape assessment into an integrative concept tentatively termed "energy land." Energy land represents a geographically aware concept that assesses the energy land use potential of a place, including the atmosphere-surface-subsurface domains, and the associated water vulnerabilities. Energy land use potential includes the net energy supply, but also the potential to absorb energy waste, such as carbon sequestration. Water vulnerability is a function of the climate and hydrology of the place under current and projected future total water demands. For example, a given hectare of land might have competing energy land potential, such as a wind farm for electricity generation, corn growing for ethanol fuel, or coal and natural gas reserves below ground, and storage of CO_2 in a very deep saline sedimentary unit. These net energy potentials could be expressed in a common unit, e.g., MJ/hectare. Water vulnerability would compare the life cycle water needs of the energy land use to the water supply of the area. Given the high visibility of the three EMEI research topics highlighted in this paper (hydraulic fracturing, geologic sequestration, and mining), a first level demonstration of the energy land concept might involve the presentation of national scale maps of existing and potential mountain-top mines, storage reservoirs for geologic sequestration of carbon, and natural gas plays targeted for hydraulic fracturing, and, in the areas of overlap, quantify the water resource vulnerability.

IV. Summary

Energy and mineral extraction and injection activities already have an enormous impact on the Nation's surface and ground water resources. As current reserves are depleted and new reserves are explored and produced, additional impacts can be expected and these impacts will likely be greater and more diverse. Increasing demands for energy and mineral resources, the desire to supply a greater fraction of energy and mineral demands from domestic sources, and the need to mitigate the production and release of greenhouse gases all argue for greater diversification of energy and mineral extraction and injection activities. Evaluating the true life-cycle impacts and costs of current and future resource extraction/injection technologies and educating the public about the advantages and limitations of resources extraction/injection activities and options to minimize resource use and consumption will help reduce potentially harmful impacts to our health and our environment. As a leader in the scientific and environmental technology community, ORD will be a leader in providing the scientifically rigorous information and assessment techniques needed to assist society in making sound choices for a more sustainable future.

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Appendix D

Protecting Aquatic Ecosystems and their Supporting Watersheds

"that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of a community."

John Wesley Powell, on "what is a watershed?"

I. Problem Statement

Aquatic ecosystems, and their supporting watersheds, provide critical economic and social benefits to society. These benefits are currently threatened by a complex array of pressures and stressors, including nutrient and sediment loading, climate change, habitat alteration, introduction of invasive species, toxic pollutants and hydrologic alteration. Protecting the integrity and beneficial uses of aquatic systems is the primary goal of the Clean Water Act. Achieving this goal requires a detailed understanding of which human uses of watersheds create critical pressures and stressors, how those stressors interact, and how they cumulatively affect the structure and function of aquatic ecosystems. By assessing the condition of aquatic ecosystems, obtaining a systems understanding of the watershed processes that help to sustain condition, and quantifying the social, economic and environmental costs of water quality degradation, we can continue to protect, maintain and restore the integrity of the nation's aquatic resources. In order to deal effectively with the large number of watersheds that are currently degraded, we need to understand the factors affecting the probability of restoration success, so that restoration actions can be prioritized. And perhaps most importantly, we need to understand the factors that influence watershed resilience, so we can predict and mitigate the hydrological alterations to watershed processes that are likely to occur with climate change.

In the face of increasing anthropogenic pressures, sustaining and restoring aquatic ecosystem integrity will require that watersheds be understood and managed as complex ecological systems (Figure 1). The interactions of watershed-scale controls, climate, and human drivers control the key watershed processes that we observe as fluxes of water, sediment and organic matter, heat and light, and nutrients and chemicals. These process, in turn, act to regulate ecosystem structure and function, aquatic habitat formation and dynamics, species and community composition, and, ultimately, aquatic biological integrity.

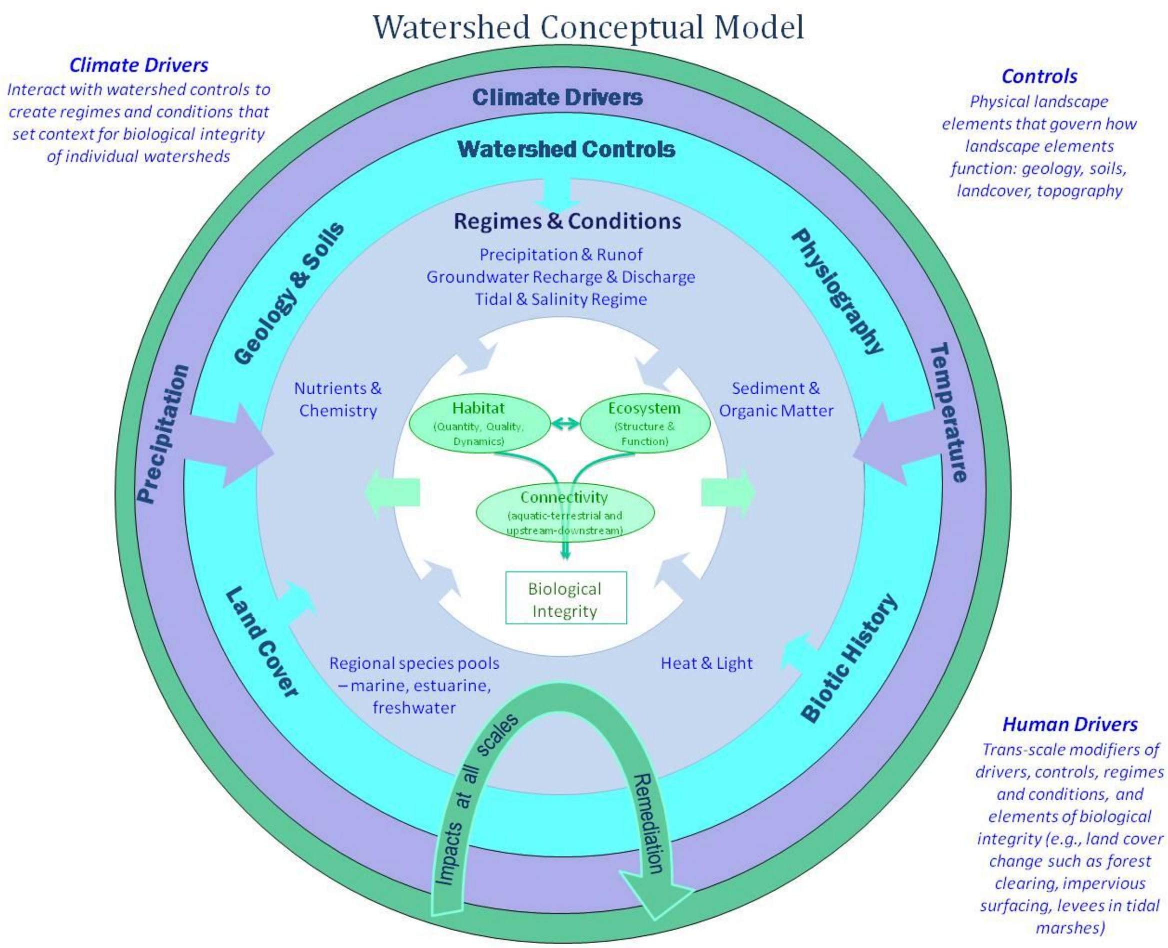

Figure 2. Conceptual model of a watershed showing the hierarchical relationship of drivers (e.g., climate and human activities), and physical elements in a watershed (e.g., geology, soils, and land cover) to processes that control the structure and function of watershed ecosystems (lentic, lotic, and coastal) (from US EPA. 2011. Healthy Watershed Integrated Assessments Synthesis Document. In review.)

II. Solutions

The primary goal of the Clean Water Act (CWA) is to "restore and protect the chemical, physical, and biological integrity of the nation's waters." Using a watershed approach to achieve this goal has been an EPA priority since the 1990s (US EPA, 1996). The approach is based on an understanding that the integrity of aquatic ecosystems is tightly linked to the watersheds of which they are a part. The approach may be implemented at a variety of scales (e.g., State, basin, small watersheds) depending on the context of the issues and decisions to be made. Using this framework, the Office of Water, EPA Regions, States, and citizen stakeholders work to protect existing aquatic resources and restore impaired water bodies, which are those that do not meet the chemical, physical or biological expectations of a natural condition.

Key information and data are needed to characterize valuable aquatic resources, to detect aquatic ecosystem impairment, and to determine where, when and how best to protect and rehabilitate these resources. A goal of ORD is to perform relevant research to address these key needs and to provide a strong technical foundation for understanding and implementing a watershed-based systems approach for regulatory protection.

Aquatic impairments often results from anthropogenic land uses that, despite social and economic benefits, have negative effects on aquatic ecosystem structure and function. Research conducted under this focal area (Protecting Aquatic Ecosystems and their Supporting Watersheds) will improve our understanding of the linkages between terrestrial and aquatic ecosystems and strengthen our ability to forecast how land usage and human activities in the watershed can affect adjacent and downstream aquatic ecosystems.

- **Goals:**

By 2025:

1. The critical attributes that define watershed integrity (e.g., natural hydrology, ecological processes, geomorphology, natural disturbance patterns) are thoroughly understood, allowing watersheds currently in good condition to be protected from degradation, and for the functional integrity of watersheds in degraded condition to be improved.
2. Human communities are understood as integral components of the watershed. Effective management strategies in the public and private sectors, aimed at optimizing the sustainable provisioning of economic, ecological, and social benefits within watersheds, are guided by a systems understanding of the watershed (understood as the totality of hydrological, ecological, economic, and social processes that occur within that system).
3. Members of the American public understand their impact on the watershed they live in, as well as the benefits they obtain from it, and thereby manage their behaviors to sustain its continued functioning.

III. Research Needs

This research program will focus on characterizing the relationship between human activities in the watershed and changes in biological and habitat condition in adjacent and downstream aquatic resources. This relationship can be used to identify thresholds for expected condition and to prioritize management activities (see Fig. 2 from Office of Water). Biological assessments are emphasized because changes in ecological condition reflect the cumulative response to multiple stressors. Ecological conditions that meet expectations of a natural condition (*attainment*) require continued protection. Ecological conditions that decline below expectations of a natural condition (*impairment,* as defined by the Clean Water Act) require restorative action, which can include stricter limits on stressors generated in the watershed. Development of scientifically defensible biological condition gradients and biological criteria are critical tools for informing management decisions on protection and restoration of aquatic ecosystems.

Research in this focal area will advance indicator and assessment methodologies. Approaches for assessment will vary depending on the resources to be protected and the watershed stressors that are anticipated. Assessment methods will succeed only if they reflect the condition of valued aquatic resources and are responsive (sensitive) to watershed stressors. Well-designed long term monitoring programs will provide relevant data for models to forecast future changes under alternative decisions and watershed changes.

Successful protection/restoration of aquatic ecosystems will require a better understanding of the characteristics (and those of their surrounding watersheds) that make them vulnerable or resilient to degradation, and that facilitate recovery from anthropogenic and natural disturbance. These factors will be critical in our ability to forecast future change, and to identify best management practices to promote protection, rehabilitation and restoration.

The effects and interactions of stressors generated outside of the watershed cannot be ignored. Regional and global stressors (e.g., climate change) can alter hydrologic, biogeochemical and biological processes that result in direct or indirect changes in ecological condition. Research to differentiate effects of watershed and regional/global stressors is necessary not only to understand cumulative impacts but to provide a backdrop for local managers to evaluate management options and performance measures. This research will serve to connect condition in individual watersheds to adjacent watersheds and the global system.

The results of this research should guide and focus the types and locations of restoration and rehabilitation measures implemented regionally and nationally. Importantly, this focal area should include programs to assess whether these restoration efforts have their intended consequences—the recovery of critical watershed/ecosystem processes—and whether the sum total of individual restoration efforts results in a measurable improvement in ecosystem conditions nationally.

Performance of any regulatory program is reviewable by the regulated community. Measures of performance must resonate with stakeholders so that they understand the value of any limitations placed upon them. Successful performance can be marked by the return of an aquatic ecosystem to a condition in which ecosystem processes are highly functional, and habitat integrity is attained. But performance measures can also be broadened to illustrate the natural benefits gained from sustaining the ecological integrity of a the system. Research in this focal area will pursue development of performance indicators and criteria that demonstrate not only ecosystem integrity, but values inherent to that integrity.

Research in this focal area will develop tools to understand the economic and social consequences of aquatic ecosystem degradation. Benefits provided by aquatic ecosystems are too often considered free and limitless, so resolve to protect them is diminished. Demonstrating the economic and social value provided by natural ecosystems (e.g., protection of safe drinking water supplies, viable fisheries, flood risk, recreational use, biodiversity, property values) will elevate public involvement in the development of non-regulatory protection and enforcement of environmental regulations.

> [Q] How can we best characterize and measure watershed condition and critical watershed processes? How do these factors vary across a range of spatial and temporal scales?
>
> > [Out] Short-Term (5-10 years): Evaluation of core metrics and methods for integrated assessments of watersheds integrity at multiple scales, including:
> >
> > - Metrics and indices of biological and habitat condition

- Metrics and indices of watershed physical processes (i.e., natural flow regimes, hydrologic connectivity, groundwater quality and transport, fluvial geomorphic processes, thermal regimes)
- Metrics and indices of chemical water quality, and critical chemical/biogeochemical processes
- Landscape-level metrics and indices of watershed integrity

[Out] Short-Term (5-10 years): Development of an integrated index of watershed integrity, and/or methods to quantify multiple aspects of watershed integrity

[Out] Short-Term (5-10 years): Development of efficient and cost-effective methods for assessing status and trends in watershed integrity at multiple scales, including biological, chemical and physical (e.g., geomorphology and material transport) factors

[Out] Long-Term (20 years): Creation of watershed classification system to simplify extrapolation of measurements to unassessed watersheds

[Out] Long-Term (20 years): Development of models and indicators to estimate watershed integrity in unassessed watersheds

[Out] Long-Term (20 years): Development of methods to support creation comprehensive nationwide maps of watershed integrity at the 12 digit HUC scale

[Q] How do we best incorporate market and non-market values into our prioritization decisions and policies on watershed and drinking water source protection and restoration?

[Out] Short-Term (5-10 years): Identify barriers to internalizing costs of degraded watershed integrity in public and private sectors decisions

[Out] Short-Term (5-10 years): Identify barriers to understanding costs of water/watershed quality in decisions made by American citizens, and develop methods to transfer this information effectively to decision-makers

[Out] Short-Term (5-10 years): Cost-benefit analyses to explore the long-term net benefit of protecting green infrastructure, habitat, processes sustaining healthy watersheds, and drinking water sources

[Out] Long-Term (20 years): Development of methods to support creation of nationwide maps of the costs of degraded water quality and benefits of water quality for watersheds at the 12 digit HUC scale

[Out] Long-Term (20 years): Engage private and public sector forces to overcome barriers to internalizing water quality costs

[Out] Long-Term (20 years): Creation of decision-support tools to aid development of market-based activities that promote watershed integrity

[Out] Long-Term (20 years): Development of guidance for advancing public support for payment of watershed services

[Out] Long-Term (20 years): Development of ecological and economic indicators that serve as basis for water/watershed quality trading

[Q] What watershed characteristics promote the sustainable, high quality condition of aquatic ecosystems? How do we identify the factors that influence resilience and vulnerability to watershed stressors, including climate and landuse change. How do these factors vary across a range of spatial and temporal scales?

[Out] Short-Term (5-10 years): Development of metrics and indices of watershed resilience that incorporates measurements at smaller scales (i.e., of the components that comprise the watershed)

[Out] Short-Term (5-10 years): Assessment of which Best Management Practices protect watershed characteristics promote resilience

[Out] Short-Term (5-10 years): Development of metrics and indices of vulnerability and restoration potential

[Out] Short-Term (5-10 years): Development of indicators and monitoring methods to detect changes in condition and/or function due to climate change and other perturbations

[Out] Long-Term (20 years): Development of models to estimate watershed status and recovery potential

[Out] Long-Term (20 years): Development of methods to support creation of comprehensive nationwide maps of resilience, recovery potential, and restoration priorities, by watershed

[Q] What pressures and stressors are most responsible for loss of ecosystem integrity? How do we improve our assessments of multiple, interacting causal factors? How do we scale these results up to support decision-making at the regional and national level?

[Out] Short-Term (5-10 years): Use of biological and habitat data to diagnose impairment

[Out] Short-Term (5-10 years): Landscape-level metrics/indices of impairment

[Out] Short-Term (5-10 years): Improved methods for statistical modeling of individual stressor-response relationships from observational data given the influence of other stressors and spatial relationships

[Out] Short-Term (5-10 years): Improved methods for developing benchmarks for individual stressors (especially nutrients, salts and flow alteration) based on observational data

[Out] Long-Term (20 years): Improved transfer of knowledge to states to improve their designation of causes under the 303d listing program

[Out] Long-Term (20 years): Development of models to extrapolate causes for unassessed watersheds

[Out] Long-Term (20 years): Development of methods to support creation of comprehensive nationwide maps of stressors responsible for impairment for watersheds at the 12 digit HUC scale

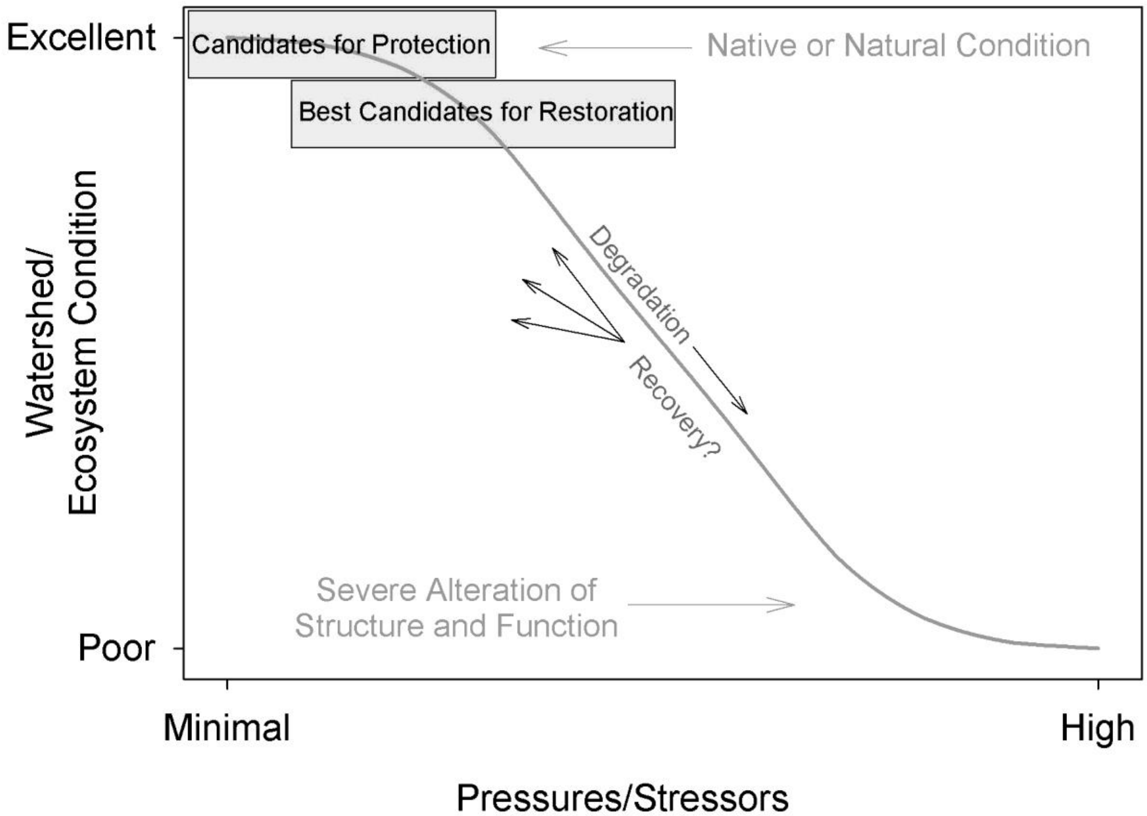

Figure 2. Conceptual model of watershed/aquatic ecosystem responses to anthropogenic stressors

The list below, while not comprehensive, outlines the indicators for which tools will be needed:

Economic	Social/Public Health	Environmental
Production of fisheries	Recreational value	Biotic Integrity
Reduced flood risk	Drinking water supply	Biodiversity
Irrigation supply	Biophilia/Aesthetics	Aquatic habitat quality
Drinking water treatment	Existence Value	Riparian habitat quality
Industrial water supply	Mental Health	Water quality
Storm protection	Property Values	Trophic state
Navigation	Carbon sequestration	Sediment supply
Sustainable forestry		Stream connectivity
Water storage		Resilience
Pharmaceutical discovery		Geomorphic integrity
Hydropower		Habitat connectivity
TMDL avoidance		In-stream and groundwater flow

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Appendix E

Contaminants and Industrial Processes

I. Problem Statement

Protection of aquatic systems, both as ecological entities and as sources of water for drinking and other human uses, is compromised by shortcomings in our abilities to adequately assess and mitigate the full range of risks posed by waterborne contaminants (chemicals and microbial pathogens). The rate at which waterborne chemical hazards are assessed with traditional approaches cannot keep pace with the rate of which new chemicals are being introduced. Better understanding the risks of chemicals is also challenged by increasingly complicated mixtures of chemicals, uncertainties about chemical transfer and transformations within the environment, and inadequacies in monitoring in situ exposures and effects. This inability to adequately assess chemical risks hinders the evaluation and advancement of remediation strategies. Similar issues compromise the assessment of microbial pathogens, including insufficient virulence data, uncertain fate and transport in the environment, and incomplete understanding of the effectiveness of treatments. Mitigation of risks typically emphasizes treatment rather than prevention, and available treatments are often costly and can result in the creation of hazardous byproducts or residual wastes that require further management. Institutional compartmentalization of the evaluation and management of wastewater, natural water bodies, and drinking water makes addressing the total problems less effective, and all of this is occurring in a period when increasing population and expanding energy demands are requiring more efficient use (and re-use) of finite water resources.

II. Solutions

A more sustainable path for the Nation's water resources requires better integrating our understanding, assessment, and management of chemical and microbial threats across the entire water cycle, and doing so in a way that recognizes the connections of water resources to the social, environmental, and industrial functions they serve. Figure 1 illustrates this connectivity with regard to chemical contaminants. It depicts the societal demand for and industrial production of chemical products, and their release to the environment and consequent effects. The figure also illustrates that, through ecological services, the environment is a source for raw materials for industry as well as providing other resources (e.g. drinking water supplies) to society. Risk assessments are needed for chemical exposures to aquatic ecosystems and humans from combined point and non-point sources. These assessments should inform risk management (e.g. treatment, management practices, regulation) to reduce exposures as needed. Risk communication is needed to inform society, industry, and other stakeholder groups of the conclusions drawn from assessments and management recommendations.

Research areas to improve sustainability of water resources are represented within the grey nested boxes (as well as the orange risk management boxes) of Figure 1, and involve both improving risk characterization with better exposure and effects assessments and reducing risks with improved treatment options and with production/use of less hazardous products. This research needs to consider the interactions depicted in Figure 1. For example, if more efficient toxicological screening tools were available, prioritization of emerging contaminants could help inform those doing research on improved treatment technologies to focus efforts on addressing the most toxic chemicals. These toxicity screening approaches in turn should be informed by improved information on the occurrence of contaminants of emerging concern in U.S. waters.

The goal for sustainability of water resources should be that water is returned to a watershed in a quality and quantity as close as feasible to when it was withdrawn, and avoids significant adverse effects on humans and aquatic ecosystems. Discharges to water bodies should be compatible with the requirements of the next (downstream) use. Net consumption of fossil energy required in the acquisition, preparation, distribution, collection, treatment, and release of water should be minimized. Certain social conventions, such as the use of drinking-quality water for all domestic uses, may require re-examination. The respective roles of individuals, industry, and agriculture in preventing unnecessary contamination of water resources may need to shift.

As suggested by the goals above and by Figure 1, effecting appropriate changes in our approach to risks from chemical and pathogens in water will require broader thinking about the larger system. Systems models and other evaluation tools are needed that can integrate and aggregate risks and benefits from a variety of alternatives, such that efficiencies in one sector of the system do not create disproportionate costs in another. For example, efficiencies in food production offered by confined animal feedlot operations must be evaluated against costs that might accrue if such facilities also release excessive pathogens, nutrients, or chemicals. Risk management needs to focus not only on technologies to treat chemicals once they have been used and released, but also consider alternatives such as process modification, product substitution, or recovery/reuse. In addition to serving as the foundation for developing sustainable alternatives, such system analyses are critical to inform society regarding risks, benefits, and more sustainable alternatives.

III. Research Needs

ORD in general and this document specifically can only address some aspects of Figure 1. In general, ORD has two primary roles: 1) to develop the means to effectively assess and communicate risks and benefits to both scientific and public audiences; and 2) identify/develop tools and technologies that would support risk reduction as needed. Within the specific charge of this document - chemicals and pathogens in water - categories were created to cluster research efforts for improving tools for sustainability of water resources. These categories are:

- Reduce the number, amount, and hazard of contaminants entering waste streams.
- Improve our ability to monitor the occurrence and effects of chemical and microbiological contaminants in the environment and drinking water supplies.
- Improve our ability to estimate ecological and human risk for chemical and microbial contaminants that do enter water resources.
- Develop sustainable means to treat or otherwise manage contaminants that cannot be otherwise controlled.

Objective 1: Reduce the number, amount, and hazard of contaminants entering waste streams.
This category relates to a variety of possible industrial and societal activities, including reducing the need for chemicals to meet specific needs, waste minimization by reuse and recycling, and re-engineering or substitution of chemicals toward those less hazardous, less persistent, and/or more easily treated. Also included would be improved management of watershed activities to reduce non-point sources of contaminants, and elimination of practices that may exacerbate contamination problems. Although ORD will conduct research on some aspects of such waste reduction, this primarily involves actions in the private sector and consideration therefore is also needed regarding what EPA should do to define the need for and facilitate such actions.

An important component of facilitating improvements in this area will be evaluations that clearly show the benefits of sustainable alternatives in ways that justify regulations or motivate private actions. Use of systems and life-cycle analyses can better connect product or behavioral choices with their broader costs and consequences, and create more public awareness and understanding of their impact on the water cycle as well as how alternatives can benefit water resources. Frameworks that can identify potential chemical or pathogen risks at early stages in product or process development will help cost-effectively avoid introduction of new contaminants; in this regard there are close ties to additional ORD research planned under the Chemical Safety and Sustainability research plan. However, while reducing or avoiding chemical use is an important component of reducing potential risks to water resources, it is clear that the need to use chemicals in both industrial and domestic settings will continue. As such, it is important to also focus attention on designing and using chemicals that can be more easily removed prior to entering the environment, will degrade rapidly and/or are less hazardous.

While direct regulation will undoubtedly play a role in creating change, it is likely that sufficient change will also depend on both individuals and institutions voluntarily changing behaviors. Therefore, it will be important to communicate research strategies and goals, study designs, plans and results with partners, stakeholders and the public, and to engage these groups at each stage of the process. A risk communication strategy should be developed that can relay scientific findings of research questions and how each of these groups may be impacted, or receive benefit. As the public and industry become aware of various issues, changes could then occur in the chemicals being produced and/or the products purchased. Incentive programs like EPA's Presidential Green Chemistry Challenge and Energy Star Program need to be considered as part of this process.

Questions

- What effective economic valuation tools exist or could be developed to determine the benefits and costs of prevention and remediation strategies?
- What assessment tools could be developed for contaminant life cycle analyses that could aid in predicting the toxicity and treatability of contaminants in water resources and how could this be incorporated into product design?

- How can industrial processes and consumer products be improved to reduce the amount, hazard and persistence of chemicals discharged to water resources?
- What management and technology practices could be used to minimize the release of pathogens into receiving waters?
- What models could be developed to forecast pathogen and contaminant risk scenarios when alternative water disinfection strategies are applied to differing source waters and complex chemical mixtures in drinking water?

Outputs and Timelines

- Short-Term (5 yr): A report that characterizes the relative toxicity between DBP mixtures and microbial protection resulting from chlorination versus chloramination considering various field matrix conditions.

Objective 2: Improve our ability to monitor the occurrence and effects of chemical and microbiological contaminants in the environment and drinking water supplies.

While efforts to reduce the use and/or release of aquatic contaminants will be very important, releases will still occur, necessitating efficient and comprehensive means to monitor contaminants present in aquatic ecosystems and drinking water systems. Improved and more cost-effective methods to identify and quantify the occurrence and ambient effects of new and emerging waterborne contaminants are needed in order to make adequate judgments about protecting human health and the environment.

The vast array of potentially hazardous contaminants that could be present in water presents an enormous challenge, so that effective prioritization of contaminants will be needed to focus exposure assessment on those contaminants (or groups thereof) most likely to pose risks. Although existing analytical techniques allow the detection of many chemicals in water at very low concentrations, further improvements are needed to allow more frequent and extensive, and less costly, monitoring of chemicals in water. Improved techniques to assess the pathogenic potential of environmental microbes are also needed, both for known pathogens and identification of new pathogens of concern. Exposure assessments also require better knowledge of transport and transformations of contaminants in drinking water, wastewater, and natural ecosystems.

In some cases, biological measures or assays are needed to supplement traditional analytical approaches, allowing assessment of toxicological or pathological potency of effluents and ambient waters containing mixtures of contaminants that are have uncertain aggregate effects. Biomarkers of exposure to or effects from contaminants need to be improved regarding their cost-effectiveness, their relationship to ecosystem and human health, and their ability to indicate causes. Effluent toxicity tests also need to be improved regarding their relationship to impacts on aquatic ecosystem. Another aspect of effects monitoring is documentation of impairments in human populations and aquatic communities, and diagnosing the causes of these impairments. Human epidemiology and aquatic community characterization/diagnosis methods are other areas of needed research and development for supporting sustainable water resources, but are also a topic of other ORD research programs and thus another area of needed coordination for SSWR.

Questions

- What cost effective field monitoring and laboratory methods need to be developed to determine the occurrence, frequency and concentration of contaminants and groups of contaminants of emerging concern, legacy chemicals and pathogens in our nations water resources and drinking water supplies?
- How can biological measures (biomarkers) be employed to enhance our ability to detect occurrence of pathogens, chemicals, or groups of chemicals, and to infer potential adverse effects on humans and aquatic organisms?
- What strategies or approaches are available to act as an early hazard identification system of emerging waterborne pathogens?
- How can approaches for testing the toxicity of effluents, non-point discharge, and ambient water be improved to better assess risks of chemical discharges to aquatic communities?
- How can the aquatic community assessments be improved to cost-effectively document and diagnose impairments?
- What analytical methodologies, monitoring strategies, and models are needed to determine changes in distribution system water quality due to sorption to or leeching from pipe materials and resuspension of biofilms?

- What analytical methodologies, monitoring strategies, and models are needed to determine the occurrence of distribution system intrusion by pathogens or chemicals and what are the human health risks due to the presence of these contaminants?

Outputs and Timelines

- Short-Term (5 yr): Analytical methods with sufficient sensitivity to inform the occurrence of contaminants and groups of contaminants to adequately inform their health risk potential.

Objective 3: Improve our ability to estimate ecological and human risk for chemical and microbial contaminants that do enter water resources.

Decisions about improving the sustainability of our water resources depend on good information regarding the risks of contaminants to aquatic ecosystem and human health. This category of research is concerned with a variety of uncertainties and limitations regarding how well those risks can currently be defined.

A great challenge for ecological and human health risk assessors is to assess more chemicals and types of endpoints with greater speed, while decreasing animal testing and using fewer resources. For EPA's Office of Water, an example of this is to identify what chemicals warrant development of drinking water criteria from a large number of candidate chemicals. The historical dependence on large numbers of in vivo toxicity tests must be reduced in favor of frameworks that make greater use of computational and in vitro techniques with only limited and highly targeted whole-organism testing. To this end, in 2007, the National Academies of Science released an expert panel report, Toxicity Testing in the 21st Century, which described a vision for the future of toxicity testing to support human health risk assessments. The report emphasized the need to develop a focused assessment approach (the Toxicity Pathway) that maximizes use of existing knowledge, while minimizing reliance on resource-intensive testing approaches. Ankley et al. (2010) proposed a framework for ecological research and assessment using the concept of Adverse Outcome Pathways (AOP). Both proposed paradigms focus on the initiating event between a toxic chemical and a biomolecule and the cascade of events at various levels of biological organization that lead to effects of concern. By supporting extrapolations across chemicals, species, and endpoints and by integrating information from molecular biology, computational toxicology and bioinformatics, etc., these frameworks, and the tools to support them, can help expedite the screening and prioritization of chemicals for more refined assessments for chemicals of high potential threat. ORD has ongoing research regarding this that is being incorporated into the CSS research program, which is another needed point of coordination for the SSWR program.

Another challenge facing chemical assessments is that of addressing groups of chemicals – both to more efficiently assess individual chemical effects using information from similar chemicals and to assess the combined effects of mixtures. Mixtures in source and drinking water can consist of many classes, such as pesticides, pharmaceuticals, metals, organic solvents, and disinfection by-products; addressing contaminants by groups would improve both the efficiency and effectiveness of risk assessment compared to traditional contaminant-by-contaminant approaches. Currently, the Office of Pesticide Programs, Office of Water, and Office of Solid Waste and Emergency Response do address drinking water mixtures as part of their environmental assessments under The Food Quality Protection Act of 1996, The Safe Drinking Water Act Amendments of 1996, and The Comprehensive Environmental Response, Compensation, and Liability Act. The success of these approaches depends on how efficiently contaminants are grouped. Current strategies exist to group chemicals include considerations of exposure co-occurrence, similarities in toxicity (e.g., same target tissue) and feasibility of monitoring and remediation. If toxicity or exposure data are lacking, chemicals can be grouped based on structural similarities of the chemicals of concern. Using the concept of toxicity pathways/AOPs described above can improve this grouping and the interpretation of effects from complex mixtures.

With regard to microbial effects, both the impact of pathogens on human health and the effect of changing microbial populations in the environment must be considered. Methods that can accurately discriminate between pathogenic and non-pathogenic strains are critical to risk assessment, but these tools need to be developed under a paradigm that links changes in the ecological landscape with the occurrence of known pathogens and emergence of novel pathogens. Understanding mechanisms that can accelerate the selection, evolution, or reproduction of pathogens in the environmental will be critical to improving assessment and management of the associated risks. Approaches are needed that can accurately discriminate between viable/infectious microorganisms and less harmful forms (stressed/non-infectious forms), as well as movement among hosts (including wildlife), to improve microbial risk assessment and epidemiology. The role of the microbiome in determining human health is emerging (Fujimura et al., 2010), as is our understanding of the nature of microbial pathogenicity and the interrelationships of microbes and chemicals in producing disease.

A few other challenges to aquatic risk assessments need consideration in the SSWR research program. Effects of chemicals on aquatic organisms have historically been assessed using single "pass-fail" criteria developed for single exposure media (water, sediment, tissue). Ecological risk assessment and the environmental criteria they support must move toward simultaneous consideration of all exposure routes. Moreover, these evaluations must move toward expressing a continuum of effect as a function of exposure intensity, so that evaluations of the costs or benefits of environmental alternatives can be made as a part of system-wide sustainability analyses. Another aspect of better defining risks in such analyses, and thus prioritizing chemicals for remediation options, is to consider how various environmental factors affect toxicity, including non-chemical stressors. There are related needs for improved techniques for cumulative risk assessment, which addresses multiple chemical stressors and non-chemical stressors, building upon epidemiological principles and related risk assessment efforts to facilitate identification of causal agents.

Questions

- What approaches should be used to apportion specific contributions of contaminants (specific contaminants and contaminant groups) from drinking water sources to total exposure levels detected in humans?
- What new models and approaches for both exposure and effects from pathogens have to be developed to assist in microbial source tracking and exposure reconstruction (e.g. assessing the relative importance of animal and human fecal pathogen contributions to microbial contamination in receiving waters)?
- What are the best tools to rapidly and efficiently prioritize single contaminants and groups of contaminants (chemicals and pathogens) for criteria and CCL development?

- What approaches exist or could be developed that could provide rapid, cost-effective effects characterization for new or existing chemicals, groups of chemicals and biological contaminants?
- What approaches should be used to assess contaminant effects on human subpopulations with different susceptibilities?
- How can aquatic life risk assessments and criteria better describe gradients of aquatic community effects to better inform risk management and cost/benefit analyses?
- What models and approaches should be used to address multiple routes of exposure and bioavailability in risk assessments?
- What methods should be used to describe the combined effects of chemical, microbial and nonchemical stressors in humans and aquatic species?
- How, and with what reliability, can aquatic life criteria be developed using more limited data than required by existing methodology?
- What byproducts are formed during the disinfection of drinking water and wastewater and what are the relative health risks for these transformation products compared to the parent compounds?
- What research approaches, tools or models can be developed to determine which contaminant(s), group(s) of contaminants or DBP(s) in the complex mixture are associated with drinking water risks found in epidemiological studies, such as potential bladder cancer, early-term miscarriage, and birth defects? And, subsequently, what drinking water technologies (including precursor removal and choice of disinfectant) can be used to minimize or eliminate those risks?
- How can exposure and toxicity characterizations be combined to assess the risks from microbial pathogens, chemical contaminants and contaminant groups in both finished drinking waters and waste waters to best enable comparisons and forecasts of risks from common or conventional treatments vs. new or alternative drinking water and waste water treatment strategies?
- What approaches can be developed to evaluate the public health and ecosystem implications of water reuse?

- What methods or approaches are needed to evaluate the public health and ecosystem implications of exposure to Concentrated Animal Feedlot Operations (CAFOs) and other biological and industrial discharges?

Outputs and Timelines

- Short-Term (5 yr): A methodology and reports that provide rapid health effects and relative risk characterization for new or existing chemicals and groups of chemicals to inform PCCL and CCL contaminant selection (available to inform CLL4 and future listings).
- Short-Term (5 yr): A protocol that can inform the relative toxicity of DBP mixtures resulting from existing and innovative treatment schemes (e.g., chlorination and chloramination substitution technologies such as ferrate and UV).
- Short-Term (5 yr): A report that characterizes the public health and ecosystem implications of water reuse in challenged areas of the country and informs possible policy options for the conditions when and how water reuse may be most appropriate.
- Short-Term (5 yr): A report that characterizes public health and ecosystem implications from exposure to CAFOs and other biological and industrial discharges.

Objective 4: Develop sustainable means to treat or otherwise manage contaminants that cannot be otherwise controlled.

This final category of research concerns risk reduction – of contaminants in waste streams to aquatic ecosystems and those in source waters to drinking water supplies – by improved wastewater and drinking water treatment. There is a need to improve upon wastewater management and drinking water protection by building on past technological practices to incorporate new innovations, green chemistry principles, information management, and risk assessment, coupled with an increased understanding of water system integrity. This path begins with better understanding the effectiveness of established treatments approaches for removing specific contaminants and contaminant groups, and of the environmental and health costs of byproducts resulting from the treatment. Particularly for wastewater treatment, future emphasis on reducing the required energy inputs is important, incorporating more use of "green infrastructure" and processes that can be fueled in large part by energy recovered within the treatment process itself. Demands for drinking water treatment include better disinfection effectiveness with fewer undesirable by-products and selective removal of priority chemicals where necessary, all while reducing net energy use. Included within this is the need for systems suitable for small communities where financial and technical limitations may be especially challenging. Protocols are needed that can provide an unbiased evaluation of both the immediate effectiveness and the overall sustainability of different treatment alternatives.

The public and private sectors should be engaged in developing and evaluating sustainable drinking water systems of the future that advance public health protection through addressing the full spectrum of ecological and public health concerns in conjunction with watershed and source water characteristics. There is a need to establish collaborations with universities, and the private sector, to develop new treatment technologies that can cost-effectively and reliably reduce health risks, through control of the types of contaminants that confront utilities today and in the future and incorporate water quality, availability, and energy constraints. Characterization of existing and emerging waterborne chemicals in aquatic ecosystems and drinking water sources along with development of treatment and remediation technologies will support efforts to quantify and reduce the potential risk of waterborne contaminants in aquatic ecosystems and drinking water. These collective advancements will continue to be integral to EPA's mission of protecting human health and the environment.

Questions

- What are the current status and likely trends in the quantities and qualities of our regional groundwater and surface water used for drinking water and other domestic uses, energy production and other industrial uses, agriculture, aquatic dependent plants and wildlife, and recreation?
- What integrated, cost-effective approaches to water resource protection, intervention, and restoration activities can be developed for watersheds?
- What tools, models or other innovative approaches can be developed to assess the effectiveness of best management practices used to reduce non-point sources of pollution?
- How can we verify the efficacy of new treatment technologies or pollution prevention approaches to protect human and aquatic ecosystems?

- How can chemical exposure characterization, toxicity characterization, and risk assessment be combined to assess and compare the microbial safety and the risks from contaminants and contaminants groups in both finished drinking waters and wastewaters treated with common and new disinfectant and wastewater treatment strategies?
- What innovative technologies can reduce the net energy requirements of drinking water and wastewater treatment?
- How can water treatment waste residuals and biosolids management approaches be managed more sustainably?
- What new drinking and waste water treatment technologies can be developed that are energy efficient, inexpensive, and practical for small communities and on-site uses?
- What protocols can be developed to evaluate innovative treatment and remediation strategies of drinking water and waste water from the private sector?
- What approaches can be developed to assess how drinking water treatment and distribution system management impact the water quality within the distribution system?
- What risk management approaches can be developed to address ecological and human health impacts of source waters that are impaired or alternative source waters that are utilized due to increased wastewater inputs, drought, climate change, or other impacts?

Outputs and Timelines

- Short-Term (5 yr): A report that characterizes different approaches for protecting watersheds to support priority CWA policy decisions.
- A report giving protocols and basis for evaluating treatment and remediation strategies of drinking water and waste water.

IV. References

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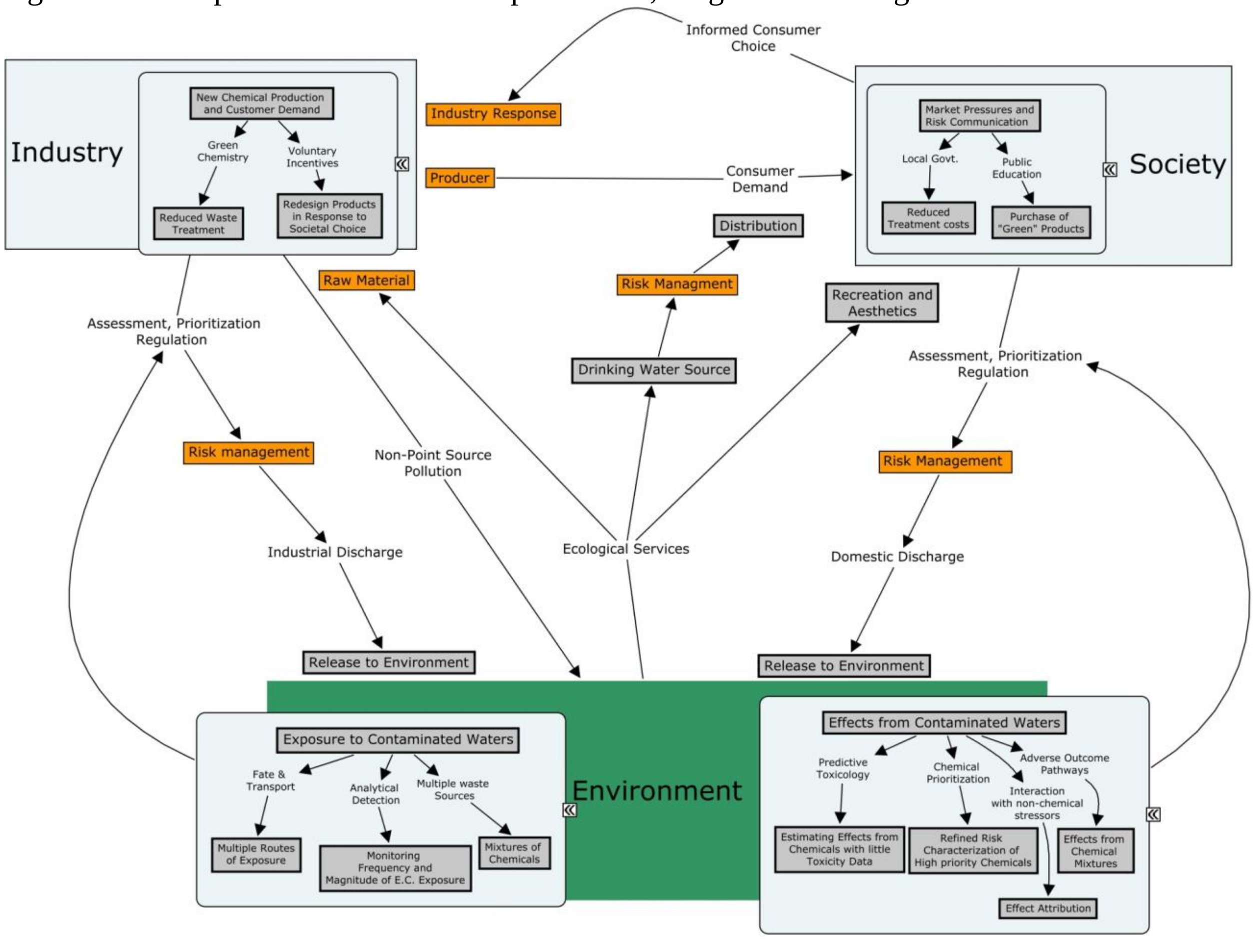
Figure 1. Conceptual flow of chemical production, usage and discharge to the environment



A. Reduce the number, amount and hazard of contaminants that enter waste streams that can impact water resources.

Question	Output
1. What effective economic valuation tools exist or could be developed to determine the benefits and costs of prevention and remediation strategies?	
2. What assessment tools could be developed for contaminant life cycle analyses that could aid in predicting the toxicity and treatability of contaminants in water resources and how could this be incorporated into product design?	
3. How can industrial processes and consumer products be improved to reduce the amount, hazard and persistence of chemicals discharged to water resources?	
4. What management and technology practices could be used to minimize the release of pathogens into receiving waters?	
5. What models could be developed to forecast pathogen and contaminant risk scenarios when alternative water disinfection strategies are applied to differing source waters and complex chemical mixtures in drinking water?*	A report that characterizes the relative toxicity between DBP mixtures and microbial protection resulting from chlorination versus chloramination considering various field matrix conditions.

B. Improve detection of the presence of chemical and microbiological contaminants (and/or their effects) in the environment.

Question	Output
1. What cost effective field monitoring and laboratory methods need to be developed to determine the occurrence, frequency and concentration of contaminants and groups of contaminants of emerging concern, legacy chemicals and pathogens in our nations water resources and drinking water supplies?*	Analytical methods with sufficient sensitivity to inform the occurrence of contaminants and groups of contaminants to adequately inform their health risk potential.
2. How can biological measures (biomarkers) be employed to enhance our ability to detect occurrence of pathogens, chemicals, or groups of chemicals, and to infer potential adverse effects on humans and aquatic organisms?	
3. What strategies or approaches are available to act as an early hazard identification system of emerging waterborne pathogens?	
4. How can approaches for testing the toxicity of effluents, non-point discharge, and ambient water be improved to better assess risks of chemical discharges to aquatic communities?	
5. How can the aquatic community assessments be improved to cost-effectively document and diagnose impairments?	
6. What analytical methodologies, monitoring strategies, and models are needed to determine changes in distribution system water quality due to sorption to or leeching from pipe materials and resuspension of biofilms?	
7. What analytical methodologies, monitoring strategies, and models are needed to determine the occurrence of distribution system intrusion by pathogens or chemicals and what are the human health risks due to the presence of these contaminants?	

1= Region 6 TMDL Unit
2 = OW HQ Office of Ground Water and Drinking Water
3 = OW Office of Science and Technology
4 = Region 6 Ecosystems Protection Branch

C. Improve the ability to estimate ecological and human risk (exposure and effects) for chemical and microbial contaminants that do enter water resources.

Question	Output
1. What approaches should be used to apportion specific contributions of contaminants (specific contaminants and contaminant groups) from drinking water sources to total exposure levels detected in humans?	
2. What new models and approaches for both exposure and effects from pathogens have to be developed to assist in microbial source tracking and exposure reconstruction (e.g. assessing the relative importance of animal and human fecal pathogen contributions to to microbial contamination in receiving waters)?	
3. What are the best tools to rapidly and efficiently prioritize single contaminants and groups of contaminants (chemicals and pathogens) for criteria and CCL development?*	A methodology and reports that provide rapid health effects and relative risk characterization for new or existing chemicals and groups of chemicals to inform PCCL and CCL contaminant selection (available to inform CLL4 and future listings).
4. What approaches exist or could be developed that could provide rapid, cost-effective effects characterization for new or existing chemicals, groups of chemicals and biological contaminants?*	Same as 3
5. What approaches should be used to assess contaminant effects on human subpopulations with different susceptibilities?	Same as 3
6. How can aquatic life risk assessments and criteria better describe gradients of aquatic community effects to better inform risk management and cost/benefit analyses?	
7. What models and approaches should be used to address multiple routes of exposure and bioavailability in risk assessments?	
8. What methods should be used to describe the combined effects of chemical, microbial and nonchemical stressors in humans and aquatic species?	
9. How, and with what reliability, can aquatic life criteria be developed using more limited data than required by existing methodology?	
10. What byproducts are formed during the disinfection of drinking water and wastewater that and what are the relative health risks for these transformation products compared to the parent compounds? *	
11. What research approaches, tools or models can be developed to determine which contaminant(s), group(s) of contaminants or DBP(s) in the complex mixture are associated with drinking water risks found in epidemiological studies, such as potential bladder cancer, early-term miscarriage, and birth defects? And, subsequently, what drinking water technologies (including precursor removal and choice of disinfectant) can be used to minimize or eliminate those risks?*	
12. How can exposure and toxicity characterizations be combined to assess the risks from microbial pathogens, chemical contaminants and contaminant groups in both finished drinking waters and waste waters to best enable comparisons and forecasts of risks from common or conventional treatments vs. new or alternative drinking water and waste water treatment strategies?*	A protocol that can inform the relative toxicity of DBP mixtures resulting from existing and innovative treatment schemes (e.g., chlorination and chloramination substitution technologies such as ferrate and UV).
13. What approaches can be developed to evaluate the public health and ecosystem implications of water reuse?*	A report that characterizes the public health and ecosystem implications of water reuse in challenged areas of the country and informs possible policy options for the conditions when and how water reuse may be most appropriate.
14. What methods or approaches are needed to evaluate the public health and ecosystem implications of exposure to Concentrated Animal Feedlot Operations (CAFOs) and other biological and industrial discharges?*	A report that characterizes public health and ecosystem implications from exposure to CAFOs and other biological and industrial discharges.

D. Develop sustainable means to manage contaminants that cannot be otherwise controlled.

Question	Output
1. What are the current status and likely trends in the quantities and qualities of our regional groundwater and surface water used for drinking water and other domestic uses, energy production and other industrial uses, agriculture, aquatic dependent plants and wildlife, and recreation?	
2. What integrated, cost-effective approaches to water resource protection, intervention, and restoration activities can be developed for watersheds?*	A report that characterizes different approaches for protecting watersheds to support priority CWA policy decisions.
3. What tools, models or other innovative approaches can be developed to assess the effectiveness of best management practices used to reduce non-point sources of pollution?*	A report that characterizes different approaches for protecting watersheds to support priority CWA policy decisions.
4. How can we verify the efficacy of new treatment technologies or pollution prevention approaches to protect human and aquatic ecosystems?	
5. How can chemical exposure characterization, toxicity characterization, and risk assessment be combined to assess and compare the microbial safety and the risks from contaminants and contaminants groups in both finished drinking waters and wastewaters treated with common and new disinfectant and wastewater treatment strategies?	
6. What innovative technologies can reduce the net energy requirements of drinking water and wastewater treatment?	
7. How can water treatment waste residuals and biosolids management approaches be managed more sustainably?	
8. What new drinking and waste water treatment technologies can be developed that are energy efficient, inexpensive, and practical for small communities and on-site uses?*	
9. What protocols can be developed to evaluate innovative treatment and remediation strategies of drinking water and waste water from the private sector?*	A report giving protocols and basis for evaluating treatment and remediation strategies of drinking water and waste water.
10. What approaches can be developed to assess how drinking water treatment and distribution system management impact the water quality within the distribution system?	
11. What risk management approaches can be developed to address ecological and human health impacts of source waters that are impaired or alternative source waters that are utilized due to increased wastewater inputs, drought, climate change, or other impacts?	

Appendix F

Built Infrastructure

I. Problem Statement

[1]Increasingly, the United States is having difficulty operating, maintaining and renewing its water infrastructure[1] to assure that public health, water resource, and aquatic ecosystem protection goals are achieved. Much of the difficulty is due to the nature of the current system design, changing demographics and growth combined with ongoing deficiencies in infrastructure replacement. These problems are exacerbated by competing regulations and a lack of a systems-economics approach within the water sector as well as from risks arising from new sources and types of pollution, concerns over emerging contaminants, climate variability and trends, and from other hazards (such as earthquakes or hurricanes). These challenges require a fundamental shift to more resilient water infrastructural solutions and technologies to sustain the quality and quantity of water available for human and ecological uses. Also, metrics are lacking for evaluating the public health and ecosystem implications from existing and declining infrastructure and to aid in selecting and maintaining innovative solutions.

II. Solutions

Improving the sustainability of the nation's water infrastructure (including components used in the agricultural and energy sectors) is our country's top water priority. Focusing on our wastewater, stormwater and drinking water systems, many exceed their designed lifetime, with some exceeding 100 years in age. In addition, current conveyance and treatment schemes may not be sufficient to address emerging challenges, especially with the concomitant decline of research and development investments leading to limited development of innovative and alternative solutions in recent years. In 2002, the EPA published "The Clean Water and Drinking Water Infrastructure Gap Analysis," also known as the "Gap Analysis" report.
The Agency estimated that if spending for capital investment and operations and maintenance remained at current levels, the potential gap in funding between what will likely be invested in

[1] The term "water" refers to source water, drinking water, stormwater, and wastewater unless otherwise specifically designated. Likewise, "water infrastructure" in this text refers to infrastructure associated with source water, drinking water, stormwater, and wastewater unless otherwise specifically designated.

our municipal water infrastructure and what is truly needed for the next 20 years would be $270 billion for wastewater infrastructure and $263 billion for drinking water infrastructure. Given today's economic realities, this funding gap is highly unlikely to be filled. Furthermore, the municipal water services consume over 7% of the nation's electricity production, whereas the imbedded energy within organics in sewers could exceed that need. The current energy drain could be further reduced by substituting conventional nitrogen and phosphorus sources used in food production by the residuals left over from energy recovery from municipal and agricultural organics. Therefore, new strategies based on innovative technologies and sustainable solutions are essential to reduce the investments required to rehabilitate and modernize our water infrastructure systems.

- **Tools to Assess Sustainability:** The first science question under Built Infrastructure is "What are the assessment tools to assess and enhance sustainability (environmental, social, economic) at various scales in the water system?". It is evident that a successful strategy must consider a broad range of (social, environmental and economic) factors that influence water infrastructure choice, operation and maintenance. Therefore, the question spans they entire series of sectors that influence water. Figure 1 which illustrates how various entities or systems rely on, are effected by, or affect the built infrastructure that communities depend upon. Knowing that energy production and economic resource recovery is achievable by different infrastructural designs and integration with the built environment not only reduces reliance on conventional watersheds to provide water, but also largely eliminates pollutant discharge to receiving waters, fundamentally mitigating most Clean Water Act concerns and providing resilience to likely climate change impacts. The real challenge is then to evolve water governance and urban landscapes, and to provide incentives to achieve this paradigm shift. While Figure 1 is conceptual, it illustrates the range of inter-relationships, such as those between architectural, land use and industry in their uses and reuse of water, energy and nutrients. Considering these inter-dependencies is necessary to achieve properly functioning, resilient and sustainable water infrastructure systems critical for public health protection, conservation of our water and energy resources, and the prevention/remediation of environmental degradation.

- **Tools to Assess Health Risk and Environmental Impact:** The second science question under Built Infrastructure is "What are the tools that tell us the water system is under control with regard to health risk and environmental impact?". Because this impacts the water sector in general, its schematic representation also covers the entire series of sectors illustrated in Figure 1. Drinking water infrastructure failures can pose immediate and serious public health risks in the community. In addition to intentional or accidental contamination risks and public health concerns, over a third of treated water is lost through leakage and other failures in the drinking water infrastructure. This translates into a significant waste of energy, capital, and natural resources through 'lost' water. Energy is also lost when corrosion and solids deposition cause restrictions in flow, thereby requiring additional energy to pump the same volume of water as what a properly maintained pipe could carry. Further, to meet firefighting flow requirements, water supply systems are hugely oversized relative to what would be required if building fires were suppressed by mist/foam or other means than potable water. Finally, microbial and chemical contaminants accumulate in distribution system solids, with episodic releases into drinking water.

Wastewater infrastructure constantly impacts groundwaters via leaks, but rain-induced uncontrolled releases of contaminated water and household backflows have immediate consequences and now account for the majority of household insurance claims nationwide. In addition to localized flooding, significant environmental, esthetic, and public health impacts result from raw sewage releases. Many factors can be related to these system failures, including infrastructure age, design/materials, installation practices, inadequate maintenance, geologic and soil conditions, population density and demographics dynamics, all compounded by impervious built surfaces. In the cases of emerging chemical contaminants in sanitary sewers and stormwater conveyance systems, even a system functioning as intended can result in water quality impacts due to either new pollutants introduced to the systems or new concerns about downstream impacts.

- **Tools to Mitigate and Prevent Risks:** The third science question under Built Infrastructure is "What are the tools and approaches that can be used to mitigate and prevent risks within built infrastructure to human health and the environment?". Overall, many of the risks can be mitigated by a change to how we design and integrate water services within the built environment. Therefore, in addition to research to assist with system transition, fundamental and applied research is required to assist in developing the new water paradigm; addressing architectural, urban landscape and resource recovery systems; and developing the sociological and governance systems to support them. This is included in the system schematic shown in Figure 3. New and improved science and engineering in undertaking systems analysis, material flows analyses, full economic costings, etc. are also required to support risk assessments so as to reduce unintended consequences for the built environment of the future. In particular, metrics are needed that can inform, at various scales and depths, cost-benefit analyses, life-cycle analyses to address environmental impacts and research on policy decisions related to regulation or guidance.

III. Research Needed

Tables 1 – 3 have the research questions for each of the three overarching science questions. All questions have outputs and timelines; however, resource availability and outside collaboration will dictate how many questions will be answered in the timeframe listed. Although there is an organizational structure to the science and research questions, it is acknowledged that there are aspects to each of the research questions that cross link across the science questions to other research questions. Therefore, the following research needs discussion is offered in a holistic fashion.

Solution strategies for shifting to more sustainable and resilient water infrastructure must address needs and risks posed by the current conditions in drinking water and stormwater/wastewater systems. Regarding drinking water infrastructure, comprehensive approaches are needed throughout the water infrastructure to pro-actively identify potential and actual pipeline leaks and failures, rehabilitate pipelines, manage pressure transients, prevent cross-connections and water storage contamination events, and improve energy use efficiency. Innovative approaches are needed that incorporate scientific advances to characterize, quantify and manage risks associated with the potential introduction, formation, and mobilization of chemical, microbial, and radionuclide contaminants through the conveyance and storage of waters used by society. Exposure and human health research is needed to assess and model potential risks associated with the current and future water infrastructure contaminants. Mitigation and assessment approaches are needed to manage unwanted microbiological, chemical, and biochemical reactions that may occur within water systems and hence pose a potential human health and ecological risk. Key water quality concerns associated with any water system include but are not limited to: microbial pathogens, vectors of disease, nitrification, treatment by-products, accumulation and release of inorganic contaminants, and potential backflow or intrusion of chemical or microbial constituents via the distribution systems. The challenge is to address these concerns in a sustainable, cost-effective manner that minimizes other environmental impacts and consumption of resources such as energy, while maximizing recovery of resources such as carbon, nutrients, and the water itself. This requires novel approaches and innovative technologies, in addition to further refinement of current technologies. Collectively, the development and implementation of innovative monitoring and response technologies may enable more extensive and effective assessment and management of the water infrastructure, thus protecting human health and the environment.

In addition to soft (social) and hard (engineered) water infrastructure solutions, perhaps the largest gains can be made by adapting natural ecosystem approaches, as exemplified by so-called green infrastructure over traditional gray infrastructure combined sewer overflow (CSO) controls. Green infrastructure practices at various scales (e.g., rain gardens, green roofs, porous pavement, etc.) give cities some control over the costs of their long-term control plan by optimizing the mix of green and gray controls, leading to right-sizing of gray infrastructure while satisfying regulatory requirements. Green infrastructure may also provide other benefits to the community, including additional urban green space, increased property values, high levels of citizen satisfaction, and a major contribution to the restoration of degraded urban core areas. Research is needed to evaluate and demonstrate the performance and cost of these technologies over the long-term so as to validate their application. Also, research is needed on the physical, social, economic, and environmental challenges and opportunities of integrating green infrastructure into communities, especially on private property. Through more sustainable stormwater management, the nation can better protect drinking water sources, water quality, aquatic ecosystems, and public health, as well as provide tools that assist communities in addressing local goals and challenges. Integrated water resource management principles and approaches and associated innovative technologies need to be developed to achieve water resource management goals while minimizing impacts on infrastructure requirements. Such approaches optimize the use of water conservation, wastewater (including gray water and rainwater) reuse, groundwater recharge of stormwater and reclaimed water, the aesthetic and health benefits of green infrastructure, and energy conservation and recovery. Integrated and sustainable wastewater management systems are of particular concern for small communities where administrative, technical and financial capacity to manage water resources is a major challenge. Given these capacity constraints, it is important that communities have the tools and context to try to maximize the potential social, environmental, health, and economic benefits of water infrastructure benefits.

Today's water distribution systems are designed to meet multiple supply needs: 1) potable requirements (e.g., drinking, cooking, cleaning, etc.); 2) fire fighting; 3) municipal, commercial, medical and industrial needs; and 4) non-potable domestic applications (e.g., toilet flushing, landscape irrigation, etc.). Alternative approaches, such as treating water to the standard of its intended use, may be more sustainable than the current approach of treating all water to drinking water standards. In some parts of the U.S., dual distribution systems have been implemented that provide a primary system for delivering high-quality drinking water and a secondary system for non-potable applications. By using alternative water sources, such as reclaimed wastewater or stormwater, to augment water supply, higher quality sources of drinking water can be preserved. Research is needed to determine at what scale and degree these secondary supplies can meet or change approaches to household firefighting and restoration of local hydrology, and quantify life-time system impacts on the overall urban water resources issue.

Similar to what cities are finding with the prospect of wholesale replacement of gray infrastructure due to consent decree orders, it is neither practical nor cost-effective to completely replace or overhaul the entire water infrastructure in a given service area. However, opportunities do exist to develop more cost-effective and efficient approaches to achieve performance, reliability, and sustainability goals to solve infrastructure-related problems. Practical approaches to modify, enhance, or retrofit existing systems are needed. Examples of approaches that have been adopted in various parts of the U.S. include supplemental treatment to improve the quality of delivered water at the point of use/point of entry, decentralized treatment, and the strategic use of dual distribution systems in situations where there is a significant use of water for non-potable purposes, or where indirect potable options are feasible and protective of public health and the environment. Greatest applicability may be found at the local level, which can reduce the need to transport water over long distances. All of these approaches address the need to use water resources in a more sustainable fashion where investments and management of this resource is consistent with its value. While the approaches exist, a key hurdle is identifying the best opportunities and developing feasible strategies that include homeowner/consumer cooperation for implementing these approaches where they will make the most impact on water sustainability. High heterogeneity in localities may mean that opportunities and strategies will not be universally applicable; consequently, a flexible framework for applying these strategies and adaptive management principles may be necessary.

The application of advanced concepts can lead to more effective approaches for comprehensive asset management for water and wastewater utilities, and better take into account their role in the built environment. Advances in design, operation, management, and monitoring of water conveyance structures that incorporate new technologies and innovations (such as real-time monitoring and control, green infrastructure, low impact development, and water reuse) may yield significant benefits in terms of public health protection, energy efficiency, economic and social benefits, cost-effectiveness, and overall sustainability. Indeed, water reclamation and resource recovery opportunities have been demonstrated for municipal wastewaters using innovative and alternative approaches. Additionally, source identification and control can lead to alternative strategies (such as fertilizer regulation) and alternative mitigation and treatment technologies (such as shading trees and pocket wetlands). Further research is needed to develop the appropriate metrics to ensure that such approaches are applied in an economically sound and sustainable manner.

Water infrastructure systems are not independent of other systems that constitute the built environment. One sector that is inexorably linked to the water sector is the energy sector. This is often referred to as the water/energy nexus. The conveyance of water to and from the built environment requires a sizable percentage of the power generated in this country. Approximately, 7% of energy use in the country is used for the treatment and conveyance of water/wastewater to and from the built environment (Carlson and Walburger, 2007), and another 14% is used for heating water (DOE, 2011). Energy requirements for conveying water are impacted by water volume, system capacity, distance, pressures, hydraulic gradients, pump efficiencies, and the overall system condition. Pipeline deterioration and failure can impose increased energy demand that needlessly subtracts from the available capacity of energy producers, and can also lead to higher costs for operation and maintenance of the water infrastructure. Energy requirements for water treatment are affected by water characteristics and flow and are significantly increased with new water-quality control requirements and advanced treatment. Alternately, power plants and agriculture utilize more than 85% of our freshwater resources for cooling purposes and irrigation. To maintain and enhance our nation's power generation and food production, water systems will need to be managed more efficiently, and opportunities for water reuse and efficiencies need to be explored along with changes to dry cooling systems and reduced needs for irrigation. Finally, different ways to recover the energy from food and fecal residuals (e.g., biogas generation) along with fertilizers (e.g., NPK) may be optimized to achieve a more sustainable built environment. Such opportunities require optimizing currently available technologies and development of highly efficient new technologies. Similar to how the energy and water sectors are closely tied together, other sectors (such as the transportation and urban planning areas) also are integrated with the water sector.

It is important to consider potential climate change mitigation benefits that could be realized from improving the energy efficiency of the water infrastructure and resource recovery. Long-term water infrastructure sustainability can also be impacted by climatic factors, such as changes in hydraulic requirements related to the frequency and intensity of storms, droughts, or other forms of weather-induced stress that may occur over the design and operating life of water distribution and treatment systems. Additionally, demographic and industrial shifts are difficult to predict, furthering the need for more adaptive water infrastructural systems. These changes will impact water quality, quantity and security and require consideration in the planning for more resilient water infrastructure. To accomplish this, integrated and trans-disciplinary research should be fostered in educational institutes to provide the next generation of staff and users. Particular emphasis should be put toward demonstrating appropriate technologies and approaches at small and disadvantaged communities, which are least likely to be able to afford or sustain a system change. Success will be demonstrated by acceptance and adoption of technologies, tools, and approaches by EPA, the states, tribes, communities, and other stakeholder groups. All results should be disseminated as widely and creatively as possible by community outreach, online education, workshops, events, webcasting, podcasting, technical assistance providers, and publishing. Feedback should be actively solicited and incorporated.

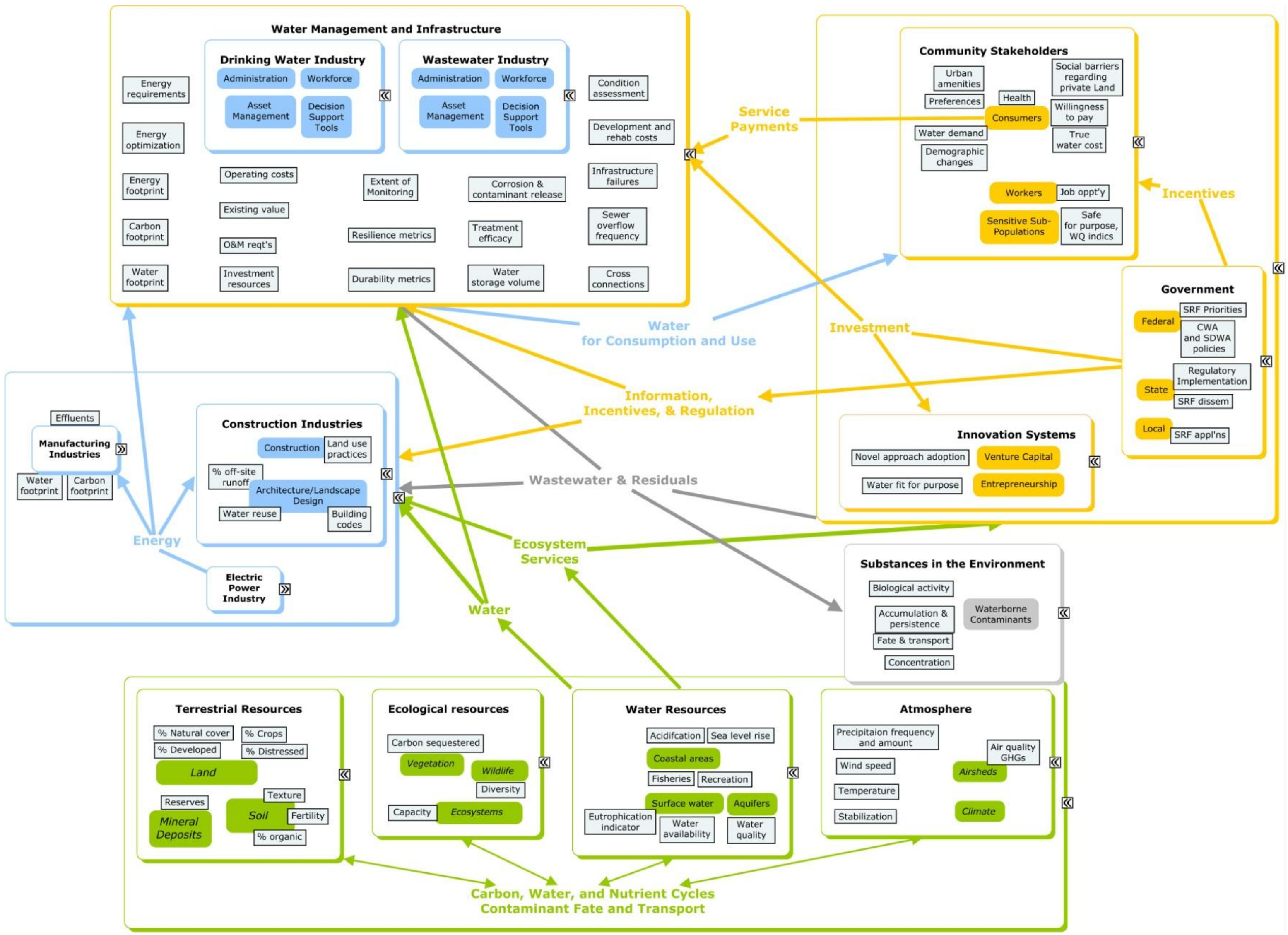


Figure 1. System Schematic for Science Questions 1 and 2 (Tools to Assess Sustainability, Tools to Assess Health Risk and Environmental Impact).

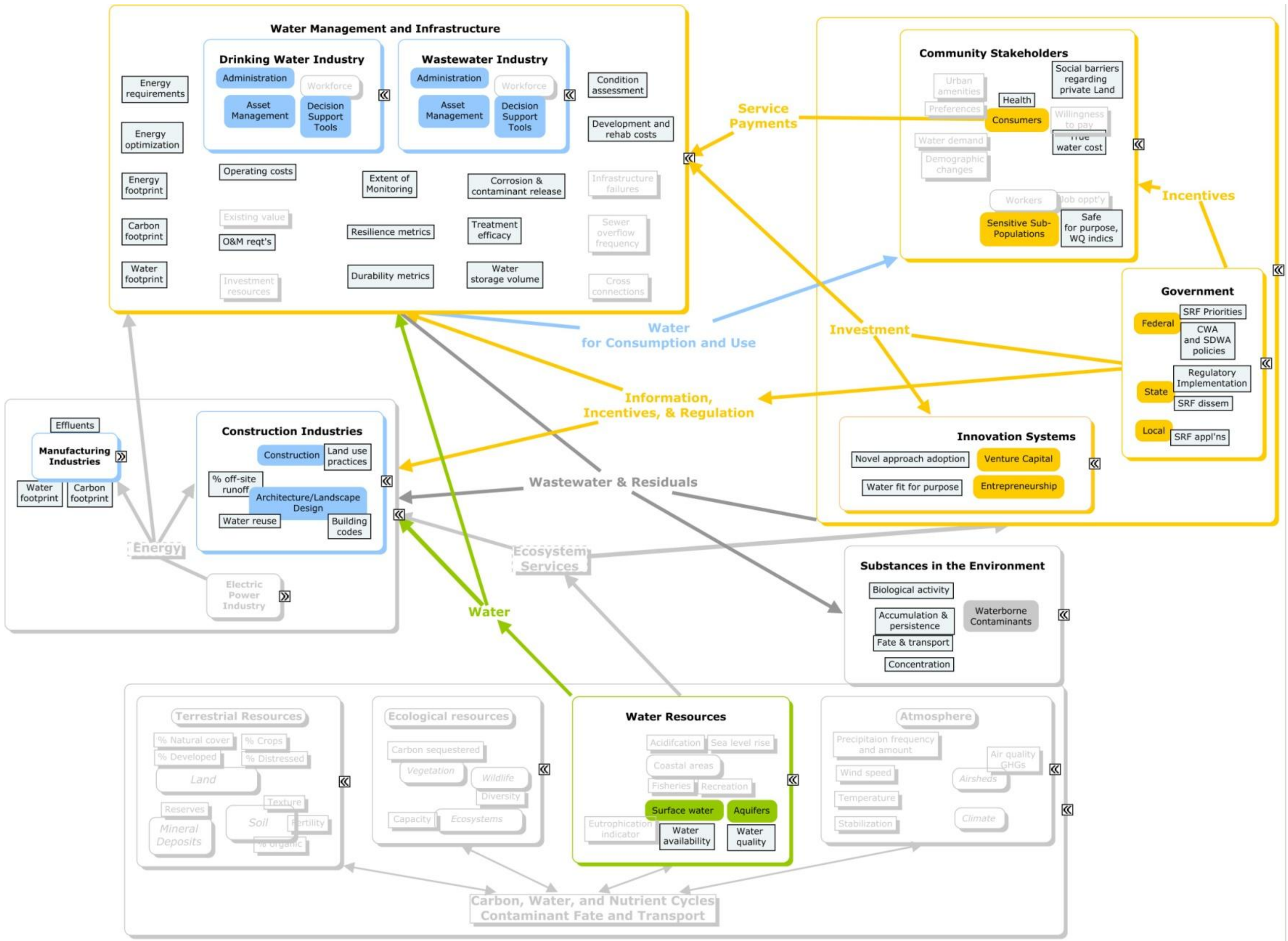


Figure 2. System Schematic for Science Question 3 (Tools to Mitigate and Prevent Risks)

IV. References

Carlson, SW and A Walburger, 2007. *Energy Index Development for Benchmarking Water and Wastewater Utilities*. Denver: American Water Works Association Research Foundation.

www.eia.doe.gov/emeu/reps/enduse/er01_us.html

Collaboration

Collaboration will be sought from the following groups:

- American Academy of Environmental Engineers (AAEE)
- Association of Environmental Engineering and Science Professors (AEESP)
- Association of State Drinking Water Administrators (ASDWA)
- American Public Health Association (APHA)
- American Society of Civil Engineers (ASCE)
- American Water Works Association (AWWA)
- ASTM
- Australian Research Council (ARC)
- Centers for Disease Control and Prevention (CDC)
- Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Environmental Defense Fund
- Instrumentation and Control Engineering Society (ICE)
- NASA
- National Park Service
- National Science Foundation (NSF)
- National Association of Corrosion Engineers (NACE)
- National Rural Water Association
- New England Water Environmental Association (NEWEA)
- NSF International
- NIST
- SBIR
- Water Services Association of Australia (WSAA)
- UKWIR
- USACE
- US Department of Agriculture (USDA)
- US EPA Area Wide Optimization Program (AWOP)
- US Department of Defense (DOD)
- US Department of Energy (DOE)
- US Geological Survey (USGS)
- US Green Building Council
- US Department of Homeland Security
- US Department of Transportation (DOT)
- Water Environment Federation (WEF)
- Water Environment Research Foundation (WERF)
- Water Research Foundation (WRF)
- WWEMA

1. What are the assessment tools to assess and enhance sustainability (physical, environmental, social, economic) at various scales in the water system?

	Research Question	Output and Timeline
A	How do we represent the system-based components of water infrastructure, interactions across other sectors, and characterize the flow and integrity of resources to identify sustainable solutions for managing the built environment?	5 years: Report and first generation tool with demos 10 years: official release of tool including demos/retrospective evaluations
B	How can the environmental footprint of the water industry be reduced to produce less waste, use fewer resources, and require less energy? What new strategies and technologies are needed by communities and what are the associated water research and knowledge gaps and needs for implementing an integrated water resource management approach that optimizes the use of water conservation, wastewater (and grey water) reuse, and ground water recharge of stormwater and reclaimed wastewater? What additional infrastructure is needed to implement these approaches (i.e., dual distribution system, advanced firefighting, etc.)?	10 years: Develop, foster, and demonstrate tools
C	What innovative approaches and technologies can be developed and demonstrated (e.g., tool-based scenarios, pilots) to minimize carbon-, nitrogen-, and energy impacts from water and wastewater treatment and infrastructure management?	10 years: Develop, foster, and demonstrate tools
D	What resources can be recovered from municipal effluents for reuse and energy production, and can an economically sound manner for recovery be demonstrated?	5 years: Coarse demonstration 10 years: Developed demonstration
E	What technologies and approaches are best to recover energy and other resources from domestic wastewater? Can it be applied to small systems?	5 years: Demonstration project
F	What are the optimal water reuse treatment technologies for different climatic regions?	2 years: report 5 years:
G	How do climate variations and demographic trends impact water infrastructure and water quality?	5 years: Report and first generation tools 10 years: Official release of tool
H	How do we improve sustainability of our water resources through environmentally sound management of residual streams?	10 years: Novel approaches and technologies
I	What incentives or drivers would best increase implementation of green technologies for stormwater runoff on private property?	5 years: Tools for communities
J	When can source protection and control strategies better address wastewater and drinking water quality impacts than updates to drinking water treatment? What are the tradeoffs between increasing treatment upstream through LID upgrades versus upgrades at the drinking water treatment and wastewater plants?	5 years: Report on metrics 10 years: Tools for utilities and communities

2. What are the tools that tell us the water system is under control with regard to health risk and environmental impact?

	Research Question	Output and Timeline
A	How can we better assess the current condition and sustainability of our existing drinking water and wastewater infrastructure, including rehabilitated infrastructure?	5 years: Report and first generation tools 10 years: Tools for communities
B	How can we better assess the extent to which human health and environmental issues are associated with declining or inadequate drinking water and wastewater infrastructure?	5 years: National-scale model for extramural review 10 years: Final model
C	What innovative analytical methodologies, monitoring strategies, and models are needed to determine the occurrence of distribution system intrusion by pathogens or chemicals and what are the human health risks due to the presence of these contaminants? [Link with Chemicals/Pathogens/Industry]	2 years: Report 5 years: First products for community and program office use
D	What innovative analytical methodologies, monitoring strategies, and models are needed to determine changes in distribution system water quality due chemical interactions, sorption, or leaching from pipe materials and resuspension of biofilms? [Link with Chemicals/Pathogens/Industry]	2 years: Report 5 years: First products for community and program office use
E	How can we better understand the potential risks caused by one infrastructure upon another from an economic, public health, and ecosystem perspective?	5 years: Draft tool developed 10 years: Finalized tool
F	How can we assess the impacts of natural disasters on our drinking water systems and include new innovations in the reconstruction of those injured systems?	5 years: Draft tool developed 10 years: Finalized tool
G	How can condition assessment technologies and approaches for other types of infrastructure (e.g., bridges) be adapted for use in drinking water, wastewater, and stormwater system assessments?	2 years: Report
H	What products are needed to assist utilities to more effectively implement comprehensive asset management, provide customer support, and meet Safe Drinking Water Act and Clean Water Act requirements?	5 years: Report and first generation tools 10 years: Tools for communities
I	What approaches can be developed to assess how technologies used during drinking water treatment impact the water quality within the distribution system (e.g. disinfectant residuals)? [Link with Chemicals/Pathogens/Industry]	2 years: Reports 5 years: First products for community and program office use
J	What is the optimal approach for expanding condition assessments to other asset types such as manholes, valves, pumps, and control panels?	5 years: Report and first generation of tools 10 years: Tools for communities

3. <u>What are the tools and approaches that can be used to mitigate and prevent risks within built infrastructure to human health and the environment?</u>

	Research Question	Output and Timeline
A	To what extent can current water treatment and distribution practices be optimized to provide safe drinking water to consumers having different water quality and quantity challenges? [Link with Chemicals/Pathogens/Industry]	5 years: Report and first generation of tools for different conditions 10 years: Final set of tools released
B	What multiple benefit tools can be developed to help water systems meet multiple infrastructure challenges (e.g., regulatory compliance, water security enhancements, and effective responses to return the system to service)?	5 years: Report and first generation of predictive models 10 years: Final set of tools released
C	What are the most sustainable innovative approaches to address the technical, administrative, and financial capacity challenges faced by communities in managing their water resources?	5 years: Report and first generation of predictive models 10 years: Final set of tools released
D	What innovative technologies will be developed for drinking water and wastewater treatment to reduce the human and environmental health risk from emerging and historical chemicals and pathogens? [Link with Chemicals/Pathogens/Industry]	5 years: Innovative technologies patented 10 years: Innovative technologies demonstrated an marketed
E	What innovative, sustainable, and affordable treatment technologies can be developed for small and disadvantaged systems to address compliance issues and what are the most sustainable approaches to address the technical, administrative, and financial capacity challenges faced by small communities in managing their water resources?	5 years: Innovative technologies patented 10 years: Innovative technologies demonstrated and marketed
F	What innovative tools, approaches, and supporting data are needed to manage water distribution systems to avoid the proliferation, retention, and mobilization of waterborne pathogens? [Link with Chemicals/Pathogens/Industry]	5 years: Report and first generation of tools 10 years: Final tools developed
G	What innovative tools, approaches, and supporting data are needed to monitor, assess, and manage distribution systems to avoid the formation, retention, or mobilization of chemicals in water distribution systems? [Link with Chemicals/Pathogens/Industry]	5 years: Report and first generation of tools 10 years: Final tools developed
H	What tools and models can be used to inform selection of treatment options and response to intentional or accidental infrastructure failures?	5 years: Report and first generation of tools 10 years: Final tools developed
I	How does green infrastructure interact with existing built environment features? What are the best practices for installing green infrastructure to avoid negative impacts such as flooding in the built environment?	5 years: Report and first generation of tools 10 years: Final tools developed
J	How do we more effectively protect source water and watersheds?	5 years: Report and first generation of tools 10 years: Final tools developed

K	What are the impacts of decentralized system failure on human health and the environment? Are there better, more reliable and longer-lived systems available?	3 years: Report 10 years: Demonstrations
L	How can we reduce the number of cross connections and eliminate water storage contamination events to reduce public risk?	3 years: Report 5 years: Demonstrated
M	How can residual streams from drinking water and wastewater utilities be best managed to reduce risk to human health and the environment? [Link with Chemicals/Pathogens/Industry]	3 years: Report 5 years: Demonstrated
N	What are the social and economic barriers to using existing technologies such as Green Infrastructure and how can the barriers be overcome?	3 years: Report
O	How can we effectively assess green infrastructure in reducing contaminants, reducing costs and providing additional benefits? What is the long-term effectiveness of green infrastructure?	5 years: Demonstrated 10 years: Tools developed
P	What are the innovative new, retro-fit, and sub-system technologies and approaches that can mitigate or replace the current aging infrastructure for drinking water and wastewater treatment and conveyance, including after a hazard disruption?	5 years: Technologies demonstrated
Q	How to best link public health epidemiological data to water treatment operation and compliance?	5 years: Report and first generation tools 10 years: Tools for program office