# DESALINATION AND WATER PURIFICATION TECHNOLOGY ROADMAP

## A REPORT OF THE EXECUTIVE COMMITTEE

Discussion Facilitated by Sandia National Laboratories
and the U.S. Department of Interior, Bureau of Reclamation

Desalination & Water Purification Research & Development Program Report #95

Sandia National Laboratories

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. AGENCY USE ONLY** ***(Leave Blank)***

**2. REPORT DATE**
January 2003

**3. REPORT TYPE AND DATES COVERED**
2003 Final

**4. TITLE AND SUBTITLE**

Desalination and Water Purification Technology Roadmap -
A Report of the Executive Committee

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**

U.S. Bureau of Reclamation
Sandia National Laboratories

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Bureau of Reclamation, Denver Federal Center
Water Treatment Engineering & Research Group
P.O. Box 25007
Denver, CO 80225-0007

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Same

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

DWPR Program #95

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Available from the National Technical Information Service, Operations Division,
5285 Port Royal Road, Springfield, Virginia 22161

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** ***(Maximum 200 words)***

The Desalination and Water Purification Technology Roadmap presents a summary of the water supply challenges facing the U.S. through 2020, and suggests areas of research and development that may lead to technological solutions to these challenges.

The Roadmap is a living document – updates to the Roadmap will be made on a regular basis to ensure that it remains current and relevant. The Roadmap will also be complimented by a series of documents, created as a result of meetings to be held with experts around the nation, focused on: discrete research projects; regulatory issues; U.S. impaired water resources; and plans to ease commercialization of technologies.

The views and opinions expressed herein do not necessarily state or reflect the policies or decisions of the Administration, the United States Government, any agency thereof, or any of their contractors.

**14. SUBJECT TERMS**
desalination/water purification/advanced water treatment/research/technology/roadmap

**15. NUMBER OF PAGES**
74

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UL | UL | UL | UL |

## Roadmapping Participants

### *Executive Committee Members*

William Blomquist, Indiana University
Shannon Cunniff, United States Department of the Interior, Bureau of Reclamation
Peter Fox, Arizona State University
David Furukawa, Separation Consultants, Inc.
Marie Garcia, Sandia National Laboratories
Michael Gritzuk, Phoenix Water Services Department
Lisa Henthorne, Aqua Resources International
Anita Highsmith, Highsmith Environmental Consultants
Thomas Hinkebein, Sandia National Laboratories (Desalination Roadmap Program Manager)
Kevin Price, United States Department of the Interior, Bureau of Reclamation
Gary Wolff, Pacific Institute

### *Working Groups*

**Membrane Technologies**
Wayne Einfeld, Sandia National Laboratories
Joyce Essien, Centers for Disease Control
Lisa Henthorne, Aqua Resources International (lead)
Anita Highsmith, Highsmith Environmental Consultants
Hari Krishna, Texas Water Development Board
Jim Lozier, CH2M Hill
Bob Yamada, San Diego County Water Authority

**Reuse/Recycling Technologies**
Peter Fox, Arizona State University (lead)
Rick Martin, United States Department of the Interior, Bureau of Reclamation
Wade Miller, WateReuse Foundation
Amit Pramanik, WERF
Bahman Sheikh, Independent Consultant
Pick Talley, Pinellas (FL) County Utilities

**Alternative/Thermal Technologies**
Joe Cotruvo, NSF International
David Furukawa, Separation Consultants, Inc.
Marie Garcia, Sandia National Laboratories
Mike Hightower, Sandia National Laboratories
Thomas Hinkebein, Sandia National Laboratories
Thomas Jennings, United States Department of the Interior, Bureau of Reclamation (lead)
Ed Knobbe, Sciperio
Ron Linsky, National Water Research Institute
Bernie Mack, Ionics Inc.
John Pellegrino, Consultant
Kevin Price, United States Department of the Interior, Bureau of Reclamation

**Concentrate Management Technologies**
Bill Beddow, CH2MHill
Mark Beuhler, Metropolitan Water District of Southern California
Shannon Cunniff, United States Department of the Interior, Bureau of Reclamation
Michael Gritzuk, Phoenix Water Services Department (co-lead)
Mike Hightower, Sandia National Laboratories
Thomas Hinkebein, Sandia National Laboratories (co-lead)
Scott Irvine, United States Department of the Interior, Bureau of Reclamation
Mike Mickley, Mickley and Associates
John Potts, McGoran & Associates
Kevin Price, United States Department of the Interior, Bureau of Reclamation
Robert Reiss, Reiss Environmental
Karen Wayland, Office of Senator Harry Reid
Ed Weinberg, EW Consultant
Gary Wolff, Pacific Institute

## ACKNOWLEDGEMENTS

The Executive Committee would like to thank the following individuals for their contributions to the Roadmap:

Michael Radnor and Jeffrey Strauss of Northwestern University, for providing their thoughts on roadmapping;

Jack Bishop of Kingsbury International, Inc., for his facilitation skills;

Goldie Piatt of Sandia National Laboratories, for her organizational and logistics support;

Kevin DeGroat, Dennis Fargo, and Douglas Eisemann of McNeil Technologies, for their facilitation of Roadmap meetings; and

Conrad Mulligan of McNeil Technologies for establishing the logic of the roadmap, organizing and facilitating workgroup and Executive Committee meetings, and writing the Roadmap report.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

## Glossary of Terms

| | |
|---|---|
| Aquifer | A subsurface feature comprised of permeable soil and rock that contains water. |
| Brackish water | Brackish water is defined by containing higher TDS levels than potable water, but lower TDS levels than seawater (in the range of 1,000 mg/l TDS to 25,000 mg/l TDS). Brackish waters can be found in coastal areas (bays and estuaries, where fresh water mixes with salt water), in aquifers (where it is usually referred to as saline water), and in surface waters (salt marshes, for instance, contain brackish water). |
| Concentrate | Concentrate is the byproduct from desalination. This byproduct contains the contaminants removed from impaired waters during desalination and water purification processes. Concentrates are generally liquid substances that may contain up to 20% of the water that is treated (i.e., for every 100 gallons of impaired waters that are treated, up to 20 gallons of that water is commingled with the removed contaminants). |
| Conjunctive use | The coordinated and integrated management of surface water and ground water resources. |
| Conventional water treatment technologies | Typical conventional water treatment consists of six basic steps: screening; coagulation to combine solids so that they settle; sedimentation to settle suspended solids; filtration; disinfection; and storage. Sometimes all of these five steps are not needed, and sometimes, additional steps are required to meet water quality standards. Dissolved ionic species and hydrocarbons in source waters require treatment using chemical additions, soda ash or weak acids, or by filtration with activated carbon or calcite filters. Conventional water treatment processes have been employed for more than 100 years. |
| Cost, Capital | Total capital cost includes the indirect costs associated with the owner's costs of studies, engineering, licenses, interest on working capital, insurance during the construction period as well as the direct capital costs. It is the owner's total investment up to the point that the plant is put into useful operation. |
| Cost, Indirect Capital | The owner's costs associated with such items as studies, planning, engineering, construction supervision, licensing, startup, public relations, and training. These costs are a part of the cost of placing the plant in operation and are in addition to the direct capital costs associated with equipment and contracts for construction. |
| Electrodialysis | The separation of substances in solution by means of their unequal diffusion through semi-permeable membranes that is conducted with the aid of an electromotive force applied to electrodes adjacent to both sides of the membrane. |
| Fouling | The reduction in performance of process equipment that occurs as a result of scale buildup, biological growth, or the deposition of materials. |
| Ground water | Water normally found underground and obtained from wells. Not to be confused with surface water such as rivers, ponds, lakes, or waters above the water table. |
| Impaired water | Impaired water is that which is contaminated by salts, metals, radionuclides, biologic organisms, organic chemicals, fertilizers, pesticides, and a host of other substances that must be removed prior to the water being suitable for potable use. |

| | |
|---|---|
| kWh | Kilowatt-hours. A measure of electrical usage. |
| Membrane | A semi-permeable film. Membranes used in electrodialysis are permeable to ions of either positive or negative charge. Reverse osmosis membranes ideally allow the passage of pure water and block the passage of salts. |
| On-demand removal | On-demand removal describes the time-relevant removal of selected contaminants to meet local requirements (i.e., removing what you want to remove when you want to remove it). |
| Osmosis | Movement of water from a dilute solution to a more concentrated solution through a membrane separating the two solutions. |
| Pilot plant | An experimental unit of small size, usually less than 0.1 mgd capacity, used for early evaluation and development of new improved processes and to obtain technical and engineering data. |
| Pretreatment | The processes such as chlorination, clarification, coagulation, scale inhibition, acidification, and deaeration that may be employed on the feed water to a water supply purification or desalination plant to minimize algae growth, scaling, and corrosion. |
| Public sector | Includes all public agencies, including Federal, State, and local governments, and non-profit research institutions. |
| Saline water | Water with dissolved solids exceeding the limits of potable water. Saline water may include seawater, brackish water, mineralized ground and surface water and irrigation return flows. |
| Salinity | Salinity is a term used to describe the amount of salt in a given water sample. Salinity is usually referred to in terms of total dissolved solids (TDS), and is measured in milligrams of solids per liter (mg/l). Seawater has a worldwide average of 35,000 mg/l TDS. Brackish waters contain between 1,000 mg/l and 25,000 mg/l TDS. Drinking water contains between 400 and 800 mg/l TDS. |
| Salt | Salt, as referred to in this document, is a catch-all term that incorporates a variety of substances found in source waters, including: calcium, sodium, magnesium, carbonate, bicarbonate, sulfate, chloride. Salts may also include lesser amounts of potassium, selenium, boron, manganese, fluoride, nitrate, iron, and arsenic. It is important to note that the salts referred to in this document are not the same as table salts (NaCl). |
| Scale | Salts deposited on heat transfer or membrane surfaces that retard the rate of heat transfer or ion or water permeation. |
| Scale inhibitor | An agent that ties up and thus inactivates certain metal ions. It may be added to a feed water to extend the limits of saturation of scaling substances. Also known as antiscalant or sequestering agents. |
| Seawater | Seawater is that water found in the oceans. Seawater has a worldwide average concentration of 35,000 mg/l TDS, 3/4 of which is NaCl. |
| Surface water | Surface waters are those waters contained in flowing sources (rivers, streams, etc.) and in still sources (oceans, seas, lakes, man-made reservoirs, etc.) |
| Synthetics | Man-made contaminants (industrial chemicals, pharmaceuticals, etc.) |
| Traditional sources of water | 'Traditional' water sources referred to in this document are primarily surface waters and ground waters that are neither brackish, saline, nor seawater. |
| Unconventional sources of water | Unconventional water sources referred to in this document are those that are produced during oil and gas extraction activities and coal bed methane production, or that are contained in saline aquifers. |

## List of Acronyms and Abbreviations

| | |
|---|---|
| A&E | Architect & Engineering |
| CBM | Coal Bed Methane |
| CFD | Computational Fluid Dynamics |
| ED | Electrodialysis |
| EPA | Environmental Protection Agency |
| EPS | Extra-cellular Polymeric Substances |
| M&E | Materials and Energy |
| MF | Microfiltration |
| MTBE | Methyl Tertiary Butyl Ether |
| NASA | National Aeronautics and Space Administration |
| NF | Nanofiltration |
| R&D | Research and Development |
| RO | Reverse osmosis |
| SDI | Silt Density Index |
| TDS | Total Dissolved Solids |
| UF | Ultrafiltration |
| ZLD | Zero Liquid Discharge |

# PREFACE

The Desalination and Water Purification Roadmap presents a summary of the water supply challenges facing the United States, and suggests areas of research and development that may lead to technological solutions to these challenges.

This Roadmap is a living document – updates to the Roadmap may be made on a regular basis to ensure that it remains current and relevant. The Roadmap may also be complemented by a series of additional documents, created as a result of meetings to be held with experts around the nation, focused on:

- Defining discrete research projects and priorities based on the information contained within this Roadmap,
- Identifying regulatory issues related to the implementation of desalination and water purification technologies, and developing potential solutions where conflicts are found;
- Identifying, evaluating, and quantifying the United States' impaired water resources to better assess the impact that desalination and water purification technologies may have on the nation's water supply;
- Generating plans to accelerate the commercialization of desalination and water purification technologies developed as a result of this Roadmap.

This Roadmap cannot exist in a vacuum – technology development must be undertaken with the context of the product's end-use in mind. Hence, future meetings will seek to bring together representatives from local, State, and Federal agencies, associations and non-governmental organizations, and the private sector so that a broader context of the nation's water supply issues may be drawn and utilized to foster and guide technological development.

The goal of this process is to:
- Develop a consensus and direction to guide investments for the creation of new water purification technologies;
- Identify the roles that various sectors of the economy (e.g., federal government agencies, the private sector, educational and non-profit organizations) can play in the creation of new water purification technologies; and
- Develop an expert group to review alternative water purification technologies.

This Page Left Intentionally Blank

## EXECUTIVE SUMMARY

Water is the backbone of our economy – safe and adequate supplies of water are vital for agriculture, industry, recreation and human consumption. While our supply of water today is largely safe and adequate, we as a nation face increasing water supply challenges in the form of extended droughts, water demand growth due to population increases, more-stringent health-based regulations, and competing demands from a variety of users.

**The Guiding Vision for the Desalination and Water Purification Technology Roadmap:**

***By 2020, desalination and water purification technologies will contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply for the United States.***

**The Roadmap Executive Committee recognizes that there is no 'silver bullet' solution to our nation's water-supply challenges.** The complexity of the challenges will require a disciplined, focused, and interdisciplinary program to create a 'toolbox' of solutions.

**Technological advances in how we purify our water are one important 'tool' that will help mitigate our nation's future water supply challenges.** Technologies originally designed to desalinate water are extremely effective in removing contaminants (ranging from naturally-occurring salts to man-made chemicals) from impaired waters. This unique ability allows these technologies to **'create' new water** from underutilized impaired sources (for example, salty groundwater, impaired rivers, and post-consumer reclaimed waters) and to **produce safe water** by removing a wider range of contaminants than possible with conventional water treatment processes. By purifying impaired waters to create 'new' water for the nation's consumers and industries, desalination technologies will also help to **ensure the sustainability of the nation's conventional water supplies** – every gallon of 'new' water created using these technologies is one less gallon that must be drawn from rivers and aquifers, and one more gallon that can be used to maintain our nation's aquatic environments.

The Achilles Heel of these desalination technologies, however, is cost – they are currently expensive to purchase and operate. These costs have, to date, limited their application to regions that both have no choice but to employ them and that can afford them (Tampa Bay's newly-built plant and the Metropolitan Water District of Southern California's plans for a new desalination facility are prime examples – both are 'losing' some portion of their traditional water supplies and have the tax and revenue base to arrange the financing of desalination facilities).

**The Desalination and Water Purification Technology Roadmap identifies areas of research necessary to develop cost-effective technological 'tools' that can be used to help solve the nation's water supply challenges.** The research areas identified in this Roadmap provide the foundation for a comprehensive, focused research and development program. These research areas were selected to both speed the evolution of existing (current-generation) desalination and water purification technologies and to lay the scientific and technical foundation for the development of advanced, next-generation technologies. Research into the areas identified in this Roadmap will:

- Reduce capital and operating costs of existing and future technologies;
- Increase operational efficiency; and
- Expand contaminant-removal capabilities.

To guide the nation's researchers in advancing the state-of-the-art, Critical Objectives and metrics (measurable targets) were established to quantify the nation's needs. For example, a driving near-term Critical Objective calls for the reduction of desalination facility operating costs by 20 percent. These Critical Objectives and metrics are expert-generated impressions of the level of technological change that must take place if desalination and water purification technologies are to become affordable for a greater number of users. Only by ensuring that the technologies are available to a wide range of users can they improve the safety, sustainability, and adequacy of our nation's water supplies at a reasonable and affordable cost.

Five broad Technology Areas were determined to encompass the spectrum of desalination and water purification technologies. Each may, individually or in combination, meet one or more Critical Objectives. These Technology Areas include:

- Membrane Technologies (technologies that desalinate and purify water by pushing it through a semi-permeable membrane that removes contaminants),
- Alternative Technologies (technologies that take advantage of non-traditional methods),
- Thermal Technologies (technologies that rely on boiling or freezing water and then capturing the purified water while the contaminants remain behind),
- Concentrate Management Technologies (technologies which consider the disposal, volumetric reduction, and beneficial use of the primary byproduct of desalination), and
- Reuse/Recycling Technologies (often membrane or alternative technologies that must be designed to handle increased contaminant loads due to their post-consumer application).

Given limited budgets, it is only through the judicious selection of research, development, and demonstration projects that the nation will generate the scientific and technical understanding necessary to evolve current-generation technologies (and thus meet our short terms problems) and develop revolutionary next-generation advanced desalination and water supply purification technologies.

And only with cost-effective and efficient revolutionary technologies will the nation be able to meet its future (25+ years out) demand for safe, sustainable, and affordable water – relying on conventional water treatment plants is an insufficient answer to the nation's evolving water supply challenges.

It is expected that institutions funding or conducting desalination and water purification research will use this Roadmap to make decisions about research direction and use the Roadmap's metrics to document progress toward meeting the identified Critical Objectives and embrace the Vision for desalination and water purification technologies. The Roadmap Executive Committee hopes that this document will serve to increase the 'research needs, priorities, directions, and successes' dialogue with research institutions, research funders, and end users (water planners, water managers, water suppliers, etc.).

## LIST OF TABLES AND FIGURES

# 1.0 INTRODUCTION

## 1.1 OVERVIEW

The United States faces severe challenges to our ability to meet our future water needs. In the coming decades, in addition to improving water-use efficiency and promoting water conservation, we as a nation will need to

- Make additional water resources available to all segments of our nation's growing population and economy across our nation's physically diverse regions;
- Provide additional water resources at a cost and in a manner that supports urban, rural and agricultural prosperity and environmental protection;
- Safeguard and improve the quality of all of the nation's water resources as future understanding of health effects are realized.

These challenges are present today in some regions of the nation and will likely become realized nationwide in the near future. Meeting these challenges will require a comprehensive technology- and policy-based program that results in technological advances, creative administrative and managerial actions, and a greater national focus on water conservation.

In recognition of these needs and challenges, Congress authorized

> "…[the] Bureau of Reclamation to complete a study to determine the most effective and efficient manner of, and to develop a technology progress plan to be used in, the development of a desalination research and development facility in the Tularosa Basin in New Mexico. The Committee recognizes that effective desalination cost reduction is the key to wider use of desalination for improving the quality of life in water-scarce regions. The Secretary of the Interior shall consult with the Secretary of Energy and the Director of the Sandia National Laboratories in the development of the technology and implementation plan." [2002 Energy and Water Development Appropriation Bill]

With this charter, the Bureau of Reclamation and Sandia National Laboratories formed a Roadmapping Team comprised of key members from government, industry, academia, and water utilities to assist in the creation of a technology progress plan as presented in this document, The Desalination and Water Purification Technology Roadmap. Working through a facilitated process, these experts developed a high-level strategic roadmap that:

- Provides an overview of the nation's water supply needs (focusing on those needs that are particularly amenable to technological or scientific solutions);
- Illustrates a sweeping national research agenda focused on meeting national needs; and
- Develops a suite of research areas that hold great potential for generating technological solutions to the nation's water supply needs.

## 1.2 The Nation's Water Issues: Solution Approaches

Over the next two decades, many regions of the nation will likely face dramatic changes in the availability of water, the quality of that water, and the regulation of the use and disposal of that water.[1] Ensuring that sufficient quantities of safe water continue to be available during times of diminished supply and increased demand will require a national focus on increasing the supply of water, ensuring its continued quality, and mitigating the environmental impacts of water use and production. Such a national focus will pay benefits at the regional scale – increased supply will allow suppliers to maintain or enhance their control over local water supplies, and will also facilitate regional control over water (in particular allowing inland and coastal regions to more effectively and equitably distribute water supplies).

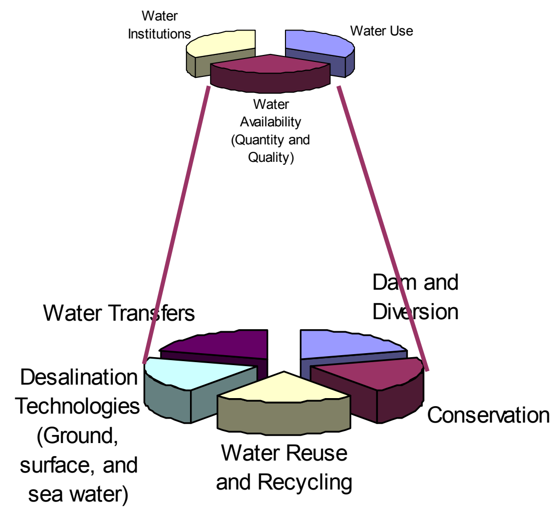



Figure 1. Desalination and water reuse and recycling are major, feasible methods of increasing our nation's water supply.

As seen in Figure 1, the National Research Council's recently-released *Assessment of the Water Resources Research Agenda for the Twenty-First Century* report divides the nations' water issues into three areas:

- Water Institutions,
- Water Use, and
- Water Availability: Quantity and Quality.

Of these three areas, technological solutions can offer improvement primarily in the area of increasing water availability. The primary means of increasing water availability include:

- Water Transfers,
- Dam and Diversion,
- Conservation and Efficiency,
- Water Reuse and Recycling, and
- Desalination Technologies.

**Water Transfers.** The transfer of water rights from one owner to another in a given water drainage area can increase local water supplies and balance resources. Constrained by fixed allotments of surface waters and diminishing aquifers, urban

[1] A discussion of the nation's current water situation and an examination of the nation's future water challenges is presented in Appendix A.

areas have taken to buying water rights from agricultural consumers (who often have senior water rights to whatever water is available). Such transfers solve, in the short-term, supply issues for those areas that can afford the transfer price. The long-term environmental, economic, regulatory, and societal implications for the nation (particularly its agricultural economy), however, are unknown.

**Dam and Diversion.** Creation of water storage capacity is a traditional means of ensuring our supply of water. Finding suitable sites where economic and environmental issues can be resolved, however, presents considerable challenges. Raising the height of existing dams and thereby increasing storage capacity offers some opportunity. Small reservoirs remain susceptible to drought and all systems are susceptible to prolonged drought (those lasting longer than five years). Such drought conditions may become more prevalent across the United States as a result of shifts in the global climate.

Additionally, diverting water can be enormously expensive, especially for inter-basin diversions where water must be 'lifted' over significant elevations (mountains) and then piped for long distances. The cost to build these infrastructures and operate them can result in very expensive water.

**Conservation and Efficiency.** Conserving water resources is one of the easiest and most effective methods of providing additional water resources (each gallon that is conserved by one user essentially 'creates' a gallon of water for another user). Vigorous public education campaigns and technological advances have resulted in the widespread adoption of conservation programs, but the volume of water they 'create' is likely to be insufficient to slake the nation's ever-increasing thirst for water. Conservation activities can also reduce the volume of in-stream flows (by reducing the amount of wastewater returned to the stream) with serious consequences to the environment.

**Water Reuse and Recycling.** Reusing our most precious natural resource is essential to increasing our water supply. Much like conservation, each gallon that is reused is one less gallon that must be drawn from our over-taxed rivers and aquifers. Increasing the volume of water that is reused is both a technological challenge and a public policy and perception challenge. Additionally, reuse of water reduces the need for disposal and somewhat mitigates this concern. This Roadmap does not address policy or perception – however, advanced water reuse treatment methods are the same as desalination technologies. Thus, by developing next-generation desalination technologies, the nation can also improve its ability to reuse and recycle water.

**Desalination.** Desalination is much more than just the treatment of seawater. Historically, seawater desalination has been viewed as an expensive alternative to developing unimpaired water sources. As these unimpaired sources have become fully allocated, our nation is now forced to turn to using these impaired water sources. Inland, the development of brackish water offers the potential for new resource development while coastal locations are looking to seawater.

**The primary technological method of generating additional water supplies is through desalination and enhanced water reuse and recycling technologies.** The efficiency of desalination and water purification technologies currently evolves at a rate of approximately four percent per year. Continuing along this path will result in future evolutions of current-generation technologies that continue to produce water that is too expensive for many applications. Thus, the primary goal of the Roadmap is to chart a series of research and development activities that will result in cost-effective, efficient revolutionary desalination and water purification technologies that can meet the nation's future needs. The Roadmap's secondary goal is to establish development activities that will accelerate the rate of improvement of current-generation desalination and water purification technologies, thus allowing these technologies to better meet the near-term needs of the nation.

## 1.3 A Vision for Desalination Technology Development

As a starting point for the development of the Roadmap, the Executive Committee of the Roadmapping Team summarized the role of desalination and water purification technologies in meeting the nation's water challenges into the following Vision statement:

> ***By 2020, desalination and water purification technologies will contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply for the Unites States.***

- **Provide safe water.** A **safe** water supply is one that meets all drinking water standards, meets all standards for use by agricultural and industrial interests, and that strives to move toward greater water security during drought, natural disasters, transport, and terrorist attacks.
- **Ensure the sustainability of the nation's water supply.** A **sustainable** water supply is one that meets today's needs without jeopardizing the ability to meet the needs of future generations.
- **Keep water affordable.** An **affordable** water supply is one that provides water to the nation's future citizenry at rates comparable to that of today.
- **Ensure adequate supplies.** An **adequate** water supply is one that guarantees local and regional availability of water and that maintains reserves of water sufficient to endure episodic shortages such as droughts.[2]

[2] In Section 2.0 of this document, 'Ensure the sustainability of the nation's water supply' and 'Ensure adequate supplies' are combined. Both needs focus on creating new water, with only a temporal difference between the two. Ensuring adequate supplies today will require the development of the same technologies that will help to ensure sustainability tomorrow.

Already the nation's fresh water supplies are hard pressed to meet growing demands. While many economical and effective steps can be taken to restrain or reduce the growth of demand, existing fresh water sources are falling behind demand in several areas of the United States at present, and this will occur in more places in the foreseeable future. Complicating the issue of balancing supplies with demands are concerns regarding water quality – the United States Environmental Protection Agency reports that 35% of the nation's river miles and 45% of the nation's lake, reservoir, and pond acreage is impaired for one or more uses. Making this water safe in the coming decades will require increasingly complex and expensive treatment to remove the contaminants that impair these waters. Decreasing demand, increasing efficiency of use and applying market forces to encourage water transfers are policy mechanisms that can help address the growing and shifting needs for fresh water. These mechanisms, however, must be complemented with technological solutions if the nation is to assure its future water supply.

For the purpose of this document, desalination refers to "the use of any process or technique for the removal and, when feasible, adaptation to beneficial use, of organic and inorganic elements and compounds from saline or biologically impaired waters, by itself or in conjunction with other processes." [Public Law 104-298]

Many of the technologies available today to treat water are either not expected to meet future water quality and quantity demands or are extremely expensive to build and operate (resulting in expensive water). New technologies will have to be developed that can efficiently remove contaminants in a cost effective manner. The challenges inherent in developing these new technologies are not insignificant – success will require comprehensive, focused research and development investments; programs to 'prove' these research findings in real-world demonstrations; and technology-transfer processes to transition promising technologies from demonstration to real-world application and commercialization. A discussion of the steps required to move new technologies to application is presented in Section 5.

Technology alone will not meet all of America's national-scale water needs – new desalination and water purification technologies are but one tool that can be use in conjunction with non-technological (policy-based) water management tools. However, solutions to many of the components of these national-scale needs can be effectively met through the expanded use of desalination and water purification technologies.

**The Present/Coming Water Shortage**

- Assuming continued per capita water use, 16 trillion additional gallons per year will be required in the United States by 2020 for municipal and light industrial uses. This is equivalent to ¼ of the combined outflow from ALL of the Great Lakes.
- In California, combined agricultural, urban, and environmental demands already exceed average supplies by 326 billion gallons per year.
- 50% of the nation's future population growth is forecast to occur in CA, TX, and FL – regions already experiencing water shortages.

The Desalination and Water Purification Technologies Roadmap traces the connection between the nation's water supply needs and the future of water desalination science and technology. It defines a research and development path for desalination technologies, beginning today and continuing through the year 2020, that, if implemented, will help find solutions to the nation's water supply needs by advancing the state-of-the-art in desalination and water purification technologies.

## 1.4 THE PURPOSE OF TECHNOLOGY ROADMAPS

Technology roadmaps serve as pathways to the future. They call attention to future needs for developments in technology, provide a structure for organizing technology forecasts and programs, and communicate technological needs and expectations among end users and the research and development (R&D) community.

Critical Technology roadmaps, of which this Roadmap is an example, are meant to clearly articulate programmatic and technical objectives. Critical Technology Roadmaps focus on "enabling" or "cross-cutting" technologies that address multiple needs. Critical Technology Roadmaps must be responsive to the needs of the nation; must clearly indicate how the science and technology can improve the nation's ability to meet its needs; and must describe an aggressive vision for the future of the technology itself.

The purpose of this Roadmap is to identify, select and develop objectives that will satisfy near- and long-term water supply-related challenges. Development of the Roadmap began with a clear discussion of major national-level water supply needs that will arise over the next several decades. From this, the Roadmapping Team identified Critical Objectives and Targets that clearly define the degree of technological improvement required to meet the nation's needs. Critical Objectives are the highest-level milestones that define the targets that a technology must meet by a given point in time. After identifying a set of Critical Objectives, the Roadmapping Team determined underlying technology areas and individual research and development projects relevant to each Critical Objective—thus mapping the pathway a technology will follow to meet each of the nation's needs. A notional illustration of this linkage is provided in Figure 2. A more detailed overview of the roadmap process is described in Appendix B**.**

## 1.5 THE STRUCTURE OF THE DESALINATION AND WATER PURIFICATION ROADMAP

The Desalination and Water Purification Roadmap is grounded in the needs of the nation and its people. Section 2.0 of this document discusses these needs as they relate to present and future desalination and water purification technologies. It is anticipated that advances in desalination and water purification technologies will play an important role in the way that water is managed and used in the United States over the next several decades. These advances will be possible not only because of past Federal investments in these technologies, but also through the integration of developments in many other areas of science and technology, particularly in the fields of process optimization, materials research, membrane design, energy saving technologies, and nanotechnology. Descriptions of how next-generation desalination technologies will aid the management and use of water in the United States are presented in five stand-alone discussions following Section 2.0.

Revolutionary desalination and water purification technologies will change the way the nation manages and uses water by providing new processes to cost-effectively and efficiently remove salts and other contaminants from impaired waters, and in doing so increase the available volumes of water while ensuring the provision of safe water. These processes, and their underlying science and technology areas, are presented in

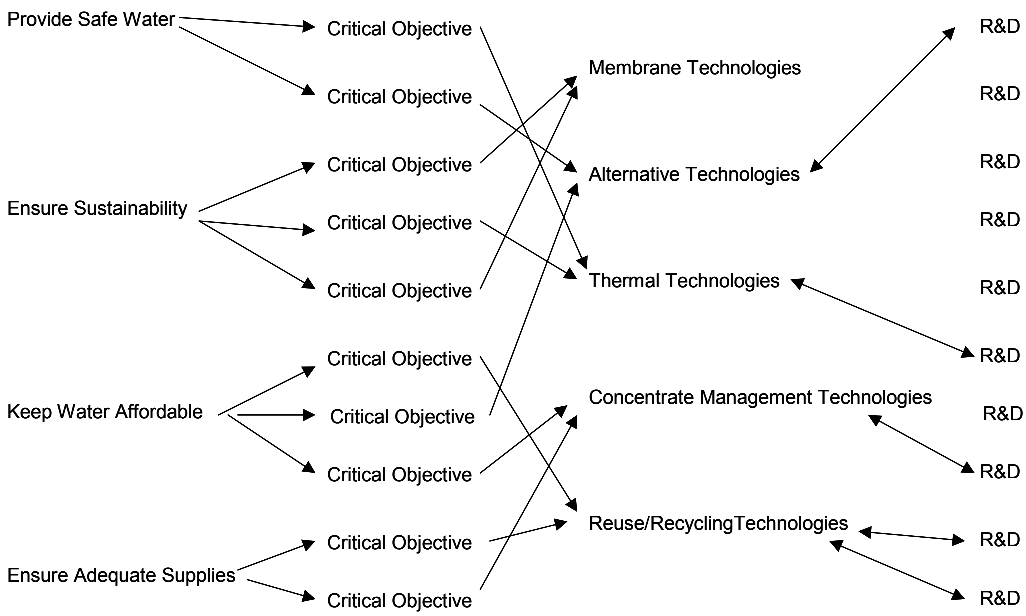



Figure 2. Notional illustration of Roadmap linkages.

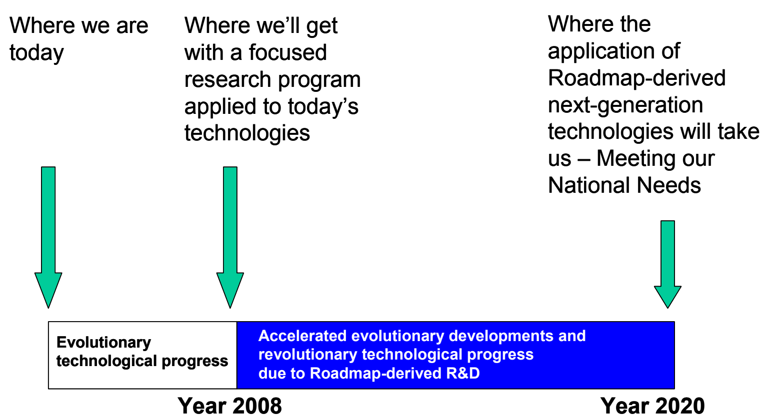
Section 3.0. Specific explanations of the five science and technology areas: membrane technologies, alternative technologies, thermal technologies, concentrate management technologies, and reuse/recycling technologies, are provided at the end of Section 3.0.

Past investments in desalination science and technology, coupled with recent advances in related science and technology areas, have resulted in desalination technologies that are poised to provide the nation with a dramatically new set of tools that can be used to help meet our nation's future water needs. Section 4.0 explores two scenarios under which the interplay of Federal investment and private sector R&D activities may impact the development of next-generation desalination and water purification technologies. Section 5.0 provides a brief overview of the next-steps for the Roadmap and the development of supporting documents to round-out the context of the Roadmap.

Appendix A provides a detailed overview of the nation's current and projected water situation – this information is integral to understanding the need for desalination and water purification technologies. Appendix B provides a more detailed discussion of the roadmapping process. Appendix C discusses the advantages presented by pursuing a 'dual track' R&D endeavor that focuses both on improving current-generation technologies (and in effect more efficiently meeting our short-term needs) and developing the revolutionary technologies that will allow us to meet our nation's long-term needs.

# 2.0 GROUNDING THE ROADMAP: ESTABLISHING NEEDS, CRITICAL OBJECTIVES, AND METRICS FOR DESALINATION AND WATER PURIFICATION RESEARCH

Critical Objectives are quantifications of America's national-scale needs – they set targets that must be met by a technology if it is to play a role in meeting the nation's needs to **provide safe water; ensure adequate supplies/sustainability; and keep water affordable.** These targets were set by the Executive Committee in anticipation of future national needs. For the specific example of cost targets in the mid-term (10-12 year) and long-term (20 year) time horizons, these targets were set to assure that all of the nation's users, including agriculture and Native Americans, are considered. The continued development of water resources for urban areas often reduces the amount of water allotted for other uses including agriculture. In order to stop this *trend*, **the cost difference between treating impaired water and unimpaired fresh water must be reduced**. In this way, the economic driver for cities to buy nearby water rights will be reduced. Hence, one long-term cost objective is to reduce the difference in treatment costs between impaired water and higher-quality water, for urban use. If this objective is not met, the trend of increasing relative use by urban areas will jeopardize many other important water uses, such as the environment, agriculture, Native American water use, industry, and recreation.




Desalination technologies historically display a four percent per year improvement in cost reduction. These improvements are a result of the introduction of membranes and subsequent evolutionary improvement in the technology. These cost reductions have been realized as a result of substantial Federal investment.

To assist government and industry researchers in meeting their full potential, this Roadmap lays out Critical Objectives that will accelerate the rate at which costs are reduced and performance is improved. **Near-term Critical Objectives** are focused on improving the state-of-the-art of currently-available technologies – in essence they seek to improve upon the four percent per year rate of improvement seen to date. **Mid/long-term Critical Objectives are needs based** – they have been created to shepherd the development of technologies that the nation will require to meet our future needs.

Near-term Critical Objectives target improvements to existing technologies (and thus meeting our short-term needs), while Mid/long-term Critical Objectives are designed to provide the science and technology base for the development of revolutionary, next-generation technologies. Meeting the Roadmap's short-term Critical Objectives will improve current desalination technologies so that they are more economical and efficient. Meeting mid/long-term Critical Objectives (which contain 'stretch targets' that are intentionally designed to be difficult to meet), will result in the development of revolutionary, next-generation technologies that are necessary to meet our nation's future water needs. **It is impossible (either practically or economically) for current-generation technologies to meet these 'stretch targets'.**

The Critical Objectives are a central focus of this Roadmap. Again, each Critical Objective includes a metric (or Target); for example, one near term Critical Objective calls for the "reduction of desalination facility operating costs by 20 percent." The historical improvement in performance in desalination processes has been 4% per year averaged over 30 years. This improvement is the result of a substantial research program that developed a revolutionary improvement, i.e., the discovery of membrane technology. The subsequent improvement is evolutionary and catalyzed by the same research program. Because continued improvement is still possible (the performance of these systems is not near the theoretical limit), a healthy research program should be able to continue the historical improvement. These metrics, developed by the Roadmapping Team, are expert-generated impressions of the level of technological change that must take place if desalination and water purification technologies are to play a significant role in meeting our nation's future water needs. The stretch targets given for the critical objectives are motivated by the need to help large and small urban areas develop impaired water sources rather than use nearby unimpaired water sources.

There is no single 'right' way of meeting the metrics for a Critical Objective – multiple technologies or combinations of technologies may provide radically different solutions that all meet a given metric. The Roadmapping Team identified five broad Technology Areas that encompass the spectrum of desalination technologies, and that may, individually or in combination, meet a given (or several) Critical Objectives (these Technology Areas are discussed in Section 3.1). Current generation desalination technologies are all drawn from these five Technology Areas, and it is from these Areas that Roadmapping Team members expect revolutionary, next-generation desalination technologies to emerge.

Specific values for the metrics are associated with timeframes – the near-term ends in the year 2008, and the mid/long-term ends in the year 2020. The near-term roadmap goals are defined in terms of improving (evolving) the performance of current-generation desalination technologies, whereas the goals for the mid/long-term are driven by the need to create advanced, next-generation (revolutionary) desalination technologies that will be a fundamental component of the nation's suite of solutions to the nation's needs.[3]

[3] For a discussion of evolutionary vs. revolutionary technologies and the benefits of pursuing 'dual-track', please see Appendix C.

A representation of a Critical Objective chart is provided in Figure 3. In each Critical Objective chart shown in Section 2.1, research and development projects are linked to a Technology Area. Thus, the Critical Objective chart serves to link a discrete research and development project within a Technology Area to the meeting of a Critical Objective, and thus a national-scale need. 'Tying' research and development activities to a concrete national need helps to ensure that R&D activities are targeted and focused on solving discrete problems and meeting national needs, avoiding the propensity of research to 'drift' from its original intent.

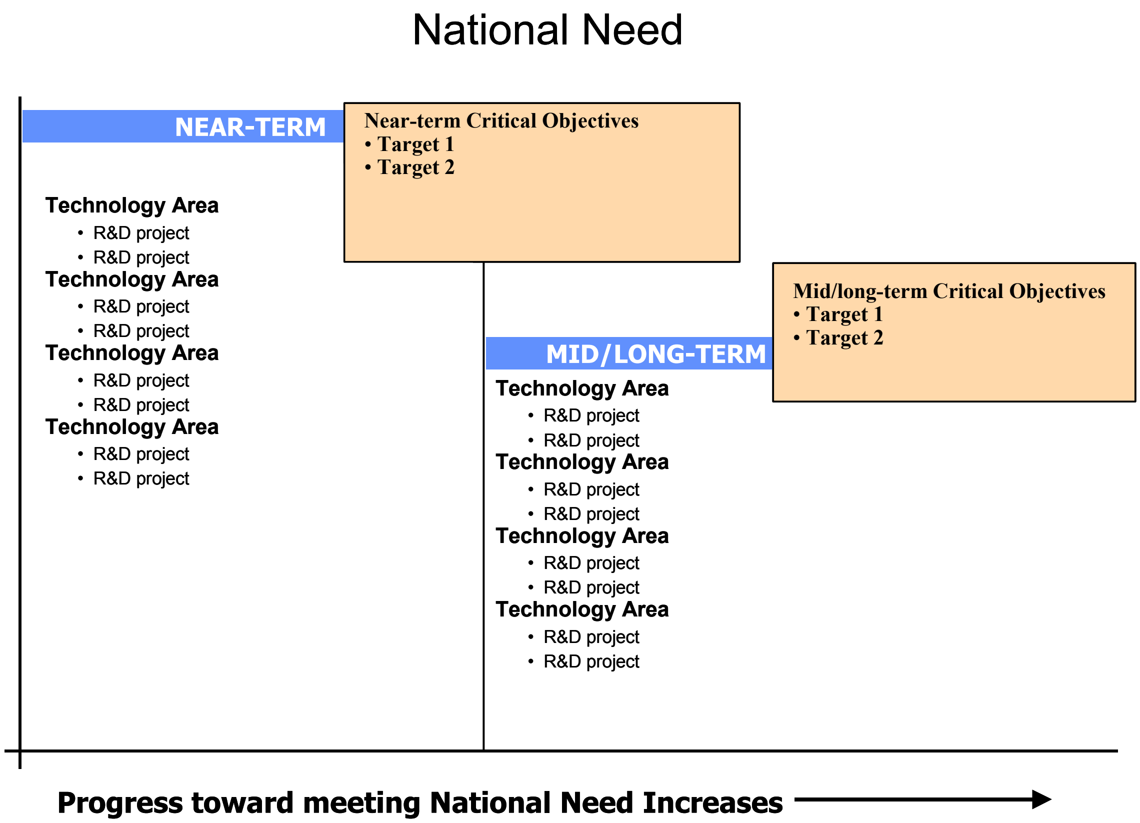



Figure 3. Sample Critical Objectives chart.

## 2.1 NATIONAL NEEDS AND CRITICAL OBJECTIVES TO MEET NEEDS

As summarized in the Vision statement in Section 1.2, the United States possesses three primary needs: **provide safe water; ensure adequate supplies/sustainability; and keep water affordable.** The United States can only meet these needs by developing a focused, interdisciplinary suite of water management tools – among which are improved current-generation desalination technologies and advanced, next-generation desalination and water purification plants and programs. This Roadmap focuses on the potential contribution of desalination and water purification technologies to meeting these needs.

With respect to desalination and water purification technologies, Table 1 below provides a summary of the Critical Objectives that technologies must achieve to help meet the nation's overall water supply needs. These Critical Objectives were developed by the Executive Committee and represent targets for technology development activities. The following discussions provide background information regarding how the Critical Objectives are tied to emerging national needs.

| NATIONAL NEED | Near-term Critical Objectives (2008) | Mid/long-term Critical Objectives (2010/2020) |
|---|---|---|
| Provide safe water | • Develop on-demand removal technologies<br>• Remove 60% of synthetics<br>• Microbial removal at 4-6 orders of magnitude (today's removal is 2-3 orders)<br>• Remove endocrine disruptors, MTBE, nitrosamines, perchlorate<br>• Develop true indicators (not just SDI and turbidity)<br>• Surface water and land disposal: Develop science-related concentrate specific regulations related to dispersion modeling of mixing zones and ion imbalance<br>• Subsurface injection: Large scale regional characterization of US subsurface injection capability | • Add all other concentrate specific regulations, refined geographically and addressing cumulative issues.<br>• Demonstrate isolation with hydrologic model of receiving formation and formation scale model of subsurface injection capability of US |
| Ensure adequate supplies/ensure sustainability | • Decrease cost of reclaimed waters by 20%<br>• Beneficial use: 5% of concentrate<br>• Reduce reject to 15% for non-surface water applications<br>• Maintain stability of reclaimed waters over time | • Decrease cost of reclaimed waters by 50% (Stretch target – 80%)<br>• Beneficial use: 15% of concentrate<br>• Reduce reject to 5% for non-surface water applications |
| Keep water affordable | • Reduce capital cost by 20%<br>• Increase energy efficiency by 20%<br>• Reduce operating costs by 20%<br>• Reduce cost of ZLD by 20% | • Reduce capital cost by 50% (Stretch target – 80%)<br>• Increase energy efficiency by 50% (Stretch target – 80%)<br>• Reduce operating costs by 50% (Stretch target – 80%)<br>• Reduce cost of ZLD by 50% (Stretch target – 80%) |

Table 1. National Needs Quantified in Critical Objectives

### *National Need – Provide Safe Water*

Our nation has historically been blessed with some of the highest quality water found anywhere on Earth – this situation is changing, however, as our nation's water quality deteriorates. The increased use of this limited resource, however, has resulted in heretofore-unknown pressures on the quality of our nation's water. An aging infrastructure provides additional pressure on water quality, as deteriorating distribution systems and water treatment plants struggle to provide consistently high quality water to consumers. And, the definition of 'safe' remains a moving target as regulations designed to protect human health will likely become increasingly stringent in the future.

Surface and ground water in the United States often contains constituents that must be removed if their concentration exceeds State or Federal levels. When their concentration exceeds regulatory limits or secondary drinking water standards, these waters are referred to as impaired. Dissolved or suspended contaminants commonly found in impaired waters include:

- Biologics,
- Salts (total dissolved solids),
- Metals,
- Chemicals,
- Radionuclides, and
- 'Pharmaceutics' (including such things as caffeine and endocrine disruptors).[4]

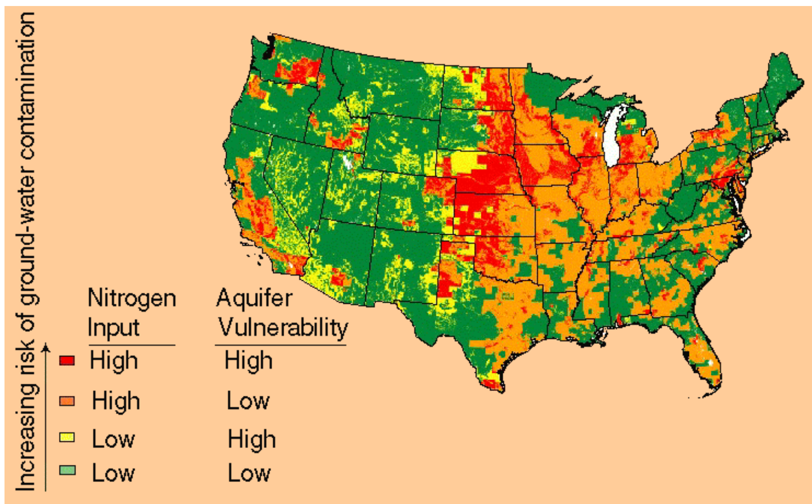



Figure 4. Extent of risk of nitrate contamination in aquifers.

Contamination of the nation's waters is a result of both human activities and natural processes. Up to 80% of the salt found in surface waters is the result of natural erosion processes. Increasingly-intensive use of waters, however, is exacerbating natural salt loads, resulting in some downstream areas becoming 'sinks' for concentrated salts. And land use practices (including urban and suburban sprawl and agricultural practices) and personal activities (primarily the widespread use of water softeners that add salts to wastewater flows) can radically change the quantity and types of contaminants found in surface and ground waters.

Impaired waters are increasingly common across the United States.[5] As an example, the vulnerability of aquifers to nitrate contamination (a byproduct of agricultural fertilizers and septic systems, among others) is displayed in Figure 4.

[4] NB: At this time, there are no regulatory limits for TDS and pharmaceutics.

[5] The United States Environmental Protection Agency reports that 35% of the nation's river miles are impaired, and that 45% of the nation's lake, reservoir, and pond acreage is impaired. 23% of the nation's river miles and 42% of the total surface impoundment acreage were assessed. Source: The

To ensure the continued safety of the nation's water supply, a focused R&D program is required to develop advances in:

- **Contaminant removal.** What contaminants must be removed from our water supplies is a moving target – as our scientific understanding of how contaminants affect people improves, regulations governing the acceptable levels of those contaminants becomes increasingly strict. Compounding this issue is the variability of our water supplies – drought and flood conditions can result in significant shifts in the ratio of contaminants in a given water supply. Thus, purification technologies must be developed that are effective at removing today's contaminants, that are flexibly-designed so that they can meet future contaminant challenges (pharmaceutics, endocrine disruptors, etc.), and robust enough to work in a variety of water supply conditions. On-demand removal technologies offer great promise in meeting these challenges.
- **Contaminant disposal.** Ensuring the safety of our nation's water supply entails not only removing contaminants, but also finding safe disposal options for those removed contaminants (for instance, one would not want to dispose of removed contaminants in a manner that would allow those contaminants to re-enter the water cycle in the near-term). Developing safe disposal options will require, among other activities, research on technologies that effectively encapsulate the contaminants, research on deactivating contaminants, and research on the fate and transport of contaminants through the environment (to discover where and how they can be safely deposited).

  Next-generation desalination plants will allow the nation's water providers to use underutilized water sources for municipal, agricultural, and industrial applications. This shift in what waters we as a nation use could permit us to draw lesser volumes from traditional (and often highly-stressed) water sources, ensuring that those waters will continue to be available to future generations. However, upgrading these impaired waters currently results in the production of large quantities of concentrate (desalination's waste stream, comprised of some percentage of the feed water and the contaminants removed from the feed water). Finding environmentally-sensitive disposal options for this concentrate that do not jeopardize the sustainability of water sources is difficult, and thus next-generation desalination plants will have to be designed to minimize the production of these concentrates, or find useful applications for them.
- **Water handling capacity.** As water quality regulations become more stringent and as our nation's waterways become more impaired, water purification technologies will be called upon to treat a greater volume of water in a given locale. This will require technologies that are capable of effectively handling greater inflow volumes and producing greater volumes of purified water.
- **Decentralization of facilities.** Providing safe water in the future will require redundancy in our nation's infrastructure. At present, large centralized water treatment plants provide water to many thousands (or hundreds of thousands) of

---

Quality of Our Nation's Waters. A Summary of the National Water Quality Inventory: 1998 Report to Congress. EPA841-S-00-001 households and businesses – such centralization is akin to putting all of our eggs in one basket; a single contamination event (be it natural or malicious) may threaten the quality of water for tens of thousands of individuals. Installing smaller-footprint, decentralized desalination and water purification facilities will reduce the impact of a single contamination event, and will provide redundancy so that water providers can maintain quality should one facility go 'off-line' (as one facility is taken out of service, other decentralized facilities will be present to take up the slack).

Figure 5 presents the Critical Objectives associated with the national need 'Provide Safe Water'. This chart is illustrative of high-priority R&D activities that were judged by the Roadmapping Team to have the greatest potential to meet the nation's needs in the short- and mid/long-terms. It is important to note that not all technology areas are applicable to a given national need – thus, not every Critical Objectives chart will contain entries for all five technology areas. It is also important to note that the near- and mid/long-terms cannot necessarily be viewed in isolation – some mid/long-term activities may be continuations of near-term projects, while others may be dedicated to developing new technologies and approaches independent of near-term activities.

**Near-term Critical Objectives**
- Develop on-demand removal technologies
- Remove 60% of synthetics
- 4-6 logs (microbial removal)
- Remove endocrine disruptors, MTBE, nitrosamines, perchlorate
- Develop true indicators (not just SDI /turbidity)
- Surface water/land disposal: Develop science related concentrate specific regulations related to dispersion modeling of mixing zones/ ion imbalance.
- Subsurface injection: Large scale regional characterization of US subsurface injection capability

## NEAR-TERM

### Alternative Technologies
- Ultrasonic
    - Supersonic
- Membrane and Membrane Combinations

### Thermal Technologies
- Hybrid - Membrane and thermal to reduce waste stream R&D project
- Develop solar ponds for energy and concentrate management
- Enhanced evaporation

### Concentrate Management Technologies
- Develop science related concentrate specific regulations for dispersion modeling of mixing zones and ion imbalance for surface water discharge R&D project
- The biology of salty water, including understanding env. impacts, using bacteria for beneficial treatment, etc.
- Research into engineered ecology/bioengineering to discover:
    - How to engineer disposal so that at least it does not harm ecosystems, and if possible is beneficial
    - Natural analogs to current treatment

**Mid/long-term Critical Objectives**
- Add all other concentrate specific regulations, refined geographically and addressing cumulative issues
- Demonstrate isolation with hydrologic model of receiving formation and formation scale model of subsurface injection capability of US

## MID/LONG-TERM

### Membrane Technologies
- Smart membranes
    - Sense contaminant differential across the membrane (in real time), automatically change performance and selectivity
- Sensor development
    - Model compounds for organics/On-line viral analyzer
    - Micro/in-situ/built-in EPS sensor to detect biofilms; particulate fouling sensor
- Membrane Research
    - Operate in range of pHs (mechanical/chemical cleaning)/
    - Adjust removal capability based on feed water quality and removal needs (2014 – pharmaceuticals removal based on molecular weight, hydrophilicity)
    - Biofilm-resistant surfaces

### Alternative Technologies
- Biomemetic
    - Active membranes/Biological sensors/Signaling capabilities/Mangroves

### Reuse/Recycling Technologies
- Develop a set of organic chemical surrogates acceptable to the public for potable reuse R&D project
- Risk comparison between various water reuse schemes and potable water counterparts

**Safety of Desalinated Water Increases →**

Figure 5. Providing Safe Water: Needs, Critical Objectives, and Metrics

### *National Need – Ensure Adequate and Sustainable Water Supplies*

Meeting future national water needs requires not only that we use today's conventional supplies wisely, but also that we enhance and supplement those supplies through water reuse, desalination, and water purification. Both elements are inextricably linked in our effort to assure adequate and sustainable water supplies.

There are no 'new' sources of conventional water available in the United States – every drop of fresh water has been located. In addition, conventional water supplies in many regions of the United States are tapped out – in these areas, quite literally every drop of water in the rivers, aquifers, and reservoirs is allocated to a use (and often multiple uses), be it agriculture, residential use, or to maintain aquatic environments and their inhabitants.

Sustainability, as it relates to water, is multi-faceted, but hinges on the premise that the nation must ensure that it's supply of water remains available for the use of future generations, and that this water retains its quality over time. This entails a host of activities ranging from demand mitigation (ensuring that we don't use more water today than our conventional supplies can sustainably provide) to environmental protection (ensuring that our use of water does not harm the aquatic environments that are so important to keeping rivers and surface impoundments healthy).

Ensuring adequate supplies in the future will require a combination of supply-side strategies (see Section 1.3 for a discussion of these strategies) and research that focuses on:

- **Finding/developing new sources of water.** As conventional sources are essentially tapped out, these new sources of water will have to come from currently under-utilized impaired sources like brackish aquifers, seawater, and the large volumes of water that are generated during energy production (oil, natural gas, and coal bed methane production, primarily, as seen in Figure 6). In addition, the nation must make better use of the water that it currently possesses. This can be accomplished through aggressive recycling and reuse of water.
- **Developing technologies that can upgrade impaired waters.** Today's water treatment plants and current-generation desalination facilities cannot cost-effectively and/or technically produce usable water from impaired sources, nor can they sufficiently treat recycled water for a variety of uses. Thus, to ensure adequate supplies for the future, next-generation desalination plants that can

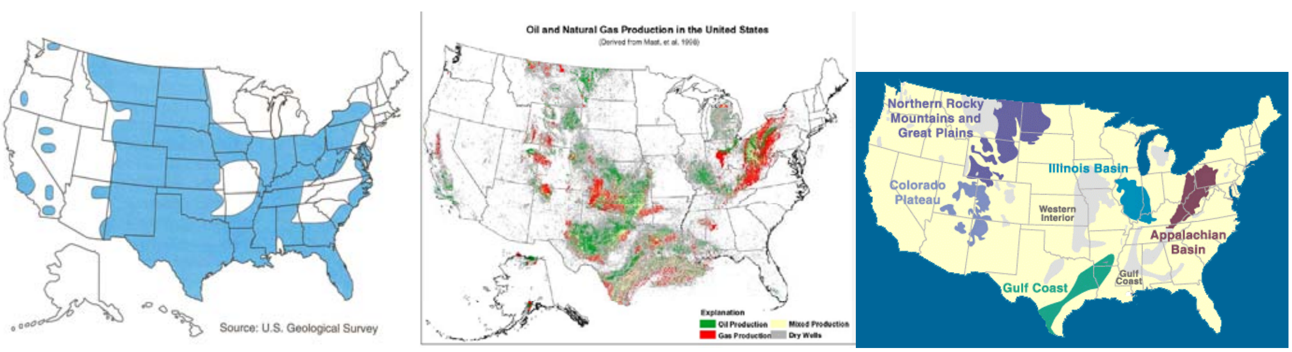



Figure 6. Location and extent of saline aquifers, oil and natural gas production, and coalbed methane reserves (respectively, shown in shaded colors). All three are sources of impaired waters that could be upgraded by desalination and water purification plants for productive use.

upgrade impaired waters and produce reliably safe recycled waters must be developed and incorporated into a comprehensive supply-side/demand-side water management strategy.

- **Decentralizing supply networks.** To realize their full potential in assuring water supplies for the nation, revolutionary desalination plants must be designed in a range of sizes so that they can be more easily (and inexpensively) installed where demand exists. Smaller-footprint facilities can make use of smaller deposits of impaired waters, thus adding to the nation's available supply of water (this principle is similar to advances seen in oil and natural gas development – as larger oil fields in the United States reach exhaustion, smaller, cheaper 'satellite' facilities are constructed that can take advantage of smaller oil deposits, and in doing so add to the available resource at a cost much reduced compared to centralized facilities). Without smaller, cheaper desalination and water purification plants, many localities that need these technologies will be unable to afford them (current-generation, centralized plants are often designed to handle far more water than smaller communities need).

Reclamation and reuse of water has become an increasingly important component of the nation's efforts to maintain water sustainability. Reclaimed waters are most frequently used in low-value applications (e.g., watering golf courses and parks) where high-quality water is not necessary. These applications essentially 'free' more high-quality water where it can be better used (for instance, in light industrial applications or for human consumption). For reclamation and reuse applications to grow (for instance, using these waters for high-quality uses), next-generation desalination technologies must be designed to produce reliably safe reclaimed waters with reduced costs and smaller facility footprints. Reduced footprints and the decentralization of water treatment processes will reduce the need for mega-infrastructures, and may expand water reclamation in cities and alleviate the need to expand existing sewerage systems. Such advancements in the state-of-the-art are necessary to gain public acceptance for human, agricultural, and environmental uses of recycled waters.

Figure 7 presents the Critical Objectives associated with the national need 'Ensure Adequate and Sustainable Water Supplies'. This chart is illustrative of high-priority R&D activities that were judged by the Roadmapping Team to have the greatest potential to meet the nation's needs in the short- and mid/long-terms. It is important to note that not all technology areas are applicable to a given national need – thus, not every Critical Objectives chart will contain entries for all five technology areas. It is also important to note that the near- and mid/long-terms cannot necessarily be viewed in isolation – some mid/long-term activities may be continuations of near-term projects, while others may be dedicated to developing new technologies and approaches independent of near-term activities.

## NEAR-TERM

**Near-term Critical Objectives**
- Maintain stability of reclaimed waters over time (with respect to biological contaminants)
- Decrease cost of reclaimed waters by 25%
- Beneficial use for 5% of concentrate
- Reduce average reject to 15% for non-surface water applications

### Membrane Technologies
- Develop mechanistic/fundamental approach to membrane design
  - CFD of feed channel
  - Conduct research to gain understanding of molecular-level effects
  - Design-in permeability
- Develop understanding of whole system (based on current knowledge)
  - Develop model of optimization
  - Research sensitivity of parameters for model
- Develop fundamental understanding of fouling mechanisms to develop indicators
  - Understand how to mitigate fouling (Understand biofouling/Optimize operational controls)

### Thermal Technologies
- Renewable energy – (in small communities)
  - Geothermal/Solar/Wind/Biomass
- Water harvesting from air
- Membrane distillation

### Reuse/Recycling Technologies
- Investigate use of constructed wetlands
- Develop large scale regional characterization of subsurface injection capability of US

## MID/LONG-TERM

**Mid/long-term Critical Objectives**
- Decrease cost of reclaimed waters by 80%
- Beneficial use for 15% of concentrate
- Reduce average reject to 5% for non-surface water applications

### Alternative Technologies
- Ion Sorption
  - Zeolite crystallization
- Sodium pump/biomimetic
- Advanced membranes/separation
  - Porcelain/thin-film/biologic/bioreactors

### Concentrate Management Technologies
- Create a "super concentrate" technology – complete solidification of residuals and 100% recapture of water
- Explore beneficial uses of concentrate including irrigation; farming; solar pond; cooling water; manufacturing; agriculture; repair of dead-end stagnant canals; energy recovery; artificial wetlands, recreations, halophilic irrigation; aquaculture
- Decentralized (Point of Use) Treatment and recycling as a way of managing concentrate

### Reuse/Recycling Technologies
- Watershed-based salinity management strategy

**Volume of Desalinated Water Increases →**

Figure 7. Ensuring Adequate Supplies/Sustainability: Needs, Critical Objectives, and Metrics

### *National Need -- Keep Water Affordable*

To meet ever-increasing demand and to satisfy both environmental needs and competing demands, water suppliers in many regions of the United States will soon turn to using non-traditional or underutilized water sources or buying water from other users or owners (primarily from agricultural users and Native American Nations). The latter holds the potential of being very expensive – water rights holders recognize that they possess an increasingly scarce product, and economic theory demands that the price for that product increase as supply diminishes. While short-term economic gains may be realized by water rights holders, such water transfers may cause other, unanticipated effects on agricultural lifestyles and economies (including reduction of our nation's agricultural independence and decreases in our food security). Reducing the cost of upgrading impaired waters is a major way to change this trend.

Cost is one of the biggest challenges to increasing the availability of water in the United States. Assuming application of currently-available advanced desalination and water purification technologies and favorable financing, the treatment cost of a gallon of purified seawater today currently costs approximately five to six times the treatment cost of fresh water (Water Treatment Estimation Routine User Manual, U.S. Bureau of Reclamation, Water Treatment Technology Program Report No. 43). Despite these high costs, several desalination projects are currently being planned to replace some part of the volume of water that Southern California now draws from the Colorado River.

Supplementary Federal funding is being sought to reduce the costs as well as the risk to water utilities that propose constructing desalination facilities. Reducing the cost of desalination technologies through coordinated R&D will help reduce the demand for federal support for the construction and operation of these facilities.

On the other side of the ledger are the vast supplies of rarely used, impaired waters found across the nation. These waters, however, require extensive treatment before they can be safely used. If we desire to have inexpensive water for agriculture, the environment, recreation and other uses whose value is not now measured in cost effectiveness, we as a nation must possess the technologies necessary to inexpensively utilize some of these water sources. The rate at which technology is evolving (a rate of approximately four percent per year reduction in cost) means that our current crop of technologies will require decades to adequately produce water at costs that are competitive with other sources. Driving down the cost of water produced from next-generation desalination technologies will require a dedicated research and development program that focuses on:

- **Increasing production efficiency.** Improving process efficiencies involves improving the quantity of water produced per unit of energy consumed.
- **Reducing capital and energy costs.** Between 65% and 81% of the cost of every gallon of water produced using current-generation desalination and water supply purification technologies is tied to capital construction costs and the cost of energy for treatment.[6] This keeps current-generation desalination and water

[6] The range is dependent upon the type of water that is available for treatment and the amount of infrastructure necessary to capture and deliver water. Using seawater results in higher energy consumption percentages, whereas using brackish water results in higher capital cost percentages. Please see the economic studies by G.A. Pittner in *Reverse Osmosis*, Z. Amjad, ed. Chapman Hall, New York (1993), and K.S. Speigler and Y.M. El-Sayed, A Desalination Primer, Balaban Desalination Publications, Santa Maria Imbaro, Italy (1994).

purification plants out of economic reach for many communities. The design of next-generation desalination technologies must be driven by the need to reduce capital and operations costs. The aggressive cost targets described in this Roadmap cannot be met without the discovery and application of innovative methods.

Figure 8 presents the Critical Objectives associated with the national need ‘Keep Water Affordable’. This chart is illustrative of high-priority R&D activities that were judged by the Roadmapping Team to have the greatest potential to meet the nation’s needs in the short- and mid/long-terms. It is important to note that not all technology areas are applicable to a given national need – thus, not every Critical Objectives chart will contain entries for all five technology areas. It is also important to note that the near- and mid/long-terms cannot necessarily be viewed in isolation – some mid/long-term activities may be continuations of near-term projects, while others may be dedicated to developing new technologies and approaches independent of near-term activities.

## NEAR-TERM

**Near-term Critical Objectives**
- Reduce capital cost by 20%
- Increase energy efficiency by 20%
- Reduce operating costs by 20%
- Reduce cost of ZLD by 20%

### Membrane Technologies
- Basic research to improve permeability
  - Minimize resistance
  - Model/test non-spiral configurations
- Develop new methods of reducing/recovering energy
- Integrate membrane and membrane system designs

### Alternative Technologies
- Capacitive desal
  - Nanotubes or large surface areas
  - Current swing sorption

### Thermal Technologies
- Forward osmosis
- Clathrate sequestration
- Hybrid – membrane and thermal

### Reuse/Recycling Technologies
- Pretreatment
  - Filtration
  - Biological coating (disinfectant)
  - Research to enable prediction of migration and recovery through aquifers

## MID/LONG-TERM

**Mid/long-term Critical Objectives**
- Reduce capital cost by 80%
- Increase energy efficiency by 80%
- Reduce operating costs by 80%
- Reduce cost of ZLD by 80%

### AlternativeTechnologies
- Magnetics
- Nanotechnology (active/smart membranes)

### Concentrate Management Technologies
- Create a “super concentrate” technology – complete solidification of residuals and 100% recapture of water
- Cross-cutting: Develop methods of immobilizing/sequestering the concentrate stream
- Cross-cutting: Develop beneficial uses for the concentrate stream to improve the economics of disposal for ZLD processes.

### Reuse/Recycling Technologies
- Enhanced membrane bioreactor technology
- Document the lifecycle economics of water reuse for various applications

**Cost of Desalinated Water Decreases →**

Figure 8. Keeping Water Affordable: Needs, Critical Objectives, and Metrics

## 2.2 NATIONAL NEEDS AS SEEN AT THE REGIONAL SCALE

The 104th Congress' Committee on Resources, speaking to Public Law 104-928 (Water Desalination Research and Development Act of 1996), wrote that the object of the bill is to "advance desalination as a source of fresh water along the three seaboards (where the majority of the U.S. population lives) and demineralization (treatment of "brackish" water) in critical interior areas."[7] Such a mandate to consider the national-scale application of desalination technologies results in discovery of some interesting contrasts between regions of the United States, and elucidation of common concerns and issues (these concerns and issues are captured in the Vision statement contained in Section 1.2 of this document).

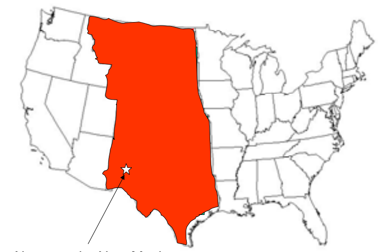
To better understand these contrasts and common concerns and issues, five case studies were developed. These examined water issues affecting:

- **Rural inland communities**;
- **The mid-Atlantic states** (comprising New York, New Jersey, Delaware, Maryland, and Virginia and the District of Columbia);
- **Inland urban areas** (as typified by Phoenix, Las Vegas, and El Paso);
- **Oil, gas, and coal basin communities**; and
- **Urban coastal communities** (the metropolises and related communities along the Pacific and Atlantic Oceans and the Gulf of Mexico).

These case studies were used by the Executive Committee to identify cross-cutting, national-scale needs and also to identify region-specific needs. Detailed discussions of the national-scale needs most prevalent in these regions follow this section.

7 U.S. House of Representatives, Committee on Resources, "104th Congress Achievements: Common Sense Solutions", http://resourcescommittee.house.gov/104cong/accomp.htm

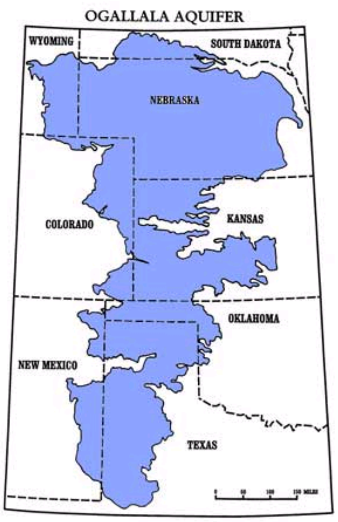
## CASE STUDY – RURAL INLAND COMMUNITIES: THE STATE OF WATER IN THE NATION'S HEARTLAND


Alamogordo, New Mexico

### Background

Alamogordo, New Mexico is typical of the small and mid-size communities found throughout the nation's heartland:

- Growth in the city's population and economy (and resultant increases in water demand) are stressing the city's traditional water supplies;
- During times of extended drought the city's supplies are only marginally able to meet the needs of all users; and
- The volume of high quality water that can be sustainably drawn from surface and groundwater sources is insufficient to meet projected future needs.




Economic and population growth in the nation's heartland has been made possible by the water provided by the Ogallala aquifer – a huge reservoir of high quality water that underlies much of the region – and the region's large rivers. These lifeblood sources of water, however, are subject to increasing stress as users draw greater volumes of water from the Ogallala aquifer than are replaced by precipitation – the effects of these unsustainable past (and current) practices are evidenced by the drying-up of wells across the Great Plains – and as drought conditions reduce the volume of water in rivers.

### Current Challenges

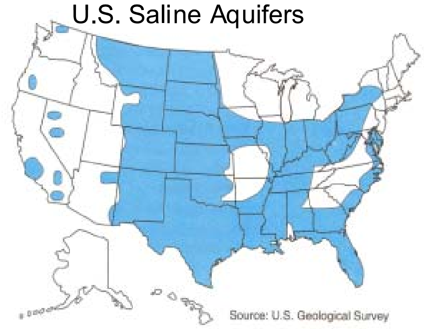
Localized shortages of high quality water (due in large part to extended droughts) are the greatest challenge facing the nation's heartland. Without sufficient and affordable water supplies, the region's largely-agricultural economy faces economic hardship above and beyond what it is currently experiencing (the agricultural sector is particularly dependent on cheap water).

Thus, this inland rural region faces the primary challenge of providing adequate, affordable supplies of water for agricultural and municipal consumers while ensuring that aquatic environments remain healthy.

### The Role of Desalination Technologies in the Nation's Heartland

The nation's heartland needs new water – the increasing severity of droughts make it plainly evident that the region's aquifers and rivers are not capable of seeing farmers through dry times as they have in the past. There is, however, the possibility of 'new' water underlying the nation's heartland – as the map at right illustrates, brackish aquifers can be found throughout the nation. This resource must be characterized for quantity, quality, and deliverability. This water is not of suitable quality to be used as it flows from the ground – the water must be desalted before it can be consumed by humans or used on most crops.

U.S. Saline Aquifers




Current-generation desalination plants are expensive to buy and operate, and thus cannot produce water at rates that are affordable for agricultural uses or for municipal use in small and medium-sized cities. Thus, the nation's agricultural heartland will need new, next-generation desalination technologies capable of producing less expensive water. While desalination technologies will likely never be able to produce water at the extremely low prices that agriculture now pays (sometimes as low as pennies per thousand gallons), reducing capital and operating costs and increasing the energy efficiency of desalination technologies will make more water available in the nation's heartland.

## CASE STUDY – THE MID-ATLANTIC: WET AND DRY AT THE SAME TIME?

### Background

The Mid-Atlantic region encompasses the States of Delaware, Maryland, New Jersey, New York, Pennsylvania, and Virginia, and the District of Columbia. This generally wet and humid region faces intense and rising demand for water from its burgeoning population and industrial and agricultural economies. Water withdrawals are rising rapidly in portions of the region: from 1990 to 1995, water withdrawals increased more than 20% in Virginia and Maryland.

The region relies on large rivers and surface impoundments to provide much of its water supply. As population grows and urbanization spreads across the Mid-Atlantic region, groundwater resources are increasingly stressed and over-drafted. Aquifers have become vulnerable to salt-water intrusion from the Atlantic Ocean. Reducing reliance on groundwater has meant relying more on surface water. Those surface waters are needed for other uses, from power generation to recreation to the protection of species and habitat, all of which are also rising in importance. And when drought conditions affect this region, all of these uses compete with one another for the diminished surface and ground water supplies that remain.

### Current Challenges

During drought years, the Mid-Atlantic region faces considerable water quality and quantity concerns. These include:

- The ability to protect vital water supply needs for public health and sanitation;
- Keeping surface water flowing in the streams and into the lakes, estuaries, and bays that are some of the region's most precious amenities;
- Preventing groundwater overdraft and further saline intrusion into aquifers; and
- Securing the quality and healthfulness all of the area's water resources from environmental and other hazards.

These challenges are complicated by population growth in inland areas – as these areas grow and increasingly claim their water, reduced supplies are available for urban areas downstream.

### The Role of Desalination Technologies in the Mid-Atlantic

There are critical needs to improve and protect water supplies and quality in the Mid-Atlantic states. Water supplies have become scarce in portions of the region already, as municipal and industrial users compete for the same fresh water sources, which are also relied upon for aesthetic, recreational, and environmental values. The quality of many fresh water sources in the region is threatened or already impaired due to a variety of factors, including naturally occurring conditions, failing or inadequate infrastructure, and existing or emerging contamination.

Improving the availability and reliability of water supplies will help meet the region's needs for drinking water and for industrial and recreational uses, as well as protecting the water needed to support species habitat and other environmental values. Improving water quality will also enhance the ability to meet all of those needs, supporting the region's economy as well as its ecology. Desalination technology can and should play an important role in improving water supply and quality in the Mid-Atlantic. For some communities in the region, desalination of brackish ground water could provide an alternative water supply, reducing the overuse of current sources and/or allowing other fresh water supplies to be left in streams for environmental, aesthetic, and recreational purposes. For other communities, desalination of ocean water could provide a sustainable and secure water supply that reduces withdrawals from surface water streams that feed sensitive estuaries and bays. On a regional scale, therefore, desalination could aid in restoring the balance between fresh water needs and fresh water supplies that has recently been upset.

# CASE STUDY – INLAND URBAN AREAS


## Background

Las Vegas, Phoenix, and El Paso typify the challenges facing urbanized regions in the inter-mountain west and southwest – rapid and sustained population growth, diverse water demands ranging from agriculture to energy production, and increasingly impaired water supplies. All three cities (and others like them across the region) are situated in arid environments that annually receive less than nine inches of rain. All rely heavily on surface waters to meet their water supply needs, with groundwater accounting for a lesser proportion of the current water supply for Las Vegas and Phoenix (El Paso draws 50% of its water from aquifers). Water reuse/recycling are expected to play a greater role in the water supply makeup of these cities in the future – El Paso expects to provide 9% of its potable water through recycling by 2020. All three cities face significant water quality challenges as the salinity levels of their surface and groundwater supplies increases over time. Coupled with this supply challenge is the problem of ever-increasing demand – all three cities are expecting demand to rise by more than 30% by 2020.

## Current Challenges

The inland urban cities of the inter-mountain west and southwest face a host of challenges that are also seen at the national level:

- The sustainability of these cities' supplies is questionable due to over-allocation of the resource– aquifers are being essentially mined for their water, with very little recharge taking place due to urbanization, storm water management, and extended and frequent droughts. The long-term sustainability of aquatic environments in the region is threatened due to intensive withdrawals and reduced drought-induced volumes.
- Providing affordable water is never easy in a desert, and costs are likely to rise in the future as surface water, groundwater, and reclaimed water must be intensively treated to remove contaminants, agricultural by-products, and salts to make it safe for consumption.
- Providing adequate supplies is complicated by an increasing population and decreasing availability of traditional waters due to drought and the need to protect aquatic environments. Ensuring adequate supplies will require a combination of increased recycling, upgrading of impaired waters, demand mitigation, and purchasing water rights.

### Salinity - an Ancient Problem

**Wheat as a Percentage of Crops Grown:**

3500 BC - 80%

2500 BC - 20%

1700 BC - 0%


Source: USGS

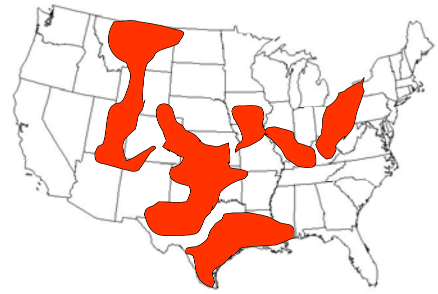
The negative impacts of impaired waters are not new to civilization. Increasing population levels and resulting demands for agricultural products resulted in increasingly saline water in the Euphrates and Tigris rivers. With no way to manage the salinity of their waters, the ability of the region to grow wheat diminished over time until it became impossible to grow this staple crop.

Today, salinity negatively affects 28% of the irrigated land in the United States.

## The Role of Desalination Technologies in Inland Urbanizations

The cities of the inter-mountain west and southwest face a daunting challenge in meeting their water needs. Due to the high (and increasing) volumes of salt in their surface water, ground water, and recycled water, these cities must turn to desalination technologies in the near future (conventional water treatment plants are unable to remove these salts). Desalting these waters, however, creates considerable volumes of concentrate wastes. Disposing of concentrate is not easy – regulations in many places prohibit if from being injected underground, and evaporation ponds (the only widely-available disposal option) require vast acreage. Thus, these cities are in desperate need of desalination technologies that produce significantly smaller volumes of concentrate (lower volumes will reduce disposal costs) at significantly reduced cost; ways to increase recovery of water from the concentrate; and beneficial uses of concentrate.

## CASE STUDY – OIL, GAS, AND COAL BASINS: A WEALTH OF UNDERUTILIZED WATER



### Background

Large volumes of water are often generated in conjunction with fossil energy production. For example, approximately 326 to 652 billion gallons of produced water are generated each year from oil, natural gas, and coal bed methane production. In many of the oil producing counties of Texas, New Mexico, and Oklahoma it is not uncommon to generate produced water at a rate of more than 30,000 gallons per minute. At present, much of this water is injected to enhance secondary recovery; where it is not injected, disposal costs range from $7-20 per thousand gallons (Petroleum Technology Transfer Council Fact Sheet, "Advanced Technologies for Managing Produced Water," Houston, 2001).

### Scope of Opportunity

In arid areas of the western United States, where energy production is widespread, existing fresh water resources are becoming increasingly scarce (see 'Nation's Heartland' case study for more details). As the nation increases energy production to meet expanding energy needs, the volumes of produced water that will be created will continue to increase. Though produced water from oil and gas production has often been injected to enhance secondary recovery of oil reserves, not all the water produced is needed for secondary recovery. Additionally, newer production techniques such as CBM may be unsuited to produced water injection.

Approximately 10 gallons of water is produced along with every one gallon of oil. If this water were treated for domestic consumption and so that it could be incorporated in the public supply, it would equate to
66% of the water used per day in WY,
23% of the water used per day in NM,
14% of the water used per day in TX, and
13% of the water used per day in OK.

For these reasons, and because disposing of these waters is so expensive, produced water may be increasingly available to supplement fresh water resources in many regions of the west and southwest and help alleviate the stress on existing fresh water supplies. Since CBM reserves are widespread throughout much of the US, CBM produced water could also be used to supplement fresh water supplies in the Midwest and eastern United States.

### The Role of Desalination Technologies in the Nation's Heartland

Produced waters contain a host of contaminants that must be removed prior to its use in municipal, agricultural, or industrial settings. Although desalination technologies produce water that is expensive when compared to traditional sources ($1 - $3 per thousand gallons compared to prices as low as pennies per thousand gallons), producing this water is much cheaper than disposing of the water. However, energy-producing regions tend to be rural and agricultural in nature, and thus are accustomed to very cheap water. Additionally, affordable pretreatment options must be developed to remove hydrocarbon contaminants from these waters.

Upgrading produced waters through the use of desalination technologies offers energy-producing regions a host of benefits:

- A 'new' source of water that will not diminish during times of drought, thus helping to ensure adequate supplies;
- A way to reduce the pressures on the huge (and stressed) Ogallala aquifer and regional surface waters, thus helping to ensure the sustainability of supplies for future generations; and
- A safe source of water for consumers in a region plagued by aquifer contamination.

## CASE STUDY – URBAN COASTAL COMMUNITIES: WATER, WATER, EVERYWHERE, BUT NOT A DROP TO DRINK

### Background

The coastal cities of California, Texas, Florida, and the eastern seaboard share similar water concerns:

- Population growth and increasing demand – The populations of Southern California, coastal Texas, and Florida have grown an average of 20% in the past decade. Commensurate with this population growth has come unsustainable growth in water demand.
- Diminishing supplies of traditional water – Urbanized coastal areas have historically drawn their surface waters from inland (often rural and agricultural) areas. Urban sprawl, however, has resulted in these inland areas becoming increasingly populated, and these new populations are using greater quantities of these surface waters for their own uses. Population growth in coastal cities has also resulted in unsustainable withdrawal of water from local aquifers, resulting in the promulgation of regulations to reduce the draw of water from these aquifers and protect the environment.

### Current Challenges

The challenges facing water planners in Southern California, coastal Texas, Florida, and the eastern seaboard are myriad – produce (or procure) sufficient quantities of water to meet the needs of their ever-increasing populations in such a manner that they do not impede economic growth or ecological balances. All three regions face concerns regarding the security of their supplies in light of competing demands and drought-induced volume fluctuations. To wit:

- The Tampa Bay region, historically dependent on water from inland aquifers, no longer enjoys unlimited access to this source of water due to recently-enacted regulations and agreements. Combined with a continuing influx of residents, the region is forced to either (or both) reduce demand or 'find' new water.
- Southern California is being forced to reduce its reliance on surplus designations of water from the Colorado River as neighboring states clamor for their legally designated share of the water. With continued population in-flows and aquifers that are threatened by seawater intrusion, water managers are facing the need to dramatically reduce consumption while they search for new sources of water.
- Coastal Texas, once a heavy user of groundwater, has been forced to shift to a greater reliance on inland-sourced surface waters due to intense subsidence as a result of groundwater withdrawals. The region now finds itself increasingly dependent upon inland surface waters and impoundments, the supply of which could be threatened by inland population growth, competing demands from agriculture, and drought.

### The Role of Desalination Technologies in Coastal Urban Areas

Finding 'new' water for urbanized coastal areas means desalinating seawater; purifying impaired waters; and increasing recycling and reuse. Current technologies produce water at a rate of $1 - $3 per thousand gallons – several times more expensive than the current cost of water.

However, these areas have precious few options – their take of inland water supplies are subject to competing needs and drought-induced volume fluctuations. Desalinating seawater, increasing the volume of recycled water, maintaining the stability of reclaimed waters (e.g., maintaining low levels of pathogens and algae while water is stored), decreasing the cost of purifying reclaimed waters, and upgrading impaired waters will allow these regions to ensure the sustainability of inland and coastal surface and ground waters while maintaining adequate supplies for people and industry. Reducing the take of surface waters will also help to maintain or improve the quality of the regions' estuaries and coastal areas. Desalination technologies also offer the promise of local control of water supplies as they will reduce dependence on upstream or inland sources as well as considerable protection against drought – no matter how little rain falls, there is always water available in the oceans.

# 3.0 DESALINATION AND WATER PURIFICATION TECHNOLOGIES AND RESEARCH AREAS IDENTIFIED TO ADDRESS THE CRITICAL OBJECTIVES

**There is no 'silver bullet' solution to the nation's future water challenges.** The complexity of the water issue will require a disciplined, focused, and interdisciplinary program to create a 'toolbox' of solutions from which the nation's water managers can choose when addressing particular water challenges. All of these tools will find applicability at some point in time. For instance:

**Solutions to the nation's water issues will evolve over time.** Where water management options such as transfers present short-term, immediate solutions to localized shortages, shifts in how water is managed on a national scale may result in the final, very long-term solution.

Between now and then, however, a combination of management options and technology applications will be required to meet our nation's evolving needs. Some water supply situations will avail themselves of policy-oriented solutions, whereas others will be more suited to technological solutions.

- **Demand reduction is important, but is insufficient in the long-term when faced with increasing population and economic growth.** The purpose of demand-reduction activities is to 'free' water for others to use (in essence, if one person reduces their demand by 50%, enough water will be 'freed' to provide an equivalent amount of water for another person).
- **Innovative water management practices offer tremendous potential in the long-term, but are difficult to implement in time to address short-term problems.** Rationalizing how water is managed at the national and state levels (e.g., instituting national standards for concentrate disposal and improved sharing of costs between water-rich and water-poor areas) has the potential to alleviate many of our water issues. Such rationalization of water management in the United States, however, will likely take far more time than the nation has to spare.
- **Technological solutions (as circled in Figure 9) offer the benefit of applicability in the next two decades.** To achieve these benefits will require the development of technologies that can remove the contaminants found in our increasingly-impaired waters; that can purify waters from the huge saline (brackish) aquifers under the United States; that can increase the reuse of water; and that can more efficiently desalinate seawater. As energy demand grows in lockstep with population, these technologies must be more energy-efficient than current technologies; must be flexible enough to remove contaminants that might be subject to regulation in the future; and they must be cheaper to build and operate than current

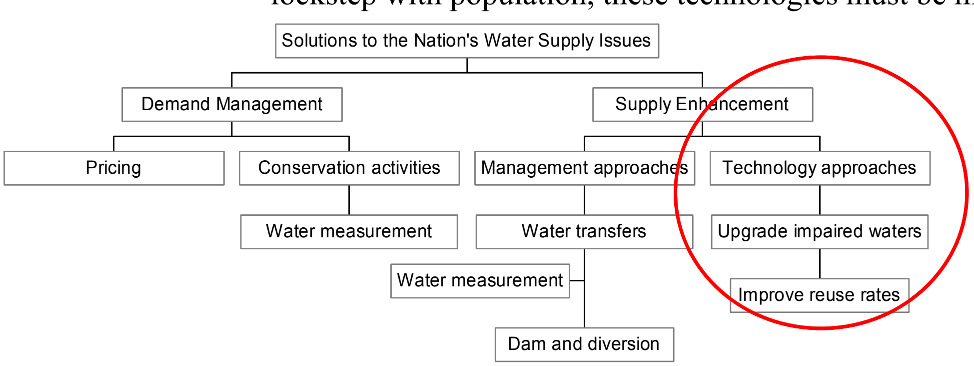



Figure 9. Hierarchy of the nation's water solution toolbox.

technologies. In essence, these technologies will add 'new' water to the nation's supply while improving upon the ability of conventional treatment plants to protect the quality of our water.

## 3.1 THE FIVE TECHNOLOGY AREAS UNDERPINNING NEXT-GENERATION DESALINATION PLANTS

The Roadmapping Team identified five Technology Areas where R&D is needed in order to create the next-generation desalination technologies:

- Membrane Technologies (technologies that desalinate and purify water by pushing it through a semi-permeable membrane that removes contaminants),
- Alternative Technologies (technologies that desalinate and purify water that take advantage of non-traditional methods),
- Thermal Technologies (technologies that rely on boiling or freezing water and then capturing the purified water while the contaminants remain behind),
- Concentrate Management Technologies, and
- Reuse/Recycling Technologies (often membrane or alternative technologies that must be designed to handle increased contaminant loads due to their post-consumer application).

Each Technology Area is discussed in a stand-alone discussion at the end of this Section. Roadmapping Team members generated a host of research ideas for each of these Technology Areas that, if accomplished, will allow these technologies to meet the regional and national-scale needs shown in Table 2 below.

Table 2 bridges the gap between the two organizational constructs of the Roadmap: the role of desalination and water purification technologies as one part of a larger solution to the nation's water supply needs, and the underpinning Technology Areas.

It is important to note that roadmapping is the development of the series of linkages that make the connections between national-scale needs and technologies. For the Desalination and Water Purification Technology Roadmap, the regional-scale needs identified in the case studies at the end of Section 2.2 provide the key linkage between the nation's needs and the research and development needed to create the next-generation desalination facility.

| **National Need →**<br>**Technology Area ↓** | **Provide Safe Water** | **Ensure Sustainability/**<br>**Ensure Adequate Supplies**<br>• **Characterization of saline aquifers in the US – combined decision analysis and economic analyses of the ability to produce and treat water (Cross-cutting theme)** | **Keep Water Affordable** |
|---|---|---|---|
| **Membrane Technologies** | • Smart membranes<br>o Contain embedded sensors<br>o Disinfection treatment<br>o 2020: sense contaminant differential across the membrane, automatically change performance and selectivity<br>• Sensor development<br>o Model compounds for organics<br>o On-line viral analyzer<br>o Micro/in-situ/built-in EPS sensor to detect biofilms; particulate fouling sensor<br>• Membrane research<br>o Completely oxidant resistant<br>o Operate in range of pHs (mechanical/chemical cleaning)<br>o Adjust removal capability based on feed water quality and removal needs (2014 – pharmaceuticals removal based on molecular weight, hydrophilicity)<br>o Biofilm-resistant surfaces | • Mechanistic/fundamental approach to membrane design<br>o CFD of feed channel<br>o Conduct research to gain understanding of molecular-level effects<br>o Design-in permeability<br>• Develop understanding of whole system (based on current knowledge)<br>o Develop model of optimization<br>o Research sensitivity of parameters for model<br>• Develop fundamental understanding of fouling mechanisms to develop indicators<br>o Understand how to mitigate fouling<br>– Understand biofouling<br>– Optimize operational controls | • Basic research to improve permeability<br>o Minimize resistance<br>o Model/test non-spiral configurations<br>• Develop new methods of reducing/recovering energy<br>• Integrate membrane and membrane system designs |
| **Alternative Technologies** | • Ultrasonic<br>o Supersonic<br>• Membrane and Membrane Combinations<br>• Biomimetic<br>o Active membranes<br>o Biological sensors<br>o Signaling capabilities<br>o Mangroves | • Ion Sorption<br>o Zeolite crystallization<br>• Sodium pump/biomimetic<br>• Advanced membranes/separation<br>o Porcelain<br>o Thin-film<br>o Biologic<br>o Bioreactors | • Magnetics<br>• Nanotechnology (active/smart membranes)<br>• Capacitive desal<br>o Nanotubes or large surface areas<br>o Current swing sorption |

Table 2. Cross-walk of National Needs and Technology Areas: Research Areas with the Greatest Potential

| **National Need →**<br>**Technology Area ↓** | **Provide Safe Water** | **Ensure Sustainability/ Ensure Adequate Supplies** | **Keep Water Affordable** |
|---|---|---|---|
| **Thermal Technologies** | • Hybrid - Membrane and thermal to reduce waste stream<br>• Develop solar ponds for energy and concentrate management<br>• Enhanced evaporation | • Renewable energy – (in small communities)<br>o Geothermal/Solar/Wind/Biomass<br>• Water harvesting from air<br>• Membrane distillation | • Hybrid – membrane and thermal<br>• Clathrate sequestration<br>• Forward osmosis |
| **Concentrate Management Technologies** | • Develop science related concentrate specific regulations for dispersion modeling of mixing zones and ion imbalance for surface water discharge.<br>• Research into engineered ecology/bioengineering to discover:<br>o How to engineer disposal so that at least it does not harm ecosystems, and if possible benefits them<br>o Natural analogs to current treatment<br>• The biology of salty water, including understanding env. impacts, using bacteria for beneficial treatment, etc. | • Create a "super concentrate" technology – complete solidification of residuals and 100% recapture of water<br>• Explore beneficial uses of concentrate including irrigation; farming; solar pond; cooling water; manufacturing; agriculture; repair of dead-end stagnant canals; energy recovery; artificial wetlands, recreations, halophilic irrigation; aquaculture<br>• Decentralized (Point of Use) Treatment and recycling as a way of managing concentrate | • Create a "super concentrate" technology – complete solidification of residuals and 100% recapture of water<br>• Cross-cutting: Develop methods of immobilizing/sequestering the concentrate stream<br>• Cross-cutting: Develop beneficial uses for the concentrate stream to improve the economics of disposal for ZLD processes. |
| **Reuse/Recycling Technologies** | • Develop a set of organic chemical surrogates acceptable to the public for potable reuse<br>• Risk comparison between various water reuse schemes and potable water counterparts<br>• Real-time sensing/monitoring/controls | • Watershed-based salinity management strategy<br>• Constructed wetlands<br>• Develop large scale regional characterization of subsurface injection capability in US | • Enhanced membrane bioreactor technology<br>• Document the lifecycle economics of water reuse for various applications.<br>• Pretreatment<br>o Filtration<br>o Biological coating (disinfectant)<br>o Research to enable prediction of migration and recovery through aquifers |

Table 2 (cont). Cross-walk of National Needs and Technology Areas: Research Areas with the Greatest Potential

## *Membrane Technologies*

Membrane technologies are the principal components of the family of advanced desalination and water purification technologies available today. Membranes are expected to play critical roles in formulating future water supply solutions. Membrane technology will be used to address continued degradation of water quality and to augment existing water resources through desalting of saline water sources such as brackish and seawater. The membrane technologies commercially available today consist of the following:

- Microfiltration (MF) membranes – used for turbidity reduction, removal of suspended solids and bacteria
- Ultrafiltration (UF) membranes – used for color, odor, volatile organics and virus removal, as well as the removal capabilities listed for MF membranes
- Nanofiltration (NF) membranes – used for water softening and sulfate removal
- Reverse osmosis (RO) membranes – used for salt removal for brackish and seawater
- Electrodialysis (ED) membranes – used for salt removal for brackish water

Membrane technologies are available in a range of configurations and operating modes, and can be pressure or vacuum-driven, or use electrical potential as the driving force as in the case of ED membranes. As more stringent, rigorous and comprehensive removal capabilities are required to meet regulations and treat complex water qualities, membrane technologies can be integrated utilizing different membrane types (as listed above) in series.

The membrane technologies commercially available today are effective but are considered capital intensive. Additionally, high-pressure membranes such as NF and particularly RO are also energy-intensive and are sensitive to fouling from various biological, organic and inorganic contaminants. Fouling increases the operational costs and can decrease the water quality produced from these membranes. Predictive modeling capability is improving and these new capabilities must be applied to membrane technology. Membrane and ancillary equipment manufacturers will continue to improve their products to gradually address the weaknesses that exist in the technologies. Due to low profit margins, however, manufacturers presently are only able to invest, on the average, 1-4% of their gross margins in R&D activities[8].

In order to significantly impact the cost and application of membrane technologies in the future, technological breakthroughs are required which will transform our existing paradigms of design, manufacture, application and operation of membrane technologies. These breakthroughs will require significant investments, more than that available from the existing profit margin in the industry. Such breakthroughs will also require 5 or more years to realize, again more than the industry can afford to dedicate on their own. As an example: membranes (except in the case of ED technology) presently remove the water stream from the contaminants, thereby utilizing considerable energy and concentrating the stream adjacent to the membrane, creating operational constraints. Technology

[8] Data from Annual Reports of membrane manufacturers are available from the companies.

breakthroughs could result in a more efficient membrane technology that would remove only the contaminants from the water stream.

### Alternative Technologies

Desalination plants in the United States are currently dominated by membrane-based and thermal-based technologies. These are known quantities that, although possessing some significant performance issues, dominate the market.

The hegemony enjoyed by thermal- and membrane-based technologies has not, however, quelled the research community's enthusiasm for exploring new and better ways to purify and desalinate water. It is from these explorations that the greatest advances in desalination and water supply purification technologies can be expected. Used alone or in combination with other existing or new technologies, alternative desalination and water supply purification technologies represent the new frontier of water research.

Various Federal agencies are engaged in their own efforts to develop alternative desalination and water supply purification technologies. NASA and the Department of Defense, among others, have need of such technologies. This Roadmap makes explicit reference to these agencies for it is vital that inter-Agency cooperation in research and development be continued and enhanced to avoid duplication of R&D efforts and speed the transfer of technologies to other agencies and the private sector.

Alternative technologies are radical in nature – they are the technologies that will result in the significant shift in the cost curve seen in Appendix C. Alternative technologies can be categorized as either nascent and emerging technologies or radical combinations/advances to existing technologies; they represent the great unknown. Alternative technologies must be developed not only to drive down the cost of producing water and to ensure the quality of our nation's water supply, but also to address the negative environmental impacts of producing concentrate wastes – without alternative technologies, the burdens of concentrate management will preclude widespread adoption of desalination technologies.

There is no shortage of alternative ideas on how to purify or desalinate water – necessity being the mother of invention, combined with innate human inventiveness, ensures the continual creation of new approaches. Hundreds of new desalination and water supply purification ideas are generated every year in the field and in the laboratory. Some show promise; others do not. Some are stand-alone technologies, others combine two or more processes in a search for greater efficiency, while still others propose to re-investigate past failures in the hopes that new materials and understanding can make them work.

### Thermal Technologies

Current thermal technology-based desalination is a mature technology that enjoys considerable use around the world. Persian Gulf nations, with dual-purpose power and water desalination systems, make extensive use of thermal desalination for municipal, industrial, and agricultural uses. Thermal technologies are not, however, widely used in the United States, due in large part to the amount of energy required by the thermal process, concerns over where to site these facilities, and a lack of centralized water and power planning that would result in less expensive thermally-desalinated water.

Current thermal technologies possess several advantages over other technologies – the process is simple (the plants essentially boil water, capturing the steam and condensing it into potable water) and results in the generation of more dilute concentrate waste. The overriding disadvantage of the process is its operating cost – thermal desalination requires huge quantities of energy (roughly 260 kilowatt-hours per thousand gallons – or one quarter of the electricity consumed by the average house in a month).[9,10,11] Cogeneration plants that are designed to produce both power and water reduce this disadvantage, although these plants are still expensive to build and operate.

### Concentrate Management Technologies

Cost effective and environmentally sensitive concentrate management is recognized as the significant hurdle to widespread adoption of desalination technologies, especially for inland regions that seek to make productive use of brackish water resources. It is a question that must be solved for the nation to be able to meet its future water needs.

Every desalination and water purification technology discussed in this Roadmap generates two process streams: product (clean water) and waste (alternately referred to as concentrate – the reject from reverse osmosis, nanofiltration, and electrodialysis/electrodialysis reversal processes; or backwash – the reject from low pressure processes). These waste streams contain concentrated salts and other contaminants that are removed during water treatment, as well as up to 50% of the feed water that enters the facility.

Disposing of these waste streams can take many forms. At present, ~ 48% of all desalination facilities dispose of their concentrate waste stream to surface waters or the ocean, while ~40% dispose of the concentrate in sewers.[12] These disposal methods are currently the most effective and least expensive options for both small systems and for larger systems located near coastal regions. The continued ability of water producers to dispose in this manner, however, will be affected by to the creation and promulgation of ever more stringent environmental protection regulations. In addition, disposal to surface waters exacerbates the salinity loading concerns for downstream water users, who must then in turn build facilities to remove this excess salt. Surface disposal can also create environmental concerns regarding water quality for aquatic species.

For larger systems located inland from the coasts, other disposal options must be pursued. The most common of these options are deep well injection and evaporation ponds. In regions where deep well injection is allowed, the cost of this disposal option adds modestly to the overall cost of the facility. In many locations, this disposal option is not allowed because of geologic or regulatory constraints stemming from concerns regarding

9 Thomas, K.E., National Renewable Energy Laboratory Report TP-440-22083, 1997

10 Speigler, K.S. and Y.M El-Sayed, A Desalination Primer, 1994

11 Annual energy consumption per household taken from http://www.energychampion.org/bg/GHGCalculator.doc

12 Mickley, Michael C, Membrane Concentrate Disposal: Practices and Regulation, Desalination and Water Purification Research and Development Program Report No. 69, U.S. Department of Interior, Bureau of Reclamation, September 2001.

potential contamination of drinking water aquifers. Furthermore, deep well injection results in the loss of the basic water resource (as technology improves in the future, the portion of the concentrate waste stream that is water may become economically recoverable – deep well disposal of concentrate wastes essentially precludes this activity). Evaporation ponds are modestly land-intensive and also result in a significant loss of the basic water resource.

Finding beneficial uses for concentrate is another 'disposal' option where sewer, surface water, evaporation pond, or deep well injection disposal options are prohibited by regulation or economics. Land disposal of concentrate is one such beneficial use. In many cases, concentrate is used to irrigate salt-tolerant crops and grasses (which are frequently used on golf courses). This disposal option, however, must be carefully monitored to protect subsurface waters and to guard against salt accumulation in soils.

The most expensive disposal options are those that create a zero liquid discharge (ZLD) waste stream. ZLD disposal is the only option currently available in many inland regions where surface water, sewer, and deep well injection disposal is prohibited. ZLD processes, however, require further development to reduce costs, and to recover the water lost during the process (capturing this water will allow it to be recycled and reused). Using currently available ZLD processes will increase desalination costs three to eight fold depending on location and the size of the facility. These increased costs are prohibitive in many locations, essentially eliminating the economic feasibility of desalination technologies. One component of the development of cost-effective ZLD processes is reducing the volume of concentrate produced – research focused on reducing the quantity of concentrate created is implicitly addressed in the Membrane Technologies and Alternative Technologies sections.

Research into concentrate disposal is one area where the national scope of the roadmap is most important. Providing science-based, concentrate-specific guidance to regulatory agencies is the most important research area. In inland areas where regulatory concerns already exist, the most important improvements must be made in disposal costs. Discovering beneficial uses of and for concentrate is one way to obtain value from this waste stream and hence to reduce cost. Additionally, reducing the quantity of concentrate produced will assure greater use of the limited water resource. The cost associated with ZLD processes must be reduced to enable desalination in those regions where surface water, sewer, or deep well disposal is impossible.

### *Reuse/Recycling Technologies*

Reclaimed waters are presently used in a variety of applications. Many industries reclaim their own process water for reuse within their facilities – these recycling activities are typically conducted on-site by the industries themselves (industries recycle water an average of 17 times before they are discharged from the facility). Power plants utilize reclaimed water for cooling purposes. In a more visible setting, municipal reclaimed waters are used to irrigate golf courses and parks, to fill man-made water features, and for habitat restoration activities and creation of wetlands. Also, plans are being laid to blend desalinated water with recycled water, allowing for expanded uses of recycled waters.

While these activities are important in offsetting the demand for 'new' water, they are at present employed only in significant numbers in the arid western states. Drier regions of the United States are leading the way in the beneficial reuse of water, but much more can be done on a national level.

Municipal reclaimed and treated waters are also used in less-obvious ways. Such highly-treated waters may be injected into existing aquifers to prevent saltwater encroachment or for storage for later use (this is an example of indirect potable reuse, and involves storing reclaimed waters in underground aquifers and then pumping the same water at a later date for potable purposes).

**Water Reuse in the United States**

The recycling and reuse of water suffers an unfair stigma in the United States that has limited the use of reclaimed waters and in particular has stopped projects where indirect potable reuse might occur. It is important to note that only 9% of the water supplied to residences needs to be of potable quality – the remaining 91% is used for watering lawns, washing cars, laundering clothes, filling toilets, and other uses. These uses do not require that the water be treated for potable purposes, and this is the crux of the argument for water recycling and reuse. The cost of incorporating new infrastructures to deliver this non-potable water, however, is a significant hurdle to more-widespread use of reclaimed waters (at present, it is cheaper to simply provide high-quality water regardless of its end-use rather than to install new infrastructures).

Many water reuse technologies are identical to those discussed in the Membrane Technologies and Alternative/Thermal Technologies sections. Therefore, the research efforts discussed in these sections hold great potential for expanding water recycling and reuse. Employing these technologies to treat reclaimed water, however, places a different set of requirements on the technologies – technologies employed to produce reclaimed waters must be designed to effectively handle higher, and more diverse, contaminant loads. This requirement is due to the nature of reclaimed waters – they are more likely to contain high levels of anthropogenic compounds (ranging from hydrocarbons to industrial chemicals to pharmaceuticals 'flushed' from humans) than are 'new' waters from aquifers or rivers – and to the need to remove extremely low levels of contaminants in order to protect human health.

Beyond economic factors, there are several key factors that limit the ability to expand water reclamation and reuse. One key factor is storage of reclaimed water – demand for reclaimed waters (generally the dry summer months) is not matched by an increase in the supply of reclaimed waters, as the 'flow' of reclaimed waters is essentially constant over time. In addition, a major use of reclaimed waters is for irrigation, where demand is seasonal. One method to resolve storage issues is to reduce the footprint of water reclamation systems thereby allowing for storage and reclamation adjacent to key areas of demand. Another method is to store the reclaimed water in percolation ponds or injection wells (these are two approaches to aquifer storage). Expanded decentralization of water reclamation systems could also alleviate the need to expand old, centralized sewerage systems in cities where expansion costs are prohibitive. Another key factor is public and regulatory acceptance for indirect potable reuse projects. Protection of public health must be demonstrated by providing reclaimed waters that have lower risks than alternative water supplies.

# 4.0 FUTURE SCENARIOS

Scenario development gives us two views of the future. Scenario development is important because it allows us to see how our technological solutions may affect the future of the water supply situation in the nation. In the first of these views, the Business-as-Usual scenario, the nation continues with limited public sector support of R&D and the continued level of investment in private sector research programs. This scenario is explored in Section 4.1. An alternate perspective is a revival of our national commitment to water supply R&D and the development of revolutionary water purification and desalination processes. This scenario is explored in Section 4.2.

The United States is rapidly approaching a decision point in how we as a nation develop water supply (quantity and quality)-related technologies. To date, technologies found in water treatment plants and water purification plants have either evolved very little from the time they were discovered (today's conventional physical- and chemical-based water treatment processes vary little from when they were first developed in the early 1900s) or are products of intensive and prodigious federal research and development support (witness the impressive efficiency gains in reverse-osmosis water purification technologies as a result of Department of Interior funding in the 1950s, 1960s, and 1970s).

**Federal Support for Desalination and Water Purification Technologies – a Fifty Year Success Story**

Federal funding for desalination and water purification technologies (largely desalting technologies) began with the passage of the Saline Water Act of 1952. In the following thirty years, the Federal government invested more than $1 billion (in 1999 dollars) on desalination research, development, and demonstration activities. This research program was, according to the Congressional Research Service, "primarily responsible for the development of reverse osmosis, and for many advances and improvements in distillation technologies." Reverse osmosis today is one of the most widely used desalination and water supply purification technologies.

The slow evolution of many water treatment technologies and processes is attributable in large part to the historically-low price of water in the United States. The nation's people and its governments have long viewed water as a fundamental human right; therefore, water has been provided by local governments to their people at rates that just nominally cover the cost of treating, supplying, and disposing of that water. This combination of low water prices and public agency-ownership of the water infrastructure has combined to limit private sector R&D – publicly-owned utilities have lacked the financial resources to install new technologies (and their lenders and public and elected officials have traditionally taken a conservative view toward the purchase and installation of technologies without proven track records) and the nominal profit margin associated with low water rates has acted to severely restrict private sector R&D.

Due to significant Federal support of R&D programs in the past, radical advances in water treatment technologies have been realized in spite of under-investment in R&D by the private sector. However, in the recent past, budgets for water supply technology research and development have been smaller and less stable, resulting in reduced R&D programs. These programs are necessary to improve the performance of current technologies and to create revolutionary technologies.

## 4.1 THE BUSINESS-AS-USUAL SCENARIO

The Business-as-Usual scenario envisions a research and development future much like today – limited public sector R&D and under-investment in private sector R&D due to low water rates and the financial inability of water agencies to develop and install new technologies. This scenario envisions that currently-available desalination technologies will have increasing importance in forming the backbone of water purification in the United States, and that these technologies will achieve, on average, only four percent per year improvements in efficiency and cost reduction. Within the next 20 years, the expected savings from this research will be substantial. However, the Business-as-Usual scenario presents some very real 'negatives' in terms of our ability to meet our national needs.

The greatest 'negative' presented by this scenario is the cost of installing and using the currently-available technologies – as seen in the Urban Coastal case study earlier, the treatment cost of impaired water with these technologies is several times more expensive than conventionally-treated fresh water (however, expensive water is better than no water at all, which is a context that may face increasing numbers of communities in the future)[13]. And with limited public and private sector R&D, we can realistically expect the capital and operational costs of these technologies to fall at an average rate of about four percent per year.

The continuing high cost of these technologies under the Business-as-Usual scenario will limit where these technologies are used, with significant ramifications for the nation's ability to meet its needs:

- Ensuring Adequate Supplies: At present, the only municipal water suppliers that employ (or are planning to employ) desalination and/or water purification plants are those that have no option. These suppliers are generally those whose traditional sources of water are no longer adequate to meet demand. At present, these communities are small in number (Tampa Bay, El Paso, the Municipal Water District of Southern California). As elucidated in the case studies and elsewhere, a much larger number of communities will soon face the specter of inadequate supply from their traditional water sources due either to regulations intended to protect aquatic environments or as a result of supply exhaustion. Where non-traditional sources are available (brackish groundwater, produced waters from hydrocarbon production, or seawater), water purification plants utilizing membrane technologies hold the promise of ensuring adequate supplies for these communities – at a cost.
- Keeping Water Affordable: The cost of installing currently available desalination water purification plants (and the resultant cost of the produced water) is the greatest 'negative' of the Business-as-Usual scenario. Today's technologies are quite capable of upgrading brackish water, produced waters, and seawater so that they can be safely consumed. However, the cost of installing and operating these plants is far beyond the reach of many communities where the need is greatest – small and mid-sized communities that cannot afford to buy water rights from

[13] (Water Treatment Estimation Routine User Manual, U.S. Bureau of Reclamation, Water Treatment Technology Program Report No. 43).

others when their traditional supplies are no longer available. Continued low prices for water will severely restrict private sector R&D that could drive down the costs of these plants, and continuing the pattern of publicly-funded R&D will not likely soon generate the level of efficiency gains seen in the 1980s and 1990s as a result of Federal research in the 1950s, 1960s, and 1970s.

## 4.2 The Renewed National Commitment Scenario

Historically low water prices and the low risk arena in which public water agencies must function inhibit the installation of new technologies that do not have an established 'track record'. These factors have limited private sector investment in water purification research and development. With profit margins reportedly in the low single digits, companies that manufacture water purification equipment or construct plants simply do not possess the financial resources to support the kinds of R&D that will result in much needed next-generation technologies. What R&D they conduct is generally applied research designed to improve or modify their existing product lines. As such, the United States possesses a limited private sector R&D enterprise capable of pursuing the development of advanced water purification technologies at the scales needed for revolutionary improvements.

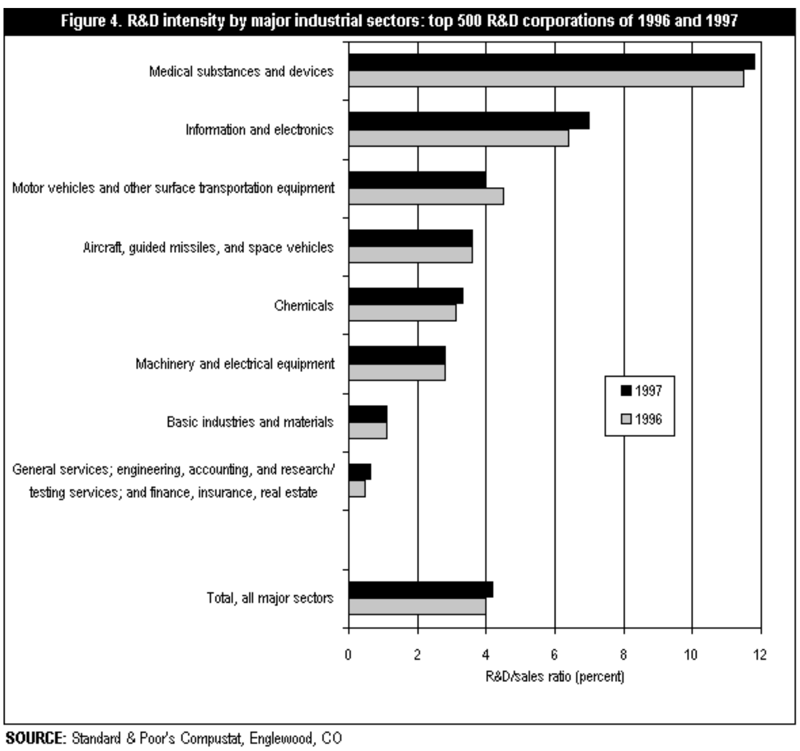



Figure 10. R&D Investments as a percentage of sales for select industries.

At present, it is estimated that U.S. water purification industry invests an estimated $5 to $10 million annually in desalination research and development – less than one percent of sales. When compared with the semiconductor industry (9% of sales invested in R&D) and other industries, it becomes obvious that U.S. firms that build desalination and water purification plants conduct very little basic or applied research and development compared to other industries. The industry is, to a large extent, living off the products developed as a result of past Federal investment in desalination research.

Past Federal investments in water purification technology development were significant. The results of these intensive programs were the commercialization of reverse osmosis membranes and impressive efficiency gains in other technologies and purification processes. The Federal government recognized in 1952 a need for advanced water purification technologies, and its consistent support of R&D activities paid off.

Today, public sector support for water purification technologies is no less important. Advances in materials science, computational modeling, manufacturing processes, and a host of other disciplines have resulted in a unique opportunity for R&D managers – with new scientific and technical knowledge, the failures of past R&D activities may be overcome, perhaps resulting in the creation of technologies that will be for future generations what reverse osmosis has been to ours.

Public sector support for water purification R&D offers the nation one huge advantage in meeting its water supply needs: acceleration.

- Accelerating the development of new sources by speeding the time to market of new technologies that can upgrade impaired waters in areas where traditional water sources are becoming exhausted;
- Accelerating our ability to purify water of emerging contaminants through the development of technologies that will ensure our water supplies remain safe during times of drought and during times of plenty;
- Accelerating the pace of improving currently-available technologies, spurring efficiency gains beyond the four percent per year typical today; and
- Accelerating the pace at which the nation produces cost-effective water purification technologies so that they more quickly become affordable for small- and mid-sized communities that need them.

## 4.3 Scenario Analysis

Both the Business-as-Usual and Renewed National Commitment scenarios end at the same point: the widespread installation (with public sector cost-sharing) of desalination and water purification technologies that are able to upgrade a variety of impaired waters and thus ensure a safe, sustainable, and affordable water supply. When the nation reaches this point, and what happens between now and then, are the primary factors to consider when deciding which path of action (or inaction) to follow.

Following the Business-as-Usual scenario (nominal public sector support for desalination and water purification R&D) suggests the possibility of some rather significant, and unpleasant, short-term impacts. As traditional water resources become exhausted (through unsustainable withdrawal patterns – demand outstripping supply), placed off-limits, or unusable (through salinity loads that conventional water treatment plants cannot handle), municipal water suppliers will be forced to either purchase water from elsewhere (an activity that could become increasingly costly as diminishing supply and increasing demand results in elevated prices) or build and operate water purification plants based on currently-available purification and desalination technologies. Such plants will be expensive to

Water supply agencies in Southern California, Texas, and Florida have formed a Desalination Coalition for the purpose of mutually pursuing Federal funding to off-set the construction and operation costs of desalination facilities. The coalition will promote a coordinated strategy with the goal to make seawater desalination cost competitive.

In Southern California, these agencies supply water to roughly half of the population of California, which has the fifth largest economy in the world. Even with this wealth, Southern California is unable to afford water purification and desalination plants without public sector funding to offset some portion of the up-front capital cost. If the economic powerhouse that is Southern California can't afford current-generation technologies without assistance, then smaller communities across the nation have even less of an opportunity to employ needed desalination technologies.

build (hence the very small number of municipal desalination and purification plants in operation in the United States) and hence will produce expensive water.

For communities that can arrange the financing for such construction projects, local water rates and taxes will rise to pay for the water and the plant's installation (both of which will serve to lower local standards of living). Such communities are likely to be few and far between (see textbox at right). For communities that cannot arrange the financing on their own, Federal assistance will be sought to offset capital costs (this is not unusual – very little of America's infrastructure has been constructed with purely state or local dollars). While the extent of Federal aid that will be requested is unknown, it is not unreasonable to expect the number of requests to increase dramatically in the coming decades as more and more communities begin to face the prospect that their traditional water sources are incapable of meeting future demand.

With public sector aid, most communities will be able to build water purification and desalination plants as necessary. This building boom will result in increasing income for private sector firms, which may spur an increase in R&D activities.

If this increase in R&D activities is realized (and there is no guarantee that it will – if the public sector shows a willingness to cost-share new desalination and water purification plants, there may be a reduced impetus on the part of private sector firms to conduct R&D to reduce costs because the public sector aid acts as a price floor), the likely result will be cheaper, more effective technologies. However, the time lag to realize these advances and related cost savings is considerable – only the most forward-thinking (and water-short) communities are seriously planning for the construction of desalination and water purification plants. Thus, the building boom that may spur private sector R&D is unlikely to be realized for decades, with the benefits of that R&D subject to its own product cycle time lag of up to a decade – in short, **the Business-as-Usual scenario suggests that next-generation desalination and water purification technologies will not become available for at least four decades (if ever).**

Under the Renewed National Commitment scenario, wherein the research and development activities proposed in this Roadmap are completed, the timeline on which these revolutionary technologies become available will be accelerated by perhaps two decades. Concurrently, such public sector support will result in more-rapid improvements to existing desalination and water purification technologies, resulting in cheaper and more effective technologies becoming available in perhaps as little as a decade. While the Renewed National Commitment scenario will not eliminate the need for public sector cost-sharing of desalination and purification plants, it will likely reduce the amount of cost-share money required over time as cheaper technologies become available more rapidly. These cheaper technologies will make safe, secure, and affordable water a reality for many communities much sooner than under the Business-as-Usual scenario, and at a reduced cost to the public sector and ratepayers.

## 4.4 Barriers to Success

The Roadmap identifies a suite of research activities that, in concert with other activities as discussed earlier, can provide technological solutions to the nation's future water needs. However, application of these technologies will not occur in a vacuum – their implementation will be guided by national- and state-level policies and regulations.

Although outside the explicit scope of this Roadmap, it is useful to discuss the nation's future water needs (and the role of public sector R&D in meeting those needs) in concert with the political and regulatory environment. It is important to note that the Roadmap makes no recommendations regarding policies or regulation. This discussion of 'Barriers to Success' is provided solely so that the reader may gain a fuller understanding of the regulatory and environmental hurdles facing implementation of current- and next-generation desalination and water supply purification technologies.

**R&D and its impact on Federal cost-sharing**

Federal cost-sharing of water infrastructure projects has been a historical fixture; today's water planners continue this trend as they seek Federal dollars to off-set some of the installation costs for desalination and water purification plants. Projections suggest that one billion dollars will be spent domestically on these plants in the coming years. Assuming a conservative 10% Federal cost share for these projects, the United States is facing a $100 million cost share bill.

Dedicating even one-tenth of this amount to advance the state-of-the-art in desalination and water purification technologies offers the nation the chance to reduce its cost-share bill – as these technologies become cheaper and more efficient, fewer cost-share dollars will need to be doled out.

Spending pennies today may save the nation dollars in the future. The Executive Committee recommends that a cost-benefit analysis be conducted to quantify these benefits.

### *'Showstoppers'*

No matter how good a technological solution, its effectiveness may be limited by local, State, or Federal policies and regulations. This can be seen today, where regulations governing the disposal of concentrate drives up operational costs to the point where the technology is uneconomic in many instances.

Roadmapping Team members generated a substantial list of issues that may impact the development and deployment of desalination and water supply purification technologies. These issues, if not addressed at both the local, State and Federal levels, may hamper the transition from current-generation technologies to the less costly and more efficient next-generation technologies that will help to assure the nation's future water needs.

Among these many issues are several that can be coined 'showstoppers'. These issues are of such importance that finding solutions to them is critical to the deployment of next-generation technologies.

Jurisdictional and Organizational Issues. The divergence of water quality standards across jurisdictions, the separation of regulatory authority over concentrate disposal from authority for other aspects of water resource management, and the inability of multiple communities to share costs of desalination and water supply purification facilities sited in one community or disposal facilities sited in another can block the widespread application of desalination and water supply purification technologies despite revolutionary improvements.

Public Perceptions of Purified Water. As bottled water labels colorfully illustrate, the public is drawn to the illusory image of their water having sprung in virgin purity from some mountain stream. The unromantic reality that all water on the planet is and must be reused is susceptible to manipulation and exploitation to foment public opposition to desalination and water supply purification technologies and facilities.

Controversies about Growth and Development and Facility Siting. In communities that have already experienced significant growth pressures that have affected residents' perceived quality of life, and in communities to which people have fled to avoid growth and urbanization, desalination and water supply purification technologies that enhance the availability and sustainability of usable water supplies may become enmeshed in local or regional controversies concerning land use, population, transportation, environmental protection, etc. if water supply improvements are seen as promoting (or at least facilitating) more growth and development.

Creation of Industry-wide Standards. At present, there are no industry-wide performance standards for the types of desalination and water purification technologies discussed in this Roadmap. In addition, there is no single, unbiased source of information regarding the performance of these technologies. This lack of independent performance testing (and hence information regarding, for instance, the life of a membrane or it's ability to remove a particular contaminant in a given environment) contributes to the slow adoption of these technologies – without solid, unbiased performance data, fiscally conservative and often risk averse public water agencies are hesitant to install desalination or water purification facilities.

While setting performance standards may not be a course of action for the public sector (beyond those in place to protect public health), the public sector does have a role to play as an independent, unbiased tester of technologies. Much as the public agencies test the performance of automobiles, so too do public agencies have a role in testing the performance of desalination and water purification technologies and in reporting the findings.

The National Centers Program, jointly administered by the National Water Research Institute (NWRI) and the Bureau of Reclamation, is an important component of this Federal R&D and testing and evaluation role. This Program is described on the NWRI website (http://www.nwri-usa.org) under the 'Programs' link. The National Centers Program includes the following Centers:

- Water Quality Improvement Center at Yuma Desalting Plant (Yuma, Arizona)
- West Basin Water Recycling Facility (El Segundo, California)
- University of South Florida (Tampa, Florida)
- Water Factory 21 (Fountain Valley, California)
- Army Water Quality and Treatment Center (Warren, Michigan)
- Aqua 2000 (San Diego, California)

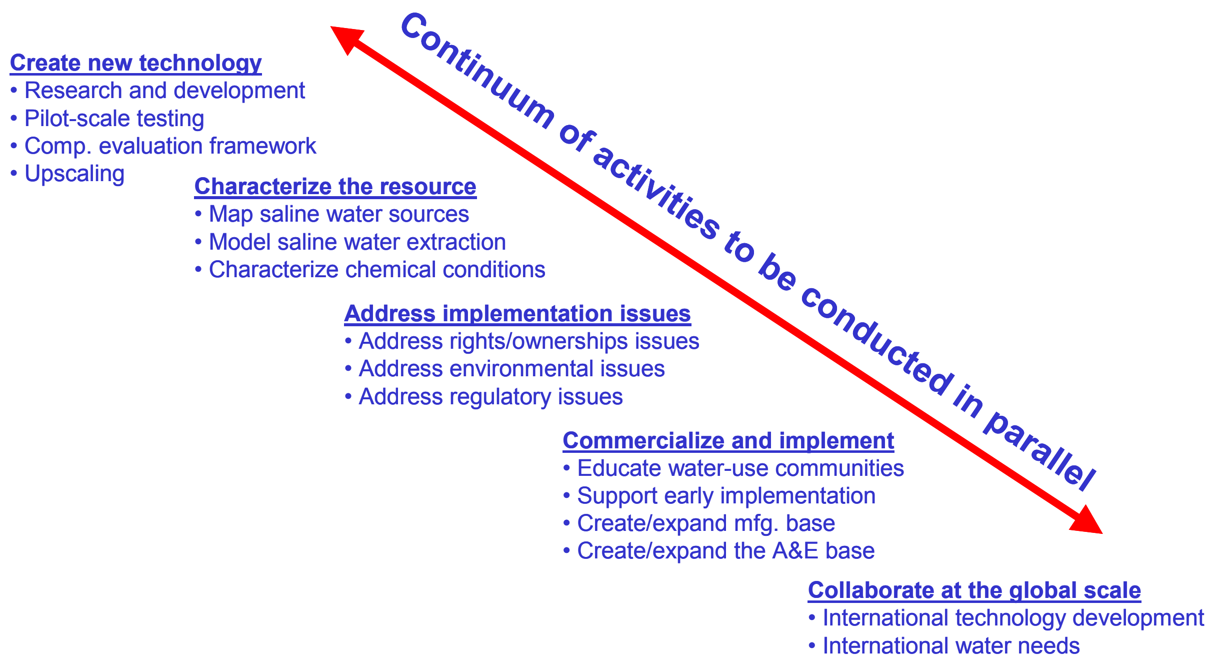
A new National Center, a proposed Tularosa Basin Research and Development Center, would, if constructed, provide a complete suite of testing and evaluation facilities for the development of advanced desalination and water purification technologies. This center would provide testing facilities for brackish water desalination and would have the necessary land resource to evaluate concentrate disposal processes. Such Centers allow for the testing of single products, and for testing of combinations of products and technologies from competing firms. These centers provide researchers the facilities to optimize the performance of a combination of products.

# 5.0 NEXT STEPS

Water – where it is found, who owns it, how and for what it is used – is a web of complex issues. The Desalination and Water Purification Technology Roadmap, in detailing a suite of research areas and critical objectives that hold the potential of producing technological solutions to our nation's water supply challenges, addresses one small piece of a much larger puzzle.

Technological development must be conducted in context - technologists must consider where their technology will be used, under what conditions, with what constraints, and by whom. A conceptualization of the broader context in which the Roadmap operates is seen below.

## Building on the Roadmap: A Coordinated, Integrated Strategy




The components presented here define the context for future technology developments - identifying where newly-developed technologies might find application (map saline water resources), under what conditions those technologies might have to operate (characterize chemical conditions), the constraints on their operation (address environmental/regulatory issues), and who will operate them (educate water-use communities, support early implementation).

The Desalination and Water Purification Technology Roadmap exists at the very upper-left of this continuum – it presents broad research areas that are representative of the types of scientific and technical advances that will be necessary for desalination and water purification technologies to find wide acceptance. The roadmapping process has revealed the need for complementary activities as shown along this continuum:

- **Create new technology.** Deciding which research proposals to fund when many are presented is a daunting task. Historically, much of the decision has been qualitative – a reviewer's opinion of the principal investigator or the 'interestingness' of the proposal. Such qualitative analyses are inappropriate when judging focused, targeted research projects. Thus, a comprehensive framework must be developed so that research projects are selected based on their ability to meet (or contribute to meeting) the metrics of the roadmap.
- **Characterize the resource.** Mapping and characterizing saline aquifers is an important part of the process to improve water availability for the nation. It is essential to know the size, delineation, and quality of our national water resources. Another part of this same program is characterizing reservoirs that might receive concentrate produced by desalination technologies.
- **Address implementation issues.** Greater attention should be paid to issues found in areas where the need for desalination is acute. The complexity of these issues (environmental, ecological, economic, regulatory, ownership, etc.) demands a focused approach to identifying the core issues and developing a framework within which interested parties can work to resolve the issues. Systematically identifying the core issues related to the deployment of desalination and water purification technologies, identifying the key actors and interested parties, and establishing a framework within which issues can be constructively discussed may reduce the *ad hoc* nature of past discussions.
- **Commercialize and implement.** Freeing the road of deployment and implementation issues will not alone cause the widespread adoption of desalination technologies. The barriers found within the industry itself and within the public will have to be mitigated or removed. Educating the public regarding the safety of desalinated water and the benefits that it provides will be important to smoothing the path for deployment. Working with the industry to develop incentives for early adoption of new technologies will speed their introduction to the marketplace. Developing independent testing facilities and creating comprehensive cost modeling software tools will also serve to mitigate barriers to commercialization.
- **Collaborate at the global scale.** The world-wide deployment of desalination technologies can be an important component in enhancing national as well as international security. The United States should continue and expand its interactions with nations around the world where water supply issues may threaten regional stability.

# APPENDIX A – THE STATE OF WATER IN THE UNITED STATES

## A.1 SUPPLY

Water is a fixed-quantity resource that can neither be created nor destroyed. The global water cycle dictates that the water we use today has been used countless times before, and will be used countless times again forever.

### *Water Supply Trends*

Only 0.5% of the earth's water is directly suitable for human consumption – the other 99.5% is composed of saltwater or locked up in glaciers and icecaps.[14] Where and in what volumes this 0.5% of usable water is found is not constant over time; global climate change can (and has) caused the distribution of water to fluctuate. Current climate models suggest, with high certainty, that the United States will experience greater variability in precipitation and run-off in the coming years (i.e., the United States is likely to experience both more-severe droughts and precipitation events). These same models are unable, however, to predict when and where these changes will occur.

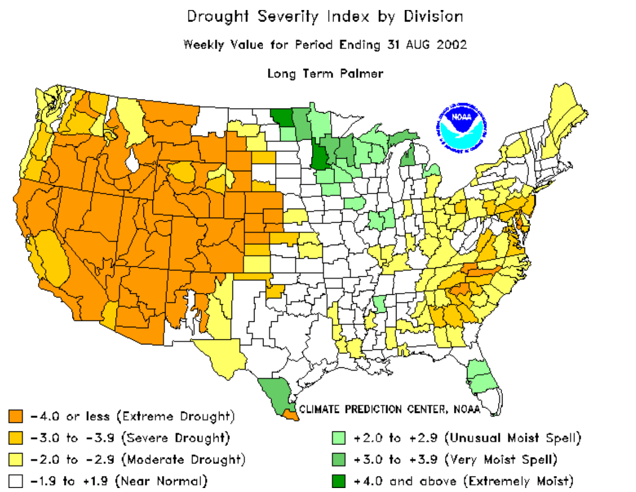



Figure A1. Extent of drought conditions in the continental United States. Moderate to extreme drought conditions exist throughout the inter-mountain and western states, and along the eastern seaboard.

At present, the United States is experiencing a widespread, multi-year drought (see Figure A1 for an indication of the severity of these drought conditions). While the causes of this drought can be (and are) argued, the effects are plainly evident. In the United States, less rain and snow has fallen recently than in past years – this negatively impacts the volume of water in rivers, surface impoundments (lakes and reservoirs), and aquifers. This impact can be seen in the level of the Great Lakes – the water level in Lake Superior is currently more than 7 inches lower than its historical average, and the level is predicted to fall another 2.2 feet by 2020.

In addition to the drought conditions currently impacting much of the United States, global climate change presents other challenges. Sea levels around the globe have risen by 15 to 40 inches since 1900, and are projected to rise another three to eight inches by 2020. As sea levels rise, coastal aquifers will suffer from increased intrusion of salt water. Such intrusions will, over time, increase the salinity of these aquifers to a point where they will require treatment by desalination plants before they can be used for human or agricultural consumption.

[14] Congressional Research Service, Desalination R&D: The New Federal Program, 1999

### Water Supplies Increasingly Strained – No 'new' sources of water

There are no 'new' sources of water available in the United States – every drop (be it fresh, saline, or seawater) has been located.[15] In addition, conventional water supplies in many regions of the United States are tapped out – in these areas, quite literally every drop of water in the rivers, aquifers, and reservoirs is allocated to a use, be it agriculture, residential use, or to maintain aquatic environments and their inhabitants.

To slake the ever-growing thirst of the nation's consumers, water planners are increasingly turning to a host of supply-side strategies to get around the 'no new water' quandary. These policies include, among others:

- **Water transfers.** Constrained by fixed allotments of surface waters and diminishing aquifers, urban areas have historically bought water rights from agricultural consumers and Indian Nations (who often have senior water rights to whatever water is available). Such purchases solve, in the short-term, supply issues for those areas that can afford such purchases. The long-term environmental, economic, and societal implications for the nation, however, are unknown.
- **Water recycling and reuse.** Recycled water currently accounts for approximately 2% of the water used in the United States.[16] By treating post-consumer wastewater for use in discrete applications, water suppliers make greater use of limited water supplies.
- **Matching water to its application.** Not all uses of water require the same quality of water. Industrial applications may require very high purity water, whereas agricultural applications may tolerate water with higher levels of salts and other impurities. Water providers are beginning to focus on providing water suitable for a particular use, not just providing high quality water regardless of its use. An example of 'water matching' is the use of recycled waters for crop irrigation, watering parks and golf courses, and purifying for industrial uses.
- **Revisiting dam and diversion.** The potential to store more water behind currently existing dams by increasing the height of those dams is one possible way to buffer water shortages. Another possibility lies in the process of releasing less water for flood control.
- **Conjunctive use or aquifer storage and retrieval.** Storage of treated water in aquifers for later use is being increasingly used. Large quantities of water can be stored in this way and this process can provide longer term buffering of supply changes.

### Water Supplies Increasingly Impaired

All surface and ground water in the United States contains contaminants that when the concentration becomes high enough must be removed. When the concentration of these

[15] This statement assumes that no currently-planned large-scale dam and diversion projects will be built in the United States. Constructing new dams and diversion projects (canals or aqueducts) is a subject that is far beyond the scope of this document.

[16] United States Geological Survey, Estimated Use of Water in the United States in 1995, viewed at http://water.usgs.gov/watuse/pdf1995/html/

contaminants exceeds the regulatory limits, these waters are referred to as impaired. Dissolved and suspended contaminants include:

- Biologics,
- Salts (total dissolved solids),
- Metals,
- Chemicals,
- Radionuclides, and
- Emerging contaminants (including such things as caffeine and endocrine disruptors whose health effects over time are currently being researched).

Contamination of the nation’s waters is a result of both human activities and natural processes. Up to 80% of the salt found in surface waters is the result of natural erosion processes. Increasingly-intensive use of waters, however, is exacerbating natural salt loads, resulting in some downstream areas becoming ‘sinks’ for concentrated salts. And land use practices (including urban and suburban sprawl and agricultural practices) can radically change the quantity and types of contaminants found in surface and ground waters.

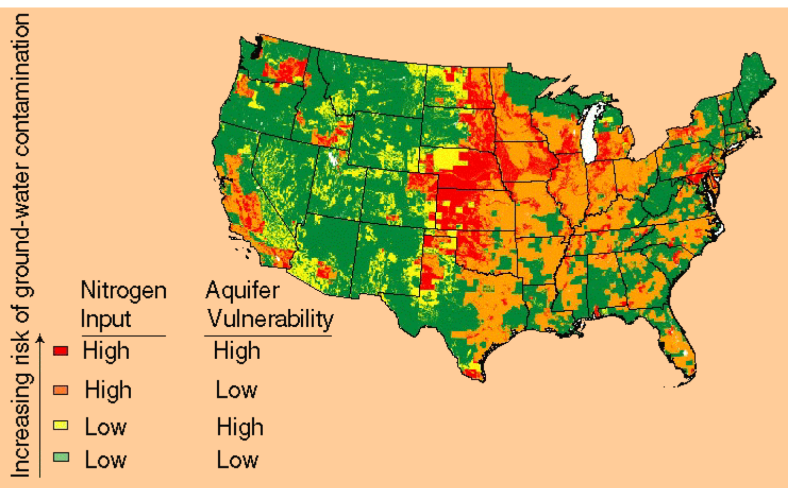



Figure A2. Extent of risk of nitrate contamination in aquifers.

Impaired waters are increasingly common across the United States.[17] As an example, the vulnerability of aquifers to nitrate contamination (a byproduct of agricultural fertilizers) is displayed in Figure A2.

Impaired water supplies present a suite of challenges to water planners – expensive and complex treatment plants must be designed to remove the array of contaminants currently found in waters, and these plants must have the flexibility to remove other contaminants as regulations change over time (or be designed in such a manner to allow for easy technological upgrades). In addition, water suppliers and planners must generate disposal solutions for the contaminants once they are removed from the water.

Impaired waters can be (and are) treated for use by agricultural, industrial, and residential consumers – at a cost. As a general rule, the more impaired a water source becomes, the more costly it is to treat – the cost of treating contaminated waters and the cost of

[17] The United States Environmental Protection Agency reports that 35% of the nation’s river miles are impaired, and that 45% of the nation’s lake, reservoir, and pond acreage is impaired. 23% of the nation’s river miles and 42% of the total surface impoundment acreage was assessed. Source: The Quality of Our Nation’s Waters. A Summary of the National Water Quality Inventory: 1998 Report to Congress. EPA841-S-00-001

disposing of the removed contaminants represents a significant challenge to the nation's water providers.

## A.2 Demand

Although a given drop of water may be used countless times, only one user may use it at a given time. Hence, agricultural, residential, industrial, and recreational users compete for available water. Figure A3 shows demand for water over time for residential, agricultural, industrial, and power production.

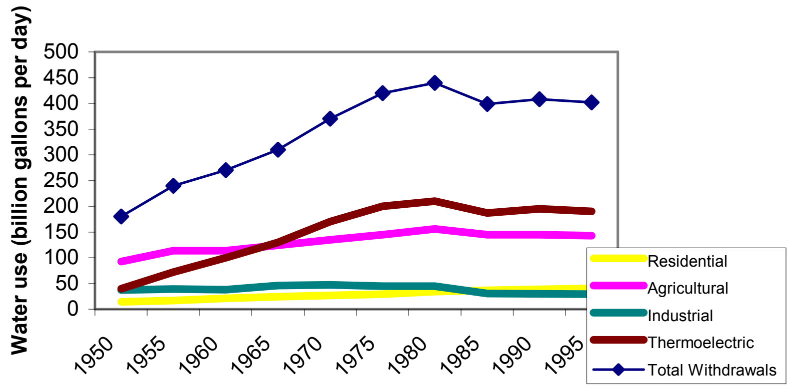



Figure A3. Freshwater withdrawals in the United States
As the chart above indicates, freshwater withdrawals in the United States peaked in 1980, dropped through 1985, and have since leveled. The cause behind this plateau in water withdrawals is singular: the withdrawal of freshwater is capped by institutional barriers. The demand for residential water, however, continues to rise in step with population, resulting in a situation where non-traditional water supplies will be increasingly utilized to make up the gap between what freshwater is available and what water is demanded.

### *Residential Demand*

Urban water planners have long recognized the need to decrease residential demand. In response to this need, water efficiency programs have been established across the country to encourage the installation of water-saving appliances.

Such efforts have succeeded in reducing the quantity of water consumed on a per capita basis. However, the positive impacts of these reductions are negated by rapid and sustained population growth in many areas of the country. Data for three of the fastest-growing states are exhibited in Figure A4.

### *Agricultural Demand*

Agriculture (including waters used for irrigation, livestock, and rural domestic consumption) in the United States consumes approximately 35% of the nation's total water every year (in Western states, agriculture accounts for up to 80% of total water use). While agricultural water management practices have improved over time (irrigation water demand declined by 2% between 1990 and 1995, while the acreage irrigated increased 1%), providing food for the nation remains

| | Arizona | California | Colorado |
|---|---|---|---|
| Total freshwater withdrawals (millions of gallons per day), 1990 | 6,570 | 35,100 | 12,700 |
| Total freshwater withdrawals (millions of gallons per day), 1995 | 6,820 | 36,300 | 13,800 |
| Percent change, 1990-1995 | +3.8% | +3.4% | +8.7% |
| Per capita freshwater use (gallons per day), 1990 | 1,790 | 1,180 | 3,850 |
| Per capita freshwater use (gallons per day), 1995 | 1,620 | 1,130 | 3,690 |
| Percent change, 1990-1995 | -9.5% | -4.2% | -4.2% |
| *Source*: Solley, Pierce, and Perlman. Estimated Water Use in the United States. 1993, 1998 (www.usgs.gov) | | | |

Figure A4. Water withdrawals and per capita use inherently water-intensive. At present, recycled waters account for only 1% of the water used to irrigate crops – the remainder is 'new' water drawn from surface and ground water sources. Nationwide, only 20% of irrigation water finds its way back to aquifers or surface waters – 8 out of every 10 gallons is essentially consumed through evaporation or uptake into crops.[18]

### *Industrial and Energy Demand*

As shown in Figure A5, water demanded by industrial and thermoelectric (energy production) consumers has flattened following thirty-five years of increasing demand. This plateau in demand is due to barriers to increased water use – namely, regulatory restrictions to maintain or increase the amount and quality of water available in rivers and surface impoundments for the maintenance of water quality, recreation, fisheries, the protection of endangered species, etc. – and to dramatic increases in the percentage of water that is recycled by industrial users.[19] However, the water demand for power production remains intense, and may grow concurrently with population growth.

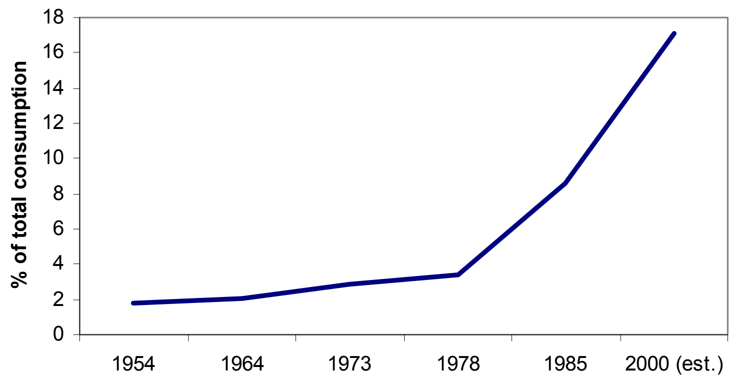



Figure A5. Industrial Water Recycling Rate in the U.S.

**This is the current water supply situation in the United States –** increasing, competing demand for a supply that is, over time, both fixed and becoming increasingly impaired. There is, at present, no widespread shortage of usable water in the United States – however, drought-exacerbated water scarcities have grown to critical levels in some regions of the nation. There exists the very real promise that water of usable quality will become increasingly scarce in the United States, and that the water that is made available will require increasing levels of treatment before it can be used by the industrial, or consumer markets, and in some cases the agricultural market.

Current and future pressures on our water supply will cause change – it is our choice as a nation as to what type of change occurs, when it occurs, where it occurs, and what effect those changes will have on society. Ignoring our national water supply problems will likely result in large magnitude, negative changes in the future. By acting today to develop revolutionary desalination and water purification technologies, we can minimize negative ramifications and maximize positive impacts.

[18] U.S. Geological Circular 1200, Estimated Use of Water in the United States in 1995, downloaded at http://water.usgs.gov/watuse/pdf1995/html/

[19] ITT Industries, Guidebook to Global Water Issues, viewed at itt.com/waterbook/recycling.asp

## A.3 Balancing Supply and Demand Today

Supply and demand in the United States is, on a national scale, in equilibrium. Despite regionalized water shortages and localized water quality concerns, the thousands of water suppliers in the United States largely meet the demands of their users using conventional water treatment technologies (see Appendix C for a discussion of conventional water treatment plants versus the desalination and water purification technologies that are the focus of this Roadmap). In today's environment of tightening water supplies, increasing demand for water is generally met through application of policy-oriented water management options including water transfers, intensive conservation programs, and increased reclamation and reuse. In a few cases (primarily Southern Florida, Southern California, and El Paso, Texas), advanced desalination and water purification facilities are being built or planned to increase the available supply of water. These facilities 'upgrade' seawater or brackish waters by removing salts and other contaminants so that they are suitable for use. The costs to build these facilities run to the tens of millions of dollars **(roughly 7 to 8 times more than the cost of a conventional water treatment plant**), and the treatment cost for the water that they produce is $1 to $3 per thousand gallons (5-6 times the treatment cost for 'conventional' fresh water).

| | |
|---|---|
| Treatment cost for fresh water from a conventional water treatment plant | $0.30-0.40/1000 gallons |
| Reclaimed water for industry in Southern California | $2.22/1000 gallons |
| Treatment cost for desalinated brackish water for residential use | $1-3/1000 gallons |
| Treatment cost desalinated seawater<br>Santa Barbara, CA (1992)<br>Cyprus-2 (1999)<br>Tampa Bay (2001) | <br>$5.50/1000 gallons<br>$3/1000 gallons<br>$2.08/1000 gallons |

Figure A6. Water Supply Costs – Today
*costs estimated using USBR cost model

At $3 per 1000 gallons, water produced using advanced desalination and water purification technologies might seem expensive. Consider, however, that consumers have shown a great willingness to pay the equivalent of $7,945 per thousand gallons for 'designer' bottled water (based on a shelf price of $.99 per half liter bottle).

**As demand increases over the next 20 years, the need to employ supply-enhancing technologies will grow. These technological solutions will blend with policy-oriented water management solutions to adjust the balance of our nation's water needs. Further, prolonged drought, changes in regulations that may require the removal of additional contaminants, increasing water salinity due to unchecked urban and suburban growth and agricultural practices, and ever-increasing demand in regions already facing water supply concerns may create a future where technological solutions will increase the robustness of our response.**

## A.4 Balancing Supply and Demand in the Future – The Need for a Focused Interdisciplinary Program

**There is no 'silver bullet' solution to the nation's future water challenges.** The complexity of the water issue will require a disciplined, focused, and interdisciplinary program to create a 'toolbox' of solutions from which the nation's water managers can choose when addressing particular water challenges. All of these tools will find applicability at some point in time. For instance:

**Solutions to the nation's water issues will evolve over time.** Where water management options such as transfers present short-term, immediate solutions to localized shortages, shifts in how water is managed on a national scale may result in the final, very long-term solution.

Between now and then, however, a combination of management options and technology applications will be required to meet our nation's evolving needs. Some water supply situations will avail themselves of policy-oriented solutions, whereas others will be more suited to technological solutions.

- **Demand reduction is important, but is insufficient in the long-term when faced with increasing population and economic growth.** The purpose of demand-reduction activities is to 'free' water for others to use (in essence, if one person reduces their demand by 50%, enough water will be 'freed' to provide an equivalent amount of water for another person). Demand-reduction activities on their own, however, will 'free' insufficient quantities of water to meet our nation's growing demand in the long-term.
- **Innovative water management practices offer tremendous potential in the long-term, but are difficult to implement in time to address short-term problems.** Rationalizing how water is managed at the national and state levels (e.g., instituting national standards for concentrate disposal and improved sharing of costs between water-rich and water-poor areas) has the potential to alleviate many of our water issues. Such rationalization of water management in the United States, however, will likely take far more time than the nation has to spare.

- **Technological solutions (as shown circled in Figure A7) offer the dual-benefit of applicability in the short-term (within the next two decades) while also holding the potential of mitigating the need for innovative water management practices in the long-term (in the years beyond 2020).** To achieve these short- and long-term benefits will require the development of technologies that can remove the contaminants found in our increasingly-impaired waters; that can purify waters from the huge saline (brackish) aquifers under the United States; that can increase the reuse of water; and that can more efficiently desalinate seawater. As energy demand grows in lockstep with population, these technologies must be more energy-efficient than current technologies; must be flexible enough to remove contaminants that might be subject to regulation in the future; and they must be cheaper to build and operate than current technologies. In essence, these technologies will add 'new' water to the nation's supply while improving upon the ability of conventional treatment plants to protect the quality of our water.

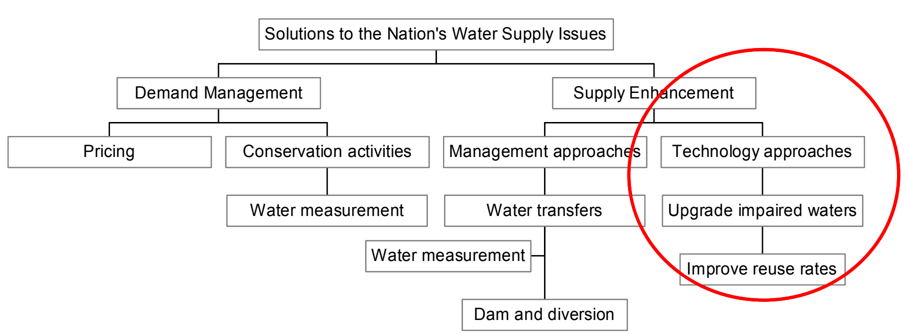



Figure A7. Hierarchy of the nation's water solution toolbox.

# APPENDIX B – THE ROADMAPPING PROCESS

This Roadmap presents an argument for the need to engage in research and development activities that will:

- Accelerate the evolution of current-generation advanced desalination and water purification technologies so that they are better able to meet the short-term needs of the nation's water providers; and
- Create the revolutionary, next-generation advanced desalination and water purification technologies that will be necessary to produce high-quality waters from increasingly-impaired sources in the mid/long-term.

These technologies, however, will have to meet some set of performance standards above and beyond what currently available technologies can meet – otherwise, why would industry or government invest in their development? As discussed in Section 2.3, current-generation desalination and water purification technologies are not cost-competitive, and present significant concentrate management problems.

**The Roadmap – Grounded in Reality**

The Desalination and Water Purification Technology Roadmap is grounded in reality. Through the development of case studies, the Roadmap establishes a suite of 'Needs' that are representative of the emerging challenges facing the nation. Working from these needs, the roadmap lays the foundation for a science and technology research enterprise the results of which will provide the technologies that can meet these emerging needs. In essence, the Roadmap examines how good today's technologies are, maps this performance against how good technologies must be in the future, and details a suite of research projects that will result in technologies that can meet the nation's future needs.

The primary goal of the desalination and water purification roadmap is to identify research areas that will result in next-generation, revolutionary desalination and water supply purification technologies that are cheaper to build and more efficient to operate than current generation-technology based plants. The secondary goal of the roadmap is to identify evolutionary research that can address the shortcomings of current-generation technologies. Thus, this Roadmap **focuses on real-world concerns** – primarily, evaluating and mapping R&D activities that will:

- Drive down the capital and operating costs of next-generation technologies;
- Increase the efficiency of these technologies by reducing energy costs and treating more water than current-generation plants of the same size;
- Reduce the post-treatment waste disposal concerns that currently hinder widespread application of desalination and water supply purification technologies;
- Allow the 'upgrading' of more diverse sources of water, to include seawater, brackish water, reclaimed (post-consumer) water, and produced waters from oil and gas activities; and
- Improve the sustainability of desalination processes through reductions in the consumption of energy and chemicals.

## B.1 The People behind the Roadmap

To ensure the development of a comprehensive Roadmap, Sandia and the Bureau of Reclamation convened an Executive Committee and a Working Group (known collectively as the Roadmapping Team) of well-respected water researchers, technologists, and consultants from Federal and local government agencies, academia, research institutions, industry associations, and the private sector.

Never before has a group convened to both identify the challenges facing the future of the nation's water supply and to link these challenges to technological solutions that must be created to assure the nation's future water supply.

## B.2 THE STRUCTURE OF THE ROADMAP

Science and technology roadmaps serve as pathways to the future. They call attention to future needs for development in technology, provide a structure for organizing technology forecasts and programs, and communicate technological needs and priorities and expectations among end-users and the research and development community.

The purpose of the desalination and water purification roadmap is to identify, evaluate, and prioritize research areas that will satisfy near-, mid-, and long-term water supply challenges. Development of the Roadmap followed this five-step process:

**Step 1:** **Identify Needs** through construction of case studies and examination of state-of-the-practice technologies. These case studies examine the challenges facing geographically-diverse regions of the United States that are representative of the challenges facing much of the nation. Case study authors were tasked with examining and evaluating the future impacts of current patterns of use, economic growth, and population increases.

**Step 2:** **Create Critical Objectives** for each of these Needs. The Critical Objectives provide the overall framework for the roadmap and represent the high-level goals of the Roadmap. The Critical Objectives ensure that research addresses specific Needs, and that research projects stay on target.

**Step 3:** **Identify Metrics** for each Objective. Metrics are quantitative values that define a Critical Objective. Metrics are comprised of near-term and long-term sub-targets. Metrics quantify the technological and scientific improvements necessary to meet the nation's future water needs. Critical Objectives may contain 'stretch' targets that serve to challenge researchers to expand the functionality and performance of technologies beyond what is currently thought possible.

**Step 4:** **Identify Technology Areas** that offer the best chances of meeting future Needs, Critical Objectives, and Metrics.

**Step 5:** **Identify Research Areas** within the Technology Areas and from which scientific understanding and technological advances could emerge to meet the 'Targets'. The Roadmap does not identify specific research projects, but rather areas of research that will provide the science and technology foundations for meeting our nation's future water needs.

### *Technology Areas for Future R&D*

A myriad of advanced desalination and water purification technologies exist – some only as curiosities in the laboratory, others in widespread commercial use across the nation. In order to effectively identify and evaluate potential research areas, the Roadmap divides the 'world' of advanced desalination and water purification technologies into the following five segments:

1. Membrane technologies
2. Alternative technologies
3. Thermal technologies
4. Concentrate management technologies
5. Reuse/recycling technologies

These five areas have defined the Bureau of Reclamation R&D programs for many years. Some of the research performed in these programs was considered "unsuccessful" at the time of its completion. Scientific advances realized in the past several decades may enable the success of these projects – for example, materials that have failed in the past may no longer fail due to advances in materials science, or important (recently discovered) concepts may work to overcome fundamental flaws in past research projects. Because of these advances, a review of the historical body of work may open new and interesting avenues of investigation for today's researchers.

### Critical Objectives and Targets

This Roadmap presents an agenda for a balanced basic science, applied research, and development research portfolio – that is, goal-oriented research to meet the needs of desalination/treatment development in the United States. Only focused, directed, prioritized, well-conceived and executed activities will result in the technological solutions that are an important component in ensuring the nation's continuing ability to provide additional supplies of water to its people, industries, and environment.

To this end, the Roadmap develops a set of 'Critical Objectives' and associated 'Targets' that quantify the future goals of research activities. These Critical Objectives were developed by Roadmapping Team members and are based on the principle of getting the most bang from each research buck. In those cases where there is no economic model of the interactions between components, reliance on the judgment of the roadmap team was required to set priorities. For more established technologies, an economic model can assist in making these priority judgments.

Figure B1 illustrates the cost structure of producing potable water from seawater in a reverse-osmosis plant (a current-generation technology employed around the world). Examining this cost breakdown quickly leads to the conclusion that the greatest economic gains are to be found in reducing energy

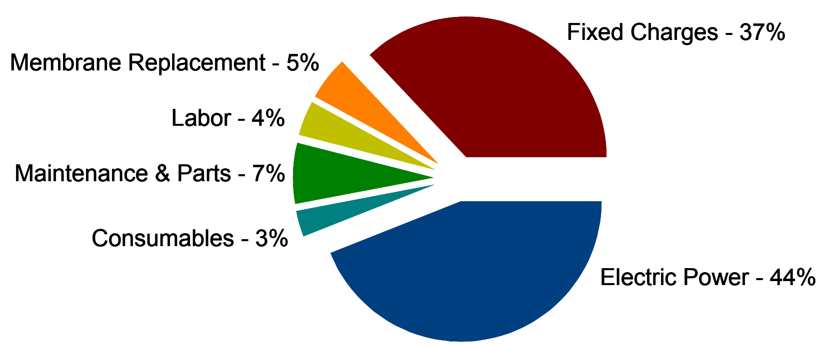



Figure B1. Cost structure for reverse-osmosis desalination of seawater consumption and fixed charges (essentially the capital cost of the reverse-osmosis equipment). Once an economic model exists, this model allow for the setting of research priorities. Those areas that produce the greatest gain should have the highest priority. Consequently, researching technological innovations that lead to a 50% reduction in labor costs (for instance, developing extensive facility automation systems) hold the potential of providing only a 2% reduction in the overall cost structure. Spending the same amount of research dollars investigating ways to reduce energy consumption by 50% however, hold the potential of providing a 22% reduction in the overall cost structure – a much larger gain from the same research dollar. The Roadmapping Team used this principle to develop the Critical Objectives found in this Roadmap.

It is important to note that the Critical Objectives and Targets are not set in stone, and may be modified as technologies develop or as demand- and supply-scenarios change. They play an important role, however, in that they provide public and private sector researchers, managers, and organizations targets at which to aim – such targets are essential for research projects such as those proposed in this Roadmap.

### *Timeframes*

The desalination and water purification technologies roadmap identifies research, development, and deployment needs through the year 2020. To facilitate discussion of these R&D needs, the Roadmapping Team considered two roadmap-specific timeframes: the near-term (out to 2008); and the mid/long-term (ranging from 2009 to 2020).

*The near-term*

Near-term research projects are defined as those projects that must be completed before or by the year 2008. Due to 'lags' between the time when research is completed to the time that it is available for real-world testing and evaluation, near-term research projects must be started immediately, or as soon as funding for them becomes available. Near-term research is generally defined in terms of current technological shortcomings – that is, fixing (as soon as possible) problems currently found in current-generation technologies – and in terms of laying the foundation for the development of revolutionary desalination and water purification technologies.

*The mid/long-term*

Mid-term research projects will provide the science and technology necessary to transition the United States from current-generation technologies to next-generation technologies. Mid-term research projects will advance current-generation technologies to their logical limits – when applied, these research projects will result in the zenith of current-generation technologies. Mid-term research projects will also introduce the first generation of revolutionary technologies into the United States.

Long-term research projects will create the second generation of revolutionary desalination and water purification technologies. Many of these technologies are exploratory and are just entering laboratory studies. Due to the longer timeframe involved with these research projects, it is not necessary that these receive aggressive funding support in the next several years.

Mid- and long-term research areas have been combined due to the uncertainties inherent in predicting the future – the farther from the present that one looks, the blurrier the picture becomes. Thus, trying to separate projects into mid-term and long-term categories may result in artificial divisions.

Mid/long-term research projects are designed to meet the future water needs of the nation as opposed to merely evolving those technologies that are currently available. Mid/long-term research projects represent progress toward meeting our nation's long-term water supply needs and the 'stretch' goals shown in Section 2.1.

Supporting a variety of mid- and long-term research projects is important from a research project portfolio-management perspective. The blurriness of the future and the inherently-uncertain nature of research success dictates that all appropriate avenues of research be followed until such time as the research proves itself unwarranted. Such an approach effectively balances risk (the likelihood that any given research project will not reach a successful conclusion) and reward (the chances that any given research project will revolutionize desalination and water supply purification).

The most useful sort of roadmap is one that provides alternative routes to one's destination.

# APPENDIX C – DEVELOPING TECHNOLOGIES TO MEET THE NATION'S NEEDS

Water planners know that the supply of water in the United States must be increased over time to meet the nation's ever-increasing demand. They also know that traditional water supplies are largely tapped out; this will force water suppliers to turn to overlooked and underutilized non-conventional or impaired sources while at the same time employing innovative water management options. The question then becomes: what technology or technologies will meet the needs discussed in Section 2?

Roadmapping participants identified five broad technology areas (see Section 3.0). Some of these technologies are currently in use, while others exist only in the laboratory. Ensuring that these technologies develop to help meet the nation's future needs will require investments to both evolve current-generation technologies and develop revolutionary, next-generation technologies.

## C.1 Evolution of Current-generation Technologies

Current-generation desalination and water purification technologies can produce the volumes of water that the nation will demand in the future – at a price. Advanced desalination and water purification plants are currently expensive to build and operate, resulting in water prices that are unpalatable in all but the most extreme situations and for all but the wealthiest consumers (generally those in large, urban areas that have no alternative means of meeting their water demand and industries that require high-quality water). Thus, the application of these current-generation advanced desalination and water purification technologies to provide water for residential users has been limited.

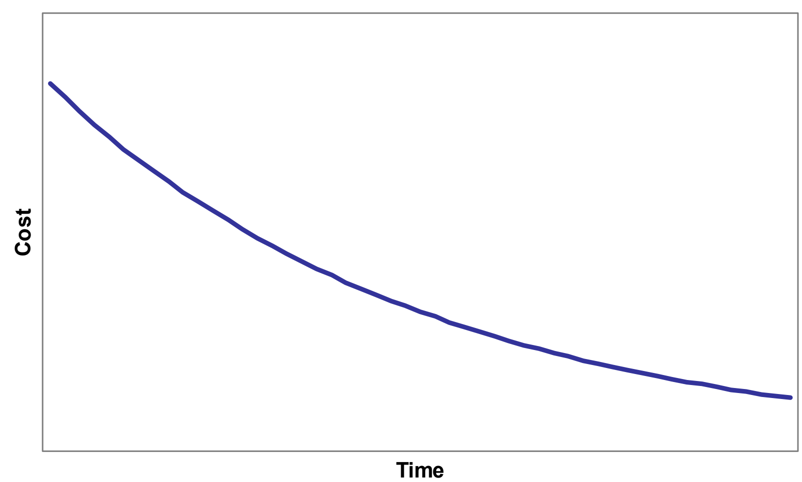



Figure C1. Historical and projected reduction in cost for water produced by current-generation desalination facilities.

Treatment cost for water from current-generation advanced desalination and water purification facilities in the United States is between $1 and $3 per thousand gallons (or up to 5-6 times more than 'conventionally treated' fresh water).[20] The cost of producing water from these advanced desalination and

[20] It must be noted here that the cost of water produced using current-generation desalination and water purification technologies varies widely across the United States depending upon location, ownership of the facility, the financing used to construct the facility, operating contracts, distribution infrastructure costs, conveyance to the customer, and a myriad other issues.

water purification technologies has declined over time, albeit at a rate of only approximately 4% per year (see Figure C1).

This improvement may be viewed in terms of the thermodynamic minimum of salt removal from seawater. For a solution of 3.5% sodium chloride, the minimum energy use due to osmotic pressure is 3 kJoules/kg of water. This may be expressed in terms of electrical energy as 3.1 kWh per 1000 gal or approximately $0.30 per 1000 gal. This energy use will never be achieved but is presented to illustrate that substantial improvement is possible.

## C.2 The Impact of Revolutionary, Next-Generation Technologies

Maintaining the status quo in R&D investments will result in more than the cost of water increasing (in terms relative to the percentage of income spent on water and wastewater services) over the next two decades in many parts of the nation.[21] For some, municipalities, it will result in buying unimpaired waters from nearby agriculture, with the possible result that local agriculture economies may suffer.

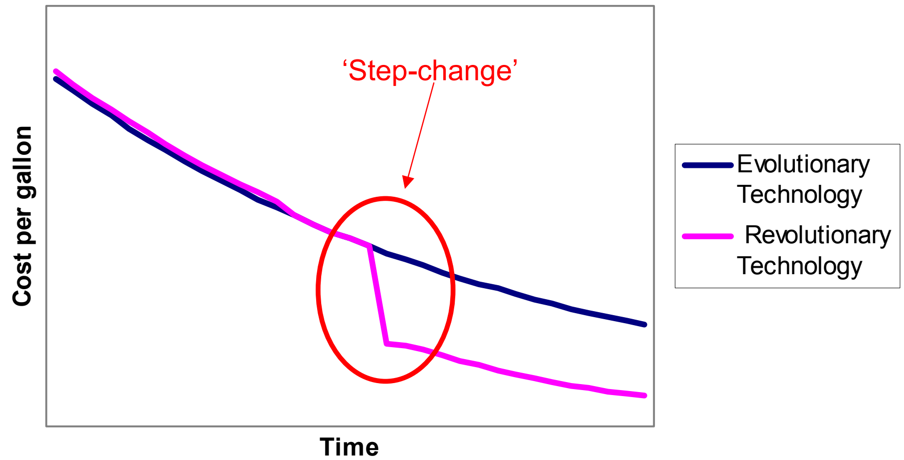



Figure C2. Supporting Revolutionary R&D: Anticipated Reductions in Cost for Next-Generation, Revolutionary Water Purification Technologies
Building on science and technology advances made over the past 10 years, revolutionary technologies offer the promise of a 'step-change' in the price of producing potable water from impaired waters.

Establishing a desalination and water purification technology research program that is "planned and prioritized in a coordinated and systematic way"[22] can reduce the absolute and relative cost of water in the next two decades. Figure C2 illustrates the impact of developing and applying revolutionary, next-generation advanced desalination and water purification technologies – an accelerated reduction in the cost of water.

Development and application of these revolutionary technologies will play an important role in meeting the nation's water needs in the coming decades. **We cannot realistically**

---

[21] This is largely due to the increasingly salinity of many of the nation's water sources. As salinity increases, so too do the costs when using conventional water treatment plants and current-generation desalination and water purification facilities. The large volumes of concentrate that these technologies generate will require costly treatment or disposal, thus increasing the per unit cost of water.

[22] National Research Council, Envisioning the Agenda for Water Resources Research in the Twenty-First Century, National Academy Press, 2001

**(that is to say, economically) increase the volume of water available in the future relying solely on conventional water treatment plants and the evolution of current-generation desalination and water purification technologies.** It is the revolutionary technologies outlined in this Roadmap that will act to fundamentally shift the cost curve for desalination and water purification technologies, making the cost of the plants accessible to a greater number of communities and the cost of the water they produce more affordable for a greater percentage of the nation's population.

## C.3 Parallel Track – Developing Evolutionary and Revolutionary Technologies Simultaneously

Solving the problems of today's technologies while developing the revolutionary, next-generation advanced desalination and water purification technologies of tomorrow will require a comprehensive parallel track R&D program. Only through such an R&D program will the nation be positioned to increase its water supply through use of overlooked and under-utilized sources.

**Conventional Water Treatment vs. Desalination and Water Purification**

Conventional water treatment plants typically utilize a hundred-years-old, five-step process: coagulation to improve water clarity; sedimentation to remove suspended solids; filtration; disinfection; and direct delivery and/or storage. Sometimes all of these five steps are not needed, and sometimes additional steps (treatment using chemical additions, soda ash or weak acids, or by filtration with granular activated carbon or calcite filters) are required to meet water quality standards. Conventional water treatments plants do not remove total dissolved solids from the source water, and their ability to remove emerging water-borne threats to human health is unknown at this time.

Advanced desalination and water supply purification plants utilize a host of methods to remove salts and water-borne threats to human health. These processes include running water through a series of membranes, distilling water and then condensing the purified water steam, freezing water, and several other approaches. All of these technologies are effective at removing salts from water and in removing water-borne threats to human health. In addition, these advanced technologies are flexible in design and application, thus offering great potential in removing emerging human health threats from our nation's water supply.