# Industrial Water Management

## A SYSTEMS APPROACH

Second Edition

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# Foreword

Minimizing the total net usage of water in industrial operations has been one of the top priorities for the Center for Waste Reduction Technologies (CWRT) of the American Institute of Chemical Engineers (AIChE) since its inception in 1991. Although much has been discussed and written about this goal in general terms, very little practical guidance has been provided—until now.

This timely publication, an update to the original 1995 edition, is a practical "how to" guide. It provides a systematic approach to water reuse, with six outstanding examples from diverse industries: an aluminum smelter, a pulp mill, a transportation equipment facility, an electric power plant, a semiconductor fabricator, and an aerospace manufacturer. The authors and contributors include proven and accepted technologies and practices, along with some new emerging technologies. For example, one chapter describes 17 different technologies that can be used for water reclamation.

The authors present this systematic approach for minimizing net water usage at an industrial facility in a straightforward manner. Using this publication as a guide, readers will be able to implement this practical approach in their own industrial settings.

CWRT is grateful to the authors of this second edition, Bill Byers, Glen Lindgren, Calvin Noling, and Dennis Peters of CH2M HILL, Inc., for the team effort that generated this new edition. We are also grateful to the AIChE Foundation, for it was their generous contribution that made this update possible.

We believe this update to the original publication will be helpful to many practicing engineers, process scientists, and production managers in implementing practical water reuse programs in their different industries.

Dr. Joseph Rogers
CWRT

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# Acknowledgments

For the authors, this monograph represents a true collaborative effort to create one of the first books on approaches to industrial water reuse. The idea for this book occurred early in 1994, out of the need and absence of references on the subject. The suggestion to create a monograph was made to one of the authors (Bill Byers) by Dr. Earl Beaver of Monsanto when he was Chair of the Center for Waste Reduction Technologies Advisory Board. His suggestion was prompted by an article written by one of our colleagues, Robert Rosain, and published in *Chemical Engineering Progress* (April 1993). Two of our colleagues (Si Givens and Ken Cable) at CH2M HILL helped to define the concept. After several months of discussions with the Center, the actual project was approved and begun during October 1994. Over the course of the year, many individuals and organizations contributed their valuable time, effort, and resources to make this book possible. Little did the authors know that so many would become involved! Without the help of the others, this book would be significantly different and less than our achievement here. At this juncture, we want to acknowledge and express our sincere appreciation to the many people who helped us.

First, we thank the Center for Waste Reduction Technologies (CWRT), which is part of the American Institute of Chemical Engineers (AIChE). Dr. Jack Weaver, Director of the CWRT, was our initial contact for the monograph. He was supportive of bringing the suggestion for creating a monograph to the Technology Transfer Committee of the CWRT. Ms. Noreen Cheleden at the CWRT provided terrific assistance in our subsequent contacts with Jack, the member companies, and the CPAS Task Force of CWRT as the project proceeded. The Technology Transfer Committee and its Clean Process Advisory System [CPAS] Task Force, chaired by Mr. Darryl Hertz, was the Managing Organization within the CWRT for this monograph. We are sincerely indebted to our CWRT Project Manager, Mr. Darryl Hertz, and the members of the CPAS Task Force (Christine Artale, Michael Chow, Judy Dorsey, Don Meyer, Dennis Olander, Pete Radecki, Lee Tonkovich, Clare Vinton, and Kai Young) for their support, direction, suggestions, and comments on the outline and draft of the monograph. We look forward to having the monograph as an integral part of the "Aqueous Pollution Prevention Design Options Tool Project" of CPAS.

We are also sincerely indebted to the CWRT member companies (kept nameless here and throughout the study) who completed and returned the water reuse questionnaire reported in the main body of the report and summarized in the appendices. The results from these contributing companies have advanced our understanding of the "what" and "where" about water reuse technologies being used in process plants. We thank you and your many plant managers who took the time to complete these evaluations!

While two of our four case study companies were willing to put their names into the monograph, we thank all four companies for the four terrific case studies that expand the horizons of industrial water reuse for our chemical engineering profession. We sincerely thank Alumax Lauralco (Montreal), the City of Colorado Springs, and their respective staffs for their support and assistance in creating two of our case studies.

Many of our colleagues at CH2M HILL helped develop the monograph to make it technically comprehensive, visually appealing, and easy to read. We thank Ken Cable and Si Givens, who worked with us early on to develop the outline for the systematic approach of the monograph. Additional technical input to the monograph came from Ken Martins, Jay Mackie, and many others. The development of the case studies would not have been possible without the help of David Drake, Mike Jury, Greg Peterson, Ken Cable, John Lee, Ron Ostop, Jay Mackie, and Karin Greenacre. Our peer reviewers during the draft phases of the monograph included Jay Mackie, Ken Cable, Si Givens, and Dick Siegel. At the front lines of the flow of information, we thank Carol Cash, Mary Murphy, and our library staff. The visual appeal, flow of text, and good grammar were possible only with the terrific support from Greg Long, Joe Larkin, and Susan Lewis, and the superb word processing staff that worked with them. We thank you all!

Bill Byers, Bill Doerr, Rajeev Krishnan, and Dennis Peters, CH2M HILL, Corvallis, Oregon, and Boston, Massachusetts, September 1995

## Acknowledgments for the Second Edition

The second edition update for this monograph has again represented a true collaborative effort both within and outside CH2M HILL. The idea for an update was suggested by Dr. Jo Rogers at AIChE to Bill Byers, one of the original authors, who spearheaded the project to update the monograph. The authors determined a scope and plan of action for updating those sections most in need of updating, and broadcast a request for input within an outside the firm. In the process, we were again struck by the number of people with valuable contributions to make, and we were fortunate to make new contacts and reinforce existing one outside the firm. We wish here to acknowledge those who had significant impacts on the quality and completeness of the second edition you see here.

The authors express sincere appreciation to the AIChE Foundation for supporting this update effort, and the CWRT Advisory Team, especially Dr. Jo Rogers, Dr. Conchita Jimenez-Gonzales, and Dr. Steven Maroldo, whose valuable and timely feedback increased the value of the final product. We are also very grateful to external authors and collaborators who helped us by supplying new case study material, or updating existing material. We especially thank Ms. Janet Millar and Mr. Kent Miller at Millar Western Forest Products, Ltd., and Mr. John Weems at Philips Semiconductors for their submission of two new case studies for this monograph that represent cutting-edge thinking in the field of water reuse. The value and experience these new cases bring to the dialogue on water reuse cannot be over-estimated

Internally at CH2M HILL, many people played a part in updating this monograph. Gerri Dickerson and Sandra Dudley from our Atlanta, Georgia, office produced another valuable new case study in aerospace parts finishing from their own project experience and research. Anurag Gupta and Rajeev Kapur from our Portland, Oregon, office contributed their expertise in regulatory changes in the Clean Air Act and the Clean Water Act to update those sections. Ed Leach, Jim Strunk, Jay Mackie, Ken Martins, Mike Jury, Ron Ostop, and Bob York all provided expert technical input, review, and feedback. Susan Christie provided extensive editing expertise to produce the final product. Our word processing, graphics, and administrative staff across several offices all contributed to assure product quality. Once again, thanks very much to all of you.

Bill Byers, Glen Lindgren, Calvin Noling, and Dennis Peters, CH2M HILL, Corvallis and Portland, Oregon, and Honolulu, Hawaii, July 2003

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# Abbreviations and Acronyms

| | |
|---|---|
| ABC | Activity-based costing |
| AC | Activated carbon |
| AIChE | American Institute of Chemical Engineers |
| ACC | American Chemistry Council |
| AOX | Adsorbable organic halogen |
| API | American Petroleum Institute |
| ASB | Aerated stabilization basin |
| BAT | Best available technology |
| BCTMP | Bleached chemithermomechanical pulp |
| BOD | Biological oxygen demand |
| BPT | Best practical treatment |
| BTEX | Benzene, toluene, ethylbenzene, xylenes |
| BTU | British thermal unit |
| CAA | Clean Air Act (and its amendments) |
| CMP | Chemical mechanical polish |
| COD | Chemical oxygen demand |
| CPAS | Clean process advisory system |
| CPI | Chemical process industries; corrugated plate interceptors |
| CTMP | Chemithermomechanical process |
| CWA | Clean Water Act (and its amendments) |
| CWRT | Center for Waste Reduction Technologies |
| DAF | Dissolved air flotation |
| DEP | Distillate equalization pond |
| DEQ | Department of Environmental Quality (Oregon) |
| DI | Deionized |
| DOE-EERE | U.S. Department of Energy Office of Energy Efficiency and Renewable Energy |
| ECF | Elemental chlorine free |
| ED | Electrodialysis; electrodeposition |
| EDI | Electrodialysis |
| EMS | Environmental management system |
| EOR | Enhanced oil recovery |
| EPA | Environmental Protection Agency |
| EPCRA | Emergency Planning and Community Right to Know Act |
| EPD | Environmental Protection Division (Georgia) |
| EPRI | Electric Power Research Institute |
| ERS | Economic Research Service |
| EV | Expected value |
| GAC | Granular activated carbon |

| | |
|---|---|
| GWD | groundwood |
| HAP | Hazardous air pollutants |
| HEN | Heat exchanger network |
| HERO | High-efficiency reverse osmosis |
| HON | Hazardous organic NESHAP |
| I&M | Inspection and maintenance |
| IPA | Isopropyl alcohol |
| ITA | Industry Technology Alliance |
| ITRS | International Technology Roadmap for Semiconductors |
| IWG | Industrial waste general |
| IWO | Industrial waste oily |
| MACT | Maximum achievable control technology |
| MECS | Manufacturing Energy Consumption Survey |
| MEK | Methyl-ethyl-ketone |
| MEN | Mass exchange network |
| MUA | Multi-attribute utility analysis |
| MVR | Multiple vapor recompression |
| NAPL | Non-aqueous phase liquid |
| NASS | National Agricultural Statistics Service |
| NDPES | National Pollutant discharge Elimination System |
| NESHAP | National Emission Standard for Hazardous Air Pollutants |
| NPDES | National Pollutant Discharge Elimination System |
| NPV | Net-present-value |
| NRCS | Natural Resources Conservation Services |
| NSSC | Neutral sulfite semichemical |
| O&M | Operations and maintenance |
| OCC | Old corrugated containers |
| OMB | Office of Management and Budget |
| ORP | Oxidation reduction potential |
| ORS | Oregon Revised Statute |
| OWRT | Office of Water Research and Technology |
| P&ID | Piping and instrumentation diagram |
| PAC | Powdered activated carbon |
| PAH | Polycyclic aromatic hydrocarbons |
| PCB | Polychlorinated biphenyl |
| PCP | pentachlorophenol |
| PEP | Process Economics Program |
| PFD | Process flow diagram |
| PhRMA | Pharmaceutical Research and Manufacturers of America |
| POTW | Publicly owned treatment works |
| ppb | part per billion (μg/L) |
| ppm | part per million (mg/L) |
| QA/QC | quality assurance/quality control |
| RDX | Research development explosive |
| RO | Reverse osmosis |
| RWR | Rinse water reclaim |
| SDI | Silt density index |

| | |
|---|---|
| SEMATECH | International Semiconductor Manufacturing Technology Consortium |
| SIC | Standard Industry Classification |
| SOCMA | Synthetic Organic Chemical Manufacturers Association |
| SOCMI | Synthetic Organic Chemical Manufacturing Industry |
| SPWCC | Semiconductor Pure Water and Chemicals Conference |
| STP | Sanitary treatment plant |
| SS | Stainless steel |
| TAPPI | Technical Association of the Pulp & Paper Industry |
| TCA | Total cost assessment |
| TCF | Total chlorine free |
| TDS | Total dissolved solids |
| TLTP | Third level treatment plant |
| TMDL | Total maximum daily load |
| TMP | thermomechanical process |
| TOC | Total organic carbon |
| TRI | Toxic Release Inventory |
| TSS | Total suspended solids |
| UF | Ultrafiltration |
| UPW | Ultrapure water system |
| USBR | U.S. Bureau of Reclamation |
| USDA | U.S. Department of Agriculture |
| USDW | Underground sources of drinking water |
| USGS | U.S. Geological Survey |
| UV | Ultraviolet |
| VCE | Vapor compression evaporation |
| VOC | Volatile organic compound |
| WAC | Weak acid cation |
| WRC | Water Resources Council |
| WRI | World Resources Institute |
| WRP | Water recovery pond |
| WSR | Water storage reservoir |
| WW | Wastewater |

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CHAPTER 1

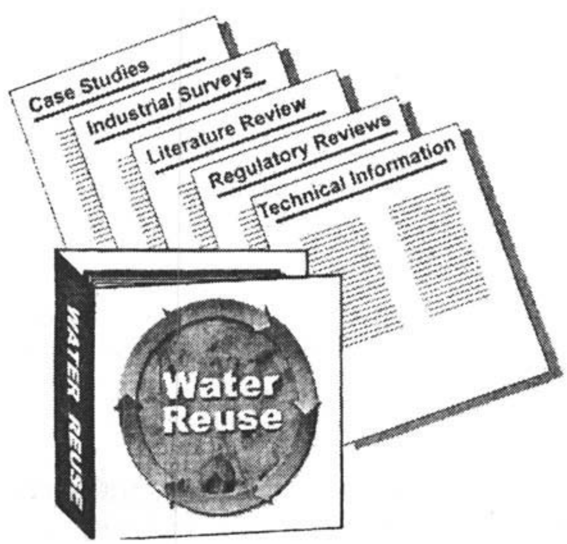
# Introduction

## 1.1 Project Purpose

Reducing material waste is one of the greatest challenges facing industry today. Because water is one of industry's major waste products, the ability to reuse wastewater would be a giant step in the direction of overall waste reduction. Before the first edition of this monograph was written, no guide existed to help conceptual process designers and process operators incorporate water use reduction and reuse principles into plant operations.

This monograph, produced by the American Institute of Chemical Engineers' (AIChE) Center for Waste Reduction Technologies (CWRT), shows how to systematically incorporate the principles of water conservation, recycling, and reuse into the design of new plants, retrofits of existing systems, and technology development.

***CWRT has taken on the stewardship of collective knowledge and experience for water reuse.***




It also contains technology summaries and case studies that support this systematic approach to water reuse, as well as recommendations for further research and developments to watch.

The information in this monograph was drawn from literature reviews, surveys of industrial practices, and the knowledge base of CH2M HILL, the firm contracted by CWRT to write the monograph.

The second edition provides an update of the original material. It includes new technologies, tools, and strategies for water reuse; new case examples for different industries; and new developments that are likely to affect this field in the coming years.

This introduction presents background information on water reuse and CWRT, explains how this monograph builds on CWRT's overall program, and describes how the monograph was developed.

## 1.2 Water Reuse— A Historical Context

Why implement water reuse in an industrial facility? A hundred years ago, in an environment of plentiful resources and few restrictions on their use or abuse, there were not compelling business reasons to do so. Thirty years ago, as environmental laws were developing, there were legal reasons to change certain industrial practices, but the changes were treated as "necessary costs," and therefore were not compelling enough to encourage changes in fundamental resource use behavior.

In today's environment, we increasingly find companies and communities running into resource limitations, both in terms of raw materials availability and the ability of the environment to absorb waste and pollution. Industrial facilities find themselves both dependent on, and able to seriously harm, entire watersheds. This situation is affecting the economics of resource use to the point that some facilities are being driven to improve efficiency and decrease waste in order to remain competitive. Responsible use of resources is no longer just a moral or legal issue, it is good business practice.

Before the beginning of the 1990s, U.S. industry viewed water as a nearly free commodity, used as a medium for receiving rejected chemicals and removing heat from processing plants. Water collected from these operations was usually sent offsite for treatment, if required, and then to surface water disposal. Water conservation and water reuse were considered justifiable only if they represented economic savings, either through material recovery or through the avoidance of treatment costs.

Industry today, however, is constantly striving to operate more efficiently. The most successful plants are relentless in their search for:

- Higher product yields
- Beneficial uses of byproducts
- Improved energy efficiency
- Safer and more reliable plant operations
- Improved public image
- Reduced environmental impacts
- Reduced use of limited resources, including labor

Some of these program areas have been emphasized more than others, but the long-term synergistic result has been continuous improvement in them all.

In support of these efforts, there have also been developments in the use of more comprehensive economic analyses to drive projects. Activity-based costing (ABC) has been developed to more accurately assign costs of management activities to certain products. Risk analysis tools have been developed to capture the cost of liabilities and chance occurrences associated with resource use. Since 1997, CWRT has been developing a total cost assessment (TCA) methodology in conjunction with its industry partners. This system provides an economic model that includes all direct and indirect costs, contingencies, and future intangible costs, such as those that might results from environmental, health, and safety effects of a decision. The TCA methodology is discussed later in this book and described in Appendix D.

Water reuse is one area in which continuous improvement has been significant. Several driving forces have encouraged today's companies to examine the possibilities for water reuse: regional water shortages, regulatory requirements, corporate waste reduction goals, and mandated public disclosures of toxic chemical discharges.

For example, the pulp and paper industry has studied total water reuse for more than 25 years, but actual "zero liquid discharge" mills came into existence only in the 1990s. And, although mills using chlorine bleaching might not achieve zero discharge, several mills in Europe and North America now have no surface water discharges Case #2 in Section 4 depicts a pulp mill that has pioneered the design and operation of a zero liquid effluent pulp process.

Other industries, notably primary metals processing and coal gasification, boast plants that have achieved or approached total water reuse.

Even though water reuse practices vary widely across climates and industries, almost every plant practices some degree of water reuse. For most plants, the obvious opportunities have already been adopted. For example, once-through cooling has been replaced with recirculation systems that use cooling towers, and some high quality wastewater streams from within plants are used to replace raw water in other, less critical processes.

Although water reuse has intrinsic benefits, it is not simple to achieve in practice. The water systems of many plants are already complex as a result of plant changes and improvements to existing systems. Isolated attempts to reuse water or change the water system are often stop-gap solutions that can cause more problems in the long term and even lead to unexpected and/or undesirable surprises in distant plant operations. For example, consider the following:

- The use of pH adjustment to overcome a scaling problem in one operation can appear to be hugely successful, only to emerge months later as scaling or corrosion at another critical location.
- Individual water conservation efforts can appear self-defeating, because concentration-based water discharge regulations become more difficult to meet as water flow decreases.

Therefore, water management strategies, industrial water reclamation[1] technologies, and a systematic approach to using them are necessary if plant-wide water reuse and effluent discharge reduction goals are to be reached. Water management strategies can be grouped according to the approach: water use efficiency, pollution prevention, or human approaches. Technologies can be grouped into several categories based on the fundamental mechanism used for treatment, for example, adsorption, filtration, or gravity separation. As an overall plan is developed for water reuse, a valuable step is to match water streams of differing quality with treatment technologies that are good candidates for reclaiming the water.

As time passes, we can expect the issues driving water reuse to evolve from regulation and legal liability to acute and pressing problems of resource limitation and economics. Public perception of environmental performance also is becoming a significant motivating factor in company decisions to fund water reuse projects. These changes in motivation, combined with the availability of appropriate technology, are driving new projects. At the same time, investments in water reuse infrastructure are becoming more economically feasible.

In some plants, actions by individual departments or process supervisors to implement water reuse have been less successful than desired or even have been detrimental to the water use strategy of the facility as a whole. Many of the advantages to be gained by improving independent processes have already been achieved.

Integrated systems thinking is needed across departments and processes in order to model an entire plant (or even neighboring plants) and understand the interdependencies. New technologies and techniques that would not have been considered by a single department can lead to breakthrough increases in performance. The systematic approach presented in this book provides a stepwise and methodical strategy for water management and water reuse that can be implemented at any level within or across facilities.

## 1.3 The Center for Waste Reduction Technologies

Established in 1991, CWRT is an industry-driven collaborative partnership affiliated with AIChE. The Center's operations are located at AIChE headquarters. Funding comes primarily

[1] The terms water reclamation and wastewater reclamation are used synonymously in the municipal wastewater treatment setting to indicate reuse of tertiary treated municipal wastewater from a publicly owned treatment work (POTW), including such secondary uses as land application. This indiscriminate use of these terms has been a point of confusion in the broader context of water reuse. Hereafter in this monograph, the term water reuse will be used to describe reuse of water, from any source, in an industrial application. Chapter 3, Water Reclamation Technologies, refers to those used to recover water for reuse in an industrial facility.

from tax exempt sponsor dues, federal entities, and the AIChE Foundation. The Center is an entity of AIChE's Industry Technology Alliances (ITA) group. Unique to AIChE, ITAs were first introduced in the 1940s. They are industry sponsored and help industry leverage resources for operational excellence.

Minimizing the total net usage of water in industrial operations has been one of CWRT's top priorities since its inception. The initial focus of CWRT was on basic research and development. But beginning in 1996, CWRT also began to respond to industry demand for business value from "environmental" monies. The Center's stated mission is to "benefit industrial sponsors and society by leveraging the resources of industry, government, and others, to identify, develop, and share non-proprietary technology and management tools that measurably enhance the economic value of sponsor organizations while addressing issues of sustainability and environmental stewardship."

CWRT's most recent activities have focused on sustainability issues and on how companies can add value through environmental health and safety commitments. Activities include thematic sponsor meetings, collaborative projects, best-practice workshops, and new technology presentations. Except for the collaborative projects, activities center around three general sponsor meetings each year. Updates on activities are available on the CWRT web site: http://www.aiche.org/cwrt.

## 1.4 Monograph Tasks and Scope

This monograph, the result of collaborative efforts by CWRT sponsor companies, has been authored by staff of CH2M HILL. It represents collected knowledge and experience from a variety of sources, including existing literature and personal experience. It has been produced in two phases: the original monograph in 1995 and this second edition update in 2002.

### 1.4.1 Scope of Original Monograph

Production of the original monograph included the following tasks:

- Gathering background information
- Organizing the document
- Developing a systematic approach
- Providing systems integration guidance tools
- Preparing case studies
- Conducting needs analysis for future research

#### *Gathering Background Information*

Background materials collected for the monograph included information on water reuse, strategies to guide the designer in an overall approach to water reuse, application of water-reclamation technologies, real-world case study examples, and information on developing issues and drivers affecting industrial water usage.

Background information for this document came from four primary sources:

- A search of recent literature, to define the current status of water reuse
- A questionnaire, used to conduct a survey of CWRT sponsors who were willing to provide information about water reuse in their operations
- Trade and technical associations, including Electric Power Research Institute (EPRI), Synthetic Organic Chemical Manufacturers Association (SOCMA), and American Chemistry Council (ACC), which provided additional information on trends in their industries
- Technical studies and designs, reviewed by the authors and their CH2M HILL associates

#### *Organizing the Document*

The monograph was organized into this introductory chapter and four additional chapters, plus references and appendices, as follows.

- Chapter 1—Introduction
- Chapter 2—The Systematic Approach
- Chapter 3—Water Reclamation Technologies
- Chapter 4—Case Studies
- Chapter 5—Developments to Watch

### *Chapter 2 - The Systematic Approach*

Chapter 2 describes an approach that systematically addresses water reuse as a plant-wide issue. This approach accomplishes the following:

- Describes the issues, motives, and driving forces for water reuse
- Identifies broad categories of water usage and water quality requirements
- Identifies problems that can be caused by closing up the water balance
- Discusses ways of matching water sources with water needs and balancing sources with needs
- Provides tools for structured evaluation and decision making
- Discusses a systems approach to dealing with these issues, in a cycle of continuous improvement

### *Chapter 3 - Water Reclamation Technologies*

Guidance on selecting water reclamation technologies is presented in tables that match types of constituents with categories of technologies.

### *Chapter 4 - Case Studies*

To select and develop the case studies for the monograph, the authors conducted the following activities:

- Examined in-house records of successful water reuse projects selected from electric power generation, primary metals processing, manufacturing, and pulp and paper operations
- Selected, where possible, case studies or examples documented in the public domain and representing a comprehensive and systematic approach to water reuse
- Made use of a water reuse questionnaire that asked CWRT member companies for published case studies that could be used to create a case study for this monograph
- Invited water reuse managers in various industries to review the case studies
- Used studies and application of water use reduction technologies from the chemical and hydrocarbon process industries to further supplement the case studies

Based on the information gained from these activities, the authors selected case studies that appeared to be most representative of the degree of water reuse achievable in process plants. To the extent that specific information could be disclosed, the authors described these processes in this monograph.

### *Chapter 5 - Developments to Watch*

A modest amount of research in some areas of water reuse could facilitate a substantial step forward. Chapter 5 identifies areas that need additional research and recommends those that seem to offer the greatest possibilities for advancing the practice of reusing water in industry.

## 1.4.2 Second Edition Update

This revision of the 1995 monograph includes updates to the data and statistics presented originally, developments in issues and drivers for water reuse, refinements to the systematic approach, water management strategies and updated information on technologies, new or additional case studies, and new economic, social, and political concerns that will affect water reuse decisions in the future.

Tasks for the update were broken down and performed as follows.

### *Gather Updated Information*

The authors consulted original sources along with new ones to track changes and update data. The information gathering task included:

- Consulting with the CWRT Advisory Team

- Conducting another search of relevant literature published since 1995
- Contacting trade and research associations
- Contacting providers of systems hardware and software
- Drawing upon internal expertise at CH2M HILL
- Tracking updates to relevant regulations

### *Update Chapter 2 (The Systematic Approach)*

Chapter 2 has been overhauled to make it more useable and readable. The authors also added a step and referenced related management techniques that are well established, such as the quality cycle for continuous improvement used in ISO 9000 and ISO 14000 implementation. The systematic approach presented here follows much the same strategy as those systems.

The authors also added extensive references to published tools and methodologies, including heat and material balance software, mass exchange networks, and cost assessments.

### *Update Chapter 3 (Water Reclamation Technologies)*

Using the new information gathered from literature search and case studies, the authors updated existing technology descriptions as appropriate.

### *Update Chapter 4 (Case Studies)*

The authors contacted several sources, including CH2M HILL in-house engineering staff, industry leaders, and trade associations, and found new case studies that replace existing ones or provide additional information on a new industry. A new case study might offer new information about technology, an update on previous reuse systems, or a compelling story about how an industry not mentioned in the first edition is implementing water reuse. Some of these cases also provide insight into new motivating factors that are driving industries toward water reuse. The new case examples are:

- Case 2: Paper Mill—Millar-Western (replaces existing paper mill case)
- Case 5: Electronics—Philips Semiconductor (new case, new industry)

### *New Chapter 5 Water use in Industries of the Future*

To date, there has not been a credible or comprehensive study on how water is used in industry. Therefore, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) Industrial Technologies Program and the American Institute of Chemical Engineers' Center for Waste Reduction Technologies (CWRT) have assembled this study on water use, water reuse, and the relationships between water and energy for several energy-intensive industries, and then extracted themes and issues common across these industries. The chapter examines water use, management of water, and the relationship of water to energy use in several Industries of the Future, selected by DOE for ongoing study because of the energy-intensive nature of their operations.

### *Update Chapter 6 (Developments to Watch)*

Several cultural, economic, and political drivers for water reuse have developed around the world over the past 6 years. Harmonization of standards, globalization of trade, global reporting standards, and a new drive toward "sustainability" have all contributed to increased motivation for water reuse projects. The authors researched these developing issues, and organized them in the same way that the issues and drivers in Chapter 2 are organized.

### *Update Appendices and References*

The authors added new or revised information and new references as appropriate. Included are references to the sources of new material.

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CHAPTER 2

# The Systematic Approach

Until fairly recently, the subject of industrial water reuse was not of compelling interest—because no regulation or practice explicitly mandated the general reuse of water. Water reuse that was performed often was the result solely of an incremental or ancillary activity. Thus, some historical water reuse approaches have produced marginal results.

This section presents a six-step strategic and systematic approach to implementing water reuse at an industrial facility and has the following characteristics:

- The approach is *strategic* because it provides an expansive, holistic, and long-term emphasis to support site and capital planning.
- The approach is *systematic* because it introduces a sequence of steps for the ordered analysis and implementation of industrial water reuse.

This chapter is divided into seven sections. Section 2.1 introduces the approach and describes the six steps of the approach very generally in six subsections. The supporting information for steps in the approach—considerations, checklists, formulae for the needed tactical elements—are provided in Sections 2.2 through 2.7, which focus on each of the six steps in a chronological manner.

## 2.1 Overview of Approach

Understanding the objectives and constraints of a water reuse program for a particular facility helps balance and satisfy the motives that are at play among the following drivers:

- Regulatory compliance
- Economics of the process
- Resource limitations
- Public perception

The six steps of a strategic, systematic approach to industrial water reuse are as follows:

1. Establish leadership and commitment for the effort.
2. Frame the problem and set boundary limits for the study.
3. Evaluate technical opportunities and water reuse techniques, develop alternatives, and define potential problems and contingencies.
4. Select a course of action.
5. Implement the new course of action.
6. Review and update the model or design as needed.


*A systematic water reuse approach requires an organized sequence of steps done in a cycle of continuous improvement.*

These elements have parallels to the "Plan-Do-Check-Act" cycle originally introduced by Deming (1993), which has been a foundation of quality efforts such as ISO 9000 and, more recently, the ISO 14000 environmental management standards. Implementing industrial water reuse demands planning, commitment, participation, and review at all levels in the facility, just like implementing a quality or environmental management system. Thus, a good systematic management approach to water reuse will have elements and organization similar to those of the proven Deming cycle (see Table 2-1). The approach described in this monograph concentrates a good deal of effort on the first three steps (planning), because good planning up front leads to a better result.

**TABLE 2-1**
*Parallels between the Quality Management Cycle and the Systematic Approach*

| Quality Management Cycle | Systematic Approach to Water Reuse |
|---|---|
| Plan | Establish leadership and commitment |
| | Establish boundary limits |
| | Develop alternatives |
| Do | Select a course of action |
| | Implement the new course of action |
| Check and act | Review and update the model or design |

### 2.1.1 Step 1—Establish Leadership and Commitment

The first step in the systematic approach is to examine the issues and drivers that are motivating an interest in water reuse, develop goals, objectives, and a business case to address these drivers, and establish organizational leadership, commitment, and accountability to achieve the objectives of water reuse. A group of those concerned must start by examining the following questions and issues:

- **Drivers.** Motivating drivers include resource recovery, local water scarcity, public image, and the ability to avoid costly and lengthy permitting procedures. Restraining or impeding drivers can include capital or space constraints, or potential forfeiture of water rights. In some cases, drivers can motivate or impede the effort, depending on the specific situation.
- **Stakeholders.** Those interested and affected by the effort must be identified, which includes internal departments or processes and external stakeholders, if any.
- **The Business Case.** In order to get management commitment, the major costs, benefits, and monetary tradeoffs must be identified and assebled into a persuasive business case. Also, the elements of risk and liability must be established. CWRT has assembled an industry collaboration to develop a total cost assessment (TCA) methodology that combines and evaluates tangible and intangible costs. This methodology is described further in subsection 2.2.10 and Appendix D.
- **Goals, and Tracking Progress.** The team must have goals and a way of tracking progress toward those goals. This early stage is the time to start planning how progress will be measured.
- **Leadership, Accountability, and Responsibilities.** It is important to establish up front who is in charge, who is on the team, what the team members will do, how they will be held accountable, and how they will be rewarded.

**Establishing Commitment.** Commitment consists of building a program plan and securing management sponsorship and funding.

### 2.1.2 Step 2—Frame the Problem

Once the leadership and commitment for instituting water reuse has been established (Step 1), the technical framework for the program should be set up via establishment of boundary limits and a technical baseline (Step 2). This step, perhaps the most far-reaching and important technical aspect of a water reuse program, could require a paradigm change or more holistic focus than would normally be considered.

The water reuse program boundary limits can be envisioned as a three-dimensional surface enveloping the areas in which water use optimization is to be performed. Boundary limits might or might not be contiguous and could contain a single unit operation, a process, a department, a whole plant, an entire watershed, an entire corporation, or another entity or group of entities. Table 2-2 presents some advantages and disadvantages of two extremes for defined boundary limits.

The following fundamental steps should be taken once the boundary limits have been established:

- Conduct a baseline materials balance
- Gather and summarize data
- Perform materials accounting

The resulting list for each depends on the extent and complexity of the selected boundary limits.

### 2.1.3 Step 3—Develop Alternatives

Having established boundary limits and a baseline, it is then time to generate and compare alternatives for reuse of water within the selected boundary limits.

- **Develop objectives.** Objectives are generated from the goals set in Step 1, but they are focused within the boundary limits.
- **Identify opportunities for water reuse.** This task can be accomplished in several ways:
  - Reviewing the baseline water and material balance

**TABLE 2-2**

*Advantages and Disadvantages of Large and Small Boundary Limits*

| **Small Boundary Limits** (e.g., a unit process) | **Large Boundary Limits** (e.g., a community) |
|---|---|
| ***Advantages*** | |
| Small stakeholder group | Large stakeholder group |
| Simple material balance | Clear reuse drivers |
| Simple, quantitative goals and performance measures | Highly effective, far-reaching |
| Short reuse analysis cycle | Substantial cost reduction |
| Low investment in reuse analysis | |
| ***Disadvantages*** | |
| Drivers often not apparent | Complex material balance and issues |
| Less effective, downstream effects | Complex qualitative and quantitative goals and performance measures |
| Limited cost reduction | Long reuse program with multiple iterations |
| | Substantial investment in reuse program |

  - Benchmarking
  - Using industry standard water management strategies
  - Reviewing available water/wastewater treatment technologies
  - Using process analysis tools, including process simulation tools and process integration approaches

- **Generate alternatives.** Each alternative will present a set course of activities that uses the opportunities, water management strategies, and technologies just listed to achieve the objectives. Many alternatives might be generated, but they must be screened to the few that show the most promise of efficiently achieving the objectives.

- **Refine the alternatives.** List the benefits, constraints, and impacts of the most promising alternatives for water reuse. Ask whether the alternatives produce results that can be measured and tracked, using the tracking ideas presented in the detailed description of Step 1 in Section 2.2. The best alternatives will show a clear path to measurable results. These alternatives, the objectives, and the performance criteria can then be carried forward into the analyses described in Step 4.

### 2.1.4 Step 4—Select a Course of Action

It is important to approach decision making as systematically as all of the other water reuse steps. In recent years, the field of decision sciences has developed around improving the decision making process. Formal decision tools exist that consider and balance different objectives and produce a solution that is both better and more easily sold to multiple stakeholders. These tools can address four major areas of concern:

- Uncertainty of future events
- Prioritization of alternatives
- Optimization of solutions across objectives
- Consensus building

Many pitfalls exist in complex decision making (Rogers et al., 1997):

- Strong biases toward alternatives that perpetuate the status quo.
- Influence by past numbers and past experiences
- Solution determined (subconsciously) before figuring out why it's best
- Overconfidence in the accuracy of estimates
- "Sunk cost biases" (biases toward incorrect solutions that have some previous investment from the company)
- Use of incorrect technical framework (Step 2 not done correctly)

The results of falling into these decision traps might sound familiar—command and control by dominant personalities, pushing of pet projects, group-think, over-reliance on simplistic estimates, and enchantment with the latest technology. These pitfalls can be costly in terms of time and money.

Decision tools are discussed in Section 2.5, with some examples.

### 2.1.5 Step 5—Implement the Course of Action

Effective implementation requires a firm grasp of project management principles. Depending on the type of action to be taken, implementation can include one or more combinations of the following elements:

- Planning
- Design and cost estimating
- Construction
- Startup and operation
- Monitoring and documentation

It is recommended that a project manager be assigned to oversee implementation of the water reuse project. Responsibilities of the project manager are:

- Focus on the stakeholders
- Create the project vision
- Build and maintain the project team
- Plan the project
- Manage resources
- Ensure safety and quality
- Implement the course of action

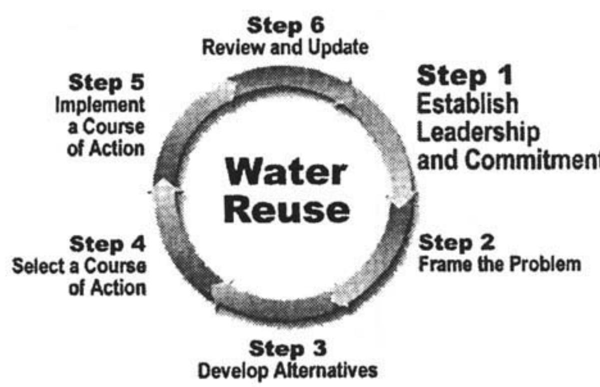
### 2.1.6 Step 6—Review and Update

A systematic approach to water reuse can result in an ongoing process, rather than a single project. The goals of water reuse, especially a goal such as zero discharge, are often too costly to achieve in one phase. Also, the economic drivers at any given time might not yet be strong enough to push water reuse efforts all the way to an ultimate, visionary goal. An iterative approach, utilizing a periodic management review process, allows progressive evaluation, justification, and implementation of incremental projects toward a larger goal.

An important part of this process is the use of a tracking system to measure progress toward the goals and objectives stated in earlier steps. Mechanisms and procedures have to be put in place to directly track and report metrics to stakeholders. Metrics could be water saved, chemical use reduction, disposal costs, or labor hours. In this feedback step, the question must be asked: "Did the improvements result in the desired outcome and provide sufficient returns?" Then endorsement for the value of the results reported must be gained to set the stage for repeating the cycle. This tracking process is crucial for carrying information into subsequent cycles of the process.

As mentioned before, parallels can be drawn to the continuous improvement cycle used in ISO Quality and Environmental Management standards. This approach uses a regular, documented review process that examines:

- Previous review results
- Performance of the current system versus original objectives and assumptions
- Changes in water reuse drivers or goals from Step 1, such as new economic incentives, changes in regulations, or new legislation
- Changes in the state or boundaries of the current system from Step 2
- Changes in available technology from Step 3
- New or changed stakeholder expectations




## 2.2 Step 1—Establish Leadership and Commitment

This effort starts with a "call to action." Some external or internal set of issues has prompted an interest in water reuse. Before diving into a solution, it is important to develop a game plan, rules, and a path forward. If the effort is to have momentum, it also must have clear leadership and support. The effort must start with understanding drivers, stakeholders, and the basic business case.

### 2.2.1 Issues and Drivers for Water Reuse

It is important to start by understanding why the organization should care about water reuse. The drivers leading an organization to consider a water reuse effort vary with each facility's environment and circumstances. Some drivers can motivate and some can impede the effort, depending on specific facility circumstances (Figure 2-1).

Industry in much of the United States historically has had the luxury of a cheap, dependable, and abundant supply of water, so that the economics for water reuse have not been compelling. However—depending on the type of industry, its location, and other specific circumstances—the need for considering water reuse is growing because of scarce supply. States such as California, New Mexico, Texas, and Arizona, which have arid local climates, have contended with limited water supply for years. As population and industry grows in these and other areas, a trend toward water conservation and reuse can be expected to develop.

Water reuse projects often are implemented in incremental and fragmented ways in response to a specific reason, such as meeting the goals of a new corporate resource conservation program. As implied in subsection 2.1.4, responding to a specific issue without considering its ramifications has often been the reason for failed attempts at water reuse. Water reuse is not as simple as it seems. It is affected by many different and potentially competing issues and drivers that create choices and shape the outcome of water reuse programs. A few of them are discussed here:

- **Product quality and potential tradeoffs with lower effluent discharge.** One example is the reuse of water washes

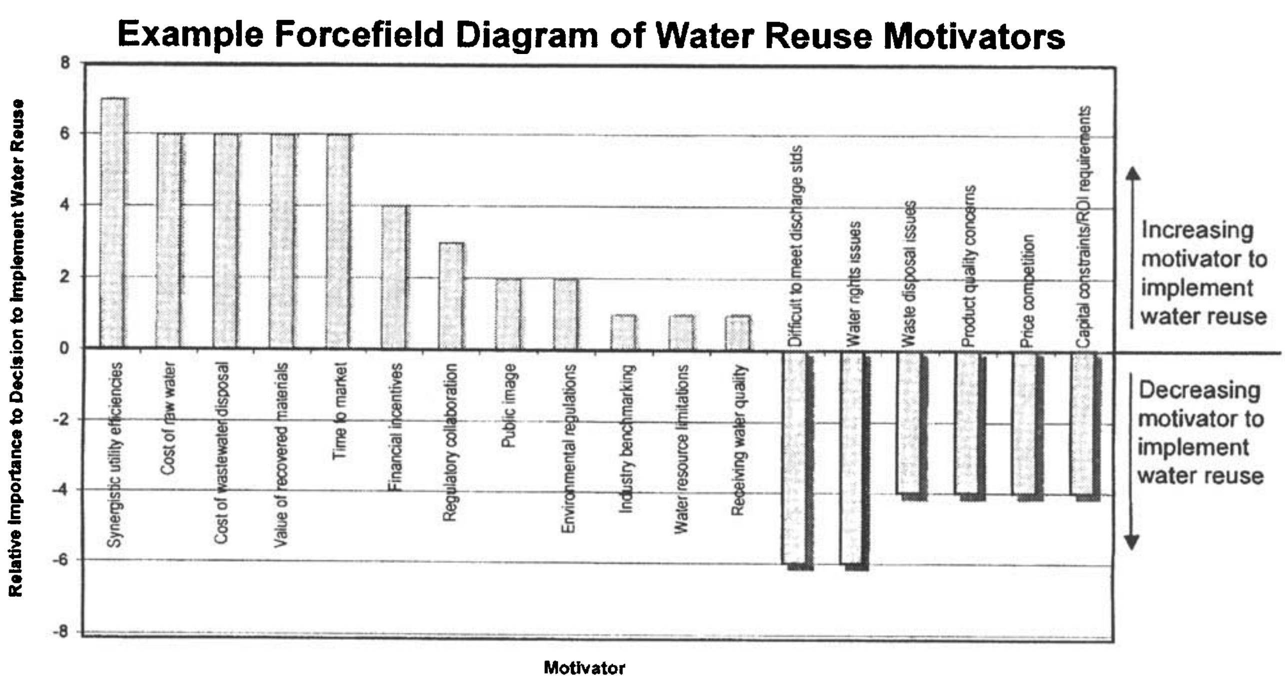



**FIGURE 2-1**
Water Reuse Motivators

or the counter current cascade of wash steps for washing a chemical compound. The change in washing and lack of attention to residuals can eventually deteriorate the quality of the substance being washed.

- **Scaling, corrosion, and potential buildup of deleterious substances.** These materials, though not problematic in the short run, can require careful inspection and periodic maintenance, which a plant may not expect or be prepared to perform. Water quality monitoring may be part of the ongoing operational requirements.
- **Energy conservation.** Though frequently overlooked, a thorough examination of the energy costs (pumping as well as heating) associated with treating water coming into a plant and water discharged from a plant might reveal significant savings if water at elevated temperatures is used throughout the plant. A case study in Section 4.3 provides a good example of such indirect savings that became the key significant driving force for water reuse.
- **Appropriative water rights.** If the facility is located in an area where appropriative water rights may be a concern, then water reuse—which would yield a reduction in the current use of water—might also mean potential forfeiture of the credits for water rights that might be needed for future expansion. This situation is not common, but in the future it could become an important issue in specific situations.
- **Comparative regulatory compliance.** If options exist, regulatory compliance costs should be compared when future costs for both end-of-pipe control compliance and voluntary water reuse represent additional capital and operating expenses above the current level. As shown in one case study, water reuse costs, when compared to costs for future end-of-pipe compliance, were found to be less severe—a benefit in favor of water reuse if a firm wants to trim future compliance costs.
- **Regulatory incentives versus disincentives.** The issues weighed in the evaluation would be costs of comparative regulatory compliance and appropriate water rights.
- **Competitive advantage.** Although difficult to measure, factors other than return on investment should be considered. For example, treated water from an adjacent facility or POTW (publicly owned treatment works) might be a source of water for a plant, and, conversely, treated water produced by the plant could have value to an adjacent facility. Both streams represent potential revenue or avoided costs, which should be considered in the cost evaluation if included in the boundary limits.
- **Public image.** Industrial water reuse can compete with other process improvement, waste treatment, or control programs that might be equally desirable, such as wetland treatment systems. The comparative costs plus public image benefits should be evaluated. Public image benefits from a water reuse program can fit into a larger strategy of corporate "greening" or "sustainability." These benefits can be significant in terms of customer acceptance for the company's products and services, but they are less tangible. The TCA framework (subsection 2.2.10, Appendix D) provides a way of quantifying and modeling intangible costs and benefits, such as customer acceptance and public image.

Following is a simplified discussion of the interrelationships among various issues. These issues and hypothetical examples are contextual and might not apply to all cases.

### 2.2.2 Regulatory Issues

Several regulations such as the Clean Water Act (CWA) and the Clean Air Act (CAA) regulate the use and discharge of water by industry. This section addresses regulatory issues related CWA and CAA only.

#### *Clean Water Act Issues*

The CWA establishes a national policy to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The Act provides the following salient statutory guidelines for existing point-source discharges (Corbitt, 1989):

- Elimination of pollutant discharge into navigable waters
- Establishment of set water quality standards to protect fish and wildlife and to provide for recreational use
- Regulation of toxic pollutant discharge to eliminate adverse environmental impacts
- Establishment of the technology necessary to eliminate the discharge of pollutants

The statute also imposes a more stringent and independent set of effluent limitations on new sources of water pollution.

The U.S. Environmental Protection Agency (EPA) enforces the CWA through a regulatory program called the National Pollutant Discharge Elimination System (NPDES). Through NPDES, the EPA grants and administers permits for point-source discharges to waterways, often through delegated authority to the states. NPDES permit standards vary regionally and are based on the environmental impacts of wastewater discharge into the receiving waters. Permits typically impose specific limits on measurable parameters of the discharge, for example, concentration and mass of contaminants, pH, flow, and temperature. An example of such a permit for a hypothetical petroleum refinery is provided in Table 2-3. It includes limits on biochemical oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), oil and grease, phenols, and other compounds or ions (Goldblatt et al., 1993). In recent years, many industrial facilities have been mandated to demonstrate, via bioassay toxicity testing, that their effluent does not have any adverse environmental impacts on freshwater and/or marine organisms such as amphipods (*Hyatella azteca* and *Rhepoxynius abronius*) and water fleas (*Daphnia magna*). As knowledge grows about the various environmental impacts, NPDES objectives can only be expected to become more stringent (McIntyre, 1993).

**TABLE 2-3**
*Typical Petroleum Refinery NPDES Permit Limits (Goldblatt et al., 1993)*

| | Discharge Limitations | |
|---|---|---|
| **Effluent Characteristics** | **mg/L[a]** | **lb/d** |
| Biological Oxygen Demand ($BOD_5$) | 15 | 21 |
| Total Suspended Solids (TSS) | 24 | 34 |
| Chemical Oxygen Demand (COD) | 150 | 213 |
| Oil and Grease | 10 | 14 |
| Phenols | 0.2 | 0.3 |
| Ammonia as N | 9 | 13 |
| Sulfides | 0.16 | 0.2 |
| Total Chromium | 0.16 | 0.2 |
| Hexavalent Chromium | 0.02 | 0.03 |
| Free Cyanide | Report | |
| Maximum Temperature | 115°F | |
| PH | 6-9 pH units | |

[a] Unless otherwise noted.

Compliance problems sometimes are created when a facility makes a sincere attempt to adhere to regulations but fails to consider the broader issues related to the regulation. Table 2-4 illustrates such an event, using a hypothetical facility with simple concentration-

TABLE 2-4

*Hypothetical Example of the Consequences of Water Reuse*

| Discharge Parameters | Before Water Reuse | After Water Reuse | Remarks |
|---|---|---|---|
| Effluent flow rate (gpm) | 200,000 | 50,000 | |
| Influent flow fate (gpm) | 220,000 | 55,000 | |
| Losses (gpm) | 20,000 | 5,000 | |
| Mass of contaminant discharged (kg/day) | 144,000 | 86,400 | |
| Reduction in waste load (%) | 0 | 40 | Achieved through pollution prevention |
| Reduction in influent water (%) | 0 | 75 | Achieved through resource conservation |
| Reduction in effluent water (%) | 0 | 75 | Achieved through resource conservation |
| TDS (mg/L) | 400 | 1,000[a] | Noncompliance of discharge standard |
| TSS (mg/L) | 100 | 200[a] | |
| Temperature (°F) | 50 | 60 | |

Note: NPDES discharge criteria are TDS = 700 mg/L, TSS = 250 mg/L, temperature = 45 to 55° F.

[a]Typically, concentrations increase nearly linearly in proportion to the fraction reused; however, allowances were made for approximately 40% reduction in mass of contaminants discharged through waste minimization and separation.

based NPDES discharge requirements for TDS and TSS.

In this case, the facility elects to reduce its raw water consumption and wastewater discharge by 75 percent by reusing wastewater as cooling tower or scrubber makeup. This change results in the water gaining a proportionally higher load of dissolved contaminants. Consequently, the effluent TDS far exceeded NPDES requirements.

With careful planning, the plant could have complied if it had reduced its consumption and discharge by only 50 percent. The processes or other factors, such as economics, that dictate the ratio of recycle (that is, sometimes requiring more than what is theoretically required to achieve compliance) might be constrained by a regulation or other factor. As this constraint is approached, other pollution prevention techniques applied upstream that reduce the contaminants in the water should be considered before reusing more of the water. By taking a systematic and holistic approach, the plant might still be able to implement water reuse projects that achieve the CWA's and its own objectives (resource conservation and pollution prevention), without resulting in noncompliance. The case studies provided in Section 4 provide evidence of the benefits of approaching water reuse projects through a systematic approach.

## *Clean Air Act Issues*

The 1990 Amendments to the CAA also affect how the process industries handle select chemicals in aqueous wastewater streams. In Title III of the CAA amendments, 174 source categories (in some cases, industry specific) with 188 specified chemicals known as hazardous air pollutants (HAPs) have been targeted for application of available control technologies. National Emission Standards for Hazardous Air Pollutants (NESHAPs) for all of the source categories were due to be promulgated before November 15, 2000, with implementation schedules extending several years after the promulgation of the standards. However, EPA still is in the process of finalizing NESHAPs for several of the source categories. The control provisions might also apply to gaseous emissions from certain wastewater streams. For instance, the NESHAPs for hazardous organic emissions from the synthetic organic chemical manufacturing industry, known as the HON rule, defines what the maximum achievable control technology (MACT) is for point source within that industry; in addition, the MACT specifically focuses on volatile organic compound (VOC) controls for air emissions from wastewater streams before discharge.

The regulation is intended to control VOC emissions from wastewater streams before they are treated or leave the site. The regulation does not affect all industry sectors now, but similar wastewater provisions and definitions of VOC MACT will soon be developed for other industries, including the petroleum and pharmaceutical industries. Thus, some facilities that are dealing with the CWA and capital expenditures for meeting discharge limits are likely to be affected by the CAA.

Though it is not explicitly a water reuse issue, the regulation might relate to reuse when, for example, a facility is considering capital spending to address wastewater MACT. A plant might wish to consider a recycle or reuse wastewater system within a process building to prevent volatile wastewater reaching a sewer or treatment plant.

To provide further information on VOC issues, CWRT has recently published a book, *Practical Solutions for Reducing Volatile Organic Compounds and Hazardous Air Pollutants* (CWRT, 2001). This book is an update of an earlier AIChE/CWRT publication that focused on commercially available "end-of-pipe" abatement equipment. The new book revisits the topic by considering the technological applicability and cost-effectiveness of "destructive" devices as well as recovery devices.

### 2.2.3 Resource Limitation Issues

Water is difficult to obtain in regions where industry is competing for a limited supply of water with various water users. Two independent studies conducted by the U.S. Bureau of Reclamation (USBR) Office of Water Research and Technology (OWRT), the U.S. Department of the Interior, and the U.S. EPA Industrial Environmental Research Laboratory concluded that the bulk of the chemical processing industry is located in water excess areas (that is, the eastern United States and the Gulf Coast) and therefore might not need to modify existing water use practices beyond what is required to meet environmental regulations (Turner, 1981; Rissmann et al., 1981).

A Water Resources Council (WRC) study indicated that although the quantity of water is sufficient to meet the requirements for all purposes, some regions, particularly in the southwest and midwest, have severe problems because of shortages resulting from inadequate distribution systems, ground water overdrafts, quality degradation of both surface and underground supplies, and institutional constraints (Ruggiero et al., 1981).

Water reuse programs provide the opportunity to alleviate such conditions by decreasing water demands. However, as water reuse decreases discharge volume, concentrations tend to increase, forcing additional treatment or changes in disposal techniques to achieve discharge standards. This presents an opportunity as well as a problem. The problem of forcing new treatment technology can be offset by the opportunity to work upstream in the plant processes to reduce contaminants in the water at their sources, which reduces the need for downstream or end-of-pipe treatment, and can save or recover valuable materials. Also, there are cases when a smaller waste stream of higher concentration is easier to treat than a large-volume, dilute stream.

In any case, the incremental costs involved in treating this stream of reduced volume and poorer quality might be justifiable because of the potential for offsetting raw water and regulatory compliance costs.

### 2.2.4 Economics

Even though all the issues discussed in previous subsections influence or motivate water reuse, the decision to reuse, particularly the extent of reuse, is dictated largely by economic feasibility and affordability. Treatment and discharge are often cheaper than reuse, but not always. Major factors determining economic feasibility include the following:

- Incremental cost of treated raw water
- Incremental cost of wastewater treatment
- Associated compliance costs

The cost of pumping and the distribution of raw and waste waters are typically included as part of the raw and wastewater costs.

### *Treated Raw Water*

Because water traditionally has been an abundant and freely available commodity, its true value has never been identified. Even in areas with limited water supply, the economic value of water is not reflected because prices are artificially controlled; that is, they are not allowed to reach free market value. Water pricing is usually governed by a group of agencies that set prices to protect revenues needed by large public (and in some cases private) investments in order to pay off long-term debts. Therefore, even though the cost of raw water is actually more expensive than the cost of reclaimed water, it is subsidized to the point that there is little incentive to reuse water (Yulke et al., 1981).

In spite of the pricing policies, the pressure of free market forces and local politics (especially in drought-affected regions) is evident from a historical review of raw water costs. According to biannual studies by Ernst & Young, Washington, D.C., since 1990 the unit price of water has risen between 10 and 12 percent every 2 years (Environmental Business Journal, 1994), almost 1.5 times that of the rate of inflation during the same period. In the near future, the price of raw water apparently will play an important role, if not the dominant one, in water reuse decision making processes.

### *Wastewater Treatment*

Wastewater treatment costs are driven primarily by discharge standards, which result from regulations based on the water quality of the receiving stream. They include toxicity-based limits. In addition to satisfying water-quality based requirements, the CWA requires the use of the best available technology (BAT) economically achievable. This requirement can lead to water quality that often equals or exceeds that of the water source and the receiving body, and it can incur exorbitant costs. Any new legislation emerging as part of the water reuse planning efforts should be closely examined.

Water reuse warrants examination, especially in the context of the additional treatment costs required to achieve a higher quality discharge. Figure 2-2 qualitatively illustrates the effects of incremental cost of wastewater reduction or treatment to achieve compliance. The example considers a hypothetical case of a facility built before the CWA that is in the process of examining the economic effects of the incremental treatment required to comply with the CWA (Goldblatt et al., 1993). The objectives of the treatment program are to reduce wastewater flows, maintain or improve wastewater quality (reduce total mass of pollutant discharge), and minimize the costs of treatment.

Point 1a in Figure 2-2 represents current operations. Point 2a represents cost reductions from optimization efforts, such as cascaded water reuse projects that require only operational changes, typically with minimal expense, although discharges might have higher concentrations (see decrease in water quality from 1b to 2b).

Point 3a (Figure 2-2) represents a step increase in wastewater treatment costs that might be attributable to capital projects that reduce both water consumption and wastewater generation. A substantial increase in water quality is achieved with marginal increase in costs (i.e.,

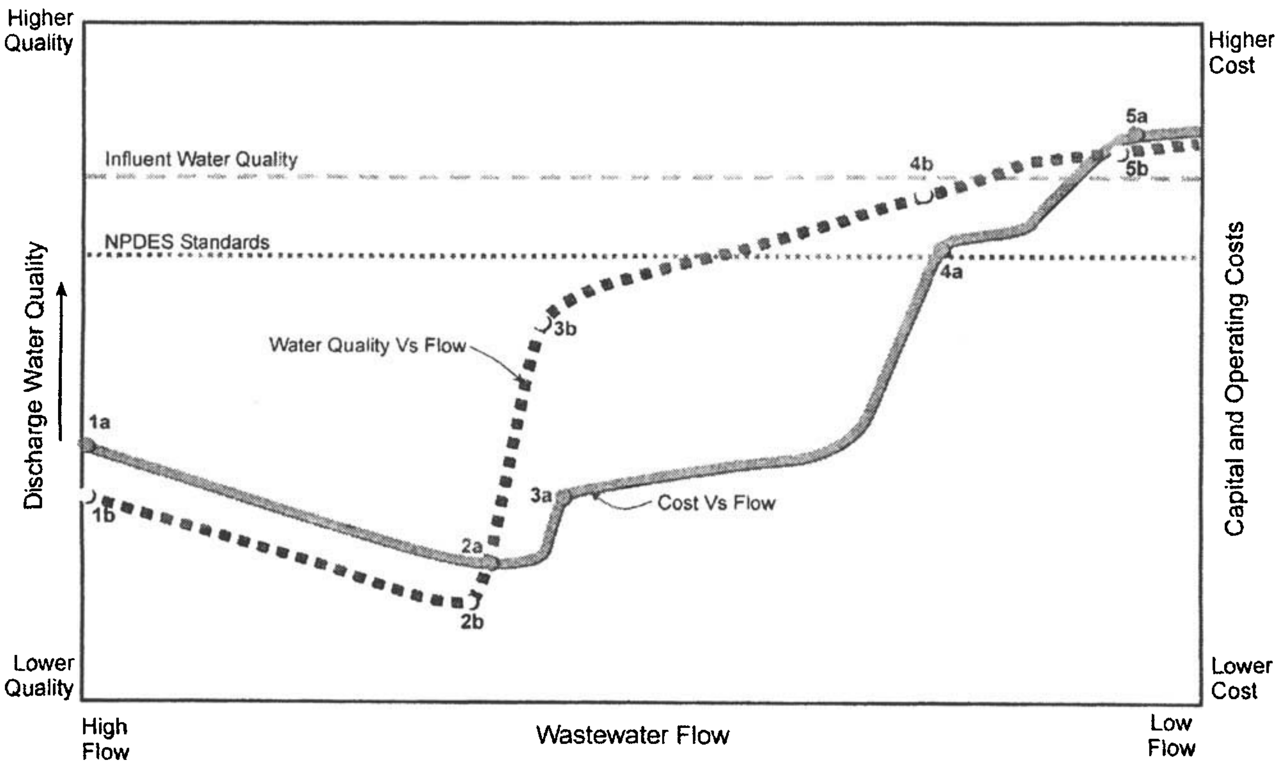



**FIGURE 2-2**
Water Reuse Impacts on Cost and Water Quality (Goldblatt et al., 1993)

water quality increases from 2b to 3b, while the associated costs increased marginally from 2a to 3a). Example projects include the following:

- Installation of facilities to allow segregation
- Reprocessing and reuse of process water
- Reuse of intermediate quality waste streams
- Installation of a sidestream softener to allow for higher recycle of cooling tower and blower blowdown

The transition from Point 3a to Point 4a (Figure 2-2) is a large-step increase in treatment costs attributable to installation of equipment such as electrodialysis units, brine concentrators, evaporation-crystallization systems, or ion-exchange units. The marginal improvement in wastewater quality from Point 3b to Point 4b thus requires a substantial increase in capital and operating costs.

Points 5a and 5b (Figure 2-2) represent the elimination of the last small amount of highly concentrated wastewater via crystallization operations.

This example illustrates that, although the incremental cost involved in achieving permit standards is steep, the disparity between the actual cost of compliance and that required to treat the water to match influent quality criteria might be small enough to motivate water reuse. This might not be relevant in other situations, but it is important in arid areas, particularly those dependent on brackish water sources needing extensive treatment before use. Also, these areas are likely to have stricter discharge standards. Not shown in Figure 2-2 are potential cost savings related to energy