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The development of a computer-based assessment tool for industrial water reuse

Waldo Alexander Margheim

To the Graduate Council:

I am submitting herewith a thesis written by Waldo Alexander Margheim entitled "The development of a computer-based assessment tool for industrial water reuse." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Richard J. Jendrucko, Major Professor

We have read this thesis and recommend its acceptance:

Robert Counce, Bruce Robinson

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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THE DEVELOPMENT OF A COMPUTER-BASED ASSESSMENT TOOL FOR INDUSTRIAL WATER REUSE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Waldo Alexander Margheim, III

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DEDICATION

I would like to dedicate this thesis to my parents, Waldo and Rose Margheim, who always told me, "Just do your best in whatever you do." Mom and dad, I did my best . . .

ACKNOWLEDGMENTS

I wish to thank Dr. Richard Jendrucko for everything that he has done for me the past two years and the opportunities that he has given me. His guidance and advice will always be appreciated. I also wish to thank Dr. Robert Counce and Dr. Bruce Robinson for serving on my thesis committee and being excellent professors that I have enjoyed learning from. Most of all, I wish to thank my wife, Kelly. Her love and support have helped make this possible.

ABSTRACT

A principal impediment to internal industrial water reuse is the lack of an orderly and timely process for the systematic evaluation of possible water reuse schemes and their comparative economic benefit. For this reason, an interactive computer-based evaluation tool was developed. The POWR (Potential Opportunities for Water Reuse) computer program performs a systematic evaluation of possible water reuse schemes for one or two water-utilizing processes within a facility with a minimum amount of user-supplied information. The Microsoft Visual Basic programming utility was used due to its ability to perform the mass balance calculations necessary to determine technical and economic feasibility in a user-friendly environment. An industrial application is presented to demonstrate the use and utility of the developed POWR program. To facilitate use of the program, a guidance manual that provides instructions and additional water reuse information and references was also developed. This product can be used as a design tool to quickly evaluate potential internal water reuse opportunities within industrial manufacturing facilities.

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I. INTRODUCTION AND BACKGROUND

Growing Need for Industrial Water Conservation

Water, as a basic human resource, is increasingly becoming scarce. Although there appears to be a large volume of water available, there is only a small percentage that is actually available for use due to problems with availability and quality. In 1995, approximately 400,000 million gallons per day (mgd) of water was withdrawn for use in the United States (Solley *et al.*, 1998). Of the 27,000 mgd that was withdrawn for industrial use, only approximately 1,000 mgd was reclaimed wastewater (Solley *et al.*, 1998). Increasing the amount of wastewater reuse for industrial and other purposes will reduce the stress that is currently being placed on fresh water supplies.

The most common form of water reuse is the use of reclaimed municipal wastewater to reduce the amount of fresh water used in various applications. The potential uses of reclaimed wastewater that have been practiced include irrigation, industrial uses, groundwater recharge and potable water supply augmentation (Fortner, 1995). The use of reclaimed municipal wastewater for non-potable uses such as irrigation and groundwater recharge is well established (Water Pollution Control Federation (WPCF), 1989). In California, where water reuse is becoming more popular and necessary due to limited water supplies, reclaimed municipal wastewater is being used for irrigation of public lands, golf courses and agricultural fields producing non-food crops (Parkinson and Basta, 1991). San Diego, California, is experiencing water supply problems to the extent that construction on a project to repurify sewage into drinking water could begin by February 2001 (Kravetz, 1998).

The ability to purify sewage effluent to the point at which it may be used as potable water is the highest form of water reclamation (Parkinson and Basta, 1991). The use of reclaimed water for potable water supply augmentation is currently being studied and discussed in many areas of

the world experiencing water shortages including Denver, Colorado. Denver's Potable Water Reuse Demonstration Project is being used to determine the viability and acceptance of treating municipal wastewater for potable use (Gorder and McNeill, 1992; Hamann *et al.*, 1992). A 1 mgd demonstration plant has been able to produce water that is as good as or better quality than the current drinking water supply. Therefore, the possibility of using municipal wastewater as drinking water is technologically feasible. The three main impediments to reusing water in this manner are the concern for human health relative to microbiological contaminants, the high cost of necessary treatment and the public perception of drinking water that was originally "sewer" water.

The importance of water conservation is commonly understood among industrial facility managers. Water reuse and recycling projects, however, are just beginning to become implemented in manufacturing facilities. While conservation typically implies preventing water from being wasted and minimizing the amount of water used, recycling water means to use water repeatedly for the same purpose. Reclaiming wastewater is the process of treating a wastewater prior to reuse. Reuse is the process of using water for more than one purpose (Breske, 1997; Jessen and Kemp, 1996; Wang and Smith, 1994; Asano and Tchobanoglous, 1991). Throughout this document, the term reuse will be used to encompass all forms of reuse including reclamation, reuse and recycling.

The WPCF (1983) estimated that by the year 2000, water used in manufacturing facilities could be used 17 times before final discharge resulting in a 62% decrease in industrial fresh water consumption. As we approach the year 2000, this prediction has not come to fruition. Several factors resulted in the falsehood of this prediction: geographical location of discharges and potential users; timing of wastewater discharges; changing requirements of potential users; and availability and cost of alternative supplies (WPCF, 1983). Fortner (1995) reported the findings of a water reuse assessment report by the Water Environment Research Foundation which

determined that additional guidelines and regulations along with the necessary research to provide the basis for these regulations is needed to enhance water reuse.

Although some industries are currently practicing water reuse, 99% of the total volume of industrial water reuse is for cooling tower operation (WPCF, 1983). Thus, very little actual process reuse is occurring in manufacturing facilities even though there are large amounts of wastewater available for treatment and reuse. Cooling tower makeup is the most popular industrial use of reclaimed wastewater because cooling towers generally consume the largest percentage of water in a facility and only require water of a modest quality (WPCF, 1983). In addition, this water does not generally come into contact with humans, therefore, the reuse of reclaimed municipal water is potentially less hazardous. Two examples of such water reuse are the Chevron Corporation's Richmond, California refinery and the country's largest nuclear power plant in Palo Verde, Arizona, which use reclaimed water from their local municipality to augment cooling tower water supplies (Parkinson and Basta, 1991).

Although the use of reclaimed municipal wastewater is becoming well established for many uses including some industrial applications, one potential form of water reuse that has been largely overlooked is internal industrial reuse of water in which process wastewater is reused within the facility instead of or prior to being discharged. Many industrial manufacturers generate substantial quantities of wastewater that potentially may be reused in the facility as process input water. However, due to the relatively low cost of water as a utility, it has been common practice to directly sewer both treated and untreated wastewater from manufacturing plants. In many cases, the internal reuse of water in manufacturing facilities may be economically attractive due to the resulting reduced costs of water consumption, treatment and discharge.

Reuse Incentives and Impediments

Water reuse is slowly becoming a necessity in many manufacturing facilities partially due to the rising costs of water disposal that have arisen due to increasingly stringent U.S. Environmental Protection Agency (EPA) and local environmental regulations and the increasing environmental awareness among consumers and producers (Klinker, 1996; Frayne, 1992; Parkinson and Basta, 1991). Many local municipalities are promulgating regulations requiring industrial water conservation measures and movement towards zero discharge facilities. The State of California enacted a Water Reclamation Law in 1992 that requires industrial users to use reclaimed water if it is available at reasonable costs (Enzweiler *et al.*, 1994). In addition, as the EPA promulgates more stringent federal regulations for industrial water discharge and disposal, treatment costs will continue to rise. Although the cost of water reuse systems may currently be relatively high, reducing the amount of water used and the amount of water discharged will result in lower present and future costs associated with treatment and disposal.

The following are potential benefits of water reuse: possibly improved process water quality, less feed water and wastewater discharge costs, lower industrial wastewater treatment costs and less demand on the municipal or fresh water supply and wastewater treatment systems (DeGenova and Shadman, 1997). In lieu of these benefits, water reuse is generally not considered in many manufacturing facilities for a number of reasons, including:

1. the relatively low cost of water and sewering charges,
2. the high cost of reuse systems engineering and design,
3. the perceived high purchase and operational cost of water reuse systems,
4. the lack of adequate knowledge concerning threshold process input purity requirements and the fear of process contamination, and
5. the lack of a systematic method of evaluating potential reuse schemes.

Internal industrial water reuse is relatively uncommon in some areas due to the general view that purchased water is available in unlimited amounts (unlike other utilities such as electricity) at low cost. The relatively low cost of fresh water and associated sewering charges appear to be the major barriers to the prospect of water reuse. However, as the supply quantities of utility-supplied water become more limited, costs for industrial customers will likely rise in a reflection of this trend (Frayne, 1992). Some municipalities are raising treatment fees and/or not allowing industrial plants to direct certain discharges to local municipal plants. Between the years of 1960 and 1995, the supply cost of municipal water in the U.S. has risen from $0.40 to $3.11 per thousand gallons and the rate of increase has also been growing in the last decade (Jessen and Kemp, 1996). Sewering charges for discharge to publicly owned treatment works (POTWs), which are generally determined by the flow rate and composition of the discharge (Mukhopadhyay, 1998), have increased similarly (Jessen and Kemp, 1996).

Many plants that use large amounts of water have been situated near a body of water so there is an adequate supply of inexpensive water. Many areas, such as the western United States, have limited quantities of available water and many other areas are beginning to experience pressure to reduce water use. Changes in climate and increases in population and industry have contributed to the reduced amounts of water available for consumer's use. Since many industries consume large quantities of water, industries are generally the first to be targeted for increasing utility costs and for water use reduction requirements.

Indeed, many water reuse systems require a large capital investment for engineering, design and system construction and operation. However, in some cases the only expense may be that due to the redirecting of the effluent of one process to the input of another process. This will relieve plant managers who are hindered from attempting certain process modifications due to a lack of capital funds. Most reuse projects result in substantial cost savings that may make a seemingly high cost system seem attractive if cost savings result in an acceptable payback period.

There is a fear that implementation of a water reuse project or the use of reclaimed water may cause process contamination that will result in production downtime. It may be inevitable that some downtime is required when implementing a reuse project, however, this downtime may have a modest cost when considered in terms of the overall economic benefit. Plant personnel are very sensitive to making production mistakes. Substantial money can be lost when a single product run is off-specification and the idea of "cleanliness is next to godliness" is very prominent in industry. Adequate bench-scale testing will eliminate most fears associated with process contamination due to the use of reclaimed water. There are several common potential uses for treated or untreated recycled water including first-stage rinsing in cleaning operations, cooling tower water makeup and general equipment clean-up for which water purity requirements are normally modest. In some cases, process wastewater may be reused directly without any treatment; in other instances wastewater can be reused if treated appropriately in-plant before reuse.

One of the keys to water reuse is being able to use "dirtier" water in a process than is currently being used. This leads to another issue that requires consideration, that of process influent water quality. Since many manufacturing plant processes utilize city tap water, it is often unknown whether "dirtier" water can be used in the process with negligible detrimental effects. Most city tap water has the same general characteristics due to the promulgation of national EPA drinking water regulations (Safe Drinking Water Act); however, facilities pay the same unit water price whether the water is purer than needed or if it needs to be treated prior to process use. For most processes, the necessary and sufficient quality of water needed to adequately perform a process function is not known. This is the case because this information was not initially needed (Schiller and Hackman, 1993). Finally, there is a lack of published information concerning the required influent quality for most industrial processes. This is the unfortunate reality of water reuse. Until a facility delegates the necessary time and manpower to conduct adequate site-

specific testing, the minimum purity requirements for most industrial processes will remain unknown.

In addition to the factors cited above, many facilities do not realize the relative purity level of the water that is treated onsite and then sewered or discharged. Onsite wastewater treatment demands high operating costs. In most facilities, the water is treated to a high level of purity only to be discharged to the local POTW for further treatment or to a stream for final discharge. This treated wastewater should be considered raw material water available for use inside the plant. In terms of some contaminants, the water that is discharged to the city POTW or local stream may be "cleaner" than the water that is purchased from the utility (Shacker and Kobylinski, 1994; Blake and Stuart, 1993). Also, discharge water quality regulations may be more stringent than some industrial process water quality requirements (Goodman and Porter, 1981). For example, the water used in the semiconductor manufacture industry is treated prior to use and the resulting process wastewater is, in many cases, purer than the water supply coming from the municipality (Morrow and Turner, 1999; DeGenova and Shadman, 1997).

Another principal impediment to industrial water reuse is the lack of availability of an orderly and timely "process" for the systematic evaluation of possible water reuse schemes and their comparative economic benefit. Particularly, there is a lack of data on the comparative costs of onsite wastewater purification systems which are needed in many cases to condition process wastewater for reuse.

Objectives of Study

The objective of this work was to provide guidance to assist water-utilizing manufacturing industries in evaluating multiple water reuse scenarios. An interactive computer program and a supplemental guidance manual provide this assistance. The software and manual have been developed to help plant engineers take the first step in implementing water reuse

projects in their facility. The tools have been designed to be simplistic and first-order for three reasons. First, the goal is to introduce water reuse concepts without overburdening complexity and begin the process of making water reuse a priority in facility management. Second, most water reuse projects must be evaluated on an individual plant basis. Most industrial processes are unique to each facility and, therefore, every water reuse project must be "field-tested" and evaluated onsite to ensure that no significant product quality or process performance degradations occur. This project was not designed to specify specific water reuse system configurations for every facility, rather, it was designed to systematically guide plant engineers in the process of selecting economically attractive water reuse projects. Third, the POWR program was developed to serve as a framework for the future development of more advanced models. The initial version of the program illustrates a fundamental method for the systematic evaluation and comparison of industrial water reuse opportunities.

In manufacturing, the most important consideration in any process or product modification is the production of profit. Effective water reuse schemes make economic sense for industrial facilities and it was the goal of this project to identify water reuse opportunities that are economically attractive and technologically achievable. Thus, this project will help provide that systematic method of developing and evaluating potential reuse schemes that appears to be lacking.

II. LITERATURE REVIEW

Historical Review of Water Use in Industry

All industrial facilities utilize water in some form or another. There are three main forms of water use in industry. First, the water used by an industry may be a component of the product produced, e.g., some of the water used in the beverage industry becomes part of the final product. Second, the water may be used as a process medium. For example, rinse tanks in an electroplating facility are used to wash excess plating chemicals from products. The water is essential for product production, but is not a component of the final product. Finally, water may be used in any number of ancillary and domestic functions. Examples of ancillary water functions include gas scrubbing, cooling, floor cleaning and lawn watering. Domestic functions include drinking water, employee showers and toilets. Cooling towers and boilers, both ancillary processes, are generally the most water intensive processes in a manufacturing facility.

Most water-utilizing processes occurring in industrial facilities use surface water or city-supplied water, while others may use groundwater as a fresh water source. Only small variations in city-supplied water quality should occur since all municipalities follow the same regulations when treating water to potable standards (Safe Drinking Water Act). Larger variations in quality will occur in industries that utilize other water sources. The water quality needed for the water to adequately perform in industrial water-utilizing processes varies widely as shown in Table 1. However, as mentioned, the quality of water used is essentially the same. As an example, water used in consumer products such as beverages and pharmaceuticals must be treated to a much higher quality than city-supplied water before it can be used in this function. Another example is in the semiconductor manufacturing industry in which iron, calcium, magnesium and organics must be removed prior to process use (Morrow and Turner, 1999). On the other hand, water of a

Table 1. Common industrial process water quality requirements.

Parameter	Pulp and paper: Mechanical pulping	Pulp and paper: Chemical, unbleached	Pulp and paper: Pulp & paper bleached	Chemical	Petrochemical and coal	Textiles: Sizing suspension	Textiles: Scouring bleach & dye	Cement
Copper					0.05	0.01		
Iron	0.3	1	0.1	0.1	1	0.3	0.1	2.5
Manganese	0.1	0.5	0.05	0.1		0.05	0.01	0.5
Calcium		20	20	68	75			
Magnesium		12	12	19	30			
Chloride	1,000	200	200	500	300			250
SO_4				100				250
SiO_2		50	50	50				35
Hardness		100	100	250	350	25	25	
Alkalinity				125				400
TDS				1,000	1,000	100	100	600
TSS		10	10	5	10	5	5	500
Color	30	30	10	20		5	5	
pH	6 - 10	6 - 10	6 - 10	6.2 – 8.3	6 - 9			6.5 – 8.5

Note: All units are in mg/L, except pH.

Source: WPCF. (1989) Water Reuse-Manual of Practice SM-3. 2nd ed. Water Pollution Control Federation, Alexandria, VA.

much lower quality than potable water may be used to irrigate lawns and wash down plant floors without any noticeable shortcomings.

In addition to the varying degrees of water quality used in industry, the quantity of water used in particular industries and for different industrial processes varies widely. Among industrial categories the primary metals industry, chemical industry and pulp and paper mills are among the largest water consumers (Betz Laboratories, 1980). Oil refineries typically use 6.5 to 9 mgd per 100,000 barrels of crude processed per day (Eble and Feathers, 1992a). The amount of water used in pulp and paper mills varies from 1 to 100 cubic meters per ton of paper produced (Lindholm and Jantunen, 1995) and typical semiconductor facilities use over 1 million gallons of ultrapure water per day (DeGenova and Shadman, 1997).

Historically, these large water-consuming industries have been located in areas close to bodies of water that may be used both as a source of fresh water and as a discharge medium for the wastewater resulting from production. Prior to the impetus of environmental regulations, there were no hesitations concerning the amount of water being used or the quality of the water being discharged. With a seemingly endless supply of water available for use, water conservation has not been a priority for many industries. In addition, with a large dilution pool, the quality of water discharged was neglected. With the promulgation of increasingly stringent environmental regulations over the past thirty years and the supply limitations of high quality water, the attitudes taken towards water use by industry have begun to change. The regulations that are requiring industries to reevaluate current water using practices have come about due to decreasing water supplies and the gradual degradation of the nation's water supplies due to industrial (and other) wastewater discharges. Industries are now required by law to control the amount and quality of wastewater discharged. The quantity of water used by industry is not regulated directly by the federal government (although it may be by local governments), but is being curtailed more by the increasing costs of municipal water.

Current Regulatory and Legal Issues

Current regulations concerning water use in industrial facilities typically focus on the treatment of wastewater discharges. The Clean Water Act of 1972 (amendments in 1977 and 1987) established the National Pollutant Discharge Elimination System (NPDES) permit program. The NPDES set standards for the quality of water that could be discharged into a receiving body of water from an industrial point source and applies to direct dischargers and POTWs. The permit effluent limitations are based on the type of industry and the specific state's water quality standards. Since the standards are industry specific, they are partially designed to prevent unfair competition among similar industries. The Safe Drinking Water Act, which was passed in 1974 with amendments in 1986, established drinking water standards. This act indirectly affects the quality of industrial discharges into streams which are also used for public water supplies (WPCF, 1983).

For industries that discharge water directly to municipal treatment plants (POTWs), in lieu of bodies of water, no federal regulations apply. However, the industrial facility may possibly have additional, more stringent discharge limits that are set and enforced specifically by each treatment facility depending on the treatment facility's capability. These municipal treatment plants also have federal and state mandated discharge limits that they must abide by. The treatment plants are also issued NPDES permits that set discharge limits based on the quality of the receiving stream. Therefore, the treatment plant must regulate their incoming stream sources so they can effectively treat all influent wastewater according to standards.

Realizing that standards regulating the treatment and disposal of wastes were not solving the root problem of waste generation, Congress enacted the Pollution Prevention Act in 1990. This act was the first piece of legislation focused on the generation rather than the treatment and disposal of wastes. In this act, a national policy was established that stated pollution should be prevented or reduced at the source whenever feasible. Pollution that is generated should be

recycled and reused and if this is not possible the wastes should be treated and disposed of in a favorable environmental manner (Freeman, 1995). Thus, industrial facilities are currently required to focus on reducing the generation of waste at the source and to recycle and reuse wastes that are inevitably generated if possible.

Although typically not identified as such, water is a raw material with a definite cost and wastewater is the resultant waste generated from the use of water. Thus, the ideas presented in the Pollution Prevention Act (1990) apply to water as well. Reducing the amount of water used, eliminating the generation of wastewater and reusing water where feasible is definitely desired over wastewater treatment and disposal as stated in the act.

To date there have been no U.S. federal regulations passed directly concerning the reuse of any form of wastewater for any purpose (EPA, 1992). Guidelines for municipal water reuse were established and published by the EPA in 1992 (EPA/625/R-92/004). However, the promulgation of actual standards are the responsibility of the states and not the federal government. As of 1992, only six states had adopted guidelines or regulations concerning industrial water reuse (EPA/625/R-92/004). These guidelines and standards have been issued to protect human health in situations that may arise when humans come into contact with municipal wastewater, which may contain toxic chemicals or pathogens, that is to be reused. The guidelines are based on the expected degree of human contact with the water to ensure that there is no risk of infection from pathogenic microorganisms (Sundberg *et al.*, 1991). The guidelines and regulations typically define treatment requirements for the wastewater based on the end use of the water. A summary of state municipal wastewater reuse regulations is given by Crook and Surampalli (1996).

Although there are state guidelines and regulations concerning the reuse of municipal wastewater, to date there have been no state or federal regulations that restrict the internal reuse of industrial wastewater within a plant (Knight and Sokol, 1991). In addition, NPDES and

similar wastewater standards are not affected if a plant is reusing wastewater, however, this should be researched thoroughly prior to initiating an internal water reuse project (Galbreath, 1994).

There may be industry-specific requirements concerning the reuse of wastewater in particular industries where the quality of water is a primary concern. For example, the food and kindred product industries may have reuse standards promulgated by the U. S. Department of Agriculture (USDA) and the Food and Drug Administration (FDA) to ensure the quality of consumer products. The quality of water needed for process use in some industries severely limits most water reuse opportunities. These industries mainly include those where product quality is directly related to the quality of the water used and include the pharmaceutical industry and the food and beverage industry where human health and safety are a concern and the electronics industry (Maughan and Mangel, 1999; Hamilton, 1996; Byers, 1995).

Methods of Water Pollution Prevention

Three approaches of waste management can be described in an evaluation of pollution prevention as discussed in the Pollution Prevention Act: source reduction, recycle/reuse and end-of-pipe treatment (El-Halwagi, 1997; Dyer and Taylor, 1994). El-Halwagi (1997) and Dyer and Taylor (1994) described similar hierarchical pyramids that establish a priority for the method of handling the waste produced within a process as shown in Figure 1. As seen from this figure, in accordance with the Pollution Prevention Act of 1990, the most desirable method of waste management is the reduction of waste at the generation point. The least preferable methods are treatment and disposal.

Over the years, many different types of water and wastewater treatment processes have been developed, tested and reported in the literature. Environmental regulations have tended to focus on this aspect of wastewater management. As time passes, an evolution is taking place in

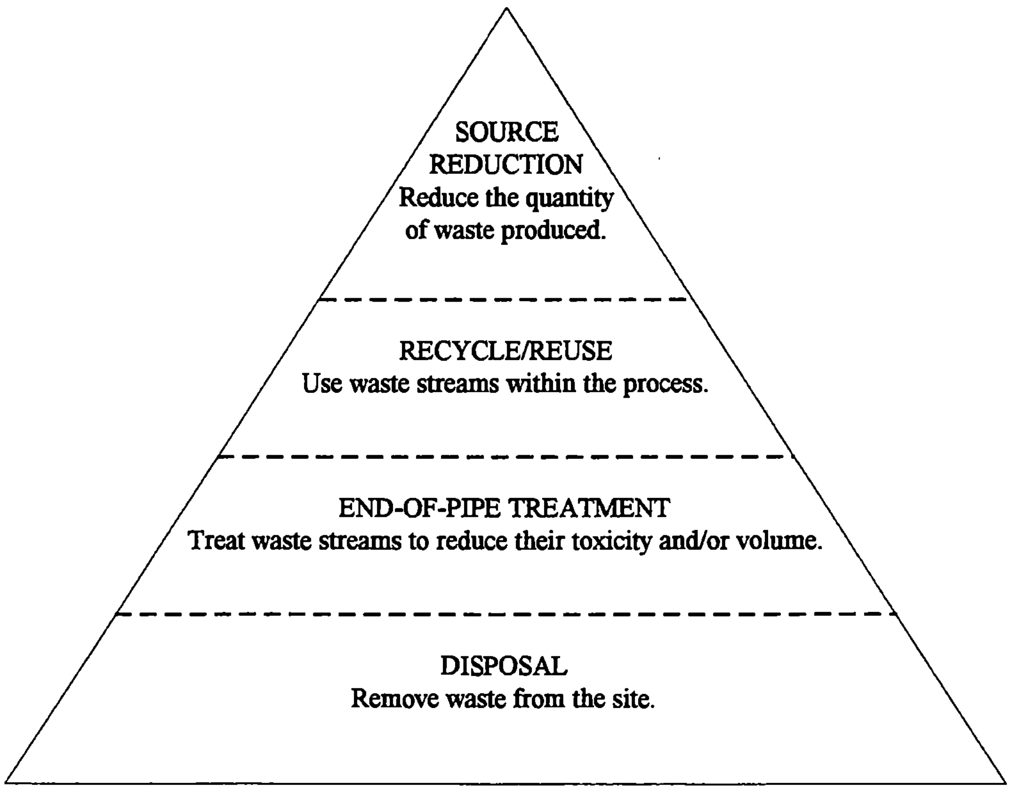


Figure 1. The hierarchical approach to pollution prevention.
Adapted from: El-Halwagi, M.M. (1997) Pollution Prevention Through Process Integration. Academic Press, San Diego, CA.
Dyer, J.A., and Taylor, W.C. (1994) Waste Management: A Balanced Approach. Paper presented at Twenty-Sixth Mid-Atlantic Industrial Waste Conference, Newark, DE.

which the ideas of recycling, reuse and source reduction are beginning to take hold and become more common than the less desirable end-of-pipe waste treatment and disposal. More industrial facilities are beginning to approach the top of the pollution prevention hierarchy pyramid in regards to their water and wastewater operations.

Water Use and Reuse Trends

As water purchase, treatment and discharge costs continue to rise, the industrial facilities interested in water reuse for economic benefits are also rising. The increasing environmental regulations are also pushing for new ways to reduce the strain on water supplies caused by industry. Trends in water use and reuse in the U.S. have been reported by the U.S. Bureau of the Census and the U.S. Geological Survey. The U.S. Bureau of the Census prepared reports called The Census of Water Use in Manufacturing every 5 years until 1982 when it was discontinued due to budget cuts (Taylor, 1998). The U.S. Geological Survey has been compiling national water use data every five years since 1950.

Current reports indicate total water withdrawals, including withdrawals for industrial use, have been decreasing steadily since 1980 (Solley *et al.*, 1998). These decreases in industrial water use may be due to a number of factors including a reduction in the number of industrial facilities utilizing water, utilization of less water-intensive processes and conservation measures, for example. Although it is possible that conservation may be a significant factor in this decrease since many industries have taken large strides in water conservation (Bowers and Maltby, 1996; Lindholm and Jantunen, 1995; Eble and Feathers, 1992a), it is unclear what the relative contribution of conservation is on this decrease based on the available information. Wastewater treatment effluent produced from POTWs in 1995 was 41,000 mgd, of which only approximately 2% was reclaimed and reused (Solley *et al.*, 1998). Although this is a 36% increase in reuse as compared to 1990 (Solley *et al.*, 1998), the amount reused for industrial purposes is still very

small. The reuse of industrial and municipal wastewater will continue to reduce the amount of water withdrawals and the amount of water being discharged.

Some industries have discovered the benefits of water conservation and reuse. A lot of process water reuse to the point of zero discharge for some facilities is currently being practiced in pulp and paper mills which use vast amounts of water in most industry processes (Silva *et al.*, 1998; Mierzejewski, 1997; Bowers and Maltby, 1996; Klinker, 1996; Patel, 1995; Culp *et al.*, 1992). The amount of water used per volume of paper product produced has also been decreasing (Bowers and Maltby, 1996; Lindholm and Jantunen, 1995). The amount of water used in oil refineries, another water-intensive industry, has also been decreasing. Refineries are currently using between 65 and 90 gallons of water per barrel of crude oil processed as compared to 2,000 gallons in 1975 (Eble and Feathers, 1992a).

With the recent interest in the global economy, international standards such as ISO 9000 and ISO 14000 are becoming more popular among industrial facilities. ISO 9000 is a quality control standard for international companies. ISO 14000 is an environmental management standard that is slowly becoming a necessity for global competition as ISO 9000 has become. It is possible that with the increased ISO 14000 certification more industries will look to water reuse.

Treatment Technologies Used for Water Reuse Applications

Numerous water treatment technologies may be used to increase the quality of wastewater streams to make them available for reuse. The choice of which treatment process(es) to use is dependent on many factors as shown in Table 2. Since the treatment technology chosen is usually based on which contaminants need to be removed, almost all water treatment technologies are potential candidates in water reuse situations because the contaminants of concern among industries are so varied. Some of the more common treatment technologies used

Table 2. Factors affecting the choice of treatment technologies.

1. Quality of the water to be treated.
2. Quality criteria for the specific reuse opportunity.
3. Effectiveness of desired contaminant removal.
4. Capital, operation and maintenance costs.
5. Reliability of system.
6. Complexity and degree of control of system.
7. Operation requirements.
8. Impact on product quality.
9. Secondary waste generation.
10. Regulatory compliance.
11. Proven performance in a similar application.

Sources: Rosain, R.M. (1993) Reusing Water in CPI Plants. *Chemical Engineering Progress*, **89**, 4, 28.
Odendaal, P.E. (1991) Wastewater Reclamation Technologies and Monitoring Techniques. *Water Science & Technology*, **24**, 9, 173.

in reuse applications include membrane separation, ion exchange, activated carbon, sedimentation and filtration (Freeman, 1995). Since a large number of treatment technologies are potentially applicable to water reuse situations and since summaries of these technologies are well documented in the literature (Zinkus *et al.*, 1998; Chang, 1996; Byers, *et al.*, 1995; Freeman, 1995; Blake and Stuart, 1993; Eble and Feathers, 1993; Eble and Feathers, 1992b; Odendaal, 1991), a discussion of these technologies would not be appropriate in this document.

New treatment methods are currently being developed that may find use in reuse applications. For example, the MYCELX™ process is a new chemical process capable of removing organic compounds from industrial wastewater (Vardeman, 1998). Currently, however, membrane separation technologies are becoming the most popular choice for reuse applications.

Characteristics of Membrane Technology

There are four major types of membrane separation technology in use today that may be used individually or in combination (series or parallel arrangements): microfiltration, ultrafiltration, nanofiltration and reverse osmosis. These four technologies operate by acting as a sieve to remove contaminants. Reverse osmosis and nanofiltration also utilize diffusion for solids removal. Pressure is applied across a semi-permeable membrane to force water through the membrane, with contaminants being retained. Thus, a treated water stream (permeate) and a smaller, highly concentrated waste stream (concentrate) result, as shown in Figure 2.

A number of characteristics make membrane processes desirable in water reuse applications as listed in Table 3. These membrane processes are growing in popularity in industrial settings and are becoming a very cost-effective approach to implementing water reuse projects in a variety of industries (Katselnik and Morcos, 1998; Lien, 1998; El-Halwagi, 1997; Vacker, 1997; Paulson *et al.*, 1996; Sinisgalli and McNutt, 1986). The ease with which these treatment processes may be added to existing facilities is a big factor for many facilities. The

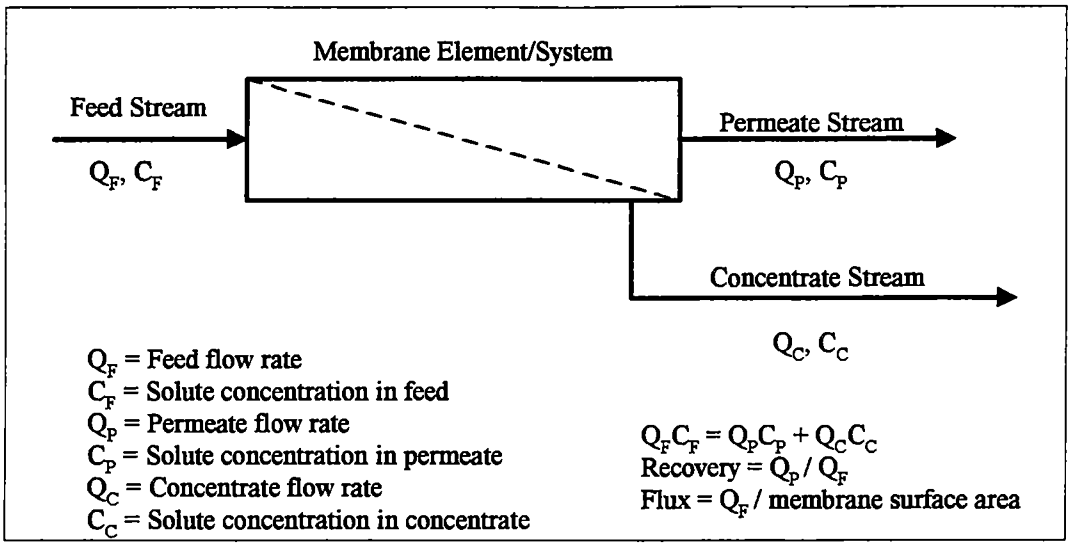


Figure 2. Operation diagram of membrane separation technology.
Adapted from: Cartwright, P.S. (1992) Industrial Wastewater Treatment with Membranes - A United States Perspective. *Water Science & Technology,* **25**, 10, 377.

Table 3. Desirable characteristics of membrane separation technologies.

1. Continuous operation.
2. Automatic and uninterrupted operation.
3. Low energy consumption and moderate cost.
4. No phase or temperature changes.
5. Compact, modular design with no significant size limitations.
6. Minimum moving parts with low maintenance requirements.
7. No effect on chemistry of contaminants present in water.
8. High contaminant selectivity.
9. Discrete membrane barrier to ensure physical separation of contaminants.
10. No chemical addition requirements.

Sources: Cartwright, P.S. (1991) Zero Discharge/Water Reuse – The Opportunities for Membrane Technologies in Pollution Control. *Desalination*, **83**, 1-3, 225.
El-Halwagi, M.M. (1997) Pollution Prevention Through Process Integration. Academic Press, San Diego, CA.

membrane processes may also be used to concentrate pollutants that may be reused or that have economic value.

The four major types of membrane separation technology are distinguished by their respective pore sizes as shown in Figure 3. This difference in pore size owes to the fact that different contaminants and slightly different recovery rates are seen in the four technologies. Reverse osmosis utilizes the smallest pore size, thus reverse osmosis is the most effective at removing contaminants. However, it costs more to operate the reverse osmosis system because a larger operating pressure is required. Some selected properties of the four membrane processes are shown in Table 4.

The proper membrane selected should provide the necessary contaminant removal at a minimum pressure and a maximum flux with minimal cost (Wolfe *et al.*, 1998). Numerous factors must be considered when choosing the proper membrane including "feedstream characteristics, potential uses and markets for recovered materials, desired effluent characteristics, concentrate characteristics and disposal options and space constraints" (Dietrich, 1995).

The increased application of reverse osmosis and other membranes is limited due to their cost and tendency for membrane fouling (Gerard *et al.*, 1998; Higginbotham and Paul, 1991). Advancements in reverse osmosis technology are making membrane systems even more affordable and useful, however. One advancement is the ultra-low pressure reverse osmosis membrane which has a high rejection rate but operates at low pressure (Nemeth, 1998). Thus, the energy consumption is significantly reduced due to the lower pressure but capital costs may also be reduced because the necessary pipes and pumps may be reduced. New low fouling membranes are also being developed (Gerard *et al.*, 1998). These membranes operate at low pressures, have high rejection rates and also have low fouling characteristics that extend the life of the membranes. Mukhopadhyay and Whipple (1997b) described a high efficiency reverse

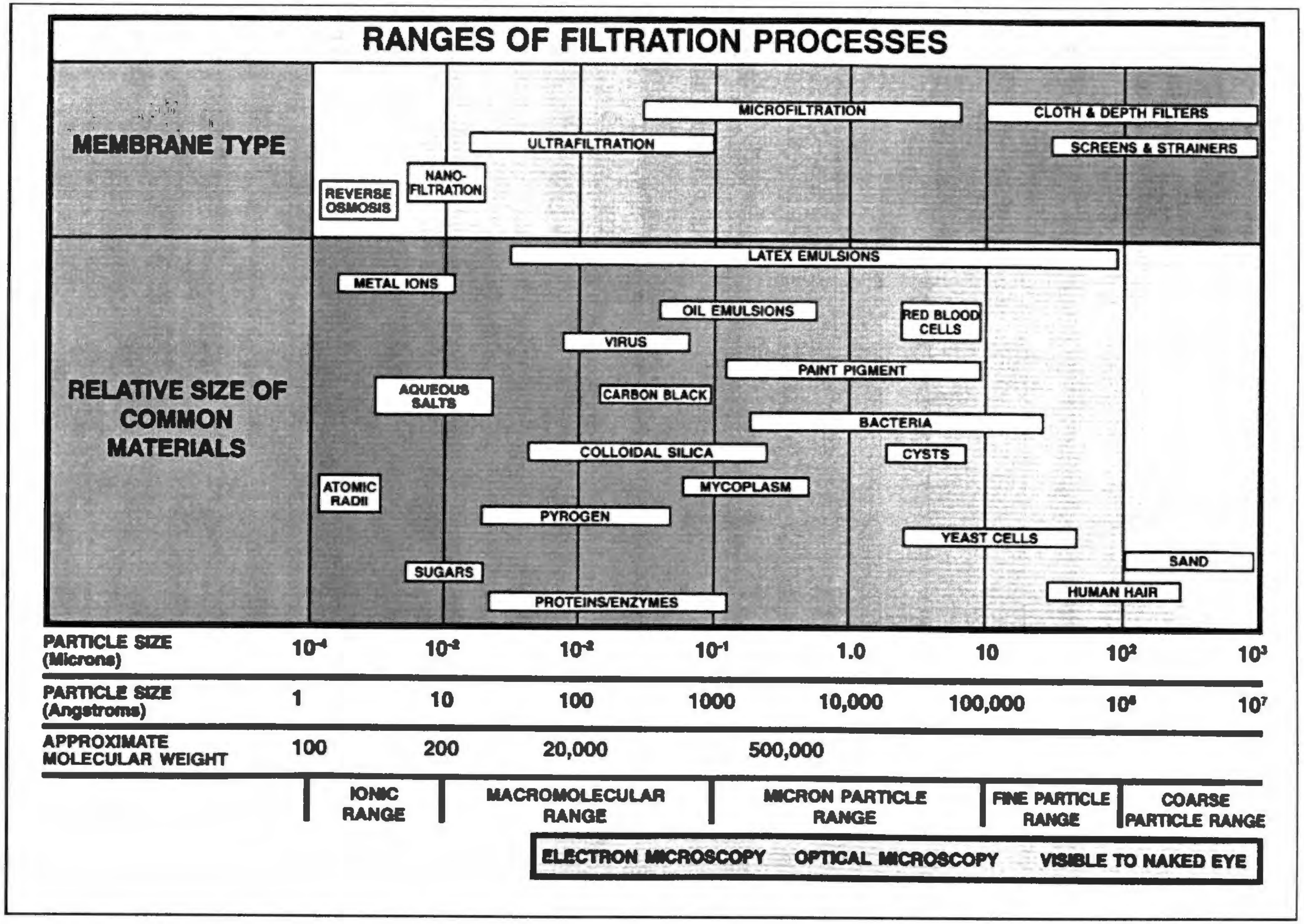


Figure 3. Water filtration spectrum.
Source: Culligan product literature.

Table 4. Selected properties of membrane separation technologies.

Membrane	Approx. pore size (microns)	General contaminants removed	Operating pressure (bars)
Microfiltration	0.1 – 1.0	Suspended solids, large colloids and bacteria	< 2
Ultrafiltration	0.003 – 0.1	Colloidal materials, large organics and viruses	1 – 10
Nanofiltration	< 0.001 – 0.003	Organics, dissolved salts	5 – 35
Reverse Osmosis	0.0005	Organics, dissolved salts	15 - 150

Sources: Lien, L. (1998) Using Membrane Technology to Minimize Wastewater. *Pollution Engineering*, **30**, 5, 44.
Henley, M. (1998) Will Nanofiltration Find Wider Acceptance in Industrial Water Applications? *Ultrapure Water*, **15**, 3, 13.
Elias, B., and Van Cleef, J. (1998) High-Shear Membrane Process and Wastewater. *Chemical Engineering*, **105**, 10, 94.

osmosis system capable of high contaminant rejection, high recovery rate and reduced fouling with reduced costs.

Proper pretreatment prior to membrane treatment is typically necessary to prevent membrane scaling, fouling and degradation (Dudley and Darton, 1997; Kucera, 1997). Typical scalants include calcium carbonate, calcium sulfate and reactive silica while bacteria, aluminum, iron and silica have the potential to foul membranes (Paul, 1999; Kucera, 1997). Various pretreatment methods and proper monitoring will maximize membrane life and minimize operating costs (Kucera, 1997).

III. RATIONALE

Summary of Need for a Logical Systematic Framework to Make Water Reuse Decisions

A systematic approach to water reuse projects has been discussed many times in the literature, with most of the approaches being very similar (Hamilton, 1996; Byers, 1995; Galbreath, 1994; Keary, 1993). Table 5 lists the generalized steps that should be followed in the implementation of a water reuse project.

The first step in the process is for the facility to set goals and objectives concerning the possible implementation of a water reuse project (Byers, 1995). Adequate background research should be conducted by consulting appropriate technical journals, trade associations, industry experts and industrial colleagues (Hamilton, 1996). Historical information such as prior attempts at water reuse in the facility should also be researched and documented to prevent renewed attempts at past failures. Depending on the prior knowledge of the plant personnel delegated for this authority, this background research process may be time intensive. Establishing goals will enable the facility to focus their efforts and determine the effectiveness and viability of potential reuse scenarios. Common goals that may be established include reducing the amount of fresh water used, reducing the amount of wastewater discharged or lowering the concentration of a particular contaminant in the discharge stream.

The next step is to properly collect and analyze plant data describing the current operating situation. A water use audit should be performed in the plant to enable the development of a plant-wide water balance (Terrell and Holmes, 1994; Blake and Stuart, 1993; Keary, 1993; Frayne, 1992). Keary (1993) determined that the following information was necessary to adequately develop a water balance. The quality and quantity of all water streams entering the plant should first be determined. Next, all processes that utilize water in the facility should be studied to determine the pattern of water use and the quality and quantity of process

Table 5. Steps in a water reuse project.

1. Collect background data and set goals.
2. Gather pertinent information.
3. Identify reuse opportunities.
4. Implement selected project(s).
5. Monitor and continuously improve.

influent and effluent. The process water purity requirements should also be determined. Often, process water purity requirements are over-prescribed. Reconsidering actual threshold contaminant levels may enhance the viability of water reuse schemes when potential reuse schemes are later considered. Finally, the quality and quantity of wastewater leaving the facility should be characterized. Additional information including current water and wastewater treatment capabilities and costs, plant layout drawings and piping drawings should also be included in the water balance summary (Hamilton, 1996; Rosain, 1993).

It has been pointed out that the establishment of a computerized database may simplify the process of developing the plant water and wastewater flow and mass balances (Rosain, 1993). Compiling this information in a database allows for easy accessibility and quick updating as needed.

Water cost information should also be gathered during this step. The cost of raw water purchases, wastewater discharge costs and water and wastewater pretreatment costs are needed to perform comprehensive economic evaluations of proposed reuse projects (Galbreath, 1994). Site-specific economic factors such as the payback period required for capital project justification may be used to determine the economic feasibility of water reuse projects.

The third step is to identify potential reuse opportunities based on the information previously gathered. In this step potential water uses are matched with available effluents. This step generally requires substantial brainstorming owing to the uniqueness of plant processes, but may be simplified by categorizing each potential water stream according to a specific contaminant of concern (Byers, 1995). The categorization of each stream in terms of general water quality makes the process of matching waste streams with potential process inputs simpler and less time consuming.

When determining potential opportunities, the highest quality wastewater should be matched with those processes requiring the highest quality makeup (Hamilton, 1996). An

effluent can only be used as an influent stream if the level of contaminants is less than the maximum allowable levels for that process (Eble and Feathers, 1992a). Once a potential reuse opportunity has been developed, it must be studied in more detail to consider specific flow rate and quality requirements and physical and piping proximity and constraints (Hamilton, 1996). Water quality may be upgraded with the utilization of treatment processes, blending wastewater with fresh water or the mixing or separating of discrete wastewater streams. These methods will provide additional reuse opportunities. It should be noted that simple water reuse schemes may be more effective than complex schemes due to the control and maintenance required of larger, more elaborate reuse systems (Hamilton, 1996).

Once multiple reuse opportunities have been developed, the proposed schemes should be prioritized based on criteria specified by plant management. This leads to the fourth step in the process: implementation of the reuse project. The commitment and cooperation of employees from management down to entry-level is required to make a water reuse project a success (Hamilton, 1996; Galbreath, 1994).

The final step in the process should be monitoring and continuous improvement. Proper monitoring of the new water reuse scheme will allow for proper evaluation and control of the new setup. The information gathered from monitoring can be used to determine if the original goals and objectives of the project were met. In addition, new goals may be established to improve upon the initial reuse design. It will be necessary to provide upgrades and improvements to the system due to the new dependencies that are created within the plant after the construction of a water reuse project (Hamilton, 1996). A process upset that causes changes in the associated water quality or quantity will be transmitted through the water reuse scheme, thus possibly affecting several processes rather than one.

Need to Reduce Time to Compare Numerous Alternatives

A water balance containing at least the minimum water quality and quantity influent and effluent values, is indeed a requirement before a plant-wide comprehensive water reuse plan may be studied and developed. The time requirement needed to gather water balance data and to evaluate potential reuse opportunities once the water balance data has been collected may be quite substantial in a typical manufacturing environment. The lack of available time to research and develop these process changes appears to be a major impediment to the implementation of pollution prevention process enhancements such as water reuse projects. It is believed that the development of a logical framework that reduces the amount of time required to research and gather water reuse information would substantially facilitate the implementation of water reuse.

This third step, in which potential reuse opportunities are identified, appears to be the most difficult step in the water reuse project decision-making process. Although many authors have briefly discussed this step, an actual systematic way of determining actual water reuse schemes has not been presented. Actual water reuse project implementation in manufacturing facilities has occurred somewhat haphazardly in the past based on personal biases. The elimination of the tedious "manual" analysis of matching effluent streams with potential users and replacing it with a computer program that analyzes process influents and effluents quickly will also allow more facilities to consider water reuse improvements. Thus, reducing the amount of data required for well-founded water reuse decision-making and providing a rapid, systematic method of determining and evaluating multiple water reuse scenarios would facilitate the implementation of industrial water reuse.

Alternatives to an Interactive Computer-Based Model

Several mathematical models were created in the 1970's and early 1980's to determine optimum water reuse strategies for a geographic region of water users and suppliers (Schwartz

and Mays, 1983; Ocanas and Mays, 1981a; Ocanas and Mays, 1981b; Pingry and Shaftel, 1979; Bishop and Narayanan, 1977; Mulvihill and Dracup, 1974; Bishop and Hendricks, 1971; Bishop *et al.*, 1971). Most of the earlier models considered only water quantity or water quality in a given analysis, however, the model by Schwartz and Mays (1983) considered both water quality and quantity simultaneously. In addition, this is the only model that considered forms of water treatment to improve purity levels and associated cost parameters. These models were developed to be used for a region of water users rather than a single water using facility. For example, in a particular region (San Antonio, Texas) the following components were analyzed in the Schwartz and Mays (1983) model: fresh water sources, water and wastewater treatment plants, primary and secondary water users and sinks.

Smith *et al.* (1979) and Shelton *et al.* (1979) described a computer model used to determine the technical and economical feasibility of water reuse on Army posts. The decision-making model consists of three phases, or tiers. The first tier consists of a questionnaire designed to assess the potential for water reuse projects on the installation. The second tier is a step-by-step procedure which uses published information detailing influent quality requirements and effluent quality of various Army post activities to design water reuse schemes. The final phase is used to determine the most effective water reuse schemes for the installation by comparing the estimated implementation costs of each of the reuse schemes. Various pieces of information are needed to run the model including the influent and effluent quality and quantity of water used in the processes, water quality changes that occur across the processes and cost data for water purchases and wastewater treatment and disposal. The model was to be used as a decision-making tool with additional engineering and design following the results obtained from the computer analysis (Shelton *et al.*, 1979).

Takama *et al.* (1980) developed a method of optimizing water allocation in a petroleum refinery. This method takes into account all water-using and wastewater-treating systems in the

refinery and all possible water reuse opportunities available between these systems. The water reuse schemes determined from this method are optimized to minimize fresh water purchase costs and wastewater treatment costs. The method constraints are that the influent stream to each process must meet the quality requirements of that process and the effluents should meet discharge regulations.

El-Halwagi and Manousiouthakis (1989) discussed the mass exchange that occurred between rich and lean process streams. Wang and Smith (1994) used this idea and applied it to water minimization by considering a water-utilizing process as a mass transfer unit and considering the exchange of contaminants from a process stream to a water stream as a contaminant mass transfer. Wang and Smith (1994) and Petela *et al.* (1994) developed this conceptual approach to minimize the amount of water used on an industrial site. By using pinch analysis (Linnhoff and Hindmarsh, 1983) based on the influent and effluent contaminant concentration and associated mass transfer of each process stream, the amount of fresh water used and wastewater generated is minimized. The water reuse schemes determined by this method are often very complex and must be simplified by using a secondary method. This secondary method reduces the complexity of the scheme while achieving the optimization target by allowing only one source of water for each water-utilizing process.

Multiple contaminants may also be addressed in the analysis developed by Wang and Smith (1994). Water becomes contaminated by the mass transfer of contaminant(s) from the process to the water. This mass transfer is assumed to be a linear function of the contaminant concentration. Thus, since the process is considered to be a mass transfer unit, different influent flow rates and contaminant concentrations can be possible mass conservation solutions. Although this analysis has been successfully tested on industrial case subjects (Smith *et al.*, 1994), many industrial processes cannot be described by this mass transfer assumption due to the fact that some processes rely on the volume of water that is used (Hamilton and Dowson, 1994).

Thus, instead of fixing the maximum influent and effluent contaminant concentrations, the volume of water required for process use must be used in the analysis (Hamilton and Dowson, 1994).

The mass transfer problem has since been addressed and the water pinch analysis previously developed has thus been improved by Wang and Smith (1995). Other problems addressed included those processes that have a fixed flow rate requirement, processes in which there is a fixed flow rate that reflects an inevitable loss (e.g., evaporation) and the case in which multiple sources of fresh water which have different qualities are available for use. Kuo and Smith (1998) developed a conceptual procedure based on the previous work of Wang and Smith (1994, 1995) in which the water-utilizing processes, regeneration systems and effluent water treatment systems are all accounted for and considered concurrently.

Dhole *et al.* (1996) built upon the above work and developed a new approach trademarked by Linnhoff March called WaterPinch™. Linnhoff March has invested over $1 million in the WaterPinch™ project and the computer program should be ready for commercial release in 1999 (Eastwood, Tainsh and Fien, 1998). Eastwood, Tainsh and Fien (1998) defined WaterPinch™ as "a systematic technique for analyzing water networks and reducing water costs for processes using advanced algorithms to identify and optimize the best water reuse, regeneration and effluent treatment opportunities." This approach involves the pinch graphical analysis along with a mathematical technique designed to complement and improve upon the graphical pinch analysis. Geographical constraints and varying water and wastewater treatment costs can be considered. WaterPinch™ has been used numerous times and has resulted in an average reduction in fresh water consumption of 15-40% and an average reduction in wastewater generation of 20-50% (Eastwood, Tainsh and Fien, 1998).

Numerous other computerized tools have been utilized for water reuse applications. A computer model was used at the McClennan Air Force Base in California to evaluate alternate

reuse schemes and to help determine which scheme to pursue (Schmidt *et al.*, 1979). Hayward-Browne *et al.* (1996) discuss a water reuse project at a stainless steel manufacturing plant from initial plant water audit to reuse project implementation. Once the audit was performed, numerous proposed reuse scenarios were determined. Then a computer model was employed to evaluate each of the reuse options by consideration of the contaminant concentrations, water treatment performance and project economics. The computer modeling approach allowed technical and economic evaluations of each proposed reuse scheme, however, the determination of potential reuse opportunities was still required to be done manually.

Some engineering consulting firms have developed computer programs to assist their consultant engineers in water reuse projects. For example, CH2M Hill has developed a program that assists in designing zero-discharge systems (Parkinson and Basta, 1991). These computer programs are generally copyrighted material of the particular company and cannot be used by manufacturing facilities without hiring the engineering firm for consultation purposes. Therefore, additional costs will be incurred by the facility seeking to incorporate water reuse in their facility.

Other computer programs have been developed for use in the water industry (WPCF, 1983; Treweek *et al.*, 1979). CHEMTRT is used to calculate the effluent water quality produced from various treatment technologies (WPCF, 1983). The precipitation of certain contaminants, complexation of ions and other chemical reactions can be modeled by the CHEMTRT program. Treweek *et al.* (1979) described a similar computer model that calculates the precipitation, complexation and solubilities of various water constituents. REUSE can be used to determine and estimate the type, size and cost of treatment technologies required to produce an acceptable effluent (WPCF, 1983). Other software has been developed to project the performance of membrane separation technologies in various applications (Truby, 1999).

The mathematical models and pinch analysis methods for the determination of water reuse opportunities appear to be too difficult for practical, time-efficient use in a variety of

manufacturing settings, although the computerized version of water pinch analysis may be reasonably user-friendly and less time-intensive. Water pinch analysis appears to be best suited for new facilities rather than facilities that are already in operation due to the entire site water balance approach required. The other developed computer programs do not necessarily develop and evaluate water reuse schemes simultaneously.

Need for the Development of a Computer-Based Model with a Guidance Manual

The experience of the University of Tennessee Industrial Assessment Center (UTIAC) reveals that most plant engineers who are responsible for projects, such as those that may involve water reuse, often do not have adequate resources (manpower, money and/or time) to properly focus on, study and implement projects of this nature. Without enough time to properly evaluate opportunities, cost benefits of such projects are not realized and reuse projects are not considered (Terrell and Holmes, 1994). Dr. Robert Stone (1999), Principal Engineer at the Federal-Mogul Corporation, a manufacturer of automotive bearings in Blacksburg, Virginia, served recently by the UTIAC, reinforced this statement. He stated that any product such as a computer program that will reduce the amount of time and money necessary to research potential capital projects would be of great value to people in his position. Dr. Stone also mentioned that providing a way of disseminating current technological information in a concise format would also be helpful. Additional concerns related to the lack of widespread membrane technology use for industrial purposes were expressed by Cartwright (1992), "lack of emphasis on recycling/recovery to date, insufficient understanding of the technologies, erroneous perceptions of process advantages, fear of risk-taking, lack of knowledge of new developments, insufficient publicity on successful applications and requirements for thorough on-site testing." Since the time and knowledge needed for the implementation of water reuse projects appears to be lacking in many industrial

settings, it appears that a product or methodology which will reduce the time requirement and increase the knowledge base needed to implement water reuse will be of significant importance.

A computer program has been designed for this project to be used to aid in simplifying potentially complex water reuse analyses. The program was designed to require a minimal set of essential input data from the user. Using input purity requirements and effluent water quality as input data, the program may be used for two purposes. First, it may be used to help identify potential reuse opportunities. Secondly, it may be used to track the concentration of a critical contaminant in a potential water reuse situation. The methodology used in the POWR program was computerized to make the methodology more reliable and much less time consuming. In addition, the program utilizes a simple, easy to use graphical interface within the popular Microsoft Windows environment.

A guidance manual, which accompanies the POWR program, was developed primarily as an instruction manual for the program and is presented in Appendix I. The guidance manual also contains information designed to educate the user. Common reuse schemes and information concerning the specific classes of contaminants that may present problems in certain reuse situations is presented. Basic water reuse concepts are presented and membrane separation technologies are explained in detail. Plant engineers tend to give attention to the quickly changing treatment technology field on a need-to-know basis. The brief explanation of the treatment technologies and applications in the guidance manual are designed to be useful in this regard. A selected listing of treatment technology vendors is also included in the guidance manual.

The software and guidance manual was developed to be used hand-in-hand not only as a functional tool but also as an educational tool. An increased knowledge and level of confidence in this area will likely result in less reluctance in considering and possibly installing water reuse systems. The program rapidly calculates savings and costs associated with several water

recycling and reuse options and will speed up the process of systematically considering alternative recycling schemes that are technologically achievable and economically attractive.

Anticipated Program Users

The computational program developed in this effort was intended to be used by manufacturing facility plant engineers, industrial consultants and industrial assessment teams. The ideal users of the program will be plant engineers who are in a position to recommend, develop and authorize water reuse projects. The program appears to be an ideal tool for a program similar to the UTIAC in which first-order waste minimization recommendations are developed for industrial manufacturers based on an in-plant industrial assessment. These consultants can gather the necessary information from a facility and utilize the POWR program to determine if any potential reuse opportunities exist at the facility. Once this information is reported to the facility management, the facility manager will have the information needed to make the decision whether or not to consume additional resources in a water reuse project.

Hierarchy of Water Use and Reuse

The basis for the developed POWR model is a conceptual influent and effluent pyramid model. This conceptual model is based on the concept of cascading water use in which wastewater is used as input for processes that require progressively lower water quality (Terrell and Holmes, 1994; Martin and Miller, 1986). Industrial water-using processes can often function adequately with water with a range of contaminant concentrations. The most common approach is to use fresh water in a parallel fashion, i.e., the same quality of utility-supplied water is used for all process inputs except those requiring an unusual level of purity, e.g., pharmaceutical products. However, most processes can be operated adequately with water of lesser quality than the "drinking water" standard that is typically utilized for utility-supplied water (Terrell and Holmes,

1994). Since the actual process contaminant threshold levels usually vary, it is logical that water can more effectively be utilized in a series, or cascading, fashion rather than in a parallel fashion. Initial fresh water may first be used in a process requiring very clean water and the effluent wastewater from this process may then be used as influent for a process that can utilize less pure water.

Figure 4 illustrates the basis for the model development. The pyramid represents processes using input water and generating wastewater. This may represent the overall quality of the water or the level of a particular contaminant. As the pyramid widens, the number and concentration of contaminants increases. Thus, the top of the pyramid represents relatively low volume flows of high quality water while the bottom of the pyramid represents low quality water. Arrows entering the left side of the pyramid represent the flow of water into a process while arrows exiting the right side represent the flow of wastewater from a process. The width of the arrow can be used to show the relative flow rate of water into and out of a process. Using Figure 4 as an example, process A requires high purity water for adequate operation. The process consumes all of the influent water (less evaporative, leak and spill losses, if any) and possibly a smaller volume of wastewater at a lower quality exits the process.

Figure 5 shows a hypothetical example of the water reuse pyramid for a test facility. The facility uses water for four different processes. A medium volume of high quality water is used for boiler makeup. A medium volume of medium to high quality water is used for the manufacturing process while a large volume of medium to low quality water is need for cooling tower makeup. Finally, a small volume of low quality water is used for plant floor cleaning. Again, progressively moving down the pyramid the quality of water needed for adequate operation of each process is reduced.

As shown in Figure 5, the quality of the water exiting the four processes is of lower quality than the input streams with a total volume less than the input total. Typically, water

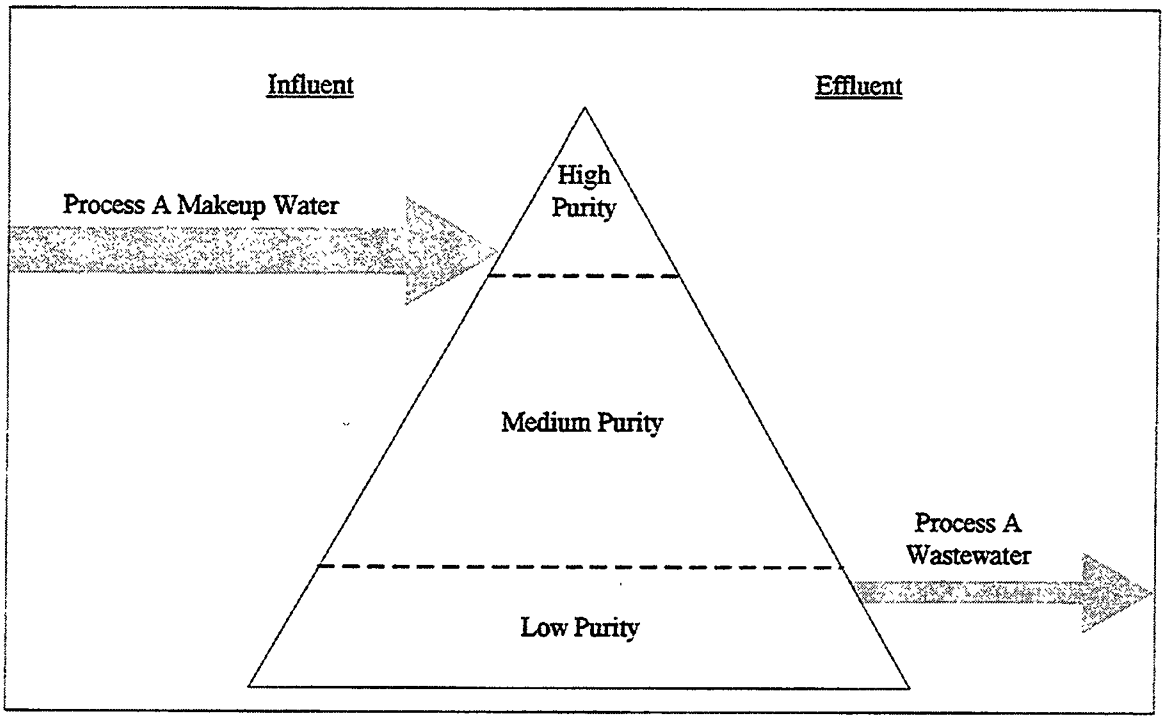


Figure 4. Water reuse hierarchy pyramid.

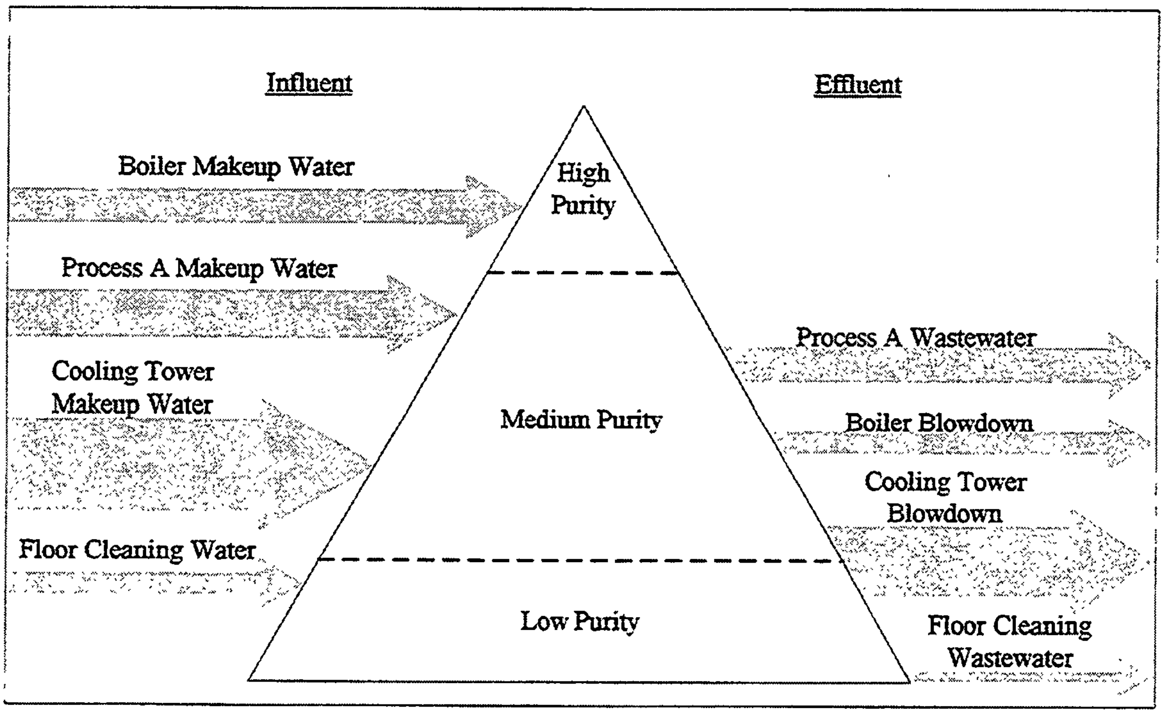


Figure 5. Hypothetical example using the water reuse hierarchy pyramid.

volume decreases when used in a process due to intended losses (e.g., evaporation of cooling tower water) or unintended losses (e.g., leaks and spills). With the water reuse pyramid complete, water reuse opportunities may be analyzed. Theoretically, the wastewater generated from processes at the top of the pyramid may be used as influent water for any and all processes lower down on the pyramid. The wastewater generated from process A and boiler blowdown may be used as cooling tower makeup with additional fresh water volume added as needed. This opportunity is possible because the effluent arrows are higher on the pyramid (higher quality) than the arrow representing cooling tower makeup water. Another possible reuse opportunity is to use process A wastewater as floor cleaning water. No additional water volume would be necessary for this alternative reuse scheme.

Treatment technologies may be considered to increase the number of potential reuse opportunities. Wastewater from a process near the bottom of the pyramid (low quality) may be treated to an extent such that it may be reused as influent for a process located closer to the top of the pyramid. This case is illustrated in Figure 6 which represents the hypothetical example used in Figure 5 with the addition of a membrane separation system, e.g., a reverse osmosis system. Once an effluent stream is treated, the quality of the wastewater is increased. Thus, the stream is moved closer to the top of the pyramid. As shown in Figure 6, membrane separation produces two streams: a high quality permeate stream and a low quality concentrate stream. Both streams for each process are shown in the figure because in some situations it may be possible to reuse concentrate streams for a process that requires minimal quality water, e.g., floor wash-down. In this example, it may be plausible to combine the effluents from process A, boiler blowdown and cooling tower blowdown and treat them with reverse osmosis if the concentration of the contaminants are of the same order of magnitude. If the waste streams vary widely in quality, segregation prior to treatment may be indicated. The resultant permeate from treatment may then be used as process A makeup water.

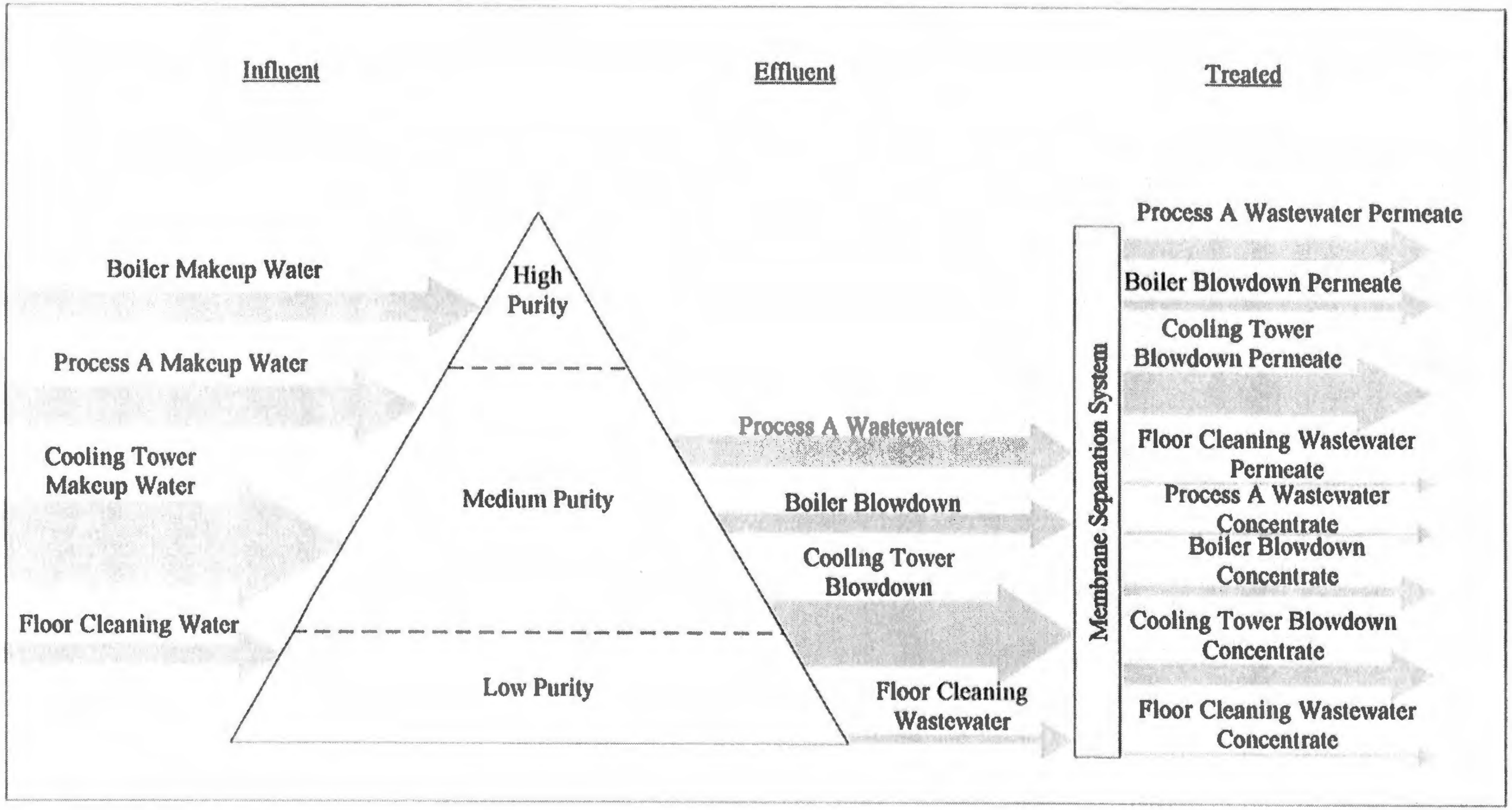


Figure 6. Hypothetical example of the water reuse hierarchy pyramid utilizing appropriate treatment before reuse.

IV. SOFTWARE DEVELOPMENT AND DESCRIPTION

Selection of Programming Software

The programming software used for the development of this computer program was Microsoft Visual Basic 6.0 Professional Edition (1998). Visual Basic is an object-based programming utility that can be used to create applications for the Microsoft Windows operating environment quickly and easily. Visual Basic may be used effectively by novice programmers to create applications with no formal training (Microsoft Corporation, 1998; Honchell and Robertson, 1996). Visual C++ is another widely used programming language. This program is much more powerful than Visual Basic and has fewer limitations, however, it has a steeper learning curve and novice programmers may not be able to effectively use it (Honchell and Robertson, 1996). Other object oriented programming languages are available and easier to use than Visual Basic, but are generally less capable.

Visual Basic was chosen because of its simplicity/learning curve and its ability/capabilities. This particular programming software can create simple graphical user interfaces in the popular Microsoft Windows operating systems environment. The graphical user interface used in the Microsoft Windows operating system is part of the reason for its popularity (Honchell and Robertson, 1996). The Visual Basic software is capable of performing the necessary simple algebraic calculations used in the developed model and is also capable of accessing information from a database which can be added to this program as a future development to store information on additional water treatment processes, for example. The other major factor in the selection of this particular software was the amount of time required to master the program to the degree needed to create the software for this project. A number of Visual Basic manuals were used as tutorials and references in developing the program (Halvorson, 1998; Microsoft Press, 1998a, b, c, d).

The Visual Basic 6.0 software also provides the opportunity to easily distribute the developed product on 3.5-inch floppy or CD-ROM disks or over the Internet. This capability allows for the product to be distributed widely for maximum utility. The program was chosen to be distributed by the use of 3.5-inch floppy disks and CD-ROM for the present time.

Development and Structure of the Program

The POWR program was developed to serve as a framework for future work. This initial version of the program illustrates a fundamental method of analyzing and comparing industrial water reuse opportunities. Once this initial framework has been established, future enhancements to the program (which will later be explained in detail) will produce a much more meaningful and functional tool. This is not to say, however, that the current program cannot be used as a resourceful tool. In addition, as with all computer models, the detailed calculations performed by the program can be accomplished manually, however for many cases, this would require a prohibitive amount of time and effort.

The program was designed to analyze water reuse scenarios for two independent water-utilizing processes in a plant. Previous methods of analyzing internal industrial water reuse scenarios often focused on all water-utilizing processes in the facility which frequently involve more than only two streams (Dhole *et al.*, 1996; Wang and Smith, 1994; Takama *et al.*, 1980). Some of these methods also employ computerized versions of the methodology used (Dhole *et al.*, 1996). It may be technically and economically impractical for an established facility to implement a water reuse project that impacts all plant processes that utilize water. Although achieving near or total zero discharge is desired, it is difficult and costly for industrial facilities to achieve, thus, attempting a cascading water use approach or near zero discharge is more effective for most facilities (Hamilton, 1996; Diepolder, 1995). Therefore, as a first step in determining potential water reuse schemes, this program was developed to analyze a set of two selected

processes. Water reuse projects involving two processes are more likely to be implemented due to ease of implementation and low capital cost rather than plant-wide projects which may require plant downtime and much expense for implementation. Most smaller water reuse projects should still achieve significant economic benefit. Since only two processes are modeled at a time with the program, the water streams with the largest volume and highest value or cost should be studied first (Breske, 1998). Throughout this discussion, the two processes chosen for analysis will be referred to as process A and process B.

The concentration of one contaminant is modeled throughout the analysis to ensure that required input purity levels are not exceeded during reuse. Although only one contaminant is modeled, additional contaminants may be analyzed for the same two processes, by conducting additional sequential runs through the program. This process may seem impractical and time-consuming. However, for many of the water reuse scenarios currently being practiced, there are generally only a few contaminants that are of primary concern which may determine the feasibility of a water reuse scenario. The contaminant chosen is one "that prevents the direct reuse of a wastewater stream" (Eastwood, Tainsh and Fien, 1998).

The contaminants are monitored throughout the two processes using simple mass balance equations neglecting chemical reactions. Only parameters that are described in terms of mass loadings can be modeled. The program cannot monitor water quality parameters such as pH and temperature directly since they are not typically defined in terms of mass loading. Temperature and pH may be measured by indirect methods, however, such as determining the hydrogen ion content and modeling it as the contaminant of concern (assuming no neutralization occurs). Also, the program does not take into account the effects of reactions between various contaminants or the potential solubilities of certain contaminants that may induce precipitation. Most species of practical concern can be modeled using this mass balance approach. It should be noted, however, that the developed program may not work as well for volatile species, either.

To maximize "user friendliness" and limit the amount of time required for initial data collection, the program was developed to require minimal, but critical, input data from the user. The specific input data required are described in detail in the following section. By minimizing the amount of plant data required, less time is required by the user for measuring and collecting program input data. Although this means that the final output data are less precise, the program was developed specifically to be a simplistic, first-order decision-making tool. Obviously, additional testing and study would be needed before implementation of a full-scale water reuse project.

Input data from the user is analyzed by comparing the composition and flow rate of the effluent wastewater streams to the maximum influent contaminant concentration and required flow rate needed for the two water-utilizing processes. It was determined that forty-six different reuse possibilities are potentially available in a system containing two water-utilizing processes and one treatment technology and possible blending with fresh water. Due to reasons discussed below, these forty-six opportunities were reduced to twenty-four different specific scenarios. The twenty-four scenarios are numbered in an arbitrary order and are listed in Table 6. The twenty-four scenarios are shown graphically along with the original operating situation in Figures AII-1 through AII-25 in Appendix II. Each of the twenty-four analyses is conducted in sequential order by the program beginning with reuse opportunity #1. When a reuse opportunity is determined to be a viable reuse option by the program, the output data for that scenario is tabulated. A reuse opportunity is deemed viable if a positive annual savings is calculated and no less complex opportunity has been determined. As an example, if the reuse opportunity in which process A effluent is to be reused directly as process B influent, the opportunity in which process A effluent is blended with fresh water prior to use as process B influent will not be considered. Savings are determined by subtracting the annual costs estimated for the potential reuse opportunity from the costs incurred by the current arrangement. The user then continues and the remaining analyses

Table 6. Description of reuse opportunities.

Reuse Opportunity #	Description
1	Process A effluent is redirected as process A influent.
2	Process A effluent is redirected as process B influent.
3	Process A effluent is mixed with process B effluent to proper proportions and redirected as process A influent.
4	Process A effluent is mixed with process B effluent to proper proportions and redirected as process B influent.
5	Process A effluent is blended with fresh water to proper proper proportions and redirected as process A influent.
6	Process A effluent is blended with fresh water to proper proper proportions and redirected as process B influent.
7	Process A effluent is treated with a treatment process as necessary and redirected as process A influent.
8	Process A effluent is treated with a treatment process as necessary and redirected as process B influent.
9	Process A effluent is mixed with process B effluent and then blended with fresh water to proper proportions and redirected as process A influent.
10	Process A effluent is mixed with process B effluent and then blended with fresh water to proper proportions and redirected as process B influent.
11	Process A effluent is mixed with process B effluent to adequate proportions and then treated as necessary and redirected as process A influent.
12	Process A effluent is mixed with process B effluent to adequate proportions and then treated as necessary and redirected as process B influent.

Table 6. (continued).

Reuse Opportunity #	Description
13	Process A effluent is treated and then blended with fresh water to adequate proportions and redirected as process A influent.
14	Process A effluent is treated and then blended with fresh water to adequate proportions and redirected as process B influent.
15	Process A effluent is mixed with process B effluent, treated as necessary and then blended with fresh water to adequate proportions and redirected as process A influent.
16	Process A effluent is mixed with process B effluent, treated as necessary and then blended with fresh water to adequate proportions and redirected as process B influent.
17	Process B effluent is redirected as process B influent.
18	Process B effluent is redirected as process A influent.
19	Process B effluent is blended with fresh water to proper proportions and redirected as process B influent.
20	Process B effluent is blended with fresh water to proper proportions and redirected as process A influent.
21	Process B effluent is treated with a treatment process as necessary and redirected as process B influent.
22	Process B effluent is treated with a treatment process as necessary and redirected as process A influent.
23	Process B effluent is treated and then blended with fresh water to adequate proportions and redirected as process B influent.
24	Process B effluent is treated and then blended with fresh water to adequate proportions and redirected as process A influent.

are completed as the user continues with the program operation. If a particular reuse scheme does not yield a reuse opportunity, the program merely bypasses this scenario and continues with the remaining scenarios until all twenty-four are performed. If none of the twenty-four scenarios provides an economically attractive reuse opportunity, the user may begin the program again and change the magnitude of any of the input variables. The program is then run again to determine potential reuse scenarios for the newly specified operating conditions.

Eight different groups exist among the twenty-four potential reuse opportunities used for dealing with the two processes. Prior to discussing these groups, a few terms must first be defined. A *combined flow* is a stream that results when two or more process effluent streams are combined, or mixed, prior to reuse. This may be done to dilute a particular contaminant of concern if one of the flows has a lower concentration than the other. This may also be done to provide additional water if the flow rate of one effluent stream is not adequate to provide the necessary influent to one of the two processes. *Blended flows* are streams that result when an effluent stream is mixed with fresh water to decrease a contaminant concentration or to provide additional flow. A *treated flow* is an effluent stream that has undergone some type of treatment to reduce the concentration of a contaminant of concern. The types of flows that are utilized in each reuse opportunity are listed in Table 7.

The first group deals only with effluent streams that may be reused directly as influent for another process. No effluent streams are combined, blended or treated. This category yields four potential reuse opportunities. Process A effluent may be reused directly as process A or B influent or process B effluent may be reused directly as process A or B influent. This category includes reuse opportunities #1, 2, 17 and 18 as shown in Figures AII-2 through AII-5 in Appendix II. This type of reuse is the simplest form in that no treatment or mixing of effluent streams is required. When using the developed program if only one process is desired to be analyzed, this may be accomplished by making the input contaminant concentration requirements

Table 7. Explanation of the types of flows used in the twenty-four reuse scenarios.

	Comparison			
Group	Combined flows	Blended flows	Treated flows	Reuse Scenario
1				1, 2, 17, 18
2	X			3, 4
3		X		5, 6, 19, 20
4			X	7, 8, 21, 22
5	X	X		9, 10
6	X		X	11, 12
7		X	X	13, 14, 23, 24
8	X	X	X	15, 16

for the second process very large or by disregarding the reuse scenarios that involve the second process.

Group 2 utilizes combined flows for the reuse opportunity analysis. Again, this category yields two potential reuse opportunities. Process A effluent may be mixed with process B effluent and then reused as either process A or process B influent. The program is coded in such a manner that the utilized mixed stream is composed of a portion of process A effluent and a portion of process B effluent that meets the required flow rate with the minimum contaminant concentration. Since many facilities mix all aqueous waste streams prior to onsite treatment and discharge, these reuse scenarios may be relatively simple to implement in a facility. This group includes reuse opportunities #3 and 4, which are shown in Figures AII-6 and AII-7 in Appendix II.

The third group of measures considers only blended streams. This category yields four potential reuse opportunities. Process A effluent may be blended with fresh water and then reused as process A influent or as process B influent. Likewise, process B effluent may be blended with fresh water and then reused as process A or B influent. The blending of the effluent stream may be required for two reasons: the effluent stream may not have a large enough flow rate to supply the process influent flow rate requirement or the effluent may have a contaminant concentration that exceeds the input purity requirement. Thus, the fresh water is used to dilute the effluent stream or increase the volume of the effluent stream. Although blending may be utilized, the code is written such that the reuse scenario is only viable if the total water consumption after reuse is less than that of the original operating situation. This group includes reuse opportunities #5, 6, 19 and 20 as shown in Figures AII-8 through AII-11 in Appendix II.

The fourth group considers treated flows. The associated removal efficiencies, recovery rates and costs of the effluent treatment processes used in the program were determined using published water treatment information as will be discussed later. This group also yields four

potential reuse opportunities. Process A effluent may be treated with a particular treatment process and then reused as process A influent or process B influent. Likewise, process B effluent may be treated with a particular treatment process and then reused as process A or B influent. It should be realized that the number of opportunities in this group is multiplied by the number of treatment technologies used in the program. Thus, since four treatment technologies are considered at the present time, this group may potentially yield sixteen reuse scenarios. These additional reuse opportunities are available in all groups that consider water treatment (categories 4, 6, 7 and 8). This fourth group includes opportunities #7, 8, 21 and 22, which are shown in Figures AII-12 through AII-15 in Appendix II.

Group 5 combines the concepts of combined and blended flows. This category theoretically yields six potential reuse opportunities. However, the opportunity in which fresh water is added to one of the effluent streams and then is mixed with the other effluent stream prior to reuse is not considered due its perceived inappropriateness. The situation in which one of the effluents is blended with fresh water and then mixed with the other process effluent is not considered because one of the principal objectives of water reuse is to reduce the amount of utility water utilized. Thus, only two potential reuse opportunities are considered in this group. Process A effluent may first be mixed with process B effluent to reduce the concentration of a particular contaminant or increase the volume of water potentially available for reuse. In the situation that the concentration level of a contaminant is still too large for reuse, the mixed stream will be blended with fresh water such that the contaminant concentration is reduced to the point that it may then be reused as either process A influent or process B influent. This group includes reuse opportunities #9 and 10 as shown in Figures AII-16 and AII-17 in Appendix II.

Group 6 considers combined and treated flows. Theoretically, six reuse opportunities are possible. The practice of treatment prior to mixing with another effluent is generally not practiced, therefore, this situation was not considered. Thus, the two potential reuse opportunities

discussed in this group are the two in which the two effluent streams are mixed prior to treatment. Process A and B effluents may first be mixed and then treated in a treatment process. The resultant stream may then be reused as process A or B influent. The streams are mixed prior to treatment to yield a lower concentration of the contaminant of concern or increase the flow volume. This group includes reuse opportunities #11 and 12 and these are shown in Figures AII-18 and AII-19 in Appendix II.

Group 7 considers treatment followed by necessary blending with fresh water. Theoretically, this category may yield eight potential reuse opportunities. However, it does not appear practical to add fresh water to an effluent stream prior to treatment because treatment technologies tend to be more efficient at higher contaminant loadings and cost is generally a function of the amount of water treated. Thus, the four situations in which the effluent stream is treated and then blended with raw water as necessary are the four used for analysis in this group. Process A effluent may be treated with a particular treatment process and then blended as necessary to make it available for reuse as process A or B influent. Likewise, process B effluent may be treated and then blended to a level such that it may be used for reuse as process A or B influent. This seventh group includes reuse opportunities #13, 14, 23 and 24 as shown in Figures AII-20 through AII-23 in Appendix II.

Group 8 deals with combined, blended and treated flows. Twelve theoretical opportunities are possible for this situation. For this situation, however, the most logical order for the water reuse scenario appears to be to combine the two effluents, treat the combined flow and then blend with fresh water as necessary. Thus, the current analysis yields two potential reuse opportunities. Process A and B effluent are mixed, treated and finally blended with fresh water as necessary. The resultant stream may then be reused as process A or B influent. This category includes reuse opportunities #15 and 16 as shown in Figures AII-24 and AII-25 in Appendix II.

The situations in which the two effluents are treated separately, or blended with fresh water prior to reuse was judged impractical and were not included in the developed program analysis.

Note that the reuse opportunities in groups 4, 6, 7 and 8, those that consider treated flows, may yield additional reuse opportunities due to the possibility of multiple treatment operations that may adequately reduce the contaminant level to a level such that the resulting process effluent may be reused. Four treatment technologies, which will be discussed later, are incorporated into this program. Therefore, with their introduction, sixty different reuse scenarios are potentially possible.

Discussion of Input Requirements

The input data required from the user for operation of this program is minimal. This was done intentionally to reduce the amount of time needed to evaluate potential wastewater reuse schemes. Although the developed program is considered to be a "first-cut" tool, additional, future modifications and enhancements can lead to increases in effectiveness and accuracy of the information obtained from the program.

The specific input information required from the user during operation of the developed computer program are explained in detail below and summarized in Table 8. All data required for program operation should be input in the units requested to ensure proper program calculations. However, although the program requests input data in specific units, different units may be used as long as no unit conversions must be performed by the program.

The first items of information needed involve the cost of the water used in the facility and the wastewater discharge unit cost. If water is purchased from a local utility and later discharged to a POTW, cost information can be obtained from analysis of the facility's water utility bills or by contacting the appropriate utility company for rate schedule information. If water is used directly from ground or surface water sources, it may be more difficult to establish a "net

Table 8. Input data required for execution of the developed program.

Contaminant of concern (selected from the given list)
Contaminant concentration in the fresh water supply (mg/gal)
Purchase cost of fresh water ($/gal)
Wastewater discharge cost ($/gal)
Influent flow rates for processes A and B (gal/yr)
Effluent flow rates for processes A and B (gal/yr)
Maximum allowable contaminant concentrations in influent for processes A and B (mg/gal)
Effluent contaminant concentration from processes A and B (mg/gal)

acquisition" cost. These costs should take into account pumping, energy and any costs incurred due to treatment of water prior to process use or treatment of wastewater prior to final discharge. Wastewater permit charges and system maintenance costs should also be included. Incorporating these costs will give a more accurate picture of potential savings, especially considering the rising costs of pretreatment often required prior to discharge. Treatment costs, if any, may be estimated from industrial data on the cost of the particular treatment utilized and the volume of water treated.

Next, a particular contaminant of concern is chosen from the supplied list for modeling in the program. The choice of the specific contaminant to consider is important because generally only a few particular contaminants are of primary concern in most reuse applications. Selection of a particular contaminant from the given list keys the program to choose if any of the four treatment technologies may be used in a given reuse scenario. Removal efficiencies, capital and operating costs of selected contaminants for the four treatment technologies considered for use are coded into the program. These values are presented and may be changed by the user if desired. The option of considering a contaminant that is not included in the provided list is possible, however, no reuse opportunities that incorporate treatment will be viable because no removal efficiency or cost data for such contaminants are available in the program unless the user provides this information. Once a contaminant is chosen, its average concentration present in the fresh water supply is input. If city tap water is used, the utility normally can provide this information. If ground or surface water is utilized in the facility, appropriate testing may be required to determine this concentration. If the fresh water supply is treated onsite prior to use in the process, the contaminant concentration in the treated water must be measured.

Five identical questions are asked for each of the two processes modeled. The first question asks for the required process input volumetric water flow rate. This program assumes constant, continuous flow rates for the processes used. Thus, if the required flow is intermittent,

an average volumetric flow rate may be calculated and used. However, any of the water reuse scenarios considered by the program may require special handling, pumping and use of storage tanks for actual implementation. These costs are not incorporated into the model due to the site-specific nature of the additional equipment needed and the lack of pertinent published information.

In some situations, only one process may be chosen for analysis. The POWR program does evaluate reuse schemes involving only one process, however, operation of the program requires information for two processes. Thus, to evaluate one process, two approaches may be used. The user may input identical information for both processes or relatively large data may be input for the second process. In either case, potential opportunities involving only one process will be evaluated along with the other twenty-four scenarios. It must be realized that any reuse opportunities involving the second process should be discarded.

Next, the maximum allowable contaminant concentration allowed for the considered process is input. It is initially assumed that the process is currently using fresh water as influent. Although such fresh water is "relatively clean", most processes can operate using "dirtier" feed water as discussed earlier. Thus, the contaminant concentration that is specified as allowable for the process without any process or product degradation is used in the program. This value is typically the most difficult to determine because site- and process-specific testing is required to determine maximum contaminant concentrations that will not cause process upsets. Although this piece of information is site- and process-specific, some influent guidelines have been established for commonly encountered processes utilizing cooling towers, boilers and other equipment (Deb and Schorr, 1996; Freeman, 1995; Sundberg *et al.*, 1991). The influent quality of some processes is regulated (e.g., the pharmaceutical industry). In such cases, the regulation requirements should be used in the program. In the guidance manual accompanying the developed program, various process influent quality requirements gathered from published

literature are included. This information may preclude some testing necessary to establish the influent purity requirements.

The effluent flow rate of each process is input next. Typically, this value will be the same value as the influent flow rate requirement. If the difference between this value and the influent flow rate value is negative, water is considered to be consumed in the process or lost due to evaporation, spillage or leakage. If the difference is positive, water is considered to be produced in process chemical reactions. Since the influent and effluent flow rates and contaminant concentrations are known, based on the mass balance over the process the amount of water and contaminant that is assumed to be produced or consumed through the process can be calculated. The potential volume and contaminant concentration changes that may occur through the process are process-specific and thus allow the user to input the influent and effluent volumes and concentrations eliminating any potential errors in the modeling.

Finally, the effluent concentration of the contaminant of each process is input. As discussed earlier, in the water reuse work performed by Wang and Smith (1994), water-utilizing processes were modeled as mass transfer elements. A specific mass of contaminant is transferred to the process water stream per unit of time. Thus, the effluent contaminant concentration could then be calculated. The analysis used by the POWR program is relatively simplistic and broadly applicable to a wide range of processes that use water. The contaminant concentration in the process input stream may or may not be changed once it has been utilized in a process. In addition, if the influent contaminant concentration were to change due to changes in operating conditions, the effluent concentration may or may not reflect this. Since these situations are potentially possible, the user of the program is given a choice. The user must first determine if the effluent contaminant concentration is dependent (a function of) or independent of the influent concentration. If the effluent concentration is a constant value and independent of the influent concentration, then that value is entered. If the effluent concentration is dependent on the influent

contaminant concentration, than the percentage of the influent concentration that remains in the effluent stream is input. The mass balance used to explain this concept can be described using Figure 7 below. The mass balance for this process can be described as follows:

$$\text{input rate} \pm \text{reaction rate} = \text{output rate}$$

$$Q_1 C_1 \pm R = \Sigma Q_i C_i$$

where Q = volumetric flow rate

C = contaminant concentration

R = reactive term representing production or loss of contaminant (e.g., by chemical reaction)

In many industrial processes there is only one or two significant outputs. For the case of a single input and a single output:

$$Q_1 C_1 = Q_2 C_2 + R$$

It was assumed that R = 0 in the developed program for simplicity. For this case, the user may simply enter a percentage of concentration change in the developed program if the effluent contaminant concentration is dependent on the influent concentration as shown below:

$$C_{Ea} = C_{Ia} \frac{T_a}{100\%}$$

where C_{Ea} = Process A effluent concentration

C_{Ia} = Process A influent concentration

T_a = Percentage of the influent concentration that remains in the effluent stream

The value of T_a may be less than or greater than 100% of the influent concentration, and the effluent concentration is assumed to be a linear function of the influent concentration.

This method of determining the effluent contaminant concentration provides a simple way to model the changes that may occur with the implementation of different reuse schemes. Since the current effluent contaminant concentration may change when a reuse system is

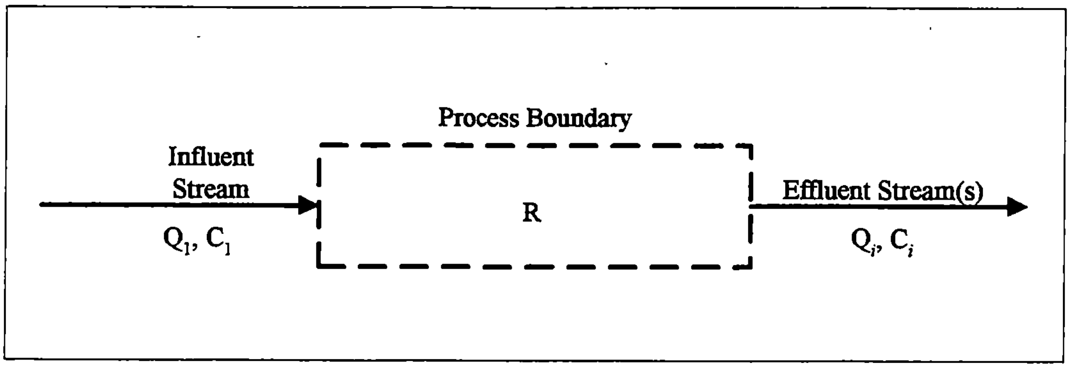


Figure 7. Process mass balance.

established due to the use of water of a lower quality, this method was developed. This method is related to the aforementioned mass transfer idea, but allows for the analysis of processes that cannot be considered simply as mass transfer units.

Treatment Processes and Basis for Costs, Removal Efficiencies and Recovery Rates Used in the Program

Although it is more desirable to be able to reuse a wastewater stream directly without having to treat it, treatment prior to reuse as required may be an economical alternative in some situations. In general, consideration of treatment alternatives to reduce contaminant concentrations in wastewater will increase the number of potential reuse opportunities available within a facility. In addition, the appropriate method of treatment may be lower in operating cost than the treatment necessary to meet discharge regulations because the quality of water needed for process use may be less than the quality requirements for discharge.

Due to time and simplicity concerns, the number of treatment technologies included in the initially developed POWR program were limited. Thus, a few of the most applicable treatment technologies for use in industrial reuse situations were selected for inclusion. Various characteristics of membrane separation technologies make these treatment processes very applicable to industrial water treatment situations as discussed earlier. Therefore, this project utilizes the following four treatment processes: reverse osmosis, nanofiltration, ultrafiltration and microfiltration. These membrane processes have commonly been used in industry for various pollution control situations and are becoming more popular in recycling and reuse applications.

For the POWR program to conduct proper technical and economic feasibility comparisons using the four treatment processes, information concerning capital costs, operation and maintenance costs, removal efficiencies and recovery rates was needed for each of the processes. Unfortunately, due to the wide variety of system and operating parameters, published, generalized cost data are relatively scarce. In addition, many variables are involved in estimating

costs and potential removal rates. In particular, it should be noted that the removal efficiencies and recovery rates of membrane treatment processes may be increased or decreased very easily by changing the number of treatment units or membrane types, by utilizing parallel or series configurations using one or more different processes, by changing operating parameters such as transmembrane pressure gradient and by using various pretreatment methods.

The determination of a suitable basis for estimating membrane separation technology costs is very difficult. Many membrane manufacturers are hesitant to discuss proposed system costs due to the uncertainties involved in a particular application. Personal conversations with membrane separation technology vendors (Comb, 1999; Moseley, 1999) yielded the following responses when asked to make generalized cost estimates for membrane processes, "very difficult, each application is unique and needs to be sized individually," "monumental task," "next-to-impossible to simplify for a workable program" and "you need to be very general."

Pilot testing is usually needed to determine cost data for membrane systems based on the membranes used and the quality of the water to be treated. Numerous variables have been shown to affect the costs of a membrane system. Incremental capital and operating costs decrease with increased capacity due to the economy of scale. In most cases, it is less expensive to treat small volume-high concentration wastewater than high volume-low concentration wastewater (Hamilton, 1996; Sethi and Wiesner, 1995; Blake and Stuart, 1993). Based on sensitivity analyses conducted by Pickering and Wiesner (1993), permeate flux was the most important variable in determining the costs of a membrane system. As the permeate flux increases, the incremental capital costs and membrane replacement costs decrease while the energy costs increase (Wiesner *et al.*, 1994; Pickering and Wiesner, 1993). Although it was determined that the permeate flux greatly affected the system costs, it was determined that the flux was a function of many variables including raw water quality and membrane effectiveness and thus, could only be estimated for a particular application by pilot studies (Wiesner *et al.*, 1994).

As shown previously in Figure 3 (p. 23), reverse osmosis utilizes the smallest pore size of the four membrane processes and thus, reverse osmosis is the most effective at removing all contaminants down to the size level of small ions (e.g., Na^+ and Cl^-). Typically, the smaller the pore size of the membrane, the higher the capital and operating costs (Woerner, 1993). This is due to the increased transmembrane pressure gradient and resultant energy costs required for low porosity membrane system operation. Thus, the relative costs of the four membrane technologies is typically: reverse osmosis > nanofiltration > ultrafiltration > microfiltration (Comb, 1999).

Regardless of the reported difficulty in estimating membrane treatment costs, a few cost models have been developed and reported in the literature. Pickering and Wiesner (1994) presented a cost model for membrane filtration processes in which total capital costs were determined with knowledge of the permeate flux, number of membrane modules, required flow rate and the time required for the membrane system operating cycles. Additional equations were presented for estimating operational energy costs. The estimates obtained from this model were reported to be +/- 30% accurate and were determined to be best utilized for comparing the various membrane processes (Pickering and Wiesner, 1994). Sethi and Wiesner (1995) developed a model that estimated the costs and performance of ultrafiltration as a function of the membrane feed water quality. This cost model is similar to that developed by Pickering and Wiesner (1994) in that the costs are determined by the flow rate and the number of membranes utilized.

Other simple cost estimates based on system capacity have been reported with capital costs ranging from $500 to almost $3,000 per gpm of capacity and operating costs ranging from $30 to over $2,000 per million gallons treated (Comb, 1999; Moseley, 1999; Byers *et al.*, 1995). Numerous other values have been reported for actual systems in operation (Gere, 1997; Adham, *et al.*, 1996; Bergman, 1996; Wiesner, *et al.*, 1994; Taylor, *et al.*, 1989). An effort was made to compile the available information to form a simple relationship between plant capacity and capital and operating costs for each of the four membrane system types considered. This resulted

in a scatter diagram with no statistical trend merit. Since the results of the POWR program are to be used for first-order decision making purposes, the capital and operating costs of the four treatment technologies were conveniently determined using conservative mid-range estimates based on the reported data mentioned above. Known relative costs of the four specific treatment processes were used to determine the specific estimates used in the POWR program (shown in Table 9). It is clear that if and when improved data become available, the values used in the model may be changed for more accurate predictive results.

Many of the same factors that are responsible for the variable costs associated with membrane treatment are also responsible for the various contaminant removal efficiencies associated with membrane treatment. Actual performance is determined by a number of local operating conditions and feed water quality, including the nature (e.g., ionic state) and size distribution of contaminants (Wiesner *et al.*, 1994; Marinas, 1991; Levine *et al.*, 1985). Therefore, treatability studies should be performed prior to the installation of any new treatment process to ensure adequate contaminant removal.

Removal efficiencies of selected contaminants for the four treatment technologies that are incorporated into the POWR program are listed in Table 10. Reported typical removal efficiencies for these systems and reported actual removal efficiencies of pilot- or full-scale membrane systems were averaged to obtain the listed values (Peters and Howton, 1997; American Water Works Association, 1996; Geselbracht, 1996; Al-Tuwayyan *et al.*, 1995; Goldblatt, 1993; Blau *et al.*, 1992). It is expected, all system and operating parameters being equal, that the degrees of contaminant removal would be dependent primarily on the membrane pore size. Thus, reverse osmosis is expected to yield the best removal efficiencies of the four membrane systems. A few of the values presented in Table 10 do not reflect this trend. However, these variances may be attributed to varying elements of process control in the systems described in the literature. In addition, the data presented are based on only a few data points for

Table 9. Membrane separation technology costs incorporated in the POWR program.

Membrane process	Capital cost ($/gpm)[1]	Operational cost ($/million gallons)
Microfiltration	1,100	500
Ultrafiltration	1,500	800
Nanofiltration	2,000	1,200
Reverse osmosis	2,400	1,500

[1]Assumed continuous operation (24 hours per day, 7 days per week, 365 days per year).

Table 10. Average percent contaminant removal efficiencies of four membrane separation technologies incorporated in the POWR program.

Parameter	Treatment Process: Microfiltration	Ultrafiltration	Nanofiltration	Reverse Osmosis
Calcium	---	---	---	99
Hardness	---	---	91	94
Alkalinity	---	---	93	89
Iron	94	---	91	92
Magnesium	---	---	---	99
Manganese	50	---	---	62
Total dissolved solids	---	---	87	90
Total suspended solids	99	100	---	100
Turbidity	99	90	79	95
Chloride	---	---	83	92
Sodium	---	---	65	92
Sulfate	---	---	54	96
TOC	---	---	25	98
BOD	---	---	67	72
COD	---	---	50	72

Note: '---' = No published data found for this contaminant removed with the used membrane processes.
Specific literature sources used to determine these removal efficiencies are shown in Table AIII-1 in Appendix III.

actual systems as shown in Table AIII-1 in Appendix III. Values in the literature that appeared to reflect atypical separations (those that were below 20% removal or those that deviated more than 20% from the aforementioned trend) were omitted. Unusual process constraints or other process-specific variables may have caused these atypical values. Thus, the validity of any one of the values presented in Table 10 is limited due to the number of data points available and the large number of system variables involved. This uncertainty in the validity of the removal efficiencies and costs used in the developed program is partially offset by allowing the user to select other than the pre-programmed removal efficiency values for a particular program analysis.

The following assumption concerning the treatment processes evaluated is used in the POWR program and is similar to the treatment assumption made in the Schwartz and Mays (1983) mathematical model. It is assumed that the treated effluent flow rate and contaminant concentration is based on the influent quantity and quality. In the POWR program, when a contaminant is chosen that can be partially removed by one of the treatment processes, the concentration of that contaminant is calculated as follows:

$$C_P = C_F\left(\frac{\text{Removal efficiency}}{100\%}\right)$$

where

C_P = the contaminant concentration in the permeate stream

C_F = the contaminant concentration in the feed stream

Removal efficiency = the efficiency listed in Table 10 for the contaminant of concern (%)

The concentration and flow rate of the concentrate stream are then calculated using the following mass balance equations:

$$C_C = \frac{Q_F C_F - Q_P C_P}{Q_C}$$

$$Q_C = Q_F - Q_P$$

where

C_C = the contaminant concentration in the permeate stream

Q_F = the feed stream volumetric flow rate

Q_P = the permeate stream volumetric flow rate

Q_C = the concentrate stream volumetric flow rate

It is noted that the volume flow balance equation assumes constant stream density.

The volumetric recovery rate of the four membrane processes is assumed to be 75%. This is the value reported as being typical by Mukhopadhyay, (1998); Mukhopadhyay and Whipple, (1997a); and Eble and Feathers, (1992b). Thus, in the POWR program, 75% of the flow rate volume entering a treatment process will be available for reuse, while the remaining concentrated 25% will not be reused.

Owing to these approximations, bench-, pilot- and field-testing should always be performed prior to the installation of any costly treatment technology to ensure adequate contaminant removal effectiveness and acceptable payback associated with system installation (Lien, 1998). System size- and process-specific variables will influence the actual removal efficiencies, recovery rates and costs of the treatment, thus the output obtained from the POWR program concerning treatment processes should only be used for first-order decision making purposes.

Data Input and Analysis

Once the user inputs the required data, each reuse scenario is considered sequentially by the program. If a reuse scenario is considered viable based on economic outcome, the output data for that scheme is displayed on the screen. The user then continues and the next viable reuse scheme is displayed. Once all the viable schemes have been displayed, the user may exit and begin the program again. As an example, the program code for reuse opportunity #1 is shown in

Appendix IV to reveal how the program steps through one of the twenty-four potential reuse scenarios to determine which scenarios are viable. Analysis of the code details how each effluent stream is systematically compared to the influent quantity and quality requirements to determine potential reuse opportunities. The entire program code is available on the CD-ROM accompanying this document. For a particular stream to be used as influent for a process, its flow rate must be larger than or equal to the flow rate required and its contaminant concentration must be less than or equal to the maximum allowable influent concentration. As discussed earlier, these conditions may be met by stream blending or combining or by treating the potentially reusable stream.

Discussion of Output Results

Summary information is presented in an output table designed to give the user specific information that can be used to compare the current water use situation with the potential water reuse scheme and to compare different water reuse schemes for relative economic benefit. Table 11 lists the data presented in the output form. The amount of water currently used and discharged along with associated costs is compared to the same quantities calculated by the computer for the reuse situation. The concentration of the contaminant of concern in the final discharge stream is also presented. This value may prove important when considering NPDES and other discharge permits and pre-existing treatment capabilities. Data presented in this manner allow a first-order economic evaluation of several potential reuse schemes. Occasionally, possibly owing to regulatory concerns, a company may desire to reduce the amount of fresh water used, wastewater discharged or the discharge concentration of specific contaminants. The output data presented will also allow for these types of evaluations.

Along with the table of output data, a schematic diagram detailing the flow patterns of each water reuse scheme is provided. Examples are exhibited in Appendix II. Each diagram

Table 11. Output information calculated by the POWR program for each viable reuse opportunity.

Current Situation	Potential Reuse Scenario	Resultant Savings
Total Water Consumption (gpy)	Total Water Consumption (gpy)	Annual Savings ($/yr)
Total Water Discharged (gpy)	Total Water Discharged (gpy)	Payback Period (yr)
Water Purchase Cost ($/yr)	Total Water Treated[1] (gpy)	Reduction in Fresh Water Consumed (gpy)
Water Discharge Cost ($/yr)	Water Purchase Cost ($/yr)	Reduction in Wastewater Discharged (gpy)
Contaminant Discharge Concentration (mg/gal)	Water Discharge Cost ($/yr)	
	Water Treatment Cost[1] ($/yr)	
	Treatment System Capital Cost[1] ($)	
	Contaminant Discharge Concentration (mg/gal)	

Note: gpy = gallons per year, yr = year(s), mg = milligrams, gal = gallon(s).

[1]If applicable.

highlights how the reuse scheme is to be implemented by showing where each water stream should be directed and the magnitude of the flow rate required.

Instructions for Program Use

The POWR program has been packaged and deployed onto three 3.5-inch floppy disks and/or one CD-ROM disk using the Packaging and Deployment Wizard in Microsoft Visual Basic 6.0 Professional Edition. The disks contain the POWR program and are used for installing the program onto the user's computer. Microsoft lists the following computer hardware requirements for applications, such as POWR, developed with Microsoft Visual Basic 6.0 Professional Edition (Microsoft Press, 1998a):

- Pentium 90 MHz or higher processor.
- VGA 640 x 480 or higher-resolution screen supported by Microsoft Windows.
- 24 MB RAM for Windows 95 or 32 MB for Windows NT.
- Microsoft Windows NT 3.51 or later, or Microsoft Windows 95 or later.

Once the first 3.5-inch floppy or CD-ROM disk is inserted into the computer's appropriate drive, the installation setup program automatically begins (otherwise, the Add/Remove Programs utility should be used). A CD-ROM copy of the POWR installation program accompanies this document. The setup program is displayed and guides the user through the setup process. Once the program is installed, it may be accessed in the same manner other programs are accessed in the Microsoft Windows operating system environment. If uninstallation of the program is desired or necessary, the user may use the Add/Remove Programs utility under the Windows Control Panel on their computer desktop to remove the POWR program.

Once the program is started, a splash screen detailing program information such as the version number and copyright information is flashed on the screen. The amount of time the splash screen remains on the screen depends on how long the user's computer takes to load the

program. On a 300 MHz, 96 MB RAM computer operating with Microsoft Windows 98 (this computer is the basis for execution times throughout), the splash screen is only shown for about one second.

The next screen, shown in Appendix V as Figure AV-1, asks the user general questions required for the analysis including the purchase and discharge costs for water. The user then clicks the "Continue" button and the next screen, shown in Figure AV-2, is displayed. The user is now asked specific information concerning the influent and effluent streams of the first process chosen for analysis. Once this information is complete, the user clicks the "Continue" button and an almost identical screen (Figure AV-3) is shown requesting the same information for the second process. The user once again clicks "Continue." Although it is not required that the input data be input in the order presented on the screen, all data fields must be complete before the "Continue" buttons will advance the user to the next screen. In addition, all input fields requesting numbers must have a positive, numeric value input to prevent an error message from being displayed.

The next screen displays the programmed membrane treatment costs and removal efficiencies for the contaminant chosen. The user may change these values if better data is available or use the pre-programmed values shown. The user is offered two choices on this particular screen: "Calculate Reuse Options" or "Exit." All screens shown in the POWR program contain an "Exit" button to allow the user to exit the program at any time. Once the user presses the "Calculate Reuse Options" button, the program sequentially begins to analyze each of the twenty-four reuse scenarios internally. The first viable reuse scheme is immediately displayed on the screen. The output data for the first viable reuse scheme is displayed on the screen in a tabular form as shown in Figure AV-4. The output form of each viable reuse opportunity gives the user four choices:

- "View Additional Reuse Opportunity Information" – This button displays a graphical representation of the reuse scheme (an example is shown in Figure AV-5). From this screen

containing the graphical representation, the user may print the screen, return to the tabular data or exit the program.

- "View Next Reuse Opportunity" – This button keys the program to analyze the next reuse opportunity for viability. The next viable reuse opportunity is then displayed on the screen in tabular form. Again, this screen change occurs almost immediately after clicking the button.
- "Print" – This button allows the user to print the screen for a hard copy of the results presented.
- "Exit" – This button ends the program.

Once each viable reuse opportunity has been displayed (those schemes that are not deemed viable by the computer are not displayed, they are merely passed by internally) a summary report of output data is shown. If no reuse scheme is deemed viable based on the information provided, the summary report is still shown with no data provided.

A blank summary report is shown in Figure AV-6. Information is provided in the summary report for every viable reuse scheme to allow for quick comparisons. As shown in Figure AV-6, the following information for each viable reuse scheme can be shown by clicking the appropriate circle: annual savings, project payback period, reduction in fresh water use, reduction in the amount of wastewater discharged and contaminant discharge concentration. Each of these reports may be printed to obtain a hardcopy of the output for future reference. Once the summary information has been viewed and/or printed, the user may exit the program.

All of the screens displayed, except the reuse scheme output forms, have a "Help" pull-down menu. The "Help" menu provides the following information and is presented in its entirety in Appendix VI:

- Input Data Questions – This section discusses each of the input questions in more detail to provide the user more insight as to what information is being requested.
- Abbreviations – A few abbreviations used in the program are spelled out.

- References – A brief list of key references that may be consulted for further water reuse information are presented.
- Uninstallation – This section provides instructions on how to remove the POWR program from the host computer, if desired.
- About – This section provides some brief information about the POWR program including the version number and copyright information.

The amount of time required for operation of the POWR program is dependent on the number of viable reuse schemes and the amount of time spent analyzing the output information. If all of the required input information is available, a typical program run in which all output forms were printed, in lieu of being viewed for any period of time on the screen, could be easily done in less than ten minutes depending on the user's computer and printer speed.

V. DEVELOPED PROGRAM CASE STUDY TESTING AND EVALUATION

Basis for Choosing the Case Study Processes

A case study using the POWR program was performed to demonstrate operation of the program and to indicate how the output information could be used in an actual application. To make the case study demonstration applicable to a wide range of industrial facilities, two common water-utilizing processes were used. One process is a typical industrial cooling tower and the second is a high-pressure boiler. Influent purity requirements for cooling towers and boilers have been widely published (Deb and Schorr, 1996; Freeman, 1995; Sundberg *et al.*, 1991) and thus, the required amount of time needed for initial data collection was minimized.

Basis for Case Study Input Data

The first information needed for input was the purchase and discharge cost of the water. White (1997) reported an average industrial purchase cost of city-supplied water of $1.49 per 1,000 gallons along with an average discharge cost of $2.05 per 1,000 gallons. The costs of any necessary treatment prior to process use or to final discharge were not included in this analysis.

Although multiple contaminants are of concern when considering reuse in cooling towers and boilers, only one was chosen for this analysis since the procedure would be similar for any contaminant chosen. The parameter of concern chosen for this analysis was alkalinity. Alkalinity is a limiting parameter in both systems (Cain *et al.*, 1997; Freeman, 1995; Betz Laboratories, 1980) due to the formation of carbon dioxide in steam that is corrosive to condensate lines (Betz Laboratories, 1980). To determine the concentration of alkalinity (measured in mg/L of $CaCO_3$) in the fresh water supply, water analysis reports from a local water treatment facility were used. According to the January-June 1997 water quality report from the Mark B. Whitaker Plant in

Knoxville, Tennessee, the average alkalinity concentration in the tap water was 67 mg/L (250 mg/gal).

The cooling tower flow rates used in this analysis are for a cooling tower operating at 5 cycles of concentration where

$$\text{cycles of concentration} = \frac{\text{makeup water rate}}{\text{blowdown water rate}}$$

$$\text{makeup water rate} = \text{evaporation rate} + \text{blowdown rate}$$

The cycles of concentration may also be expressed as the ratio of the concentration of the critical contaminant in the circulating water to the concentration in the makeup water (Betz Laboratories, 1980). The reported makeup flow rate required for the cooling tower is 81,000 gpd (29,565,000 gal/yr) (Betz Laboratories, 1980). The cooling tower operates with five cycles of concentration and thus, has a continuous blowdown rate of 16,200 gpd (5,913,000 gal/yr). Typical cooling tower blowdown has approximately 40 mg/L (150 mg/gal) of alkalinity (Meier and Fulks, 1990). Although the cooling towers are currently utilizing city water for makeup, the maximum alkalinity concentration that can be present in the makeup without negative effects is 350 mg/L (1,320 mg/gal) (Freeman, 1995).

The boiler described in this example is from a typical calculation presented by Betz Laboratories (1980). The boiler operates at a pressure of 600 psig and a blowdown rate of 5.0%, where

$$\%\ \text{blowdown} = \frac{\text{blowdown water rate}}{\text{feed water rate}} \times 100\%$$

The feed water rate is 631,000 gpd (230,315,000 gal/yr) and the blowdown rate is approximately 32,000 gpd (11,680,000 gal/yr). A typical alkalinity concentration in boiler blowdown is 375 mg/L (1,420 mg/gal) (Meier and Fulks, 1990). For a boiler operating at a pressure of 600 psig, the maximum alkalinity concentration in the feed water is estimated to be 100 mg/L (380 mg/gal) (Deb and Schorr, 1996).

With all of the required data collected, the next step was to convert the data into the required units. Once this was accomplished the POWR program was started. The general information (in the required units) was input into the program as shown in Figure 8. Next, the information from the two processes was input as shown in Figures 9 and 10. The pre-programmed treatment removal efficiency and cost data was accepted and the "Calculate Reuse Options" button was then pressed. Immediately the first reuse opportunity was calculated and shown on the screen.

Output Results of the Case Study

As shown in Figure 11, eighteen potential reuse opportunities were deemed viable by the POWR program. Six of these reuse schemes did not require treatment of any type. The two reuse schemes with the largest potential annual savings were reuse opportunity #9 and reuse opportunity #10 (see reuse opportunity description in Table 6 on pages 46 and 47). These two reuse schemes provide potential annual savings of over $60,000 and eliminate the discharge of water from the boiler and cooling tower.

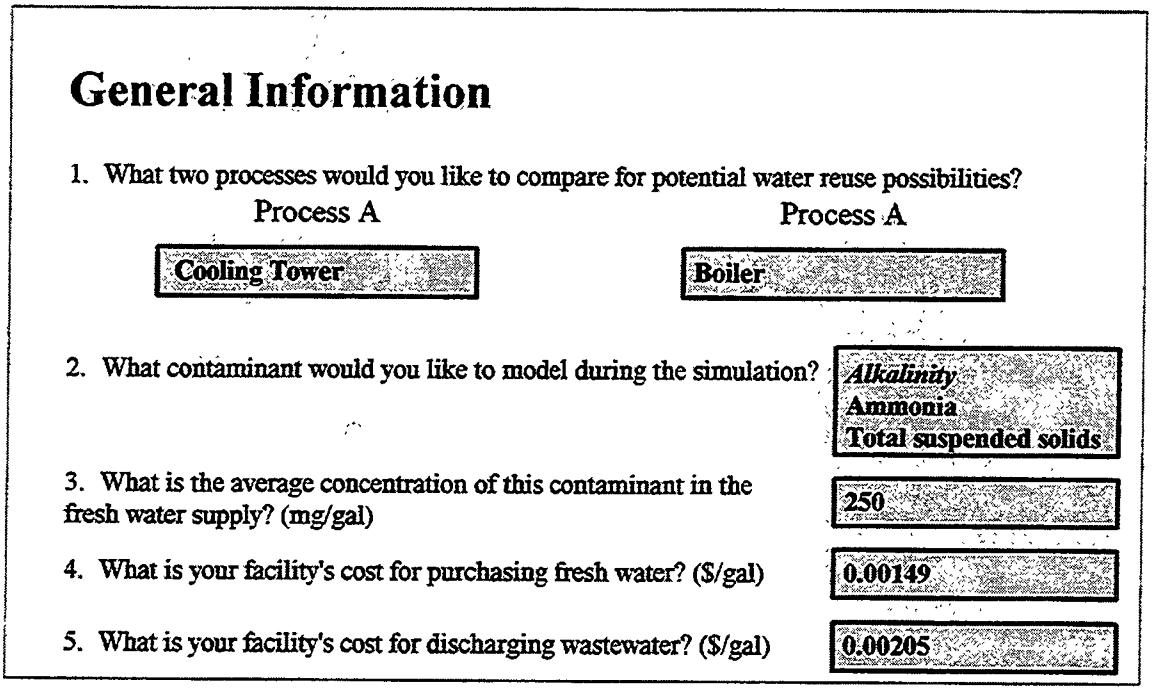


Figure 8. Case study general information input screen.

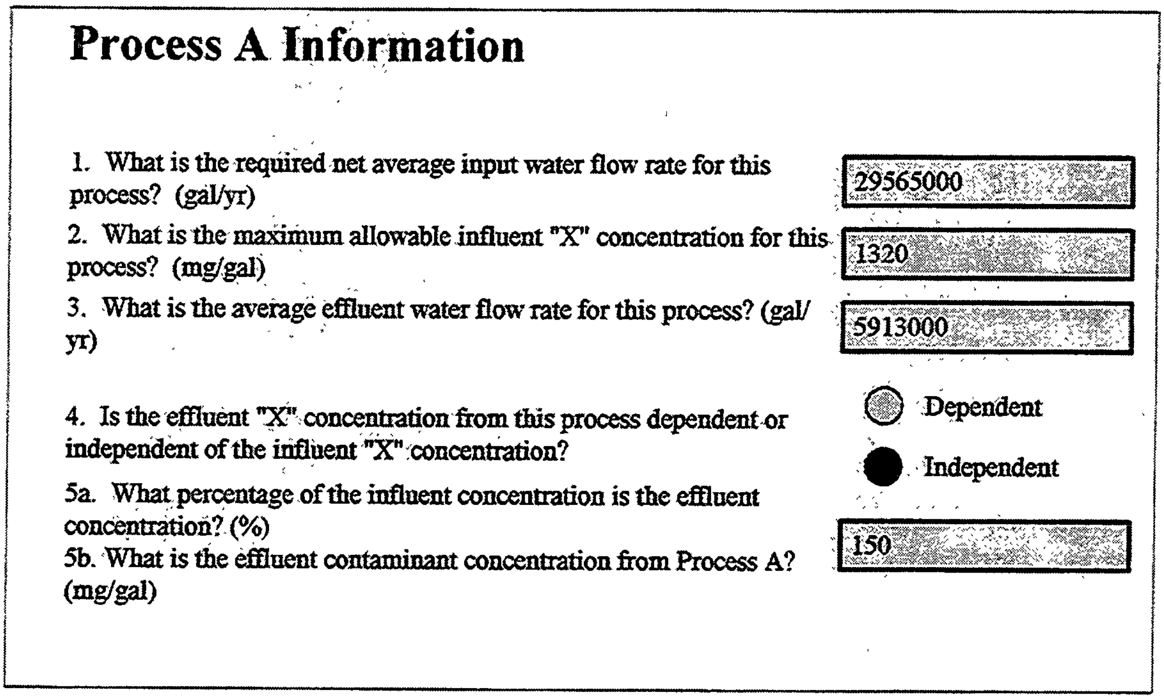
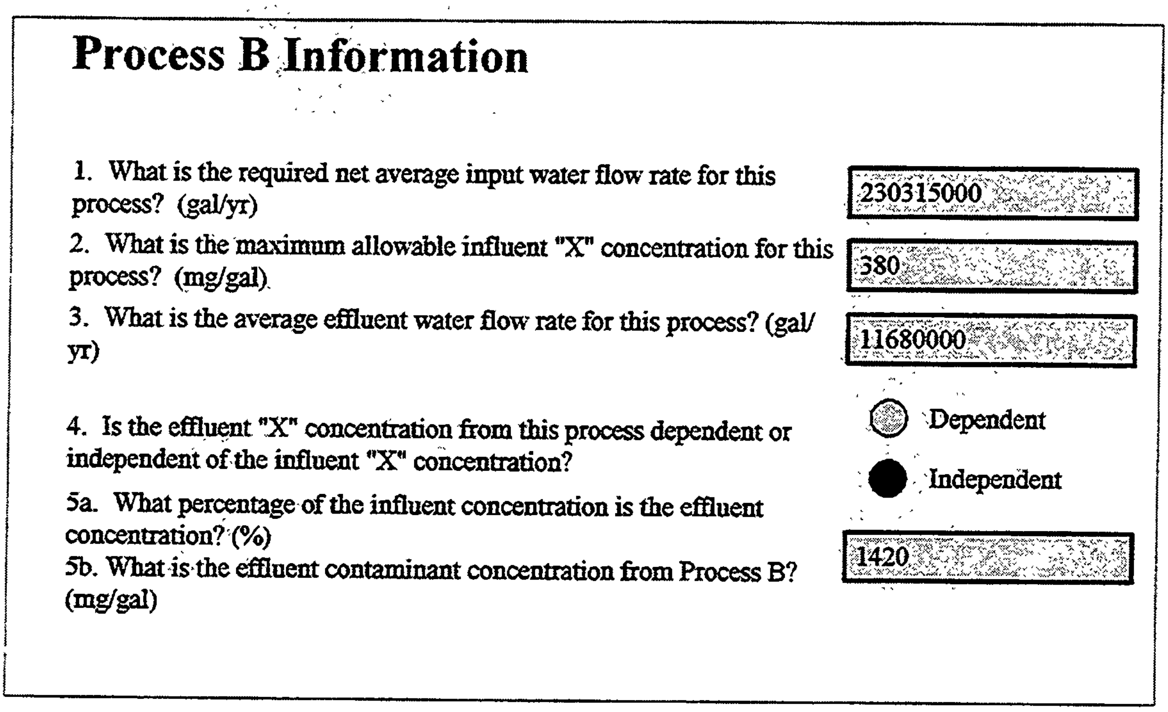


Figure 9. Case study process A information input screen.



Process B Information

1. What is the required net average input water flow rate for this process? (gal/yr) — 230315000

2. What is the maximum allowable influent "X" concentration for this process? (mg/gal) — 380

3. What is the average effluent water flow rate for this process? (gal/yr) — 11680000

4. Is the effluent "X" concentration from this process dependent or independent of the influent "X" concentration?

- Dependent
- Independent

5a. What percentage of the influent concentration is the effluent concentration? (%)

5b. What is the effluent contaminant concentration from Process B? (mg/gal) — 1420

Figure 10. Case study process B information input screen.

Summary Report

Cooling Tower
Boiler

- ● Annual Savings
- ◎ Payback Period
- ◎ Reduction in Fresh Water Consumed
- ◎ Reduction in Wastewater Discharged
- ○ Contaminant Discharge Concentration

R.O. #1		R.O. #12-MF		R.O. #17	
R.O. #2		R.O. #12-UF		R.O. #18	
R.O. #3		R.O. #12-NF		R.O. #19	$41,347/yr
R.O. #4		R.O. #12-RO		R.O. #20	$41,347/yr
R.O. #5	$20,932/yr	R.O. #13-MF		R.O. #21-MF	
R.O. #6	$20,932/yr	R.O. #13-UF		R.O. #21-UF	
R.O. #7-MF		R.O. #13-NF		R.O. #21-NF	
R.O. #7-UF		R.O. #13-RO		R.O. #21-RO	
R.O. #7-NF		R.O. #14-MF		R.O. #22-MF	
R.O. #7-RO		R.O. #14-UF		R.O. #22-UF	
R.O. #8-MF		R.O. #14-NF		R.O. #22-NF	
R.O. #8-UF		R.O. #14-RO		R.O. #22-RO	
R.O. #8-NF		R.O. #15-MF		R.O. #23-MF	$25,170/yr
R.O. #8-RO		R.O. #15-UF		R.O. #23-UF	$21,666/yr
R.O. #9	$62,279/yr	R.O. #15-NF		R.O. #23-NF	$16,994/yr
R.O. #10	$62,279/yr	R.O. #15-RO		R.O. #23-RO	$13,490/yr
R.O. #11-MF		R.O. #16-MF	$37,913/yr	R.O. #24-MF	$25,170/yr
R.O. #11-UF		R.O. #16-UF	$32,635/yr	R.O. #24-UF	$21,666/yr
R.O. #11-NF		R.O. #16-NF	$25,598/yr	R.O. #24-NF	$16,994/yr
R.O. #11-RO		R.O. #16-RO	$20,320/yr	R.O. #24-RO	$13,490/yr

Figure 11. Case study summary report screen.

VI. RESULTS AND DISCUSSION

Interpretation of the Case Study Software Results

Using the results provided by the POWR program the user can analyze the various reuse schemes and economic data provided to choose the best reuse scheme for further consideration. Reuse opportunities #16, 23 and 24, although viable for the case study presented, include treatment processes. These reuse schemes provide a smaller annual savings than reuse schemes #9, 10, 19 and 20 and increase plant operation and maintenance time due to the installation and operation of new treatment processes. If the membrane technology were treating a waste that contained a valuable contaminant, as may be the case in treating electroplating rinse waters, these opportunities should be further investigated. In reuse opportunities #23 and 24, boiler blowdown is reused as a portion of cooling tower or boiler makeup water. The potential for these reuse schemes has been documented in the literature (Hamilton, 1996; Wong, 1995; Galbreath, 1994). Reuse opportunities #19 and 20 are also considered viable. The use of boiler blowdown for use as partial cooling tower makeup has been documented (Galbreath, 1994). However, depending on the chemicals used, there may be incompatibilities between the chemistries of the boiler and cooling tower streams (Galbreath, 1994).

In reuse opportunities #5, 6, 9 and 10, cooling tower blowdown is reused as partial makeup to the cooling tower or to the boiler. Reuse opportunities #9 and 10 appear to be more promising because the effluent from the boiler and the cooling tower is reused, thus less makeup water is required. Finally, since the quality of water used in cooling towers is less critical than in boilers, reuse opportunity #9 appears to be the reuse scheme that would be the most attractive for further consideration.

Recommendations for the Participant

With the information provided by the POWR program, the user should now consider other contaminants that may cause problems in the cooling tower/boiler water recycle scheme. Sensitivity analyses may also be run by changing one input parameter at a time. This procedure may provide valuable insight into how a number of variables may alter the outcome of the proposed reuse scheme. Now that a reuse scheme has been presented, further research should be performed prior to bench- and pilot-scale studies to ensure adequate recycle system operation. In addition, other factors not determined by the POWR program such as piping, pumping and system maintenance requirements should be considered.

Evaluation of the Proposed Recommendation

Once the initial data was collected, the POWR program was started and reuse scheme data was presented in less than ten minutes. Obviously, this computerized method significantly minimizes the time needed to determine potential reuse schemes. The results of the case study presented agree with reuse schemes that have been published in the literature as discussed above. The POWR program will not design a water reuse scheme for a particular industrial application and was not intended to do so. The POWR program does, however, significantly reduce the amount of time required for an industry to evaluate, design and build a water reuse system. This is accomplished, as shown in this case study, by performing the tedious influent and effluent calculations required for determining reuse schemes. Armed with this computer-calculated information, the user rapidly completed one of the steps required for the successful implementation of a water reuse project.

VII. RECOMMENDATIONS FOR FUTURE INVESTIGATION

Develop and Use Improved Software

The computer program developed for this project was designed to establish the framework for a comprehensive water reuse analysis tool. The following is a short discussion detailing the necessary steps required to build upon and enhance the usefulness of this tool. Obvious potential improvements include allowing for more permutations of water reuse schemes such that three or more processes may be compared simultaneously. Allowing the user to choose the number of processes to be modeled will enhance the potential usefulness of the program and allow entire plant surveys to be conducted. Another useful addition to the program would be to allow for the inclusion of more than one contaminant. Currently, multiple contaminants can be modeled in the program by conducting multiple program runs. The treatment of multiple contaminants in an enhanced program would substantially reduce program execution time. These enhancements will require additional coding in the program to allow for the additional comparisons of influent and effluent purity and quantity values. It would require even larger amounts of code to optimize the potential reuse opportunities that may arise when modeling for additional processes and contaminants owing to the multiplicative effect of the increased number of permutations.

Other potential upgrades to the program would require less additional coding. Providing a basis for updating and adding potential treatment technologies would enhance the program's effectiveness. The user may also specify the viability of some reuse opportunities by, for example, specifying that the program show only those opportunities with a payback period of less than, say, three years. Providing a simpler routine for altering one input data parameter value at a time would provide a simple and quick method to perform sensitivity analyses.

It should be noted that the above changes to the program will require more time spent by the user in initial data collection. For example, if three instead of two processes were to be analyzed for potential coupled reuse schemes, additional information concerning the third process would need to be collected as program input. This increased time requirement may or may not justify the amount of additional, more specific information obtained from the enhanced program.

The guidance manual accompanying the software can be expanded in the future to include additional case studies and documentation of successful water reuse projects as they are reported. Documenting the technical and economic feasibility of water reuse projects is vital to convincing industrial facility management personnel that water reuse projects should be implemented. The guidance manual should not, however, contain too much material as to overwhelm readers. The manual is designed to provide basic information and to show that water reuse is technically and economically feasible in many typical industrial situations.

The type of logic used in this software in which influents and effluents are compared for possible reuse, may be applied to other resources in industrial facilities. One such resource may be waste heat. As an example, consider the waste heat produced by the operation of air compressors used in almost all manufacturing facilities. This waste heat may be redirected to other heat-utilizing processes in much the same way wastewater may be redirected for use as influent for another process. The waste heat from air compressors may be used to preheat boiler feed water or to supplement space heating in manufacturing areas. The airflow volume is analogous to the water flow rate while the temperature of the air stream is analogous to the contaminant concentration in the water. The similarities between the reuse of water and the reuse of heat make this design approach and software applicable to both situations.

Water Reuse Future Research

The difficulty in obtaining membrane separation technology information as discussed earlier is currently a significant impediment to the use of membranes in industrial water reuse applications. Additional research in this area could provide more general performance and cost data, thus reducing the amount of initial bench-scale testing required for membrane system installation.

Due to the site-specific nature of water-utilizing processes and potential reuse opportunities, future research is needed to identify problems with specific reuse scenarios. In addition, process influent quality requirements are not well documented for most specific plant unit operations utilizing water. The acceptable cleanliness for boiler and cooling tower feed water and the use of reclaimed municipal wastewater in cooling towers are well documented. However, the "cleanliness" needed for other processes and actual documentation of other reuse scenarios is not as well known. Understanding process input purity requirements and the changes in contaminant concentrations that occur through a process are the keys to improving model prediction reliability and increasing the number of facilities that reuse water onsite.

It is believed that increasing the water reuse knowledge base will stimulate additional study, research and implementation of industrial water reuse projects. More importantly, transferring this information to the plant personnel who really need it, plant engineers and plant managers, will be the key to increasing the initiation of water reuse projects. This could ultimately lead to a significant reduction in the dependency on currently depleting fresh water supplies.

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APPENDICES

APPENDIX 1

POWR PROGRAM USER GUIDANCE MANUAL

A guidance manual designed to supplement the POWR program instruction manual was designed to help convince plant engineers that many different water reuse opportunities have previously been considered at adequate technical and economic levels of concern. The following information, which was presented earlier in this document, will be in the guidance manual.

- Characteristics of Membrane Technology (p. 19)
- Hierarchy of Water Use and Reuse (p. 37)
- Discussion of Input Requirements (p. 53)
- Treatment Processes and Basis for Costs, Removal Efficiencies and Recovery Rates Used in the Program (p. 60)
- Discussion of Output Results (p. 68)
- Instructions for Program Use (p. 70)

This information will not be repeated here for this document, however, additional information that will be included in the guidance manual is presented next in this Appendix.

Disclaimer Concerning Technical and Economic Feasibility

The lists of potential reuse streams and associated water reuse case studies presented later reveal that often many water reuse opportunities are possible. Such projects have proven to be both technically and economically feasible. In addition, with some reuse schemes there is a possibility that some water-utilizing processes will be operated with a higher quality water than that previously used. This may prove beneficial in some cases due to the increased process efficiency associated with the use of higher quality water (e.g., for parts cleaning). Likewise, the quality of the wastewater generated may be higher. This may improve the quality of the resultant

permeate stream of some treatment processes resulting in a water stream that has increased potential to be reused (DeGenova and Shadman, 1997).

When using the POWR program and when considering the implementation of identified water reuse schemes, some cautions must be pointed out. When determining the acceptable influent quality of a process influent stream, appropriate bench-scale testing should be performed. Although minimum quality standards for some processes are reported in the literature (Deb and Schorr, 1996; Freeman, 1995; Sundberg *et al.*, 1991), testing which includes the effects of site-specific variables will ensure that product quality will not be affected by changes in process water quality. If new treatment technologies are to be utilized, they should also be properly tested and evaluated for site-specific effectiveness. With some treatment processes, residual wastes may be produced and must be properly handled and disposed.

The implementation of water reuse projects will increase the complexity and intra-dependency of water-using processes within a facility. Proper monitoring and control systems should be installed as needed to prevent possible operational problems. Employees should be properly trained and instructed on the new operation setup and someone should be given the responsibility for managing the new reuse system (Hamilton, 1996).

Prior to implementing a water reuse project, it must be ensured that all standards and environmental regulations are being met. Although there are no identified federal or state laws directly concerning internal industrial water reuse (EPA, 1992), many industry-specific standards do exist. For example, the Semi-conductor Equipment and Materials International (SEMI) sets standards for the quality of water used in the semiconductor industry while the American Society for Testing and Materials (ASTM) determines standards for electronics-grade process water (DeSilva, 1996). Additional water quality standards may be required by the USDA and FDA (Esvelt *et al.*, 1979).

Another potential concern when implementing water reuse projects is ISO 9000 and 14000 certification. Especially for facilities that are both ISO 9000 and ISO 14000 certified, there appears to be a potential conflict of interest in the case of water reuse. On one hand, the quality standards associated with ISO 9000 would appear to condemn the practice of reusing water because it may be of a lesser quality than the water originally used in the manufacturing process. Although there should not be any degradation in product quality associated with the use of this reclaimed water, "dirtier" water is being used. On the other hand, the environmental standards associated with ISO 14000 would appear to encourage the practice of reusing water because there would be a reduced need of fresh water and less wastewater discharged into the environment.

Conversation with Sue Jackson (1999), Director of Environmental Services with the Excel Partnership, dispelled this apparent conflict. According to Ms. Jackson, both ISO standards are generic management system standards. ISO 9001 would not prescribe a specific water quality level to be used in a process, rather it would provide the means of establishing a quality control system. Similarly, under ISO 14001, an organization develops environmental objectives, procedures and targets to reduce environmental impacts. The standard does not specify these objectives and targets, rather it provides a system which enables the facility to meet their self-imposed targets.

Finally, the analyses performed in the POWR program do not consider the possible costs associated with consulting, research, testing and system installation. The savings reported by the program are calculated from user-supplied water purchase and wastewater discharge cost data. Capital and operating costs for the membrane separation treatment technologies have been estimated from published literature and conversations with water treatment professionals. This program was designed to provide first-order cost estimates and was not designed to include all potential additional costs related to implementation of a particular water reuse project.

Common Water Reuse Opportunities

There are often many sources of wastewater within manufacturing facilities and many potential uses of this wastewater exist which may or may not require on-site treatment. Due to recent advances in water and wastewater treatment, any water stream may be treated to any quality desired. Then, theoretically, any wastewater stream is a potential candidate for reuse. Although it may be technologically feasible to recycle almost all wastewater streams, it is seldom economically feasible based on normally acceptable payback periods for capital improvements.

Many manufacturing operations that utilize fresh water can effectively utilize wastewater. Typical uses for reclaimed wastewater inside a facility include cooling tower makeup, boiler makeup, aqueous parts cleaning, equipment and floor cleaning water, gas cleaning and scrubbing systems and many industry-specific processes. Reuse in such situations has been practiced for many years (Mierzejewski, 1997; Betz Industries, 1980). The sources of reusable wastewater shown in Table AI-1 have been documented to be recyclable in certain situations where these sources are available.

Although too numerous to list here, many industry-specific process wastewaters may be reused. For example, the following process wastewaters have been reported to have been reused in some situations: ammonia plant process condensate, chemical plant process condensate, refinery sour water stripper bottoms, paper mill process water and steel mill process water (Betz Laboratories, 1980). Some of the potential sources listed in Table AI-1 should be reused with caution due to the unpredictability of quantities available and contaminant concentration levels (Hamilton, 1996).

Since once-through cooling towers use large amounts of water, most industrial cooling towers in use today utilize circulating water so that only a portion of the water is discharged as blowdown or overflow. Often, cooling water systems make up the largest percentage of water use in an industrial plant (Betz Industries, 1980). In addition, the quality of water used for

Table AI-1. Potential sources of reusable wastewater.

Municipal secondary treated effluent	Steam condensate (not returned to boiler)
Industrial wastewater treatment effluent	Rainfall
Cooling tower blowdown	Stormwater
Boiler blowdown	Filter and ion exchange backwash
Analytical instrument discharge	Filtration system reject streams
Ion exchange regeneration rinses	

Source: Hamilton, R.L. (1996) Cascading Water Balances for Optimum Water Reuse. Paper presented at Corrosion 96: The NACE International Annual Conference and Exposition, Houston, TX.

cooling tower makeup is modest (Deb and Schorr, 1996; Freeman, 1995; Sundberg *et al.*, 1991), as shown in Table AI-2. These two factors make cooling towers a prime candidate for supply with recycled water. The wastewater resulting from many varied processes may potentially be used to supplement cooling tower makeup water and may also be possible to cascade water use when utilizing multiple cooling towers (Betz Laboratories, 1980). In such situations, the blowdown from one cooling tower is cascaded, or becomes makeup water or makeup supplement water for another tower. As the quality of the fresh water source increases, the effectiveness of cascading cooling tower water flows increases (Galbreath, 1994).

When multiple boilers are operated in a facility, the makeup water may be used in a cascading fashion similar to that for cooling towers described above. Normally, the primary purpose of this reuse scheme is to recover the heat from the high-temperature blowdown water that results in fuel savings. High-pressure boiler blowdown, which is generally low in solids, may be reused as makeup water for lower pressure boilers which require water of a lower quality (Betz Laboratories, 1980). Since the blowdown water is already heated, the requirement of heating the low-pressure boiler feed water is minimized or eliminated. Recommended boiler feed water criteria are listed in Table AI-3. As seen in this table, boiler water quality requirements are generally dependent on the operating pressure (Cain *et al.*, 1997; Betz Laboratories, 1980). High pressure boilers require purer water because the increased temperatures and pressures enhance corrosion rates and reactivity with dissolved oxygen (Hollander *et al.*, 1999; Hollander and Freedman, 1997).

In some situations it may be possible to reuse boiler blowdown as cooling tower makeup water or as a portion of the makeup, however, the high temperature of the boiler blowdown may pose problems in a reuse scheme (Hamilton, 1996). Galbreath (1994) reiterates the possible temperature effects and other limitations including the following: "the overall impact of the blended chemistry including pH effects, conductivity, phosphates, particulates, as well as soluble

Table AI-2. Cooling tower water quality specifications.

Parameter	Recommended limit
Aluminum	0.1
Iron	0.5
Manganese	0.5
Alkalinity	350
Ammonia	< 50
Calcium	50
Chloride	500
Hardness	650
pH	6.9 – 9.0
Phosphate	4
Silica	50
Sulfate	200
Total suspended solids	100
Total dissolved solids	500
Coliform, #100 mL	< 2.2
MBAS (Surfactant)	1
Total organic carbon	< 50
Magnesium	0.5
Bicarbonate	24
Chemical oxygen demand	75

Note: All measurements in mg/L, except pH and coliform.
Sources: Sundberg, S.R., Parker, J.D., Chapman, R.L., and Rippon, D.W. (1991) Reclaimed Wastewater for Industrial Utilization. Paper presented at American Water Resources Association Water Supply & Water Reuse: 1991 & Beyond, San Diego, CA.
Freeman, H.M. (1995) Industrial Pollution Prevention Handbook. McGraw-Hill, Inc., New York, NY.
Deb, A.K., and Schorr, P. (1996) Industrial Water Reuse. Paper presented at 1996 American Water Works Association Annual Conference, Toronto, Ontario, Canada.

Table AI-3. Recommended industrial boiler feed water quality criteria.

Parameter[1]	Low Pressure (<150 psig)	Intermediate Pressure (150-700 psig)	High Pressure (>700 psig)
Silica	30	10	0.7
Aluminum	5	0.1	0.01
Iron	1	0.3	0.05
Manganese	0.3	0.1	0.01
Calcium	[2]	0.4	0.01
Magnesium	[2]	0.25	0.01
Ammonia	0.1	0.1	0.1
Bicarbonate	170	120	48
Sulfate	[2]	[2]	[2]
Chloride	[2]	[2]	[2]
Dissolved solids	700	500	200
Copper	0.5	0.05	0.05
Zinc	0.01	0.01	[2]
Hardness	350	1	0.07
Alkalinity	350	100	40
pH	7.0-10.0	8.2-10.0	8.2-9.0
COD	5	5	1
Hydrogen sulfide	[2]	[2]	[2]
Dissolved oxygen	2.5	0.007	0.0007
Suspended solids	10	5	0.5

[1]All units in mg/L, except pH.
[2]After adequate pretreatment to meet the other limiting values, the concentration of this parameter has not been a problem or limiting value in boiler operation.
Source: Deb, A.K., and Schorr, P. (1996) Industrial Water Reuse. Paper presented at 1996 American Water Works Association Annual Conference, Toronto, Ontario, Canada.

and insoluble metals in the boiler blowdown; incompatibilities of certain boiler and cooling polymeric dispersants." Treatment suggested in order to reuse the boiler blowdown for cooling tower makeup may be as simple as lime softening (Galbreath, 1994). Lime softening will remove most boiler treatment chemicals and in any case some newly formulated boiler dispersants are more compatible with cooling water chemistries.

Concentrate streams resulting from water and wastewater treatment processes may also be utilized as a source of fresh water. A few specific examples are cited below. Water used in a fast rinse and backwash of the regeneration of a fixed bed ion exchanger can be used for processes with modest quality requirements such as for cooling system makeup (Hamilton, 1996; Galbreath, 1994). The reject wastewater (concentrate stream) from a membrane separation process, e.g., reverse osmosis, may also potentially be reused for some modest water quality processes (Hamilton, 1996). The backwash water used to remove the suspended solids from a wastewater purification filter may also possibly be reused since this is fairly clean water (Hamilton, 1996). DeGenova and Shadman (1997) list a number of water reuse opportunities, including the use of the reject flow from a reverse osmosis unit for cooling tower makeup, air scrubbers or for irrigation.

Air pollution control equipment that utilizes water may also be a potential candidate for reuse. For example, cooling tower blowdown may be used as gas scrubber makeup water in some situations (Hamilton, 1996).

Documented Case Studies of Water Reuse

Documented case studies of industrial water reuse projects have been collected to assist in proving the adequacy and appropriateness of water reuse projects. A significant limitation in the implementation of water reuse projects appears to be the difficulty that plant personnel have in keeping abreast of recent advances. When a potential reuse plan is discovered, there may be

uncertainties as to the potential effectiveness and the possible level of disruption to plant operations. Providing data in the form of documented case studies allows plant personnel to realize the feasibility of reuse ideas in a practical implementation sense and in an economic sense. A few of the successful water reuse projects are briefly summarized in Table AI-4 to illustrate the range of water reuse possibilities for various industries.

Major Contaminants of Concern and Input Purity Requirements for Common Industrial Processes

Among published water reuse papers and documented water reuse projects, some contaminants are described as being of particular concern in certain processes. The contaminants of primary concern are industry and process-specific (Puckorius *et al.*, 1998). The concentrations of these contaminants may limit or prevent some potential reuse opportunities. Typically, these contaminants are partly responsible for one of the following negative effects in reuse systems: scaling and deposit formation, increased corrosion rates and increased microbiological activity. A few of the most problematic contaminants for common reuse opportunities are listed in Table AI-5. Once the parameters of concern are determined for a specific reuse scheme, the appropriate monitoring techniques may be selected and utilized.

As discussed previously, cooling towers are a common target for water reuse due to their large water quantity usage (due to evaporation) and low water quality requirements. Specific contaminants that may cause problems in cooling towers are listed in Table AI-6. The contaminants that are of concern in cooling tower operation are those that affect the corrosivity of the water, cause scaling or enhance microbiological growth. Thus, the concentrations of these contaminants must be kept in control by proper monitoring, addition of biocides, adjustment of cycle time and amount of blowdown.

Table AI-4. Documented water reuse case studies.

Type of Facility	Measure(s)	Reference
Kelly Air Force Base	Treated industrial wastewater is reused for golf course irrigation. Electroplating rinse waters are treated with ion exchange and reused as electroplating rinse water.	Ryan and Backlund, 1996.
Military field facility	Laundry and shower water is reused after the following treatment: coagulation, activated carbon and polymer adsorption, settling and filtration and chlorination.	Scholze, Jr. and Smith, 1988.
Metal finishing facility	Rinse water is treated for reuse using reverse osmosis.	Tragellis, 1993.
Metal finishing facility	Rinse water is treated for reuse using ion exchange and microfiltration.	Friedlander and Tragellis, 1996.
Electroplating facility	Reverse osmosis is used to treat rinse water. Permeate stream is returned to the rinse tanks and concentrate stream is returned to the plating tanks.	Cartwright, 1992.
Dyestuffs plant	Ultrafiltration and reverse osmosis are used to treat process water. Permeate stream is used for air emission control processes and equipment cleaning and concentrate stream is reused in the dying process.	Jessen and Kemp, 1996.
Metropolitan Water Reclamation District of Greater Chicago	Treated wastewater is reused internally for equipment washdown, cooling water, pump cooling and lubrication, irrigation, odor suppressant, foam control and retention pond dilution.	Knight and Sokol, 1991.
Chevron U.S.A. Richmond Refinery	Treated municipal effluent is used as cooling tower makeup.	Yoloye *et al.*, 1996.
Construction site	Treated municipal effluent is used for soil compaction and dust control.	Crook and Okun, 1987.
Paper mill	Treated municipal effluent is used as process water.	Crook and Okun, 1987.

Table AI-4. (continued).

Type of Facility	Measure(s)	Reference
Power plant	Treated municipal effluent is used for cooling tower makeup. Cooling tower blowdown is used in air emission control scrubbing equipment.	Crook and Okun, 1987.
Rockwell International Corporation	Treated municipal effluent is used to cool rocket engine deflector pads at one test facility.	Crook and Okun, 1987.
Copper rod mill	Reverse osmosis and nanofiltration is used to treat copper rinse water. The permeate is reused as rinse water and the concentrate is reused in the pickling bath.	Lien, 1998.

Table AI-5. Common contaminants of concern for industrial water reuse opportunities.

Total suspended solids	Biological oxygen demand	Turbidity
Total dissolved solids	Chemical oxygen demand	Sulfates
Calcium	Magnesium	Iron
Iron	Sodium	Heavy metals
Ammonia	Nitrate	Chloride
Fluoride	pH	Total organic carbon

Sources: Rosain, R.M. (1993) Reusing Water in CPI Plants. *Chemical Engineering Progress*, **89**, 4, 28.
Jessen, H.M., and Kemp, P.M. (1996) Striving for Water Recovery and Reuse. *Environmental Engineering World*, **2**, 6, 14.

Table AI-6. Contaminants that may cause problems in a cooling water system.

Parameter	Potential problem
Total dissolved solids	Increased corrosivity and effluent toxicity
Total suspended solids	Increased deposition potential
Biochemical oxygen demand	Biofouling potential
Ammonia	Aggressive to copper metallurgy, increased corrosivity
Phosphates	Biofouling, adversely affects cooling water treatment
Oil and grease, metals	Fouling
Sulfides	Corrosivity
Hardness, Silica, Alkalinity	Scaling
Organics	Foaming in recirculating water

Sources: Galbreath, L.G. (1994) Water Conservation and Reuse Options. Paper presented at Watertech '94, Houston, TX.
Frayne, S.P. (1992) Minimize Plant Wastewater. *Hydrocarbon Processing*, **71**, 8, 79.
Strauss, S.D. (1991) Water Management for Reuse/Recycle. *Power*, **135**, 5, 13.

Many of the concerns associated with the reuse of water in cooling towers, such as deposit formation and increased corrosion rates, are concerns for water reuse as boiler feed water as well (Cain *et al.*, 1997). Boilers require substantially higher purity feed water than cooling towers, thus water reuse opportunities involving boilers are less common.

Other contaminants of concern vary with industry and the specific processes used in manufacturing. The semiconductor industry, which uses relatively large amounts of water for process cooling and rinsing operations, operates within strict industry standards (Deb and Schorr, 1996). The primary contaminants that are of concern are residual organic solvents present in the rinse water that may degrade the computer chip circuit connections (DeGenova and Shadman, 1997; Deb and Schorr, 1996; Sinisgalli and McNutt, 1986). In the textile industry, color is typically the parameter that will limit potential reuse options and in some cases solids present in the water may interfere with process chemicals in a negative manner (Goodman and Porter, 1981). In the electroplating industry, many various contaminants such as sodium, iron and calcium may cause problems by causing brittleness or deposits of the plated pieces (Deb and Schorr, 1996).

Possible Problems Associated With Reuse

The most common problem associated with the reuse of wastewater is the concentration of dissolved solids (Schiller and Hackman, 1993). As water containing dissolved solids and other contaminants is recirculated without treatment, the contaminant concentrations typically increase. The accumulation of dissolved solids content may contribute to mineral deposits on equipment (Hamilton, 1996). Magnesium silicates and calcium phosphates may also form scale on equipment surfaces (Sundberg *et al.*, 1991; Rebhun and Engel, 1988). Scale formation will decrease the heat transfer efficiency of cooling towers and other heat exchangers and increase the pressure drop in piping networks (Martin and Miller, 1986). When water is to be recirculated in

processes such as for cooling tower use, the dissolved solids concentration must be monitored. Once the concentration reaches an unacceptable level, a portion of the recirculated water is blown down, or discharged, and fresh water is then added to the system (Schiller and Hackman, 1993).

Corrosion is another potential problem of water reuse, especially in recirculating systems such as cooling towers (Byers, 1995; Rosain, 1993; Rebhun and Engel, 1988). Corrosion is generally dependent on pH and total dissolved solids concentrations (Sundberg *et al.*, 1991). Ammonia (leaking from chiller systems) may also be corrosive to some surfaces (Rebhun and Engel, 1988). Proper precautions must be taken such that water circulation equipment and process equipment can properly resist the potential increased corrosion ability of the water (Bolick and Yolton, 1996).

Biofouling is another concern especially when using reclaimed municipal wastewater. Treated municipal effluent and other wastewaters high in nitrogen and phosphorus concentrations are likely to cause biofouling without proper precautions (Rebhun and Engel, 1988). Microbiological growth may plug pipes and other equipment and increase wear and maintenance (Klinker, 1996). Potential solutions to biofouling problems include the use of chlorine dioxide and bromine chloride biocides to control microorganism growth (Klinker, 1996; Wijesinghe *et al.*, 1996).

Two other less discussed problems may occur upon the implementation of a water reuse project. Once a reuse system is in place, certain dependencies are created within the plant and thus there may be reduced plant reliability (Byers, 1995). If a process that supplies fresh water to another process shuts down, the process receiving effluent cannot operate (without an alternate supply). Previously, however, only the one process would be out of service since other processes would still have fresh (utility) water as a source. As indicated above, another problem is the buildup of trace contaminants (DeGenova and Shadman, 1997; Byers, 1995). Contaminants at previously undetectable levels may build in recirculating systems after the initiation of a water

reuse project. These contaminants may later negatively affect the process or may build to levels that violate discharge permits. There may also be chemical interactions between contaminants such as precipitation reactions that were initially not present in the system (Blake and Stuart, 1993).

Monitoring Requirements

Many of the potential problems associated with water reuse may be eliminated or reduced with initial bench-scale testing and continuous monitoring after implementation. Proper testing can reveal how many processes will be affected by changes in water quality. However, some problems such as increasing dissolved solids concentration may not be noticed in a bench-scale test due to the short amount of testing time used and the controlled nature of these tests (Schiller and Hackman, 1993). Therefore, online instrumentation should be utilized and may even be required in some industries such as the pharmaceutical industry (Maughan and Mangel, 1999). Monitoring the water quality in reuse systems will minimize system upsets (DeGenova and Shadman, 1997). Having a fresh water backup system may be necessary to prevent long periods of downtime if recycle system upsets become common. Treatment processes, if used in a water reuse system, should also be monitored to ensure proper operation. Lueck (1998) discusses a computerized reverse osmosis monitoring system including the appropriate operating parameters that should be continuously measured.

Treatment Vendor Contacts

Table AI-7 provides contact information for numerous membrane equipment manufacturers and vendors in the United States.

Table AI-7. Membrane technology vendors.

Company	Location	Contact Information	World Wide Web site	Products
U.S. Filter/Memcor Products	9690 Deereco Road, Suite 410 Timonium, MD 21093	Tel: (410) 560-3024 Fax: (410) 561-3017	http://www.usfilter.com	RO, NF, UF, MF
Culligan International Corporation	One Culligan Parkway Northbrook, IL 60062	Tel: (800) 285-5442 Fax: (847) 205-6030	http://www.culligan.com	RO
Ionics, Incorporated	65 Grove Street Watertown, MA 02472-9131	Tel: (617) 926-2500 Fax: (617) 926-4304	http://www.ionics.com	RO, UF
Koch Membrane Systems, Incorporated	850 Main Street Wilmington, MA 01887-3388	Tel: (800) 343-0499 Fax: (978) 657-5208	http://www.kochmembrane.com	RO, NF, UF, MF
Dow Chemical Company	P.O. Box 1206 Midland, MI 48641-1206	Tel: (800) 447-4369 Fax: (517) 832-1465	http://www.dow.com	RO, NF, UF, MF
Osmonics, Incorporated	5951 Clearwater Drive Minnetonka, MN 55343-8995	Tel: (800) 848-1750 Fax: (612) 933-0141	http://www.osmonics.com	RO, NF, UF, MF
Mobile Process Technology	2070 Airways Boulevard Memphis, TN 38114-0867	Tel: (901) 744-1142 Fax: (901) 743-0867	http://www.mobileprocess.com	RO, NF, UF, MF
Pall Water Processing	2200 Northern Boulevard East Hills, NY 11548	Tel: (888) 873-7255 Fax: (516) 484-3216	http://www.pall.com	RO, NF, UF, MF
Remco Engineering	410 Bryant Circle Ojai, CA 93023	Tel: (805) 646-3706 Fax: (901) 646-3923	http://www.remco.com	RO, NF, UF, MF
Hydranautics	401 Jones Road Oceanside, CA 92054	Tel: (619) 901-2500 Fax: (619) 901-2578	http://www.membranes.com	RO, UF
Aqua Pura-Tempest Environmental Systems, Inc.	101 West Markham Avenue Durham, NC 27701-1314	Tel: (919) 688-1460 Fax: (919) 688-1466	http://www.aquapura.com	RO, UF

Note: RO = reverse osmosis, NF = nanofiltration, UF = ultrafiltration, MF = microfiltration.

Bibliography and Other References

The guidance manual will include all references previously listed in this document plus the following contact information in Table AI-8 for various water and wastewater organizations and associations that may be of interest.

Table AI-8. Additional sources of water and wastewater information.

Organization	Location	Contact Information	World Wide Web site
Environmental Protection Agency – Office of Water	401 M. Street, S.W. Washington, D.C. 20460		http://www.epa.gov/OW/ OW-General@epamail.epa.gov
Water Environment Federation	601 Wythe Street Alexandria, VA 22314-1994	Tel: (800) 666-0206 Fax: (703) 684-2492	http://www.wef.org
American Water Works Association	6666 West Quincy Avenue Denver, CO 80235	Tel: (303) 794-7711	http://www.awwa.org
Water Quality Association	4151 Naperville Road Lisle, IL 60532	Tel: (630) 505-0160 Fax: (630) 505-9637	http://www.wqa.org info@mail.wqa.org
USDA National Extension Water Quality Database			http://hermes.ecn.purdue.edu:8001/ server/water/water.html
Water Reuse Association of California	915 L. Street, Suite 1000 Sacramento, CA 95814-3701	Tel: (916) 442-2746 Fax: (916) 442-0382	http://www.webcom.com/h2o/ law@ngke.com
Water Technology National Trade Publications	13 Century Hill Drive Latham, NY 12110		http://waternet.com
Tall Oaks Publishing *UltraPure Water*	P.O. Box 621669 Littleton, CO	Tel: (303) 973-6700 Fax: (303) 973-5327	http://www.talloaks.com water@talloaks.com
Environmental Solutions Information System	1339-165 Bennett Drive Longwood, FL 32750	Tel: (407) 339-0314 Fax: (407) 339-0314	http://www.cleanerworld.com info@cleanerworld.com
Advanced Reclamation Technologies	9445 East Doubletree Ranch Road Scottsdale, AZ 85258	Tel: (602) 391-9939 Fax: (602) 391-6794	http://www.h2oreuse.com rjj214@aol.com
WaterWiser: The Water Efficiency Clearinghouse	6666 West Quincy Avenue Denver, CO 80235	Tel: (800) 559-9855	http://www.waterwiser.org/
Association of Water Technologies, Incorporated	8201 Greensboro Drive, Suite 300 McLean, VA 22102	Tel: (800) 858-6683	http://www.awt.org awt@awt.org

Table AI-8. (continued).

Organization	Location	Contact Information	World Wide Web site
Water and Waste Water Dot Com	3948 South Third Street, No. 121 Jacksonville Beach, FL 32250	Tel: (904) 280-4656 Fax: (904) 273-1399	http://www.waterandwastewater.com
Water – Wastewater Web			http://www.w-ww.com webmaster@w-ww.com
Water Online			http://www.wateronline.com
WasteWater Engineering Virtual Library			http://www.cleanh2o.com cleanh2o@cleanh2o.com

APPENDIX II

REUSE OPPORTUNITY DIAGRAMS

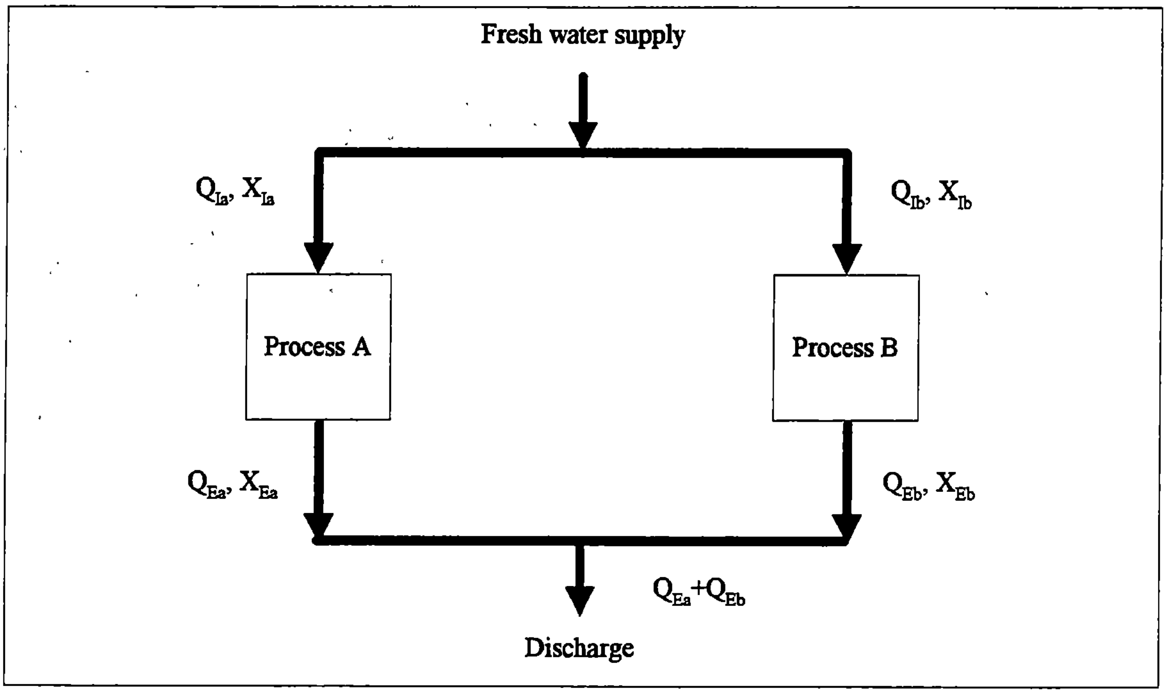

Figure AII-1. Diagram of the initial water flow situation prior to reuse.

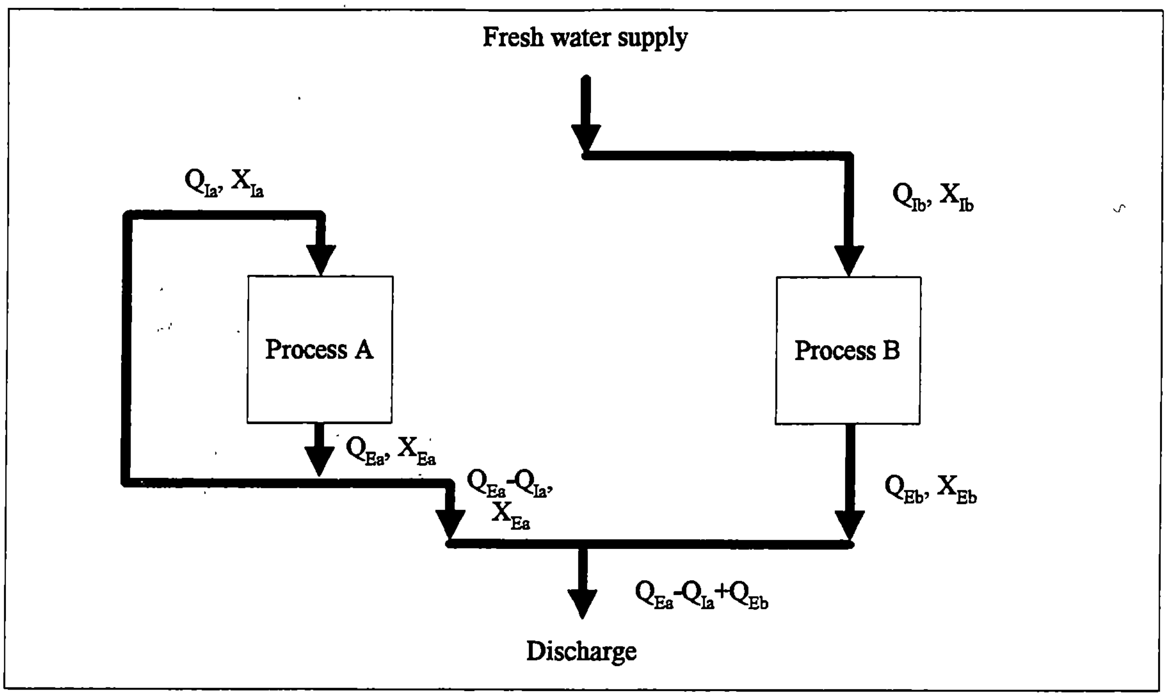

Figure AII-2. Diagram of reuse opportunity #1.

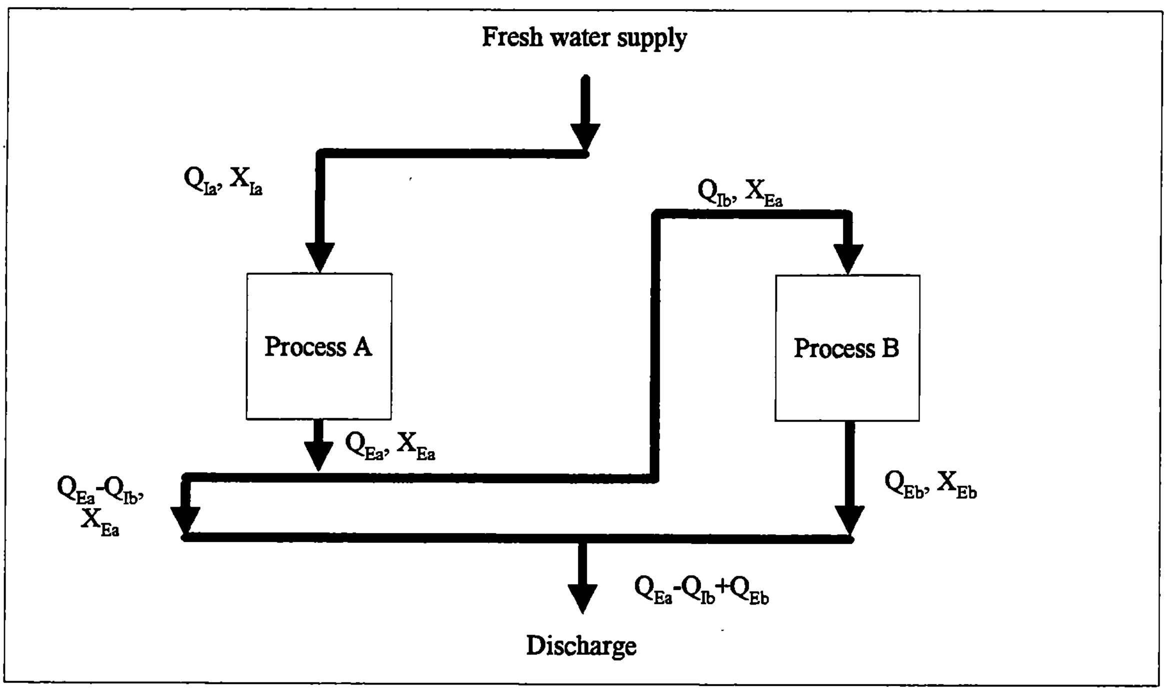

Figure AII-3. Diagram of reuse opportunity #2.

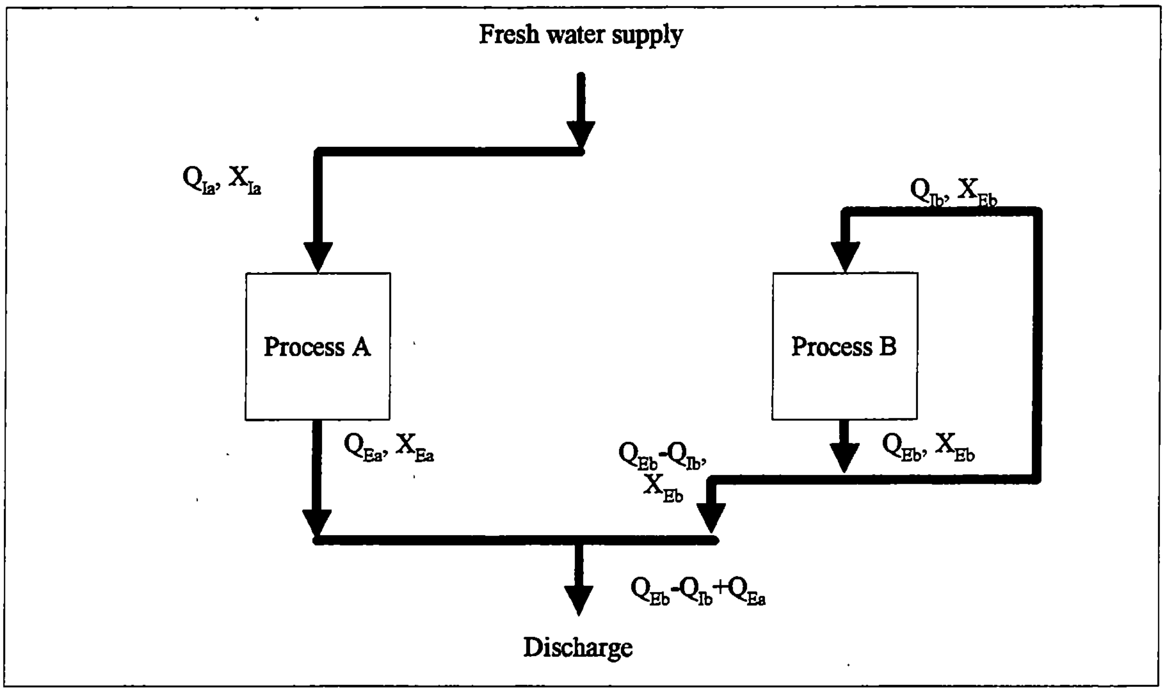

Figure AII-4. Diagram of reuse opportunity #17.

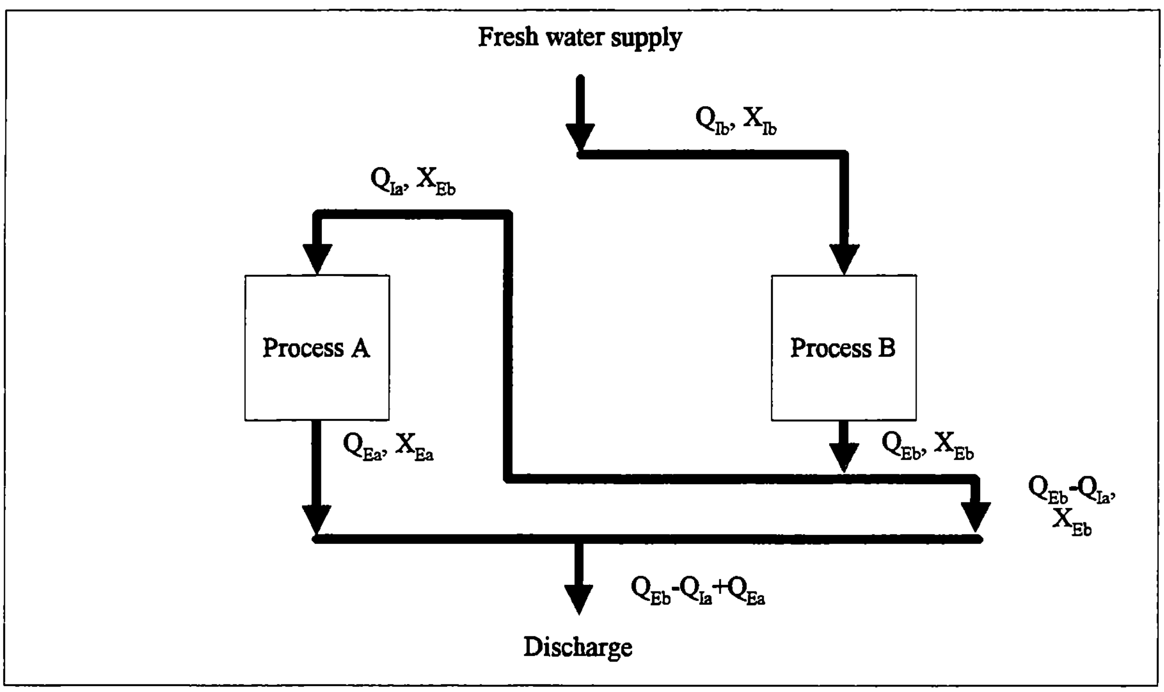

Figure AII-5. Diagram of reuse opportunity #18.

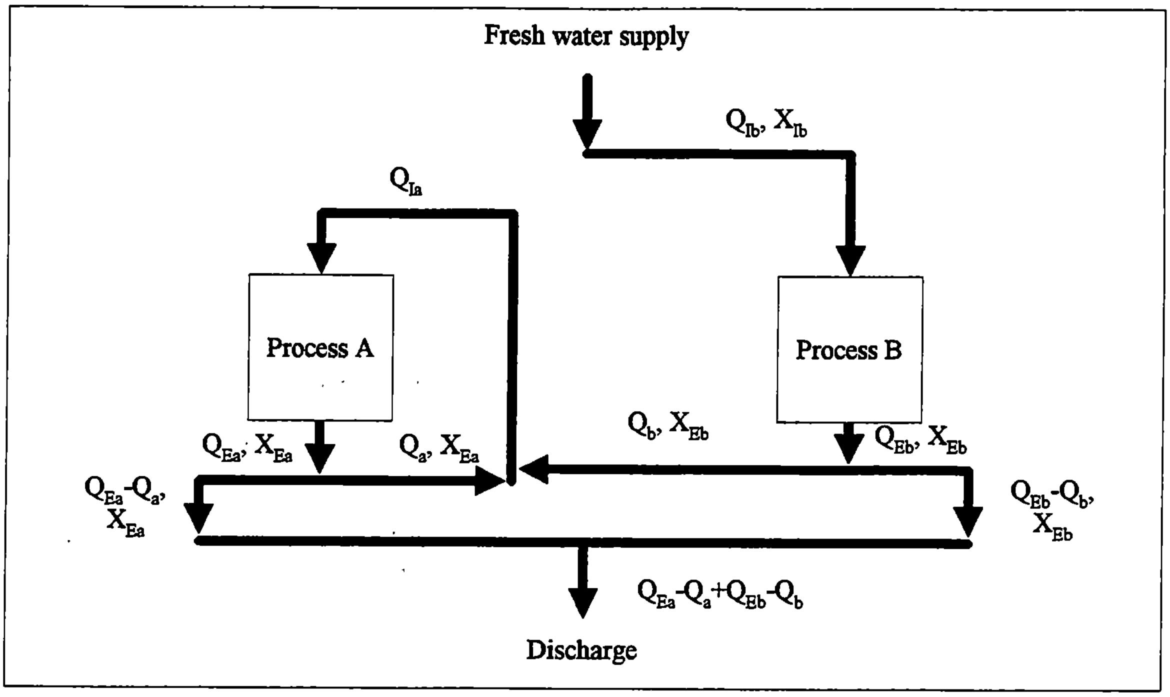

Figure AII-6. Diagram of reuse opportunity #3.

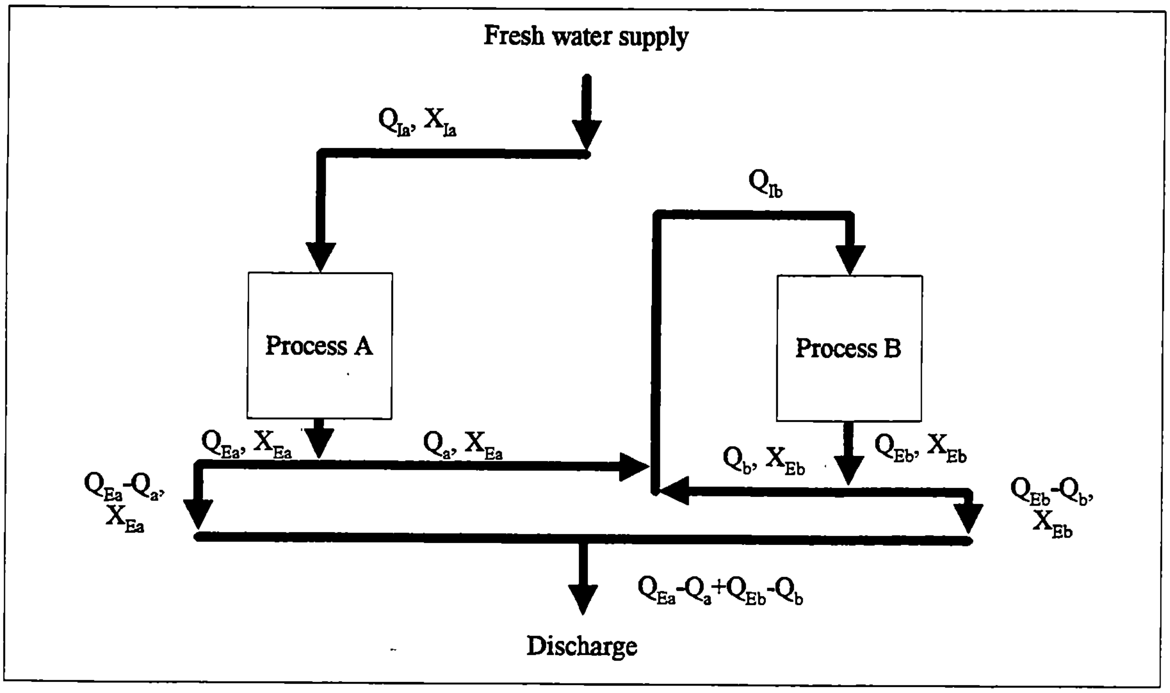

Figure AII-7. Diagram of reuse opportunity #4.

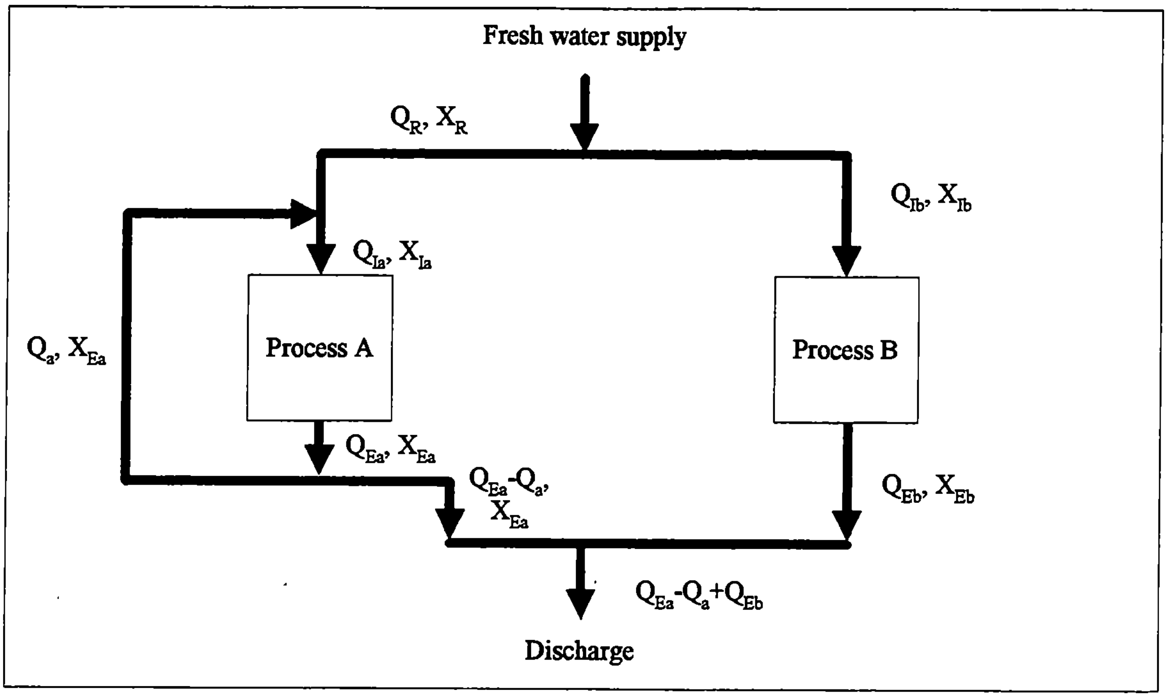

Figure AII-8. Diagram of reuse opportunity #5.

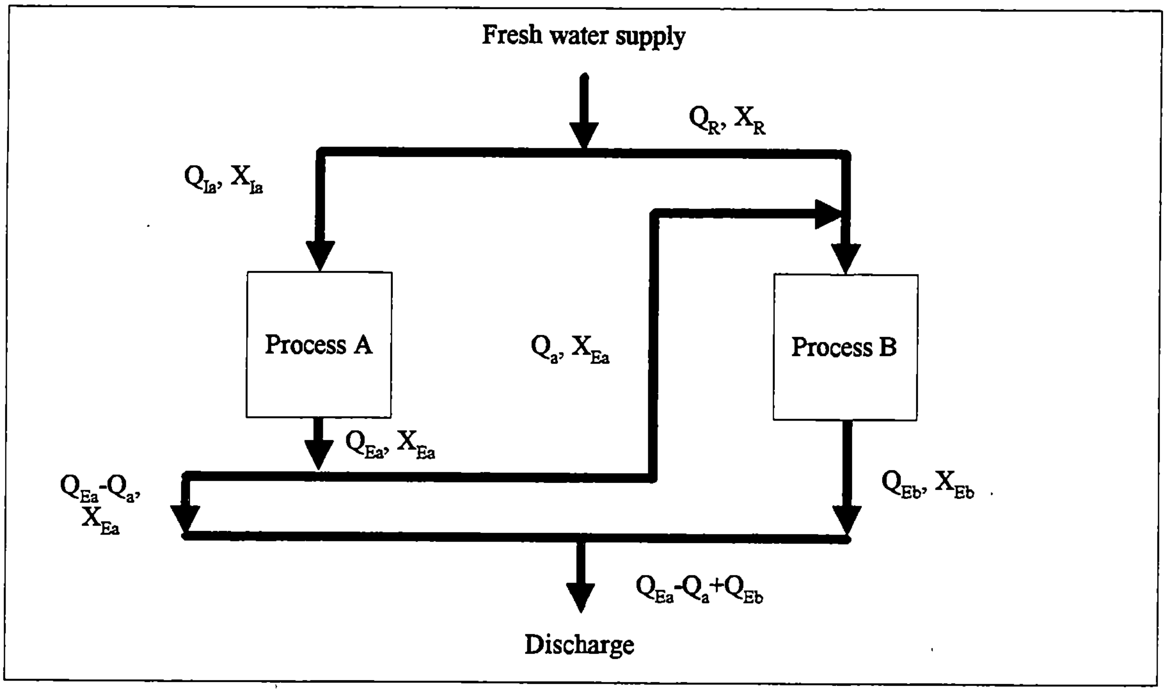

Figure AII-9. Diagram of reuse opportunity #6.

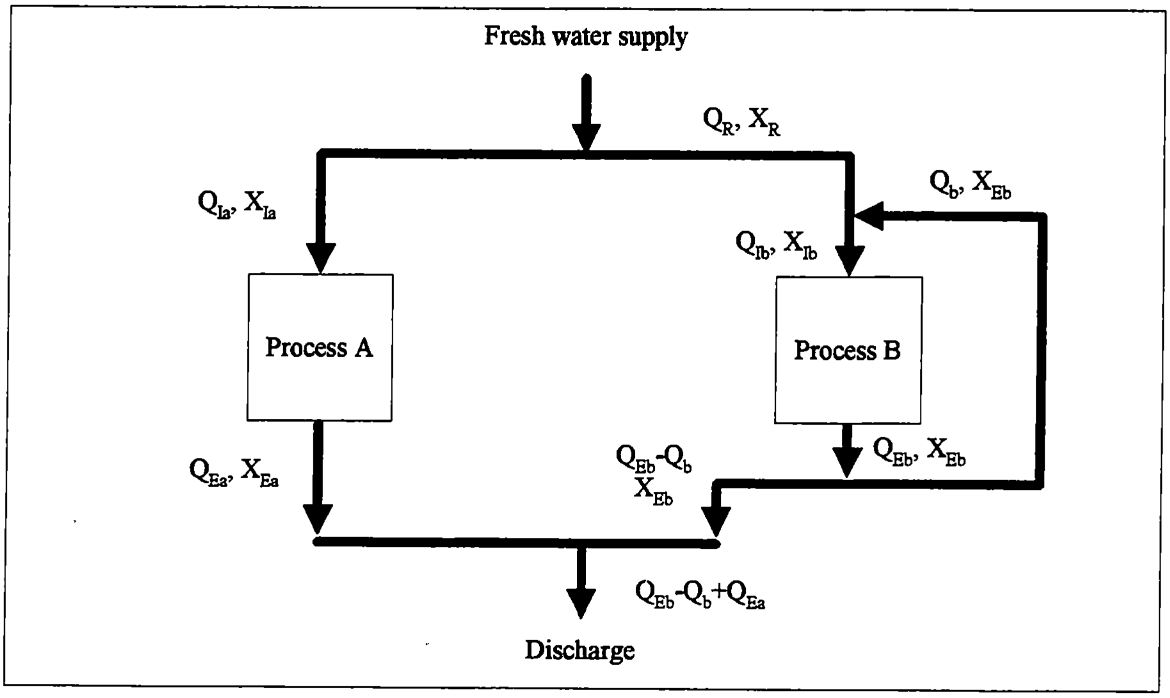

Figure AII-10. Diagram of reuse opportunity #19.

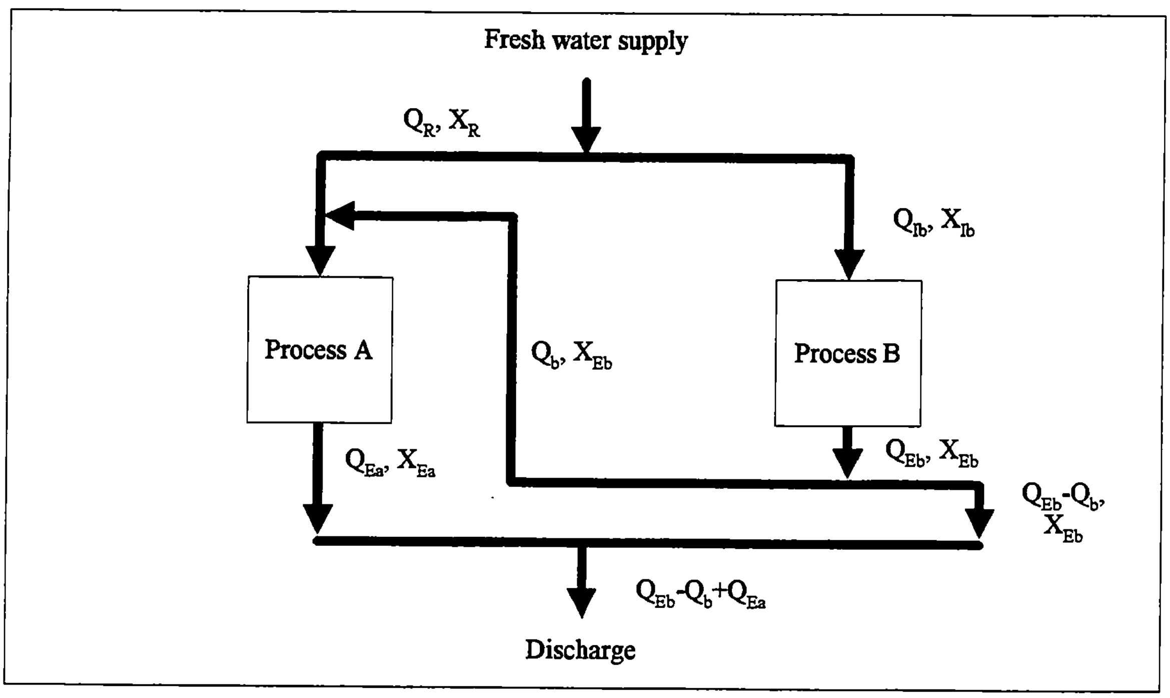

Figure AII-11. Diagram of reuse opportunity #20.

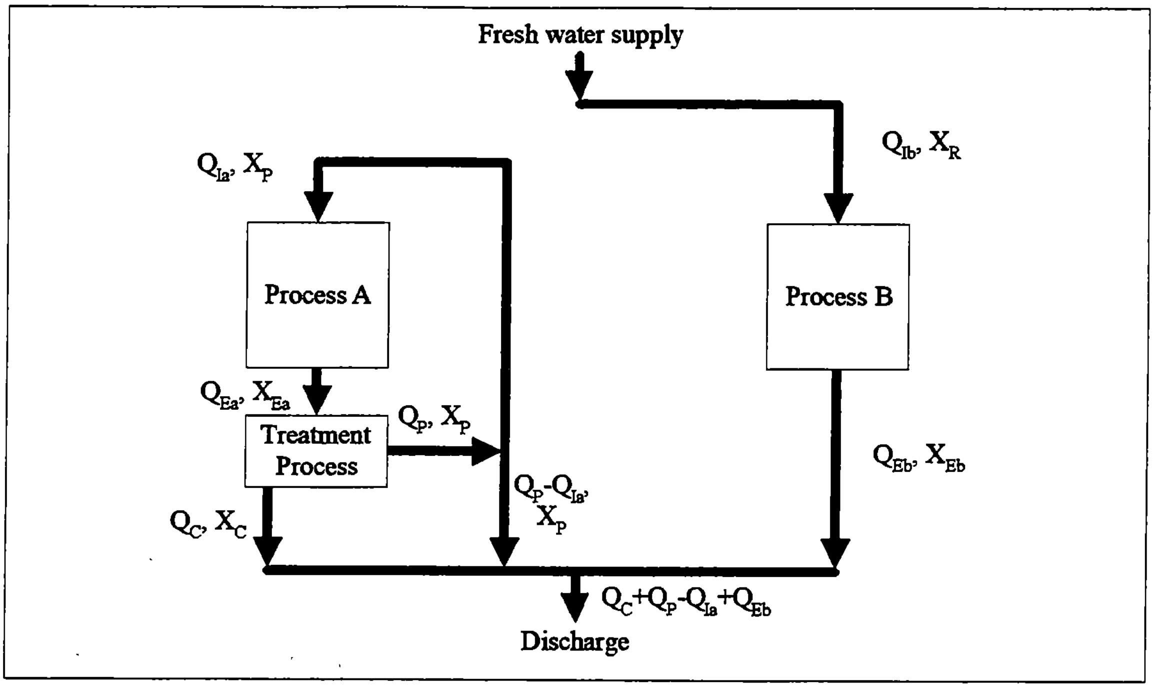

Figure AII-12. Diagram of reuse opportunity #7.

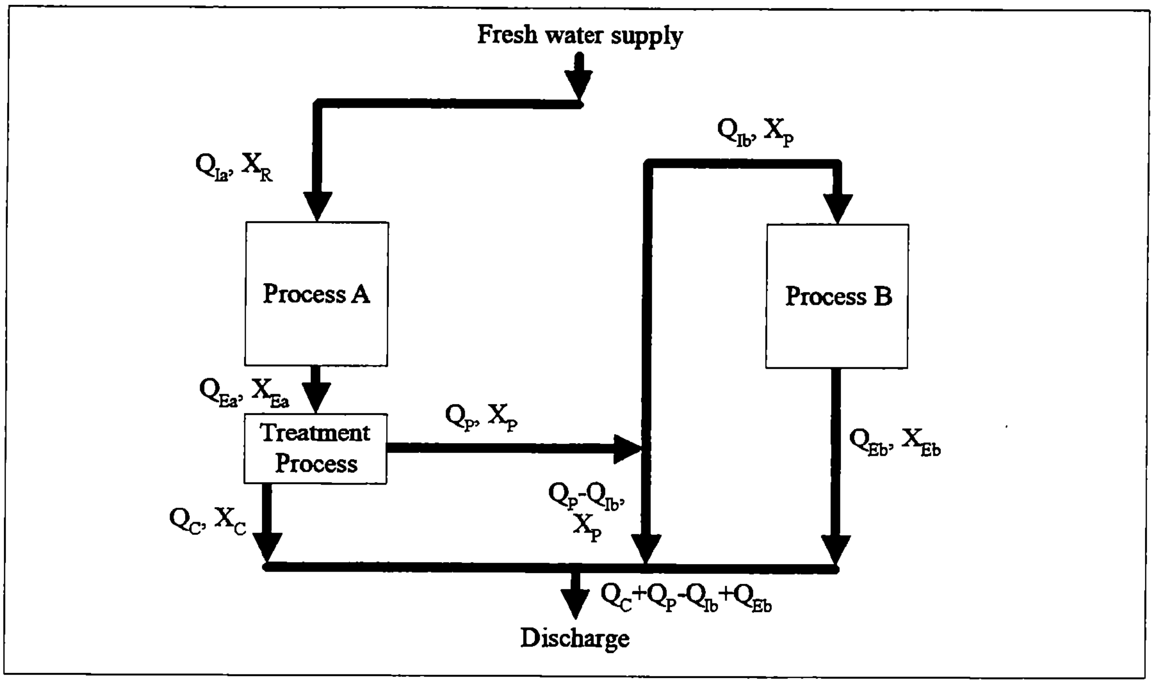

Figure AII-13. Diagram of reuse opportunity #8.

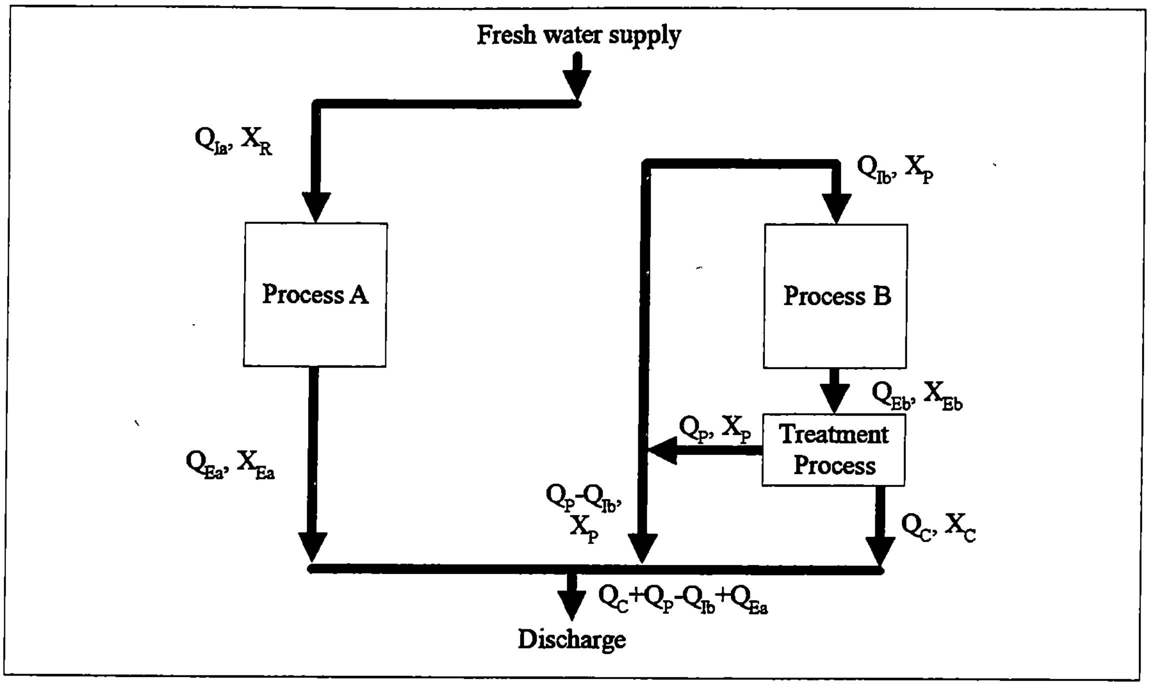

Figure AII-14. Diagram of reuse opportunity #21.

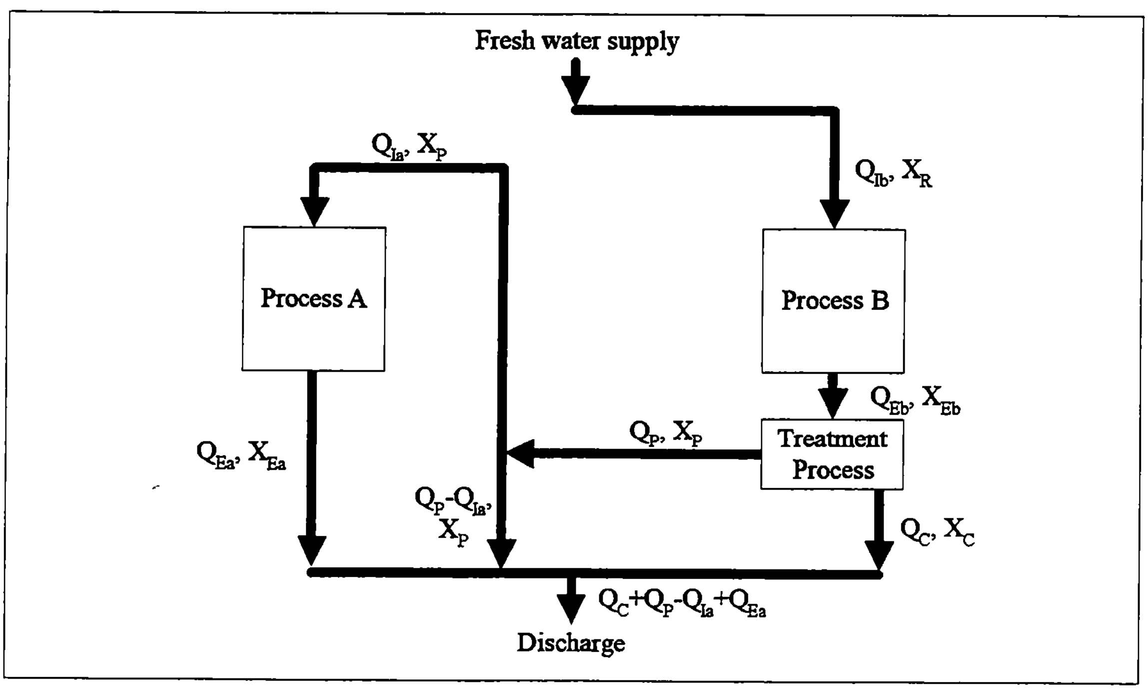

Figure AII-15. Diagram of reuse opportunity #22.

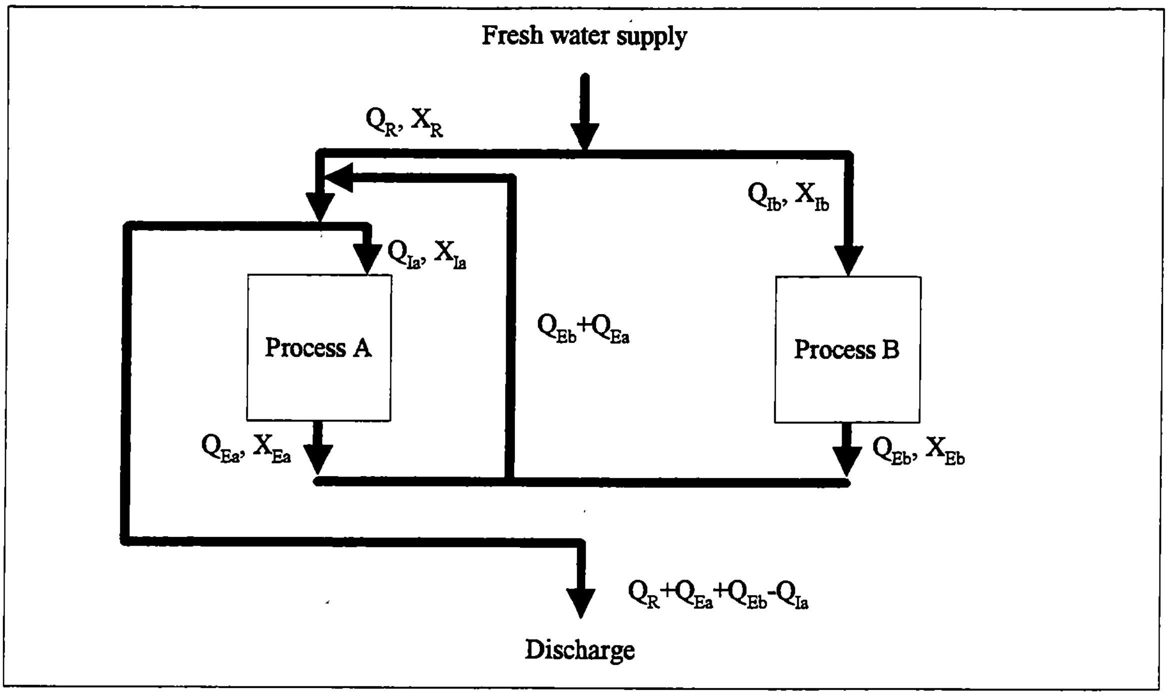

Figure AII-16. Diagram of reuse opportunity #9.

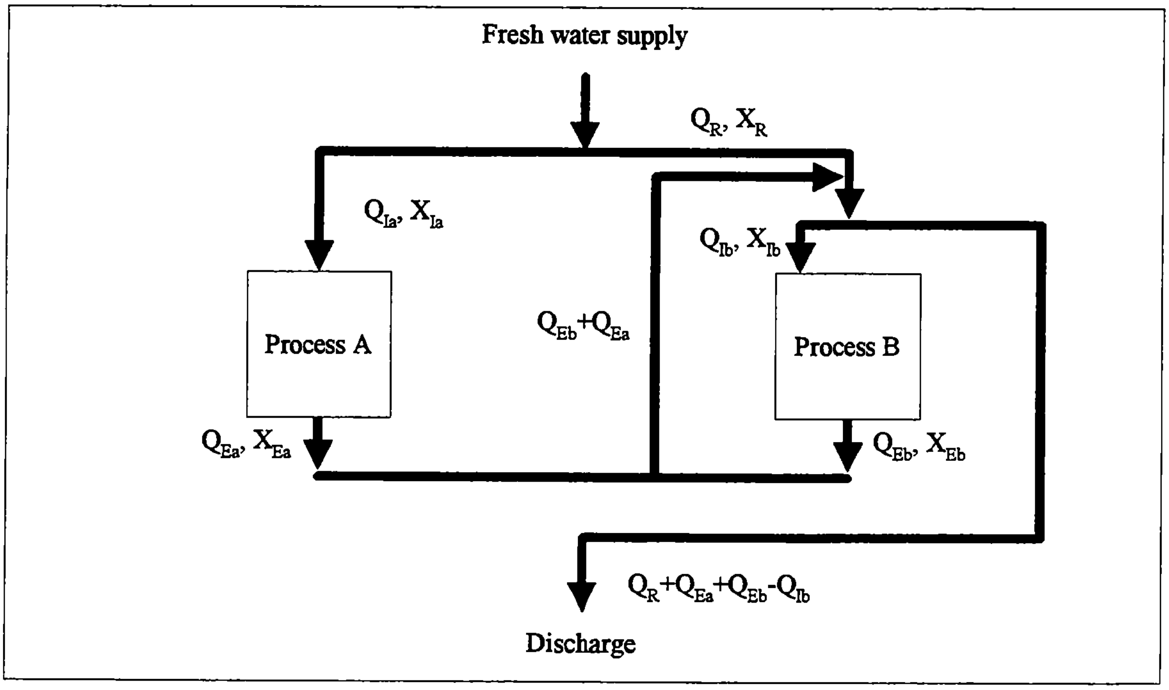

Figure AII-17. Diagram of reuse opportunity #10.

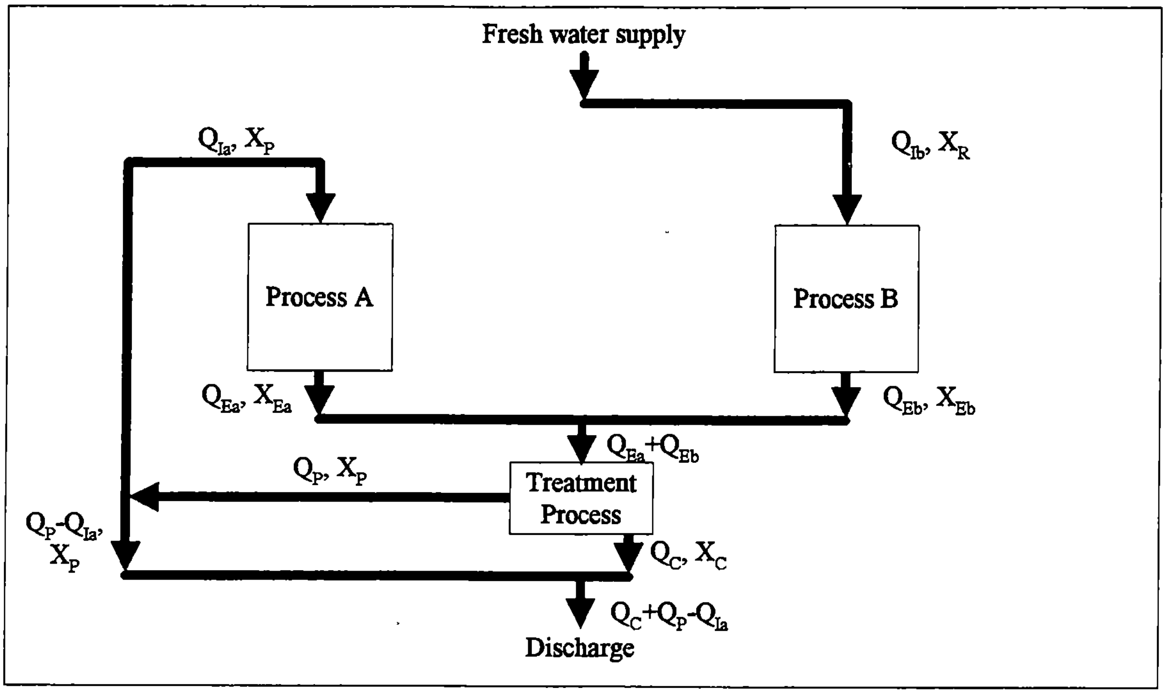

Figure AII-18. Diagram of reuse opportunity #11.

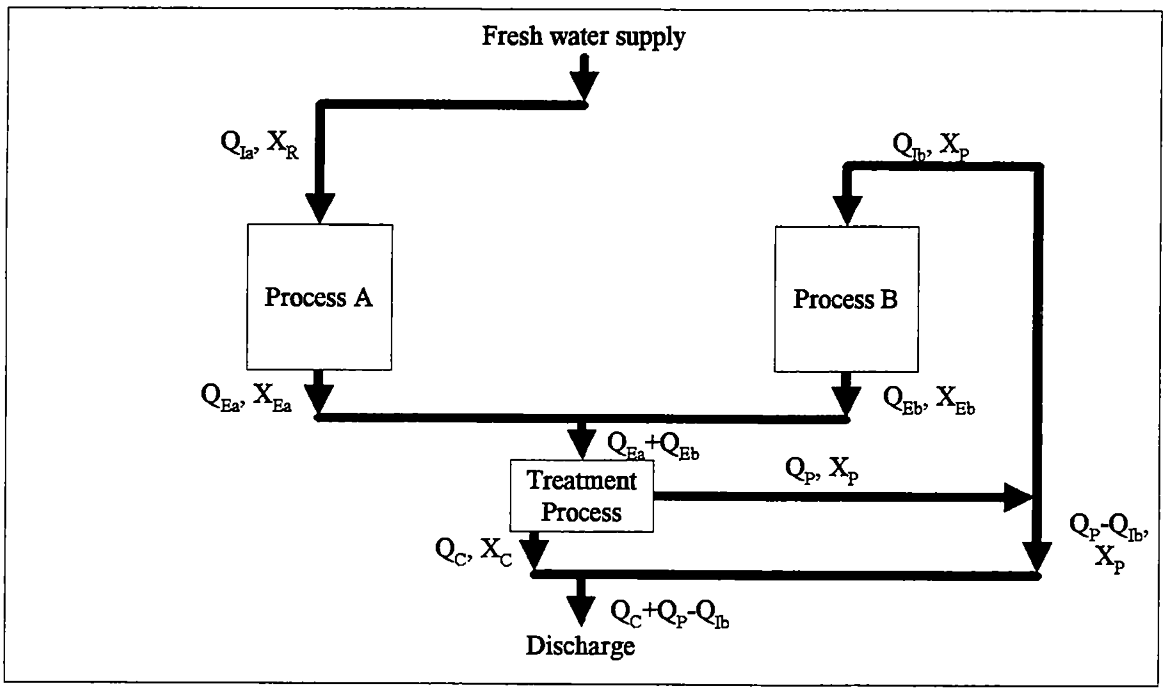

Figure AII-19. Diagram of reuse opportunity #12.

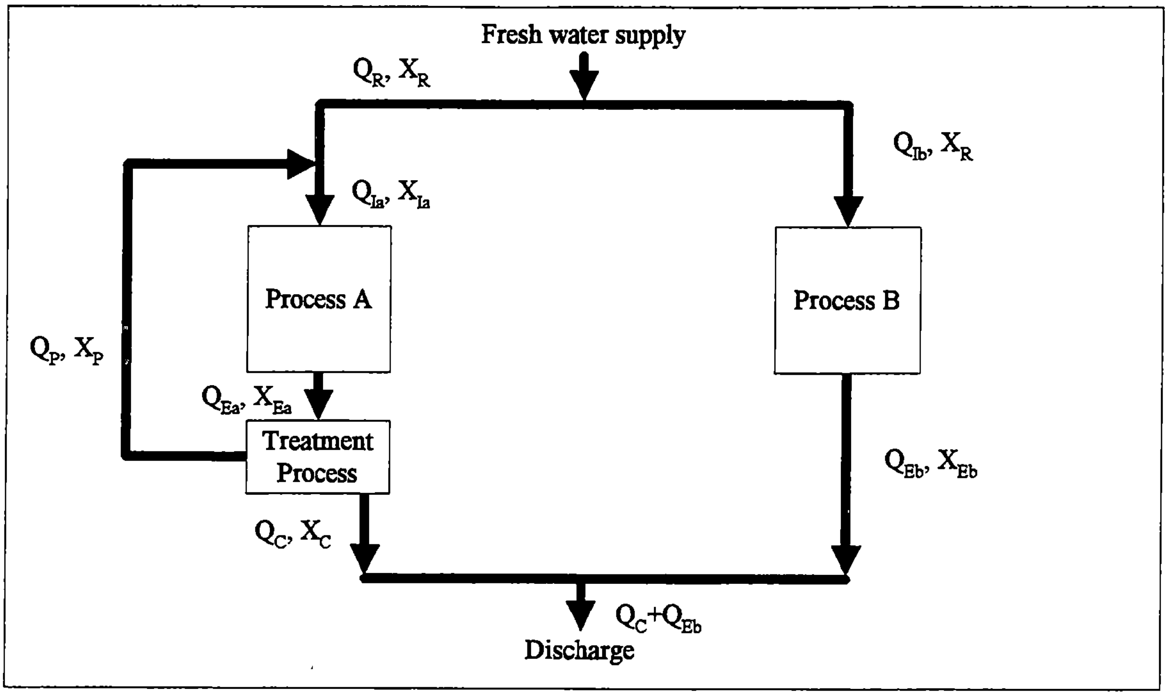

Figure AII-20. Diagram of reuse opportunity #13.

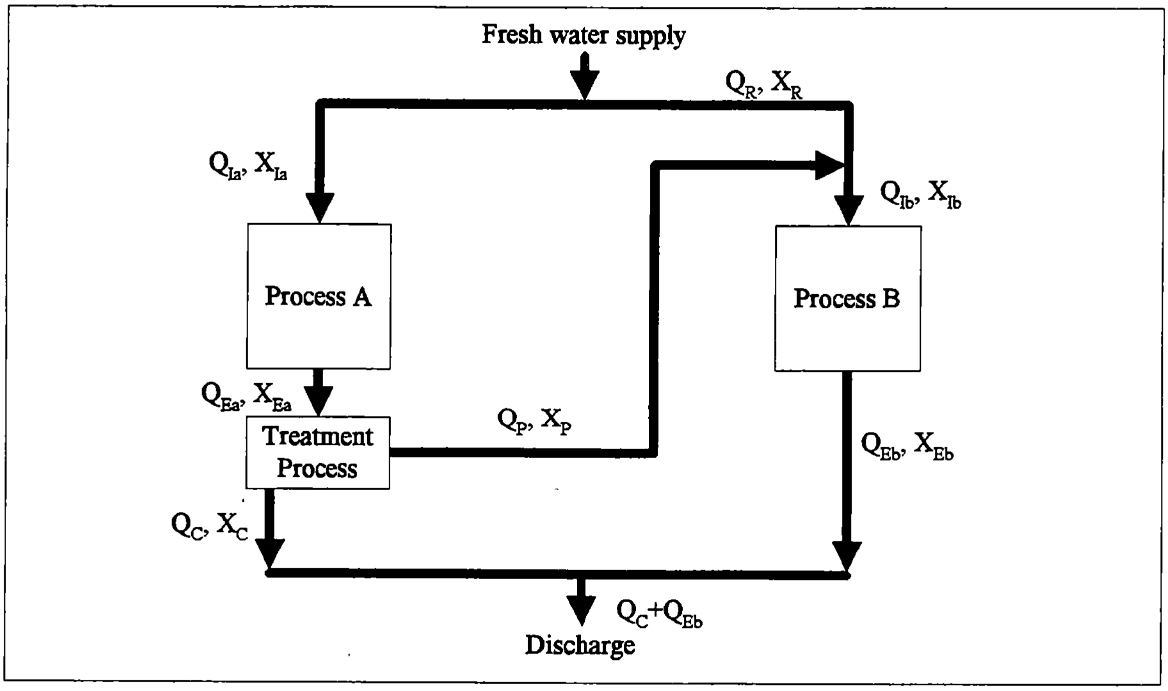

Figure AII-21. Diagram of reuse opportunity #14.

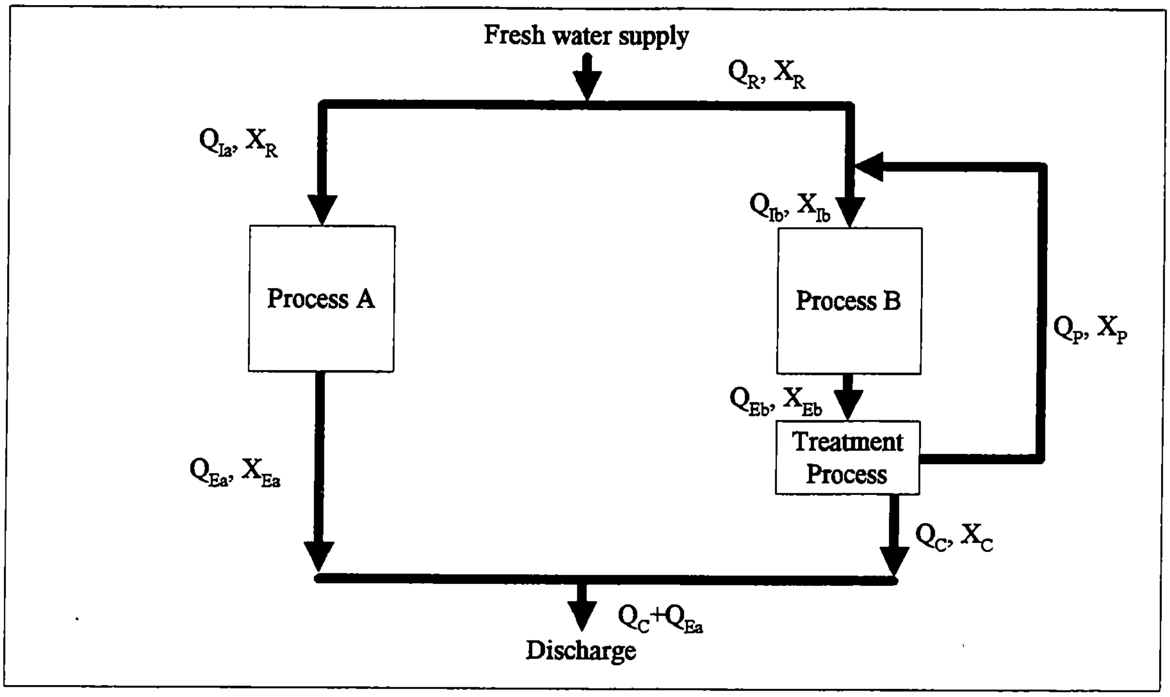

Figure AII-22. Diagram of reuse opportunity #23.

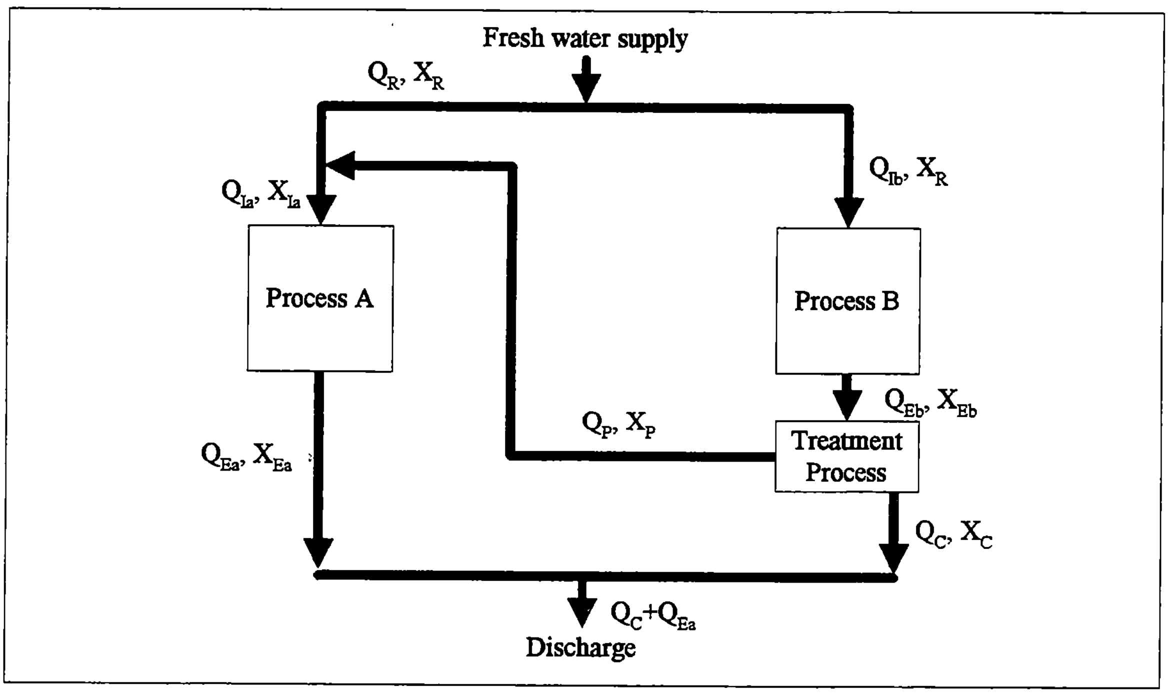

Figure AII-23. Diagram of reuse opportunity #24.

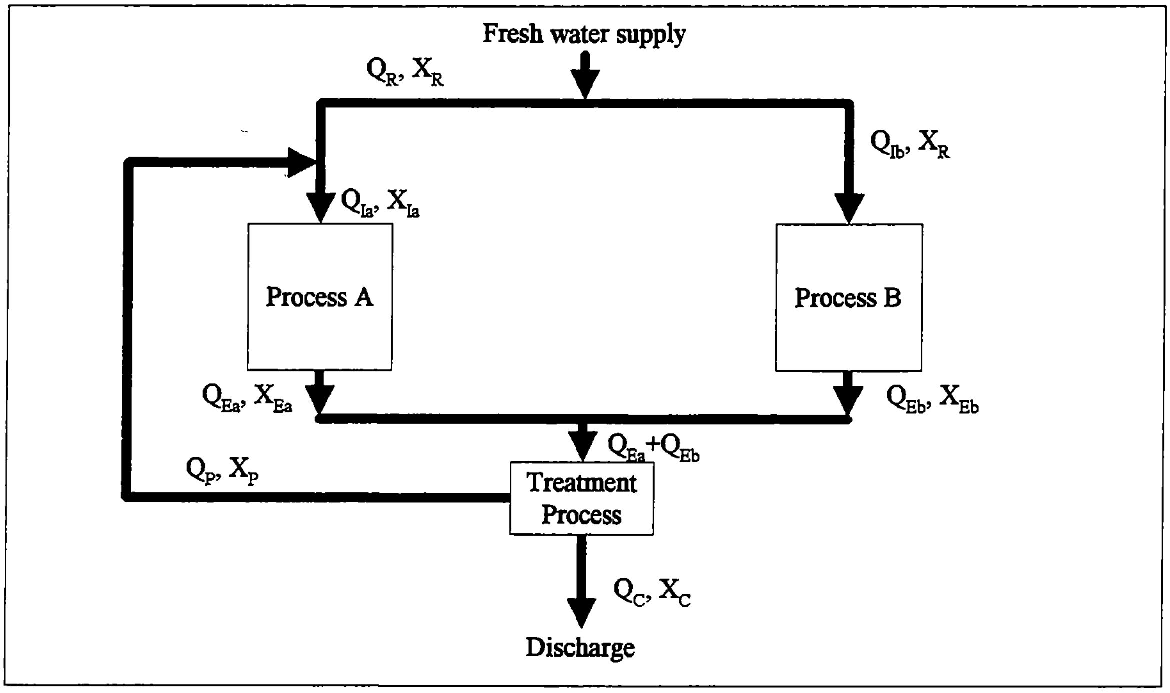

Figure AII-24. Diagram of reuse opportunity #15.

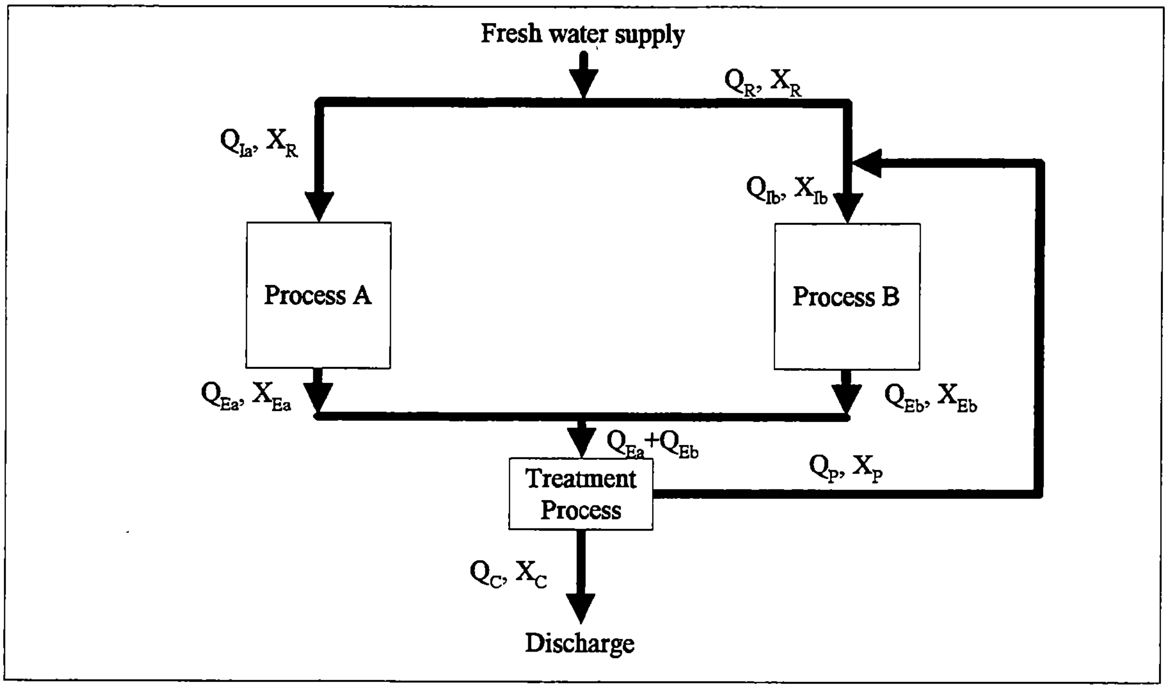

Figure AII-25. Diagram of reuse opportunity #16.

APPENDIX III

Table AIII-1. Information used to determine average percent contaminant removal efficiencies incorporated in the developed program.

Parameter	Reported Percent Removal	Treatment Process	Source
Calcium	99	Reverse osmosis with microfiltration pretreatment	3
	99	Reverse osmosis	5
Hardness	91	Nanofiltration	6
	99	Reverse osmosis with microfiltration pretreatment	2a
	89	Two-stage reverse osmosis with microfiltration pretreatment	4
Alkalinity	93	Nanofiltration	6
	92	Reverse osmosis with microfiltratin pretreatment	2a
	91	Two-stage reverse osmosis with microfiltration pretreatment	4
	85	Reverse osmosis with microfiltration pretreatment	3
Iron	94	Microfiltration	1
	91	Nanofiltration	6
	100	Reverse osmosis	5
	87	Two-stage reverse osmosis with microfiltration pretreatment	4
	90	Reverse osmosis with microfiltration pretreatment	2a
Magnesium	99	Reverse osmosis with microfiltration pretreatment	3
	98	Reverse osmosis	5
Manganese	50	Microfiltration	1
	64	Reverse osmosis with microfiltration pretreatment	3

Table AIII-1. (continued).

Manganese	60	Two-stage reverse osmosis with microfiltration pretreatment	4
Total dissolved solids	87	Nanofiltration	6
	94	Reverse osmosis with microfiltration pretreatment	2a
	93	Reverse osmosis with microfiltration pretreatment	3
	84	Two-stage reverse osmosis with microfiltration pretreatment	4
Total suspended solids	99	Microfiltration	1
	100	Ultrafiltration	5
	100	Reverse osmosis	5
Turbidity	99	Microfiltration	1
	90	Ultrafiltration	5
	79	Nanofiltration	6
	99	Reverse osmosis with microfiltration pretreatment	2a
	90	Reverse osmosis	5
Chloride	83	Nanofiltration	6
	95	Reverse osmosis	5
	94	Reverse osmosis with microfiltration pretreatment	3
	94	Reverse osmosis with microfiltration pretreatment	2a
	83	Two-stage reverse osmosis with microfiltration pretreatment	4
Sodium	65	Nanofiltration	6
	93	Reverse osmosis with microfiltration pretreatment	2a
	91	Reverse osmosis with microfiltration pretreatment	3
Sulfate	54	Nanofiltration	2b

Table AIII-1. (continued).

Sulfate	93	Two-stage reverse osmosis with microfiltration pretreatment	4
	97	Reverse osmosis	5
	99	Reverse osmosis with microfiltration pretreatment	3
TOC	25	Ultrafiltration	5
	98	Reverse osmosis	5
BOD	67	Ultrafiltration	5
	93	Reverse osmosis	5
	50	Two-stage reverse osmosis with microfiltration pretreatment	4
COD	50	Ultrafiltration	5
	88	Reverse osmosis	5
	55	Two-stage reverse osmosis with microfiltration pretreatment	4

Sources:
1. Peters, J.J., and Howton, C. (1997) Ceramic Filters Boost Water Treatment Flows, Slash Costs. *Power*, **141**, 1, 86. Pretreatment prior to reverse osmosis and ion exchange in a steam plant.

2. American Water Works Association. (1996) Water Treatment Membrane Processes. McGraw-Hill, Inc., New York, NY.
a. Results from the Vero Beach, Florida drinking water facility treating groundwater.
b. Results from the Fort Meyers, Florida drinking water facility treating groundwater.

3. Geselbracht, J. (1996) Microfiltration/Reverse Osmosis Pilot Trials for the Livermore, California, Advance Water Reclamation Project. Paper presented at Joint AWWA/WEF Water Reuse Conference, San Diego, California. Pilot plant results from the treatment of secondary effluent from a water reclamation plant demonstration facility.

4. Al-Tuwayyan, K.I., Chang, E.Y., and Codizal, J. (1995) Reuse of Reclaimed Wastewater for Industrial Process Water. Paper presented at First Specialty Conference on Environmental Issues in the Petroleum & Petrochemical Industries, Manama, Bahrain. Pilot plant results from the treatment of reclaimed water for possible reuse.

5. Goldblatt, M.E. (1993) How to Justify Water Conservation Projects. *Hydrocarbon Processing*, **72**, 12, 65. Reported typical contaminant removal of a typical wastewater.

6. Blau, T.J., Taylor, J.S., Morris, K.E., and Mulford, L.A. (1992) DBP Control by Nanofiltration: Cost and Performance. *Journal AWWA*, **84**, 12, 104. Pilot plant results from the treatment of groundwater for disinfection by-product control.

APPENDIX IV

EXAMPLE OF CODE USED IN DEVELOPED PROGRAM

(Reuse Opportunity #1 Code)

```
'Program written using Microsoft Visual Basic 6.0 Professional Edition.

'Written by Waldo A. Margheim, III, for a thesis in partial fulfillment for the requirements of the
degree of M.S. in Environmental Engineering, May 1999.

'Exit Program.
Private Sub Command1_Click()
        End
End Sub

'View next reuse opportunity.
Private Sub Command2_Click()
        Load frmOutput2
        frmOutput.Hide
End Sub

'Print page without command buttons.
Private Sub Command3_Click()
        Command1.Visible = False
        Command2.Visible = False
        Command3.Visible = False
        Command4.Visible = False
        frmOutput.PrintForm
        Command1.Visible = True
        Command2.Visible = True
        Command3.Visible = True
        Command4.Visible = True
End Sub

'View additional reuse opportunity #1 information (reuse diagram).
Private Sub Command4_Click()
        Load frmDiagram1
        frmDiagram1.Show
End Sub

'Determine if reuse opportunity #1 is possible.
Private Sub Form_Initialize()
        If frmProcessA.Option1.Value = True Then
                Ta = Val(frmProcessA.XEa)
                If Ta > 100 Then
                        Load frmOutput2
                        frmOutput.Hide
                Else
                        XEa = (Ta * XR) / 100
                End If
```

```
        Else
                Ta = 0
                XEa = Val(frmProcessA.XEa)
        End If
        If XEa > XIa Then
                Load frmOutput2
                frmOutput.Hide
        Else
                If QEa < QIa Then
                        Load frmOutput2
                        frmOutput.Hide
                Else
                        'Calculate Reuse Opportunity #1 output information
                        frmOutput.Show
                        lblROTotalWaterConsumed = Format(QIb, "###,###,##0") & "
                            gallons/year"
                        lblROTotalWaterDischarged = Format(QEa + QEb - QIa,
                            "###,###,##0") & " gallons/year"
                        lblTotalWaterTreated = "N/A"
                        lblROWaterPurchaseCost = Format(PurchaseCost * (QIb),
                            "$##,###,##0") & "/year"
                        lblROWaterDischargeCost = Format(DischargeCost * (QEa + QEb -
                            QIa), "$##,###,##0") & "/year"
                        lblWaterTreatmentCost = "N/A"
                        lblTreatmentInvestmentCost = "N/A"
                        If QEa + QEb - QIa = 0 Then
                            lblROContaminantDischargeConcentration = Format(0,
                                "##,##0.000") & " mg/gallon"
                        Else
                            lblROContaminantDischargeConcentration = Format(((QEb * XEb)
                                + ((QEa - QIa) * XEa)) / (QEa + QEb - QIa), "##,##0.000") & "
                                mg/gallon"
                        End If
                            lblAnnualSavings = Format(QIa * (DischargeCost + PurchaseCost),
                                "$##,###,##0") & "/year"
                            lblPaybackPeriod = "Immediate"
                            lblReductionRawWaterConsumed = Format(QIa, "###,###,##0") &
                                " gallons/year"
                            lblReductionWastewaterDischarged = Format(QIa, "###,###,##0")
                                & " gallons/year"
                End If
        End If
End Sub

'Calculate current operating information.
Private Sub Form_Load()
        Call Form_Initialize
        lblTime.Caption = Time
        lblDate.Caption = Date
        If frmProcessA.Option1.Value = True Then
```

```
            Ta = Val(frmProcessA.XEa)
            XEa = (Ta * XR) / 100
        Else
            Ta = 0
            XEa = Val(frmProcessA.XEa)
        End If
        If frmProcessB.Option1.Value = True Then
            Tb = Val(frmProcessB.XEb)
            XEb = (Tb * XR) / 100
        Else
            Tb = 0
            XEb = Val(frmProcessB.XEb)
        End If
        lblTotalWaterConsumed = Format(QIa + QIb, "###,###,##0") & " gallons/year"
        lblTotalWaterDischarged = Format(QEa + QEb, "###,###,##0") & " gallons/year"
        lblContaminantDischargeConcentration = Format((((QEa * XEa) + (QEb * XEb))/(QEa+
            QEb)), "##,##0.000") & " mg/gallon"
        lblWaterPurchaseCost = Format(PurchaseCost * (QIa + QIb), "$##,###,##0") & "/year"
        lblWaterDischargeCost = Format(DischargeCost * (QEa + QEb), "$##,###,##0") &
            "/year"
End Sub
```

APPENDIX V

SCREENS USED IN THE DEVELOPED PROGRAM

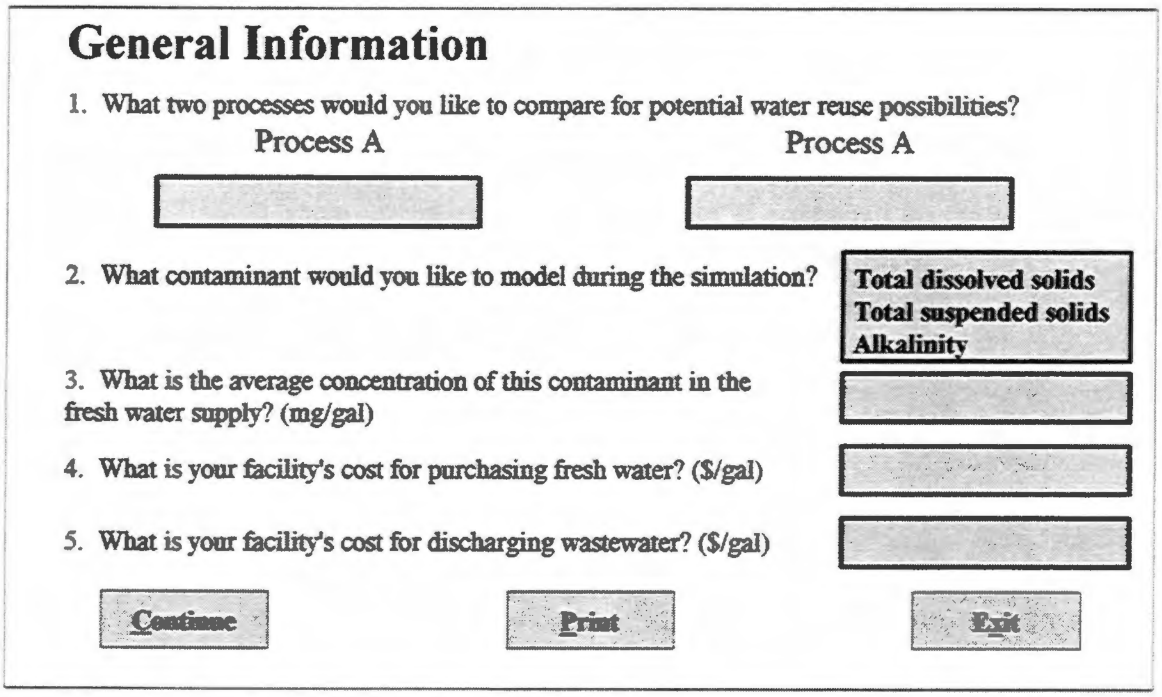

Figure AV-1. POWR general information screen.

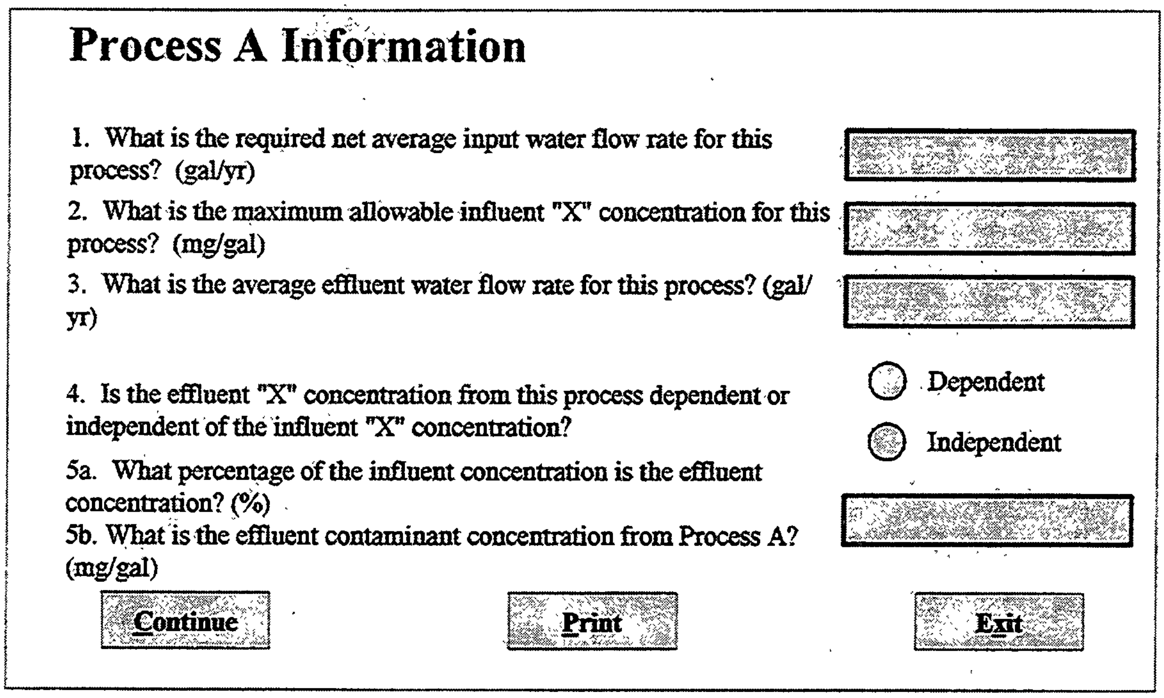

Figure AV-2. POWR process A information screen.

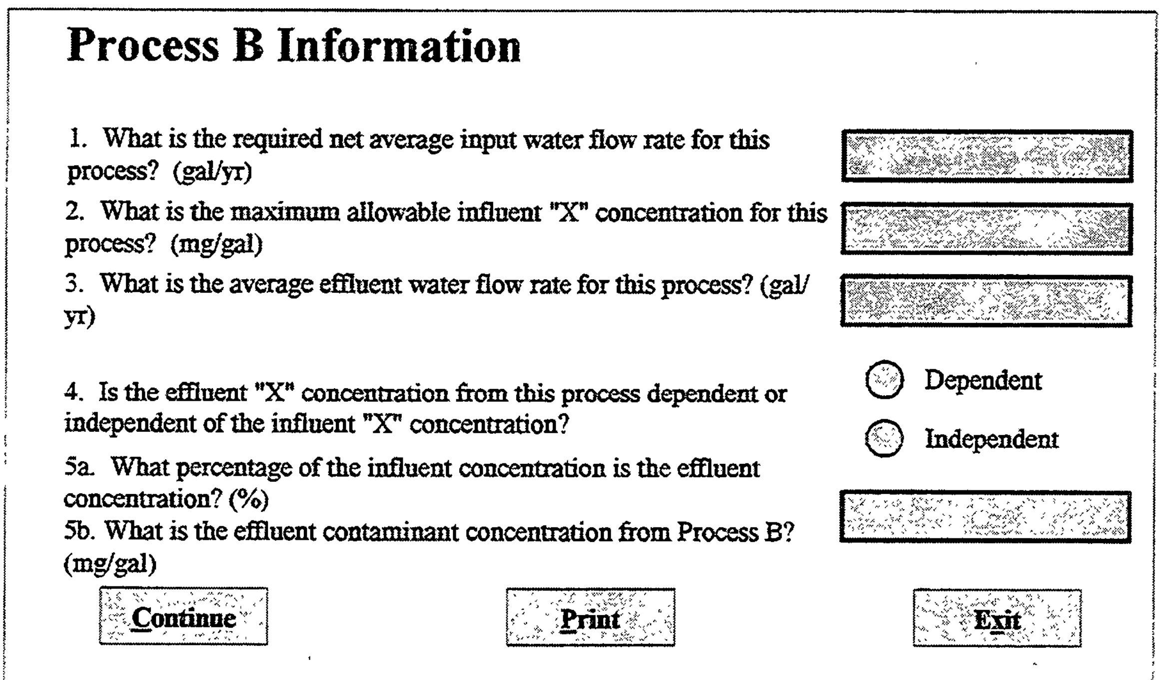

Figure AV-3. POWR process B information screen.

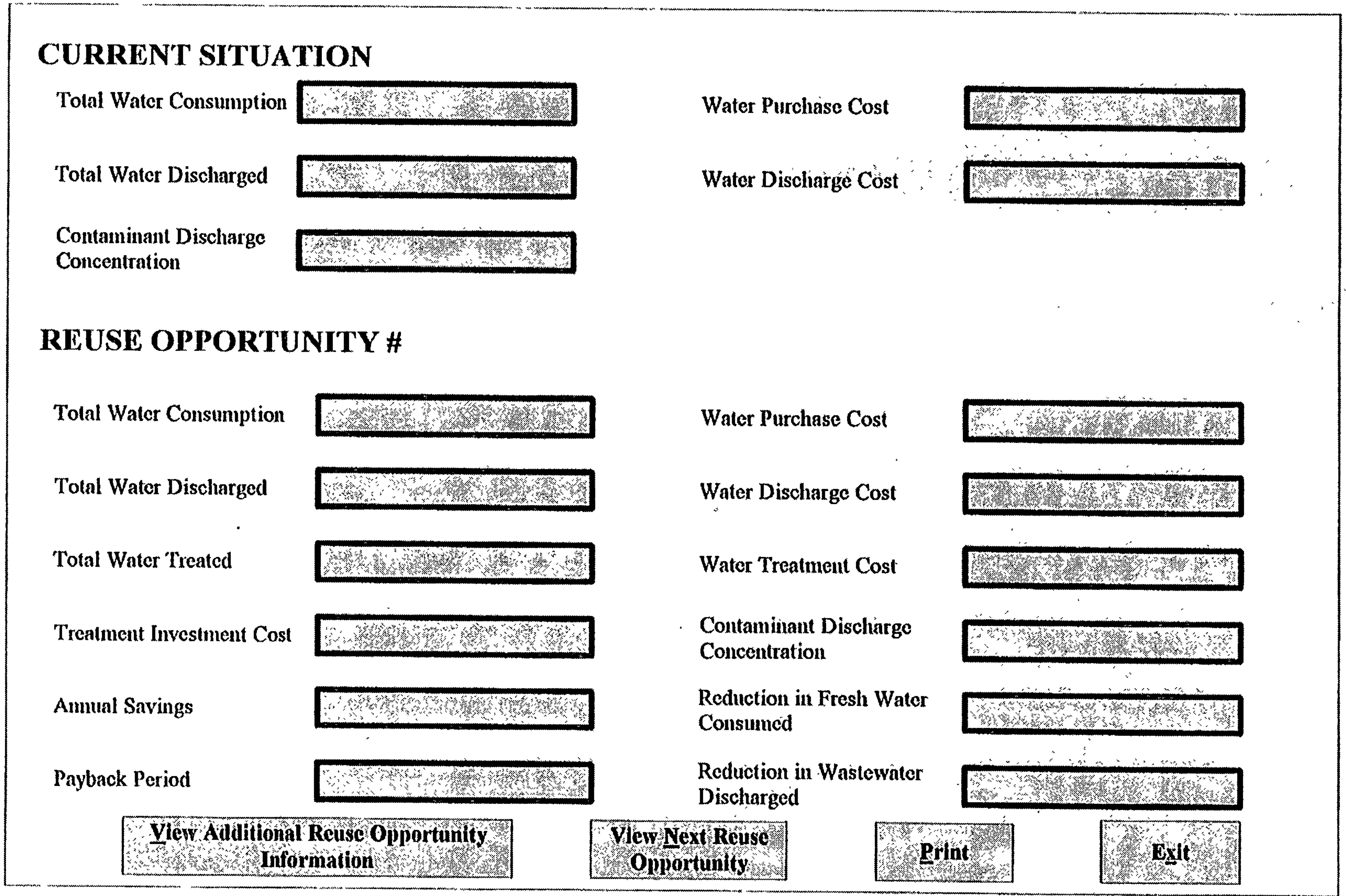

Figure AV-4. POWR reuse opportunity tabular output screen.

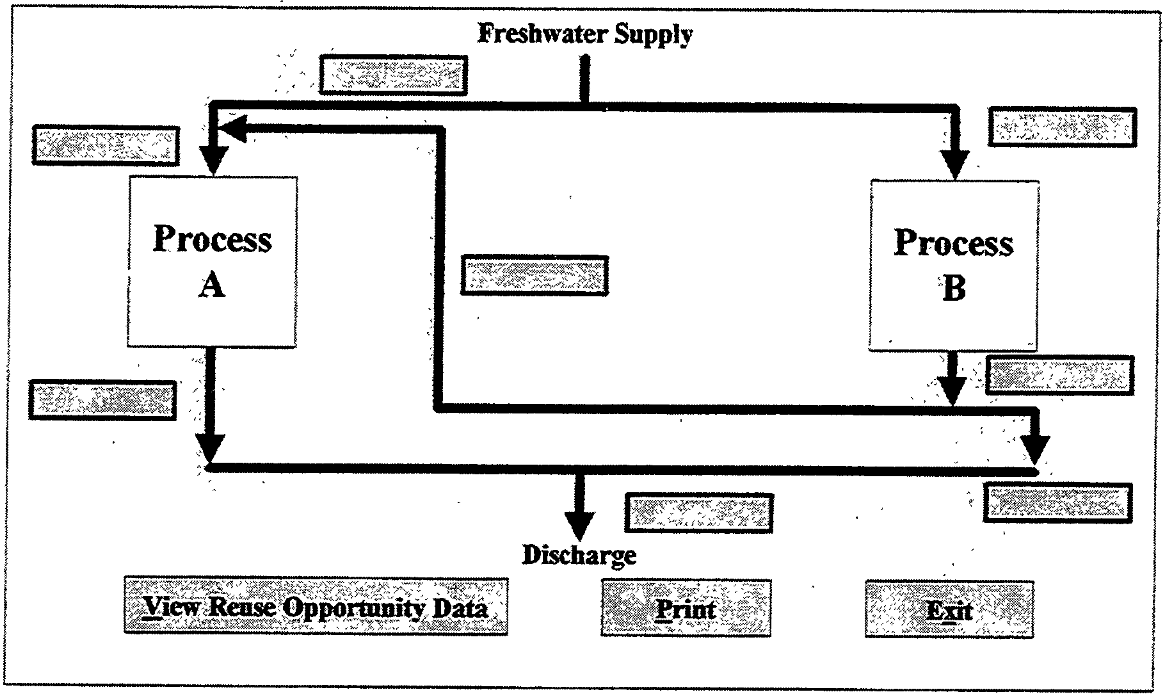

Figure AV-5. POWR reuse opportunity graphical output screen.

Summary Report

Print Report   Exit

- Annual Savings
- Payback Period
- Reduction in Fresh Water Consumed
- Reduction in Wastewater Discharged
- Contaminant Discharge Concentration

R.O. #1		R.O. #12-MF		R.O. #17	
R.O. #2		R.O. #12-UF		R.O. #18	
R.O. #3		R.O. #12-NF		R.O. #19	
R.O. #4		R.O. #12-RO		R.O. #20	
R.O. #5		R.O. #13-MF		R.O. #21-MF	
R.O. #6		R.O. #13-UF		R.O. #21-UF	
R.O. #7-MF		R.O. #13-NF		R.O. #21-NF	
R.O. #7-UF		R.O. #13-RO		R.O. #21-RO	
R.O. #7-NF		R.O. #14-MF		R.O. #22-MF	
R.O. #7-RO		R.O. #14-UF		R.O. #22-UF	
R.O. #8-MF		R.O. #14-NF		R.O. #22-NF	
R.O. #8-UF		R.O. #14-RO		R.O. #22-RO	
R.O. #8-NF		R.O. #15-MF		R.O. #23-MF	
R.O. #8-RO		R.O. #15-UF		R.O. #23-UF	
R.O. #9		R.O. #15-NF		R.O. #23-NF	
R.O. #10		R.O. #15-RO		R.O. #23-RO	
R.O. #11-MF		R.O. #16-MF		R.O. #24-MF	
R.O. #11-UF		R.O. #16-UF		R.O. #24-UF	
R.O. #11-NF		R.O. #16-NF		R.O. #24-NF	
R.O. #11-RO		R.O. #16-RO		R.O. #24-RO	

Figure AV-6. POWR reuse oportunity summary report screen.

APPENDIX VI

POWR PROGRAM "HELP" MENU CONTENTS

Input Data Questions

- Process A Name – Enter a descriptive name for the first process that you would like to analyze.
- Process B Name – Enter a descriptive name for the second process that you would like to analyze.
- Contaminant of Concern – Choose the particular contaminant that you would like modeled through the program. The choice of the specific contaminant to consider is important because generally only one or two particular contaminants are of primary concern in most reuse applications. Selection of a particular contaminant keys the program to choose if any of the treatment technologies may be used in a given reuse scenario.
- Concentration of Contaminant in Fresh Water – Enter the concentration of the contaminant in the water supply that has been chosen as the contaminant of concern.
- Cost of Purchasing Water – If water is purchased from a local utility and later discharged to a POTW, cost information can be obtained from analysis of the facility's water utility bills or by contacting the appropriate utility company for rate schedule information. If water is used directly from ground or surface water sources, it may be more difficult to establish a "net acquisition" cost. These costs should take into account pumping, energy and any costs incurred due to treatment of water prior to process use or treatment of wastewater prior to final discharge.
- Cost of Discharging Water – If water is purchased from a local utility and later discharged to a POTW, cost information can be obtained from analysis of the facility's water utility bills or by contacting the appropriate utility company for rate schedule information. These costs should take into account any costs incurred due to treatment of wastewater prior to final

discharge. Wastewater permit charges and system maintenance costs should also be included.

- Influent Flow Rate – Enter the required flow rate of the process. If the required flow is intermittent, an average volumetric flow rate may be calculated and used. However, any of the water reuse scenarios considered by the program may require special handling, pumping and use of storage tanks for actual implementation.
- Effluent Flow Rate – Enter the effluent flow rate of the process. Typically, this value will be the same value as the influent flow rate requirement. If the difference between this value and the influent flow rate value is negative, water is considered to be consumed in the process or lost due to evaporation, spillage or leakage. If the difference is positive, water is considered to be produced in process chemical reactions.
- Influent Contaminant Concentration – Enter the contaminant concentration that can be allowed in the process without any process or product degradation. This value is typically the most difficult to determine because site- and process-specific testing is required to determine maximum contaminant concentrations that will not cause process upsets. Although this piece of information is site- and process-specific, some influent guidelines have been established for commonly encountered processes.
- Dependent or Independent? – The contaminant concentration in the process input stream may or may not be changed once it has been utilized in a process. In addition, if the influent contaminant concentration were to change due to changes in operating conditions, the effluent concentration may or may not reflect this. Since these situations are potentially possible, determine if the effluent contaminant concentration is dependent (a function of) or independent of the influent concentration. If the effluent concentration is a constant value and independent of the influent concentration, then that value is entered. If the effluent

concentration is dependent on the influent contaminant concentration, than the percentage of the influent concentration that remains in the effluent stream is input.

Abbreviations

- mg = milligrams
- yr = year
- gal = gallons

References

A few of the references listed in the bibliography and Table AI-8 are shown in the POWR program for reference purposes.

Uninstallation

To remove the POWR program from Windows 95 or higher or Windows NT 3.51 or higher:

1. Click the Windows "Start" button, click "Settings", and then click "Control Panel".
2. Double-click "Add/Remove Programs".
3. On the "Install/Uninstall" tab, click "Add/Remove".
4. Follow the instructions on the screen.

About

This screen displays the program name and version number. In addition, the following statement is displayed on the About screen. "This program has been designed to determine potential water reuse opportunities within industrial manufacturing facilities. This program was

written by Waldo A. Margheim, III, for a thesis in partial fulfillment of the requirements of the degree M.S. in Environmental Engineering, May 1999."

VITA

Waldo A. Margheim, III, was born in Oakley, Kansas, on December 21, 1973. Mr. Margheim attended and graduated from Oakley High School in May 1992. He attended Kansas State University in Manhattan, Kansas between August 1992 and May 1997. Here he received a B.S. degree in Civil Engineering and a secondary major in Natural Resources and Environmental Science. In August 1997, Mr. Margheim entered the graduate program in environmental engineering at the University of Tennessee, Knoxville, earning an M.S. in Environmental Engineering in May 1999. Mr. Margheim was employed as an Engineering Associate at the University of Tennessee Industrial Assessment Center during his graduate studies.