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INTEGRATED WATER RESOURCES PLANNING AND MANAGEMENT AT THE LEVEL OF AN INDUSTRIAL PARK

by

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TABLE OF CONTENTS

Page

Appendices

LIST OF TABLES

Page

LIST OF FIGURES

Page

ABSTRACT

Water is becoming a scare resource in many parts of the world due to increasing population, intensive agriculture, and rapid industrial development. Meanwhile, wastewater is becoming a heavy burden to industries and the natural environment. Water reuse and wastewater minimization are becoming increasingly important strategies for individual industries. However, integrated industrial water management system at an industrial park level to determine synergies have not yet been adequately investigated.

The principles of industrial ecology have been applied to analyze the material and energy flows in industrial parks in order to explore the optimal patterns. Tools for designing modifications to these material and energy flows are also beginning to emerge. However, a review of industrial ecology literature indicates a lack of quantitative study regarding the environmental and financial benefits of establishing these material and energy linkages. By combining with tools from other disciplines, such as system analysis, industrial ecology could provide a useful conceptual framework for promoting effective and efficient resource planning and management through a systems approach. This is especially important for water management in areas of water shortage, such as the area of China that is the focus for this study.

This study is one step in this process. It presents a framework for effective and efficient management of water resources within an industrial park by taking a systems approach to conventional water management practices, designed to minimize industrial water use and maximize wastewater reuse among different tenants of an industrial park. The framework is composed of four elements, namely a management information system, policies & regulations, economic instruments and capacity building. Among them, the most important is that its management information system contains a quantitative model, assisting to identify cost-optimizing reuse scenarios. This model shows the feasible water reuse opportunities based on water quality and quantity, treatment cost, transportation cost and other related costs.

The feasibility and applicability of this framework was tested through a case study, namely industries in Tianjin Economic Development Area (TEDA) in China. The test results show that both freshwater use and wastewater discharge can be saved with minimal system cost. A water cost sensitivity analysis was carried out for testing how economic instruments, like pricing strategy, can influence water reuse. The results show us that right user fee systems can further help save freshwater use and reduce wastewater discharge.

Generally, this framework could serve as an effective and efficient water management approach in those industrial parks with water shortage issues. Many of China's economic and technological development zones fall into this category. It may also have applications for analyzing the use and reuse of other materials at the level of an industrial park.

LIST OF ABBREVIATIONS

ADB	Asian Development Bank
APELL	Awareness and Preparedness for Emergencies at the Local Level
ARICs	Asian Rapidly Industrializing Countries
CEIN	Canadian Eco-Industrial Network
CIDA	Canadian International Development Agency
CP	Cleaner Production
DfE	Design for Environment
DIET	Designing Industrial Ecosystems Tool
DUT	Dalian University of Technology
EID	Eco-Industrial Development
EIN	Eco-Industrial Network
EIP	Eco-Industrial Park
EMS	Environmental Management System
EPB	Environmental Protection Bureau
EPMS	Environmental Protection Monitoring Station
FaST	Facility Synergy Tool
GEC	Guitang Eco-Complex
GIS	Geographical Information System
GTZ	Deutsche Gesellschaft für Technische
ICAST	Institute for Communication and Analysis of Science and Technology
IE	Industrial Ecology
IEAT	Industrial Estate Authority of Thailand
IWRPM	Integrated Water Resources Planning and Management
LCA	Life Cycle Assessment
MBIs	Market-Based Instruments
MIS	Management Information System

NGOs	Non-Government Organizations
PP	Pollution Prevention
PRIME	Private Sector Participation in Managing the Environment
RBCs	Rotating Biological Contractors
RICs	Rapidly Industrializing Countries
SAT	Soil-Aquifer Treatment
SEPA	State Environmental Protection Administration
SMEs	Small and Medium Sized Enterprises
TEDA	Tianjin Economic Development Area
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNIDO	United Nations Industrial Development Organization
US-AEP	US-Asia Environmental Partnership
US EPA	US Environmental Protection Agency
WRI	World Resource Institute
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Water is essential not only to the maintenance of life, but also to the development and functioning of agriculture, cities and modern industry. It is unique in our economy because of its multiple roles and functions and can be used for transportation and power generation, for waste disposal, recreation, agriculture, and is essential both in manufacturing and in the service sector (Shelef 1991; Asano and Levine 1996). However, while the total amount of available water resources on the planet earth remains constant, demand is increasing with the growth of the human population, especially in cities, in addition to industry and agriculture. This trend will necessitate increasing efforts to conserve water and foster its reuse.

Once used in our cities, farms and industries, water is usually contaminated. This contamination can result in treatment costs for municipalities and industry, and negative impacts on fisheries, human health, recreation, aesthetics, as well as natural ecosystems (Shelef 1991). Important wastewater sources are those industrial sectors, where the properties of wastewater are more complicated than those of other kinds of wastewater and the negative impacts on the environment are even more severe (Mann and Liu 1999). Accordingly, industrial wastewater minimization is being increasingly recommended.

Meanwhile, industrial parks have become an increasingly important form of industrial development worldwide. This is because within an industrial park the problems of zoning can be minimized by grouping various types of industrial activities, and costs of infrastructure and utilities can be reduced by concentrating activities in planned areas (Côté and Balkau 1999). In addition, complementary industries and services provided by industrial parks can entail diversified effects on the surrounding region and stimulate regional development (UNIDO 1997).

This research links water management and industrial park management together by developing an integrated water resources planning and management framework. This section introduces the water crisis that exists in some parts of the world, wastewater issues, especially, focusing on the current situations in China. This is because industrial park managers in China are facing both a water crisis and wastewater pollution problems, but with very limited technological, political or economic resources. Such background information can help the readers better understand why this research is significant and necessary.

1.1.1 Water Crisis

In many parts of the world, a growing shortage of clean fresh water is the most pressing environmental problem (WRI et al 2001; Arms 1994). Lack of water hampers economic development in many countries, especially in developing countries and creates conflicts between users. In some cases, it prevents such nations from producing enough food to feed their population (Pareek 1992). Further, groundwater aquifers are being pumped down faster than they are naturally replenished in parts of India, China, the U.S. and elsewhere (Bouwer 2000). Disputes over shared water resources have led to violence and continue to raise local, national and even international tensions (ADB 1999). According to the recent world resource report (WRI et al., 2001), more than one billion people lack access to clean drinking water; and two and a half billion do not have adequate sanitation services. This report predicts that over 2.7 billion people will face severe water shortages in 2025.

In China, water shortages are already the most critical environmental issue. China is one of the thirteen countries in the world classified as poorest in water resources (ADB 1999). The country's overall net water resources are 2,812.4 cubic kilometers, of which 828.8 cubic kilometers are groundwater resources, the per capita water volume is only 2201 cubic meters, less than 30% of the average global figure (WRI et al. 2001). This is in large part due to its large population. Furthermore, the natural water resources are distributed unevenly, especially in northern and eastern China where per capita volume has been estimated at 392 and 953 cubic meters respectively. In the large cities of Tianjin and Beijing, the per capita volume is 157 and 329 cubic meters respectively (Varis and Vakkilainen 2001). Distribution of groundwater is also skewed with average groundwater deposits in the south over four times greater than the north (Study Group of Sustainable Development of Chinese Academy of Sciences 2000). Water crises occurred in more than 400 cities in China at the beginning of 2000 (Zhu, et al., 2001). Satellite photographs show hundreds of lakes disappearing and local streams going dry in recent years, as water tables fall and springs cease to flow. Millions of Chinese farmers are finding their wells pumped dry. The demand for water by industry is growing even faster. Assuming very conservative economic growth of 5 percent a year from 1995 until 2030, industrial water use would increase from 52 billion tons to 269 billion tons (China Environmental Report 2001).

Therefore, one of the largest challenges now facing the Chinese government is how to meet the soaring water needs of its swelling urban and industrial sectors without undermining both its own agriculture and the world's food security. Unfortunately, due to an old industrial infrastructure and inefficient water distribution, water efficiency in industries is still very low. The water recycling and reuse ratio in industries is around 25% in most cities with few cities exceeding 50% (Zhu, et al., 2001). Consequently, in many Chinese cities, the authorities have to resort to tighter control of the water supply, limiting supply time and consumption volume during the dry season, which will further impede China's development.

1.1.2 Wastewater Issues

Wastewater is characterized in terms of its physical, chemical, and biological composition. Appendix 1 lists the principal physical properties and the chemical and biological constituents of wastewater and their sources.

Wastewater has multiple negative impacts on our natural environment and human society. With untreated wastewater being continuously discharged into rivers, lakes and coastal waters, the ecosystems will continue to degrade. For instance, wastewater sources from municipalities to local water bodies have inordinately high amounts of pollutants such as BOD, ammonia nitrogen, volatile phenols, mercury, light lubricating oils and heavy metals, therefore, degraded the local water system (World Bank 1997; World Bank

2001). This degradation includes wetland destruction, groundwater contamination and eutrophication (US EPA 1992). Also, with the high rate of wetland habitat destruction, all types of aquatic and terrestrial species are affected since most wetlands are used for breeding, resting, and feeding grounds for many species. Groundwater is a source of freshwater access and recharge of surface water bodies. But with the continuous discharge of untreated chemically contaminated effluents from industrial plants, such groundwater becomes polluted and not suitable for human use in many parts of the world. Eutrophication is mainly caused by the overload of nutrients entering the water system from urban runoff, agriculture and food processing. It can result in algal blooms, leading to depletion of oxygen and fish kills (China Environmental Report 2003). Beaches and shorelines can become fouled by masses of rotting, stinking algae.

Social impacts of wastewater include waterborne diseases and food security. Widespread contamination of surface and drinking water by pesticides and nitrates result in regional diseases such as gastric illnesses and cancers (China Environmental Report 2003). Preventable water-related diseases kill an estimated 10,000 to 20,000 children every day, and the latest evidence suggests that we are falling behind in efforts to solve these problems (World Bank 2001). For instance, massive cholera outbreaks appeared in the mid-1990s in Latin America, Africa and Asia. Millions of people in Bangladesh and India drink water contaminated with arsenic (WRI et al., 2001). Food security is another concern. This is because the pollutants can affect and contaminate vital crops such as grain production in many countries where wastewater is used for irrigation of farmlands.

In China, a major issue is that existing water sources are being polluted to the point that they can no longer be used, exacerbating other water scarcity problems (China Environmental Report 2003). Lakes and rivers have inordinately high amount of pollutants such as BOD, ammonia nitrogen, volatile phenols, mercury, light lubricating oils and heavy metals (World Bank 1997; World Bank 2001; China Environmental Report 2001). The total wastewater discharge in 2001 in China reached 62 billion tons (China Environmental Report 2001). Of the 532 rivers, 436 show various degrees of pollution. Furthermore, the discharge of 30 billion tons per year of sewage, 97.3% of which is untreated, results in 1.5 million cases of acute schistosome infections per year (Ma 1999). Only 6 of China's 27 biggest cities provide drinking water that meets government standards, resulting in the incidence of 10.6 cases of typhoid fever per 100,000 people (World Bank 2001).

The total volume of industrial wastewater is about 17.1 billion tons in 1999 and is largely untreated (Ma 1999). Due to the complex nature of such industrial wastewater, its discharge to the local water bodies entails many negative impacts to aquatic ecosystems. Most aquatic systems are now contaminated with heavy metals and other toxins that make them unfit even for irrigation, much less for human consumption, and further increase the water supply crisis (Varis and Vakkilainen 2001). Specific problem industries include paper and pulp mills, chemical and petrochemical industries, metal treatment, dyeing and leather tanning plants (China Environmental Report 2001).

Over recent years government at all levels and most industrial enterprises have become aware of problems caused by industrial pollution. With the implementation of regulations, the total volume of industrial wastewater discharged was reduced from 22.2 billion tons in 1995 to 17.1 billion tons in 1999, and the percentage of industrial wastewater treated was increased to about 88% as a whole (Zhu et al., 2001). But most of these measures are end-of-pipe oriented, rather than prevention of pollution. An integrated water resource management approach is still in its infancy.

1.1.3 Industrial Park Development

According to UNIDO (1997), an industrial park can be defined as a tract of land developed and subdivided into plots according to a comprehensive plan with provision for roads, transport and public utilities for the use of a group of industries. Through industrial parks, firms benefit from economy of scale in terms of land development, construction, and common facilities (Côté et al. 1994). Among developed countries, there are approximately 8,800 industrial parks in the US; 1,200 in Canada; 200 in the UK; and 300 in Germany (UNEP 1997). This trend is even stronger in rapidly industrializing countries (RICs). For instance, during the past decade, the number of industrial parks grew rapidly in Asian Rapidly Industrializing Countries (ARICs), with their numbers increasing dramatically to about 4,000 in 2001 (Yang et al 2001). In China alone, UNEP (2001) reports that in 1998 there were more than 2,000 industrial areas, of which 113 were central government-approved national, provincial, and municipal estates.

Industrial parks have played an important role in the national development strategies of many countries and have been irreplaceable where economic development is concerned (Yang et al., 2001). In China, such parks have become important showcases and bases for development of an export-oriented economy in their regions. They are the most active areas for foreign investment. They are serving as bases for parent cities to readjust their industrial structures and renovate old enterprises, as well as providing places where Chinese methods of enterprise management are changing to adopt to the norms of international management practice (Geng and Côté 2003).

Generally, an industrial park is land reserved by its municipal authority for industrial development. It usually includes an administrative authority, making provisions for continuing management, enforcing restrictions on tenants and detailed planning with respect to lot sizes, access and facilities. Further, in some countries, industrial estates have a dual function as production and residential areas, such as China and Thailand, which is different from the North American model in which estates are predominantly manufacturing based (Geng and Côté 2001; Geng and Côté 2003). Generally, a typical Chinese industrial estate has an industrial production area, a scientific research area, a residential area, and a business and service area. Some typical characteristics are as follows.

Independent- Industrial estates were separated from their parent cities and equipped with necessary support infrastructure.

Comprehensive- Industrial estates have been designed for a variety of purposes and for different categories of industry.

Superior- Industrial estates enjoy better infrastructure and investment conditions due to better planning and support.

Intensive- Their activities are typically capital-, revenue- and technology- intensive.
Concentrated- Industrial estates are concentrated in the eastern coastal areas and in medium to large size cities, usually on the periphery of cities and in suburban areas. (Yang et al 2001)

Industrial estates currently have one of the highest growth rates in China with a heavy concentration of investment from both at home and abroad (Geng and Côté 2003). They are usually based in areas with an advanced economy, a well-developed industrial foundation, and a comprehensive distribution of industrial sectors. For example, while the total acreage of economic and technological development zones (a major form of Chinese industrial estates) has reached 4000 square kilometers, about 0.04% of China's territory, the accumulated direct foreign investment in such zones accounts for about 10% of the national total of realized foreign capital inflow (Geng and Côté 2001). The 1996 per capita productivity of some manufacturing businesses in such zones, such as those in Shanghai, Tianjing, Dalian, Beijing and Kunshan, reached as much as 200,000 RMB (1 CAD=6 RMB) or more (Geng and Côté 2001).

Attention has increasingly focused on environmental issues that have emerged during this period of construction and operation of industrial parks. Such issues include increased pollution, water treatment costs, safety problems and health care costs, loss of biodiversity and challenges to coastal zone management (UNEP 2001). The impact of industrial estates is even graver when coupling with natural resource scarcity issues.

Management of industrial estates and environmental protection bureaus are seeking ways to minimize their impacts in the face of worsening environmental problems. These issues have not yet been fully considered and integrated into the planning and implementation process, leading to serious impact and damage both within the estates and to surrounding communities. One solution has been to adopt principles of environmental management, which encourage government and businesses to integrate sustainable practices, comply with environmental regulations and implement a systemic approach for a wiser use of resources (Geng and Côté 2003). To implement environmental management, several tools have been developed such as cleaner production (CP), APELL (Awareness and Preparedness for Emergencies at the Local Level), and environmental management systems (EMS) (Geng and Côté 2001; Geng and Côté 2003). Currently, Chinese industrial estates are exploring these tools as a means to mitigate environmental factors.

Many of the tools have been designed for application at the individual facility level (e.g. cleaner production), but there is increasing recognition that sustainability issues can only be affectively addressed at a multi-industrial and spatial level, such as eco-industrial development. Some of these concepts are still in the infancy, like industrial ecology, while other approaches like EMS have been in application over the last five years (Geng and Côté 2001; Geng and Côté 2003).

In summary, the water crisis and wastewater pollution have impeded sustainable industrial development. Due to the presence of many industrial plants in close proximity, industrial parks have become large major water users and wastewater producers. Industries with high water consumption and wastewater production include chemical, petrochemical, petroleum refining, pharmaceutical, pulp and paper, metal and mineral, steam electric power, certain food and consumer products, textile and electronic component industries (Mann and Liu 1999).

In China, the shortage of water and wastewater pollution are the most crucial environmental issues since most of the industrial parks have located in China's eastern coastal areas, where water shortage and water pollution have become an impediment to sustainable development. In order to alleviate this situation, some industrial estate managers have adopted many approaches, including cleaner production, centralized wastewater treatment, wastewater levy system, water quota pricing system, and wastewater discharge permit system. Unfortunately, the implementation of these approaches is inefficient and fragmented. In many estates, people still pursue the development approach of "pollute first, clean up later", and regard end-of-pipe methods as standard and acceptable. Due to lack of cooperation and integration, many water reuse and recycling opportunities have been lost.

Therefore, water, as an indispensable and increasingly scarce resource for industrial development, should be conserved as much as possible. As such, it is critical for industrial park planners and managers to seek an integrated approach to reduce the total water use and optimize utilization of this resource. Consequently, to develop an integrated water resource planning and management model at the level of an industrial park seems to be a necessary initiative as industrial parks grow in number and size. Such an approach could help alleviate water supply pressure and reduce wastewater emission to local water bodies, which further contribute to the objective of sustainable development.

1.2 RESEARCH SIGNIFICANCE

This study has both academic and practical significance, which can be summarized as follows:

1.2.1 Linking Engineering and other Disciplines

The idea for this study arose from the realisation that researchers in industrial ecology, particularly in the development of industrial ecosystems, and researchers in chemical engineering, particularly in the area of water reuse and wastewater minimization, are working toward similar goals, namely, optimizing resource use within an industrial system. This study is developed and undertaken in an interdisciplinary context, linking chemical engineering with industrial ecology emphasizing water reuse and wastewater minimization, mathematical programming, and water resource management. By doing so, industrial ecologists can benefit from the quantitative analysis of water engineering, while water engineers can benefit from the vision of industrial ecology.

1.2.2 Fostering Systems Analysis

This research situates a quantitative model within an integrated water resource planning and management framework by linking the industrial ecology concept with water reuse and wastewater minimization practices. It can assist water users and other stakeholders within an industrial park to look at the total system, regarding the industrial park as an ecosystem and aiming to foster optimal freshwater distribution and reduce total wastewater discharge with least cost and impact.

1.2.3 Addressing Water Crisis

Water shortages continue to be a grave problem in many parts of the world and strategies to improve water resource planning and management are constantly needed. With more than 20,000 industrial parks around the world, this study addresses such needs and attempts to provide an integrated framework whereby industrial park managers and tenant companies might be able to collaborate in water conservation, technology and reuse.

1.2.4 Demonstration for Other Parks

The integrated framework developed in this thesis is intended to be versatile and should be able to assist other industrial parks in optimizing water efficiency, reducing both total freshwater consumption and wastewater discharge, helping industrial park managers to alleviate their total water supply challenge, and tenant companies to reduce their wastewater treatment burdens. Long-term impacts will include strengthened capacity for sustainable industrial development and systemic implementation of environmentally sensitive planning and management in critical regions.

1.2.5 Potential Application to other Materials

While this case study is specific to water resource, the quantitative model developed in this study may have application as a framework for the analysis of flows of many types of other materials such as energy sources and/or other raw materials.

1.3 RESEARCH OBJECTIVES

The purpose of this research is to investigate the potential application of an integrated water resource planning and management framework at the level of an industrial park and to see how it might help an industrial park deal with water resource depletion and wastewater issues. This framework could serve to enable managers to take an approach to a number of plants within a defined geographical area such as an industrial park. The framework should be versatile with the concerns of China in mind, recognizing the urgent requirements of China for effective and efficient sustainable water management. The following are the research objectives:

- To develop a quantitative optimization model that can be applied in an integrated water resource planning and management framework for industrial parks.
- To test the feasibility and applicability of this framework in a case study.

1.4 THESIS STRUCTURE:

This thesis has been organized into seven chapters. Besides this introduction chapter, the remainder of this thesis is structured as follows:

Chapter 2 reviews the literature relevant to industrial ecology, eco-industrial development, water reuse, integrated water planning and management.

Chapter 3 describes the methods used to this project, which include research process, data collection and analysis, as well as relevant research ethical issues.

Chapter 4 describes the integrated water resource planning and management framework for an industrial park into which the quantitative model fits. Each element of this framework is outlined in detail.

Chapter 5 introduces how to development the quantitative model, including the system analysis approach, system components, objective function, and constraints

Chapter 6 presents the research finding and results in TEDA, including an overview of the city of Tianjin and TEDA, questionnaire results, survey data and optimal water network scenarios.

Chapter 7 analyzes research results, evaluates the potential impacts of economic instruments, specifically water resource price on total water use savings and wastewater reduction, discusses model feasibility and applicability, and summarizes the potential benefits which may be gained through adoption of such a model, as well as contributions to knowledge.

Chapter 8 is the conclusion, summarizing this study and presenting recommendations for future study.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

With the development of industrial ecology, eco-industrial development has been promoted as an effective strategy for industries to realize sustainable development. One tenet of industrial ecology requires that waste should be viewed as potential resources to be husbanded rather than as waste to be discharged. In terms of water resources, this means that water reduction, reuse, and recycling should be employed both within and among different users. Current wastewater treatment technologies can reclaim almost all kinds of wastewater, which makes water reuse and recycling possible (Bouwer 2000). In addition, integrated approaches to water resource planning and management have been applied at the river basin and regional levels for decades (Mitchell 1994). However, such an integrated approach has not been applied at the industrial park level, where many large water users consume great amount of water and discharge too much wastewater into local aquatic environment. The premise of this study is that industrial parks can be viewed as watersheds.

This chapter reviews the literature on industrial ecology, industrial ecosystems and eco-industrial development, water reuse, and integrated water resources planning and management. Such a review develops the context and need for this research.

2.2 INDUSTRIAL ECOLOGY

2.2.1 The Concept of Industrial Ecology

Over the last few decades, environmental problems have become a priority issue for governments, industries, citizens, environmental organizations, and other interest groups. The traditional "end-of-pipe" pollution control methods mandated by "command-and-control" regulations have been inefficient because pollutants are generally transferred from one medium to another, and economically companies had to comply with the regulations regardless of the total costs (Karamanos 1995). Moreover, the implementation, monitoring and enforcement of these regulations was costly, sporadic and in many cases incomplete, resulting in continuing contamination of the environment.

A preventative approach on environmental management became crucial.

Industrial ecology builds on earlier concepts of pollution prevention and eco-efficiency, adding a systems viewpoint. Furthermore, industrial ecology adds an ecological dimension, acknowledging that industry must be integrated with and operated within the limits of the surrounding biological ecosystem (Côté and Smolenaars 1997). It models industrial systems after natural systems, where the output of one organism becomes the input for another and the benefit from each process is maximized (Desrochers 2002). In this way, groups of companies and industries that interact can maximize materials efficiency. Thus, industrial ecology has become a new powerful analytical tool to think beyond a mechanistic, fragmented view of environmental problems and solutions (Hoffman 2003).

Industrial ecology is still in its infancy as a concept and field. Seager and Theis (2002) found that a uniform framework of industrial ecology has yet to be established or proposed. Even so, scholars more or less agree that industrial ecology contains three key elements:

"1. It is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the biosphere;
2. It emphasizes the biophysical substratum of human activities, namely, the complex patterns of material flows within and outside the industrial system, in contrast with current approaches which mostly consider our economy in terms of abstract monetary units, or alternatively on energy flow.
3. It considers technological dynamics, namely, the long-term evolution of clusters of key technologies as a crucial element for the transition from the current unsustainable industrial system to a viable industrial ecosystem of the future." (Erkman 2001)

These perspectives indicate that industrial ecology is the study of the technologies and flows of material and energy in the industrial, service, and consumer sectors, and the effect of those flows on the environment. It shows how industrial processes relate to the natural processes of the ecosystem, which includes human and their economic and social activities (Hoffman 2003). The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them.

According to the generally accepted principles of industrial ecology, the overall impact of industrial activities is considered by recognizing that the stages of extraction, manufacture, and disposal are linked across time, distance, and economic sectors (Frosch 1995). Lowe (2001) proposed that industrial ecology defines the system boundary to incorporate the natural ecosystem and seeks to optimize material flow within the system. Its premise is that the overall approach to industrial production must be redesigned to emulate and work in unison with natural systems in order to achieve both sustainability and continued profitability.

2.2.2 Development of Industrial Ecology

The concept of industrial ecology has been evolving essentially since 1989, spurred on by the publication of "Strategies for Manufacturing", which appeared in the mainstream journal Scientific American (Frosch and Gallopolous 1989). In that paper, the authors stated:

"The traditional model of industrial activity, in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of, should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized and the effluents of one process… serve as the raw material for another process."

Ayres (1989) introduced the concept of industrial metabolism, which encompasses both production and consumption with the recognition that in many places the major human sources of environmental problems are shifting from production to consumption processes. Since then, numerous researchers and industry representatives have been developing and refining the concept. Now it is gaining recognition not only in business communities, but also in academic and government circles.

The Journal of Industrial Ecology (MIT press) was launched, and in early 2001, the International Society for Industrial Ecology was founded. The latter promotes industrial ecology as a way of finding innovative solutions to complicated environmental problems and facilitating communication among scientists, engineers, policy-makers, managers and others who are interested in how environmental concerns and economic activities can be better integrated[1].

Côté and Cohen-Rosenthal (1998) reviewed some of the definitions of eco-industrial parks (EIPs), the primary arena for testing and implementing industrial ecology. They discussed the characteristics of EIPs and introduced the experiences of establishing eco-industrial parks in North America, Europe and Japan. On the basis of these, they presented their thoughts on the essential characteristics of eco-industrial parks, which could be used for the establishment of industrial parks as ecosystems.

Burstrom and Korhonen (2001) studied the potential roles of a municipality in regionally oriented environmental management and development planning. They suggested that a municipality could serve as an institutional anchor tenant to provide the regional industrial ecology effort. In return these efforts could provide a basis for increased cooperation between public and private actors of a region as well as integration of regional environmental and development issues.

By tracing some of the historical and intellectual antecedents of the field, Seager and Theis (2000) suggested that life cycle assessment and systems analysis could be two of the most promising analytical methods for industrial ecology. Also, they found that no single measure is sufficiently developed to prioritize among qualitatively disparate types of environmental impacts although a number of comparative environmental metrics may be employed in cost-minimization or thermodynamic efficiency studies.

Thomas (2003) studied the application of industrial ecology in the development of policies. He pointed out that there is a need for better understanding of the potential and

[1] See http://www.is4ie.org/.

limitations of a range of promising approaches including: (a) technological innovation, (b) voluntary and cooperative approaches to environmental management, (c) substitution of services for products, (d) recycling and reuse, (e) reduction in the amounts of materials used in products, and (f) substitution of scarce resources with those that are plentiful.

Given the fact that some Chinese industrial parks are quite similar to a small municipality in terms of size and functions and the park managers are from public sectors, this research will test Burstrom and Korhonen's suggestion in the developing world. Also, since the nature of this research is to employ a system analysis approach to maximize water efficiency at the industrial park level, the expected research results can be used to test how the system approach can help improve eco-efficiency. Therefore, this research will further contribute the development of industrial ecology from different perspectives.

2.2.3 Strategies and Tools of Industrial Ecology

Strategies to promote industrial ecology can be implemented from several different perspectives due to its broad conceptual framework. Chertow (2000) suggests dividing industrial ecology activities into those that focus on the firm or unit process level, at the inter-firm, district or sector level, and finally at the regional, national, or global level. Figure 2-1 shows this hierachical application framework of industrial ecology.

At the firm or unit process level, industrial ecology focuses on products and their lifetime impact on the environment. Life-cycle assessment (LCA), pollution prevention (PP) or cleaner production (CP), design for environment (DfE) and dematerialization are the primary tools.

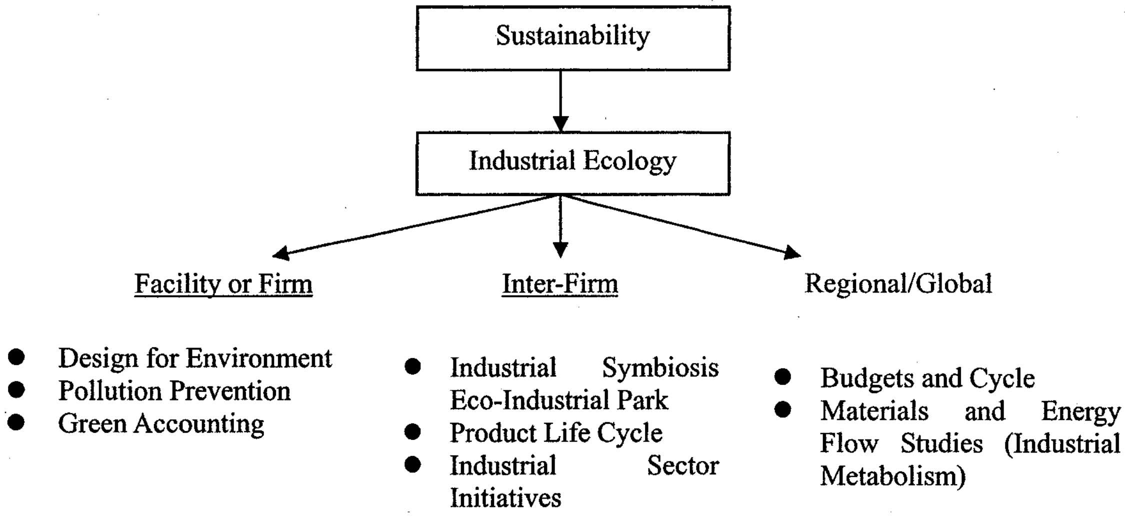

Figure 2-1. Hierachical framework of industrial ecology (Chertow 2000)

LCA is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and material uses and releases on the environment (Graedel and Allenby, 2003). The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/reuse/maintenance; recycling; and final disposal (Curran, 1996). Life cycle assessments are often completed to aid in decision-making, such as in the plastic versus paper bag or cloth versus disposable diaper debates (Freeman et al., 1992).

According to the U.S. EPA (1990), pollution prevention is a strategy involving the use of materials, processes, or practices that reduce or eliminate the creation of pollution or wastes at the source. Cleaner production is “the continuous application of an integrated preventive environmental strategy applied to processes, products, and services to increase overall efficiency and reduce risks to humans and the environment” (UNEP official website). Both can reduce operating costs and increase profitability through better production efficiency, improved public image, better access to financial resources, reduced business risk from accident and regulatory enforcement and stronger competitiveness. Cleaner production is essentially the same as pollution prevention, but with a slightly larger scope.

DfE is a systematic approach that considers all potential environmental implications of a product in the design phase. It requires designing products for durability, repair, remanufacture and reuse in order to reduce their environmental burdens. DfE designates a practice by which environmental considerations are integrated into product and process engineering design procedures. Accordingly, DfE takes a systemic perspective, albeit at the product and process level (Graedel and Allenby 1995).

Dematerialization is a technique by which "more efficient use of a given material for a given function" is achieved by reducing material input per unit of output (Ayres 1997). Advances in the electronics industry are often cited as classic examples of dematerialization; the work of a computer that used to be the size of a room can now be completed using a device smaller than one's hand. Similarly, in striving for greater fuel efficiencies, automobile makers have produced less massive (in the scientific sense of the word) vehicles when comparisons are made within a given size class.

At the inter-firm, district or sector level, the main application of industrial ecology is to encourage the development of eco-industrial clusters or parks (EIP). "EIP is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water and materials" (Lowe et al 1997; Lowe 2001). By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only (Lowe et al 1997). The goal of an EIP is to improve the economic performance of the participating companies while minimizing their environmental impact. Components of this approach include new or retrofitted design of park infrastructure and plants, pollution prevention, energy efficiency, and inter-company partnering. Through collaboration, this community of companies becomes an industrial ecosystem. Section 2.3 has a detailed introduction to eco-industrial parks.

At the regional, national or global level, one key strategy for applying industrial ecology is the creation of eco-industrial networks (EIN). EIN involves developing new local and regional business relationships among industries and between the private sector, government and educational institutions in order to use existing and new energy, material, water, human and infrastructure resources to improve production efficiency, investment competitiveness, community and ecosystem health (Canadian Eco-Industrial Network 2001). It can also be broadened to national or even global levels. It is part of a broader emerging trend toward a system-based approach to improving environmental management and competitiveness. One type of EIN is the "greening" of supply chains, in which efforts are made to reduce environmental impacts and improve resource efficiency. The design of returnable and reusable packaging for shipment of goods to industrial customers is one example.

Another tool at this level is industrial metabolism, which attempts to understand the total pattern of energy/material flows from initial extraction of resources to final disposal of wastes (Lowe 1993). Industrial metabolism aims at understanding the complex patterns and dynamics of flows and stocks of materials and energy within the industrial system as well as their interactions with the biosphere, and therefore, can help carry out regional, national or global material and energy flow analysis. Such an analysis allows researchers and managers to determine the quantity of minerals, forest, water and other resources that are extracted and to know the mass of wastes generated in each exchange (Ayres 1997). Many scholars have already implemented materials flow analysis at regional and national levels. For instance, Marco et al., (2000) carried out materials flow analysis of the Italian economy by applying the principles of industrial metabolism.

2.2.4 Barriers and Limits

Although industrial ecology has been applied in many countries, industries and situations, a number of limitations and barriers still exist, which prevent or limit the successful development of industrial ecology. These barriers can be grouped into the following categories:

Institutional Barriers

A successful application of industrial ecology will depend on the involvement of multiple stakeholders. But disciplines can create institutional barriers. For instance, ecologists often think of industry as being the source of environmental problems while industrial engineers consider ecological limits as constraining. Education and incorporation of ecological ideas is crucial. Also, many policy-makers have come to view industrial byproducts as a nuisance to be destroyed rather than as potentially useful resources. Under current legal practice, liability considerations for hazardous materials can favor disposal over selling and/or transferring the material for reuse. The original seller of any material used in a product implicated in a damage suit can be held liable, even if the material has been remanufactured and transformed by a number of different parties to produce the final product (Frosch 1994). Recovery, transport cost discrimination against secondary materials, subsidies to the primary sector and minimum content laws mandating the use of 'virgin material' further favor disposal over selling and/or transferring the material for reuse (Desrochers 2002). Where there is an increasing recognition of the need to go beyond "command-and-control" regulations, industrial ecologists have so far failed to discuss the possibility of recapturing the best features of the common law approach to pollution problems (Desrochers 2002).

Technical and Informational Barriers

Technical barriers limit the waste exchange linkages that can be formed among industries. This makes it difficult if not impossible to get a truly closed-loop system. Certain wastes and byproducts contain contaminants, which impede their reuse and/or make them dangerous to handle (Frosch 1994). A lack of methods for separating/converting/purifying certain waste streams into a form that is useable by other industries as input is a hindrance. Moreover, companies hesitate to implement industrial ecology due to technical confidentiality and trade secrecy concerns. Companies tend to be secretive about their waste streams, as well as their waste treatment technology. They fear if competitors know about their byproducts, they may deduce protected trade secrets (Frosch 1995). Also, informational barriers often stifle the progress of byproduct synergy projects. Systems for acquiring and disseminating cost information within many organizations are poor (Frosch 1994). Information about cost is usually not available to all individuals in a company who may be able to utilize it for the good of the company. In addition, information on materials is not always collected and presented in a manner that is useful to decision-makers (Ayres 1994). It is often the case that the answer to "who might need the information?" is not clear. Furthermore, standard management practices do not often track costs in a manner that is useful to product or process engineers. Consequently, there is still a great demand for developing information technologies to facilitate information access and sharing.

Economic Barriers

Economic barriers prevent many companies from implementing industrial ecology. One criticism of industrial ecology is that it could discourage pollution reduction and process improvement (Chertow 1999). When wastes are seen as a commodity, reducing them may adversely affect a company's short-term profits. There is an ongoing discussion about reducing pollution and improving resource efficiency. In any event, we cannot get waste down to zero. In this situation, pollution reduction may not be viewed as a priority and companies are discouraged from updating their systems and plant equipment. Costs are also involved in collecting, transporting and separating wastes and byproducts. In addition, these activities require information, effort and energy, which all have an accompanying dollar value.

Quantification

Although many tools have been developed for the implementation of industrial ecology, some of them are more qualitative, like life-cycle assessment, design for environment, and dematerialization, which make industrial ecology more like a kind of philosophy, rather than an independent discipline (Erkman 2001). This less quantitative limit impeded people to push for changes in industrial-environmental relations. Unless there are some convincing data through quantitative analysis and study, it's hard to persuade decision makers and site engineers to accept the principles of industrial ecology and put them into practice. Some tools, like system analysis and materials balance, are suitable for such quantitative study, but relevant pilot studies are still few and more quantitative studies on analyzing material flows are still crucially needed to show people the benefits (both economic and environmental) of implementing industrial ecology.

Generally, although there are barriers and limits, industrial ecology offers exciting prospects for the development of a more holistic approach to the adoption of environmental management plans, particularly in developing countries. It will be extremely important to carry out more quantitative studies in industrial ecology. Incorporating system analysis would assist 1) the diagnosis of present and future problems, 2) realistic valuation of resources used and 3) set priorities for action.

2.3 INDUSTRIAL ECOSYSTEM AND ECO-INDUSTRIAL DEVELOPMENT

2.3.1 Industrial Ecosystem

Industrial developments are usually in planned locations away from residential land uses to protect against possible nuisances such as noise, odors, and heavy truck traffic (UNIDO 1997). Such an arrangement is wise, except as urban areas grow they inevitably encroach on industrial areas. In the long run it is not sustainable because there is simply not enough room to continue separating land uses (UNIDO 1997).

The best way to deal with these problems is to change the way we think about industrial land uses, for industry to change their industrial processes to reduce waste, and make industry fit the environment instead of changing the environment to fit industry. Waste could be reduced if industrial systems operated more like natural ecosystems, namely using recycled materials instead of raw materials in the manufacturing process, and producing materials that can again be recycled after consumption. By adopting this approach, the industrial system could be viewed as an industrial ecosystem.

Initially, an industrial ecosystem was generally conceived as a collection or cluster of co-located industrial facilities, such as an industrial park, and was frequently referred to as an eco-industrial park (EIP). This is because industrial parks contain diverse industries, and economies of scale can be achieved. For example, many small to medium-sized companies in industrial parks cannot afford the cost or time needed to implement their environmental management systems but they would benefit (economically and ecologically) from the provision of common environmental services (Côté, et al., 1994). Creating spin-off businesses that repair products, rent equipment or use the wastes of other industries as their basic inputs can reduce the total waste outputs and diminish demand for treatment facilities. More recently, the geographic scale of industrial ecosystems has expanded, and often refers to systems defined by political boundaries such as port authorities, cities or municipalities (Dunn and Steinemann 1998; Korhonen 2001; Burstrom and Korhonen 2001). In the future, it is possible that industrial ecosystems could be defined by bioregional boundaries, and may be thought of as bio-industrial regions. However, much of the current literature in this field is still related to EIPs. Industrial parks seemed an obvious place to start, given their relative abundance, contribution to environmental problems, and their familiarity. However, the goals of eco-industrial development are the same regardless of scale, and most of the strategies and theories initially developed for EIPs can be applied to different scales.

2.3.2 Perspectives of Industrial Ecosystem

2.3.2.1 Nature as the Model

As discussed in the section of industrial ecology, one of the two basic tenets of industrial ecology is that lessons learned from nature can be applied to industrial operations. In this way, the basic characteristic of an industrial ecosystem is that its functions are analogous to a biological system. Many aspects of natural ecosystems can also be incorporated into an industrial ecosystem. Two of the qualities of a natural ecosystem that are desirable for an industrial ecosystem are resiliency and stability. A resilient and stable industrial ecosystem will require a variety of companies to ensure that, just like in a biological ecosystem, all appropriate niches are filled (Côté and Smolenaars 1997). For example, the resiliency that biodiversity supports could be mimicked in an industrial system by ensuring a "diverse assembly of businesses" (Côté and Hall 1995). Companies operating in an industrial ecosystem may take on roles analogous to biological ones, such as producers, consumers, scavengers and decomposers. As explained by Geng and Côté (2002), in the language of industrial ecology, producers represent those industries that extract materials and provide raw materials for other industries. Industrial consumers are those companies that utilize the raw materials derived from producers and manufacture products for secondary and tertiary consumers. Scavengers are those that feed off the wasted resources of other companies, collecting and separating resources, making them available to decomposers. Decomposers are those that use the wasted resources from both producers and consumers and transform them back as new materials or nutrients. Composting facilities are excellent examples of decomposers.

In addition to being resilient and stable, biological ecosystems contain interdependencies and have a more balanced competitiveness. This is in contrast to current industrial systems, which place great importance on independence and competitiveness (Côté and Cohen-Rosenthal 1998). Nonetheless, incorporating this aspect of biological ecosystems into industrial ecosystems is possible, since "... companies are embedded in chains or webs of suppliers and customers, similar to those chains and webs which occur in indigenous or natural ecosystems. In addition, industries are dependent on resources available in the environment to ensure their productivity" (Côté and Cohen-Rosenthal 1998).

Finally, biological ecosystems have achieved symbiosis, "...the intimate living together of two kinds of organisms, where such an association is of mutual advantage..." (Webster's New World Dictionary 1986). Symbiotic relationships should be encouraged in industrial ecosystems "...to make maximum use of inputs, products, and waste materials. In other words, cycles of materials and networks of producers, suppliers and recyclers analogous to food webs in nature would be encouraged." (Côté et al., 1994)

2.3.2.2 Objectives, Functions and Benefits of Industrial Ecosystems

The overall objective of an industrial ecosystem is to ensure sustainable use of natural and financial resources by operating within the carrying capacity of the surrounding natural ecosystem. Secondary objectives include reductions in materials and energy use and reductions in the waste output (Côté and Hall 1995). Based on their review of the literature, Côté and Cohen-Rosenthal (1998) found that the essential functions of an industrial ecosystem are to:

"1. Define the community of interests and involve that community in the design of the park.

2. Reduce the environmental impact, or ecological footprint, through substitution of toxic materials, absorption of carbon dioxide, material exchanges and integrated treatment of wastes.

3. Maximize energy efficiency through facility design and construction, co-generation and cascading.

4. Conserve materials through facility design and construction, reuse, recovery, and recycling.

5. Link or network companies with suppliers and customers in the wider community in which the eco-industrial park is situated.

6. Continuously improve the environmental performance by the individual businesses and the community as a whole.

7. Have a regulatory system which permits some flexibility while encouraging companies to meet performance goals.

8. Use economic instruments which discourage waste and pollution.

9. Employ an information management system which facilitates the flow of energy and materials within a more or less closed-loop.

10. Create a mechanism which seeks to train and educate managers and workers about new strategies, tools, and technologies, to improve the system.

11. Orient its marketing to attract companies which fill niches and complement other businesses. "

There are ecological, financial, and social benefits to such a strategy. The ecological benefits include conservation of natural resources and a reduction of the environmental impact of industrial operations, achieved through more efficient material and energy use, reduced waste discharge, substitution of toxic materials, and absorption of carbon dioxide "reducing carbon dioxide emissions" (Côté et al 1994; Côté and Hall 1995; Côté and Cohen-Rosenthal 1998). The financial benefits include cost savings achieved through more efficient materials and energy use, potentially lower insurance costs, and lower waste treatment requirements (Côté et al 1994; Côté and Hall 1995; Lowe 1997).

Additional financial benefits include increased revenues from the sale of wastes (Côté et al 1994); increased sales due to 'green' and niche marketing and more competitive production methods (Lowe 1997; Côté and Cohen-Rosenthal 1998); and the avoidance of regulatory penalties (Lowe 1997; Lowe, 2001). The most obvious social benefit is an improvement in public health achieved by reducing or even eliminating the discharge of many wastes to the air, soil, or water systems on which the public depends (Côté et al 1994; Côté and Hall 1995). Other social benefits include increased local employment, increased educational opportunities, and the opportunity to integrate community efforts such as "...recreation, wellness, transport and day care facilities (Côté and Cohen-Rosenthal 1998).

2.3.2.3 Material and Energy Cycling

There are many different factors that can affect the design and operation of an industrial ecosystem. These factors include location, the mix of companies, financial viability, information management, and the establishment of materials/energy cycling. According to Lowe (1993), establishing material and energy cycling was one of the first goals of an industrial ecosystem, the ultimate goal of industrial ecology is to bring the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials. In this nearly closed loop system, the wastes of one process become the raw materials for another process (Frosch and Gallopoulos 1989).

The emphasis on material and energy flows has developed for two reasons. Firstly, this strategy builds on already familiar strategies of pollution prevention and process integration. Secondly, since our environmental problems are most commonly associated with pollution caused by material or energy flows, it seems logical to begin by addressing those flows. As Odum (1989) notes: "Attention for many years has focused on increasing outputs, that is, yields. Whatever inputs that would increase yield on the short term were provided with little regard to efficiency or production of unwanted outputs such as non-point pollution". There has been such a focus on this aspect of industrial ecology. Two new names for it have emerged: by-product synergy and industrial symbiosis. These terms refer to the "... synergy among diverse industries, agriculture, and communities resulting in profitable conversion of by-products and wastes to resources promoting sustainability" (Chertow 2000).

It is already"... common for two companies and even more to develop mutually advantageous relationships in which the waste products of one company form a valued input product for another" (Cohen-Rosenthal 1996). As Frosch (1995) and Lowe (1996) note, many industrial complexes have established material exchanges, although they remain major emission sources. So, material exchanges are not a new idea. The petro-chemical sector is a good example. However, the advantage of applying material and energy cycling from an industrial ecology approach is that "A fully developed industrial ecology might not necessarily minimize the waste from any specific factory or industrial sector but should act to minimize the waste produced overall" (Frosch 1995).

2.3.3 Eco-Industrial Development

Eco-industrial development (EID), which is based on the idea that a flourishing economy and environmental health can coexist, offers an "invitingly concrete" way to integrate environmental management and meet environmental, economic, and community development goals (Chertow 2000). It adds value to businesses and communities by optimizing the use of energy, materials, and community resources. While it draws from pollution prevention approaches focusing on the efficiency of individual firms, its unique contribution is its emphasis on inter-firm resource exchange linkages (Desrochers 2002). Just as in natural ecosystems, interconnected entities form symbiotic relationships to insure survival and resource efficiency. For business, value is added as its waste byproducts, water, and energy are cycled back into the overall production stream of an industrial park or region. This closing of the loop results in the conservation of natural resources and lower disposal and production costs. Also, eco-industrial development offers strategies to achieve greater efficiency through "economies of systems integration", where partnerships between businesses meet common service, transportation, and infrastructure needs (Ayres 1996). Therefore, eco-industrial development offers the most tangible way for planners to apply industrial ecology, and has been employed by countries both in the developed and developing world for their sustainable industrial development.

The research group in the School for Resource and Environmental Studies at Dalhousie University developed the first guide to designing and operating industrial parks as ecosystems in 1994 and provided a set of principles, strategies, guidelines and support systems (Côté, et al, 1994). Their work was based in Burnside Industrial Park, Nova Scotia, Canada. In 1998, an Eco-Efficiency Center was founded there to help tenant companies improve their ecological effectiveness and economic efficiency, disseminate advanced methods and information on pollution prevention, eco-industrial parks, and create networks. The group has also been involved many international eco-industrial development efforts, including mainland China, Taiwan, Philippines, Indonesia, and Thailand. At approximately the same time, Lowe et al (1997) completed the first handbook for eco-industrial parks, where they overviewed the concepts, policies, strategies and planning methods for designing an eco-industrial park Lowe. In 2000, he completed another EIP handbook for the Asian Development Bank, which has now been revised and translated into Chinese (Lowe and Geng 2003).

The first active academic group on EIP in the US was the Eco-Industrial Development Program at Cornell University which eventually became part of the National Center for Eco-Industrial Development, jointly run by the University of Southern California and Cornell University, and funded by the Department of Commerce. This center has already been conducting research and supporting community partnerships for eco-industrial development for several years through its Eco-Industrial Development Program[1]. The mission of the Center is to facilitate job creation and sustainable industrial expansion in distressed communities around the nation by applying principles of industrial ecology, establishing eco-industrial parks, and expanding use of environmentally benign manufacturing processes and techniques[2].

The research group in the Yale School of Forestry and Environmental Study is another

[1] Please see http://www.cfe.cornell.edu/wei/EIDP (March 2003).
2 Please see http://www.usc.edu/schools/sppd/research/NCEID/center.html (March 2003).
[2] Please see http://www.usc.edu/schools/sppd/research/NCEID/center.html

academic research group in this new field in the U.S. and has conducted 18 studies of industrial symbiosis and produced many research papers since 1997 (Hollander 2001). For example, Chertow (2000) reviewed the small industrial symbiosis literature and some antecedents, as well as early efforts to develop eco-industrial parks as concrete realizations of the industrial symbiosis concept. Through reviews, she pointed out that input-output matching, stakeholder processes, and materials budgeting appear to be useful tools in advancing eco-industrial park development. Also, she found that evolutionary approaches to industrial symbiosis are important in creating the level of cooperation needed for multi-party exchanges.

In terms of technical tools for eco-industrial development, there are also some initiatives. In Brownsville, Texas, an input-output model (Bechtel model) used for a large petroleum refining complex has been adapted by Bechtel to a regional materials' flow to simulate a virtual eco-industrial system (Hollander 2001). Elaborate lines connect reported byproducts from one company with those needed by other companies. The U.S. Environmental Protection Agency contracted the development of a similar product called Designing Industrial Ecosystems Tool (DIET). This software program includes a linear programming optimization model, designed to aid decision makers and planners in identifying combinations of industrial facilities that contain economic and environmental potential for an eco-industrial park at a given site (Giannini-Spohn 1997). Unfortunately the DIET was never maintained by the US EPA.

Casavant (2000) used chemical process simulation to create a model of an industrial ecosystem comprising five companies. The model accounted for the input, output, product, by-product, and discharge streams for each of the five companies that participated in the study. Her study indicated that process integration could be a useful tool to evaluate the inclusion of different companies to determine how to optimize a number of industries and integrate them into an industrial ecosystem, namely, which one fills niches in the system.

With regard to the application of eco-industrial development, there are now hundreds of projects undertaken in many countries. In the U.S, there are over 30 projects[1]. In Canada the Canadian Eco-Industrial Network (CEIN) was launched in January 2000, funded by Natural Resources Canada, Environment Canada, and Dalhousie University (CEIN 2000). Preliminary feasibility studies have been completed for Saint John, New Brunswick.; the Alberta Industrial Heartland, Alberta.; Sarnia-Lambton, Ontario.; Sault Ste-Marie, Ontario.; Montreal, Quebec.; and Sorel-Tracy, Quebec. (Peck et al., 1998). In Japan, since the term "eco-industrial park/estate" is not commonly used, the exact number of projects is unknown. One category of such projects in Japan is known as eco-towns. One estimate indicates that there are currently about 60 eco-town projects operating or under development, including those that are still in the planning and consideration phases (Lowe 2001). In Europe, such initiatives have taken place in France, Austria, Italy, Finland, Germany, Britain, Sweden and Norway (Lowe 2001; Côté and Cohen-Rosenthal 1998; Korhonen et al., 2001; Magerholm Fet 2001; Fleig 2000).

In developing countries, many projects are also being undertaken, especially in Asian Rapidly Industrializing Countries (ARICs), such as Thailand, the Philippines, China, and India. In Thailand, the Industrial Estate Authority of Thailand (IEAT) has recently evaluated the feasibility of transforming all their existing 29 industrial estates into eco-industrial parks (Lowe 2001). With the support of the Deutsche Gesellschaft für Technische (GTZ), five sites were chosen as the first demonstration projects. According to Chiu (2001), the first initiative incorporates by-product exchange, resource recovery, cleaner production, community programs, and development of eco-industrial networks linking estate factories with industry outside the estates. They have identified utilization of by-products as an early concern, but they also found that opportunities for exchanges among the factories at any one estate are limited. As a result, when they develop their estate plans, they began to build an eco-industrial network between their companies and suppliers outside the estates as a priority (Chiu 2002).

The Philippine government is very active in its program of grouping complementary industries in a system by using the principles of industrial ecology (US-AEP 1999). The

[1] Please see http://www.cfe.cornell.edu/wei/EIDP/eid.html

Department of Trade and Industry and its Board of Investment have considered EIPs to be the highest form of the industrial clustering program. They led the first of the industrial ecology experimental projects in the Philippines, called Private Sector Participation in Managing the Environment (PRIME), sponsored by the United Nations Development Program (UNDP). This project was designed to encourage business competitiveness while conserving the country's natural environment through environmental management system and cleaner production (UNDP 2001). It includes an industrial ecology module, which is supposed to promote waste reduction in the country's industrial growth centers by restructuring industrial systems to minimize waste and maximize recycling of materials and energy (US-AEP 1999). As the first stage, six industrial estates joined the demonstration projects. Five industrial estates in Laguna and Batangas Provinces are participating in the by-product exchanges. The sixth site is located in Bataan Province and owned by Philippine National Oil Company (Lowe 2001; Chiu 2002).

In India, a Swiss-based organization, the Institute for Communication and Analysis of Science and Technology (ICAST), played a key role in introducing industrial ecology into India through field research, conferences, and workshops. ICAST has conducted four industrial metabolism studies on different industrial systems in India. Their approach is first to analyze the flow of resource through the whole system, then to re-define the issues on the context of resources. On the basis of these, they set the priorities for action and identified the potential reuse and recycling opportunities. By doing a detailed study of the utilization of identified critical resources, they proposed a strategic planning for optimizing selected resources (Erkman and Ramaswamy 2000).

In China, an investigation undertaken by Dalian University of Technology (DUT) shows that there are over 30 projects attempting to implement eco-industrial development principles. Figure 2-2 presents the distribution of these projects. But these are not eco-industrial parks unless the parks committed to lowering overall emissions through symbiosis. In some cases the term eco-industrial park appears to be used to attract more investment. The nature of such projects includes a collection of companies making "green" products, a collection of environmental technology companies, an industrial park increasing the degree of landscaping, or a park committed to low emission efforts.

Figure 2-2 The distribution of eco-industrial park projects in China

Among those efforts in the world, probably the most well-known eco-industrial development effort grew over thirty years in the town of Kalundborg, Denmark. There, a network of firms organized to utilize one another's byproducts, reducing waste and creating an adaptive industrial ecosystem. Due to a freshwater shortage, they have also taken steps to recycle as much water as possible both at the individual company level and through inter-firm collaboration. For example, besides its internal wastewater reuse program, by getting surface water from the lake of Tissø and treated wastewater from Statoil refinery, Asnæs Power Station reduced its groundwater consumption by 90%. Also, the wastewater from Novozymes A/S and Novo Nordisk A/S is part of a genuinely symbiotic relationship: Novozymes A/S treats all wastewater up to a level corresponding to the wastewater of an ordinary household. From Novozymes A/S, the treated wastewater is pumped to the treatment plant of Kalundborg Municipality where a final treatment process takes place. This is because the Novozymes A/S wastewater is of a relatively high temperature, making it easier for the municipal treatment plant to treat its wastewater. In this collaboration process, the environment is also the winner as the overall discharge of nitrogen into Jammerland Bugt is reduced. Wastewater is also discharged from Asnæs Power Station into the treatment plant of Kalundborg Municipality. Then, all the treated wastewater is led to a recycling reservoir together with the runoff from the surrounding fields and surplus water from Tissø in the winter period. The recycling reservoir has a capacity of 220,000 cubic meters of water, which are used in the power station processes again (Gertler 1995; Chertow 2000; Lowe 2001).

Generally, industrial ecology is a useful framework for helping to achieve a more sustainable industrial development. Practically, it requires people to develop industrial ecosystems, especially eco-industrial parks. Industrial parks have the potential to be important players in implementing eco-industrial development because they contain a diversity of companies and service functions that allow the creation of considerable synergies (Balkau 2002). Up to now, most environmental actions within industrial parks have focused on achieving compliance with pollution standards rather than contributing to sustainable development policy. There is a need to plan and manage industrial parks by facilitating the creation of synergies among their tenants, establishing cooperative arrangements for environmental information and services, and providing key functions such as materials exchanges and waste minimization advice on a park-wide basis. This thesis will use water as an example to test how to encourage synergies among those tenants, and therefore, the next sections will review the current stage of the art on water reuse and integrated water management.

2.4 WATER REUSE

All water is recycled through the global hydrologic cycles. However, planned local water reuse is becoming increasingly important for two reasons (Bouwer 1993). One is that discharge of sewage into surface water is becoming increasingly difficult and expensive as treatment requirements become more and more stringent to protect the quality of the receiving water for aquatic life, recreation and downstream users (Bouwer 2000). The cost of the increasingly stringent treatment may be so high that it becomes financially attractive for people to treat their water for local reuse rather than for discharge (Shelef 1991). The second reason is that wastewater is often a significant water resource that can be used for a number of purposes, especially in water short areas (Bouwer 1997). The most logical reuse is for non-potable purposes, such as agricultural and urban irrigation, industrial uses (cooling and processing), fire fighting, environmental uses (wetlands, wildlife refuges, riparian habitats, urban lakes), dust control, toilet flushing, etc (US EPA 1992). This requires treatment of the effluent so that it meets the quality requirements for the intended use. Adequate infrastructures like storage pools, canals, pipelines, and dual distribution systems are also necessary so that waters of different qualities can be transported to different destinations (Bouwer 2000). In addition, aesthetics and public acceptance are important aspects of water reuse, especially where the public is directly affected. In this section, water reuse applications, including the application of wastewater reuse, internal wastewater minimization, and water reuse planning, will be reviewed.

2.4.1 Wastewater Reuse Applications

The purpose of this section is to present wastewater reuse applications and to emphasize the water quality requirements in order to protect the environment and mitigate heath risks. The principal reuse categories include (1) agricultural and urban irrigation, (2) industrial applications, (3) groundwater recharge, and (4) potable reuse (US EPA 1992). Appendix 2 is a table of categories of wastewater reuse and potential constraints. These constraints are further discussed below:

<u>Agricultural and urban irrigation</u>

Agricultural and urban irrigation is the most applicable purpose for wastewater reuse in terms of volume (Mara and Caincross 1989). This is because usually agricultural and urban irrigation doesn't require high quality water. Most of reclaimed wastewater can be used for crop irrigation, park, greenbelt, school yard, residential garden and golf course irrigation.

However, if not properly managed, such applications may result in surface and groundwater pollution. Due to health concerns, people may be reluctant to purchase such crops. Also, where reclaimed wastewater is used for irrigation, biological agents including bacterial pathogens, helminth, protozoa and viruses may pose the health risks (US EPA 1992). In many developed countries, this is not permitted because of these risks.

Industrial water reuse

Industry can be considered as a significant source of reusable wastewater. The main industrial application is cooling because cooling tower make-up water represents a significant water reuse for many industries (Bouwer 1997). For industries such as electric power generating stations, oil refining, and many other types of manufacturing plants, one-quarter to more than one half of the total water use is cooling tower make-up (US EPA 1992). Because a cooling tower operates as a closed-loop system, it can be viewed as a separate water system within its own specific set of water quality requirements. Thus, using reclaimed wastewater for cooling tower make-up is relatively easy and is practised worldwide. Other industrial applications of wastewater reuse include boiler feed, process water and water for heavy construction (US EPA 1992).

The main constraints for industrial uses include constituents related to scaling, corrosion, biological growth and fouling, public health corrosion, particularly aerosol transmission of pathogens in cooling water (US EPA 1992)

Groundwater Recharge

Groundwater recharge can be used to (1) reduce, stop, or even reverse declines of groundwater levels, (2) protect underground freshwater in coastal aquifers against saltwater intrusion from the ocean, and (3) store reclaimed wastewater and surface water, including flood or other surplus water for future reuse. It is also achieved in land treatment and disposal systems where wastewater is disposed of via percolation and infiltration (Bouwer 1997).

In order to protect against accidental potable water reuse, the potable reuse should be indirect, meaning that the effluent must first be filtered through soil and geological formations before it can be delivered to public water supply systems (Bouwer 1993). However, the surface water route has several disadvantages, including algae growth that can cause taste and health problems since some algal metabolites are toxic. To minimize algae growth, the wastewater may then have to be treated to remove nitrogen and phosphorous, which increases the reuse costs. Also, water is lost by evaporation and the water is vulnerable to recontamination by animals and human activities. These disadvantages do not occur with the groundwater route, where water also receives soil-aquifer treatment (SAT) benefits (Bouwer 2000). Groundwater recharge also enables seasonal or longer storage of the water to absorb differences between water supply and demand, and mixing of the effluent water with native groundwater when it is pumped from wells (US EPA 1992).

The major concern with groundwater recharge using reclaimed wastewater is that potentially adverse health effects may be caused by the introduction of pathogens or trace amounts of toxic contaminants. Because of the increasing concern for long term health effects, effort should be made to reduce the number of chemical species and the concentration of specific organic constituents in the recharge water (Bouwer, 1993, 1997, 2000).

Potable Water Reuse

Potable use of reclaimed sewage effluent is a practice of last resort although unplanned or incidental potable reuse occurs all over the world where reclaimed sewage effluent is discharged into streams and lakes that are also used for public water supplies, and where cess pits, latrines, septic tanks, and sewage irrigation systems leak effluent to underlying groundwater that is pumped up again for drinking (Bouwer 2000). Even when all these treatment steps are used and the water meets all drinking water quality standards, direct potable reuse where the treated effluent goes directly from the advanced treatment plant into the public water supply system (pipe-to-pipe connection) is not recommended (Bouwer 1997). People see this as a "toilet-to-tap" connection and public acceptance will be very low.

Potential constraints for potable water reuse include constituents in reclaimed wastewater, especially organic chemicals and their toxicological effects, aesthetics and public acceptance, health concerns about pathogen transmission, particularly viruses (US EPA 1992).

Besides these applications, reclaimed wastewater also can be used for recreational and environmental uses, like marsh enhancement, lake and pond recharge, fishery and snow-making, and for non-potable urban uses, like fire protection, air conditioning and toilet flushing (US EPA 1992). The concerns for such applications mainly focus on health concerns of bacteria and viruses and eutrophication impacts on aquatic life (Metcalf and Eddy 1991).

2.4.2 Internal Wastewater Minimization

A good water reuse project begins with individual process optimization. Drivers include cost reduction, compliance with stricter regulations, reduction of emission fees, improvement of operating efficiency, and improved public image (Mann and Liu 1999). Cleaner production can help a company identify possible water reuse opportunities within its boundary so as to reduce total freshwater consumption and wastewater discharge. Cleaner production methods include process change, water audit and process integration.

<u>Process Change</u>

Process change means that water conservation by industry can be achieved by redesigning existing processes and facilities to make them more efficient. For example, the use of water by water-cooled electric power plants, one of the most water-consumptive industries in the world, could be cut one-fourth by using dry cooling towers, although these require more energy and are more expensive to operate than wet cooling towers (Asano and Levine 1996). Another example is that countercurrent-rinsing stages can greatly reduce the freshwater demand for rinse operations. According to Smith (1995), other methods include: "

- Increasing the number of stages in extraction processes that use water;
- Using spray balls for more effective internal vessel washing;
- Improving control of cooling towers blowdown;
- Fixing triggers to hoses to prevent unattended running;
- Improving energy efficiency to reduce steam demand and hence reduce the wastewater generated by the steam system through boiler blowdown, aqueous waste from boiler feedwater treatment, and condense loss;
- Increasing condensate return from steam systems to reduce boiler blowdown and aqueous waste from boiler feedwater treatment;
- Improving control of boiler blowdown."

<u>Water Audit</u>

A water audit means that facility management personnel should check all the elements that relate to water supply, use and wastewater emission in order to find potential leakages, losses, and unreasonable applications. By completing the audit procedures, personnel will be able to anticipate the capital and labor costs of a wastewater minimization project and predict the monetary savings that will result from water conservation measures. Potential outcome of an internal water audit is the identification of opportunities for internal water reuse, wastewater regeneration and recycling.

Water reuse means that wastewater can be reused directly in other water-using operations when the level of previous contamination does not interfere with the water-using operation. This reduces both freshwater and wastewater volumes but leaves the mass load of contaminant unchanged.

Wastewater regeneration means partial or total treatment to remove the contaminants that would otherwise prevent reuse. Such water then can be reused in other water-using operations. The regeneration is any operation that removes the contaminants that prevent reuse and include filtration, pH adjustment, and carbon adsorption (Tehobanoglous and Burton 1991). Regeneration reuse reduces both freshwater and wastewater volumes and decreases the mass load of contaminants.

Regeneration recycle means that wastewater can be regenerated so as to remove contaminants and then recycle such water. In this case, regenerated water may enter the water-using operations in which the water stream has already been used. Also, recycle can sometimes create a buildup of undesired contaminants not removed in the regeneration process. Figure 2-3 shows internal water reuse, regeneration reuse and regeneration recycle.

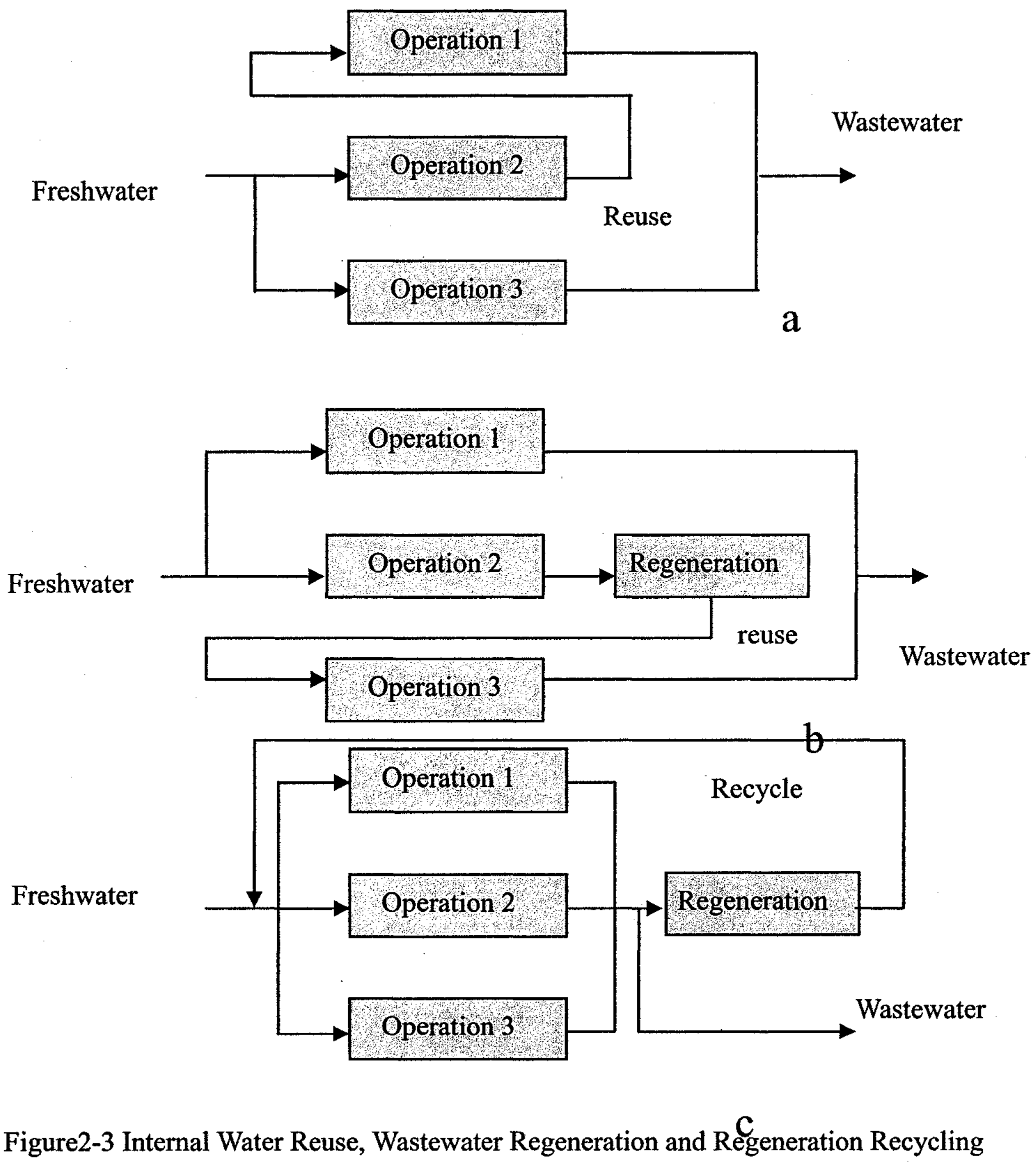

Figure2-3 Internal Water Reuse, Wastewater Regeneration and Regeneration Recycling

<u>Process Integration</u>

Process integration represents an important branch of process engineering initiated in the late 1970s and refers to the system-oriented, thermodynamics-based, integrated approaches to the analysis, synthesis, and retrofit of process plants. The goals of process integration are (1) to integrate the use of materials and energy and (2) to minimize the generation of emissions and wastes.

In terms of its application in wastewater minimization, a new method called water-pinch technology was recently developed. Water-pinch technology is a type of mass-exchange integration involving water-using operations, which provides a fundamental understanding of the global flow of water within a manufacturing process and employs this holistic understanding in identifying performances targets and optimizing the generation and routing of species through the process (El-Halwagi 1997). It involves transferring water from rich process streams (decreasing their concentrations) to lean process streams (increasing their concentrations) so that each stream reaches its desired outlet concentration while minimizing wastewater production and utility consumption. It enables plant engineers to solve a number of problems when retrofitting existing facilities and designing new water-using networks in manufacturing processes. These problems or challenges include the maximum water-reuse target and the minimum wastewater generation target and the minimum treatment flow rate target in an effluent treatment system for a manufacturing process (Mann and Liu 1999).

By applying water-pinch technology, industrial engineers can analyze a water use system and determine:

- the minimum flow rate target for freshwater consumption
- the minimum flow rate target for wastewater generation
- appropriate guidelines for a systematic synthesis of water-using networks and effluent-treatment systems (including guidelines for retrofitting existing facilities) that meet those targets.

Water pinch technology plays a significant role in identifying a minimum freshwater flow rate. It also provides a means first, to identify a goal for water reuse and second, to pinpoint key water reuse opportunities that will allow the engineer to design a water-using network that approaches the minimum flow rate targets as closely as possible. Therefore, it can be used to identify the bottleneck of a design problem and to predict the minimum amount of water required (Yang, Lou and Huang 2000).

Other methods that can be applied for internal wastewater minimization include water balance analysis (Reeves, 2000), heuristic optimization (Almato et al., 1997), zero discharge (Byers, 1995; Hu et al., 1999), etc. All these methods can help individual companies and units improve their water efficiency and reduce wastewater discharge. However, there will be bottlenecks if such methods can only be applied at individual company level. This is because some treated wastewater may not be suitable to be reused within one plant, but still has value for other companies. Although internal wastewater minimization is a good start for saving water, some methods, like process integration, can also be applied to multiple manufacturing facilities as opposed to its normal practice of optimizing multiple processes in one manufacturing facility (Casavant 2000). Therefore, the same idea could be applied for water reuse planning at inter-firm level.

2.4.3 Water Reuse Planning

Successful water reuse planning is usually carried out through modeling water systems. Although models can only approximate real life conditions, they provide a means of evaluating options and potential directions of processes. Such models support decision-makers in project evaluation and implementation (Oron 1996). Modeling also allows for the testing of hypothetical alternative plans of water use.

Mathematical programming techniques are the most applicable and useful modeling tools for water reuse planning and have emerged in recent years as instrumental tools in systematizing water reuse planning (Bishop and Hendricks 1971). This trend has been accelerated by virtue of two factors: the tremendous growth in the use of computers and the recent advances in developing large-scale optimization algorithms (Oron 1996). Practically, we can set up our objective as minimizing the cost of the system or the amount of wastewater, or maximizing the recovery of generated wastewater. Examples of equality constraints include water balances, environmental (e.g., concentration of certain pollutants should be below specific levels), technical (e.g., pressure, temperature, or flow rate should not exceed some given values). To date, there are already many applications in industry.

Bishop and Hendricks (1971) presented one of the first applications of system analysis to the problem of water reuse. They approached the problem as a transshipment problem and used linear programming techniques to obtain solutions. This very simple model did take into account the cost of treatment plus the cost of transportation, but these costs were assumed to be linear. The question of when and what size to build any new projects was not considered. Consequently, Bishop and Narayanan (1977) further developed the transportation water allocation model to include stochastic and seasonal factors in water availability.

Rios et al. (1975) approached the problem of water supply to a region where the availability of freshwater was limited. They tried to minimize the demand of freshwater by enhancing water recycling and reuse practices. This model consisted of one super source, which could provide freshwater to every user in the region; one super sink, where wastewater would eventually be discharged; and the users that could recycle their own water or send it to any other users by treating it to comply with any quality requirements. The model consists of a nonlinear objective function to minimize cost subject to linear constraints. However, it is not very applicable in the sense that (1) all water sources were considered as one source only, (2) the wastewater sent to the sink was no longer available for supply and (3) no regional treatment plants were considered.

Pingry and Shaftel (1979) presented a nonlinear model which takes into consideration both flow requirements and water quality. Their model allowed individual sources to be considered, and interactions between users and treatment plants and among users was possible. The solution technique consisted of an iterative method in which a transshipment problem with a nonlinear objective function was solved for a given set of quality parameters at each iteration. Consisting of the concentrations in the effluent from users and treatment plants were determined by a search technique. The model was applied to a hypothetical case to show its application.

Ocanas and Mays (1981a) presented a nonlinear model to aim to minimize the cost of water treatment, wastewater treatment, and transportation (including piping and pumping) on a regional basis that minimizing the overall cost of water supply. Their model incorporates quality constraints, which are inherently nonlinear, into the model formulation and was solved through a large-scale generalized reduced gradient technique. After that, they further developed their model for determining the optimum allocation of water and reuse of wastewater for multi-period planning (Ocanas and Mays 1981b). This model considers the capacity expansion of treatment facilities and was applied using a planning horizon consisting of three periods in the City of San Antonio, Texas.

Schwartz and Mays (1983) developed a dynamic programming model to determine water allocation schemes for several time periods. This model considered sources of various qualities; in particular, it included three rivers near San Antonio, Texas, two of poor quality and one of high quality. Vieira and Lijklema (1989) presented a similar model that determined the optimal size and location of treatment plants for a specific region in Portugal.

Oron (1996) presented a management model for integrated wastewater treatment and reuse systems. In his model, the optimum of the objective function is evaluated subject to a series of technological, social, health and environmental constraints. He also considered economy of scale by setting objective function as nonlinear. The results of his model provide information regarding the system layout and related optimal investment and operational expenses.

Wilchford and Lund (1997) presented a shortage-handling model that identified options for demand management during droughts of varying duration. Their model was applied to the East Bay Municipal Utility District system in California. They incorporated water quality into their model in a binary fashion: customers desire either high or low quality water.

Zabel et al (1998) introduced how the use of economic instruments for water planning and management can help reduce total water use and encourage water reuse by the European Commission. They then assessed the impact of the schemes on water extraction and effluent discharges and evaluated the feasibility of the application of incentive charging schemes. The main contribution of their study was that correct design of economic instruments could help conserve water resources and minimize the total emissions.

Some efforts have also been undertaken to model water reuse within an industrial park. For instance, Keckler and Allen (1999) used a linear programming model to evaluate water reuse scenarios at a large industrial park in Houston, Texas. Through the model, facilities could be added or deleted, water separated or blended, and types of treatment differentiated. However their model didn't integrate the relevant capital costs (such as pipelines) and operation and maintenance expenses, which may be less applicable to an existing industrial park.

Nobel and Allen (2000) present another linear programming model that identifies cost-optimal reuse scenarios applied to water reuse planning scenarios. In their model, they utilized Geographical Information System (GIS) to provide the capability to compute distances based either on latitude and longitude or on addresses, which may better consider the relevant capital costs and is useful in analyzing existing systems. However, this model didn't consider how to optimize the unwanted wastewater from the wastewater treatment plant. It's a specialized model suitable for a specific park. Also, it would not be applicable to those developing countries where GIS is not widely available.

Generally, these applications indicate that modeling water system is a useful way to help decision makers identify the potential reuse scenarios while keeping minimal costs and test how the hypothetical optimal water reuse plan can improve water efficiency, including amounts on freshwater saving and wastewater reduction. Some efforts have been tried at the industrial park level. However such efforts did not consider the economy of scale since they employed the linear programming technique. Also, capital costs were not incorporated into the objective function and the surplus treated wastewater was not considered as a potential source for other uses. Furthermore, although the above-mentioned approaches are widely applied by industries, there are still many barriers to water reuse. The cost of implementation is a significant economic deterrent. Regulations that are intended to restrict emissions can have the effect of discouraging innovative wastewater minimization efforts. Corporate cultures are also somewhat unreceptive to this concept. But water shortages and increasing concerns about water contamination are forcing planners and managers to rethink opportunities for reusing water. Due to lack of integration of these novel approaches on wastewater minimization and lack of consideration on synergies among different companies, many potential water reuse and wastewater reduction opportunities may have been lost. Therefore, a universal integrated method considering all these factors and applicable at the industrial park level is still needed.

2.5 INTEGRATED WATER PLANNING AND MANAGEMENT

2.5.1 The Concept

The subject of integrated water resources planning and management (IWRPM) has been discussed for at least thirty years (Braga 2001). Immediately after the creation of the International Water Resources Association, this issue was pursued by planners and analysts throughout the world with some degree of success. Today, the complexity of planning and management for water resources has posed new challenges to this concept. Basically, the problem is the multidisciplinary nature of the planning and management process.

According to Griggs (1999), IWRPM is a framework for planning, organizing and controlling water systems to balance all relevant views and goals of stakeholders. This definition includes two dimensions of interdependence: balancing views and goals of stakeholders (social interdependence) in the context of managing water systems (ecological interdependence). By including these two dimensions, the shared responsibility for the integrated approach is highlighted, and the importance of clarifying responsibility for leadership becomes more easily seen.

IWRPM requires that people should consider the big picture of water issues. According to Mitchell (1989), integrated water management has three levels: "

- It can imply the systematic consideration of the various dimensions of water, including surface and groundwater, water quantity and quality. This means that water comprises an ecological system that is formed by a number of interdependent components. Each component may influence other components and need to be managed with regard to its interrelationships. At this level of integration, attention for management is directed to joint consideration of such aspects as water supply, wastewater treatment and disposal and water quality.
- It can imply that water is also a component interacting with other systems. This means that we should address the interactions between water, land and other systems and recognize that changes in any one may have consequences for the others. Management should pay attention to issues such as floodplain management, erosion control, non-point sources of pollution, preservation of wetlands and fish habitat, agricultural drainage and the recreational use of water.
- The third level means that water also interacts with social and economic development. At this level, the approach is on the scale recommended by the Brundtland Commission, with its stress upon the relationship between environment and economy. The concerns at this level are to determine the extent to which water is both an opportunity for and a barrier against economic development, and to ascertain how to ensure that water is managed and used so that development may be sustained over the long run. Management's interests therefore turns to the role of water in producing hydroelectricity, in facilitating transportation of goods and in serving as an input to manufacturing or industrial production."

These three levels indicate that it is appropriate and desirable to think comprehensively, that is trying to identify and consider the broadest possible range of variables which may be significant for IMRPM.

An integrated water resources planning and management system (IWRPMS) provides the basis for improvements in overall water management. It is a process that water managers can employ to optimize water usage. Therefore, it has been accepted as the most efficient approach to water planning and management in many countries (Mitchell 1990).

2.5.2 Implementing IWRPM

Integrated water resources planning and management requires the concurrency of many professionals to deal with different aspects of the planning process and an understanding of the needs of the various users. The effective operation of such a system depends on the quantity and quality of data; the timely acquisition and receipt of data; the ability of the decision maker to organize, process, analyze, and evaluate the meaning of the data; the capability to predict future availability of flows; the ability to monitor and predict water quality; and a decision-support capability where decisions are made to minimize the effect of wastewater and to optimize water usage. Figure 2-4 shows the process of implementing IWPM.

Data acquisition and processing

Having adequate data is one of the most important prerequisites to integrated and sustainable water management. The more accurate information water managers have concerning present and future availability of water supply and quality, the more likely that available water will be optimized. Various types and sources of data are needed to conduct a water assessment or analysis. Some of these can be summarized as follows:

1)Precipitation, surface water and groundwater data. These data are needed to analyze the availability of water —both for planning and for operational management of water supplies within the study boundary. Examples of such data are surface water volume, groundwater volume, evaporation, and precipitation, as well as their quality.

2) Water demand data. Water demand data consist of water quantity and quality data from different users. Both water quantity and quality measurements and water losses data are needed to establish the water balance.

3) Water management information. This information is becoming extremely useful in the integrated water planning and management process. Such information includes water management structures, water pricing mechanisms, and water regulations. Without a good understanding of the water management structure, it will be difficult to find the potential institutional barriers for IWRPM. Information on water pricing can help decision-makers understand how market-based instruments influence water consumption and wastewater discharge. Information on water regulations and their enforcement will help decision-makers revise those regulations that may impede the implementation of IWRPM and improve their enforcement efficiency.

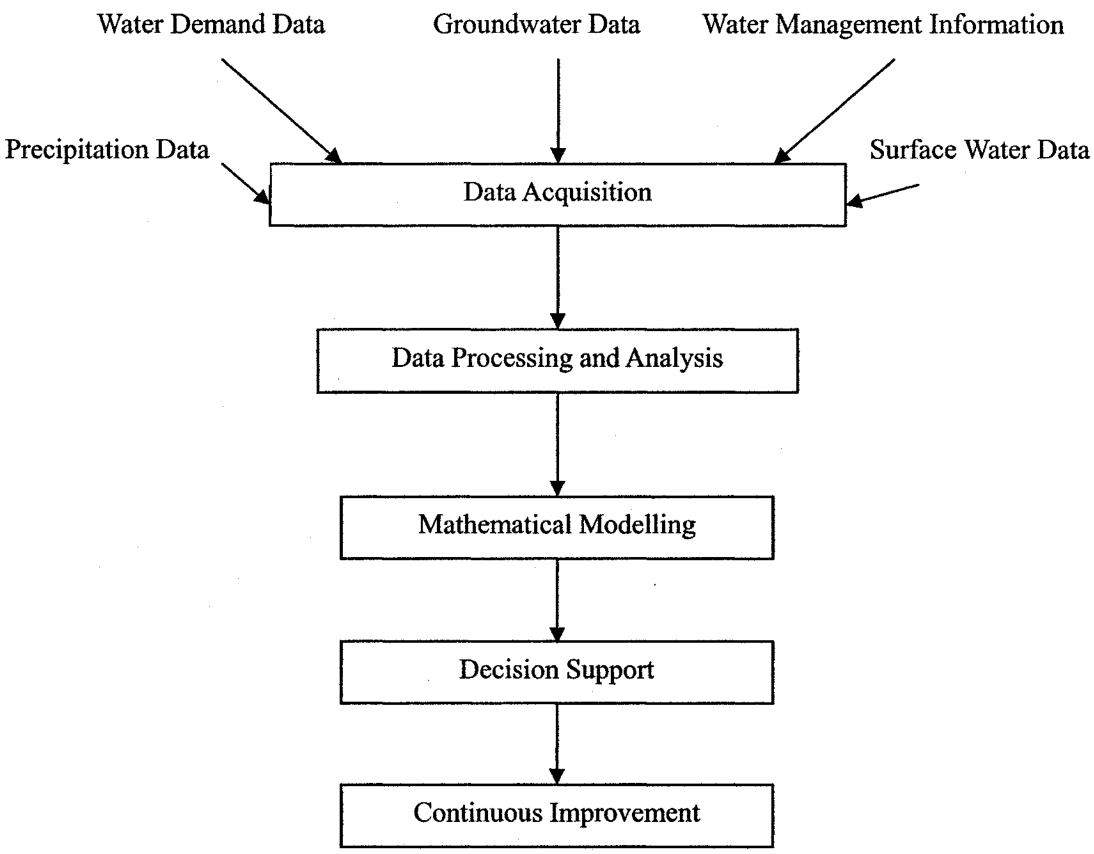

Figure 2-4 The Process of Integrated Water Resources Planning and Management

After the above-mentioned data and information have been collected, a detailed data process and analysis will then help identify incorrect data and information and find more requests on data and information. A further survey may be necessary in some cases.

Mathematical Modelling

Mathematical models and modeling systems are capable of producing accurate predictions of optimized water allocation and reuse scenarios for critical locations by adopting system analysis methods. Water managers use this information to allocate water or to alert water users to take proactive actions to minimize losses. There are various approaches to establishing hydrologic modeling capabilities, from using a simple linear model to using sophisticated nonlinear models or even a multiple objectives model and simulation systems that run on scientific workstation computers.

Decision-Support

Insufficient available resources, increasing pollution, and poor water management practices are leading numerous states to a situation of hydrological stress. This requires that decision-makers should make their decisions by scientific analysis rather than subjective observations. Consequently, responsible water management requires an underlying knowledge of water resource, distribution, use and disposal. It also requires the accumulation of qualitative and quantitative information to adapt these conceptual models to a management locale, and the selection of appropriate management options that in some manner optimize the decision criteria. By combining simulation modelling, optimization techniques, heuristics and artificial intelligence techniques, geographical information system (GIS), associated databases for calibration and execution, and user interface components, a decision support system for IWRPM will be developed. Such decision-support systems utilize current water quantity and quality data and provide information to water managers and water stakeholders on how to optimize water usage, minimize the impact of wastewater discharge and maintain environmental quality.

Continuous Improvement

Integrated water resource planning and management is not a one-off mission. It requires water managers to regularly monitor their water situations, including changes on quantity and quality, and then re-run the model to produce accurate prediction data for optimizing water allocation and identifying reuse scenarios. It also requires water managers to promote their water management practices in order to meet with the new water challenges. Thus, it can then help the decision makers adopt correct measures and continuously improve their water resource efficiency.

In addition, water resources planning and management can be characterized by negotiation, consensus building, and multipart decision-making. This process is essential because of the present better understanding of the needs of aquatic ecosystems, a change in the world's perception of environmental benefits, increased awareness of water managers that they have ''customers'' to respond to, and the need for greater flexibility in response to changing system requirements.

2.5.3 Application of Integrated Water Resource Planning and Management

During the past decade, systems analysis has been employed extensively in integrated water planning and management, especially as a quantitative method. Water managers use the results from such analysis to decide how to improve their water efficiency. Such work can be classified into two categories: the optimal distribution of the water resources to satisfy the demands within a region, and the optimal treatment of the wastewater produced in a region to satisfy water quality management policies.

Novotny (1996) described those components of the integrated water quality management and planning process. He pointed out that watershed management is the most integrated management approach to water quality remediation and restoration within a region. He also addressed socio-economic impact on the population and cost impacts that could prevent attainment of the water quality goals.

Harremoës (1997) used tools like input-output analysis and cradle to grave analysis to study integrated water and waste management, in combination with compilation of identified sets of values with respect to sustainable use of water resources and the ultimate fate of the environment and quality of life. He also discussed the role of engineers and suggested that engineers should make available as many technical options as possible to society and to put these options into the proper perspective in relation to the objectives of society.

Vanrolleghem et al (1999) raised an 11-step procedure for analysis, planning and implementation of integrated urban wastewater management system. They recognized the importance and difficulties of collecting the necessary data for calibration/validation and recommended to maximize the information retrieval from measuring campaigns. They also found that sensitivity analysis can support objective design.

Lotov et al (2000) presented an integrated water quality management model, which has been applied to the reconstruction of the Volga river program. Their model can help obtain pollutant transport data through the use of their simulation software and help decision-makers identify feasible goals for water quality and devise strategies for investment allocation among multiple regions in the river basin.

Le and Gupta (2000) introduced an integrated water management model to investigate the water resources planning and management problem for a tidal basin having a complex reservoir-river network system. This model addressed an optimal operating policy for the interlinked reservoir system, hydropower plant and water treatment facilities as well as the irrigation systems that utilize both surface water and groundwater to obtain the optimum benefit from the water supply, agriculture and hydropower production.

Durham et al (2002) introduced another integrated water resource management method through reuse and aquifer recharge. They addressed that integrated water resource management needs a holistic long-term approach that must be supported by legislation, agreed quality standards and international finance to enable projects to take place. They then employed case studies to demonstrate the solutions, including the benefits of proven hydrogeological expertise, cash crop production by reusing brackish municipal wastewater and aquifer recharge for saline ingress and indirect potable use.

Varis and Lahtela (2002) presented an analytical framework for integrated water resource management and tested this framework by using a case study from the Senegal River basin. They then evaluated the suitability of the introduced framework and hypothesis as well as the Bayesian network model for these types of situation.

In summary, most applications found in the literature focus on watershed level or regional level. Except for the work of Keckler and Allen and Nobel and Allen, there is no systemic application research at the industrial park level. However, industrial parks contain many large water users and discharge much wastewater with different contaminants. Some contaminants may be toxic and hazardous to the local water body, therefore, finding the best methodology for integrated water resources planning and management at the industrial park level becomes essential, especially in areas suffering from water shortages.

2.6 SUMMARY

Industrial ecology is an emerging framework for characterizing relationships between businesses; and analyzing their economic and environmental performance (Hollander 2003). Studies on industrial ecology have mainly focused on characterizing material and energy flows in industrial systems and on describing cases in which modifications of the material and energy flows can result in environmental and economic benefits. Practically, industrial ecology encourages eco-industrial development, which is based on the idea that a flourishing economy and environmental health can coexist, offers an "invitingly concrete" (Chertow 2000) way to integrated environmental management and meet environmental, economic, and community development goals. It adds value to businesses and communities by optimizing the use of energy, materials, and community resources. Tools for designing industrial ecosystems are just emerging (Lowe 2001; Giannini-Spohn 1997). Therefore, more tools for material flow optimization are needed. Water is one of these materials.

In response to an increasing water crisis, stricter wastewater emission and pollution control legislation, higher wastewater treatment costs and increased penalties for non-compliance have been adopted in many jurisdictions. Water reuse and wastewater minimization are now being introduced as useful strategies for saving freshwater resource, in an attempt to mitigate the conflict among users and alleviate the pollution of water bodies, etc (Barrett 1999). With suitable treatment, current technologies can reclaim most kind of wastewater at a cost so that such water can be used for agricultural and landscape irrigation and groundwater recharge, industrial uses (indirect cooling water, water-washing process, wet scrubber, etc); non-potable urban uses (fire control, toilet conditioning) and recreational/environmental uses (lakes and ponds, marsh enhancement, etc), etc (Metcalf and Eddy 1991).

A number of companies have undertaken water reuse and wastewater minimization programs and have realized significant financial and environmental benefits (El-Halwagi 1997; Mann and Liu 1999). However, most of these programs only take internal optimization into consideration, focusing on cleaner production. As a consequence, these programs do not incorporate potential co-recovery or co-treatment options that could be economically and technically efficient, with industries sharing costs for equipment, facilities and transportation. A holistic and systematic method for planning and managing water reuse is still in its infancy.

The review also found that current water resource planning and management practices have moved from fragmented and unsystematic approaches to more holistic and integrated approaches, highlighting water reuse and water efficiency. Models have been developed as a decision support tool to assist in determining water reuse options and costs. A program with these types of characteristics would be described as incorporating integrated resource management principles. However, current integrated water resources planning and management mainly focuses on river basin or region level. From a review of the existing literature, there is very little research on integrated water resources planning and management at an industrial park level. The existing research is case-specific, which only suits their local situations. A universal methodology for integrated water resource planning and management at industrial park level is critically needed.

The focus of this research is on the development of a framework of integrated water resource planning and management within an industrial park setting that incorporates the key principles of industrial ecology, water reuse and integrated water planning and management, allowing managers to manage increasingly scarce resources while permitting some further economic growth. It is intended that this research will not only contribute to providing a new methodology for water planning and management at the industrial park level by combining industrial ecology with integrated water management, but also providing a useful tool to assist industrial park managers as well as company managers in handling their materials flow in a more sustainable way.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 INTRODUCTION

Studies regarding system modeling and its application raise numerous methodological issues that should be addressed in the research methodology. This chapter describes the methodologies used to complete this thesis, which include the nature of the research, the research approach, and ethical considerations.

3.2 THE NATURE OF THE RESEARCH

The nature of this research project is both quantitative and qualitative. It is felt that multiple sources of evidence would strengthen the research. Methods integrated into this study include a review of relevant literature, system model development, and a case study for testing the model. The benefits to using quantitative and qualitative research methods are that it allows for a triangulation of evidence (Yin 1989). The concept of triangulation is based on the assumption that any bias inherent in particular data sources, the investigator, and the method are neutralized when used in conjunction with other data sources, investigators and methods (Fowler 1993). This would mean, for example, that using both surveys and in-depth interviews will assist in ensuring that the data and information collected are correct and strengthen the final results of a study.

On the one hand, quantitative research is often conceptualized by its practitioners as having a logical structure in which theories determine the problems to which researchers address themselves in the form of hypotheses derived from general theories. These hypotheses are invariably assumed to take the form of expectations about likely causal connections between the concepts which are the constituent elements of the hypotheses (Bryman 1988). Therefore, quantitative research seeks to quantify or reflect observations about those raised hypotheses with numbers. As such, quantitative researchers attempt to describe relationships among variables mathematically, and to apply some form of numerical analysis to test those hypotheses. On the other hand, qualitative research allows researchers to view the behavior of respondents in a natural setting, allowing for a depth of understanding and flexibility (Chadwick et al 1984). By combining quantitative and qualitative methods together, one can contribute to the understanding of different aspects of the phenomenon in question. This is particularly useful in this interdisciplinary research involving many different fields, allowing the researchers to better analyze the complex and dynamic interactions between industrial systems and water systems and seek the optimal solutions. One note that should be addressed is that this research project is slightly more weighted in the realm of quantitative research as it focuses on system modeling and its application.

3.3 RESEARCH APPROACH

This thesis is essentially an attempt to apply industrial ecology principles in the planning and management of water resources within an industrial park. Therefore, its existence should not be merely an academic document, which enriches the discipline of water resource management, but also has to be practical, in the sense that it can be used to aid planning and decision-making processes in the area of water resource management.

In order to achieve the above objectives, the first step for this research is to review the related literature. Literature reviews were focused on industrial ecology and eco-industrial development, water reuse, and integrated water management, particularly, the application of mathematical optimization in the field of water planning and management. Such a review indicated the importance of carrying out this study because of the limitation of the existing research and provided a theoretical foundation. Then, based on this review, an integrated framework could be created by considering the realities of an industrial park, accommodating all the development objectives. The framework should facilitate industrial park planners and managers in designing development policies and programs for ensuring that the total sum of all development activities within an industrial park will be environmentally and economically sound and lie within its water carrying capacity. Such a framework should incorporate the industrial ecology principles, such as industrial symbiosis, reuse and recycling, into traditional water planning and management practices and provide an integrated solution on sustainable water use.

After that, a case study approach is employed in order to test the model. The advantage of using a case study is that it allows researchers to test their theoretical hypothesis within a real-life context (Sinkule and Ortolano 1995). Such a test can indicate if the framework is applicable and what limits may exist so that the researchers can further improve it. Site and partner selection for this case study was based upon some principles, including the water situation, management's attitudes and interests, information and data availability.

A training seminar was then hosted in order to ensure that participants understand the significance and the method of this study, as well as the assistance they may provide. A survey was done in order to obtain the relevant data and information building on and clarifying existing information. It should be noted that the cornerstone of data collection for this research is quantitative methodology using a questionnaire and interviews.

The research focus was to test the quantitative model contained in the framework by using these data and analyzing and discussing the results. After all the data were analyzed and categorized, the data were then put into the optimization solver. After running the solver, the results were released for further analysis and revision. Several informal meetings with the local stakeholders were held in order to get their comments on the results. Discussion included the test of economic instruments, model feasibility and applicability. Finally, some conclusions were summarized and some recommendations were noted for future study. Figure 3-1 is the research process flow.

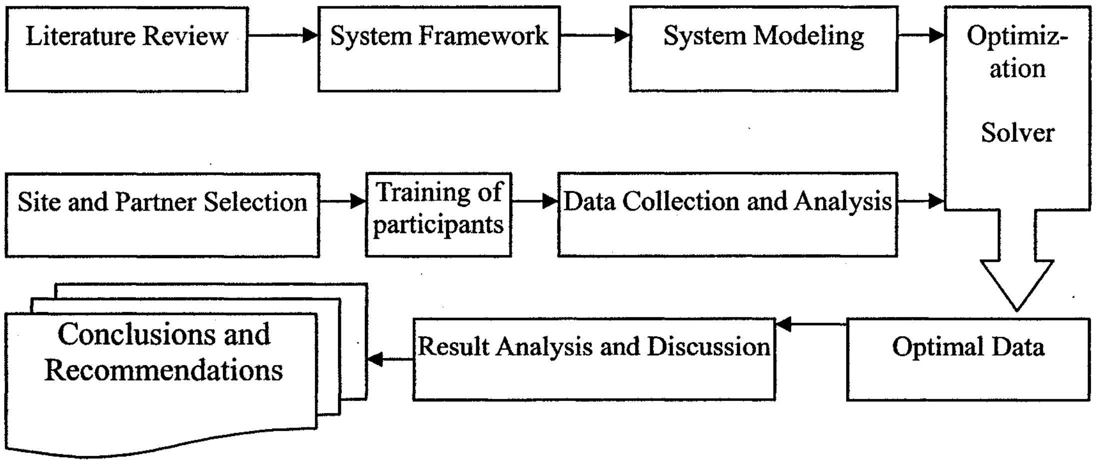

Figure 3-1 Research Process Flow

3.4 DATA COLLECTION AND ANALYSIS

Data availability and exactness are very important for this study. Several types of data were gathered using a number of methods, including document review, and key-informant interviews.

3.4.1 Document Review

The identification, collection and review of primary and secondary documentation is a valuable source of information for this quantitative and qualitative study. Once access has been gained to the required documentation, it allows the researcher some freedom in collection time, it represents little intrusion, and can save researcher time and money as compared with some methods such as solely relying on key-informant interviews to collect such information. However, in some cases, document review can be difficult in that it may be hard to gain access to the necessary documentation. It requires some time to locate the necessary information, and transcribe it for research purposes (Creswell 1994).

All documents reviewed in this research were collected from the Environmental Protection Bureau, the Economic Development Bureau, the Social Development Bureau and the Urban Construction Bureau at Tianjin Economic Development Area (TEDA). Documentation took the form of government documents, planning reports, meeting minutes, discussion papers, press releases, newsletters and personal notes. By reading these documents, basic information on Tianjin and TEDA, as well as their water issues, was gained.

3.4.2 Key-Informant Interviews

Key-informant interviews are a valuable source of information in this interdisciplinary research and can provide a great deal of information on a specific subject. Informants can often provide information not attainable through document searches or survey interviews. However, the value of key-informant interviews is dependent on the selection of the informants. Responses were expected to differ due to particular sectoral perspectives. They represent one individual's views, and are the result of interviews or discussions with the researcher present, which may bias responses (Creswell 1994).

In this study, key-informants were selected based on their experience in the field of water planning, water management, water and wastewater treatment through their position of employment. The individuals employed in these positions were contacted and asked to participate in the study. Informal discussions with local scholars and company managers further aided in initially identifying these individuals.

3.4.3 Data Organization and Analysis

The data collected should be categorized in order to facilitate the research. In this study, a process of iteratively reviewing data and developing groups or categories of related information, was used. Groups or categories were then reviewed and revised if necessary. Once groups were developed for each data set, all data was coded and summarized into tabular form. An analytical table was developed to gather and organize the information coming from the different sources collected. Some incorrect data were deleted with rational analysis and further interviews were carried out in order to get the right data.

3.5 ETHICAL CONSIDERATIONS

The main ethical consideration related to this research study was ensuring participant confidentiality. According to Bower and Gasparis (1978), confidentiality should be preserved by every possible means to protect the interests and benefits of project participants. Mitchell and Drapter (1983) further argued that the researcher must respect the individual's right to privacy, confidentiality, and informed consent. Consequently, confidentiality was promised to interviewees and companies in order to increase the likelihood of receiving personal insights and frank opinions rather than the official positions of the organization being represented. Before conducting interviews or receiving questionnaires, respondents were briefed on the purpose of the study, a brief written outline of the researcher's background, as well as the study objectives. Also, they were informed that their participation in the research was voluntary, and told that all information obtained in the interview would be confidential. The participants were told they could withdraw from the study at any time and refuse to answer any questions. They were also asked if their company name could be used within the study. If they declined, they were told they would be assigned a code to ensure confidentiality in the study. Due to their sensitivity, all the companies surveyed in this research finally were assigned a code even though some companies did not demand anonymity.

3.6 SUMMARY

This chapter has explained and justified the method used for this research and explored some of the issues raised by this approach. Research nature is more quantitative, but the description of the system is qualitative. Research process was presented, and finally research ethical issues were discussed.

The next chapter will describe the integrated water plan and management framework at the level of an industrial park.

CHAPTER 4. AN INTEGRATED WATER RESOURCES PLANNING AND MANAGEMENT (IWRPM) FRAMEWORK FOR AN INDUSTRIAL PARK

4.1 INTRODUCTION

Industrial parks in a number of countries and regions in the world are facing significant water management issues due to limited supply, rising demand in all sectors, and a lack of integrated planning. The development and implementation of a comprehensive, integrated water management strategy with water reuse as a major component is one way to mitigate the impact of the increasing imbalance between limited supplies and rapidly growing demand, as well as addressing such issues as the significant deterioration of environment, extensive mining of groundwater reserves, and increased pollution. This chapter builds on section 2-5 and introduces the concept of IWRPM at the industrial park level and presents a conceptual framework for its application. This framework provides the foundation for the development of a system optimization model that focuses on developing efficient and effective water reuse strategies at the industrial park level.

4.2 THE CONCEPT OF IWRPM AT THE INDUSTRIAL PARK LEVEL

Because water is the basis for ecosystem functioning and an essential resource for development , its use affects the social, economic, and natural environments of a region. In the past, water resources were often developed on a single-purpose basis, focusing mainly on such activities as hydropower, irrigation, navigation or water supply. Large publicly-funded, single-purpose projects were characteristic of water management in North America and Europe in the first half of the 20th century, leading to the almost complete usage of the available sites for dams and other related civic works (Bouwer 1997). This approach was common until the late 1960s, when pressure from NGOs and other groups resulted in national environmental laws being passed in many countries, requiring that other objectives, beyond economics, be considered in the use of natural resources (US EPA 1992). New requirements, such as Environmental Impact Assessment, necessitated the development of more integrated approaches to resource management.

Today, public environmental awareness has strengthened and grown around the world.

There is increasing pressure to conserve resources and to use them wisely, which requires new decision-making mechanisms in order to select alternatives for planning and managing water resources. The old cost-benefit analysis and top-down approaches are being replaced by multiple-objective, multiple-decision-maker models in which stakeholders, NGOs, and government agencies all participate in the decision-making process (Mitchell 1994). This new paradigm requires a restructuring of existing institutions and the collaboration of professionals of different backgrounds to handle the difficult task of conducting planning and management initiatives in an integrated fashion.

As discussed in Chapter 2, integrated water resources planning and management is a systematic approach that ensures that the views and goals of all relevant stakeholders are considered. This approach also requires that all pertinent factors related to water issues should be considered in the decision-making process. Such a holistic approach requires not only supply management, but also demand management, water conservation, transfer of water to uses with higher economic returns, water quality management, recycling, and reuse of water. Integrated water resources planning and management also addresses issues related to public involvement, public health, environmental and ecological aspects, socio-cultural aspects, conjunctive use of surface water and groundwater, and water pollution control.

Consequently, the development and implementation of IWRPM at the industrial park level requires planners and management to consider the broader environmental and social implications of their decisions. In terms of water issues this means that industrial park managers and tenants need more information about the metabolism of the resource as well as the environmental and social implications of their activities. Through a more holistic analysis of all the water elements it will be possible for industrial park managers to modify their water system in order to achieve economic benefits, protect the environment, and contribute to community well-being. Figure 4-1 presents a conceptual framework for IWRPM within an industrial park.

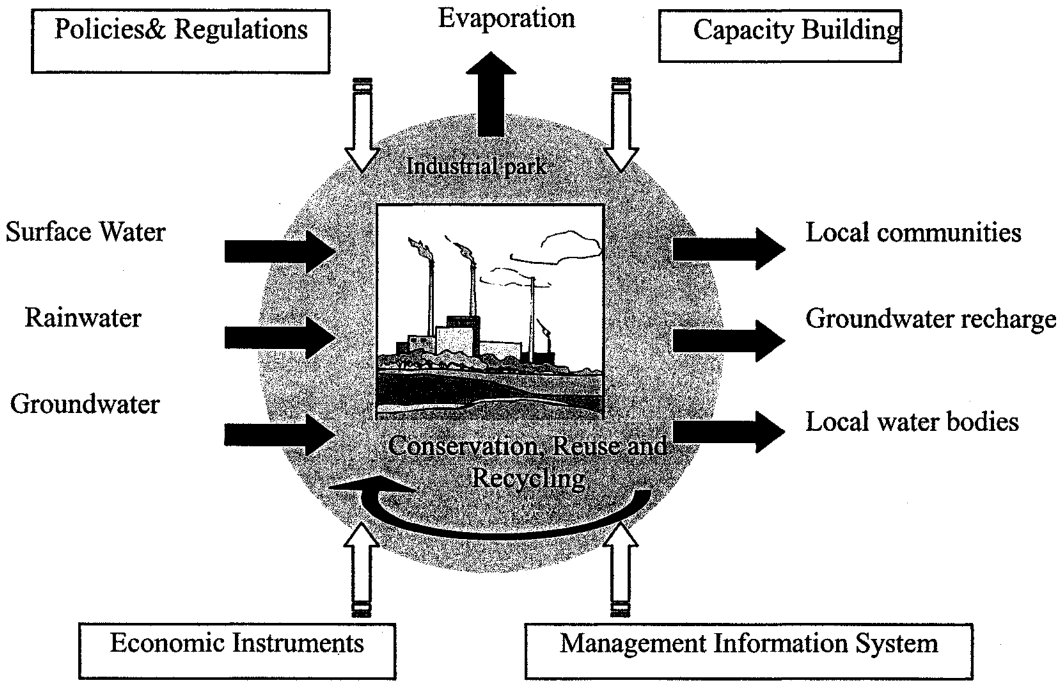

Figure 4-1 Conceptual Framework for IWRPM within an Industrial Park

Understanding of the key influences on the metabolism of water in the industrial park is critical to the optimization of that resource. Figure 4-1 illustrates the water flow within an industrial park. The input flow includes surface water, rainwater and groundwater, which should be conserved, reused and recycled within the industrial park. The output flow includes the evaporation loss and surplus flow from water users. Such a surplus flow should be used to recharge groundwater, be delivered to local communities, or be safely discharged to local water bodies as the last order. This figure also indicates that the successful implementation of IWRPM at the industrial park level depends on four key elements for guiding the system: (1) policies & regulations; (2) economic instruments; (3) capacity building; and, (4) management information system. The following sections will introduce these four components in some detail as the basis for an assessment of a major industrial park in China. While all four components have a significant impact on the management of an industrial park, a greater emphasis will be placed on the management information system, namely, the development of a quantitative model which can demonstrate optimal water reuse scenarios and potential water saving and wastewater reduction through a quantitative system analysis approach. The identification of optimal water reuse strategies is of particular importance for those industrial parks located in areas suffering from water crisis and wastewater pollution, such as China. It encourages systematic optimization of current available water resources through water reduction, reuse and recycling, minimizing the negative impact of waste flows, and supports tenant companies to collaborate with each other, in co-recovery, co-treatment, and direct or indirect reuse.

4.3 POLICIES AND REGULATIONS

The successful development of water reuse projects and their role in enhancing the integrated water management within an industrial park requires new policies and regulations to promote and control wastewater reuse, and coordination between the concerned authorities, public education, health risk studies, and the choice of the most appropriate technologies for the given reuse applications, plant size, and local conditions.

Policies are required to address institutional barriers to implementation of the IWRPM. There are often complex administrative arrangements for water resource planning and management, especially for industrial parks in developing countries. For example, in China a local environmental protection bureau is in charge of wastewater discharge and pollution, an infrastructure bureau is in charge of water supply, a construction bureau is in charge of water resources extraction, and an economic planning committee is in charge of water resources planning and allocation (Zhu et al., 2001). None of these are subordinate to another, nor can any of them play a leading role. This artificial segmentation makes an integrated water resources planning and management system difficult to achieve at a policy level. Therefore, institutional arrangements and restructuring may be crucial and necessary. One possible solution would be the establishment of a new administrative institution that can integrate supervising authority over water-related issues at the industrial park level. Another option would be to create an inter-agency task force with the mission of developing a more integrative policy framework and coordinating day-to-day management of water resources.

Also, policies should help adjust the industrial structure of an industrial park, for example, by limiting the development of large water using industries, relocating large water users to a water abundant park and balancing water demands among tenants by assessing their water efficiency. Regulations that can help solve potential conflicts among tenants and industrial parks and between tenants should be stipulated. Other policies, like those that can encourage cleaner production and water cascading among tenants and can facilitate the coordination of the relationship between industrial parks and local communities, should also be revised or adopted according to local realities. In order to do so, industrial park management can help establish a committee for dealing with these issues. The committee members should include park managers, tenant representatives, government agents, and other stakeholders so that everyone's wishes and benefits can be fairly considered. These members should work together to prepare appropriate regulations, enforce the implementation of relevant policies, and arbitrate potential conflicts. This measure might facilitate coordination of different stakeholders.

Generally, since the ultimate goal of IWRPM at the industrial park level is to achieve sustainable management of water resources within an industrial park, an integrated approach on policies and regulations should be employed, rather than only addressing water issues in a single disciplinary context. Such integrity requires that industrial park managers should integrate all the relevant policies in a broader complex system including natural, social, and economic contexts at an early stage in order to avoid potential water resources problems which might result from policies encouraging rapid economic growth.

The overall target of an integrated policy environment is to achieve sustainable water management within an industrial park and its surrounding region. To reach such a goal, four strategies, including supply management, demand management, efficiency management, and emission management should be adopted. In terms of each strategy, the respective management target should be to maximize resource input, keep demand within resource capacity, maximize the efficiency of use, and limit the discharge of pollutants within the environmental capacity. Each of these management targets could be achieved through various detailed measures. Figure 4-2 outlines such a policy framework.

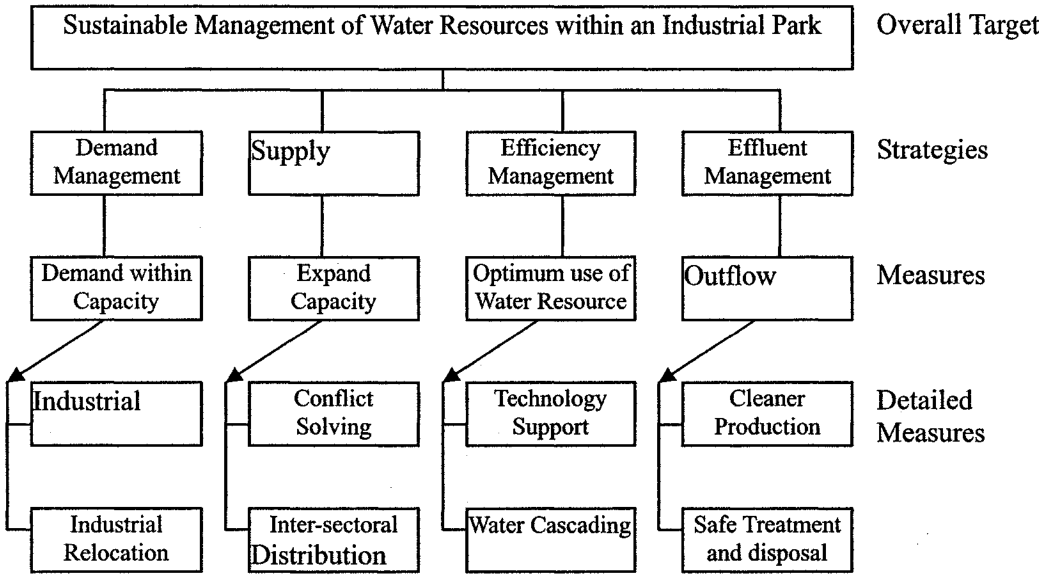

Figure 4-2 Outline of A Policy Framework for IWRPM at the Industrial Park Level

The successful implementation of this integrated policy framework requires industrial park management to establish effective monitoring and evaluation mechanisms, to consider appropriate economic incentives as well as penalties, and to ensure increased community involvement in the process of water resource planning and management. Furthermore, decision-makers should consider the concerns of all relevant stakeholders. A tri-sector partnership between tenants, industrial park managers and public authorities brings added value to both the communities and to all parties. By working together, they can systematically reduce the total freshwater consumption and wastewater discharge and conflicts related with water supply and demand. During this process, water professionals in the private sectors need to play a more direct role in such a joint approach as they can make a positive contribution to sustainable solutions. In this regard, the successful water reuse case in Kalundborg has tested its applicability, where the local government, tenant companies and local communities collaborate with each other in order to share water-related information and seek water reuse opportunities across different sectors (Lowe et al., 1997).

Since the future is always unpredictable and changeable, water policies and regulations at the industrial park level cannot remain the same over a prolonged period of time. An adaptive management approach which facilitates adjustments to policies and regulations when the assumptions on which the policies and regulations are based change or prove to be incorrect, and/or when new developments take place or are expected, is recommended. In other words, water policies and regulations at the industrial park level should be considered as a journey, rather than as a final destination.

4.4 ECONOMIC INSTRUMENTS

The growing scarcity and rising cost of water has led to an increased awareness that water must be allocated and used more efficiently. Economists concluded that it is best done by treating water as an economic resource (Winpenny, 1994). Economic instruments, like prices, quotas, and effluent charges can play a key role in water conservation at the industrial park level, helping ensure sustainable usage through such activities as waste minimization and an efficient allocation regime. Economic instruments can also be used to provide incentives for the development of water-efficient technologies, reuse and recycling. Various economic instruments that can be used at the industrial park level are as follows:

Prices

Pricing instruments are generally based on the premise that tenant companies will respond rationally to financial incentives and disincentives. A basic tenet of current natural resource management is that consumers and dischargers should pay prices for water services in accordance with the principles of economic efficiency. Such a pricing system will equate demand and supply for water services at the economically appropriate level and in an environmentally acceptable way (Asano and Mills 1990).

In order to achieve more efficient water demand management, the consumer and the polluter should be required to pay the full social cost (including the capital, operation, maintenance and external costs associated with its use) of providing water and related services, including treatment and damage costs. The adoption of this principle will create more efficient administrative arrangements for the integrated management of water and the other natural resources. If the price of water is below that which reflects water resource availability, supply and treatment, then tenants are inclined to waste water (e.g. by not identifying and repairing leakages) or use it inefficiently (e.g. by overuse or inappropriate use). Alternatively, when the price of water reflects that which reflects water resource availability, supply and treatment, there will be an economic incentive for water to be allocated rationally (e.g. between different sectors) and for the development and use of water-efficient technologies involving the substitution of capital for water (e.g. the application of cleaner production). Likewise, tenants may seek potential users for their wastewater in order to generate revenue rather than pay for wastewater treatment, thus increasing water efficiency. A challenge that industrial park managers and tenants are facing is how to set up a water tariff on the basis of water quality.

Quotas

Quotas for water use have proved to be a powerful tool to control water use at a regional level (Zhu et al, 2001). The application of a quota system can also be useful at the industrial park level. The successful implementation of a quota system is dependent on "a planned water use system" operated by industrial park managers. Such a system sets up penalty mechanisms for water use that exceeds the given quota. Tenants would be required to pay several times the normal rate for water when they exceed the given quota. This measure can encourage tenants to apply state-of-the-art water conservation technologies and seek potential collaboration opportunities with their neighbors in the industrial park. By doing so, both internal water recycling ratios and systematic water efficiency could be greatly increased.

Effluent Charges

The primary objectives of effluent charges are to recover the costs borne by the regulatory authority for its pollution control function, to change the behaviors of the dischargers, and to raise funds for cleaner production. Funds raised could be utilized in support of research and development related with water reuse and recycling.

Such charges should be stipulated by industrial park managers and local regulatory authorities together by considering the local situations. Charges should first cover the administration cost of the license, which is usually fixed, and the monitoring costs for compliance sampling. Charges should also cover the costs related to wastewater treatment, cleaner production, and relevant research and development activities. The charges can also be used for subsidizing water conservation equipment for some large water users. Monitoring costs are related to the contents of the discharge and the type of water received. As the monitoring costs are higher for the more difficult-to-analyze hazardous organic compounds, effluents containing these substances should be subject to higher charges. Similarly, effluents discharged to vulnerable waters require more frequent monitoring and therefore higher charges.

By doing so, effluent charges may serve as a significant incentive to reduce total water consumption and wastewater discharge in an industrial park, and improve economic and financial effectiveness and efficiency.

The above-mentioned arguments demonstrate that economic instruments should be regarded as an important element of integrated water resources planning and management within an industrial park. These arguments indicate how to best utilize the insights and instruments of economics in the design and management of IWRPM. However, economic instruments should be used in conjunction with other measures (e.g. top-down approach, capacity building, and policy integration) in order to achieve the intended results.

4.5 CAPACITY BUILDING

Capacity building has emerged as an essential requirement for the efficient management and planning of water resources (Mitchell 1990). Capacity building includes the strengthening of institutions (both intra- and inter-sectoral), managerial systems and human resources, developing effective means to facilitate community participation and communication, and promoting the creation of favorable policy environments.

The need to better manage available water resources, to assure fair and equitable allocation of water among all the users within an industrial park, and to protect the environment has forced industrial park planners and managers to carry out integrated planning and management. Those agents include industrial management, government officials, tenants, research institutions, community organizations, financial organizations.

Awareness raising activities, including TV promotions, newsletters and workshops, should be carried out periodically in order to build understanding. Such initiatives can provide forums at which experiences from different parts of the world and from different institutions could be objectively reviewed and lessons drawn from these combined experiences. These activities also can create opportunities for stakeholders to strengthen their mutual understandings and friendship, which will be the solid foundation for further collaboration on water issues. On the basis of such initiatives, a local network on water issues could be established as a mechanism for the exchange of experiences, the transfer of technology, and enhanced cooperation across disciplines. Such a network can take advantage of modern information technologies via the Internet so that the various water resources stakeholders participate fully in its management.

Generally, capacity building should directly reflect the needs and overall conditions of the industrial park concerned. As such, it should be a long-term process, with clearly enunciated short, medium, and long-term goals which can be evaluated periodically. The needs at various levels should be specifically considered. Good communication, the exchange of information, and extensive interactions between different stakeholders and levels are essential requirements for any successful capacity building process. Industrial park management should take the leadership role in this progress. Moreover, functional networks are an effective way to complement traditional technical assistance.

4.6 MANAGEMENT INFORMATION SYSTEM

Management Information System (MIS) refers broadly to a computer-based system that provides decision makers with the tools for organizing, evaluating and efficiently running their businesses (Messner et al., 2000). In order to provide past, present and prediction information, an MIS can include software that helps in decision making, data resources such as databases, the hardware resources of a system, decision support systems, people management and project management applications, and any computerized processes that enable the organization to run efficiently. In terms of environmental fields, it can provide accurate and timely information to decision makers for their strategic planning of resource and environmental management.

As pointed out in Chapter 2, integrated water reuse planning and management can include the modeling of the water systems so as to support decision-makers to evaluate and test water reuse options. Consequently, a key component of an effective management information system for IWRPM at the industrial park level would be a quantitative model, helping to identify the potential water reuse opportunities among tenants and provide quantitative information on total freshwater savings and wastewater reduction with the least cost. Chapter 5 will detail the model development.

4.7 IMPLEMENTATION OF IWRPM WITHIN AN INDUSTRIAL PARK

The successful implementation of IWRPM largely is a systems engineering process and needs the involvement of different parties and people. If not well organized, it will fail to help industrial park planners and managers optimize their available water resources. Similar to the implementation progress described in section 2.5.2, but with a consideration of industrial park's features, the implementation of the IWRPM conceptual framework at the industrial park levels consists of six consecutive stages. Every stage can be further sub-divided into several phases (figure 6-63). The systematic follow-up of the implementation stages confirms inclusive consideration of all relevant components.

4.7.1 Organization Establishment and Preliminary Assessment

Use of the systems approach would be facilitated if responsibilities for IWRPM were consolidated and a team approach was initiated. Their team should involve representatives from The first step is to establish a new specific organization for IWRPM. Members are from industrial park management, tenants, local government officials, community representatives, water engineers, economists, and other stakeholders. Such a team should have multiple disciplinary expertise and represent all the stakeholders' benefits.

The next step is to establish the boundary limits for the study. AThis means to include all potential water reuse and wastewater minimization opportunities should be considered when setting boundary limits, including the entire site. If the boundary limits are too narrow, then many water reuse and wastewater reduction opportunities may be lost. Many successful integrated water management projects have proved that reasonable establishment of the boundary limits can help balance and satisfy regulatory compliance, economic investment, internal resource limits, and technology availability (Oron 1995).

They then need to carry out a park level water audit within the boundary limits in order to understand the current status of their water problems. On the basis of this audit, a preliminary assessment (data collection and analysis) should be done in order to recognize the potential constraints and develop objectives.

4.7.2 Data Collection and Analysis

At this stage, in order to apply this model, planners and managers of industrial parks should carry out a park level water audit within the boundary limits in order to understand the current status of their water problems. Data should be and collected data from all the water elements in the park and establish a comprehensive database should be established according to what has been described in Chapter 4. DOn the basis of this audit, a preliminary assessment should be done in order to identify recognize the potential constraints and develop objectives. During this process, efforts they have to convince their tenants of the significance and benefits of IWRPM should be carried out in order so as to eliminate, or at least reduce, ~~the~~ potential barriers such as the tendency of because some tenants to may consider such information as proprietary their business datasecrets. They also need to collect ~~the~~ broader information on local communities' needs, groundwater recharge and landscaping in order to encourage more water reuse[WHY collect this data—you should explain things a bit more rather than simply making a statement]s. This needs the involvement of experts from hydrological engineering, civil engineering and other fields.

Integrated management can create enormous data demands and it will never be possible or cost-effective to assemble all the relevant information if decisions are to be taken within reasonable time periods. Often, dDecisions have to be made without complete information and with a degree of uncertainty. Planners and managers must therefore prioritize their information needs, discuss with related agencies the compatibility of databases, and ensure that the data coming from those agencies is adequate and is understood.

4.7.3 Quantitative Modelling

This stage uses a mathematical model for revealing the optimal water allocation and reuse scenarios. After gaining the necessary data, the planners and managers need to find appropriate optimization software to work out the quantitative model. Today, several commercial optimization solvers exist that can deal with such non-linear problems, including like MINOS, CONOPT, and MATLAB (Paczynski et al., 2000). The planners and managers can choose one to meet their needs by considering their own conditions, although availability and complexity should be considered in making that choice. After running the model, planners and managers need to calculate the potential savings on freshwater and wastewater discharge, which can help decision-makers make smart decisions on water resource allocation within an industrial park. Team members may find different scenarios when they use different objective functions, variables and parameters, and constraints. Thus, they need to undertake a comparison study in order to identify the advantages and disadvantages of the various options before a final selection can be made. In addition, the results will also facilitate industrial park managers to make appropriate water management policies and stipulate related training programs. Finally, the team should assess those relevant risks, analyzing potential limits and seeking solutions.

4.7.4 Solution and Implementation

Based on Stage 3, the team can prepare a detailed analysis of the most preferred alternatives in terms of local reality and then submit them for decision-makers to make the final decision. Another task at this stage is to prepare detailed guidelines for implementation once the final option is determined. These guidelines should comprise a training and education module, a financial support module, a technical support module, a policy support module, and a conflict-solution module. These guidelines should consider the tradeoff between water reuse goals, available budgets, human resources, schedule and available technologies. The guidelines would serve as a road map for the water reuse program. Cost analysis must be included in the implementation plan, otherwise, it will be very difficult to obtain funding and support from senior management. During the implementation period, suitable monitoring mechanisms should be established.

4.7.5 Feedback and Improvements

The last step in this systematic approach is the continued review of stakeholders' feedback and an update of the design or implemented project and a reiteration of the prior steps. This is because production process, raw water quality, discharge limits and plant goals may change and affect the dynamics of water reuse and water conservation. Technologies may advance and become more cost-effective. Also, the relevant information should be updated, new water reuse opportunities should be investigated, and the implementation plan should be evaluated and revised as requirement. This approach will continuously facilitate the improvements to the overall water efficiency.

4.8 KEY FACTORS FOR SUCCESS OF IWRPM

While implementing IWRPM in an industrial park, some barriers may exist and even affect its success. For instance, the cost of implementation is a significant economic deterrent. Information may be limited in some cases, while some data may not be correct in other cases. Regulations that are intended to restrict emissions can also have the effect of discouraging innovative wastewater minimization efforts. The relevant technologies are still in the process of development and improvement with high risks. Corporate cultures are often unreceptive to this new approach. In addition, due to lack of integration of these novel approaches and lack of collaboration on synergies among different companies, many potential water reuse and wastewater reduction opportunities may still be lost. Therefore, seeking solutions to these barriers is critical.

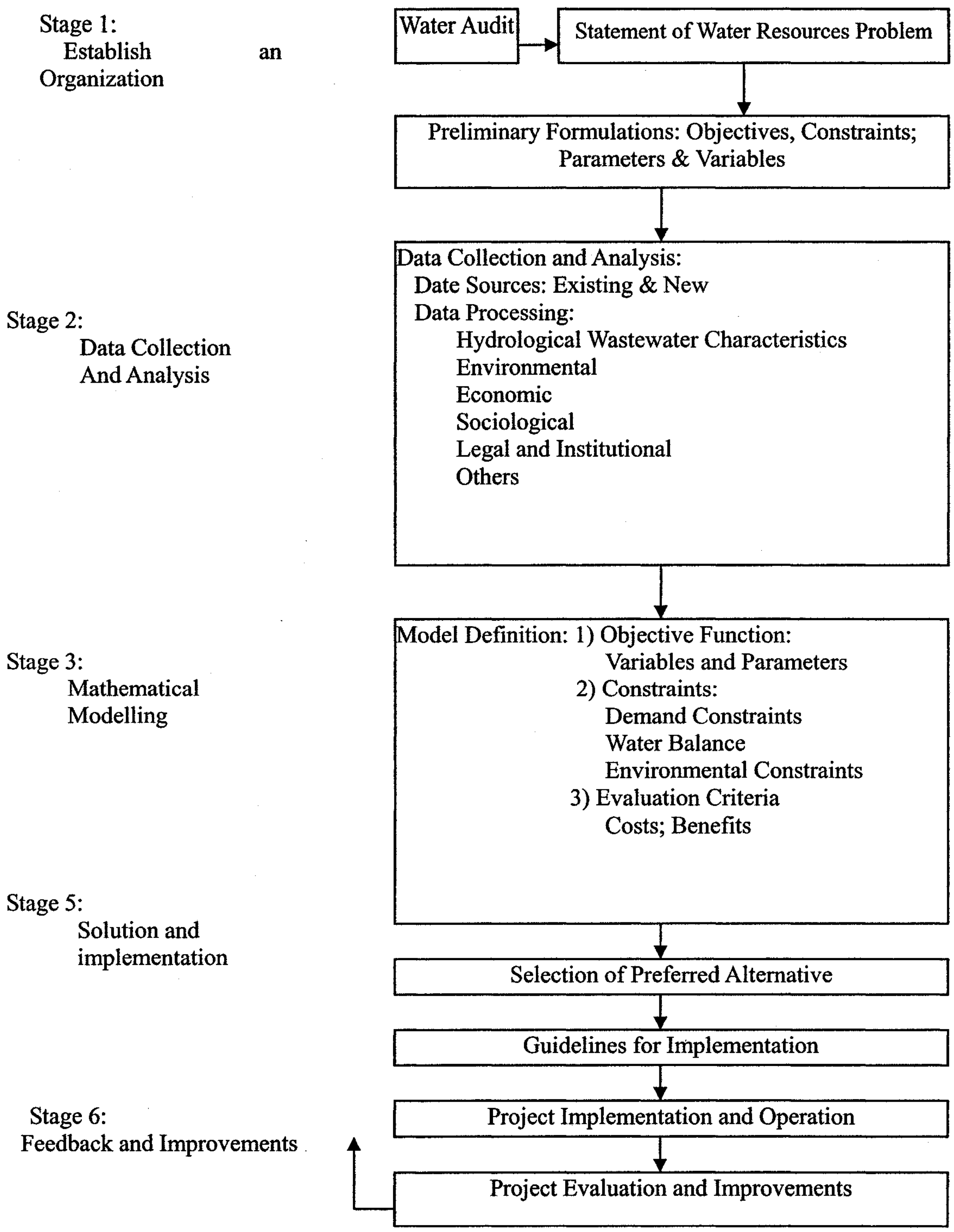

Figure 4-3 Stages in Integrated Water Resources Planning and Management for an Industrial Park

Six key factors can contribute to the success of IWRPM at the industrial park level: economic, financial, regulatory, psychological, organizational and technical factors. The economic, financial and psychological factors depend on two main conditions: (1) the internal motivation of industrial park managers and tenants to jointly establish a meaningful economic analysis and a rigorous financial plan and gaining of public acceptance; and (2) external non-controlled constraints such as slow institutional decision-making processes, politician's subjectivity, and stakeholders' personality. The psychological factor is essential for initiating, implementing and sustaining a long-term wastewater reuse program. Surveys on the public's attitude toward various wastewater reuse projects indicate that public acceptance tends to increase with income and education (Shelef, 1991). Consequently, development and social acceptance of wastewater reuse standards is an essential step for the development of social acceptance of wastewater reuse. These reuse standards must be adapted to the country's administrative framework. Further, capacity building (e.g. public education) is another important factor for success because such measures can increase awareness and motivations.

The organizational factor governs the implementation time and quality of such a project, not its success or failure. In the case of a complex administrative organization, the development could be restricted by conflicts between organizations such as industrial park managers and tenants or between tenants. Therefore, an administrative reorganization may be necessary to guarantee the development of wastewater reuse into a general water management scheme. Fragmentation is consistently recognized as an impediment to effective integration (Mitchell 1994). As no single organizational approach can entirely eliminate the boundary or edge problems among agencies (Mitchell 1994), attention should be focused on mechanisms to reduce organizational overlap or gaps, and facilitate greater coordination among agencies. In this regard it is suggested that organizational approaches should be situational, coordinated and cooperative.

The technical factor is the least important, as available technologies make it possible to reach any water quality required by users and regulatory compliance. Various extensive and intensive technologies can be applied, depending on local situations, plant size, and water quality standards (Lazarova et al., 1998). However, the choice of the most appropriate technologies plays a key role for the reliable operation of the reclamation plants and the guarantee of water quality at lower operation and maintenance costs.

4.9 SUMMARY

Integration requires the conscious and systematic consideration of the many diverse elements of a resource management issue in seeking optimal solutions (Mitchell 1990). In conceiving, designing, implementing, and maintaining IWRPM within an industrial park, complementary and competing objectives must be balanced to anticipate and solve problems. This chapter introduced a process for framework development. It first presented the concept of IWRPM at the industrial park level, then described the system framework, as well as some key factors for its success.

CHAPTER 5 MODEL DEVELOPMENT

5.1 INTRODUCTION

In this chapter, the development of a quantitative optimization model to assist decision makers in the identification and implementation of effective water reuse strategies will be undertaken. Since the development of this model utilizes the system analysis method, the initial discussion will focus on the key attributes and techniques of this method. Subsequently, the model, including its components, objective function, and constraints will be presented.

5.2 SYSTEM ANALYSIS METHOD

The complexity of industrial production demands a systems approach to problem solving. Every corporate enterprise, from a small business to a large multinational corporation, is part of a larger economic system or web. Companies are interlinked to other companies via an increasingly complex supply chain. The complexity and scale of industrial systems increases by understanding that these systems are inherently dependent on the resources provided by biophysical ecosystems. This perception underscores the need for a systemic approach to designing and operating industry within ecological limits (Casavant 2000). Managers of industrial parks have to consider multiple industries, materials, and impacts in a highly complex system. Therefore, a system analysis approach is required if industrial park managers are to find more environmentally and financially beneficial ways to plan and manage their water resources.

System analysis typically requires a mathematical model that characterizes the relationships and constraints governing various systems components. Such a model is usually the result of a careful analysis of the system in question in which quantitative links among components are established. Practically, system analysis aims to optimize system performance. Such an optimization is a three-step process, including problem formulation and system representation, determination of system effectiveness, and implementation of algorithms and solution methods to find the optimal configuration (Beightler et al., 1967; Diwekar and Small 1999). In the following sections, each of these steps is discussed and their relevance to water reuse in an industrial park is outlined.

5.3 PROBLEM FORMULATION AND SYSTEM REPRESENTATION

The most critical element of optimization is to clearly formulate the problem as it is the prerequisite. The focus of problem formulation is to develop an objective function, which must be expressed in uniform units of measurement, such as dollars, or measures of productivity/efficiency. For industries and probably industrial parks, current environmental management approaches focus primarily on maximizing profits (or minimizing total costs) while maintaining compliance with emission constraints (Paczynski, et al. 2000). Consequently, in this thesis, system analysis can be a design tool to help decision-makers focus on all the elements of the metabolic system involving water within an industrial park towards a single objective i.e minimizing total costs, while maintaining compliance with water quality, quantity, and emission constraints.

However, before the objective function can be established, the characteristics of the metabolism of water in the industrial park must be understood and represented. From the perspective of industrial ecology, such a system representation requires the characterization of material, energy and information flows and reservoirs, often at a combination of local and regional scales (Diwekar and Small 1999). The regional scale may be important because the major water supplies are found outside the boundary of the industrial park or municipality. With regard to the metabolism of water and its use within an industrial park, various components, including water distribution system, water treatment plants, water users, wastewater treatment plants and water sinks, should be described in detail in order to show their own characteristics and how they interact with other elements. The following sections will introduce these elements for a typical industrial park in detail.

5.3.1 Water Sources

The possible water sources within an industrial park include precipitation, surface, ground sources and desalinated seawater. Each source is defined by: (1) location; (2) water availability, which is expressed as the maximum water yield; and, (3) quality profile, which is defined in terms of the concentrations of each contaminant being used to enforce the water quality constraints during the planning process. Water is usually sent to a water treatment plant from water sources in order to satisfy its quality according to the local potable water standard, or extracted directly by those water users that do not require potable water without previous treatment. Figure 5-1 is a schematic presentation of this subsystem.

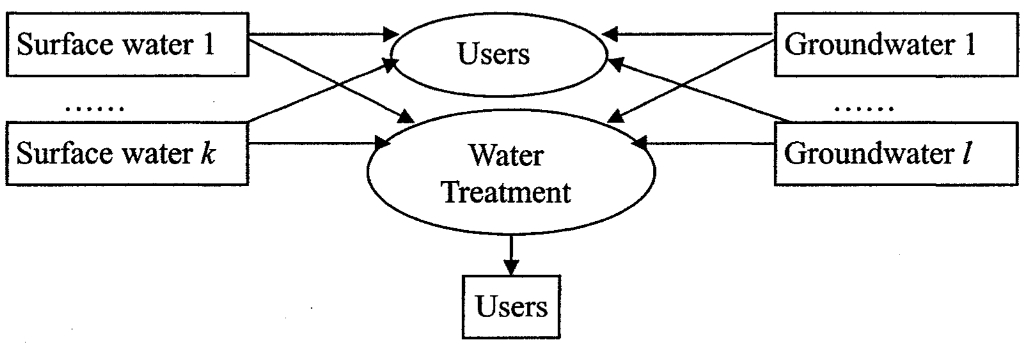

Figure 5-1: Schematic presentation of the interaction of water sources with other system elements

5.3.2 Water Treatment Plant

The water treatment plant is defined by: (1) location in the park; (2) production capacity; (3) water losses; and, (4) treatment performance, as given by the removal efficiencies that the plant achieves for each contaminant. Figure 5-2 expresses its interaction with other system elements.

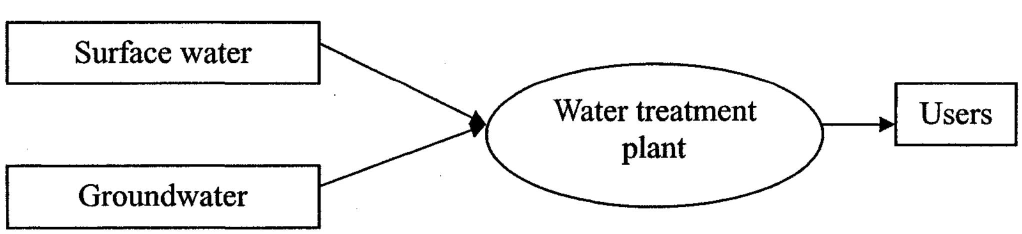

Figure 5-2: Schematic presentation of water treatment plant interaction with other system elements

5.3.3 Water Users

A water user is an element in the system that demands water. Tenant companies, management units, domestic users, and landscape sites are major users. A user is defined by: (1) location; (2) water demand; (3) water losses; and (4) water quality requirements, which represent the maximum acceptable concentration for each contaminant. This study is based on the premise that some users can recycle water within their own operations or send the water directly to another user if its quality can satisfy that user's demands. A user can also receive water from a surface or groundwater source, or a water treatment plant. It also can receive reclaimed wastewater from the wastewater treatment plant. If the effluent cannot be recycled or reused by other users, such effluent is sent to the wastewater treatment plant for further treatment. The quality of such effluent entering the wastewater treatment plant should at least meet with the input requirements of the wastewater treatment plant, therefore, previous treatment may be necessary for some users. Figure 5-3 describes one potential user's interaction with other system elements.

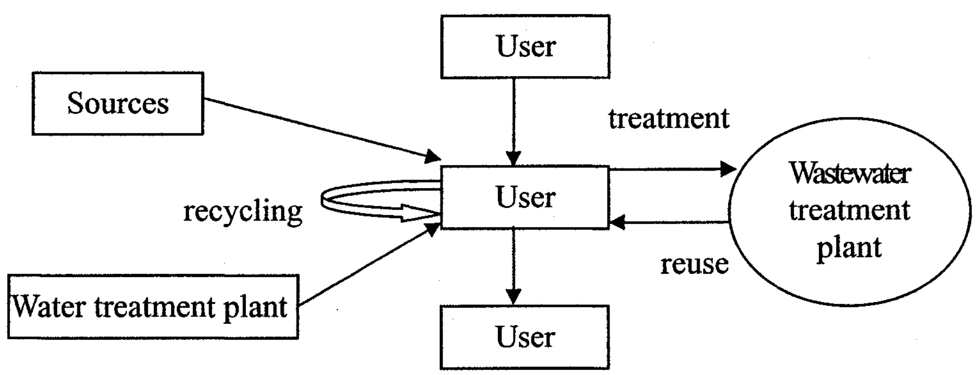

Figure 5-3: Schematic presentation of a user interaction with other system elements

5.3.4 Wastewater treatment plant

The wastewater treatment plant is defined by: (1) location in the park; (2) maximum flow capacity; (3) water loss; (4) influent quality requirements; (5) treatment performance, as given by the removal efficiencies achieved for each pollutant; and, (6) reliability and consistency of performance. This study assumes that the wastewater treatment plant receives influent from the users in the park and sends some back to the users if the quality is acceptable. The surplus effluent from the plant will be sent to recharge the local groundwater according to the local groundwater recharge demand, for landscaping or stored in suitable tanks or reservoirs, sent to local communities, as determined by local needs, or safely sent to the local receiving water bodies as the last order. Figure 5-4 presents its interaction with other system elements.

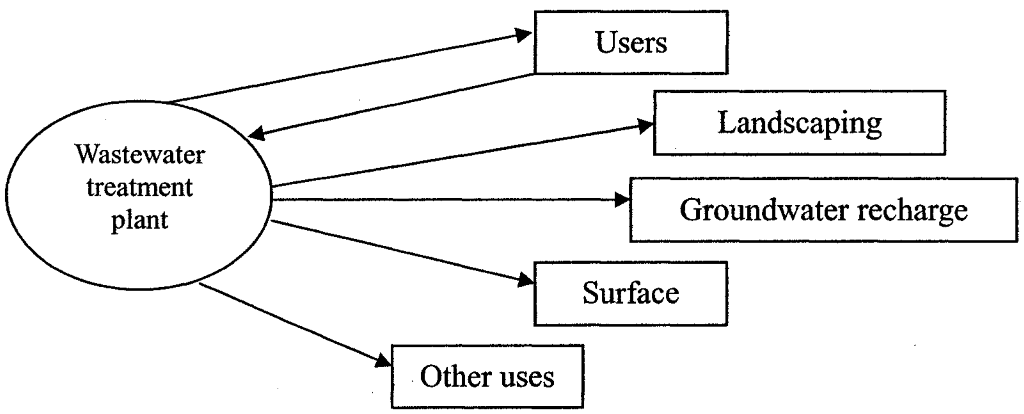

Figure 5-4: Schematic presentation of the wastewater treatment plant interactions with other system elements

5.4 NOMENCLATURE

There are a number of quantities and qualities of water that must be factored into the analysis of the metabolism of water in an industrial park. The following nomenclature is useful for the interpretation of the objective function and constraints and could be categorized as two levels, namely, water quantity category and water quality category: (The units for flows are in 10^3 m^3 per day, and the units for pollutant concentration are mg/l.)

5.4.1 Water Quantity:

XF_k amount of fresh water from surface and ground source k to water treatment plant;

XS_{li} amount of water from surface and ground water source l to user i without treatment;

XF_i amount of freshwater sent from water treatment plant to user i;

XT_i amount of reclaimed water from wastewater treatment plant to user i;

XTT_i amount of wastewater from user i to the wastewater treatment plant;

XTU_{ji} amount of wastewater from user j to user i without treatment;

XRR amount of reclaimed water from wastewater treatment plant to ground source for recharging groundwater;

XLS amount of reclaimed water from wastewater treatment plant for landscaping;

XOD amount of reclaimed water from wastewater treatment plant for other uses;

XOA amount of any other feasible applications of reclaimed wastewater;

$C(P_n)_i$ pollutant n concentration leaving user i;

N number of users within an industrial park;

D_i water required by user i;

L_i water losses by user i;

LT water losses at water treatment plant;

LTT water losses at wastewater treatment plant;

TC treatment capacity at water treatment plant;

TTC treatment capacity at wastewater treatment plant;

GC groundwater recharge request;

DLS landscaping request;

5.4.2Water Quality:

$LS(P_n)$ local pollutant n standard for freshwater;

$LT(P_n)$ local pollutant n standard for wastewater discharge

$LRG(P_n)$ local pollutant n standard for groundwater recharge by reclaimed water;

$DLS(P_n)$ local pollutant n standard for landscaping by reclaimed water;

$CF(P_n)$ pollutant n concentration of freshwater from water treatment plant;

$CT(P_n)$ pollutant n concentration of reclaimed water from wastewater treatment plant;

$S(P_n)_i$ pollutant n standard required by user i;

P_n pollutant n, n=1,2,…,N; (such as BOD, COD, TSS, TOC, etc)

N number of pollutants;

5.5 OBJECTIVE FUNCTION

After gaining an appreciation of the system elements and their inter-relationships, the final stage in the problem formulation and system description step is to define an objective function, which is limited by a number of technological and environmental constraints. In terms of an industrial park, we can define our objective as finding the most cost efficient solution for the supply and reuse of water. Within an industrial park, the total costs include that of water and wastewater treatment, the distribution cost, including piping and pumping, and the amortized construction cost for new pipes. Economic analysis of these costs is developed based on capital investments and operation & maintenance (O&M) costs. Capital investments consist of an individual water treatment unit, the transport and construction of water facilities. O&M costs comprise personnel salaries, management expenses, inputs (energy consumption and chemical costs), and maintenance costs (equipment repair and replacement).

Cost data varies with treatment capacity, market prices for construction, energy, chemicals and equipment, management and operation conditions, as well as water quality (Asano and Levine 1996). It has been difficult to estimate such costs in the planning stages. The authenticity of cost estimation data is dependent on the number of projects involved in establishing criteria, including the types of projects, and the local conditions under which such projects have been constructed (Shah and Reid 1970). One solution is to use mathematical formula to express the relation between costs and water flows (US EPA 1978a). Such formula are based on valid cost statistics and their intelligent interpretation. Regional differences and the economies of scale need to be considered in creating such formula since they affect costs of different types (US EPA 1979).

The piping costs can be expressed in the form of αQ^{β},where Q is the flow transported through pipes (U.S. EPA, 1978a; Wang e al., 1987; Oron, 1996; Cao and Gu, 1997; Tian et al., 2001). The α and β are coefficients, with β expressing the economies of scale, where usually $0<\beta<1$. This is because economies of scale were among the main factors influencing researchers to consider water system costs, where the locations of sources and their waste flows were fixed in advance, as are the regional treatment plant locations and the allowable pipeline routes. These economies of scale imply concavity when the functions are continuous. Similarly, the construction costs for pipes and pumps are expressed as $\alpha_1 Q^{\beta 1}$US EPA, 1978b; Wang et al., 1987; Oron, 1996; Cao and Gu, 1997; Tian et al., 2001) and the pumping costs are expressed as $\alpha_2 Q^{\beta 2}$(US Army Corps of Engineers, 1973; US EPA, 1978a; Wang e al., 1987; Oron, 1996; Cao and Gu, 1997; Tian et al., 2001). The water and wastewater plant treatment costs also have a form similar to the pumping and piping costs (US EPA, 1978c, 1979; Wang e al., 1987; Oron, 1996; Cao and Gu, 1997; Tian et al., 2001). Therefore, for the purposes of this study, the objective function will be set up to minimize the sum of daily piping costs, daily pumping costs, daily water and wastewater treatment costs for the whole system, and amortized daily construction costs for new pipes and pumps if water reuse is necessary. It can be expressed by the following equation:

Minimize:

$$\sum_{w\in W}\alpha_w Q_W^{\beta_w}+\sum_{z\in Z}\alpha_z Q_Z^{\beta_z}+\sum_{p\in P}\alpha_p Q_p^{\beta_p}+\alpha_l(\sum_i XF_i)^{\beta_l}+\alpha_l(\sum_i XTT_i)^{\beta_l} \quad (1)$$

Here W is the set of possible pipes connecting sources, users, treatment plants, and disposal sites (sinks), the first part of the equation represents the whole daily piping costs. Z is the subset of pipes requiring pumping, and the second part of the equation represents the whole daily pumping costs. P is the subset of new pipes and pumps considering water reuse, and the third part of this equation represents the amortized daily construction costs of new pipes and pumps. The fourth represents the daily water treatment plant costs, and the fifth represents the daily wastewater treatment plant costs. For those countries where such empirical equations are available, planners and managers can directly use the data from their literature. For those countries where such equations are unavailable, planners and managers can ask the site engineers to provide the unit cost for piping (including construction, operation and maintenance), pumping, water and wastewater treatment, then make the problem a linear optimization problem although it won't reflect economies of scale by doing so.

5.6 DETERMINATION OF SYSTEM EFFECTIVENESS

From an industrial ecology perspective, the second step of system optimization is the determination of measures of system effectiveness, namely, setting up constraints subject to the objective functions, with an inclusion of environmental considerations. The constraints define a feasible domain in the decision space (O'Leary et al., 1990). Subject to the nature and scope of the water planning and management problem, the constraints can express restrictions placed on the water quality. For reuse, constraints should be subject to environmental regulations on wastewater, water demands, health risks, user's quality requirements, water balance, capacity constraints, nonnegative constraints, groundwater recharge request, and landscaping requests. The following is a detailed description of these constraints:

(1) Demand Constraints:

$$\sum_{i} XFi + \sum_{l} XSli + \sum_{i} XTi + \sum_{j,i} XTUji + \sum_{j,i} XTBUji \geq Di^{(2)}$$

This equation states that the amount of all the possible inflows to a water user should be at least equivalent to its demand. This set of linear constraints forces the demand for each user i to be satisfied.

(2) Water Balance Constraints:

$$XF_i + XT_i + \sum_{j} XTU_{ji} + \sum_{l} XS_{li} + \sum_{j} XTBU_{ji} - XTT_i - \sum_{i} XTU_{ij} - \sum_{i} XTBU_{ij} = L_i \forall i \quad (3)$$

These sets of linear constraints prevent violation of any mass balances throughout the system for each user, water treatment plant, and wastewater treatment plant. For users, the water balance equation can be expressed as following:

For water treatment plants, the water balance equation can be expressed as following

$$\sum_{k} XF_{k} - \sum_{i} XF_{i} = LT \qquad (4)$$

This equation states that water loss within water treatment plant equals to all the inflows minus all the outflows.

Similarly, for the wastewater treatment plant, the water balance equation should be:

$$\sum_{i} XTT_{i} - \sum_{i} XT_{i} - XRR - XLS - XOD = LTT \qquad (5)$$

This equation states that all the treated wastewater expect loss should be reused by users if quality is not a problem, for groundwater recharge, landscaping use, or other feasible uses.

(3) Capacity Constraints:

These linear constraints limit the water flow entering a treatment plant according to its capacity.

For a water treatment plant, this constraint should be expressed as following:

$$\sum_{k} XF_{k} \leq TC \qquad (6)$$

This means that the amount of raw water entering a treatment plant should be less than its maximum treatment capacity.

For a wastewater treatment plant, this constraint should be expressed as:

$$\sum_{i} XTT_{i} \leq TTC \qquad (7)$$

This means that the amount of wastewater entering a wastewater treatment plant should be less than its maximum treatment capacity.

(4) Water Quality Constraints:

This set of constraints forces the water flow distribution in the system to satisfy the quality requirements of each user.

For direct wastewater reuse from company *j* to company *i*, it may be possible only when:

$$C(P_n)_j \leq S(P_n)_i \qquad (8)$$

This means the level of every pollutant concentration from company *j* should be lower than that of the quality requirement of company *i*.

For reclaimed wastewater reuse from wastewater treatment plant to company *i*, it may be possible only when:

$$CT(P_n) \leq S(P_n)_i \qquad (9)$$

This means the level of every pollutant concentration from wastewater treatment plant should be lower than that of the quality requirement of company *i*.

For wastewater reuse from company *j* to company *i* by blending with freshwater, the ratio of wastewater to freshwater can be calculated by the following equation:

$$\gamma = \frac{C(P_n)_j - S(P_n)_i}{S(P_n)_i - CF(P_n)} \qquad (10)$$

This ratio can help determine the minimum dilution.

And then the relation between XF_i and $XTBU_{ji}$ should be:

$$XF_i = \gamma \times XTBU_{ji} \qquad (11)$$

This equation indicates that the amount of freshwater for blending with reclaimed wastewater must be $(r\text{-}1)*100\%$ larger than $XTBU_{ji}$ for the required dilution.

(5) Environmental Regulation Constraints:

This set of constraints requires the quality of freshwater from water treatment plant to satisfy the local freshwater quality requirements, and the quality of reclaimed water from wastewater treatment plants to satisfy the local groundwater recharge standard or the local landscaping standard or any other environmental use standards (e.g. lake and marsh enhancements).

For a water treatment plant, it can be expressed as:

$$CF\left(P_n\right) \leq LS\left(P_n\right) \qquad (12)$$

This equation states that the level of every pollutant concentration from water treatment plant should be lower than that of the local freshwater quality requirement.

For a wastewater treatment plant, it can be expressed as:

$$CT\left(P_n\right) \leq LT\left(P_n\right) \qquad (13)$$

This equation states that the level of every pollutant concentration from wastewater treatment plant should be lower than that of standard for local wastewater discharge.

For groundwater recharge, it can be expressed as:

$$CT\left(P_n\right) \leq LRG\left(P_n\right) \qquad (14)$$

This equation states that the level of every pollutant concentration from wastewater treatment plant for groundwater recharge should be lower than that of standard for groundwater recharge.

For landscaping, it can be expressed as:

$$CT\left(P_n\right) \leq DLS\left(P_n\right) \qquad (15)$$

This equation states that the level of every pollutant concentration from wastewater treatment plant for landscaping should be lower than that of standard for landscaping.

(6) Nonnegative Constraints:

This set of constraints requires that all the inputs and variables should be at least nonnegative.

$X>=0$, X represents all the inputs and variables, (16)

(7) Groundwater Recharge Constraint:

This constraint requires that the amount of recharging groundwater by reclaimed wastewater should be no more than the daily demand for groundwater recharge. It can be expressed as:

$XRR<=GC$ (17)

(8) Landscaping Constraint:

This constraint requires that the amount of landscaping using reclaimed wastewater should be no more than the daily demand for landscaping. It can be expressed as:

$XLS<=DLS$ (18)

Then, by choosing a suitable optimization solver, this management information system can reveal the optimal water reuse scenario with the least system costs, guiding industrial park managers and tenant companies to reduce the total freshwater consumption and wastewater emission, in other words, making the most effective and efficient use of the resource. The choice of solver had to satisfy certain characteristics. These are availability, simplicity, cost and so on.

5.7 SUMMARY

This chapter is a detailed introduction of model development. It first introduced the system analysis methods for developing the model, and then described the system elements. The main focus of this chapter is to present the objective function and constraints.

Chapter 6 introduces the case study in which this framework is applied and the approach is tested.

CHAPTER 6 RESULTS AND FINDINGS

6.1 INTRODUCTION

In order to test the feasibility and applicability of the model within the context of an integrated water planning and management, a case study approach was employed. The case study site is the Tianjin Economic Development Area (TEDA), where the water crisis is increasingly severe. This chapter first introduces how the research partners were selected and then describes the current conditions in the city of Tianjin and TEDA respectively, with particular reference to their water issues as revealed through research surveys. The main focus of this chapter is to describe the data collected and the results obtained through the application of the quantitative model presented in Chapter 5.

6.2 RESEARCH PARTNER SELECTION

This research focuses on the development and application of a quantitative optimization model within an integrated water resource planning and management framework for an industrial park. In order to prove its feasibility, the model was tested in the Tianjin Economic and Development Area (TEDA), the largest industrial zone in China.

There are several economic and technological development zones and many industrial parks in China. The selection of the Tianjin Economic Development Area (TEDA) as a case study site was based on a number of criteria. First, this industrial zone is the largest in China according to its total industrial production. Its demonstration effect on other Chinese industrial parks is likely to be great. Second, TEDA is eager to apply innovation to its resource and environmental management processes. In 2000, TEDA was designated as an ISO 14001 national demonstration district by China's State Environmental Protection Administration (SEPA) and in 2002, initiated their eco-industrial park (EIP) project. Third, TEDA has experience working with international organizations such as Division of Technology, Industry and Economics at the United Nations Environment Programme (UNEP) and has been active with bilateral Japanese-Chinese environmental projects (TEDA 2002). The Environmental Protection Bureau (EPB) of TEDA expressed their openness to actively participate in the study and provided research facilities and other logistical support. Also, because most of their tenants are wholly foreign owned enterprises and joint ventures, they tend to have a higher level of environmental awareness and would like to collaborate with each other in terms of resource and environmental management. Fourth, TEDA was suitable for the research study given their environmental challenges, especially, their increasingly severe water crisis. They are facing not only a freshwater resources challenge, but also are experiencing a deteriorated aquatic environment due to excessive wastewater discharge. They regard integrated water resource planning and management as one of the key elements of their eco-plan. In addition, the Environmental Protection Bureau (EPB) at TEDA was interested in this research. In 2002, they co-hosted a workshop with UNEP, SEPA and Dalhousie University. As indicated by Thurston et al (1994), the three main factors for successful research in China include formal institutional affiliation, more informal collegial and personal ties, and a concept of mutual benefit. The selection of the research location and host institution demonstrate that all these factors are present.

6.3 OVERVIEW OF THE TIANJIN REGION

6.3.1 The City of Tianjin

The Tianjin Economic Development Area (TEDA) is located in Tianjin Municipality, China. The city is located on the eastern part of the North China Plain, neighboring the country's capital city of Beijing. Geographically, the city is located in the warm temperate zone, with annual mean temperatures between 11 and 12 degrees Celsius, and annual mean precipitation of approximately 630 mm (Gao 2002). Tianjin is a municipality directed under the Central Government, as well as an "open" city, covering an area of 11,300 square km and with a population of six million in the urban areas. Figure 6-1 is a map of Tianjin in China.

Figure 6-1 Map of Tianjin in China

As one of China's biggest industrial centers, Tianjin has built up an extensive industrial system including such sectors as machinery, electronics, textiles, chemicals, metallurgy, and foodstuff. Tianjin is also one of China's most prosperous business areas as well as a distribution center for goods and materials in North China (Gao 2002). It is a key hub of land and sea communications. Its port, consisting of Tianjin, Tanggu and Xingang Harbours, is an important Chinese seaport, serving as the most convenient sea outlet for Beijing, as well as North and Northwest China. The port, accessible to ocean freighters of ten thousand tons class, has opened more than 20 international ocean shipping routes. Besides these, Tianjin has a well-developed road transportation network, regular air-service to over 30 cities throughout the country, and inland water shipping, in addition to pipelines for oil transport. Figure 6-2 is a map of the city of Tianjin, indicating the location of Tianjin Economic Development Area (TEDA).

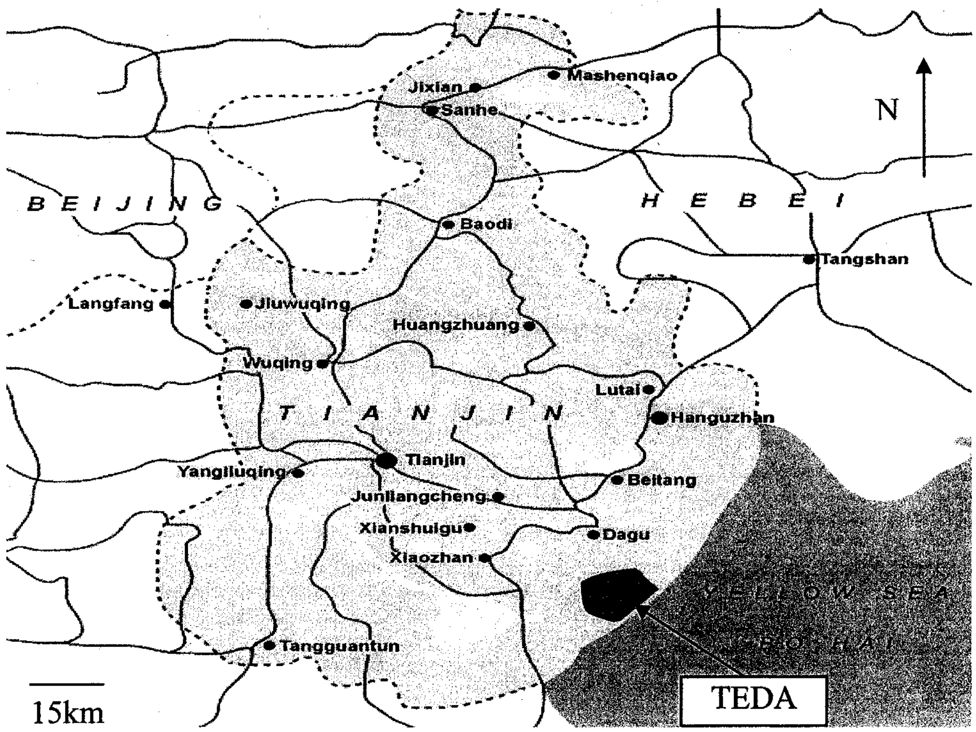

Figure 6-2 Map of Tianjin City

6.3.2 Water Issues in Tianjin

One of the country's seven largest river basins, the Haihe River Basin, is also one of the most polluted and water-scarce (TEDA 2002). It covers a total area of about 310,000 square kilometers and includes portions of five different provinces and two mega-cities. Tianjin is located in the estuarine part of the river and covers 11,200 square kilometers, equal to 5.3 times the area of the Tokyo metropolis in Japan (Haihe Water Resource Management Committee 1997).

Two factors form the background of Tianjin's water issues. One is the imbalance between natural resource distribution and the region's social and economic stature in China. The share of land area, population and arable land of the region in the country are 3.3%, 9.8% and 10.9%, respectively, while the share of water resource distribution is only 1.5%. As a result, the *per capita* water resource availability is only 430 cubic meters per year, 16% of the country's average level (Haihe Water Resource Management Committee 1997). Despite this situation, the region plays a very important socio-economic role. The basin holds one of China's five largest urban agglomerations, with Beijing and Tianjin, and

Tianjin is the largest industrial center in northern China. The second factor is the rapid industrialization and economic growth of the city and surrounding region that have occurred in recent decades. Because water demand upstream has grown rapidly, the downstream city of Tianjin has suffered. Water demand in Tianjin City is also growing, as the GDP of the city grew tenfold from 1978 to 1996 and the urban population grew by 1.5 million persons (Haihe Water Resource Management Committee 1997).

Among many other concerns, a deficit of total available water resources, overuse of groundwater, and deteriorating water quality are three major water resource related issues. The environmental impacts are significant and diverse, including desertification, land subsidence, dropping water tables, saltwater intrusion into groundwater and soil salinization among many others (TEDA 2002).

6.4 TIANJIN ECONOMIC DEVELOPMENT AREA (TEDA)

6.4.1 Location

The Tianjin Economic Development Area (TEDA), a special development zone on the Bohai Bay in North China, is located in the eastern portion of Tianjin Municipality, approximately 50 kilometers from the city of Tianjin. TEDA was founded in 1984 and provides essentially the same preferential policies, incentives, and flexible measures as other special economic zones in China. It has a planned area of nearly 36 square kilometers, including separate sections for industrial development and mixed residential, financial and commercial uses. Figure 6-3 is the functional planning map of TEDA. Consequently, TEDA functions in a similar manner to a small municipality, being divided between three main areas - industrial, commercial, and residential - with some limited agricultural activities within its boundaries. The total population living in the industrial estate was 53,893 at the end of 2002. There are approximately 152,000 workers or managers traveling between the city of Tianjin and the estate everyday (TEDA 2003).

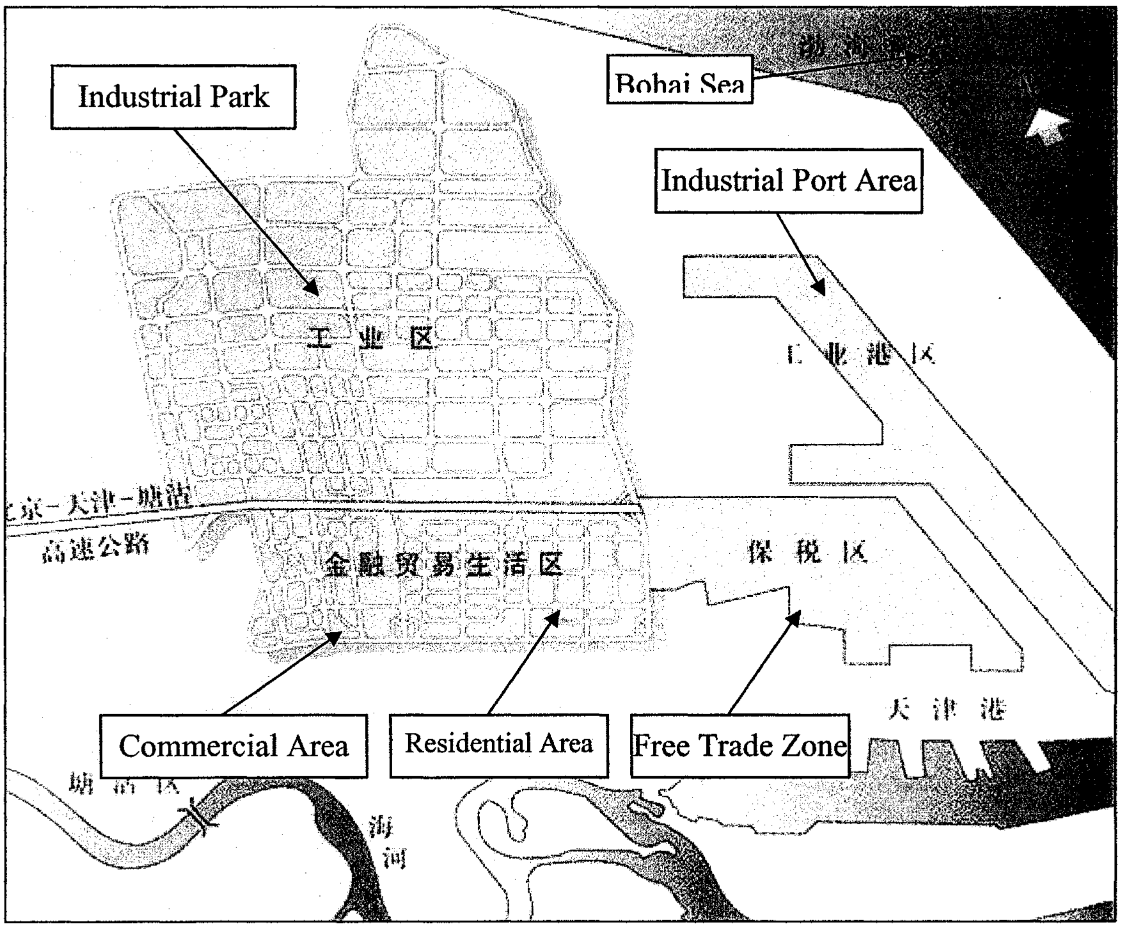

Figure 6-3 Functional Planning Map of TEDA

6.4.2 Government

While the Tianjin Municipal government has responsibility for TEDA, the zone has its own administrative agency to oversee the daily administration of the park. This agency is called the TEDA Administrative Commission and it is comprised of a Chairman and a large number of departments and bureau branches (Appendix 3). Under this system, the main bureau responsible for environmental protection is the Environmental Protection Bureau (EPB). This bureau's portfolio includes the Comprehensive Administration Department (in charge of environmental enforcement), General Engineer's Office (in charge of research and development), and the Environmental Protection Monitoring Station (in charge of environmental quality monitoring) (TEDA 2002).

6.4.3 Industry Profile

TEDA can be classified as an outer suburban estate with comprehensive functions given its varied companies and industries. Businesses in the estate cover a range of ownership-types that include joint ventures, private companies, state-owned enterprises, and wholly foreign owned enterprises. Numerous tenant sites, especially companies with a staff of more than 400 employees, have both manufacturing buildings and residential buildings within their compounds. This is in keeping with Chinese government policy whereby businesses are expected to provide social benefits to employees such as food and accommodation.

TEDA reflects the trend of most Asian industrial estates as it has a large number of tenants from diverse countries which tend to be competitive with one another. Within TEDA there are over 3,300 foreign-invested enterprises, including 28 companies that are ranked among the Fortune 500 group (TEDA 2001). Total investment in the park has reached close to US $ 12.6 billion (TEDA 2003). Through eighteen years' development, TEDA has established four pillar sectors: (1) electronic communications; (2) foodstuff; (3) bio-medicine; and, (4) machinery manufacturing. Well-known multi-national companies include Motorola, Hyundai, Samsung Electronics, Hartwell Textile, Coca-Cola, General Electric, Dingyi Food, SEW, Novozymes, and GlaxoSmithKline (TEDA 2001).

6.4.4 Infrastructure

TEDA receives its electrical power supply from 2 sub-stations that are connected to the China North Power Grid. Government-owned companies run these stations and the energy is purchased by the TEDA administration and then sold to local industries and residential areas. Central heating in the zone is supplied by four large central boilers, connected through pipelines to buildings in the zone. District heating is used throughout the residential areas. Liquid Petroleum Gas is supplied to 100% of the residents for cooking (TEDA, 2001).

Water is drawn from the Erwangzhuang reservoir for a maximum daily supply capacity of 80,000 m^3 of freshwater in the estate (TEDA, 2001). Some groundwater is extracted for heating purposes in winter as such water is warmer than surface water (60-70 degree centigrade). TEDA has two wastewater treatment facilities in operation. One is for municipal wastewater treatment and industrial wastewater treatment, and another one is a specialized Electroplating Wastewater Treatment Center, which treats and recycles wastewater with heavy metals (TEDA 2002). According to a local regulation, it is prohibited for tenant companies to discharge their wastewater directly into Bohai Sea in order to prevent local seawater pollution.

In terms of capacity building, TEDA has access to 20 universities and numerous scientific and technical research institutes in the greater Tianjin area (Wei 2002, personal communication)[1]. Already some collaborative projects between TEDA and the Environmental Science Institute of Nankai University and the Faculty of Environmental Engineering of Tianjin University have been carried out (Wei 2002, personal communication), such as environmental impact assessment and environmental software development for TEDA.

6.5 SURVEY RESULTS AT TEDA

A detailed survey was done in TEDA in order to obtain information on its water issues. Survey methods included documents review and key informant interviews. This section presents the survey results at the total site level, including water scarcity, water supply, water management department, water use, wastewater issues, water conservation, and reuse.

6.5.1 Water Scarcity

For almost two decades, TEDA and the Tianjin region have suffered from a water deficit problem due to scarcity of resources and resource depletion. In 2000, 2001, and 2002, Tianjin faced severe drought conditions (Wei 2002, personal communication) and as early as the mid-1990's, the area's main reservoir for freshwater, Erwangzhuang, was utilized to capacity. Early efforts to tap other reservoir sources did little to alleviate the pressure for freshwater needs because the whole North China region is suffering from

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[1] Wei is the chief engineer at TEDA EPB.

water shortages and the surrounding areas are reluctant to provide a portion of their decreasing water supply to TEDA. Consequently, the current water deficit in TEDA continues to be grave. As a result, the local administrative government must contend with supply issues and increasingly tense competition among various districts and counties vying for the resource. Additionally, in an environment workshop in 2002, the TEDA Administrative Commission recognized several water-related problems specific to the TEDA industrial estate. These included an overall problem with water shortages, groundwater depletion, and seawater intrusion (TEDA 2002). TEDA is also faced with the challenge of polluted coastal waters, due to the presence of high levels of inorganic matter and phosphates. In the late 1990's and after several red tide scares, Tianjin municipality was targeted for remediation initiatives under the government's Trans-Century Green Project (1996 – 2000). However, despite these efforts, pollution remains a significant problem (SEPA 2003).

6.5.2 Water Supply

There are several types of sources for water supply in TEDA. These include surface water, groundwater, and seawater. Surface water and groundwater are the most highly used sources, providing 26.82 million m^3 of water in the year 2001 for the zone's consumption needs. Of this amount, 25.33 million m^3 (94.4%) was surface water, and 1.49 million m^3 (5.6%) was groundwater (TEDA 2002). The main source of surface water (16.37 million m^3) is the Erwangzhuang reservoir, which receives water from the Luan river, a branch of the Haihe river. Water from the Erwangzhuang reservoir is further treated in the TEDA Water Treatment Plant (WTP) and the potable water from WTP is classified as Class I under the national standards for drinking water (Appendix 4 lists national standards for drinking water). Other water is obtained from the Tanggu Freshwater Treatment Plant (8.96 million m^3) under a long-term agreement (TEDA 2002). Studies have shown that water quality has deteriorated due to industrial and domestic pollution (TEDA 2002). Groundwater use occurs only in winter for heating purposes.

TEDA also has access to a large supply of seawater given its location, but this source of water has not been highly exploited. Desalinization options are still considered too expensive and the use of seawater in manufacturing operations has been limited to a few companies in the estate that are co-located next to the shoreline. Examples of businesses in TEDA using seawater daily in their operations include a heating plant and some recreation sites, like sauna rooms and swimming pools. In total, they process 5,000 m^3/day of seawater for use as a coolant and cleaning solvent (Fan 2002, personal communication)[1].

6.5.3 Water Use

The system for processing and selling water in TEDA is as follows. Water is purchased by the TEDA administration at a discounted rate from the municipality (1.48 RMB per m^3) and is then resold to tenants (Yan 2002, personal communication)[2]. Water prices are subsidized by TEDA through the Financing Bureau, which also absorbs the cost of water used within TEDA government departments. Based on water sales, water users in TEDA are classified as industrial (70%), commercial (20%) and residential (10%) (Yan 2002, personal communication). The charges for water per ton vary depending on different uses but the fees range from 2.20 RMB/per m^3 for residential users to 3.0 RMB/per m^3 for industrial users (Yan 2002, personal communication). The Planning and Water Saving Office at the Construction Bureau (PWSO) is in charge of monitoring water processed into the park. They claim they regularly account for 86.66% of processed water. Thus, 13.33% is not accounted for due to factors such as leakage (TEDA 2002).

Once freshwater has entered the park, consumption is controlled not only by the above-mentioned fees but also through a quota system. Similar to water pricing, quotas differ between users and sectors. The TEDA government sets quotas further to consultation with the Tianjin municipal government. The only published quota for water use in TEDA is residential, which states that families are limited to 9 m^3 per month. If quotas are exceeded, water costs can double (TEDA 2002). Industry is also subject to quotas but setting allocations is done on an individual company basis in conjunction with the TEDA administration and is dependent on manufacturing needs. In general, TEDA claims that

[1] Fan is the chief engineer at TEDA wastewater treatment plant.
[2] Yan is the chief of environmental management section at TEDA EPB.

companies comply with their quotas. For example, PWSO reported that in 2001, 94% of companies in TEDA were able to stay within their established water quota (TEDA 2002). In some cases, arbitrary limits to water might be set during months when there have been unforeseen water shortages (Fan 2002, personal communication).

In terms of water use, a ranking of priority in sector-wise water resource allocation was identified through the interviews. Urban municipal water is the highest priority, followed by industrial usage, environmental use, and, finally, irrigation use (Fan 2002, personal communication). Ecological water use is often neglected although a certain amount of water is essential to sustain natural ecosystems and hydrological cycles.

6.5.4 Wastewater

Once water resources have reached the effluent stage, the wastewater treatment plant in TEDA processes it. This plant has a total capacity of 20,000 m^3 a day (TEDA 2002). However, given ongoing shortages, the facility has not been operated at capacity (Fan 2002, personal communication).

Within TEDA there is a dual pipe system for storm water runoff and for industrial and residential effluent. Storm water pipes, some of which are open gutters, release water directly into the sea without treatment. Industrial, commercial, and residential wastewater is processed through the plants, receiving secondary treatment before releasing into the ocean. All companies are required to comply with national water discharge regulations before releasing their wastewater into the general sewage system. This means wastewater must be treated to a Class III Industrial Standard (Integrated Waste Water Discharge Standard – General Use – GB8978-1996, see appendix 5). Several tenant companies have their own wastewater treatment equipment at their manufacturing sites to reduce costs or avoid fines from the wastewater treatment plant, including Novozymes and Dingyi Food (Yan 2002, personal communication). The administrative cost of treating wastewater is covered by the TEDA administration and subsidized in part by freshwater fees that have a built-in charge for wastewater processing. For every m^3 of freshwater sold, 0.8 RMB (or US$.10) is allocated for wastewater processing (TEDA 2002).

TEDA's wastewater treatment facilities work in conjunction with the Environmental Protection Monitoring Station (EPMS) at the Environmental Protection Bureau (EPB) to monitor the quality of water effluent among businesses in the park. Metering devices are not used among tenants and the TEDA administration relies on a standard calculation to determine wastewater quantity statistics for each company. This calculation is based on a rate of consumption where wastewater is considered to be 80-85% of the total water consumed (Fan 2002, personal communication).

6.5.5 Administrative Structure for Water Management

There are several departments and bureaus related to water management in TEDA. These include the Planning and Water Saving Office (PWSO) at the Construction Bureau (for water planning and conservation) and the Environmental Protection Bureau (EPB) (for water quality monitoring and wastewater emission). Other departments related to water management include the social development bureau (for water-related health issues), the policy research office (for water policies), the revenue bureau (for water tax), and the financing bureau (for water infrastructure budget and water-related subsidies). Key elements of a planning and management structure are in place, but they are yet integrated.

Among these branches, the most active department for water resource management in TEDA is the Planning and Water Saving Office (PWSO) at the Construction Bureau, which operates with a staff of twelve and focuses specifically on reducing freshwater consumption among all types of users. Their mandate is to plan and manage water affairs in the zone and to develop and implement conservation strategies (Yan 2002, personal communication). The office's daily activities include training tenant companies on the management of water-saving and monitoring water use in the estate through a computerized system. However, their system does not have enough data on water quality and quantity, only basic information, such as company contact information and annual water use quantity, is reserved. They also regularly host workshops or other education activities to increase people's awareness of water conservation and to disseminate information on water-related activities in the park (Yan 2002, personal communication).

Moreover, on behalf of TEDA's administrative government, PWSO is also in charge of managing the Water Treatment Plant (WTP) and Wastewater Treatment Plant (WWTP), two state-owned plants. Figure 6-4 presents the administrative structure for water management at TEDA.

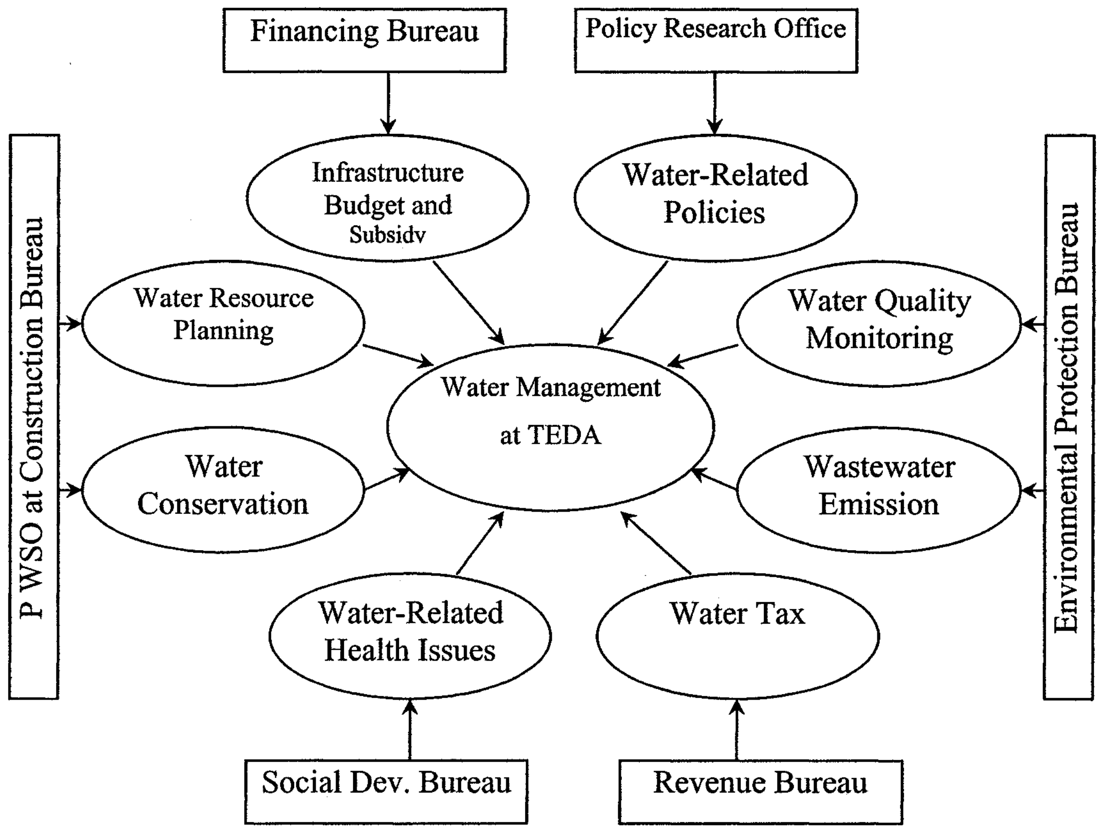


Figure 6-4 Administrative Structure for Water Management at TEDA

Given the increasing concern over the scarcity of water resources in TEDA, there has been some coordination among the various departments related to water issues. To date, there have been two strategy meetings between the heads of the Planning and Water Saving Office, TEDA Administrative Commission, Financing Bureau, Water and Wastewater Treatment Plants and the Environmental Protection Bureau to discuss conservation strategies (Yan 2002, personal communication). However, this type of inter-departmental cooperation is not the norm, and therefore regular meetings for the group have not been planned. None of these agencies are subordinate to one another, nor can any of them play a leading role on water conservation and reuse. In many cases, the water-related jurisdiction of these agencies is not clear. In addition, the water treatment plant is authorized by PWSO to take the lead responsibility on guiding water conservation and stipulating relevant policies (Yan 2002, personal communication). However, the water treatment plant's income depends on selling more water. Thus, there is some concern about the effective and efficient planning and management of water resources in TEDA. As a result, people are considering the possibility of setting up a new administrative institution which has integrated supervision authority over water-related issues at the zone level.

6.5.6 Water Conservation and Reuse

It is useful to highlight some of the initiatives undertaken by TEDA to encourage water conservation among users in the estate. Primarily implemented through the Planning and Water Saving Office, these strategies include encouraging the use of water-saving technology, cleaner production, awareness and education outreach activities, and incentives such as awards and certificates.

TEDA has undertaken several outreach activities related to water conservation. These include placing advertisements and articles in the local newspaper. There has also been a strong campaign to raise awareness through signage such as information billboards, posters in the workplace, and the widespread use of stickers. In TEDA, there are two annual water conservation events. One is a designated week to deal with water conservation under the National Construction Week and the other is the National Saving Resource Week (Yan 2002, personal communication)

Companies that have successfully saved water in their operations are also eligible to receive certificates and awards recognizing their efforts. These awards are not monetary, and recipients are announced in the *Binhai Timely,* a local newspaper. Their case studies serve as examples for other companies (Yan 2002, personal communication). TEDA has also changed their landscaping practices to incorporate heartier, less water-dependent and acidic plants such as rose bushes, phoenix trees, acacias, and reintroduced indigenous flora such as local grasses (Fan 2002, personal communication).

Treated wastewater in TEDA is either released into the sea or is increasingly being reused within the estate as a viable option to freshwater. To regulate the quality of middle water (a Chinese term for reclaimed treated wastewater), the Tianjin Government has set local quality standards for users (Appendix 6). Since 1990, the Tianjin municipal government has increasingly been enacting legislative measures to encourage the use of middle water. One of their regulations is a requirement that all new large-scale business projects such as industrial development, hotels, restaurants, and department stores (covering 20,000 m^2) have middle water systems in operation. As a result of this legislation, several capacity-building initiatives such as academic-private sector linkages have been initiated. For example, the Faculty of Environmental Engineering of Tianjin University helped to create formulas for calculating the costs of water treatment, wastewater treatment, piping and pumping, which can be used for systematic water reuse planning (Tian et al., 2001). Yan (2002) states that the water-recycling ratio reached 34% in 2001. However, survey results indicate that most of the reuse happened internally, which means that the companies re-use such treated wastewater through internal process control, changes or improvement.

From the above findings and results, it can be seen that TEDA is facing a severe water crisis. Water issues are becoming barriers for TEDA's further development. In order to overcome this situation, TEDA has adopted some useful measures, including policy reform, capacity building activities, and economic instruments (e.g. water fees and quotas). But the current institutional framework for water management is still fragmented and inefficient, current management approaches are not well integrated, and quantitative planning and management tools have not been applied. In order to overcome these barriers, park management should take actions to address the four key components introduced in the conceptual framework in Chapter 4 (integrated policies, capacity building, information management, and economic instruments). The following sections will provide greater detail on how the quantitative modeling approach can improve their overall water efficiency. The contribution of economic instruments, using the example of water pricing, will be addressed in Chapter 7.

6.6 SURVEY RESULTS AT INDIVIDUAL COMPANY LEVEL

6.6.1 Company Selection

Generally speaking, the key criteria for selecting participating companies revolved around the quantity and quality of their water demand and wastewater discharge. Specifically, the criteria were:

- The selected organization must be a main water user and wastewater producer.
- The selected organization has the incentives to improve their water management and would like to join this study.
- Documentation and relevant data for this organization must exist and be accessible.
- Individuals in the selected organization must be accessible and open to discuss through interviews and informal discussions.

On the basis of these criteria, TEDA EPB provided a list of the company names, contact information and information of the water consumption and wastewater discharge of these companies to the principal researcher. A workshop was hosted in September 2002 with the help of TEDA EPB. The top twelve water users at TEDA were invited and the objectives and significance of this research were introduced. Of these, six companies finally decided to participate in the study. These are a power plant, a landscaping company, a chemical company, a textile company, a pharmaceutical company, and a electrical products company. In terms of water use quantity in TEDA, they rank No.1, No.2, No.3, No.4, No.6 and No.7 respectively. Besides these six companies, due to their important roles on water supply and wastewater treatment, the local water treatment plant (WTP) and wastewater treatment plant (WWTP) were also invited to participate. Therefore, in total, eight entities were identified as research participants. However, these represent a small percentage of the companies in TEDA as there are over 3,000 tenants in TEDA. Most of these are small water users and in many cases it is impossible to get accurate water related data from all the companies. Consequently, all other water users are regarded as one user and are not separated. Because four of these companies did not want their names released, all the companies were assigned codes. These companies were given the option of declining to participate at any time in the study. Within each company, the senior manager in charge of water management was identified as the primary contact. A seminar was then hosted in order to let those managers further understand the relevance of this research and what information and assistance they would be asked to provide.

6.6.2 Survey Results

A detailed survey was carried out among those participating companies in order to collect necessary information and data on their water use and wastewater discharge. Questionnaires were administered during formal workshops and interviews, so the interviewer could probe respondents for greater clarity in answers and consistency in question objectives (Fowler 1993). Appendix 7 is the basic questionnaire used for this survey, designed to gather basic information on water input and output data (quantity and quality), water losses and other water-related issues. In this questionnaire, two water parameters are considered, including SS and COD. More parameters can be added for model optimization, but may make the solution more complex. SS and COD are widely used by water reuse planners (Ocanas and Mays 1981; Keckler and Allen 1999; Xie et al., 2002) and can be used as water parameters for non-potable water reuse. (Note: Some researchers use SS and BOD as water parameters. Since COD value has fixed ratio to BOD value, such substitution is feasible (Xiao 2002)).

Questionnaire surveys were forwarded to eight companies in order to get information on the quantity and quality of their water use, the distances between different water users, as well as related water management issues. However, the response to the questionnaire was limited, with five of the questionnaires returned. Especially, data on water quality (both use and discharge) from these companies are extremely poor because most of them do not collect such data. Some data were finally obtained on the basis of their water engineers' experiences and knowledge. In other cases, confidentiality concerns limited the availability of data. It was necessary to follow up with personal visits. Consequently, greater emphasis was placed on the interview process to elicit general background, as well as project-specific data. With the support of officials at EPB, much useful information was obtained through interviews, although some companies still refused to answer questions. Except for the landscaping company, all other companies in this study installed internal wastewater treatment facilities and have wastewater monitoring programs. This internal infrastructure facilitates water reuse since such programs can ensure the continuous supply of treated wastewater with relatively stable quality, which is very important for the application of the model.

Table 6-1 shows water quantity and quality data for selected companies through surveys. All the data in this table are daily average ones.

Table 6-1 Water Quantity and Quality Data

Company	Water Demand (10^3m^3/day)	Effluent (10^3m^3/day)	Input Quality (mg/l)		Output Quality (mg/l)	
			COD	SS	COD	SS
1**	6.21	0	300	200	N/a[1]	N/a
2*	6.38	1.12	50	30	70	200
3*	3.22	2.33	0	5	400	52
4**	2.65	0.55	0	5	120	73
5*	1.16	0.70	40	50	130	131
6**	1.10	0.70	20	10	150	200
Others[2]	11.21	6.45	0	0	n/a[3]	n/a
WTP*	36.84	31.93	n/a	n/a	0	1
WWTP*	11.85	10.07	400	200	40	11

Note: 1.N/a means not applicable;
2.Others mean all other users in TEDA;
3.n/a means not available;
* based on actual measured data;
** based on estimated data.

Table 6-2 lists the distances among selected tenants and these data have been collected because they influence the costs of piping and pumping, as well as construction costs for building the new connections. The distances reflect the actual lengths of pipe between companies. All the distances among tenants are provided by the TEDA Environmental Protection Bureau. They pointed out that most were estimated from their planning maps, which makes the results less exact than the real situation.

One note should be addressed is that the landscaping company at TEDA has a storage pond. Staff members in this company transport the water from this pond to irrigation sites by trucks. When applying the model, all the reusable water should be first delivered to this pond for storage. Also, distances between this company and others are based on the distances between this pond and other companies.

Table 6-2 Distances among Companies

Distances (km)	1	2	3	4	5	6	7	8
1	0	4.1	3.9	2.7	1.9	0.8	5.8	4.7
2	4.1	0	0.4	1.4	1.2	2.5	2.2	2.9
3	3.9	0.4	0	1.7	0.3	2.0	3.2	4.1
4	2.7	1.4	1.7	0	2.2	1.1	3.5	4.7
5	1.9	1.2	0.3	2.2	0	2.7	4.2	1.9
6	0.8	2.5	2.0	1.1	2.7	0	5.5	4.6
7	5.8	2.2	3.2	3.5	4.2	5.5	0	N/a
8	4.7	2.9	4.1	4.7	1.9	4.6	N/a[1]	0

Note: 1. N/a means not applicable.

Table 6-3 lists the cost functions for this study, which were taken from a recent study done by Tian's group at Tianjin University (Tian et al., 2001). According to cost formulas provided by them, piping costs were integrated with pumping costs together because Tianjin is located on the North China plain and the land in TEDA is very flat. The construction costs formulae are based on non-corrodable PVC pipes. Daily operation and maintenance costs for the water treatment plant and wastewater treatment plant include those related to energy costs, salaries, amortized depreciation expenses, materials expenses (disinfectants and other chemicals, etc), overhead, and other miscellaneous expenses (Tian et al., 2001). As discussed in Chapter 5, these functions incorporate a standard set of costs.

Table 6-3 Cost Functions

Description	Cost Function for Application[a] (RMB)
1. Water treatment plant Operation and maintenance	$4211Q^{0.83}$ [b]
2. Wastewater treatment plant Operation and maintenance	$10281Q^{0.86}$
3. Piping and pumping a. Operation and maintenance b. Construction	 458*distance(km)$Q^{0.78}$ $1.2513*10^6$*distance(km)$Q^{0.76}$

Note: a. In this case, daily amortized construction cost for new pipes and pumps will be amortized by 15 years (365 days per year), with an annual interest rate of 5%.
b. The unit for Q is 10^3m^3

There is currently little water reuse in TEDA. Tenant companies discharge their wastewater to the wastewater treatment plant for further treatment. Then, the treated wastewater from the wastewater treatment plant is discharged into the Bohai Sea, rather than being used as a new water source. Figure 6-5 shows the current water flow in TEDA.

Another survey finding is that the maximum treatment capacity of the water treatment plant is 50,000 m^3/day and the water loss rate is 13.33%, while the maximum treatment capacity of the wastewater treatment plant is 20,000 m^3/day and the water loss rate is 15%. The loss rate is an important factor in determining actual water inputs.

On the basis of these data, the next step is to seek potential water reuse opportunities among these participating companies based upon water quality. A matrix is employed in order to find potential water reuse opportunities, which can be found in Figure 6-6. In this matrix, number 1 means that the quality of the effluent from user *j* can meet the quality demand of user *i*, and 0 means that user *i* cannot use the effluent from user *j* directly.

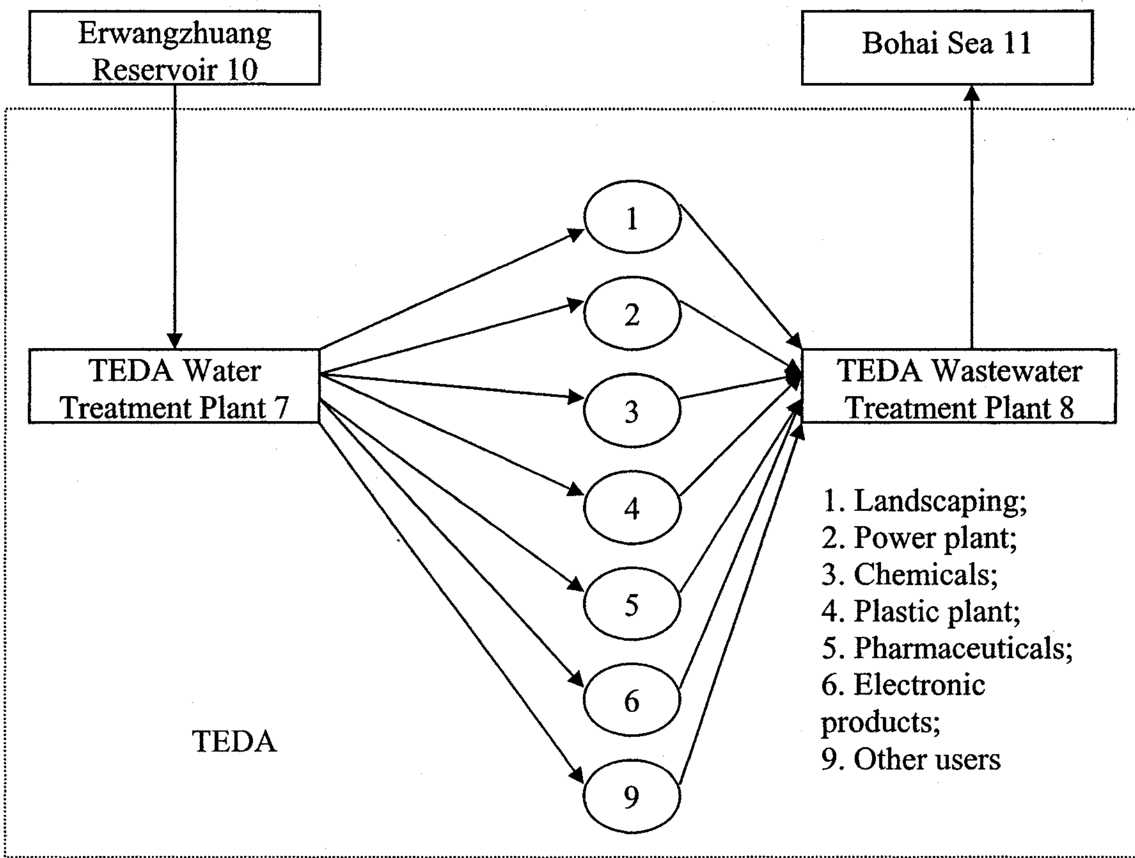


Figure 6-5 Current Water flow diagram of TEDA industrial park

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	1	1	1	1	1	1	1
2	0	0	0	1	0	0	1	1
3	0	0	0	0	0	0	1	0
4	0	0	0	0	0	0	1	0
5	0	1	0	1	0	1	1	1
6	0	0	0	0	0	0	1	1
7	0	0	0	0	0	0	0	0

Figure 6-6 Water reuse opportunities matrix among tenants

6.7 MODEL OPTIMIZATION

With these data, the next step is to run the quantitative model presented in Chapter 5 in order to seek the optimal water allocation scenario. Therefore, the objective function and constraints should be set up on the basis of the actual TEDA situation.

6.7.1 Objective Function

As previously stated, the objective in this case is to determine the minimum daily water system cost in TEDA considering water reuse. The costs include daily water and wastewater treatment costs and daily transporting costs consisting of piping and pumping costs, as well as those daily amortized construction costs for new pipes and pumps. Therefore, the objective function is the minimization of the sum of daily piping and pumping costs, daily water and wastewater treatment costs, and daily amortized construction costs for new pipes and pumps, namely, to minimize:

$$\sum_{w\in W}\alpha_w Q_w^{\beta_w}+\sum_{p\in P}\alpha_p Q_p^{\beta_p}+\alpha_t(\sum_i XF_i)^{\beta_t}+\alpha_t(\sum_i XTT_i)^{\beta_t} \quad (1)$$

Here W is the set of possible pipes connecting sources, users, treatment plants, and disposal sites (sinks), the first part of the equation represents the whole daily piping and pumping costs. P is the subset of new pipes and pumps considering water reuse, and the second part of this equation represents the amortized daily construction costs of new pipes and pumps. The third represents the daily water treatment plant costs, and the forth represents the daily wastewater treatment plant costs. All these symbols have been explained in Chapter 5.

6.7.2 Constraints

In this case, based on the water reuse matrix (figure 6-5), there are 29 variables, which include

$Q_{7\text{-}1}$ water flow from water treatment plant to company 1;

$Q_{7\text{-}2}$ water flow from water treatment plant to company 2;

$Q_{7\text{-}3}$ water flow from water treatment plant to company 3;

$Q_{7\text{-}4}$ water flow from water treatment plant to company 4;

$Q_{7\text{-}5}$ water flow from water treatment plant to company 5;

$Q_{7\text{-}6}$ water flow from water treatment plant to company 6;

$Q_{7\text{-}9}$ water flow from water treatment plant to other users;

$Q_{1\text{-}8}$ water flow from company 1 to wastewater treatment plant;

$Q_{2\text{-}8}$ water flow from company 1 to wastewater treatment plant;

$Q_{3\text{-}8}$ water flow from company 1 to wastewater treatment plant;

$Q_{4\text{-}8}$ water flow from company 1 to wastewater treatment plant;

$Q_{5\text{-}8}$ water flow from company 1 to wastewater treatment plant;

$Q_{6\text{-}8}$ water flow from company 1 to wastewater treatment plant;

$Q_{9\text{-}8}$ water flow from other users to wastewater treatment plant;

$Q_{2\text{-}1}$ water flow from company 2 to company 1;

$Q_{3\text{-}1}$ water flow from company 3 to company 1;

$Q_{4\text{-}1}$ water flow from company 4 to company 1;

$Q_{5\text{-}1}$ water flow from company 5 to company 1;

$Q_{6\text{-}1}$ water flow from company 6 to company 1;

$Q_{8\text{-}1}$ water flow from wastewater treatment plant to company 1;

$Q_{4\text{-}2}$ water flow from company 4 to company 2;

$Q_{8\text{-}2}$ water flow from wastewater treatment plant to company 2;

$Q_{2\text{-}5}$ water flow from company 2 to company 5;

$Q_{4\text{-}5}$ water flow from company 4 to company 5;

$Q_{6\text{-}5}$ water flow from company 6 to company 5;

$Q_{8\text{-}5}$ water flow from wastewater treatment plant to company 5;

$Q_{8\text{-}6}$ water flow from wastewater treatment plant to company 6;

$Q_{10\text{-}7}$ water flow from reservoir to water treatment plant;

$Q_{8\text{-}11}$ water flow from wastewater treatment plant to Bohai Sea;

$Q_{i\text{-}j}$ represents water flow from node i can be reused by node j. Its unit is $10^3 m^3$/day.

Constraints in this case include water demand for each user, water balance for each node and the requirements for water blending, capacity constraints, quality constraints, and environmental regulation constraints, as well as non-negative constraints.

(1) Water demand for each user

$$Q_{2\text{-}1} + Q_{3\text{-}1} + Q_{4\text{-}1} + Q_{5\text{-}1} + Q_{6\text{-}1} + Q_{7\text{-}1} + Q_{8\text{-}1} = 6.21 \quad (1)$$

$$Q_{7\text{-}2} + Q_{4\text{-}2} + Q_{8\text{-}2} = 6.38 \quad (2)$$

$$Q_{7\text{-}3} = 3.22 \quad (3)$$

$$Q_{7\text{-}4} = 2.65 \quad (4)$$

$$Q_{2\text{-}5} + Q_{4\text{-}5} + Q_{6\text{-}5} + Q_{7\text{-}5} + Q_{8\text{-}5} = 1.16 \quad (5)$$

$$Q_{7\text{-}6} + Q_{8\text{-}6} = 1.10 \quad (6)$$

$$Q_{7\text{-}9} = 11.21 \quad (7)$$

(2) Water balance

$$Q_{7\text{-}1} + Q_{7\text{-}2} + Q_{7\text{-}3} + Q_{7\text{-}4} + Q_{7\text{-}5} + Q_{7\text{-}6} + Q_{7\text{-}9} = 31.93 \quad (8)$$

$$Q_{1\text{-}8} + Q_{2\text{-}8} + Q_{3\text{-}8} + Q_{4\text{-}8} + Q_{5\text{-}8} + Q_{6\text{-}8} + Q_{9\text{-}8} = 11.21 \quad (9)$$

$$Q_{10\text{-}7} = \Sigma Q_{7\text{-}i} / 0.867 \quad (i = 1, 2, 3, 4, 5, 6, 9) \quad (10)$$

$$\Sigma Q_{8\text{-}j} + Q_{8\text{-}11} = \Sigma Q_{j\text{-}8} * 0.85 \quad (j = 1, 2, 3, 4, 5, 6, 9) \quad (11)$$

(3) Requirements for water blending

In this case, effluent from node 3 can be sent to node 1 by blending with fresh water. The ratio r_1 = (400−300) / (300−0) = 0.33, and thus the resulting constraint is

$$0.33\, Q_{3\text{-}1} <= Q_{7\text{-}1} \quad (12)$$

Effluent from node 4 can be sent to node 2 by blending with fresh water. The ratio r_2 = (73−30) / (30−0) = 1.44

and thus the resulting constraint is $1.4\, Q_{4\text{-}2} <= Q_{7\text{-}2}$ (13)

Effluent from node 8 can be sent to node 6 by blending with fresh water. The ratio r_3 = (40−20) / (20−0) = 1

and thus the resulting constraint is $Q_{8\text{-}6} <= Q_{7\text{-}6}$ (14)

Effluent from node 2 can be sent to node 5 by blending with fresh water. The ratio r_4 = (200−50) / (50−1) = 3.06

and thus the resulting constraint is $3.06\, Q_{2\text{-}5} <= Q_{7\text{-}5}$ (15)

Effluent from node 4 can be sent to node 5 by blending with fresh water. The ratio r_5 = (120−40) / (40−0) = 2 and thus the resulting constraint is $2\,Q_{4\text{-}5} <= Q_{7\text{-}5}$ (16)

(4) Capacity constraints

These linear constraints limit the water entering a treatment plant according to its capacity.

For water treatment plant, this constraint should be expressed as following:

$$Q_{10\text{-}7} <= 50 \quad (17)$$

For wastewater treatment plant, this constraint should be expressed as:

$$Q_{1\text{-}8} + Q_{2\text{-}8} + Q_{3\text{-}8} + Q_{4\text{-}8} + Q_{5\text{-}8} + Q_{6\text{-}8} + Q_{9\text{-}8} <= 20 \quad (18)$$

(5) Nonnegative Constraints:

This set of constraints requires that all the inputs and variables should be at least nonnegative.

$$Q_{i\text{-}j} >= 0 \quad (19)$$

(6) Environmental regulation constraints

This set of constraints forces the quality of freshwater to satisfy local potable water quality requirements, and the quality of reclaimed water from wastewater treatment plant to satisfy local discharge standard. By checking relative standards (appendix 5, 6), all the environmental regulations have been complied with.

6.7.3 Results

The model has a non-linear objective function and linear constraints. This non-linear program was solved by using CHJM, a Chinese solver specifically designed for modeling linear, non-linear and mixed integer optimization problems (Tang and Qin, 1994). This solver was used because it has relatively friendly interface and can handle global optimization issues, while other solvers were not easily available or too expensive. Figure 6-7 shows the optimal flows for this run (Scenario 1), and Table 6-4 lists the summary figures for this case, including savings on total costs and total freshwater, as well as total reduction of wastewater discharge.

Table 6-4 Summary figures for scenario 1 (minimal cost)

	Total costs RMB/day	Freshwater 10^3m^3/day	Wastewater 10^3m^3/day
Without reuse	$2.005*10^6$	36.84	10.07
With reuse	$1.797*10^6$	30.61	5.48
Saving Percentage	10.37%	16.9%	45.58%

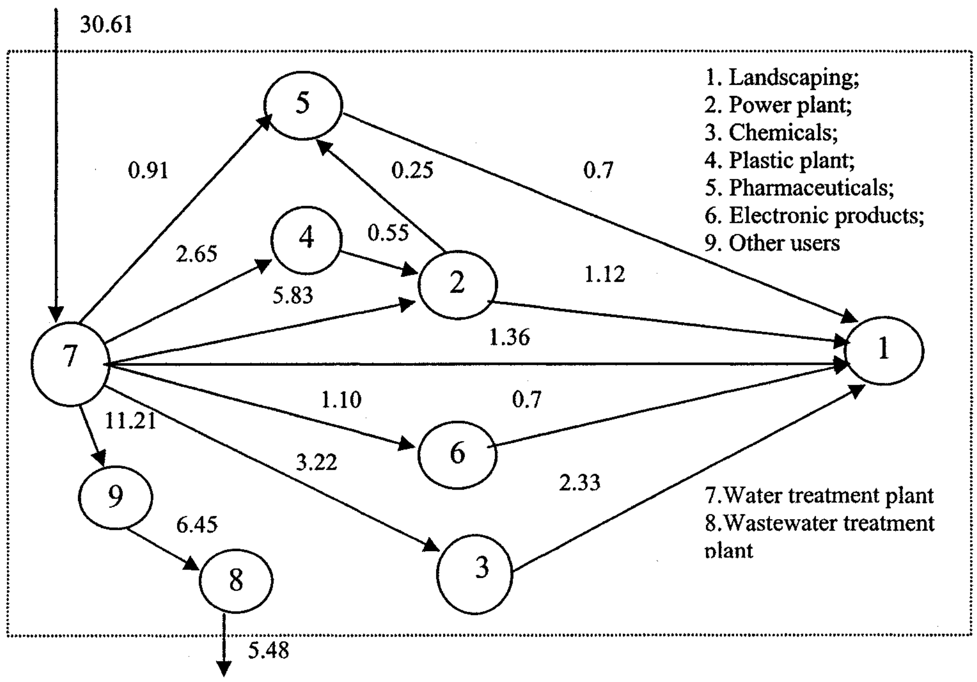


Figure 6-7 Optimal flow with minimal cost (Scenario 1)

The above results indicate that reclaimed wastewater will not be reused by any user, which means that TEDA still has potential to reduce total freshwater consumption. The largest potential scenario for reducing total freshwater consumption will be under the circumstance of "zero emission", which means that all the reclaimed wastewater from the wastewater treatment plant will be fully reused by the users. By changing $Q_{8\text{-}11}$ as zero in the constraint (11) and running the model again, the optimal results for a zero emission scenario are identified. Figure 6-8 shows the optimal flows for this run (Scenario 2), and Table 6-5 lists the summary figures for this scenario, including savings on total costs, total freshwater supply, and wastewater discharge reduction.

Table 6-5 Summary figures for zero emission scenario

	Total costs RMB/day	Freshwater 10^3m^3/day	Wastewater 10^3m^3/day
Without reuse	$2.005*10^6$	36.84	10.07
With reuse	$2.256*10^6$	24.29	0
Saving Percentage	-12.52%	34.1%	100%

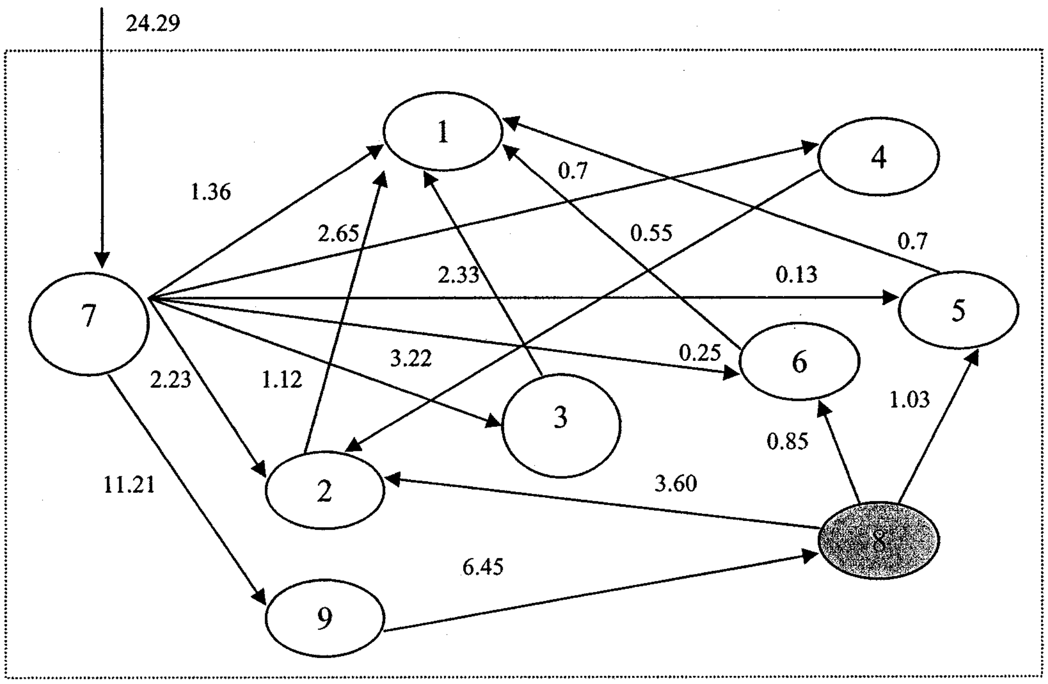


Figure 6-8 Optimal flow for zero emission

From the above results, it can be determined that total costs will be increased by 23.26%, but total freshwater use is decreased by 34.1%, while total discharge is zero. Consequently, this scenario is optimal as it realizes both the best freshwater conservation and zero emission benefits, when cost is not a factor.

Between the first scenario and the zero emission scenario, many different water distribution scenarios can be described. These can provide decision-makers with the complete economic and environmental surface so that they can understand the full set of alternatives and the trade-offs among them in terms of the desired objectives. In order to get these scenarios, the value of $Q_{8\text{-}11}$ ($5.48*10^3 m^3$/day) in the water balance constraint equation (equation 11) which relates to the reclaimed wastewater from wastewater plant to Bohai Sea in the scenario 1 is constantly decreased by 0.01, i.e 10 m^3/day, until this value becomes zero. This decease results in 546 possible scenarios. By rerunning the optimization solver, 546 new scenarios were created. Each scenario shows decision-makers the total water system cost, as well as total freshwater saving and wastewater discharge reduction. Appendix 9 shows all the optimal flow data for different scenarios. This way allows decision-makers to choose the relative weights for environmental and economic impacts by considering their own perspectives. They can choose the best scenario on the basis of their budget, their water conservation plan, and technological feasibility. Appendix 8 shows some selected scenarios when $Q_{8\text{-}11}$ was set up as 4.95, 4.45, 4.30, 4.20, 3.95, 3.70, 3.35, 2.95, 2.70, 2.35, 1.95, 1.45, 0.95, 0.85, 0.55 ($10^3 m^3$/day) respectively (scenario 2-8, 10-17). Table 6-6 shows total freshwater use and total wastewater discharge reduction for these scenarios.

On the basis of these runs, three figures are presented in order to show the trade-offs between the total cost, total freshwater reduction and total wastewater reduction. Figure 6-9 shows the changing trend between the percentage of the reduction of total freshwater use and the percentage of total cost savings. This figure indicates that with water reuse, the total cost is first reduced by 10.37% (scenario 1), while the total freshwater use is reduced by 16.91% and then the total cost will be linearly increased when total freshwater savings is increased. Figure 6-10 shows the changing trend between the percentage of the reduction of wastewater discharge and the percentage of total cost savings. This figure indicates that with water reuse, the total cost is first reduced by 10.37% (scenario 1), while the total wastewater could be reduced by 45.6%, and then the total cost will be linearly increased if the industrial park management want to reduce more wastewater discharge. This means that TEDA will have to pay a higher cost in order to realize more water savings or reduce total wastewater emission. Figure 6-11 shows the changing trend between the percentage of reduction of total freshwater use and the percentage of reduction of total wastewater discharge. This figure indicates that the total wastewater discharge will be linearly reduced when more freshwater is saved, which means that a natural resource conservation benefit (freshwater saving) can be gained together with an environmental benefit (wastewater discharge reduction). Therefore, these figures can help analyst explicitly identify the trade-off between the total cost, total freshwater reduction and total wastewater reduction.

Table 6-6 optimal flow data for different scenarios

Scenario	Total freshwater use (10^3m^3/day)	Percentage of freshwater use reduction	Percentage of total cost savings	Total wastewater discharge (10^3m^3/day)	Percentage of wastewater reduction	Total cost (10^6rmb/day)
0	36.84	0	0	10.07	0	2.005
1	30.61	16.91%	10.37%	5.48	45.58%	1.797
2	30.00	18.57%	7.33%	4.95	50.84%	1.858
3	29.42	20.14%	5.34%	4.45	55.81%	1.898
4	29.25	20.61%	4.49%	4.30	57.30%	1.915
5	29.13	20.93%	3.99%	4.20	58.29%	1.925
6	28.84	21.72%	2.79%	3.95	60.77%	1.949
7	28.56	22.48%	1.70%	3.70	63.26%	1.971
8	28.15	23.59%	0.20%	3.35	66.73%	2.001
9	28.11	23.70%	0	3.31	67.13%	2.005
10	27.69	24.83%	-1.45%	2.95	70.71%	2.034
11	27.40	25.62%	-2.39%	2.70	73.19%	2.053
12	27.00	26.71%	-3.74%	2.35	76.66%	2.080
13	26.54	27.96%	-5.24%	1.95	80.64%	2.110
14	25.96	29.53%	-7.03%	1.45	85.60%	2.146

15	25.38	31.11%	-8.73%	0.95	90.57%	2.180
16	25.27	31.41%	-9.08%	0.85	91.55%	2.187
17	24.92	32.36%	-10.52%	0.55	94.54%	2.216
18	24.29	34.07%	-12.52%	0	100%	2.256

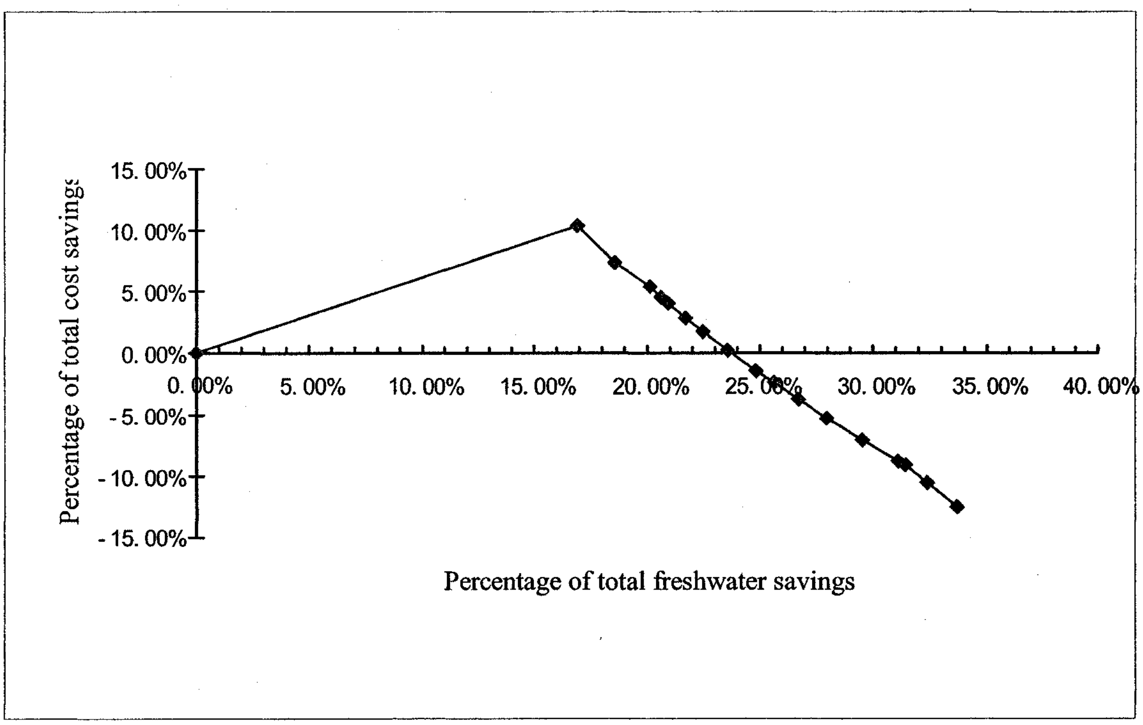


Figure 6-9 Percentage of total freshwater savings related to the percentage of total cost savings (The points in this figure represent the selected scenarios out of 546 scenarios.).

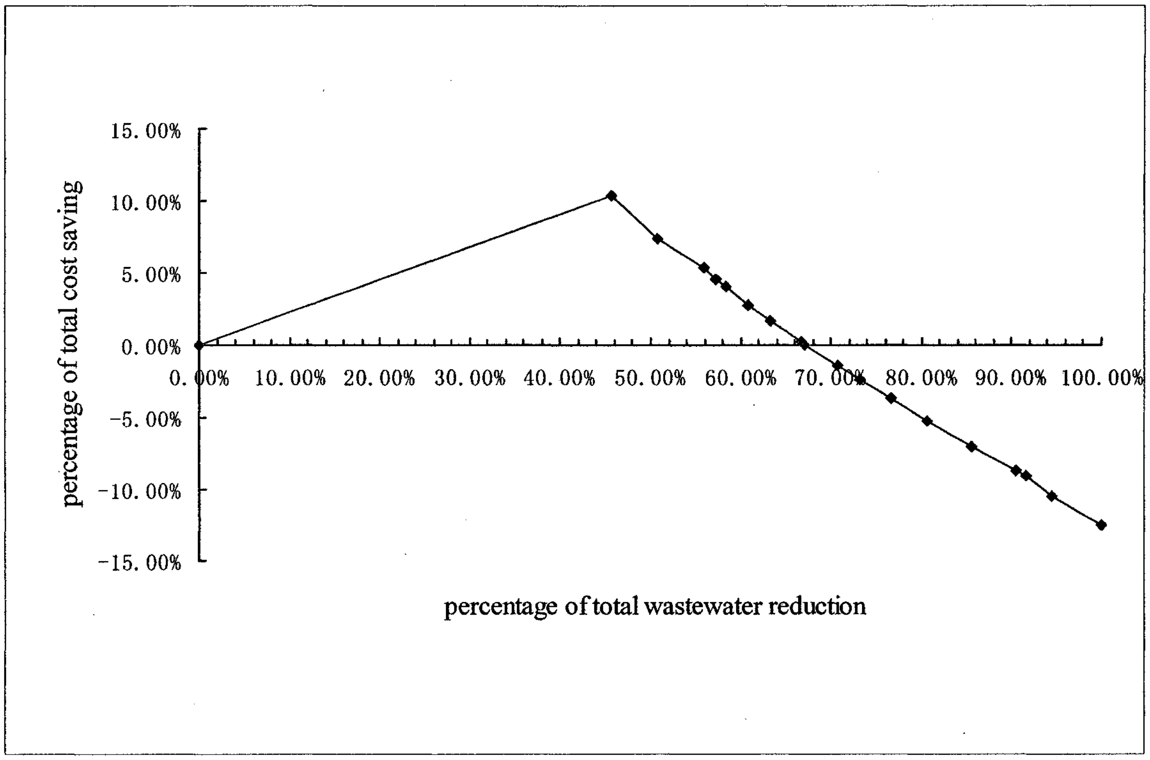


Figure 6-10 percentage of total wastewater reduction vs. percentage of total cost savings (The points in this figure represent the selected scenarios out of 546 scenarios.)

Scenario 9 is the one for keeping the total cost unchanged. This scenario shows that freshwater savings of 23.70% could be achieved and wastewater discharge could be reduced by 67.13% while the total cost is not changed. Figure 6-12 shows the new optimal flow for this scenario. From the ninth scenario the total cost is even higher than the original total cost (e.g. non-optimal scenario), which means that additional investment would be needed in order to conserve freshwater or reduce total wastewater emission.

Figure 6-13 shows the changing trend between freshwater unit cost and the percentage of total freshwater savings. From this figure, we can find that the freshwater unit cost is increased by increasing the percentage of freshwater savings, but the curve is somewhat concave. This fact reflects the principle of economies of scale, since the amount of total freshwater use is reduced with reuse. But generally the changing amount is very minor, which means that such changes should not become a barrier from an economic point of view.

The surplus reclaimed wastewater from the wastewater treatment plant should be further used for some non-potable purposes, like fire control, groundwater recharge, construction purposes, or irrigation in neighboring communities, rather than being discharged into the local Bohai Sea. Compared with other alternatives, groundwater recharge will be a better option because TEDA is located in the world's largest land subsidence area (TEDA 2002). Recharging groundwater by surplus reclaimed wastewater can certainly alleviate land subsidence and seawater intrusion problems and help restore the local ecosystem. In terms of groundwater recharge, many methods are available. Some are inexpensive, like surface spreading, but need more land and suitable hydro-geological conditions; others are more expensive, like direct injection, but require less land (US EPA, 1992). Planners and managers could invite local hydro-geological experts to carry out a study in order to choose an appropriate method. Due to its complexity, budget, time limits and many other reasons, this model doesn't include the cost for groundwater recharge. Similarly, this model doesn't include the costs for other uses, such as construction purposes.

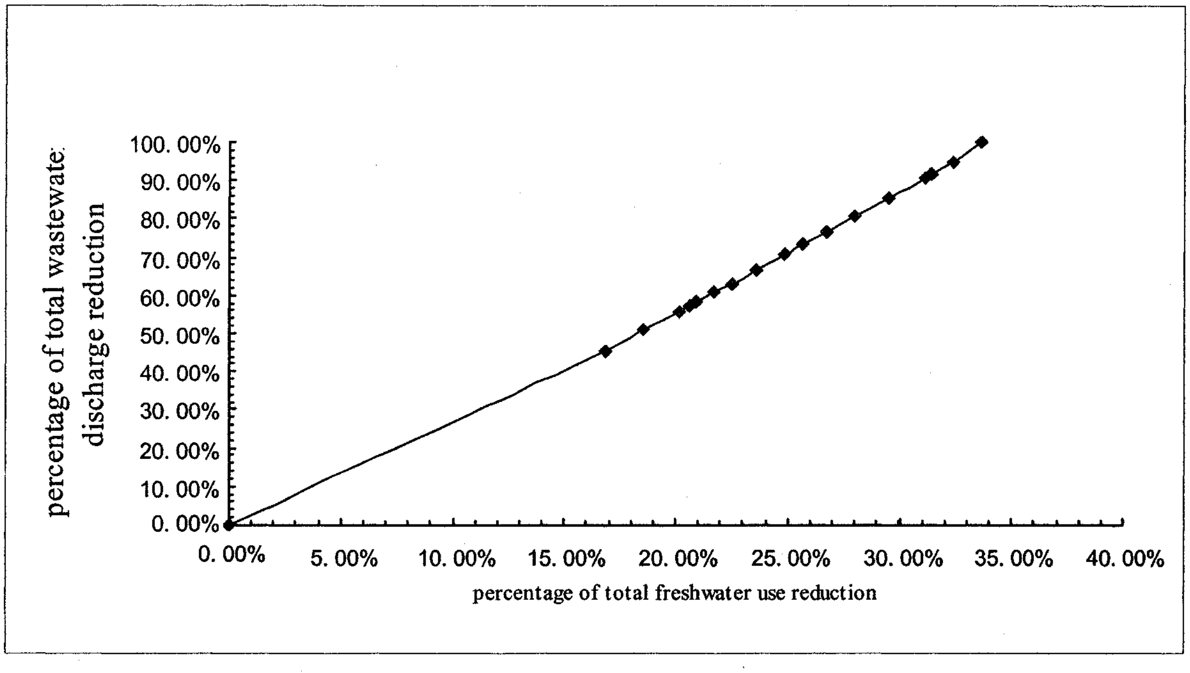


Figure 6-11 Percentage of total freshwater use reduction vs. percentage of total wastewater discharge reduction (The points in this figure represent the selected scenarios out of 546 scenarios.)

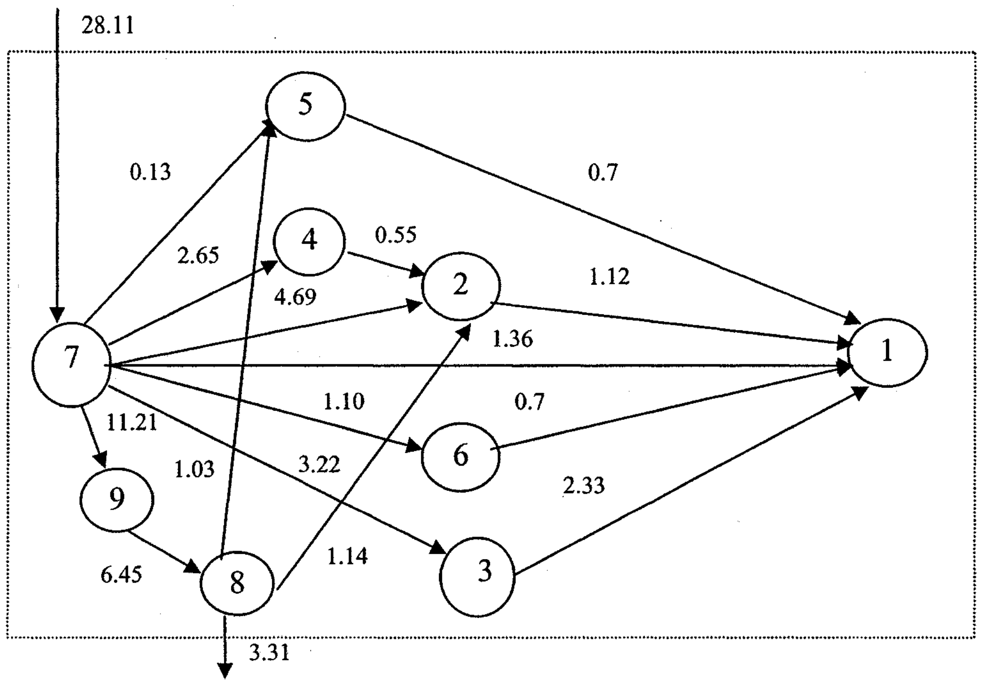


Figure 6-12 Optimal flow with no additional cost (Scenario 11)

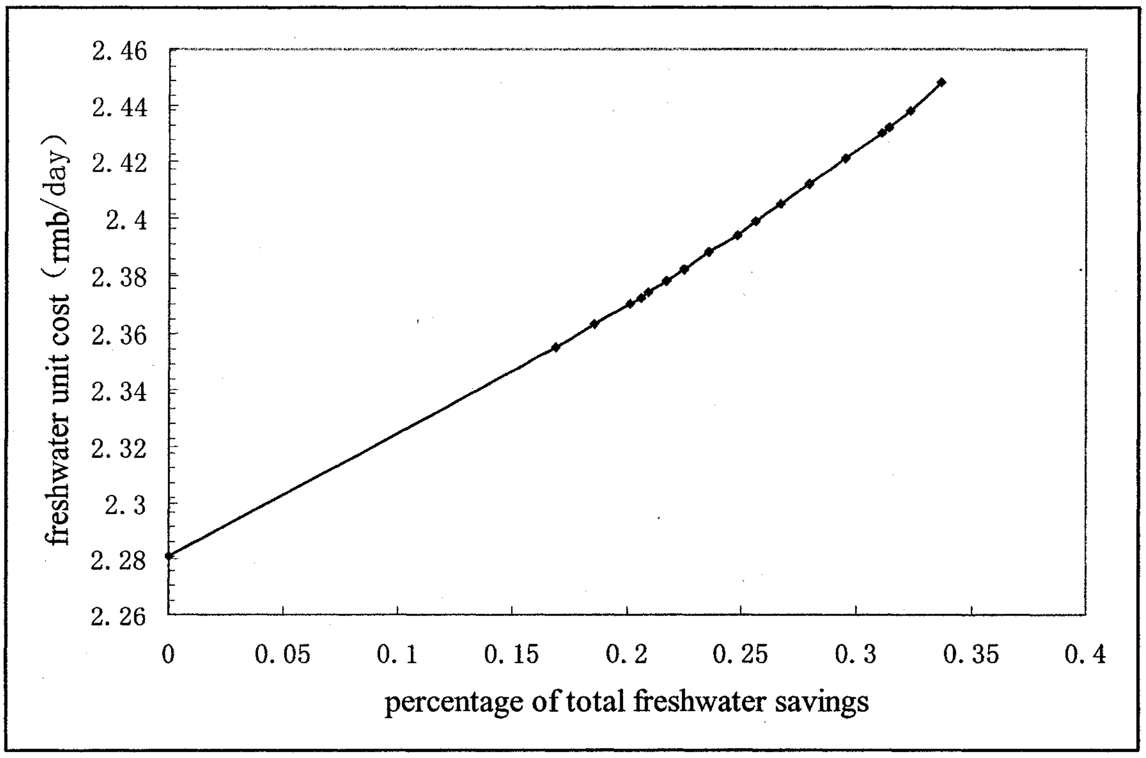


Figure 6-13 Freshwater unit cost and the percentage of total freshwater savings (The points in this figure represent the selected scenarios out of 546 scenarios.)

6.8 SUMMARY

This chapter described the application of integrated water resource planning and management model to a case study which involved some of the main water users, a water supply and treatment facility and a wastewater treatment facility in an industrial zone in China. It was designed to assess the application of the quantitative model in assisting managers to make the optimum use of available water resources.

The Tianjin Economic Development Area was selected as the study area. Therefore, the city of Tianjin and its water issues were first reviewed, then the development of TEDA, including its general information, government, industrial profiles, infrastructure, water challenges, were introduced.

The main focus of this chapter was to test the applicability of the quantitative water planning and management model. Application of the quantitative model at TEDA indicates its merit and usefulness in selecting the best planning alternative. Results from the field study revealed that both savings on freshwater and wastewater discharge can be gained at the same time, while keeping costs to a minimum. Such results allow decision makers to choose the best alternative from an array of different alternatives by considering their water and budget realities.

Chapter 7 will test the impacts of economic instruments to the model application results, discuss the quantitative model applicability, and summarize the benefits of model application, as well as contribution to knowledge.

CHAPTER 7 DISCUSSION

7.1 INTRODUCTION

Given its size, innovation, data availability, and the water crisis facing it, the TEDA case study provided an opportunity to test the quantitative model developed in Chapter 5. The results demonstrated feasible and optimal solution data and scenarios for water re-use among water users. The case study also raised many issues that are further considered in this chapter. First, a cost sensitivity analysis for testing the effects of economic instruments on the quantitative model is presented. Second, the model applicability is outlined. Finally, the benefits of applying this model and its contribution to knowledge are summarized.

7.2 COST SENSITIVITY ANALYSIS

As suggested in Chapter 4, specific economic instruments are available to enhance integrated water resource planning and management within an industrial park. These instruments can help ensure sustainable usage, minimize wastage, ensure efficient allocation, and provide incentives for the development of water-efficient technologies, reuse, and recycling. This contention is based on the principle that people respond rationally to financial incentives and disincentives. If the price is too low and below its real cost, it will be wasted or used inefficiently. But if the price reflects its real cost, there is an economic incentive for water to be allocated rationally and for the development and use of water-efficient technologies and reuse and recycling (Grimble 1999). However, due to time and research scope limits, it will be impossible to test every instrument in the case of TEDA. Consequently, pricing strategy has been chosen as an instance to see how economic instruments can help provide incentives for the development of water reuse and recycling at the inter-firm level.

Pricing strategy has been chosen as it is often a significant factor in the decision-making process in terms of implementing a water reuse project. There may be good technical or environmental reasons for water reuse, but if the costs are deemed to be too high or the financial benefits too low, the project might not be undertaken. Therefore, an economic analysis, such as cost sensitivity analysis, is needed. Such an analysis can justify how an appropriate pricing strategy provides water reuse incentives for water users within an industrial park.

Sensitivity analysis is the study of how the variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation and aims to ascertain how the model depends upon the information fed into it, upon its structure and upon the framing assumptions made to build it (Breierova and Choudhari 1996). In terms of IWRPM within an industrial park, cost sensitivity analysis is used to determine how "sensitive" a quantitative model is to cost changes that could be imposed by decision-makers.

In the case of TEDA, cost sensitivity analysis involved testing how significant changes of water resource price affected the model optimization results. The method involved varying specific cost factors while leaving all other cost factors unchanged, namely, increasing the coefficient α for the water treatment plant in Scenario 1 (figure 6-7) by 50%, 100%, 150%, and 200% respectively to reflect increased charges for freshwater resource supplies. In order to differentiate from those scenarios presented in Chapter 6, the original Scenario 1 (figure 6-7) is now listed as Scenario S-1, and the four new scenarios as Scenario S-2, S-3, S-4, and S-5 respectively. Table 7-1 shows the new optimal flow results. Figure 7-1 shows the original optimal flow for scenario 1 (here as S-1, the same as figure 6-7), figure 7-2 shows the optimal flow for scenario S-2, figure 7-3 shows the optimal flow for scenario S-3, figure 7-4 shows the optimal flow for scenario S-4, and figure 7-5 shows the optimal flow for scenario S-5.

Table 7-1 The new optimal flow results for changing coefficient a

Scenario	a increased by a percentage of	Value of a	Total freshwater reduction percentage	Total wastewater discharge reduction	Total cost reduction percentage
S-1	0	4211	16.9%	45.6%	8.85%
S-2	50%	6316.5	16.9%	45.6%	-26.72%
S-3	100%	8422	16.9%	45.6%	-59.09%
S-4	150%	10527.5	17.0%	45.9%	-91.90%
S-5	200%	12633	34.1%	100%	-144.17%

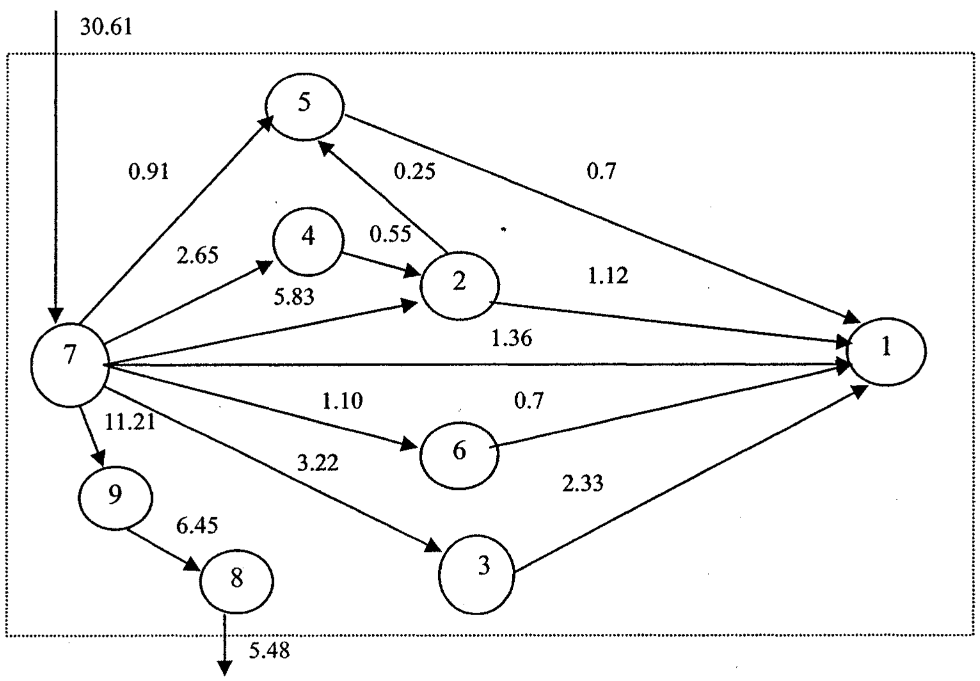


Figure 7-1 Optimal flow for Scenario S-1 (a =4211)

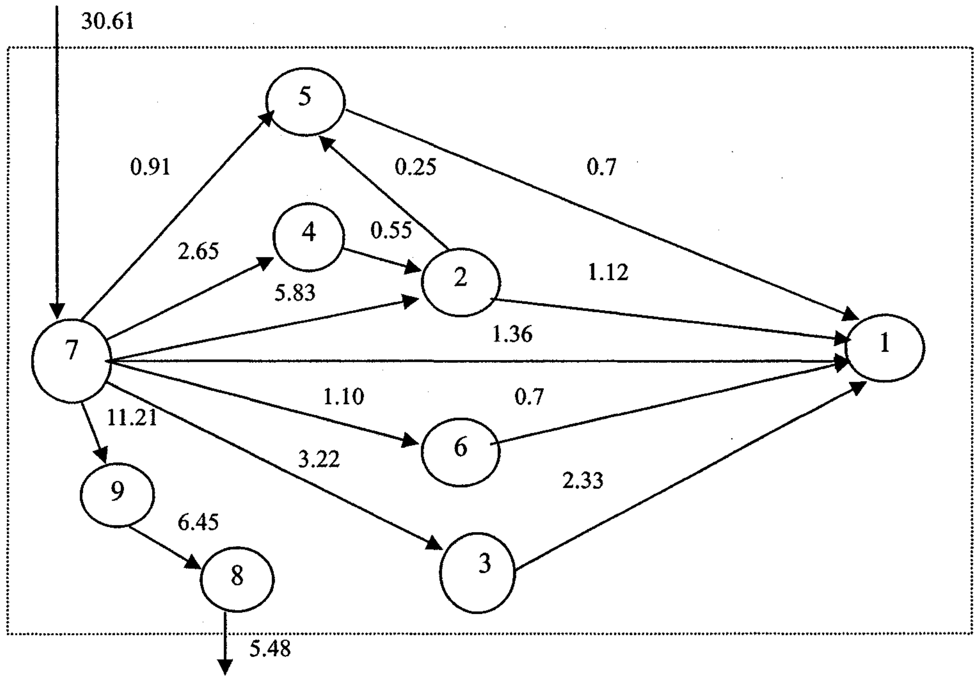


Figure 7-2 Optimal flow for Scenario S-2 (α =6316.5, increased by 50%)

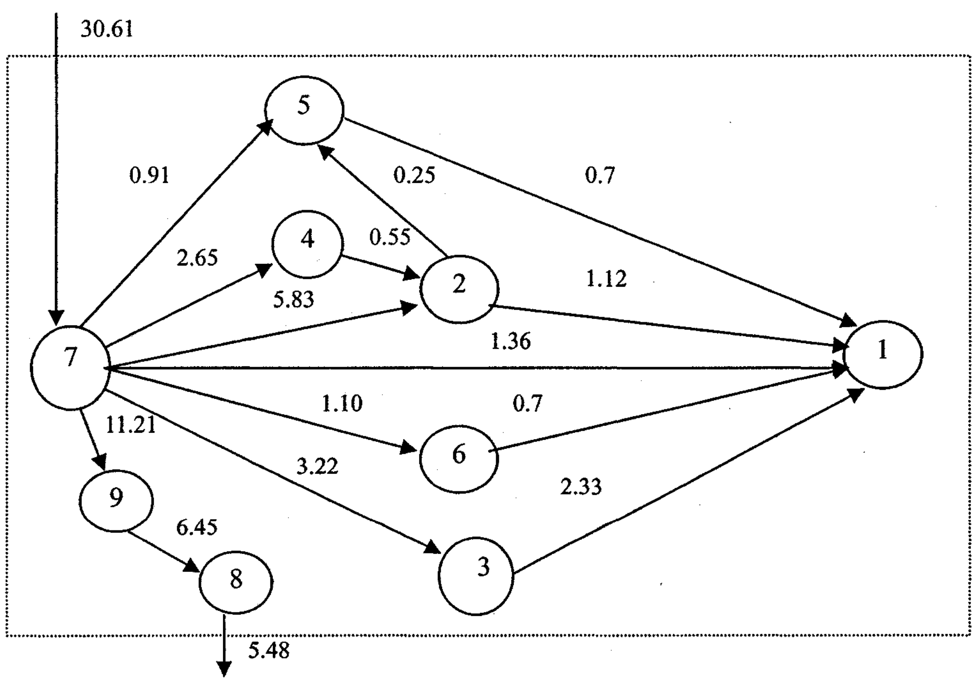


Figure 7-3 Optimal flow for Scenario S-3 (α =8422, increased by 100%)

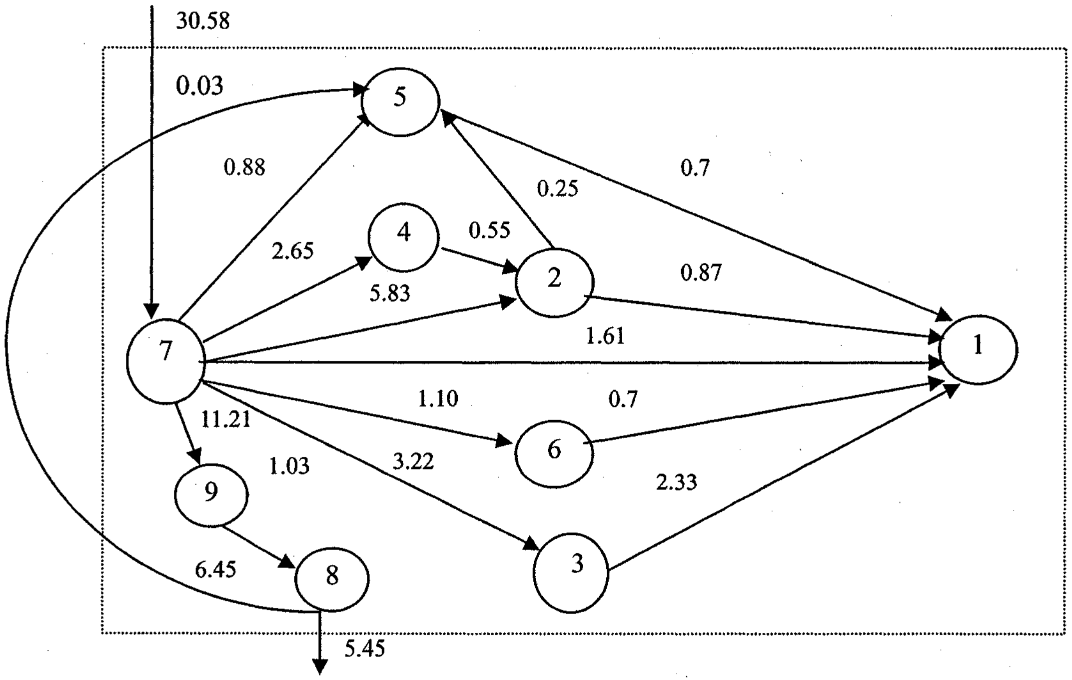


Figure 7-4 Optimal flow for scenario S-4 (α =10527.5, increased by 150%)

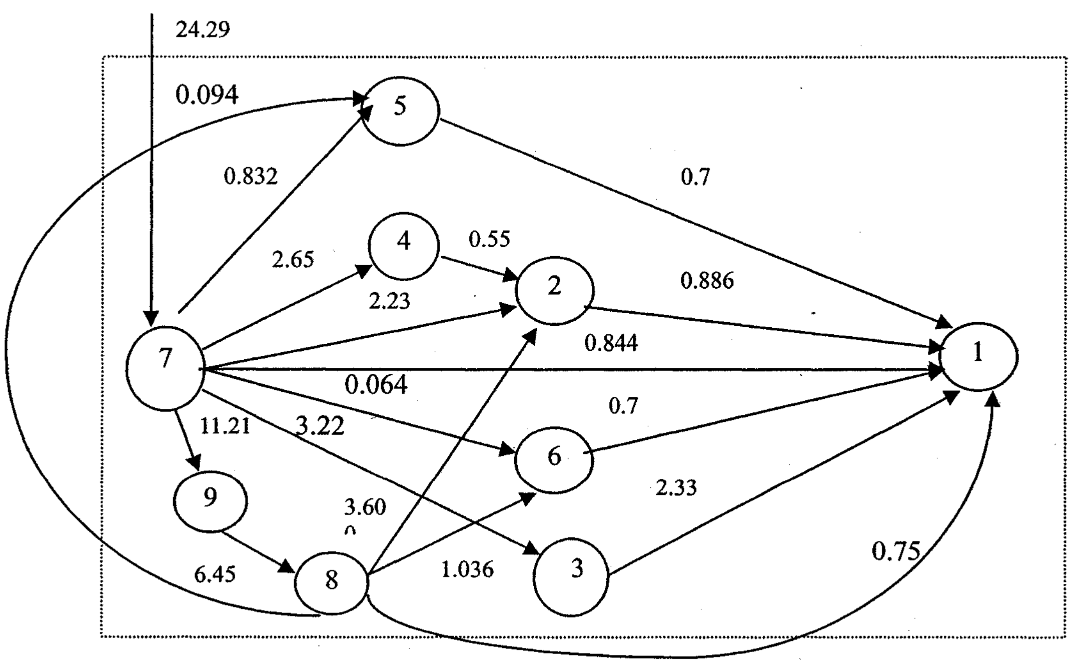


Figure 7-5 Optimal flow for scenario 6-5 (α =12633, increased by 200%)

From these figures, we can see that Scenario S-2 and S-3 are the same as scenario S-1. These data indicate that freshwater price does not affect the optimal flow when the value of coefficient α for the water treatment plant is much smaller than that of the wastewater treatment plant (scenario S-2 and scenario S-3), but it will begin to affect the optimal flow when the value of coefficient α for the water treatment plant is slightly closer to that of the wastewater treatment plant (scenario S-4). It will significantly affect the optimal flow when the value of coefficient α for the water treatment plant is significantly higher than that of the wastewater treatment plant (scenario S-5). In this case, a saving of 34.1% of total freshwater use can be achieved, and there is no wastewater discharge from the system (zero emission), but the total cost will be increased by 144.17%.

This cost sensitivity indicates that to be effective, water prices should be able to influence the behavior of those causing the environmental impact. It leads to a deeper understanding of why economic instruments can improve the overall effectiveness of IWRPM at the industrial park level. It also illustrates how sensitive the scenario results are to an increase in freshwater price. By implementing an effective pricing strategy, industrial park managers can complement the traditional "command and control" approach to water resource management and achieve an environmental objective, such as the reduction of total freshwater use and wastewater discharge. Increased water charges can be used to cover administrative costs, to finance environmental improvements (e.g. cleaner production), or to subsidize the operation of the wastewater treatment plant and the maintenance of freshwater infrastructure, therefore, providing water reuse incentives for water users within an industrial park..

7.3 MODEL APPLICABILITY

This quantitative model provides an integrated approach for maximizing water resource efficiencies within an industrial park. The model has been designed to allow flexibility in its application. Different park planners or managers should apply this model by considering their respective situations since water resources needs, conditions, and priorities differ from region to region and park to park. Some parks may only have one water source linked with the local water piping system, while other parks may have diversified sources. Also, industrial park planners and managers do not need to identify the quality and quantity requirements of all the water users in order to apply the optimization model. Some parks may have hundreds of water users, which may make the calculation process impossible. However, most users consume relatively little water and may not be in a position to utilize any reclaimed wastewater. According to Chi, often the top ten water users in an industrial park or zone consume over 75 % of all the water resources (Chi personal communication, 2002)[1]. Therefore, planners and managers may only need to consider those large water users and avoid incorporating other small water users into the model. In this regard, they will need to calculate the exact influent amount to the wastewater treatment plant and the exact effluent amount from the water treatment plant and regard all small users as one user.

The model assumes that system parameters are constant during the planning period. Thus the problem can be simplified since many uncertainties may make it very complicated. For instance, if the input value of SS is always changing, then the model cannot be run at all. In this case, the model user has to input an average value of SS as a constant. Also, when applying this model within an industrial park, industrial park managers should not ask those participating companies that can reuse reclaimed wastewater to uninstall their current water connections with the freshwater treatment plant. These users still require some potable water for sanitation purposes. Therefore, a dual piping system is needed. This measure helps avoid potential water supply crises, especially when the water quality from some users changes and doesn't meet with the input demand of receiving users.

The model is designed to handle a large number of common water/wastewater parameters, such as BOD, COD, TSS, TOC, TDS, and metals. This number can be increased if necessary. There may be upwards of 20 water constitutes that must be tracked and monitored to assure reliable operation (Byers 1995). Therefore, simplification is required if industrial park managers want to systematically implement the principles of integrated water resource planning and management. Developing categories of water streams and

[1] Chi is a senior engineer at National Water Conservation Office, Beijing.

water requirements can greatly simplify this task. To accomplish this may require some trial and error, but can provide significant benefits. In many cases, two or three common constituents, like COD, BOD and TSS, are enough to be tracked (Byers 1995; Keckler and Allen 1999; Nobel and Allen 2000). The initial survey can help get such information from the users. However, if a single parameter makes the water unusable for many or most applications (such as Hg or Cu), then the planners and managers would assume that wastewater from this user could not be reused by any other users.

This model considers capital cost, including those related to energy costs, salaries, amortized depreciation expenses, materials expenses (disinfectants and other chemicals, etc), overhead, and other miscellaneous expenses. Such a consideration can better reflect the real total costs related with water system. For example, once a new pipe needs to be built up between two water users for water reuse, the construction cost for such a connection should be included in the total costs. Especially, such a cost is usually much higher than the operation and maintenance costs, therefore, it should be included in the objective function. In this regard, the TEDA case study exactly reflects this fact. Table 6-6 shows us that the total costs will be increased when we are trying to reduce the total water use. This is because the new pipes and pipes must be built up for water reuses among different water users. Consequently, the decision makers have to consider this factor for making their decisions.

This model doesn't consider water reuse or recycling inside the users' facilities. In order to further optimize water resource utilization, all the users should first initiate their own water reuse or recycling program for processes. New technologies and management methods which were introduced in Section 2.3, can be very effective and efficient mechanisms to reduce total water consumption.

Basically, the model will have more flexibility by setting up the potential water users as variables rather than constants. If an additional company moves in, planners and managers can simply incorporate information by inputting the new information concerning water requirements, and then run the solver again in order to obtain a new water reuse scenario. Similarly, when a company leaves the park, the variables and constraints can be changed so as to identify a new water reuse scenario to reflect the changing circumstances.

Generally, this model can address broader environmental, social, and economic effects by including them in the objective function to be optimized. However, this may be very complicated because it's difficult to simultaneously optimize for multiple objective functions, at least some of which are not quantifiable. Here attention will, for the time being, focus on minimizing the whole water network cost since cost is always the planners and managers and users' most important concern. Even by doing so, some environmental, social, and economic effects can still be gained, including reduction of freshwater use and wastewater discharge, improved public image, reduced total costs, increased revenue, and competitive ability. Thus, multiple-objective optimization is gained

In order to improve model performance, this quantitative model should be applied with other tools, such as economic instruments, and supported by appropriate policies, and capacity building. By taking the pricing strategy as an example, the cost sensitivity analysis in section 6.2 has demonstrated the effectiveness of economic instruments. Appropriate policies can facilitate the implementation of the model and help overcome institutional barriers. For instance, in order to encourage water reuse at the inter-firm level, policies on solving potential conflicts among water users, such as how to share the infrastructure costs for new connections, and how to monitor the quality of reclaimed wastewater, should be established. Furthermore, capacity building activities can promote the adoption of new water saving technologies and improve the knowledge and awareness of stakeholders, which may help convince them to participate in such an innovative program.

7.4 BENEFITS

The above analysis and discussions indicate that the application of the integrated framework within an industrial park, such as the case of TEDA, could bring added values to both the industrial communities and to all stakeholders. By combining the principles of industrial ecology and integrated water resources planning and management, this new approach could provide comprehensive economic, environmental, and societal benefits. The following sections detail some of these benefits.

7.4.1 Economic Benefits

Like the introduction in Section 2.3, an industrial ecosystem can achieve cost savings through more efficient materials and energy use, potentially lower insurance costs, and lower waste treatment requirements (Côté et al 1994; Côté and Hall 1995; Lowe 1997). With regard to water planning and management, this means that conservation of financial resources relative to water system can be realized since this framework encourages water reuse both at individual and inter-firm level with a least cost. For instance, water resource costs, wastewater treatment costs, as well as environmental liability and insurance costs relative to water issues, could be reduced. Also, additional financial benefits of developing industrial ecosystem include increased revenues from the sale of wastes (Côté et al 1994); increased sales due to 'green' and niche marketing and more competitive production methods (Lowe 1997; Côté and Cohen-Rosenthal 1998); and the avoidance of regulatory penalties (Lowe 1997; Lowe, 2001). In terms of water issues, it means the overall competitive capacity of an industrial park can be increased. In addition, potential income through sale of reclaimed wastewater could be gained.

7.4.2 Environmental Benefits

Section 2.3 described that the ecological benefits of developing industrial ecosystems include conservation of natural resources and a reduction of the environmental impact of industrial operations, achieved through more efficient material and energy use, reduced waste discharge, substitution of toxic materials, and absorption of carbon dioxide "reducing carbon dioxide emissions" (Côté et al 1994; Côté and Hall 1995; Côté and Cohen-Rosenthal 1998). Section 2.5 introduced that integrated water resource planning and management systematically considers the various dimensions of water, including surface and groundwater, water quantity and quality, as well as all stakeholders' concerns, therefore, help conserve water resources, reduce wastewater emission, and improve the health of water systems. The integrated framework developed in this study combines the principles of these two innovative strategies and could gain various environmental benefits. For instance, the results of the case of TEDA indicates that water resources can be conserved and wastewater emission (namely pollution) can be reduced by encouraging water reuse, therefore, health for local aquatic ecosystems can be improved. Moreover, by incorporating groundwater recharge constraints, the quantitative model can help reduce groundwater depletion, prevent potential reverse decline of groundwater levels, and, protect underground freshwater in coastal aquifers against saltwater intrusion.

7.4.3 Societal Benefits

The case of TEDA indicates that some societal benefits of applying this framework could be achieved, such as improved public awareness by carrying out capacity building programs, and improved public health by reducing water consumption and wastewater emission. By restructuring management structure on water issues, this framework can encourage more collaboration among tenant companies and between tenants and industrial park management, as well as between industrial park and local communities, therefore, strengthening community relations.

7.5 CONTRIBUTION TO KNOWLEDGE

The main contribution of this work is the development of a conceptual framework for integrated water resources planning and management at the level of an industrial park. Implementation of this framework employed a systems analysis method to incorporate all the aspects related to water planning and management together, including policies, economic instruments, information systems, and capacity building. By doing so, decision makers can identify the potential water planning and management gaps and seek an integrated solution by considering all the stakeholders' concerns.

A key feature of this conceptual framework was the development of a quantitative optimization model for water re-use that could have universal application. Unlike previous relevant works which were designed for specific sites (Keckler and Allen 1999; Nobel and Allen 2000), the proposed model can be used within any industrial park and even has the potential to be applied within a larger system, such as a city. The model integrates the relevant capital costs (such as pipelines) and operation and maintenance expenses and also considers economy of scale by setting objective function as nonlinear, which could gain economic, environmental and societal benefits at the same time. This approach also sets the proposed model apart from previous models developed by Keckler and Allen.

The model considers the features of an industrial park, where tenant companies are concentrated in a given area. They share a common water source and wastewater treatment facility and many water users do not need potable water for their operation, therefore, reuse opportunities at inter-firm level exist. In contrast to other integrated water reuse models at watershed level (Rios et al., 1975; Pingry and Shaftel, 1979; Ocanas and Mays, 1981; Oron, 1996), this model allows for blending of water streams to obtain various degrees of purity. Such dilution of wastewater makes more economic and environmental sense because there is no need to treat such wastewater.

In terms of industrial ecology, this study indicates that system optimization could serve as a promising analytical method for industrial ecology by using the example of water and helps fill a need for quantitative tools to improve the application of industrial ecology concepts. When constructing, validating, and calibrating mathematical models at an inter-firm level, integrated economic, environmental and social benefits can be gained and the overall performance of an industrial ecosystem can be improved. Such a method makes more sense in those developing countries, where resource crises often are more severe and the budget generally is more limited.

Unlike the DIET and Bechtel models (Giannini-Spohn 1997; Hollander 2001), the model presented in this thesis is a non-linear programming optimization model and can reflect the economy of scale inherent in industrial ecosystems. When equipped with a user-friendly interface, the model has the potential to serve as a decision support system for industrial park managers. Due to its flexibility, the model could be an easily maintained, technical tool for eco-industrial development. Moreover, by using the case of water, this research expanded on the study presented by Casavant (2000), namely, progress integration or progress optimization can be applied at an inter-firm level to maximize the overall eco-efficiency, as well as the study of Nobel and Allen (2000).

In addition, this model presents a methodology for the development of the necessary information base on inputs, outputs, and by-product exchange opportunities. The same methodology for developing this integrated model can also be applied to analyze other materials, such as energy or oil products, which will further enrich the literature of industrial ecology and the practices of eco-industrial development.

7.6 SUMMARY

This chapter discussed issues related to the application of a conceptual framework for IWRPM and the implementation of a quantitative optimization model for water reuse. Results suggest that the effective application of such a framework depends on the implementation of a planning and management process that is multi-objective in scope and incorporates the preferences of multiple decision makers. By carrying out a cost sensitivity analysis, this chapter tested how economic instruments can influence the implementation of IWRPM in an industrial park. Results indicate that when being set at the correct level, increased water charges could help reduce freshwater use and wastewater discharge. The primary focus of this chapter was the description of the model applicability and successful implementation, as well as those multiple benefits gained from applying this model. In addition, the research contribution to knowledge was summarized.

Chapter 8 will present the conclusions for this study and raise recommendations for further study.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 RESEARCH CONCLUSIONS

Achieving sustainability requires that the traditional end-of-pipe approach on waste management must be replaced by more holistic and systemic approaches (Banks, 1994). Pollution prevention and cleaner production are one step toward that goal but focus on internal process optimization and waste reduction, which limits its application. As a new innovative strategy for sustainable industry, industrial ecology proposes that implementation of a resource management program should incorporate waste reduction, material reuse and recycling and disposal with minimal environmental impacts. It helps to describe the flows of material and energy and challenges people to think beyond mechanistic and fragmented views of environmental problems and solutions (Hoffman 2003). By applying industrial ecology approach, savings can be created through minimization of inputs, substitution of materials, maximization of use of materials, and reduction of energy and disposal costs (Karamanos 1995).

At the industrial park level, the concept of industrial ecology has been adopted and implemented, to a limited degree by focusing on a group of industries operate symbiotically (Chertow 2000). It encourages integrated resource management within the boundaries of an industrial park. It engages traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, and water. It also requires managers to co-treat their wastes and consider by-products as resources rather than wastes. Benefits of eco-industrial development include promotion of economic performance, improvement of environmental quality, and social stabilization. It may be more applicable in developing countries where environmental challenges are even more pressing, environmental legislation is minimal, and the earlier stage of industrialization offers opportunities for adopting state-of-the-art solutions ("leapfrogging") (Fleig, 2000).

Water provides crucial benefits such as irrigation for agriculture, industrial development, habitat for myriad plants and animals, aesthetics, recreational opportunities, and a symbol of vitality in addition to basic health and sanitation. However, a number of countries and regions in the world are facing water scarcity due to limited water sources, rising demand in all sectors, and lack of planning efforts. The development and implementation of a comprehensive integrated water planning and management strategy with water reuse is one way to avoid the further increase in water use since wastewater reclamation entails the provision of a continuous supply of water with almost consistent water quality (Asano and Mills 1991).

This thesis links industrial ecology with an integrated water resource planning and management framework within an industrial park. It is designed to assist industrial park managers and tenant companies to optimize all the available water resources (surface water, rain/snow water and groundwater), maximizing reuse and recycling both at individual company and multi-firm levels, and minimizing total discharge by landscaping, recharging groundwater, transporting surplus to local communities or emitting into local water bodies as the last order. The framework illustrates that the successful implementation of IWRPM at industrial park level depends on four key elements, namely, policies & regulations, economic instruments, a management information system, and capacity building.

The main contribution of this research is the development of a comprehensive modeling tool for the implementation of sustainable integrated water planning and management at the industrial park level, allowing for the identification of the optimal water management scenario based on water reuse according to local conditions. To test the framework, a case study on TEDA, China, was employed. Surveys revealed that many water reuse opportunities were lost and water management was still fragmented due to a lack of collaboration and synthesis among different agencies. By applying the quantitative model, evaluation of the facilities indicated that both freshwater use and wastewater discharge could be reduced if water reuse was practiced among tenant industries. In addition, a cost sensitivity analysis revealed that economic instruments, such as pricing strategy, could help further reduce freshwater use and wastewater discharge when they are correctly applied.

Generally, in the case of TEDA, it is possible to see that the concept has merit and that the application of such a model could help an industrial park tackle their water resource issues in an effective manner. Here are some research conclusions based upon the theoretical analysis and case study:

- An integrated techno-economic framework for water resources planning and management with an industrial park was developed. This framework contains four elements, namely, policies & regulations, economic instruments, information management systems, and capacity building. The key is that its information management system contains a quantitative model for identifying the potential water reuse scenario among those tenants. By applying this framework, multiple economic, environmental, and social benefits could be gained;
- The quantitative model was tested in TEDA, where it was found that about 16.9% of total freshwater consumption can be saved and wastewater discharge can be reduced by up to 45.6%, while the total system cost can be decreased by 10.37%;
- The percentage of total freshwater saved can be increased up to 23.70% with no additional cost;
- Zero emission will result in a 34.1% freshwater saving, but the total cost will be increased by 12.52%; and,
- When the coefficient for a water treatment plant is increased by 150%, additional freshwater savings can be realized. When increased by 200%, zero emissions can be achieved. Consequently, when the coefficient α for a water treatment plant is close to or higher than that for a wastewater treatment plant, further reductions in total freshwater use are possible, supporting the premise that the adoption of appropriate economic instruments (like increasing the freshwater charge) can contribute to reductions in total water use and wastewater discharge.

This research indicates that such an integrated water resources planning and management framework can bring economic, environmental, and societal benefits together. It indicates that a quantitative model can be incorporated into industrial ecology study and help fill the gap that industrial ecology lacks in quantitative study approaches. Also the methodology presented in this thesis is applicable to the analysis of flows of many types of other materials within an industrial ecosystem, such as energy use and/or other raw materials.

8.2 RECOMMENDATIONS

Based on the results, analysis and discussion relating to this thesis, the following recommendations are presented.

- The research demonstrated that industrial parks may have significant water reuse opportunities. It also suggested that the conceptual framework and the quantitative optimization model should be a useful tool for approaching a wide variety of material flow analysis, like oil products, greenhouse gas emission, and energy. To test other materials using the methodology developed in this study will enhance quantitative approaches to industrial ecology and enrich industrial ecology theories. It will assist industrial park managers and tenants in identifying more material reuse opportunities.
- More studies on how to apply economic instruments for improving water efficiency at the industrial park level in the real world are needed so that industrial park managers could better apply economic instruments to plan and manage their water resources. Topics may include how to price middle water and wastewater from users, how to share costs related with water reuse among tenants, and how to decide water quotas by considering local situations.

9.0 REFERENCES

Almato, M, E. Sanmarti, A. Espuna and L. Puigjaner, "Rationalizing the Water Use in the Batch Process Industry", *Chemical Engineering*, Vol. 21, Suppl., pp. S971-S976, 1997.

Andrews, C., 1999. "Putting Industrial Ecology into Place", *Journal of the American Planning Assotiation*, Vol.65, No.4, pp364-374.

Arms, K, 1994. *Environmental Science*, second version, pp.102, Saunders College Publishing, Orlanda, Florida.

Asano, T and R. Mills. 1990. "Planning and Analysis for Water Reuse Projects", *JOURNAL AWWA*, January, 1990, pp.38-47.

Asano, T and A. Levine, 1996. "Wastewater Reclamation, Recycling and Reuse: Past, Present and Future", *Water Science and Technology*, 33(10-11):pp1-14.

Ashford, N. A. 1997. "Industrial Ecology: the Neglected Issue in Industrial Ecology", *Journal of Cleaner Production*, Vol.5, No.1-2, pp.115-121.

Asian Development Bank (ADB). 1999. *Strategic Options for the Water Sector.* T.A. 2817-PRC. Final Report prepared by Hydrosult Inc. and China Institute of Water Resources and Hydropower Research for the Asian Development Bank (ADB).

Asian Development Bank (ADB). 2001. *Poverty Reduction and Economic Growth: The Asian Experience*, Asian Development Bank Headquarter, Manila.

Ayres, R.U, 1989. "Industrial Metabolism and Global Change", *International Social Science Journal*, vol. 121.

Ayres, R.U,.1994. "Industrial Metabolism: Theory and Policy", in the book of *Industrial metabolism: restructuring for sustainable development*, United Nations University Press, Tokyo, Japan.

Ayres, R.U, 1997. "Industrial metabolism: work in progress", Working Paper (97/09/EPS), INSEAD, Fontainebleau, France.

Banks, R.D. 1994. "How to Spur the "Greening" of Industry in Rapidly Industrializing Countries". *Industry and Environment* (UNEP IE), Vol.17, No.3, pp42-44.

Belmonte, C., et al. 1999. "GIS Tools Applied to the Sustainable Development of Water Resources", *Agricultural Water Management*, 40(1999), pp.207-220.

Bishop, A. and Hendricks, D. 1971. "Water Reuse Systems Analysis". *Journal of the Sanitary Engineering Division (ASCE)*, 97(SA1): 41-57.

Bishop, A. and Narayanan, R. (1977). "Seasonal and Stochastic Factors in Water Planning". *Journal of the Hydraulics Division (ASCE)*, 2(HY10): 1159-1172.

Bouwer, H. 1993. "From Sewage Farm to Zero Discharge", *European Water Pollution Control*, Vol.3, No.1, pp.9-16.

Bouwer, H. 1997. "Role of Groundwater Recharge and Water Reuse in Integrated Water Management", *the Arabian Journal for Science and Engineering*, Vol.22, No.1c, pp123-131.

Bouwer, H. 2000. "Integrated Water Management: Emerging Issues and Challenges", *Agricultural Water Management*, 45(2000), pp.217-228.

Bower,T.R and P. Gasparis, 1978. *Ethics in Social Research: Protecting the Interests of Human Subjects*, pp23. Praeger Publishers, New York.

Braga, B.P.F. 2001. "Integrated Urban Water Resources Management: a Challenge to 21 Century". *Water Resources Development*, Vol.17, No.4, pp.581-599.

Breierova, L and M, Choudhari. 1996. *An Introduction to Sensitivity Analysis*, Technical Report for Massachusetts Institute of Technology, D-4526-3, Boston.

Brown, T.C, 2000. "Projecting US Freshwater Withdrawals", *Water Resource Research*, 36(3), pp769-80.

Bryman, A. 1988. Quantity and Quality in Social Research. Unwin Hyman Ltd, London. pp18.

Burstrom, F., and Korhonen, J., 2001. "Municipalities and Industrial Ecology: Reconsidering Municipal Environmental Management", *Sustainable Development*, Dev.9, pp36-46.

Byers, W, 1995. How to Implement Industrial Water Reuse: A Systematic Approach, Center for Waste Reduction Technologies(CWRT), pp45-49, American Institute of Chemical Engineerings (ALChE) New York.

Canadian Eco-Industrial Network. 2001. Eco-Industrial Network Development Worldwide, *Canadian Eco-Industrial Network Newsletter*, June, 2001.

Cao and Gu. 1997. "Optimum Cost Model for Environmental Water Treatment Engineering", *Journal of Tongji University*, Vol.25, No.5, pp.548-552.

Casavant, T. 2000. *Industrial Ecosystems: The Future of Process Integration*. Master Thesis, School for Resources and Environmental Studies, Dalhousie University.

Chadwick, B., Bahr, H. and S. Albrecht. 1984. "Chapter 6: Survey Research Questionnaire Studies." *Social Science Research Methods*. Englewood Cliffs, NJ: Prentice-Hall Inc. pp.134-162.

Chen, X, and Bacareza, L.B. 1995. "Application of Economic and Regulatory instruments for Environmental Management in Asian Industrializing Countries". *Industry and Environment*, Vol.18, No.4, pp16-20.

Chertow, M.R. 2000. "Industrial Symbiosis: Literature and Taxonomy", *Annual Review of Energy and the Environment*, 25(2000): 313-337.

China Environmental Report, 2001. China State Environmental Protection Administration, Beijing.

China Environmental Report, 2003. China State Environmental Protection Administration, Beijing.

Chiu, A.S.F. 2001. "Sustainable Development and Industry in Asia and the Pacific." *UNEP/UNIDO industry position paper to World Summit for Sustainable Development.* UNEP Regional Office of Asia Pacific: Bangkok.

Chiu, A.S.F. 2002. "Eco-Industrial Development in Asian Industrial Estates." *Proceedings of European Commission Science & Technology Forum, World Summit for Sustainable Development,* 2 September 2002, Johannesburg.

Cohen-Rosenthal, E., 1996. "Designing Eco-Industrial Parks: The US Experiences", *Industry and Environment*: Environmental Management of Industrial parks, Vol.19, pp13-18.

Côté, R.P, et al. 1994. *Designing and Operating Industrial Parks as Ecosystem*, School for Resource and Environmental Studies, Dalhousie University.

Côté, R. P., and Hall, J., 1995. "Industrial Parks as Ecosystems", *Journal of Cleaner Production*, Vol.3, No.1-2, pp41-46.

Côté, R. P., and Smolenaars, T., 1997. "Supporting Pillars for Industrial Ecosystems", *Journal of Cleaner Production*, Vol.5, No.1-2, pp67-74.

Côté, R. P., and Cohen-Rosenthal, E., 1998. "Designing Eco-Industrial Parks: A Synthesis of some Experiences", *Journal of Cleaner Production*, Vol.6, September, no.3-4, pp181-188.

Creswell, J.W. 1994. *Research Design: Qualitative and Quantitative Approaches*. Sage: Thousand Oaks, Ca. pp227.

Crook, J. 1991. Quality Criteria for Reclaimed Water. *Water Science and Technology*, 24(9):109-121.

Curran, M.A. 1996. *Environmental Life-Cycle Assessment*, Mcgraw-Hill, New York.

Desrochers, P. 2002. "Industrial Ecology and the Rediscovery of Inter-firm Recycling Linkages: Historical Evidence and Policy Implications", *Industrial and Corporate Change*, Vol.11, No.5, pp.1031-1057.

Diwekar, U and Small, M. 1998. "Industrial Ecology and Process Optimization", *Journal of Industrial Ecology*, Vol.2, No.3, pp.11-13.

Dorau, W, 1998. Removal of Pathogens from Wastewater Effluents by Microfiltration Technology. *Europ. Water. Manag.*, 1(2), pp42-52.

Duan, N. 2001. "Make Sunset Sunrise: Efforts for Construction of the Guigang Eco-Industrial City". Draft paper from Chinese Research Academy of Environmental Sciences, Beijing, presented at the April 2001 workshop: *New Strategies for Industry*, Manila.

Dunn, B.C., and Sternemann, A., 1998. "Industrial Ecology for Sustainable Communities", *Journal of Environmental Planning and Management*, 41(6), pp.661-672.

Durham, B, et al. 2002. "Integrated Water Resource Management-Through Reuse and Aquifer Recharge", *Desalination*, issue 152, pp.333-338.

Edgar, T.F and Himmelblau, D.M, 1988. *Optimization of Chemical Processes*, McGraw-Hill, New York.

El-Halwagi, M. M. 1997. *Pollution Prevention through Process Integration: Systematic Design Tools*, Academic Press, San Diego;

Erkman, S.2001. "Industrial Ecology: a New Perspective on the Future of the Industrial System", *Swiss Medicine Weekly*, Issue 131, pp.531-538.

Erkman, S. and Ramaswamy, R. 2000. "Industrial Ecology as a Tool for Development Planning—Twinning Industrial Ecology and Cleaner Production". *Cleaner Production 2000*, Montreal, Canada. Conference proceeding available at: http://www.agrifood-forum.net/db/cp6/ArticleErkman.doc .

Feng, J.Y, 1995. Environmental Protection in China's Industrial Development Zones, *Environmental Protection*, Vol.12, No.4, pp.22-33.

Fleig, A.K. 2000. *Eco-Industrial Parks as a Strategy Towards Industrial Ecology in Developing and Newly Industrialised Countries*. Report prepared for The Deutsche Gesellschaft für Technische.

Fowler, F. 1993. *Survey Research Methods*. 2nd Ed. Newbury Park, CA: SAGE

Publications, Inc. pp. 155.

Freeman, H.M et al. 1992. "Industrial Pollution Prevention: A Critical Review", *Journal of the Air & Waste Management Association*, Vol.42, No.5, pp.618-634.

Frosch, R, 1995. "Industrial Ecology: Adapting Technology for a Sustainable World", *Environment*, Vol.37, No.10, pp16-28.

Frosch, R, 1994. "Industrial Ecology: Minimizing the Impact of Industrial Waste", *Physics Today*, November, pp63-68.

Frosch, R., and Gallopoulos, N, 1989. "Strategies for Manufacturing", *Scientific American*, Sep 1989, pp144-152.

Gao, M. 2002. *The Tianjin Municipality Environmental Protection Report*, Tianjin Environmental Protection Bureau, Tianjin.

Geng, Y. 2000." The Environmental Management of Hotels in China". *Proceeding of the Third Mainland China-Taiwan Environmental Management Symposium*, Dalian, China. (in Chinese)

Geng, Y and Wu, C.Y. 2000. "Designing and Operating Industrial Parks as Ecosystem in China", *Journal of Central South China University*, Vol.7, No.3, pp.9-15.

Geng, Y and Côté, R. 2001. "EMS as an Opportunity for Enhancing China's Economic Development Zones: the Case of Dalian", in *Environmental Management for Industrial Estates-A Resource & Training Kit*, UNEP Division of Technology, Industry and Economics, Production and Consumption Branch, Paris.

Geng, Y. 2002. "Development Strategies of Eco-City". *Proceedings of Mainland China-Taiwan Eco-Industrial Development Symposium*, Taipei. (in Chinese)

Geng, Y and Côté, R. 2002. "Scavengers and Decomposers within an Eco-Industrial Park", *International Journal of Sustainable Development and World Ecology*, Vol.9, No.4, pp.333-340.

Geng, Y and Côté, R. 2003. "Environmental Management System at the Industrial Park Level", *Environmental Management*, Vol.31, No.6, pp784-794.

Gertler, N. 1995. *Industrial Ecosystems: Developing Sustainable Industrial Structures.* Dissertation for Master of Science in Technology and Policy and Master of Science in Civil and Environmental Engineering at Massachusetts Institute of Technology, Cambridge, MA.

Giannini-Spohn, S. 1997. "Designing Industrial Ecosystems Tools.", U.S. Environmental Protection Agency, Washington, DC.

Graedel, T.E and B.R. Allenby. 1995. *Industrial Ecology*, first edition, Prentice Hall, New

Jersey, pp322-344.

Graedel, T.E and B.R. Allenby. 2003. *Industrial Ecology*, second edition, Prentice Hall, New Jersey, pp367-388.

Griggs, N.S. 1999. Integrated Water Resources Management: Who Should Lead, Who Should Pay?", *Journal of the American Water Resources Association*, Vol.35, No.3, pp.527-534.

Grimble, R.J. 1999. "Economic Instruments for Improving Water Use Efficiency: Theory and Practice", *Agricultural Water Management*, 40(1999), pp.77-82.

Haihe Water Resource Management Committee. 1997. *Medium and Long Term Water Supply Plan of Haihe River Basin*. Haihe Water Resource Management Committee: Tianjin (in Chinese).

Hamner, B. 1997. "Industrial Ecology in East Asia". *Journal of Industrial Ecology*, Vol.1, No.4, pp6-8.

Harremoës, P. 1997. "Integrated Water and Waste Management", *Water Science and Technology*, Vol.35, No.9, pp.11-20.

Hoffman, A. 2003. "Linking Social Systems Analysis to the Industrial Ecology Framework", *Organization and Environment*, Vol.16, No.1, pp.66-86.

Hollander, J.B. 2001. "Implementing Sustainability: Industrial Ecology & Eco-Industrial Park", *Economic Development Review*, Fall (2001): 78-86.

Horowitz, D.L. 1989. "Is there a Third World Policy Process?", *Policy Science*, 22(3/4), pp.197-212.

Hu, H.Y, N. Goto and K. Fujie, "Concepts and Methodologies to Minimize Pollutant Discharge for Zero-Emission Production", *Water Science and Technology*, Vol. 39, No.10-11, pp9-16, 1999.

Karamanos, P. 1995. "Industrial Ecology: New Opportunities for the Private Sector", *Industry and Environment*, October-December, pp38-40.

Keckler, S.E. and Allen, D.T. (1999). Material Reuse Modeling. *Journal of Industrial Ecology*, Vol.2, No.4, pp.79-92.

Korhonen, J, et al. 2001. "Industrial Ecosystem in the Finnish Forest Industry: Using the Material and Energy Flow Model of a Forest Ecosystem in a Forest Ecosystem in a Forest Industry System", *Ecological Economics*, 39(2001), pp.145-161.

Korhonen, J., 2001. "Some Suggestions for Regional Industrial Ecosystems-Extended Industrial Ecology", Eco-Management and Auditing, Aud.8, pp57-69.

Lazarova, V. et al. 2000. "Enhancing of Integrated Water Management and Water Reuse in Europe and the Middle East", *Water Science and Technology*, Vol.42, No.1-2, pp.193-202.

Le, V.D and Gupta, A.D. 2000. "Water Resources Planning and Management for Lower Dong Nai River Basin, Vietnam: Application of an Integrated Water Management Model", *Water Resources Development*, Vol.16, No.4, pp.589-613.

Lifset, R. 1997. "Why Industrial Ecology". *Journal of Industrial Ecology*, Vol.1, No.4, pp1-2.

Lotov, A.V, et al., 2000. "Efficient Strategies: An Application in Water Quality Planning", in *Decision Support System for Sustainable Development*, International Development Research Council (IDRC) and Kluwer Academic Publishers, Norwell, USA.

Lowe, E, 1993. "Industrial Ecology-An Organizing Framework for Environmental Management", *Total Quality Environmental Management*, 3(1), pp73-85.

Lowe, E, 1996. "Industrial Ecology", *Technology Review*, October.

Lowe, E. 1997. "Creating By-Product Resource Exchanges for Eco-Industrial Parks, *Journal of Cleaner Production*, Vol.5, No.1-2, pp.57-65.

Lowe, E., et al., 1997. *Discovering Industrial Ecology: An Executive Briefing and Sourcebook*, Batelle Press, Columbus, Ohio.

Lowe, E. 2001. *Eco-Industrial Park Handbook for Asian Developing Countries*, funded by Asian Development Bank, available by: http://www.indigodev.com/Handbook.html.

Lowe, E and Geng, Y. 2003. *Industrial Ecology and Eco-Industrial Park*. China Chemical Industry Press, Beijing.

Ma, J, 1999. *China's Water Crisis*, China Environmental Science Press, Beijing.

Magerholm Fet, A. 2001 "Cleaner Production and Industrial Ecology", a presentation at *NATO/CCMS Pilot Study on Cleaner Products and Processes*, Oviedo, Spain, May 6-11, 2001.

Mann, G. J., and Y. A. Liu. 1999. *Industrial Water Reuse and Wastewater Minimization*, McGraw-Hill, New York.

Mara, D. and Caincross, S. 1989. *Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture: Measures for Public Health Protection*. World Health Organization, Geneva, Switzerland.

Marco, O., Lagiois, G. and Mazzacane, E.P, 2000. "Materials Flow Analysis of the Italian Economy", *Journal of Industrial Ecology*, Vol. 4, Number 2, pp55-70.

Messner et al., 2000. "Energy Planning", in *Model-Based Decision Support Methodology with Environmental Applications*, Kluwer Academic Publishers, Dordrecht, Netherland.

Metcalf and Eddy Inc. 1991. *Wastewater Engineering: Treatment, Disposal and Reuse.* Third Edition, McGraw-Hill, New York.

Mitchell, B. and Draper, 1983. "Ethics in Geographical Research", *The Professional Geographer, 35(1), 9-17.*

Mitchell, B. 1990. "Integrated Water Management", in *Integrated Water Management: International Experiences and Perspectives*, edited by Mitchell, pp.1-12, B. Belhaven Press, London.

Mitchell, B. 1994. "Addressing 'Edge' Problems in Land and Water Management in the Sokolo-Rima River Basin, Nigeria", *Geoforum*, 25(2), pp.133-143.

Nobel. C.E. and Allen, D.T. (2000). Using Geographical Information Systems (GIS) in Industrial Water Reuse Modeling. *Process Safety and Environmental Protection: Transactions of the Institute of Chemical Engineers*, Part B, Vol.78, pp.295-303.

Novotny, V. 1996. "Integrated Water Quality Management", *Water Science and Technology*, Vol.33, No.4-5, pp.1-7.

O'Brian, J.A, 1990. *Management Information Systems*, Irwin Inc., Boston, pp.128-149.

Ocanas, G. and Mays, L. 1981a. "A Model for Water Reuse Planning". *Water Resources Research*, 17(1): 25-32.

Ocanas, G and Mays, L. 1981b. "Water Reuse Planning Models: Extensions and Applications", Water Resource Research, Vol.17, No.5, pp.1311-1327.

Odum, E.P. 1989. "Input Management of Production Systems", *Science*, Vol.243, No.1, pp.177-182.

O'Leary, T.J, et al., 1990. "Validating Expert Systems", *IEEE Expert* 5(3): pp51-58.

Oron, G. 1996. Management Modeling of Integrative Wastewater Treatment and Reuse Systems. *Water Science and Technology*, Vol.33, No.10-11, pp.95-105.

Paczynski, J et al. 2000. *Model-Based Decision Support Methodology with Environmental Applications*, Kluwer Academic Publishers: Amsterdam.

Pareek, N.K, 1992. "Industrial Wastewater Management in Developing Countries", *Water Science and Technology*, Vol.25, No.1, pp.69-74.

Peck, S., and Callaghan, C., 1997. "Gathering Steam: Eco-Industrial Parks Exchange Waste for Efficiency and Profit", *Alternatives*, Vol.23, Spring, No.2, pp6.

Peck, S., Callaghan, C. and R. Côté, "Eco-Industrial Network Development:

Opportunities for Progress in Canada", Environment Canada (1998), 86 pp.

Peer Consultants, P.C and University of Dayton Research Institute, 1992. User's Guide: Strategic Waste Minimization Initiative, version 2.0, US Environmental Protection Agency, Cincinnati, Ohio.

Piazza, J.R, 1992. "A Systems Engineering Methodology for Manufacturing Waste Minimization", *AT&T Technical Journal*, Mar/Apr, pp.11-18.

Pingry, D.W. and Shaftel, T.L. 1979. "Integrated Water Management with Reuse: a Programming Approach", *Water Resource Research*, Vol.10, No.2, pp.8-14.

Postel, S.L, 2000. "Water and World Population Growth", *Journal of AWWA*, 92(4),pp.131-8.

Reeves, G. 2000. "Wastewater Minimization with Chemical-free Water Treating", *Environmental Progress*, Vol. 19, No.4, pp.292-298.

Rios, R.A, et al. 1975. "A Non-linear Programming Model for Evaluating Water Supply Policies in the Texas Coastal Zone", *Technical Report, EHE-75-07, CRWR-130*, Center for Water Resource, University of Texas, Austin.

Sample, D, el al. 2001. "Geographic Information Systems, Decision Support Systems, and Urban Storm-Water Management", *Journal of Water Resources Planning and Management*, Volume.155, No.3, pp.155-161.

Seager, T.P. and Theis, T.L. 2002. "A Uniform Definition and Quantitative Basis for Industrial Ecology", *Journal of Cleaner Production*, 10(2002), 225-235.

Schwartz, M. and Mays, L. 1983. "Models for Water Reuse and Wastewater Planning". *Journal of Environmental Engineering (ASCE)* 109(5): 1128-1147.

SEPA. 2003. *China's Annual State Environmental Report 2003*. SEPA Official Document, Beijing.

Shelef, G. 1991. "Wastewater Reclamation and Water Resources Management", *Water Science and Technology*, Vol.24, No.9, pp.251-265.

Shuval, et al. 1986. *Wastewater Irrigation in Developing Countries- Health Effects and Technical Solutions*. World Bank Technical Paper Number 51, The World Bank, Washington, D.C.

Simonovic, S.P. and Fahmy, H.A, 1999. "New Modelling Approach for Water Resources Policy Analysis", *Water Resource Research*, 35(1), pp295-304.

Sinkule, B. and L. Ortolano. 1995. *Implementing Environmental Policy in China.* Westport, Connecticut: Praeger Publishers. pp 209.

Smith, R, 1995. "Wastewater Minimization", Chapter 8, in *Waste Minimization through Process Design*, A.P. Rossiter, editor, McGraw-Hill, New York.

Study Group of Sustainable Development of Chinese Academy of Sciences, 2000. *The Strategy Report of Sustainable Development in China*, pp110-261, Science Press, Beijing.

Tang, H.W. and Q, X.Z. 1994. *Optimization Technology*. Dalian University of Technology Press, Dalian. (in Chinese)

Tchobanoglous, G. and Eliassen, R. 1969. The Indirect Cycle of Water Reuse. *Water and Wastes Engineering*, Vol.6, No.2, pp.35-41.

TEDA. 2001. *TEDA Development Report 2001*, TEDA, Tianjin.

TEDA. 2002. *TEDA Annual Environmental Report 2002*, TEDA, Tianjin.

TEDA. 2003. *TEDA Yearbook 2002*, TEDA, Tianjin.

Tehobanoglous, G and F. L. Burton, 1991. *Wastewater Engineering: Treatment, Disposal and Reuse*, 3rd edition, McGraw-Hill, New York.

Thomas, V. 2003. "Industrial Ecology: Policy Potential and Research Needs", *Environmental Engineering Science*, Vol.20, No.1, pp.1-9.

Thurston, A., Turner-Gotts, K., and L. Reed. 1994. *China Bound, Revised: A Guide to Academic Life and Work in the P.R.C.* Washington, D.C.: National Academy of Sciences, Social Science Research Council, and the Committee on Scholarly Communication with China. 272 pp.

Tian, et al. 2001. "A Study on Optimizing a City's Potable Water and Middle Water System", *Water Supply and Discharge*, Vol.27, No.5, pp23-27.

United Nations Industrial Development Organization (UNIDO). 1997. *Industrial Estates: Principles and Practices.* Vienna, Austria: UNIDO. 47 pp.

United Nations Environment Programme (UNEP). 1997. *Environmental Management for Industrial Estates.* Technical Report No. 39. Paris, France: United Nations Environment Programme - Industry and Environmental Parks. 138 pp.

United Nations Environment Programme (UNEP). 2001. *Environmental Management in Industrial Estates in China.* Paris, France: United Nations Environment Programme, Division of Technology, Industry and Economics. 95 pp.

US-AEP. 1999. *Place-Based Public Policy in Southeast Asia: Developing, Managing, and Innovating for Sustainability.* United States-Asia Environmental Partnership, Washington.

USA. Army Corps of Engineers, Fort Worth District. (1973). *Wastewater Management*

Plan, Colorado River and Tributaries, Texas, technical appendix, vol.3, Fort Worth, Texas.

USA. EPA. 1978a. *Analysis of Operations & Maintenance Costs for Municipal Wastewater Treatment Systems.* Technical Report MCD-39. General Services Administration, Building 41, Denver Federal Center, Denver, Colorado, 80225.

USA. EPA. 1978b. *Construction Costs for Municipal Wastewater Conveyance Systems: 1973-1977.* Technical Report MCD-38, General Services Administration, Building 41, Denver Federal Center, Denver, Colorado, 80225.

USA. EPA. 1979. *Estimating Water Treatment Costs, Volume 2 Cost Curves Applicable to 1 to 200 MGD Treatment Plants.* Office of Research and Development, Cincinnati, Ohio, 45268.

US EPA, 1986. *Design Manual-Municipal Wastewater Disinfection.* EPA-625/1-86/021, Water Engineering Research Laboratory, Cincinnati, Ohio.

US EPA. 1990. *Pollution Prevention Handbook*, Washington.

US EPA. 1992. *Guidelines for Water Reuse.* US EPA and USAID, Washington.

Vanrolleghem, P. et al. 1999. "Setting up Measuring Campaigns for Integrated Wastewater Modelling", *Water Science and Technology*, Vol.39, No.4, pp257-268.

Varis, O, 1999. "Water Resources Development: Vicious and Virtuous Circles", *Ambio*, 28(7), pp599-603.

Varis, O and Vakkilainen. 2001. "China's 8 Challenges to Water Resources Management in the First Quarter of the 21st Century", *Geomorphology*, 41(2001), pp.93-104.

Varis, O and Lahtela, V. 2002. "Integrated Water Resources Management along the Senegal River: Introducing an Analytical Framework", *Water Resources Development*, Vol.18, No.4, pp.501-521.

Vieira, J. and Lijklema, L. (1989). Development and Application of a Model for Regional Water Quality Management. *Water Resources*, 23(6): 767-777.

Wang, F,K, et al. 1987. *Economic Analysis Handbook for Industrial and Municipal Wastewater Treatment*, Tsinghua University Press, Beijing.

Wang, Y.P and R.Smith, 1994a. "Wastewater Minimization", *Chemical Engineering Science*, 49:981.

Wang, Y.P and R.Smith, 1995. "Wastewater minimization with Flowrate Constraints", *Transactions of the Institution of Chemical Engineers*, Vol.73, Part A, pp899-904.

Water Pollution Control Federation, 1989. *Water Reuse* (second edition). Manual of practice SM-3, Water Pollution Control Federation, Alexandria, Virginia.

Wilchford, O. and J.R.Lund. 1997. "Shortage Management Modelling for Urban Water Supply Systems". *Journal of Water Resources Planning and Management*, 123(4), pp.250-258.

Winpenny, I. 1994. *Managing Water as an Economic Resource*. Routledge/ODI, London, 133p.

World Bank. 1997. *China 2020 Series: Clear Water, Blue Skies*. Washington, DC: World Bank. 114p.

World Bank. 2001. *China: Air, Land and Water-Environmental Priorities for a New Millennium*. Washington DC: World Bank. 149p.

World Resources Institute, UNEP and UNDP, 1993. *World Resources (1992-1993)* (Chinese version), pp213-620, Chinese Environment Press, Beijing.

World Resources Institute, UNDP, UNEP and World Bank. 2001. *World Resources 2000-2001, People and Ecosystems: The Fraying Web of Life.* Elsevier Science, Oxford, UK.

Xiao. 2002. *Water Reuse Technologies*. Chemical Industry Press, Beijing.

Xinhua News Agency, 2000. "*400 cities in China Facing Widespread Water Crisis*", Guangzhou Daily, July.20, A3 (in Chinese).

Yang, J.T. (2001). *The Environmental Management of Industrial Estates in China: Issues and Perspectives*. Paper presented at the Environmental Management of Industrial Estates Workshop, 8-11 July, Dalian, China.

Yang, Y.H., H.H. Lou and Y.L. Huang, "Sysnthesis of an Optimal Wastewater Reuse Network", *Waste Management*, Vol 20, Page 311-319, 2000.

Yin, R.K. 1989. "Case Study Research: Design and Methods". *Applied Social Research Methods Series*, Volume 5. Sage Publications: Beverly Hills, Ca.

Zabel, T.F., et al. 1998. "The Use of Economic Instruments for Water Management in Selected EU Member Countries", *Journal of the Chartered Institution of Water and Environment Management*, Vol. 12, No.4, pp. 268-272.

Zhu, Q.H. and Geng, Y. 2002. "Integrating Environmental Issues into Supplier Selection and Management", *Greener Management International* (UK), Issue 35, pp.27-40;

Zhu, Q.H. and Côté, R. 2004. "Integrating Green Supply Chain Management into an Embryonic Eco-industrial Development: a Case Study of the Guitang Group", *Journal of Cleaner Production*, Vol.12, No.8-10, pp.1025-1036.

Zhu, Z.Y, et al., 2001. "Water Shortage: a Serious Problem in Sustainable Development of China", *International Journal of Sustainable Development and World Ecology*, Vol.8, No.2, pp233-237.

APPENDIX 1

Physical, chemical and biological characteristics of wastewater and their sources (Metcalf and Eddy Inc. 1991)

Characteristics	Sources
Physical properties:	
Color	Domestic and industrial wastes, natural decay of organic materials
Odor	Decomposing wastewater, industrial wastes
Solids	Domestic water supply, domestic and industrial wastes, soil erosion, inflow/infiltration
Temperature	Domestic and industrial wastes
Chemical constituents:	
Organic:	
Carbohydrates	Domestic, commercial, and industrial wastes
Fats oils, and grease	Domestic, commercial, and industrial wastes
Pesticides	Agricultural wastes
Phenols	Industrial wastes
Proteins	Domestic, commercial, and industrial wastes
Priority pollutants	Domestic, commercial, and industrial wastes
Surfactants	Domestic, commercial, and industrial wastes
Volatile organic compounds	Domestic, commercial, and industrial wastes
Other	Natural decay of organic materials
Inorganic:	
Alkalinity:	Domestic wastes, domestic water supply, groundwater infiltration
Chlorides:	Domestic wastes, domestic water supply, groundwater infiltration
Heavy metals	Industrial wastes
Nitrogen	Domestic and agricultural wastes
PH	Domestic, commercial, and industrial wastes
Phosphorus	Domestic, commercial, and industrial wastes; natural runoff
Priority pollutants	Domestic, commercial, and industrial wastes
Sulfur	Domestic water supply; domestic, commercial, and industrial wastes
Gases:	
Hydrogen sulfide	Decomposition of domestic wastes
Methane	Decomposition of domestic wastes
Oxygen	Domestic water supply, surface-water infiltration
Biological constituents:	
Animals	Open watercourses and treatment plants
Plants	Open watercourses and treatment plants
Protists:	
Eubacteria	Domestic wastes, surface-water infiltration
Archaebacteria	Domestic wastes, surface-water infiltration
Viruses	Domestic wastes

APPENDIX 2

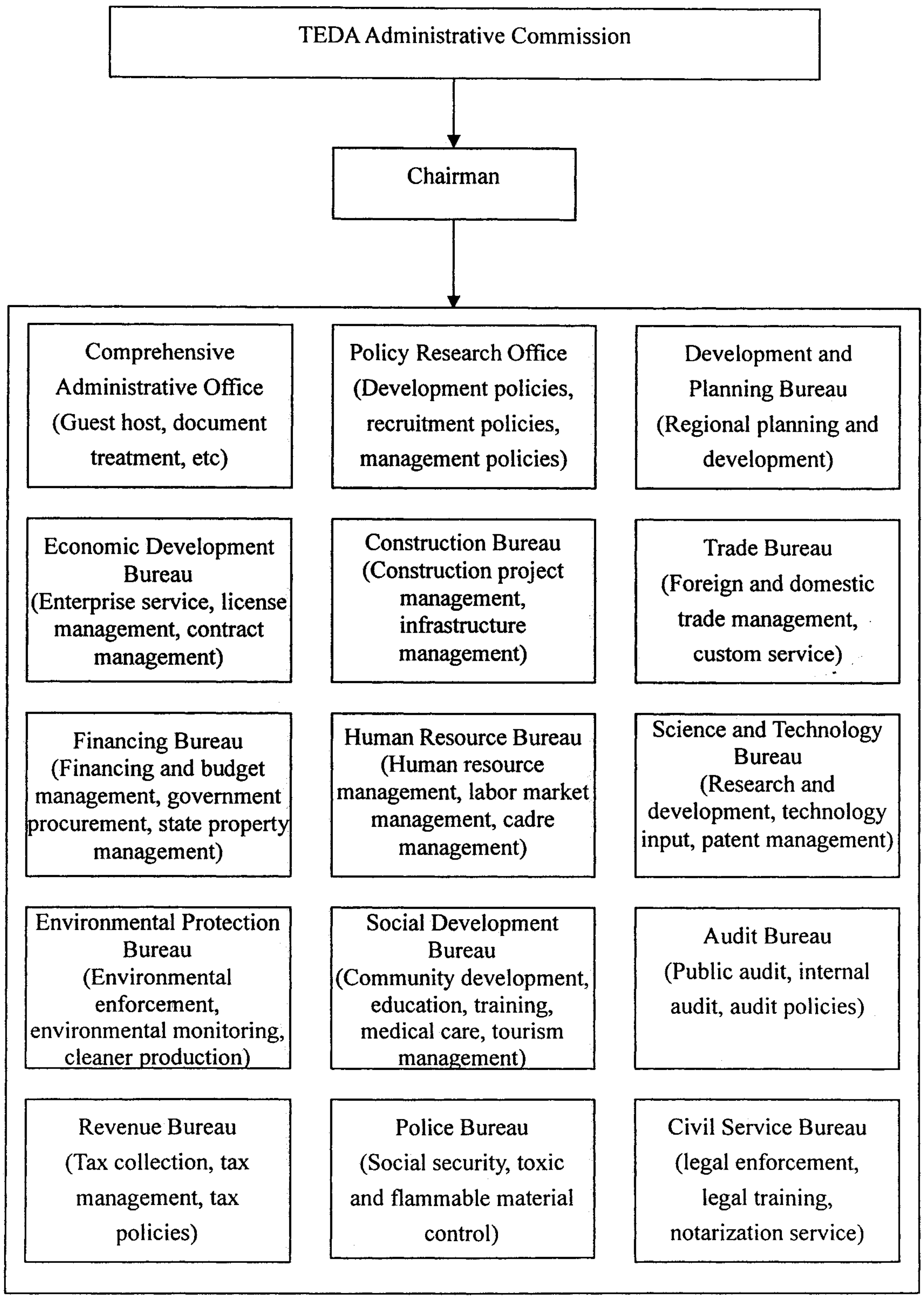
Categories of Wastewater Reuse and Potential Constraints (Metcalf and Eddy Inc, 1991)*

Wastewater Reuse Categories	Potential Constraints
Agricultural and Urban Irrigation Crop irrigation Park School yard Freeway median Golf course Greenbelt Residential	Surface and groundwater pollution if not properly managed; Marketability of crops and public acceptance; Public health concerns related to pathogens (bacteria, viruses and parasites); Use area control including buffer zone. May result in high user costs.
Industrial recycling and reuse Cooling Boiler feed Process water Heavy construction	Constituents in reclaimed wastewater related to scaling, corrosion, biological growth, and fouling; Public health concerns, particularly aerosol transmission of pathogens in cooling water.
Groundwater recharge Groundwater replenishment Saltwater intrusion control Subsidence control	Organic chemicals in reclaimed wastewater and their toxicological effects; Total dissolved solids, nitrates, and pathogens in reclaimed wastewater
Recreational/environmental uses Lakes and ponds Marsh enhancement Streamflow augmentation Fisheries and snowmaking	Health concerns of bacteria and viruses; Eutrophication due to N and P in receiving water; Toxicity to aquatic life
Non-potable urban uses Fire protection Air conditioning Toilet flushing	Public health concerns on pathogens transmitted by aerosol; Effects of water quality on scaling, corrosion, biological growth and fouling; Cross-connection
Potable reuse Blending in water quality Reservoir Pipe to pipe water supply	Constituents in reclaimed wastewater, especially trace organic chemicals and their toxicological effects; Aesthetic and public acceptance; Health concerns about pathogen transmission, particularly viruses.

* Arranged in descending order of projected volume of use.

APPENDIX 3

Administrative Framework of the TEDA Administration Commission



APPENDIX 4

National Standard for Drinking Water
GB5749
Ministry of Construction

Items	Class I	Class II
pH	6.5-8.5	6.5-8.5
Turbidity	<=3	N/a
Total Hardness (mg/l) (as $CaCO_3$)	<=350	<=450
Odor	3 threshold odor number	4 threshold odor number
Color	<=15 color units	<=20 color units
Manganese (mg/l)	<=0.1	<=0.1
Iron (mg/l)	<=0.3	<=0.5
Total Dissolved Solids (mg/l)	<1000	<1000
Silver (mg/l)	<=0.05	<=0.05
Nitrite (mg/l)	<=1	<=1
Benzene (μg/l)	<=0.01	<=0.01
Coliform Bacteria (number/l)	<=1000	<=10000
Cadmium (mg/l)	<=0.01	<=0.01
Lead (mg/l)	<=0.05	<=0.07
Mercury (mg/l)	<=0.001	<=0.001
Nitrate (mg/l)	<=10	<=20
Selenium (mg/l)	<=0.01	<=0.01
Arsenic (mg/l)	<=0.05	<=0.05
Chromium (mg/l)	<=0.05	<=0.05
Beryllium (mg/l)	<=0.0002	<=0.0002
Fluoride (mg/l)	<=1.0	<=1.0
Cyanide (mg/l)	<=0.05	<=0.05
Zinc (mg/l)	<=1.0	<=1.0
Copper (mg/l)	<=1.0	<=1.0
Radionuclides (bq/l)	<=1	<=1
Chlorite (mg/l)	<250	<250
Methoxychlor (μg/l)	<=1	<=1
Pentachlorophenol (mg/l)	<=0.002	<=0.004
Taste	No Objectional Taste	No Objectional Taste
Sulfate (mg/l)	<250	<250

Data from "*Water Reuse Technologies*", edited by Xiao 2002.

APPENDIX 5

National Standard for Wastewater Discharge
GB8978-1996
(Ministry of Construction)

Items	Class I	Class II	Class III
pH	6-9	6-9	6-9
SS (mg/l)	50	80	120
BOD_5 (mg/l)	20	30	300
COD (mg/l)	60	120	500
NH_3-N (mg/l)	15	25	40
Oil and Grease (mg/l)	10	15	100
TOC (mg/l)	20	30	N/a
Color	<=50 color units	<=80 color units	N/a
Manganese (mg/l)	<=2.0	<=2.0	<=5.0
Bis Phthalate (mg/l)	<=0.4	<=0.6	<=1.0
LAS (mg/l)	<=5.0	<=10	<=20
Toluene (mg/l)	<=0.1	<=0.2	<=0.5
Benzene (μg/l)	<=0.1	<=0.2	<=0.5
Coliform Bacteria (number/l)	<=500	<=1000	<=5000
AOX (mg/l)	<=1.0	<=5.0	<=8.0
PCP (mg/l)	<=5.0	<=8.0	<=10
Cyanide (mg/l)	<=0.5	<=0.5	<=1.0
Selenium (mg/l)	<=0.1	<=0.2	<=0.5
Phosphorous (mg/l)	<=0.1	<=0.1	<=0.3
Nitrobenzene (mg/l)	<=2.0	<=3.0	<=5.0
Chlorobenzene	<=0.2	<=0.4	<=1.0
Fluoride (mg/l)	<=10	<=10	<=20
Anilin (mg/l)	<=1.0	<=2.0	<=5.0
Zinc (mg/l)	<=2.0	<=5.0	<=5.0
Copper (mg/l)	<=0.5	<=1.0	<=2.0
Phosphate (mg/l)	<=0.5	<=1.0	N/a
Phenol (mg/l)	<0.3	<0.4	<1.0
Methoxychlor (μg/l)	<=1.0	<=1.0	<=2.0
Pentachlorophenol (mg/l)	<=5.0	<=8.0	<=10
CCl_4 (mg/l)	<=0.03	<=0.06	<=0.5
Petroleum (mg/l)	<=5	<=10	<=20

Data from "*Water Reuse Technologies*", edited by Xiao 2002

APPENDIX 6

Tianjin Standard Quality of Middle Water

Items	Landscaping	Construction use	Toilet flushing or car washing
pH	6.5-9	4-9	6.5-9
SS (mg/l)	200	1000	50
BOD_5 (mg/l)	80	30	20
COD (mg/l)	300	100	50
NH_3-N (mg/l)	20	30	30
TDS (mg/l)	1200	1000-5000	100
TOC (mg/l)	20	30	20
Color	<=30 color units	<=50 color units	<=30 color units
Manganese (mg/l)	<=0.1	<=1.0	<=0.1
Iron (mg/l)	<=0.4	<=0.4	<=0.4
Detergent (mg/l)	<=1.0	<=1.0	<=1.0
Toluene (mg/l)	<=0.1	<=0.2	<=0.1
Turbidity	10	20	5
Coliform Bacteria (number/l)	<=100	<=100	<=100
Phosphorous (mg/l)	<=0.1	<=0.1	<=0.1
Nitrobenzene (mg/l)	<=1.0	<=2.0	
Chlorobenzene	<=0.2	<=0.4	

Data from "TEDA Annual Environmental Report 2002".

APPENDIX 7

Questionnaire for integrated water resource planning and management at Tianjin Economic Development Area (TEDA)

Interviewer: Yong Geng, Ph.D candidate,

Department of Chemical Engineering, Dalhousie University

Company name:	Company Address:
Business type:	Contact person:
Tel: Fax;	E-mail:

Input requirements:

Quantity requirement: (tons/day)

Sanitary	Process	Others	Total

Quality requirements: (mg/L)

TSS	TOC	BOD	COD	Ph	Alkalinity	Faecal coliform counts	Turbidity

1. What are the current water issues in your company?

2. If some water from other companies can be used in your company, do you accept it? If not, what's your concern?

3. If treated wastewater from wastewater plant can meet with your demand, do you accept it? If not, what's your concern?

4. Do you like to collaborate with other tenants in TEDA in terms of water management?

5. What's your opinion on current water management in TEDA?

6. What's your vision on systematic water management at TEDA level?

APPENDIX 8

Optimal flow for scenario 2-8, 10-17

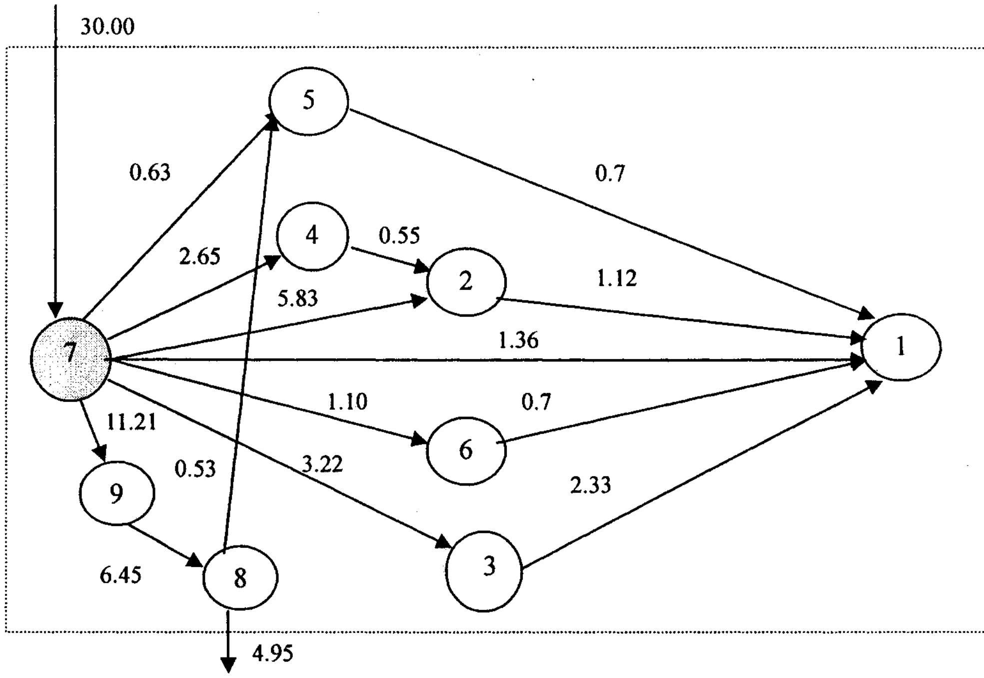


Figure A-1 Optimize flow for scenario 2 in which the total freshwater use is reduced by 18.57%

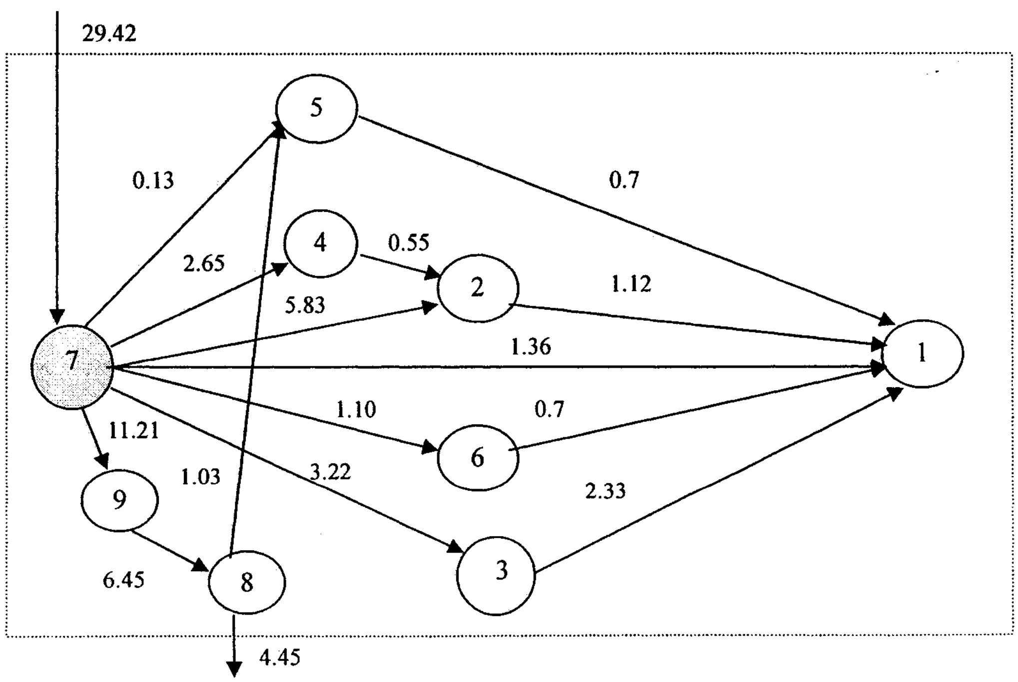


Figure A-2 Optimize flow for scenario 3 in which the total freshwater use is reduced by 20.14%

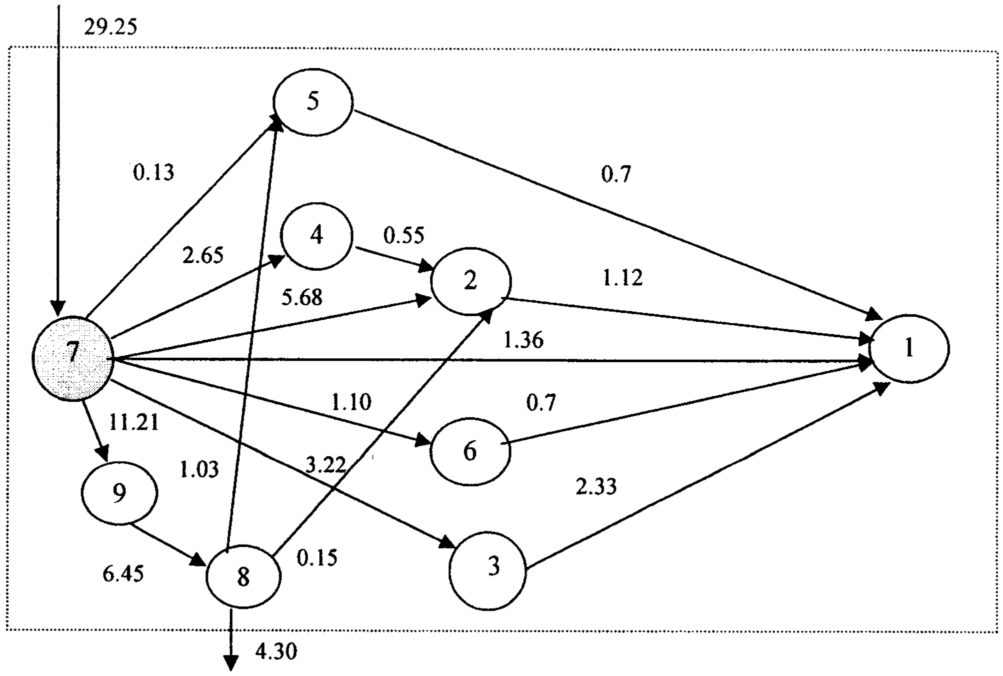


Figure A-3 Optimize flow for scenario 4 in which the total freshwater use is reduced by 20.61%

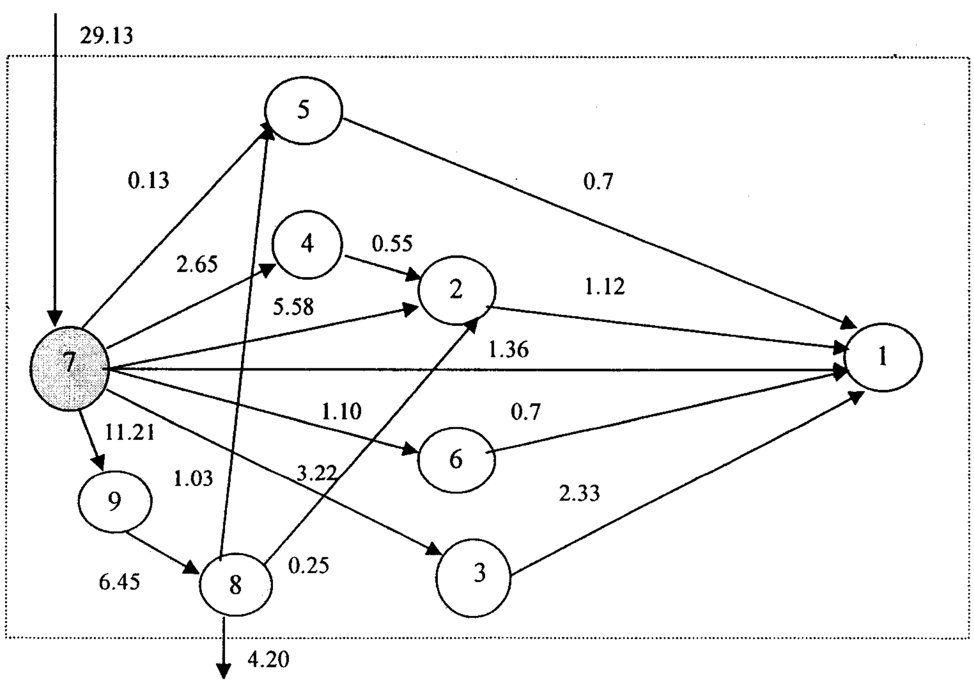


Figure A-4 Optimize flow for scenario 5 in which the total freshwater use is reduced by 20.92%

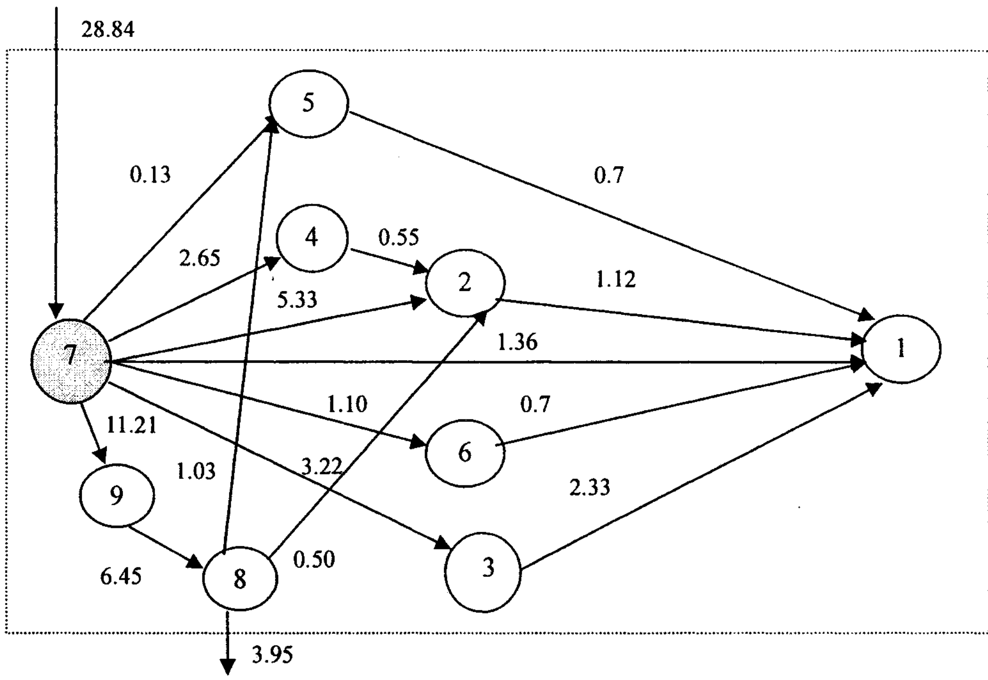


Figure A-5 Optimize flow for scenario 6 in which the total freshwater use is reduced by 21.70%

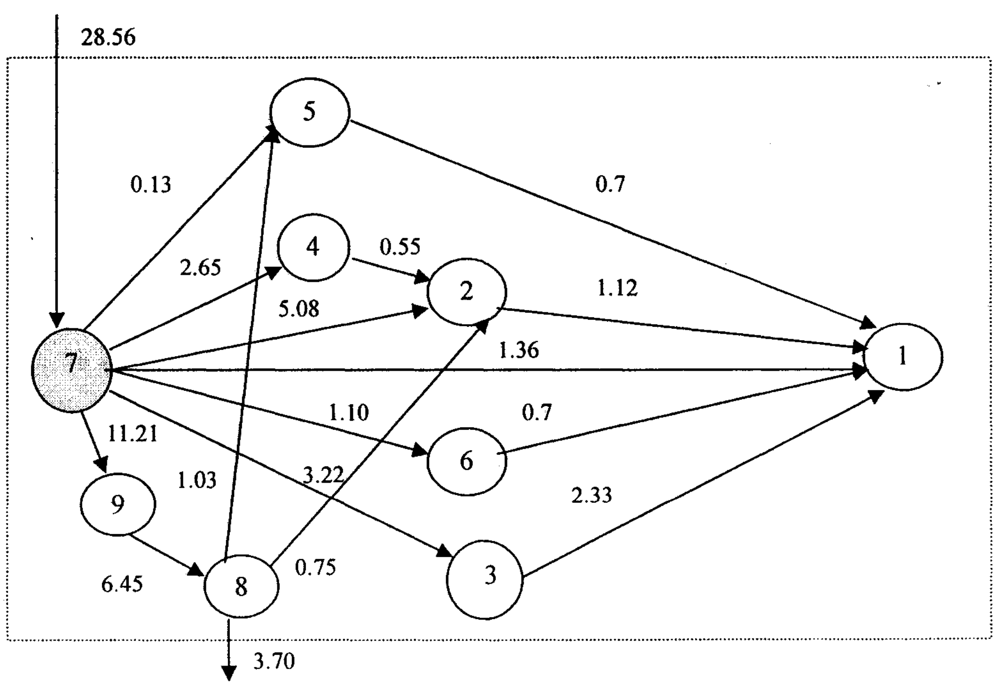


Figure A-6 Optimize flow for scenario 7 in which the total freshwater use is reduced by 22.48%

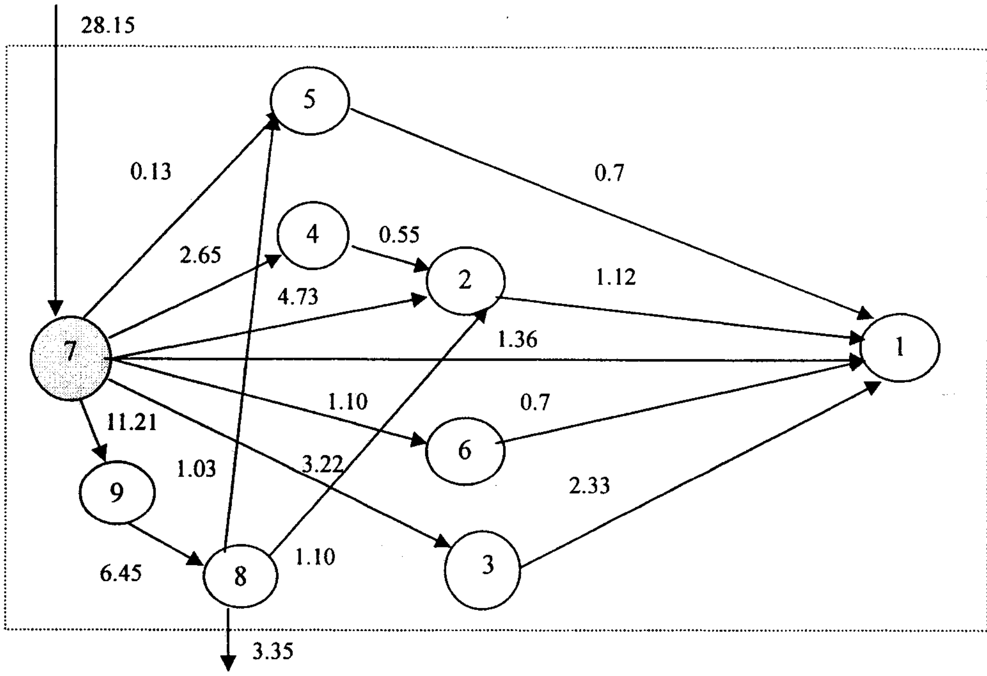


Figure A-7 Optimize flow for scenario 8 in which the total freshwater use is reduced by 23.58%

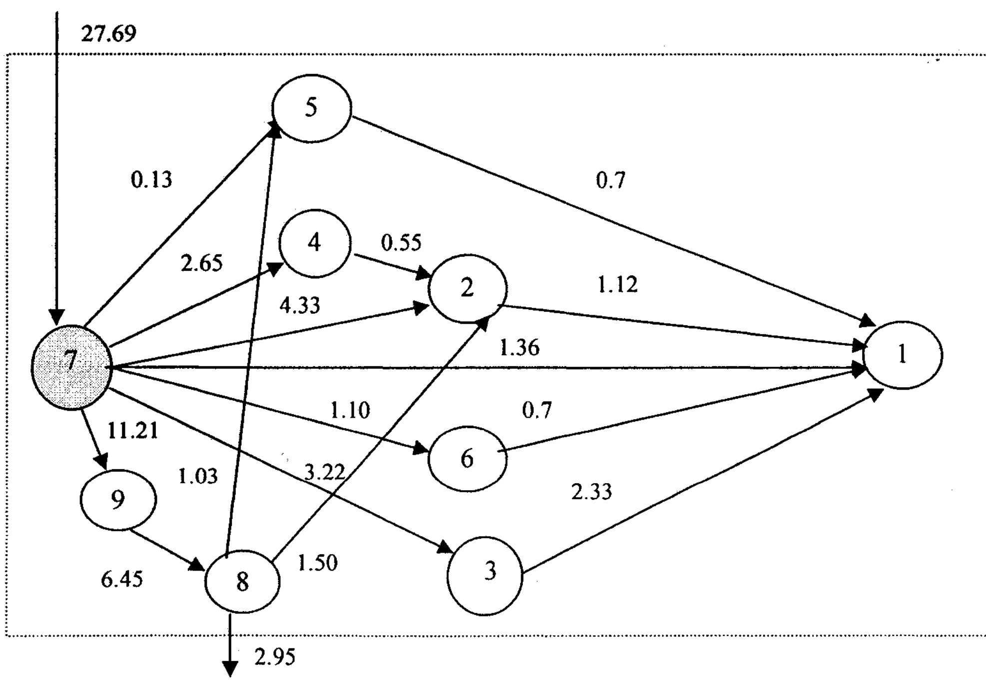


Figure A-8 Optimize flow for scenario 10 in which the total freshwater use is reduced by 24.83%

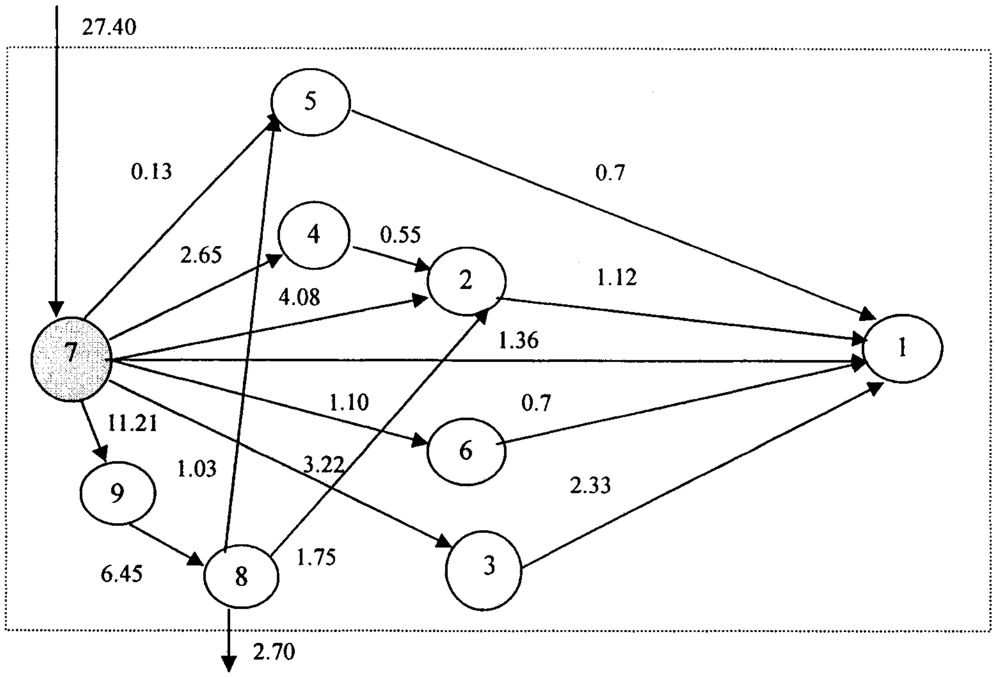


Figure A-9 Optimize flow for scenario 11 in which the total freshwater use is reduced by 25.62%

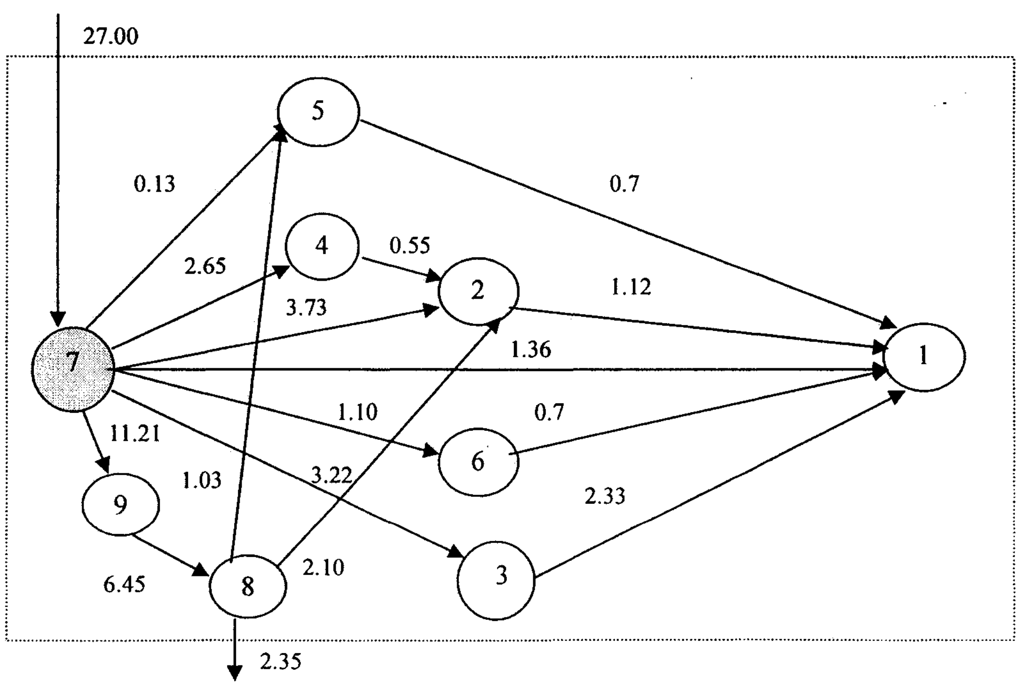


Figure A-10 Optimize flow for scenario 12 in which the total freshwater use is reduced by 26.71%

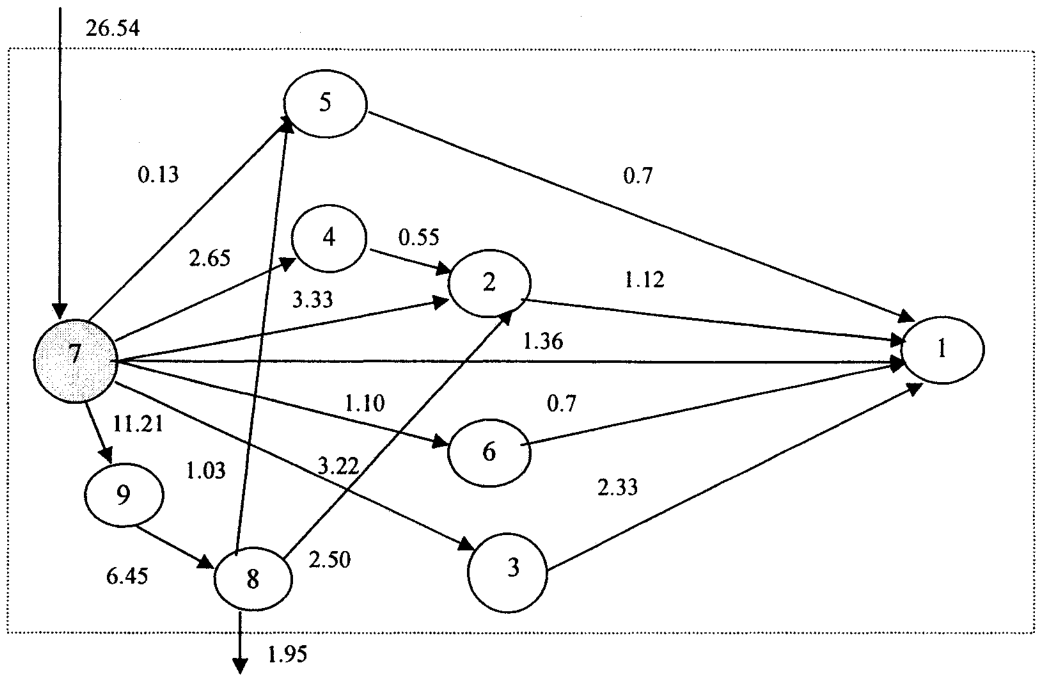


Figure A-11 Optimize flow for scenario 13 in which the total freshwater use is reduced by 27.97%

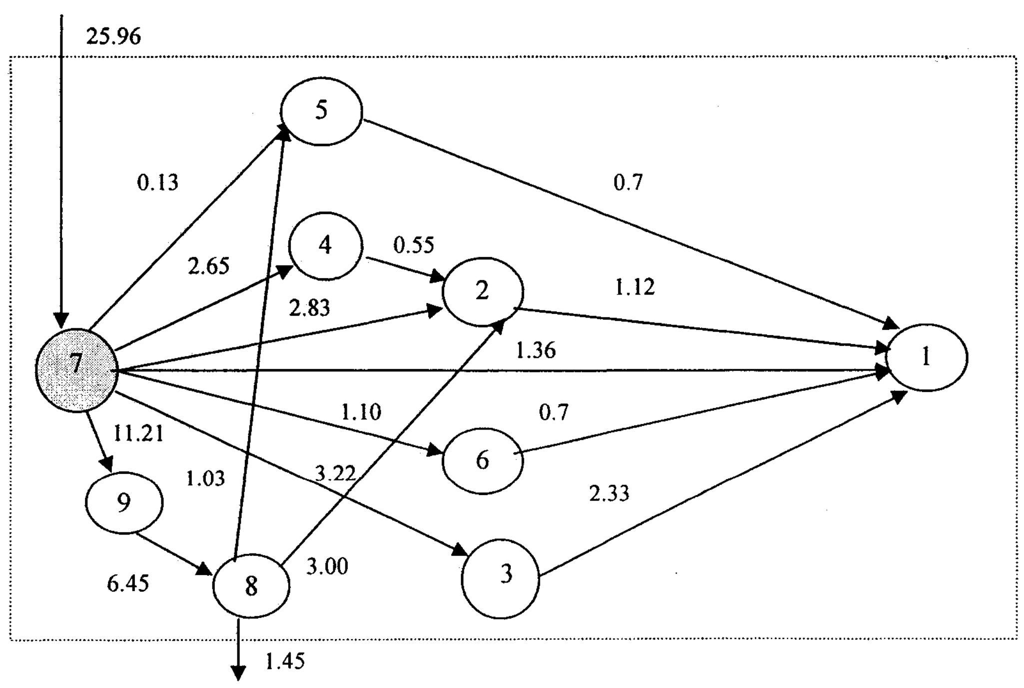


Figure A-12 Optimize flow for scenario 14 in which the total freshwater use is reduced by 29.53%

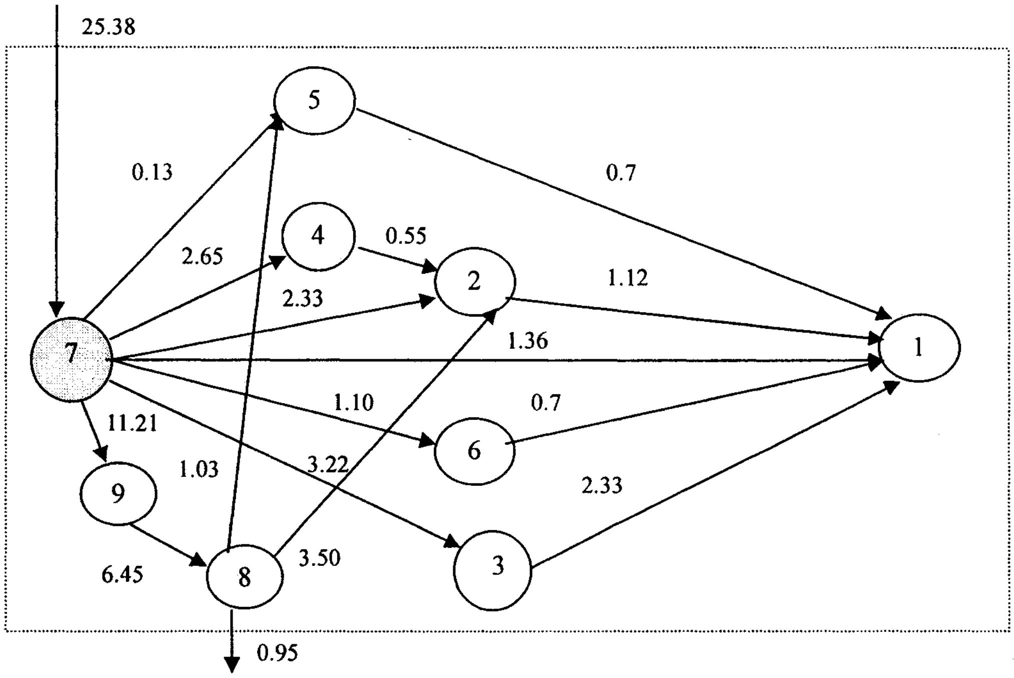


Figure A-13 Optimize flow for scenario 15 in which the total freshwater use is reduced by 31.10%

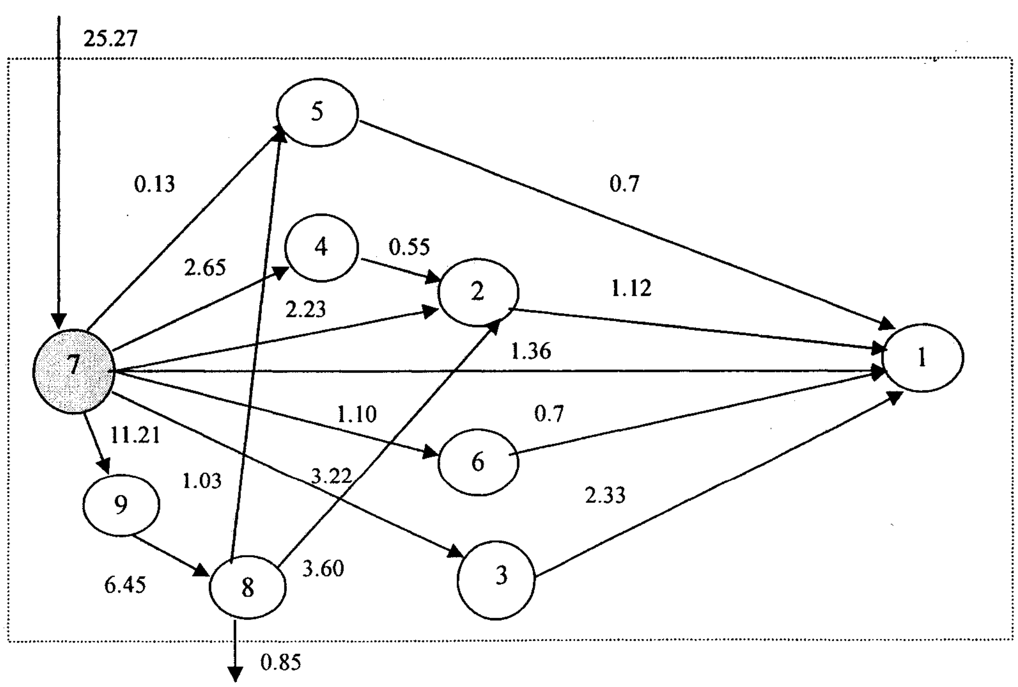


Figure A-14 Optimize flow for scenario 16 in which the total freshwater use is reduced by 31.41%

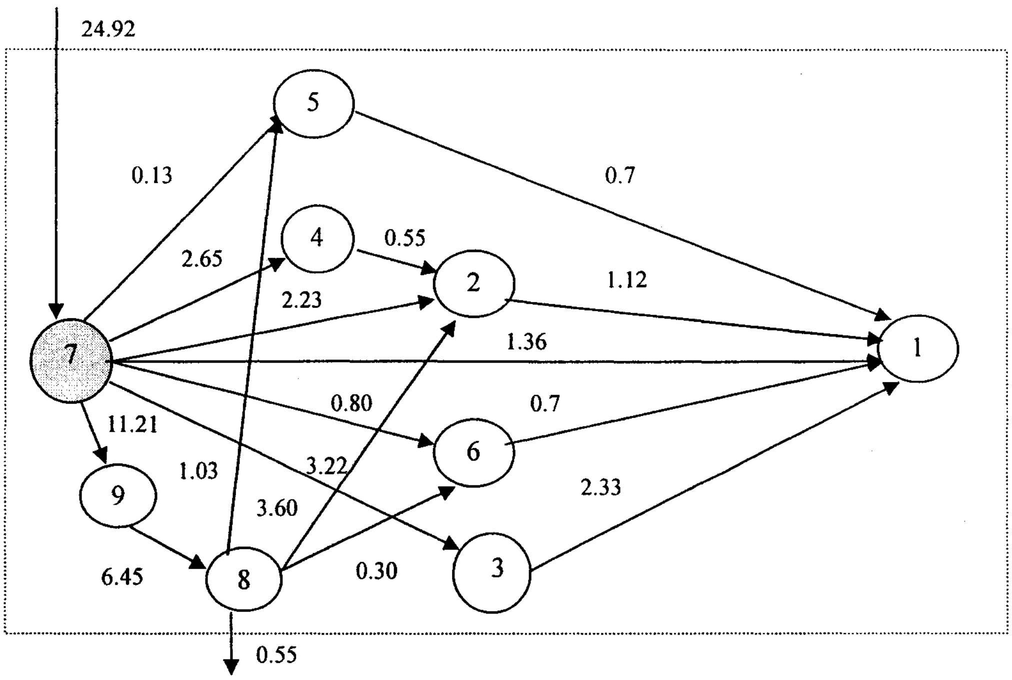


Figure A-15 Optimize flow for scenario 17 in which the total freshwater use is reduced by 32.35%

APPENDIX 9

Table 6-6 optimal flow data for different scenarios

Scenario	Total freshwater use (10^3m^3/day)	Percentage of freshwater use reduction	Percentage of total cost savings	Total wastewater discharge (10^3m^3/day)	Percentage of wastewater reduction	Total cost (10^6rmb/day)
0	36.84	0	0	10.07	0	2.005
1	30.61	16.91%	10.37%	5.48	45.58%	1.797
2	30.60	16.94%	10.32%	5.47	45.68%	1.798
3	30.59	16.97%	10.27%	5.46	45.78%	1.799
4	30.58	16.99%	10.22%	5.45	45.88%	1.800
5	30.56	17.05%	10.17%	5.44	45.98%	1.801
6	30.55	17.07%	10.12%	5.43	46.08%	1.802
7	30.54	17.10%	10.07%	5.42	46.18%	1.803
8	30.53	17.13%	10.02%	5.41	46.28%	1.804
9	30.52	17.16%	9.98%	5.40	46.38%	1.805
10	30.51	17.18%	9.93%	5.39	46.47%	1.806
11	30.49	17.24%	9.88%	5.38	46.57%	1.807
12	30.48	17.26%	9.83%	5.37	46.67%	1.808
13	30.47	17.29%	9.78%	5.36	46.77%	1.809
14	30.46	17.32%	9.73%	5.35	46.87%	1.810
15	30.45	17.35%	9.68%	5.34	46.97%	1.811
16	30.44	17.37%	9.63%	5.33	47.07%	1.812

17	30.42	17.43%	9.58%	5.32	47.17%	1.813
18	30.41	17.45%	9.53%	5.31	47.27%	1.814
19	30.40	17.48%	9.48%	5.30	47.37%	1.815
20	30.39	17.51%	9.43%	5.29	47.47%	1.816
21	30.38	17.54%	9.38%	5.28	47.57%	1.817
22	30.36	17.59%	9.33%	5.27	47.67%	1.818
23	30.35	17.62%	9.28%	5.26	47.77%	1.819
24	30.34	17.64%	9.23%	5.25	47.86%	1.820
25	30.33	17.67%	9.18%	5.24	47.96%	1.821
26	30.32	17.70%	9.13%	5.23	48.06%	1.822
27	30.30	17.75%	9.08%	5.22	48.16%	1.823
28	30.29	17.78%	9.03%	5.21	48.26%	1.824
29	30.28	17.81%	8.98%	5.20	48.36%	1.825
30	30.27	17.83%	8.93%	5.19	48.46%	1.826
31	30.26	17.86%	8.88%	5.18	48.56%	1.827
32	30.25	17.89%	8.83%	5.17	48.66%	1.828
33	30.23	17.94%	8.78%	5.16	48.76%	1.829
34	30.22	17.97%	8.73%	5.15	48.86%	1.830
35	30.21	18.00%	8.68%	5.14	48.96%	1.831
36	30.20	18.02%	8.63%	5.13	49.06%	1.832
37	30.19	18.05%	8.58%	5.12	49.16%	1.833
38	30.18	18.08%	8.53%	5.11	49.26%	1.834

39	30.17	18.11%	8.48%	5.10	49.35%	1.835
40	30.16	18.13%	8.43%	5.09	49.45%	1.836
41	30.14	18.19%	8.38%	5.08	49.55%	1.837
42	30.13	18.21%	8.33%	5.07	49.65%	1.838
43	30.12	18.24%	8.28%	5.06	49.75%	1.839
44	30.11	18.27%	8.23%	5.05	49.85%	1.840
45	30.10	18.30%	8.18%	5.04	49.95%	1.841
46	30.09	18.32%	8.13%	5.03	50.05%	1.842
47	30.08	18.35%	8.08%	5.02	50.15%	1.843
48	30.07	18.38%	8.03%	5.01	50.25%	1.844
49	30.05	18.43%	7.98%	5.00	50.35%	1.845
50	30.04	18.46%	7.93%	4.99	50.45%	1.846
51	30.03	18.49%	7.88%	4.98	50.55%	1.847
52	30.02	18.51%	7.83%	4.97	50.65%	1.848
53	30.01	18.54%	7.78%	4.96	50.74%	1.849
54	30.00	18.57%	7.33%	4.95	50.84%	1.858
55	29.99	18.59%	7.28%	4.94	50.94%	1.859
56	29.98	18.62%	7.28%	4.93	51.04%	1.859
57	29.97	18.65%	7.23%	4.92	51.14%	1.860
58	29.95	18.70%	7.18%	4.91	51.24%	1.861
59	29.94	18.73%	7.13%	4.90	51.34%	1.862
60	29.93	18.76%	7.08%	4.89	51.44%	1.863

61	29.92	18.78%	7.08%	4.88	51.54%	1.863
62	29.91	18.81%	7.03%	4.87	51.64%	1.864
63	29.89	18.87%	6.98%	4.86	51.74%	1.865
64	29.88	18.89%	6.93%	4.85	51.84%	1.866
65	29.87	18.92%	6.88%	4.84	51.94%	1.867
66	29.86	18.95%	6.88%	4.83	52.04%	1.867
67	29.84	19.00%	6.83%	4.82	52.14%	1.868
68	29.83	19.03%	6.78%	4.81	52.23%	1.869
69	29.82	19.06%	6.73%	4.80	52.33%	1.870
70	29.81	19.08%	6.68%	4.79	52.43%	1.871
71	29.80	19.11%	6.68%	4.78	52.53%	1.871
72	29.78	19.16%	6.63%	4.77	52.63%	1.872
73	29.77	19.19%	6.58%	4.76	52.73%	1.873
74	29.76	19.22%	6.53%	4.75	52.83%	1.874
75	29.75	19.25%	6.48%	4.74	52.93%	1.875
76	29.73	19.30%	6.48%	4.73	53.03%	1.875
77	29.72	19.33%	6.43%	4.72	53.13%	1.876
78	29.71	19.35%	6.38%	4.71	53.23%	1.877
79	29.70	19.38%	6.33%	4.70	53.33%	1.878
80	29.69	19.41%	6.28%	4.69	53.43%	1.879
81	29.67	19.46%	6.28%	4.68	53.53%	1.879
82	29.66	19.49%	6.23%	4.67	53.62%	1.880

83	29.65	19.52%	6.18%	4.66	53.72%	1.881
84	29.64	19.54%	6.13%	4.65	53.82%	1.882
85	29.63	19.57%	6.08%	4.64	53.92%	1.883
86	29.61	19.63%	6.08%	4.63	54.02%	1.883
87	29.60	19.65%	6.03%	4.62	54.12%	1.884
88	29.59	19.68%	5.99%	4.61	54.22%	1.885
89	29.58	19.71%	5.94%	4.60	54.32%	1.886
90	29.57	19.73%	5.89%	4.59	54.42%	1.887
91	29.55	19.79%	5.89%	4.58	54.52%	1.887
92	29.54	19.82%	5.84%	4.57	54.62%	1.888
93	29.53	19.84%	5.79%	4.56	54.72%	1.889
94	29.52	19.87%	5.74%	4.55	54.82%	1.890
95	29.51	19.90%	5.69%	4.54	54.92%	1.891
96	29.50	19.92%	5.69%	4.53	55.01%	1.891
97	29.49	19.95%	5.64%	4.52	55.11%	1.892
98	29.48	19.98%	5.59%	4.51	55.21%	1.893
99	29.47	20.01%	5.54%	4.50	55.31%	1.894
100	29.46	20.03%	5.49%	4.49	55.41%	1.895
101	29.45	20.06%	5.49%	4.48	55.51%	1.895
102	29.44	20.09%	5.44%	4.47	55.61%	1.896
103	29.43	20.11%	5.39%	4.46	55.71%	1.897
104	29.42	20.14%	5.34%	4.45	55.81%	1.898

105	29.41	20.17%	5.29%	4.44	55.91%	1.899
106	29.40	20.20%	5.24%	4.43	56.01%	1.900
107	29.38	20.25%	5.19%	4.42	56.11%	1.901
108	29.37	20.28%	5.14%	4.41	56.21%	1.902
109	29.36	20.30%	5.04%	4.40	56.31%	1.904
110	29.35	20.33%	4.99%	4.39	56.41%	1.905
111	29.34	20.36%	4.94%	4.38	56.50%	1.906
112	29.33	20.39%	4.89%	4.37	56.60%	1.907
113	29.32	20.41%	4.84%	4.36	56.70%	1.908
114	29.30	20.47%	4.74%	4.35	56.80%	1.910
115	29.29	20.49%	4.69%	4.34	56.90%	1.911
116	29.28	20.52%	4.64%	4.33	57.00%	1.912
117	29.27	20.55%	4.59%	4.32	57.10%	1.913
118	29.26	20.58%	4.54%	4.31	57.20%	1.914
119	29.25	20.60%	4.49%	4.30	57.30%	1.915
120	29.24	20.63%	4.44%	4.29	57.40%	1.916
121	29.23	20.66%	4.39%	4.28	57.50%	1.917
122	29.21	20.71%	4.34%	4.27	57.60%	1.918
123	29.20	20.74%	4.29%	4.26	57.70%	1.919
124	29.18	20.79%	4.24%	4.25	57.80%	1.920
125	29.17	20.82%	4.19%	4.24	57.89%	1.921
126	29.16	20.85%	4.14%	4.23	57.99%	1.922

127	29.15	20.87%	4.09%	4.22	58.09%	1.923
128	29.14	20.90%	4.04%	4.21	58.19%	1.924
129	29.13	20.93%	3.99%	4.20	58.29%	1.925
130	29.12	20.96%	3.94%	4.19	58.39%	1.926
131	29.11	20.98%	3.89%	4.18	58.49%	1.927
132	29.10	21.01%	3.84%	4.17	58.59%	1.928
133	29.09	21.04%	3.79%	4.16	58.69%	1.929
134	29.08	21.06%	3.74%	4.15	58.79%	1.930
135	29.06	21.12%	3.69%	4.14	58.89%	1.931
136	29.05	21.15%	3.64%	4.13	58.99%	1.932
137	29.04	21.17%	3.59%	4.12	59.09%	1.933
138	29.03	21.20%	3.54%	4.11	59.19%	1.934
139	29.02	21.23%	3.49%	4.10	59.29%	1.935
140	29.01	21.25%	3.44%	4.09	59.38%	1.936
141	28.99	21.31%	3.39%	4.08	59.48%	1.937
142	28.98	21.34%	3.34%	4.07	59.58%	1.938
143	28.97	21.36%	3.29%	4.06	59.68%	1.939
144	28.96	21.39%	3.24%	4.05	59.78%	1.940
145	28.95	21.42%	3.19%	4.04	59.88%	1.941
146	28.94	21.44%	3.14%	4.03	59.98%	1.942
147	28.92	21.50%	3.09%	4.02	60.08%	1.943
148	28.91	21.53%	3.04%	4.01	60.18%	1.944

149	28.90	21.55%	2.99%	4.00	60.28%	1.945
150	28.89	21.58%	2.94%	3.99	60.38%	1.946
151	28.88	21.61%	2.89%	3.98	60.48%	1.947
152	28.87	21.63%	2.84%	3.97	60.58%	1.948
153	28.85	21.69%	2.79%	3.96	60.68%	1.949
154	28.84	21.72%	2.79%	3.95	60.77%	1.949
155	28.83	21.74%	2.74%	3.94	60.87%	1.950
156	28.82	21.77%	2.69%	3.93	60.97%	1.951
157	28.81	21.80%	2.64%	3.92	61.07%	1.952
158	28.79	21.85%	2.59%	3.91	61.17%	1.953
159	28.78	21.88%	2.54%	3.90	61.27%	1.954
160	28.77	21.91%	2.49%	3.89	61.37%	1.955
161	28.76	21.93%	2.44%	3.88	61.47%	1.956
162	28.75	21.96%	2.39%	3.87	61.57%	1.957
163	28.74	21.99%	2.34%	3.86	61.67%	1.958
164	28.73	22.01%	2.34%	3.85	61.77%	1.958
165	28.72	22.04%	2.29%	3.84	61.87%	1.959
166	28.71	22.07%	2.24%	3.83	61.97%	1.960
167	28.70	22.10%	2.19%	3.82	62.07%	1.961
168	28.69	22.12%	2.14%	3.81	62.16%	1.962
169	28.67	22.18%	2.09%	3.80	62.26%	1.963
170	28.66	22.20%	2.04%	3.79	62.36%	1.964

171	28.65	22.23%	2.00%	3.78	62.46%	1.965
172	28.64	22.26%	2.00%	3.77	62.56%	1.965
173	28.63	22.29%	1.95%	3.76	62.66%	1.966
174	28.61	22.34%	1.90%	3.75	62.76%	1.967
175	28.60	22.37%	1.85%	3.74	62.86%	1.968
176	28.59	22.39%	1.80%	3.73	62.96%	1.969
177	28.58	22.42%	1.75%	3.72	63.06%	1.970
178	28.57	22.45%	1.75%	3.71	63.16%	1.970
179	28.56	22.48%	1.70%	3.70	63.26%	1.971
180	28.55	22.50%	1.65%	3.69	63.36%	1.972
181	28.54	22.53%	1.60%	3.68	63.46%	1.973
182	28.53	22.56%	1.55%	3.67	63.56%	1.974
183	28.52	22.58%	1.50%	3.66	63.65%	1.975
184	28.51	22.61%	1.50%	3.65	63.75%	1.975
185	28.50	22.64%	1.45%	3.64	63.85%	1.976
186	28.48	22.69%	1.40%	3.63	63.95%	1.977
187	28.47	22.72%	1.35%	3.62	64.05%	1.978
188	28.46	22.75%	1.30%	3.61	64.15%	1.979
189	28.45	22.77%	1.25%	3.60	64.25%	1.980
190	28.44	22.80%	1.20%	3.59	64.35%	1.981
191	28.42	22.86%	1.20%	3.58	64.45%	1.981
192	28.41	22.88%	1.15%	3.57	64.55%	1.982

193	28.40	22.91%	1.10%	3.56	64.65%	1.983
194	28.39	22.94%	1.05%	3.55	64.75%	1.984
195	28.38	22.96%	1.00%	3.54	64.85%	1.985
196	28.36	23.02%	0.95%	3.53	64.95%	1.986
197	28.35	23.05%	0.90%	3.52	65.04%	1.987
198	28.34	23.07%	0.90%	3.51	65.14%	1.987
199	28.33	23.10%	0.85%	3.50	65.24%	1.988
200	28.32	23.13%	0.80%	3.49	65.34%	1.989
201	28.31	23.15%	0.75%	3.48	65.44%	1.990
202	28.29	23.21%	0.70%	3.47	65.54%	1.991
203	28.28	23.24%	0.65%	3.46	65.64%	1.992
204	28.27	23.26%	0.60%	3.45	65.74%	1.993
205	28.26	23.29%	0.60%	3.44	65.84%	1.993
206	28.25	23.32%	0.55%	3.43	65.94%	1.994
207	28.24	23.34%	0.50%	3.42	66.04%	1.995
208	28.22	23.40%	0.45%	3.41	66.14%	1.996
209	28.21	23.43%	0.40%	3.40	66.24%	1.997
210	28.20	23.45%	0.35%	3.39	66.34%	1.998
211	28.19	23.48%	0.30%	3.38	66.43%	1.999
212	28.18	23.51%	0.30%	3.37	66.53%	1.999
213	28.17	23.53%	0.25%	3.36	66.63%	2.000
214	28.15	23.59%	0.20%	3.35	66.73%	2.001

215	28.14	23.62%	0.15%	3.34	66.83%	2.002
216	28.13	23.64%	0.10%	3.33	66.93%	2.003
217	28.12	23.67%	0.05%	3.32	67.03%	2.004
218	28.11	23.70%	0.00%	3.31	67.13%	2.005
219	28.10	23.72%	-0.05%	3.30	67.23%	2.006
220	28.08	23.78%	-0.05%	3.29	67.33%	2.006
221	28.07	23.81%	-0.10%	3.28	67.43%	2.007
222	28.06	23.83%	-0.15%	3.27	67.53%	2.008
223	28.05	23.86%	-0.20%	3.26	67.63%	2.009
224	28.04	23.89%	-0.25%	3.25	67.73%	2.010
225	28.03	23.91%	-0.30%	3.24	67.83%	2.011
226	28.02	23.94%	-0.30%	3.23	67.92%	2.011
227	28.00	24.00%	-0.35%	3.22	68.02%	2.012
228	27.99	24.02%	-0.40%	3.21	68.12%	2.013
229	27.98	24.05%	-0.45%	3.20	68.22%	2.014
230	27.97	24.08%	-0.50%	3.19	68.32%	2.015
231	27.96	24.10%	-0.50%	3.18	68.42%	2.015
232	27.95	24.13%	-0.55%	3.17	68.52%	2.016
233	27.94	24.16%	-0.60%	3.16	68.62%	2.017
234	27.92	24.21%	-0.65%	3.15	68.72%	2.018
235	27.91	24.24%	-0.70%	3.14	68.82%	2.019
236	27.90	24.27%	-0.70%	3.13	68.92%	2.019

237	27.89	24.29%	-0.75%	3.12	69.02%	2.020
238	27.88	24.32%	-0.80%	3.11	69.12%	2.021
239	27.87	24.35%	-0.85%	3.10	69.22%	2.022
240	27.85	24.40%	-0.90%	3.09	69.31%	2.023
241	27.84	24.43%	-0.90%	3.08	69.41%	2.023
242	27.83	24.46%	-0.95%	3.07	69.51%	2.024
243	27.82	24.48%	-1.00%	3.06	69.61%	2.025
244	27.81	24.51%	-1.05%	3.05	69.71%	2.026
245	27.79	24.57%	-1.10%	3.04	69.81%	2.027
246	27.78	24.59%	-1.15%	3.03	69.91%	2.028
247	27.77	24.62%	-1.15%	3.02	70.01%	2.028
248	27.76	24.65%	-1.20%	3.01	70.11%	2.029
249	27.75	24.67%	-1.25%	3.00	70.21%	2.030
250	27.73	24.73%	-1.30%	2.99	70.31%	2.031
251	27.72	24.76%	-1.35%	2.98	70.41%	2.032
252	27.71	24.78%	-1.40%	2.97	70.51%	2.033
253	27.70	24.81%	-1.40%	2.96	70.61%	2.033
254	27.69	24.84%	-1.45%	2.95	70.71%	2.034
255	27.68	24.86%	-1.50%	2.94	70.80%	2.035
256	27.67	24.89%	-1.55%	2.93	70.90%	2.036
257	27.65	24.95%	-1.55%	2.92	71.00%	2.036
258	27.64	24.97%	-1.60%	2.91	71.10%	2.037

259	27.63	25.00%	-1.65%	2.90	71.20%	2.038
260	27.62	25.03%	-1.70%	2.89	71.30%	2.039
261	27.61	25.05%	-1.75%	2.88	71.40%	2.040
262	27.60	25.08%	-1.75%	2.87	71.50%	2.040
263	27.59	25.11%	-1.80%	2.86	71.60%	2.041
264	27.58	25.14%	-1.85%	2.85	71.70%	2.042
265	27.56	25.19%	-1.90%	2.84	71.80%	2.043
266	27.55	25.22%	-1.90%	2.83	71.90%	2.043
267	27.54	25.24%	-1.95%	2.82	72.00%	2.044
268	27.53	25.27%	-2.00%	2.81	72.10%	2.045
269	27.52	25.30%	-2.04%	2.80	72.19%	2.046
270	27.51	25.33%	-2.04%	2.79	72.29%	2.046
271	27.49	25.38%	-2.09%	2.78	72.39%	2.047
272	27.48	25.41%	-2.14%	2.77	72.49%	2.048
273	27.47	25.43%	-2.19%	2.76	72.59%	2.049
274	27.46	25.46%	-2.19%	2.75	72.69%	2.049
275	27.45	25.49%	-2.24%	2.74	72.79%	2.050
276	27.43	25.54%	-2.29%	2.73	72.89%	2.051
277	27.42	25.57%	-2.34%	2.72	72.99%	2.052
278	27.41	25.60%	-2.34%	2.71	73.09%	2.052
279	27.40	25.62%	-2.39%	2.70	73.19%	2.053
280	27.39	25.65%	-2.39%	2.69	73.29%	2.053

281	27.37	25.71%	-2.44%	2.68	73.39%	2.054
282	27.36	25.73%	-2.49%	2.67	73.49%	2.055
283	27.35	25.76%	-2.54%	2.66	73.58%	2.056
284	27.34	25.79%	-2.59%	2.65	73.68%	2.057
285	27.33	25.81%	-2.59%	2.64	73.78%	2.057
286	27.32	25.84%	-2.64%	2.63	73.88%	2.058
287	27.31	25.87%	-2.69%	2.62	73.98%	2.059
288	27.29	25.92%	-2.74%	2.61	74.08%	2.060
289	27.28	25.95%	-2.79%	2.60	74.18%	2.061
290	27.27	25.98%	-2.79%	2.59	74.28%	2.061
291	27.26	26.00%	-2.84%	2.58	74.38%	2.062
292	27.25	26.03%	-2.89%	2.57	74.48%	2.063
293	27.24	26.06%	-2.94%	2.56	74.58%	2.064
294	27.22	26.11%	-2.99%	2.55	74.68%	2.065
295	27.21	26.14%	-2.99%	2.54	74.78%	2.065
296	27.20	26.17%	-3.04%	2.53	74.88%	2.066
297	27.19	26.19%	-3.09%	2.52	74.98%	2.067
298	27.18	26.22%	-3.14%	2.51	75.07%	2.068
299	27.17	26.25%	-3.19%	2.50	75.17%	2.069
300	27.16	26.28%	-3.19%	2.49	75.27%	2.069
301	27.14	26.33%	-3.24%	2.48	75.37%	2.070
302	27.13	26.36%	-3.29%	2.47	75.47%	2.071

303	27.12	26.38%	-3.34%	2.46	75.57%	2.072
304	27.11	26.41%	-3.39%	2.45	75.67%	2.073
305	27.10	26.44%	-3.39%	2.44	75.77%	2.073
306	27.09	26.47%	-3.44%	2.43	75.87%	2.074
307	27.08	26.49%	-3.49%	2.42	75.97%	2.075
308	27.06	26.55%	-3.54%	2.41	76.07%	2.076
309	27.05	26.57%	-3.59%	2.40	76.17%	2.077
310	27.04	26.60%	-3.59%	2.39	76.27%	2.077
311	27.03	26.63%	-3.64%	2.38	76.37%	2.078
312	27.02	26.66%	-3.69%	2.37	76.46%	2.079
313	24.01	34.83%	-3.74%	2.36	76.56%	2.080
314	27.00	26.71%	-3.74%	2.35	76.66%	2.080
315	26.98	26.76%	-3.79%	2.34	76.76%	2.081
316	26.97	26.79%	-3.84%	2.33	76.86%	2.082
317	26.96	26.82%	-3.89%	2.32	76.96%	2.083
318	26.95	26.85%	-3.89%	2.31	77.06%	2.083
319	26.94	26.87%	-3.94%	2.30	77.16%	2.084
320	26.93	26.90%	-3.99%	2.29	77.26%	2.085
321	26.91	26.95%	-4.04%	2.28	77.36%	2.086
322	26.90	26.98%	-4.04%	2.27	77.46%	2.086
323	26.89	27.01%	-4.09%	2.26	77.56%	2.087
324	26.88	27.04%	-4.14%	2.25	77.66%	2.088

325	26.87	27.06%	-4.19%	2.24	77.76%	2.089
326	26.86	27.09%	-4.19%	2.23	77.86%	2.089
327	26.84	27.14%	-4.24%	2.22	77.95%	2.090
328	26.83	27.17%	-4.29%	2.21	78.05%	2.091
329	26.82	27.20%	-4.34%	2.20	78.15%	2.092
330	26.81	27.23%	-4.34%	2.19	78.25%	2.092
331	26.80	27.25%	-4.39%	2.18	78.35%	2.093
332	26.79	27.28%	-4.44%	2.17	78.45%	2.094
333	26.78	27.31%	-4.49%	2.16	78.55%	2.095
334	26.76	27.36%	-4.49%	2.15	78.65%	2.095
335	26.75	27.39%	-4.54%	2.14	78.75%	2.096
336	26.74	27.42%	-4.59%	2.13	78.85%	2.097
337	26.73	27.44%	-4.64%	2.12	78.95%	2.098
338	26.72	27.47%	-4.64%	2.11	79.05%	2.098
339	26.71	27.50%	-4.69%	2.10	79.15%	2.099
340	26.70	27.52%	-4.74%	2.09	79.25%	2.100
341	26.68	27.58%	-4.79%	2.08	79.34%	2.101
342	26.67	27.61%	-4.79%	2.07	79.44%	2.101
343	26.66	27.63%	-4.84%	2.06	79.54%	2.102
344	26.65	27.66%	-4.89%	2.05	79.64%	2.103
345	26.64	27.69%	-4.94%	2.04	79.74%	2.104
346	26.63	27.71%	-4.94%	2.03	79.84%	2.104

347	26.61	27.77%	-4.99%	2.02	79.94%	2.105
348	26.62	27.74%	-5.04%	2.01	80.04%	2.106
349	26.60	27.80%	-5.09%	2.00	80.14%	2.107
350	26.58	27.85%	-5.09%	1.99	80.24%	2.107
351	26.57	27.88%	-5.14%	1.98	80.34%	2.108
352	26.56	27.90%	-5.19%	1.97	80.44%	2.109
353	26.55	27.93%	-5.19%	1.96	80.54%	2.109
354	26.54	27.96%	-5.24%	1.95	80.64%	2.110
355	26.53	27.99%	-5.24%	1.94	80.73%	2.110
356	26.51	28.04%	-5.29%	1.93	80.83%	2.111
357	26.50	28.07%	-5.34%	1.92	80.93%	2.112
358	26.49	28.09%	-5.34%	1.91	81.03%	2.112
359	26.48	28.12%	-5.39%	1.90	81.13%	2.113
360	26.47	28.15%	-5.44%	1.89	81.23%	2.114
361	26.46	28.18%	-5.49%	1.88	81.33%	2.115
362	26.45	28.20%	-5.49%	1.87	81.43%	2.115
363	26.44	28.23%	-5.54%	1.86	81.53%	2.116
364	26.43	28.26%	-5.59%	1.85	81.63%	2.117
365	26.42	28.28%	-5.64%	1.84	81.73%	2.118
366	26.41	28.31%	-5.64%	1.83	81.83%	2.118
367	26.39	28.37%	-5.69%	1.82	81.93%	2.119
368	26.38	28.39%	-5.74%	1.81	82.03%	2.120

369	26.37	28.42%	-5.79%	1.80	82.13%	2.121
370	26.36	28.45%	-5.79%	1.79	82.22%	2.121
371	26.35	28.47%	-5.84%	1.78	82.32%	2.122
372	26.33	28.53%	-5.89%	1.77	82.42%	2.123
373	26.32	28.56%	-5.94%	1.76	82.52%	2.124
374	26.31	28.58%	-5.94%	1.75	82.62%	2.124
375	26.30	28.61%	-5.99%	1.74	82.72%	2.125
376	26.29	28.64%	-6.03%	1.73	82.82%	2.126
377	26.27	28.69%	-6.08%	1.72	82.92%	2.127
378	26.26	28.72%	-6.08%	1.71	83.02%	2.127
379	26.25	28.75%	-6.13%	1.70	83.12%	2.128
380	26.24	28.77%	-6.18%	1.69	83.22%	2.129
381	26.23	28.80%	-6.23%	1.68	83.32%	2.130
382	26.21	28.85%	-6.23%	1.67	83.42%	2.130
383	26.20	28.88%	-6.28%	1.66	83.52%	2.131
384	26.19	28.91%	-6.33%	1.65	83.61%	2.132
385	26.18	28.94%	-6.38%	1.64	83.71%	2.133
386	26.17	28.96%	-6.38%	1.63	83.81%	2.133
387	26.15	29.02%	-6.43%	1.62	83.91%	2.134
388	26.14	29.04%	-6.48%	1.61	84.01%	2.135
389	26.13	29.07%	-6.53%	1.60	84.11%	2.136
390	26.12	29.10%	-6.53%	1.59	84.21%	2.136

391	26.11	29.13%	-6.58%	1.58	84.31%	2.137
392	26.09	29.18%	-6.63%	1.57	84.41%	2.138
393	26.08	29.21%	-6.63%	1.56	84.51%	2.138
394	26.07	29.23%	-6.68%	1.55	84.61%	2.139
395	26.06	29.26%	-6.73%	1.54	84.71%	2.140
396	26.05	29.29%	-6.78%	1.53	84.81%	2.141
397	26.04	29.32%	-6.78%	1.52	84.91%	2.141
398	26.03	29.34%	-6.83%	1.51	85.00%	2.142
399	26.02	29.37%	-6.88%	1.50	85.10%	2.143
400	26.01	29.40%	-6.93%	1.49	85.20%	2.144
401	25.99	29.45%	-6.93%	1.48	85.30%	2.144
402	25.98	29.48%	-6.98%	1.47	85.40%	2.145
403	25.97	29.51%	-7.03%	1.46	85.50%	2.146
404	25.96	29.53%	-7.03%	1.45	85.60%	2.146
405	25.95	29.56%	-7.08%	1.44	85.70%	2.147
406	25.93	29.61%	-7.08%	1.43	85.80%	2.147
407	25.92	29.64%	-7.13%	1.42	85.90%	2.148
408	25.91	29.67%	-7.18%	1.41	86.00%	2.149
409	25.90	29.70%	-7.18%	1.40	86.10%	2.149
410	25.89	29.72%	-7.23%	1.39	86.20%	2.150
411	25.88	29.75%	-7.28%	1.38	86.30%	2.151
412	25.86	29.80%	-7.33%	1.37	86.40%	2.152

413	25.85	29.83%	-7.33%	1.36	86.49%	2.152
414	25.84	29.86%	-7.38%	1.35	86.59%	2.153
415	25.83	29.89%	-7.43%	1.34	86.69%	2.154
416	25.82	29.91%	-7.43%	1.33	86.79%	2.154
417	25.81	29.94%	-7.48%	1.32	86.89%	2.155
418	25.79	29.99%	-7.53%	1.31	86.99%	2.156
419	25.78	30.02%	-7.58%	1.30	87.09%	2.157
420	25.77	30.05%	-7.58%	1.29	87.19%	2.157
421	25.76	30.08%	-7.63%	1.28	87.29%	2.158
422	25.75	30.10%	-7.68%	1.27	87.39%	2.159
423	25.74	30.13%	-7.68%	1.26	87.49%	2.159
424	25.72	30.18%	-7.73%	1.25	87.59%	2.160
425	25.71	30.21%	-7.78%	1.24	87.69%	2.161
426	25.70	30.24%	-7.83%	1.23	87.79%	2.162
427	25.69	30.27%	-7.83%	1.22	87.88%	2.162
428	25.68	30.29%	-7.88%	1.21	87.98%	2.163
429	25.67	30.32%	-7.93%	1.20	88.08%	2.164
430	25.65	30.37%	-7.93%	1.19	88.18%	2.164
431	25.64	30.40%	-7.98%	1.18	88.28%	2.165
432	25.63	30.43%	-8.03%	1.17	88.38%	2.166
433	25.62	30.46%	-8.03%	1.16	88.48%	2.166
434	25.61	30.48%	-8.08%	1.15	88.58%	2.167

435	25.60	30.51%	-8.13%	1.14	88.68%	2.168
436	25.59	30.54%	-8.13%	1.13	88.78%	2.168
437	25.58	30.56%	-8.18%	1.12	88.88%	2.169
438	25.56	30.62%	-8.23%	1.11	88.98%	2.170
439	25.55	30.65%	-8.23%	1.10	89.08%	2.170
440	25.54	30.67%	-8.28%	1.09	89.18%	2.171
441	25.52	30.73%	-8.33%	1.08	89.28%	2.172
442	25.51	30.75%	-8.33%	1.07	89.37%	2.172
443	25.50	30.78%	-8.38%	1.06	89.47%	2.173
444	25.49	30.81%	-8.43%	1.05	89.57%	2.174
445	25.48	30.84%	-8.43%	1.04	89.67%	2.174
446	25.47	30.86%	-8.48%	1.03	89.77%	2.175
447	25.46	30.89%	-8.53%	1.02	89.87%	2.176
448	25.45	30.92%	-8.53%	1.01	89.97%	2.176
449	25.44	30.94%	-8.58%	1.00	90.07%	2.177
450	25.43	30.97%	-8.63%	0.99	90.17%	2.178
451	25.41	31.03%	-8.63%	0.98	90.27%	2.178
452	25.40	31.05%	-8.68%	0.97	90.37%	2.179
453	25.39	31.08%	-8.73%	0.96	90.47%	2.180
454	25.38	31.11%	-8.73%	0.95	90.57%	2.180
455	25.37	31.13%	-8.78%	0.94	90.67%	2.181
456	25.36	31.16%	-8.83%	0.93	90.76%	2.182

457	25.34	31.22%	-8.88%	0.92	90.86%	2.183
458	25.33	31.24%	-8.88%	0.91	90.96%	2.183
459	25.32	31.27%	-8.93%	0.90	91.06%	2.184
460	25.31	31.30%	-8.98%	0.89	91.16%	2.185
461	25.30	31.32%	-8.98%	0.88	91.26%	2.185
462	25.29	31.08%	-9.03%	0.87	91.36%	2.186
463	25.28	31.11%	-9.08%	0.86	91.46%	2.187
464	25.27	31.41%	-9.08%	0.85	91.56%	2.187
465	25.26	31.43%	-9.13%	0.84	91.66%	2.188
466	25.25	31.46%	-9.18%	0.83	91.76%	2.189
467	25.24	31.49%	-9.23%	0.82	91.86%	2.190
468	25.23	31.51%	-9.28%	0.81	91.96%	2.191
469	25.21	31.57%	-9.33%	0.80	92.06%	2.192
470	25.20	31.60%	-9.38%	0.79	92.15%	2.193
471	25.19	31.62%	-9.43%	0.78	92.25%	2.194
472	25.18	31.65%	-9.48%	0.77	92.35%	2.195
473	25.17	31.68%	-9.53%	0.76	92.45%	2.196
474	25.16	31.70%	-9.58%	0.75	92.55%	2.197
475	25.14	31.76%	-9.63%	0.74	92.65%	2.198
476	25.13	31.79%	-9.68%	0.73	92.75%	2.199
477	25.12	31.81%	-9.73%	0.72	92.85%	2.200
478	25.11	31.84%	-9.78%	0.71	92.95%	2.201

479	25.10	31.87%	-9.83%	0.70	93.05%	2.202
480	25.09	31.89%	-9.83%	0.69	93.15%	2.202
481	25.07	31.95%	-9.88%	0.68	93.25%	2.203
482	25.06	31.98%	-9.93%	0.67	93.35%	2.204
483	25.05	32.00%	-9.98%	0.66	93.45%	2.205
484	25.04	32.03%	-10.02%	0.65	93.55%	2.206
485	25.03	32.06%	-10.07%	0.64	93.64%	2.207
486	25.02	32.08%	-10.12%	0.63	93.74%	2.208
487	25.00	32.14%	-10.17%	0.62	93.84%	2.209
488	24.99	32.17%	-10.22%	0.61	93.94%	2.210
489	24.98	32.19%	-10.27%	0.60	94.04%	2.211
490	25.97	29.51%	-10.32%	0.59	94.14%	2.212
491	24.96	32.25%	-10.37%	0.58	94.24%	2.213
492	24.95	32.27%	-10.42%	0.57	94.34%	2.214
493	24.93	32.33%	-10.47%	0.56	94.44%	2.215
494	24.92	32.36%	-10.52%	0.55	94.54%	2.216
495	24.91	32.38%	-10.57%	0.54	94.64%	2.217
496	24.90	32.41%	-10.62%	0.53	94.74%	2.218
497	24.89	32.44%	-10.62%	0.52	94.84%	2.218
498	24.87	32.49%	-10.67%	0.51	94.94%	2.219
499	24.86	32.52%	-10.72%	0.50	95.03%	2.220
500	24.85	32.55%	-10.77%	0.49	95.13%	2.221

501	24.84	32.57%	-10.82%	0.48	95.23%	2.222
502	24.82	32.63%	-10.82%	0.47	95.33%	2.222
503	24.81	32.65%	-10.87%	0.46	95.43%	2.223
504	24.80	32.68%	-10.92%	0.45	95.53%	2.224
505	24.79	32.71%	-10.97%	0.44	95.63%	2.225
506	24.78	32.74%	-10.97%	0.43	95.73%	2.225
507	24.76	32.79%	-11.02%	0.42	95.83%	2.226
508	24.75	32.82%	-11.07%	0.41	95.93%	2.227
509	24.74	32.84%	-11.07%	0.40	96.03%	2.227
510	24.73	32.87%	-11.12%	0.39	96.13%	2.228
511	24.72	32.90%	-11.17%	0.38	96.23%	2.229
512	24.71	32.93%	-11.22%	0.37	96.33%	2.230
513	24.70	32.95%	-11.22%	0.36	96.43%	2.230
514	24.69	32.98%	-11.27%	0.35	96.52%	2.231
515	24.68	33.01%	-11.32%	0.34	96.62%	2.232
516	24.67	33.03%	-11.32%	0.33	96.72%	2.232
517	24.65	33.09%	-11.37%	0.32	96.82%	2.233
518	24.64	33.12%	-11.42%	0.31	96.92%	2.234
519	24.63	33.14%	-11.47%	0.30	97.02%	2.235
520	24.62	33.17%	-11.47%	0.29	97.12%	2.235
521	24.61	33.20%	-11.52%	0.28	97.22%	2.236
522	24.59	33.25%	-11.57%	0.27	97.32%	2.237

523	24.58	33.28%	-11.57%	0.26	97.42%	2.237
524	24.57	33.31%	-11.62%	0.25	97.52%	2.238
524	24.56	33.33%	-11.67%	0.24	97.62%	2.239
526	24.55	33.36%	-11.72%	0.23	97.72%	2.240
527	24.53	33.41%	-11.72%	0.22	97.82%	2.240
528	24.52	33.44%	-11.77%	0.21	97.91%	2.241
529	24.51	33.47%	-11.82%	0.20	98.01%	2.242
530	24.50	33.50%	-11.82%	0.19	98.11%	2.242
531	24.49	33.52%	-11.87%	0.18	98.21%	2.243
532	24.48	33.55%	-11.92%	0.17	98.31%	2.244
533	24.47	33.58%	-11.97%	0.16	98.41%	2.245
534	24.46	33.60%	-11.97%	0.15	98.51%	2.245
535	24.45	33.63%	-12.02%	0.14	98.61%	2.246
536	24.44	33.66%	-12.07%	0.13	98.71%	2.247
537	24.42	33.71%	-12.07%	0.12	98.81%	2.247
538	24.41	33.74%	-12.12%	0.11	98.91%	2.248
539	24.40	33.77%	-12.17%	0.10	99.01%	2.249
540	24.39	33.79%	-12.22%	0.09	99.11%	2.250
541	24.38	33.82%	-12.22%	0.08	99.21%	2.250
542	24.37	33.85%	-12.27%	0.07	99.30%	2.251
543	24.36	33.88%	-12.32%	0.06	99.40%	2.252
544	24.35	33.90%	-12.32%	0.05	99.50%	2.252

545	24.34	33.93%	-12.37%	0.04	99.60%	2.253
546	24.32	33.98%	-12.42%	0.03	99.70%	2.254
547	24.31	34.01%	-12.47%	0.02	99.80%	2.255
548	24.30	34.04%	-12.47%	0.01	99.90%	2.255
549	24.29	34.07%	-12.52%	0	100%	2.256