A Study on Urban Water Reuse Management Modeling

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Systems Design Engineering

Waterloo, Ontario, Canada, 2004

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

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Abstract

This research deals with urban water reuse planning and management modeling in the context of sustainable development. Rapid urbanization and population growth have presented a great challenge to urban water resources management. As water reuse may alleviate pollution loads and enhance water supply sources, water reuse is being recognized as a sustainable urban water management strategy and is becoming increasingly attractive in urban water resources management. An efficient water reuse planning and management model is of significance in promoting water reuse practices.

This thesis introduces an urban water reuse management and planning model using optimization methods with an emphasis on modeling uncertainty issues associated with water demand and water quality. The model is developed in conjunction with the overall urban water system with considerations over water supply, water demand, water distribution, water quality, and wastewater treatment and discharge. The objective of the model is to minimize the overall cost of the system subject to technological, societal and environmental constraints. Uncertainty issues associated with water demand and treatment quality are modeled by introducing stochastic programming methods, namely, two-stage stochastic recourse programming and chance-constraint programming.

The model is capable of identifying and evaluating water reuse in urban water systems to optimize the allocation of urban water resources with regard to uncertainties. It thus provides essential information in planning and managing urban water reuse systems

towards a more sustainable urban water resources management. An application was presented in order to demonstrate the modeling process and to analyze the impact of uncertainties.

Acknowledgements

I would like to express my gratitude to my supervisors, Prof. Kumaraswamy Ponnambalam and Prof. Paul Calamai for their excellent courses, outstanding guidance and continuous support during my study and the work leading to this thesis. I appreciate Prof. David Clausi and Prof. Murray Haight for reviewing this thesis, and for their insightful and valuable suggestions. Also I want to thank Prof. Douglas Dudycha and Prof. Peter Deadman for their excellent GIS courses.

Special thanks to our Graduate Secretary Ms. Vicky Lawrence for her kindness and advice throughout my study at the Department of Systems Design Engineering.

Thanks to the Natural Sciences and Engineering Research Council of Canada for the financial support through my supervisors. My appreciation to Prof. Geoffrey Wall, Dr. David Wood and Dr. Geng Yong and the Eco-Plan China Project Committee for the support they provided. Thanks to Ms. Patti Cook, Ms. Jessica Winkler, Mr. Tim Walton and Mr. Manfred Klein for the material and information they provided for this research.

My deep gratitude to John & Joy Hamilton for their kindness and prayers, and to all my friends for their help, encouragement and friendship all along the way on my journey of completing my master's degree.

I greatly thank my parents for their love, support and faith that made me who I am. I want to thank my parents-in-law, my sisters, brothers and their families. Sincerest thanks to my wife, Yingping, for her love and all she has done for me. She has always been a great source of inspiration, has always been a soild support throughout my work and has made a great difference in my life.

To the memory of my father, Zhang Yong Guo

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Chapter 1

Introduction

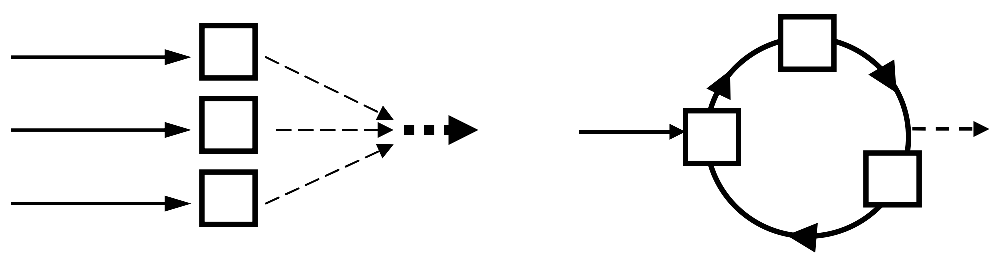
1.1 Background and Motivation

During the last century, rapid urbanization and population growth have resulted in many environmental problems. Among those the most serious are water shortage and pollution. People around the world are beginning to realize the interactions between human beings and the environment. Human activities are affecting the natural water ecological cycle in many ways such as: the reduction of forested areas, the shrinkage of the grass land for grazing, and the spread of urban growth resulting in increased rainwater lost to runoff; overexploitation of groundwater resources have decreased groundwater levels and caused problems of seawater intrusion; toxic industrial discharge and the extensive use of chemical fertilizers have polluted much of the water supply. Many regions in the world are facing the great challenge of water shortage and pollution, and the situation is getting worse. The United Nations Environment Programme (UNEP) identified that water shortage and global warming are the two most worrying problems for the new millennium and the World Water Council believes that by 2020 the world will need 17% more water than is currently available (WWC, 2000).

As populations are generally concentrated in urban areas, urban demands on water resources have increased rapidly during the last few decades, and urbanization continues to worsen the situation. According to a United Nations report (United Nations, 1989), over the last 50 years, the urban population has been tripled and now accounts for nearly half of the total population. The world water demand has also tripled since 1950 and is continuing to rise as 80 million more people are added each year. As urban populations place greater pressure on water supplies, expansion of water supplies is usually the only means employed to meet the growing water demands; at the same time the economical and ecological limits of the water supplies have generally been ignored. The fact is that in many regions of the world, water consumption is nearing or surpassing the limits of natural systems (Postel and Oasis, 1993). For example, Liaoning, the northeast province of China, is a traditional industrial base of China and has a large urban population (25.7 millions of total population of 42.38 millions) with heavy water consumption. In recent years, excessive extraction of water has resulted in the sinking of the ground in a 1,500-square-kilometer area and intrusion of seawater in more than five cities (Zhang, 2000). The government has banned construction of new wells and other facilities for extracting groundwater in certain cities since it is realized that water resource management has to comply with the standards of sustainable development.

Like Liaoning province, many communities in the world are seeking a sustainable water management strategy. Sustainable Development was defined by the World Commission on Environment and Development (WCED) as: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). For several decades, water reuse has been recognized as a component of sustainable urban water management strategy and has been practiced by many communities. Water reclamation and reuse are regarded as a "win-win" strategy for both reducing pollution and enhancing water supply resources (Parkinson *et al.,* 2000).

In a traditional urban water system, after water use, wastewater is treated to certain legalized quality levels when discharged into receiving water bodies. Such a water use system is generally regarded as a once-through system (Indigo, 2003), as illustrated in Figure 1.1 (a). In such system water is only used once, so the efficiency of water use is low. Figure 1.1 (b) represents a looped system created when treated wastewater is reused for some applications which do not require high-quality drinking water, such as irrigation and sanitation. Wastewater reuse practices will help in satisfying more water demands while effluent discharge can be reduced. Although a looped system is relatively complex, it provides much higher water use efficiency.



(a) Once-through system (b) Looped system

Figure 1.1 Once-through and looped system

From the success of many practices over the past decades, water reuse has become an important consideration in the optimal planning and efficient use of water resources

(Asano and Levine, 1996). Due to the complex nature of the water resource problems, water reuse planning and management modeling is being investigated in order to promote such practices. Among the many management models, optimization models are very important in providing essential information for decision makers about the water resource management and planning. Meanwhile, in practice, uncertainty issues associated with reuse water demand and water quality have to be considered as they often pose a great challenge in better modeling a water reuse system.

The research presented in this thesis focuses on urban water reuse management in the context of sustainable development, and introduces a state of the art urban water reuse management model which utilizes a network flow optimization model and various stochastic programming methods. The results from this research are important in aiding the achievement in sustainable urban water resource management practices.

1.2 Objectives

The main objective of this research is to develop a water reuse model using optimization and stochastic programming methods in order to facilitate urban water reuse planning and management. This model will be used in determining the optimum reuse of treated wastewater on a regional basis by optimizing urban water allocation and promoting water reuse. Wastewaters from all sectors, along with fresh water, will be considered as candidate sources of water supply for users within the water system. By introducing stochastic programming methods to model the uncertainty with water demand and quality, better decisions will be obtained for water reuse planning. Additionally, GIS techniques will be employed to add more flexibility to the model for data processing and geographical analyses.

1.3 Organization of the Thesis

This thesis contains six chapters. The first chapter (this chapter) introduces the background, motivation and objectives of this research. The second chapter gives a detailed introduction on urban water reuse and reviews existing water reuse modeling studies. Chapter 3 demonstrates the methodologies being used in this study. The network flow optimization model, stochastic programming methods, including two-stage stochastic recourse programming and chance-constrained method, and GIS are introduced in this chapter. Chapter 4 describes the model development and optimization formulation. Chapter 5 illustrates the model application in a hypothetical example problem and discusses the modeling results. Chapter 6 concludes this research and recommends directions for future research on this subject area.

Chapter 2

Background and Literature Review

This chapter consists of four sections. The first section outlines the concept of sustainable development and its relationship with urban water systems and water reuse. The second section introduces aspects related to urban water reuse. The third section reviews existing water reuse management models. Summary is presented in the last section.

2.1 Sustainable Development and Urban Water Reuse

As discussed earlier, rapid urbanization and population growth continue to exert profound impacts and pressure on urban water resources. The Dublin Statement (ICWE, 1992) notes:

> *"After a generation or more of excessive water use and reckless discharge of municipal and industrial wastes, the water crisis felt in the majority of the world's major cities is critical and getting worse. The sustainability of urban growth is threatened by curtailment of water supplies and increasing pollution, as a result of the depletion and degradation caused by past profligacy".*

As water scarcity forces the development of more distant water supply sources, the costs of meeting water demands are growing rapidly and a larger aquatic ecosystem might be threatened. In short, long distant water supplies may not be sustainable. So what is a sustainable urban water system? ASCE (1998) provided a definition:

> *Sustainable urban water systems should over a long time perspective provide required services while protecting human health and the environment, with a minimum use of scarce resources.*

In other words, the objective of sustainable development of urban water systems is to satisfy the water demands at a lower cost affordable to the society with the minimum environmental and social impacts. Reuse of treated wastewater for beneficial purposes offers a potential new water supply resource that can replace existing fresh water supply sources for some operations. As well, water reuse also reduces the rigorous and costly treatment requirements for effluent discharge to surface waters. For example, the removal of nutrients such as nitrogen and phosphorous is very costly; but for most non-portable water reuse applications such nutrient removal is unnecessary and actually contraindicated when used for irrigation. On the other hand, by eliminating effluent discharges through water reuse, a community may be able to avoid or reduce the need for expanding the costly advanced wastewater treatment processes. In short, a water reuse program can serve both water conservation and pollution abatement purposes (EPA, 1992). Therefore, water reuse is considered an important element of sustainable urban water resource management.

2.2 Urban Water Reuse

This section discusses urban water reuse in more detail. First, it is necessary to clarify some terminologies used in water reuse. Most of the explanations are referred to Asano (1998):

1) Wastewater reclamation and wastewater

Wastewater reclamation refers to treatment processes which treat wastewater to predetermined levels of water quality, which facilitates reuse. Wastewater includes wastewaters discharged from urban water consumption sources such as residential, commercial, institutional and industrial sources. Rainwater and storm-water collected by urban sewer system are also considered as wastewater.

2) Water reuse

The term “water reuse” is interpreted in a broad sense. Water reuse includes the use of treated water for all beneficial purposes, including agricultural irrigation, industrial cooling and other non-potable or potable applications.

3) Reclaimed water

Reclaimed water is treated wastewater of certain quality levels suitable for some specific reuse applications.

4) Direct reuse

Direct reuse describes water reuse applications in which treated reclaimed water is directly transported to the points of reuse. Direct reuse is generally planned reuse.

5) Indirect reuse

Indirect reuse implies discharge of an effluent into receiving waters (surface water or groundwater) for assimilation and withdrawals downstream, which do not represent planned direct water reuse.

6) Water recycling

Water recycling typically refers to water reuse applied in industrial systems. Usually the effluent from certain industrial water use processes is recollected, treated and then returned back to the industrial process. Water recycling is often practiced in a single plant or industrial process.

In this study, water reuse refers to planned direct urban water reuse. Indirect water reuse and water recycling are not within the scope of this study because, in contrast to direct urban water reuse, indirect reuse is often practiced in a much larger geographical scale (e.g., in a river basin) while water recycling is often practiced in a much smaller geographical scale (e.g., in an industrial plant).

2.2.1 Brief Introduction to the History of Water Reuse

Water reuse has a long history dating back to ancient times. However, according to Asano and Levine (1996), the development of programs for planned reuse of wastewater began in the 1910's and some of the earliest water reuse systems were developed during the 1920's. The first industrial water reuse was implemented in the 1940's and in the 1960's when Colorado and Florida developed urban water reuse systems. During the last thirty years, research works were extensively focusing on technical barriers and health risks associated with water reclamation (Asano *et al*., 1996; Jacques *et al*., 1996). At the same time some earlier optimization models were developed for water reuse planning (Bishop *et al*., 1971; Mulvihill *et al*., 1974; Rios *et al.* 1975; Pingry *et al*., 1979; Ocanas *et al*., 1981; Schwartz *et al*., 1983; Vieira *et al*., 1989; Jacques *et al*., 1996).

During the last decade, wastewater reuse has gained much attention in many parts of the world as one means to alleviate the growing pressures for increasing water supplies for various applications. Technically speaking, modern wastewater treatment facilities are able to treat wastewater to the quality levels eligible for any purposes (Asano *et al.*, 1996). It has been recognized throughout the world that water reuse is an important factor in pursuing the optimal planning and efficient use of water resources.

2.2.2 Water Reuse Applications and Treatment Requirements

In an urban water system, reclaimed water can be used to replace potable standard water currently being used for many purposes. As discussed in the first chapter, engineered urban water reuse can create a looped water system where water reclamation and reuse take place. Figure 2.1 (Asano *et al*., 1996) shows an example of such a looped system with water reuse activities such as irrigation and groundwater recharge, etc.

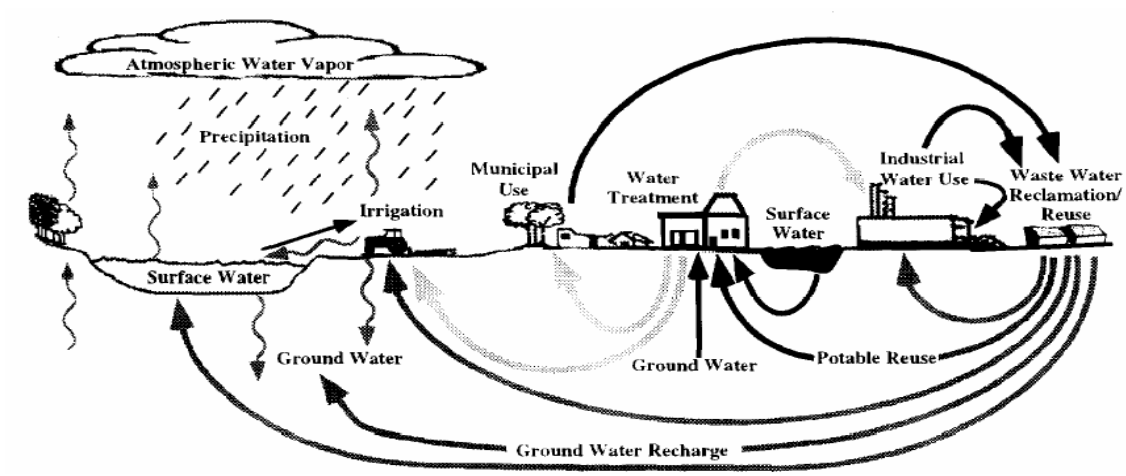


Figure 2.1 The concept of engineered urban water cycle with reuse (Asano *et al.*, 1996)

Entering the system from the surface or from ground water sources to municipal water treatment plants, freshwater follows several steps, such as: water distribution, water use, wastewater discharge, wastewater treatment and then its return for certain forms of reuse. The water quality levels required by the specific water reuse applications and the water available for reuse determine the feasibility of the specific water reuse practice. Reuse water quality generally depends on the corresponding treatment processes.

According to U.S. EPA's *Guidelines for Water Reuse* (1992), water reuse applications can be classified into certain categories. In the order of water quality requirements from the highest to the lowest, these categories are briefly introduced as followings:

1) Potable reuse

Potable reuse is the water reuse application with the highest quality requirements. Due to the health risk concerns to the general public, potable reuse is not widely practiced.

2) Unrestricted urban and recreational uses, and agricultural irrigation of food crops

Very high levels of treatment are required to applications in this category. This represents the highest level of water reuse that is currently practiced in the world. Typical treatment processes include secondary treatment, filtration and disinfection, with strict quality requirements on some parameters such as effluent biochemical oxygen demand (BOD), turbidity, total and/or fecal coliforms, disinfectant residuals and pH levels etc.

3) Restricted-access urban use, restricted recreational use, and agricultural irrigation of non-food crops

This category defines the water reuse situation in which only limited populations have access to reclaimed water. In this category, reuse water for irrigation is beneficial because the nutrients in wastewater are good chemical fertilizers. As a result, using reclaimed water to irrigate golf courses and other landscapes is widely practiced. For example, 419 golf courses in Florida were irrigated with 110mgd (million gallons per day) of reclaimed water (FDEP, 2001). Typical wastewater treatment for reuse includes secondary treatment, disinfection, with slightly lower quality requirements than the previous category.

4) Industrial reuse

Statistically, in primary resource and manufacturing industries, less than 20% of their water intake is consumed and, therefore, there are many opportunities for reuse between industries or other urban water use sectors. Treated municipal wastewater can be reused for industrial water supply. Furthermore, most industrial water reuse focuses on recycling and process modifications within the boundary of one plant (Bowman, 1994). In water reuse modeling studies, little attention has been given to study the opportunities of water reuse between industries. Typical reclamation treatment for municipal wastewater in this category includes secondary treatment and disinfection.

Table 2.1 shows the detailed water reuse categories and corresponding treatment requirements. Some studies, such as Safaa and Shadia's (2002) decision support system, contribute to the management and optimal selection of wastewater treatment trains that can produce the highest possible quality water for reuse at the lowest possible costs.

Table 2.1 General urban water reuse applications and treatment requirements

Water Reuse Applications		Treatment Requirements for Various Parameters								
General Category	Specific Uses	Pathogen Removal	Disin-fection	Suspd. Sol. Removal	DO* Presence	BOD** & COD*** removal	Nutrient Removal	Taste, Odor, Color Removal	Trace Organics & Metals Rem.	Excess Salinity Removal
Agricultural irrigation	Crop irrigation	xx	xxx	xxx	xx	xxx	--	x	xx	x
Landscape irrigation	Parks, golf courses, residential, school yard, freeway medians, cemeteries, greenbelts	x	--	x	x	x	--	x	x	--
Industrial reuse	Cooling, boiler feed, processing water, heavy construction	xx	xx	xxx	xxx	xxx	xxx	xxx	xx	xx
Groundwater recharge	Groundwater replenishment, salt water intrusion, subsidence control	xxx	xx	xxx	xx	xxx	xxx	xxx	xxxx	--
Recreational and environmental reuse	Lakes and ponds, marsh enhancement, stream flow augmentation, fisheries, snowmaking	xxxx	xxxx	xxx	xxxx	xxxx	xxxx	xxxx	xxxx	xx
Other non-potable urban reuse	Fire protecting, air conditioning, toilet flushing	xxxx	xxxx	xxxx	xxxx	xxxx	xxx	xxxx	xxxx	xx
Potable reuse	Blending in water supply, pipe to pipe water supply	xxxxx	xxxxx	xxxxx	xxxx	xxxxx	xxxx	xxxxx	xxxxx	xxx

(--) no need; (x) slight need; (xx) moderate need; (xxx) strong need; (xxxx) stringent requirements; (xxxxx) very stringent requirements.

* Dissolved Oxygen. ** Biochemical Oxygen Demand. *** Chemical Oxygen Demand. Adapted from Shelef (1991) and Asano (1996)

2.2.3 Water Reuse Quality Criteria

The most important consideration in developing a water reuse system is that the quality of the reclaimed water be appropriate for its intended use. Main reuse water quality parameters include pathogen and chemical constituents. Pathogen is the most common concern associated with non-potable reuse of reclaimed municipal water due to the risk of transmission of infectious disease. Chemical constituents in municipal wastewater may affect the acceptability of such water for food crop irrigation, indirect potable reuse, and some industrial applications. Some typical water constituents and quality parameters include the following: suspended solid measured as Total Suspended Solids (TSS); organics measured as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Total Organic Carbon (TOC); dissolved inorganics measured as Total Dissolved Solids (TDS) and specific elements (e.g., Ca, Mg). In water reuse applications, these constituents have certain effects on the specific applications. For example, suspended solids may absorb organic contaminants, heavy metals and plug-up equipment and cause fouling; while organics may promote growth of slime-forming organisms, cause aesthetic and nuisance problems and reduce heat transfer efficiency and water flow; dissolved inorganics may promote corrosion by increasing the electrical conductivity of the water and cause scaling (US EPA, 1992). Thus, these parameters are commonly used in water reuse studies and applications.

2.3 Review on Urban Water Allocation and Reuse Modeling

The development and application of personal computers have enabled the use of comprehensive numerical modeling techniques and various scenario analyses to better understand and evaluate the urban water resource problems. It has been long recognized that integrative management modeling is essential for evaluating and optimizing treatment and reuse of wastewater. Water reuse planning and management modeling can provide a systematic approach to assessing the potential reuse water market, and identifying and evaluating water reuse opportunities among major users in the system. This section provides a review of existing research on water reuse modeling and identifies the needs for improvement in this subject area.

During the 1970's, several system analysis and modeling studies on water reuse management have been conducted. One of the first applications to the problem of water reuse was presented by Bishop and Hendrisks in 1971. They modeled the problem as a simple un-capacitated transhipment problem with considerations of treatment and transportation costs in linear form. The model was focused on determining the amount of treatment necessary for each supplier-destination pair with two quality parameters, biological oxygen demand (BOD) and total dissolved solids (TDS). Mulvihill and Dracup (1974) tried to minimize the cost of supplying water from several sources, including the provision for recycling reclaimed water. The modeling of all users as one large user with one quality requirement was the major disadvantage of this model. Another limitation was not allowing water reuse among users, the only way to reuse the treated wastewater was by recycling such water to the sources. As discussed earlier, this should be considered as indirect reuse. On the other hand, Rios *et al.* (1975) tried to minimize fresh water demand by allowing water recycling and reuse practices. In Rios' model, one super source and one super sink were assumed, namely, all water supplies were distributed from the super source, and all wastewater was assumed to be discharged into the super sink. Water reuse between users was allowed in this model (i.e., users could recycle their water or send it to any other users by treating it to comply with any quality requirements). Another study in the 1970's was Pingry *et al.*'s (1979) nonlinear model which took into account both flow requirement and water quality. The model considered individual sources, allowed the interactions between users and wastewater treatment plants, but did not include different treatment levels in wastewater treatment. In short, during this period of time, all models were in some way lacking (ignoring water reuse opportunities, disallowing multiple water sources, simplifying wastewater treatment complexities, etc).

During the 1980's, more complex water reclamation and reuse models were presented. Perhaps the most important was the one developed by Ocanas and Mays (1981). Their water reuse model could be used to determine the optimum reuse of wastewater on a regional basis. This model used a nonlinear objective function subjected to both linear and nonlinear constraints. The model included quality constraints and provided the flexibility of adding more quality parameters. Moreover, the model took into consideration quality changes caused by users and treatment plants resulting from the inclusion of reuse water as influent. However, the accuracy of this quality-change modeling is hard to assess and this model is difficult to solve. Schwartz and Mays (1984) and Vieira and Lijklema (1989) developed models using dynamic programming. Their models offered the ability to determine the optimal size and location of treatment plants with consideration of water demand over certain time periods.

Over the last decade, environmental and health risk issues associated with water reuse began appearing in some water reuse studies. Jacques and Anastasia (1996) discussed the risk analyses of wastewater reclamation and reuse. Their objective was to show how engineering risk analysis may be used to quantify the risk of wastewater reuse and to lead the way for developing a decision support system for wastewater reclamation and reuse. They suggested that the expected benefits and costs could be expressed as a function of risk and that Geographic Information Systems (GIS) could be used for data processing. Oron (1996) presented an integrative approach for reusing domestic treated wastewater with considerations over levels of treatment, water supply and demand, transportation and storage requirements, and environmental pollution and health risk. However, only domestic treated wastewater was considered as a reuse water source and the health risk issues were not clearly stated.

Some industrial ecological studies also contributed to water reuse modeling in the last decade. Studies in industrial ecology generally focus on characterizing material and energy flows in industrial systems and analyzing cases where modifications of the material and energy flows could result in environmental and economical benefits. Keckler's material reuse model (1998) is one of the industrial ecology models demonstrating water flow design in industrial parks. The model identified water reuse opportunities between different industries using a linear programming method. Based on Keckler's material reuse model, Nobel (1998) developed an ArcView GIS model to quantitatively identify and display the results of matched water reuse source-destination pairs on GIS maps. Keckler's work considered water reuse opportunities between industries by allowing blending of various industrial effluents while Nobel's work focused on GIS visualization of water reuse opportunities by a simple quality matching mechanism. However, their models were not developed in conjunction with the overall urban water system.

In summary, studies on urban water reuse management modeling exist in the literature. However, the uncertainty issues associated with water demand and treatment quality in water reuse modeling has not received much attention. Variations in demand for reclaimed water, as well as the uncertainty in water quality are major concerns in evaluating water reuse opportunities. For example, depending on different weather condition, reuse water demands for irrigation might change dramatically. In the case of residential and municipal reuse water uses, weather conditions also play an important role in the rate of water consumption. For industry water reuse, production activity and manufacturing levels are usually affected by economics. Uncertainty with effluent quality often reflects treatment instability. Quality uncertainty has a significant effect on water reuse management such as safety considerations during periods of noncompliance with water quality standards. Consideration of uncertainty issues requires incorporation of stochastic programming into the water reuse model. Moreover, besides being used for visualization, GIS could be used to enhance a model's capability in data processing and other applications of water resource management.

As discussed above, continuing research on urban water reuse modeling is needed. Improvements should be made in aspects such as: full conjunction with the overall urban water system, accuracy in cost estimation, uncertainty modeling of water demand and quality, and integration with GIS for data processing and result presentation.

2.4 Summary

This chapter introduced urban water systems and water reuse issues, reviewed water reuse modeling studies, discussed the strengths and weaknesses associated with existing models and identified directions for further research. The new model proposed in this thesis is intended to fulfill the need for an improved systems analysis tool for urban water reuse planning and management. The next chapter introduces the main methodologies used to develop the model: Network Flow Optimization model, Stochastic Programming methods and Geographic Information Systems.

Chapter 3

Methodology

This chapter presents the methodologies used for developing the proposed urban water allocation and reuse model. In the first part of this chapter, the network flow optimization model and stochastic optimization methods, namely two-stage stochastic programming and chance-constrained programming, are introduced. These methods form the base of the model. In the second part of this chapter, GIS and its applications in water resource management are briefly discussed.

3.1 Optimization Methods

Optimization methods are often used in water resource management to solve the corresponding complex problems. Optimization is the analytical process applied to a system of dependent components with the goal of optimizing (maximizing or minimizing) certain criteria such as profits or costs (Suvrajeet *et al.,* 1999). Because of the interdependency of conflicting variables and the large number of interrelationships between them the optimization process is usually complicated. In typical urban water management optimization models, the objective is to minimize the total cost of the system with constraints that water must be delivered to spatially extensive demand sites in required quantities and with satisfactory quality. This also reflects the concepts of sustainable development of urban water systems as discussed in the previous chapter.

Various optimization methods can be applied to constrained optimization problems. Due to the general structure of the water system and the characteristics of the objective function and constraints in our water reuse and allocation model, a special optimization model, the network flow optimization model, was chosen to develop the model. Stochastic optimization methods, namely two-stage stochastic recourse programming and chance-constrained programming, were incorporated to model the uncertainty issues associated with water demand and quality.

3.1.1 The Network Flow Optimization Model

Linear programming was developed by George B. Dantzig in 1947 to find the optimal allocation of resources in large supply and economics problems (Albers *et al.,* 1986; Edgar *et al.,* 1988). Over the past several decades, linear programming has become a fundamental planning tool that is commonly used in engineering, business, economics, environmental studies, and other disciplines. "Research on specialized problems, such as assignment, transportation, and network problems, have made linear programming methodology indispensable in many industries, including airlines, energy, manufacturing, and telecommunications", Suvrajeet (1999) summarized. As a special linear programming method, the minimal network flow optimization model is now introduced.

Network flow optimization models are typically described in terms of supplies and demands for a commodity in a network system. In the model, nodes are defined as model transfer points, arcs interconnect the nodes, and commodity flows on the arcs (Ford *et al.,* 1962). Generally, there are many feasible choices for flow transferring along arcs, and costs or values associated with the flows. The attributes of nodes are usually supplies or demands, while the attributes of arcs are usually the flow capacities that limit the flows along them. Nodes with supplies are often referred to as sources and nodes with demands are often referred to as sinks. An optimal solution of the network flow model can be regarded as the overall least cost (or maximum value) set of flows for which supplies find their ways through the network to meet the demands.

Applying the model to our water reuse system, water users (demand sites) are treated as sinks, and water suppliers (supply sites) are treated as sources and both are nodes in the network. The links from sources to sinks are arcs (source-destination pairs). The amount of water transferred from source to sink is the flow rate, which is usually the decision variable of the optimization problem.

According to Bazaraa *et al.* (1977) the network optimization model can be expressed in a general form as following:

Minimize: $$\sum_{(i,j)\in A} C_{i,j} x_{i,j} \tag{3.1}$$

Subject to: $$\sum_{(j,k)\in A} x_{j,k} - \sum_{(k,i)\in A} x_{k,i} = b_k \quad \forall k \in N \tag{3.2}$$

$$0 \le x_{i,j} \le U_{i,j} \quad \forall (i,j) \in A \tag{3.3}$$

where expression (3.2) is flow balance constraints; expressions indicated by (3.3) are non-negativity and flow capacity constraints; notations are listed below:

$i, j \in N$ nodes of the network;

$(i, j) \in A$ arcs of the network;

b_k is the net demand of node k, (if $b_k \geq 0$);

$|b_k|$ is the net supply of node k, (if $b_k \leq 0$);

$Arc(k,i) \in A$ arcs leaving node k;

$Arc(j,k) \in A$ arcs entering node k;

$C_{i,j}$ is the unit flow cost on arc (i,j), $x_{i,j}$ is the flow rate on arc (i,j);

$U_{i,j}$ is the flow capacity on arc (i,j).

A simple node-arc network diagram for the proposed water allocation and reuse model is shown in Figure 3.1, where: nodes 1 and 2 represent a surface water source and a groundwater source respectively, node 3 represents a water treatment plant; node 4 through 7 represent water users, nodes 8, 9 and 10 represent a wastewater treatment plant collecting and treating wastewater with 2 levels of wastewater treatment processes generating water for reuse, and node 11 represents a receiving water body.

Some typical model variables and parameters are also shown in the figure where *x, C, b* are as previously defined. For water reuse modeling, demand *D* for users has to be introduced. Demand *D* is the total amount of water required by the user, usually consists of net demand *b* and the amount of water discharged from the user after use. For irrigation users (e.g., node 4 in Figure 3.1), demand D_4 equals its net demand b_4, since all water supplied are consumed without discharge. As well, for water reuse modeling, other parameters such as water quality and facility's capacity have to be considered. Thus, in addition to flow balance constraints, water demand, water quality, and capacity limit make up the main constraints for the water reuse model.

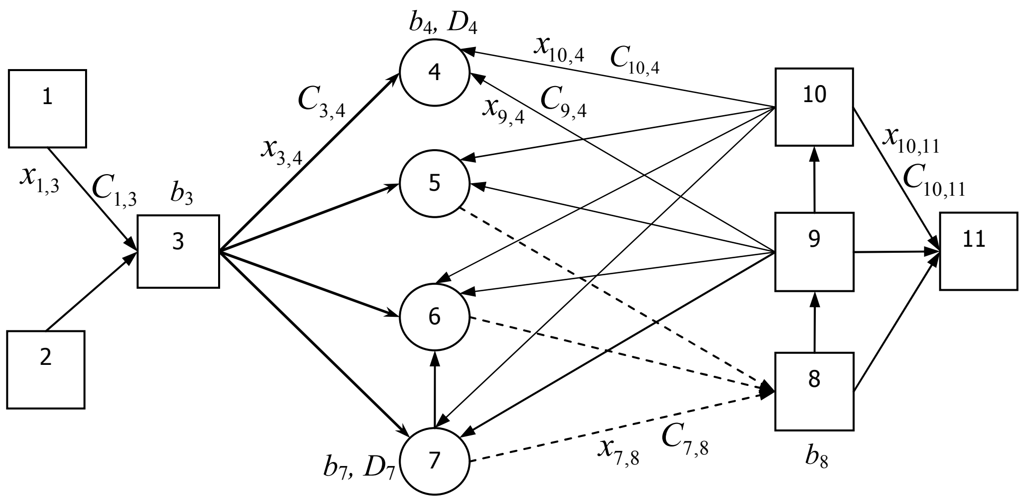


Figure 3.1 Node-arc network with variables and parameters

3.1.2 Stochastic Programming Methods

In planning urban water resource allocation and reuse, uncertainty issues in water demand and treatment system reliability must be considered. Variations in demand for reclaimed water, as well as the uncertainty in water quality, are major concerns in evaluating water reuse opportunities. Generally, these uncertainties have great effects, such as safety considerations, during periods of noncompliance with water quality standards. This requires the incorporation of stochastic programming methods, introduced in this section, into the model. Generally, there are several efficient stochastic programming methods for modeling uncertainty issues. Two such methods are the two-stage stochastic recourse programming method and the chance-constrained stochastic method. Most stochastic programming methods are based on the assumption that the probability distributions of the uncertain data are known or estimations can be obtained (Henrion, 2004). According to probability theory, random events can be quantitatively measured by mathematical methods.

Mathematically, the terms "mean", the "variance" (square of the standard deviation) and the type of the probability distribution are used to describe a random variable. The following gives a brief introduction based on Gottfried *et al*. (1973) and Papoulis (1991). Considering the elements of the set S contained in the event $\{X \leq x\}$, the probability of this event, denoted by $\Pr\{X \leq x\}$, is a number that depends on x and is denoted by $F_x(x)$. For a continuous random variable x, $F_x(x)$ is called the probability distribution function and the derivative:

$$f_x(x) = \frac{dF_x(x)}{dx} \tag{3.4}$$

is called the probability density function. For example, the *normal* probability density function is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{3.5}$$

where the parameters μ and σ^2 are the mean and the variance of the normal random variable. The mean μ measures the location and the variance σ^2 measures the expected spread of the variables about the mean. The greater σ^2, the greater the variables scatter.

3.1.3 Two-Stage Stochastic Recourse Programming

The most widely applied and studied stochastic programming models are two-stage stochastic recourse models. In the two-stage stochastic recourse model, according to Prékopa (1995), the decision variables are explicitly classified according to whether they are implemented before or after an outcome of the random variable is observed. *First-stage* decisions are decisions that are implemented before knowing the outcome of the random event. These first-stage decisions can be regarded as proactive and are often associated with planning issues such as capacity expansion or aggregate production planning; while *second-stage* decisions are decisions that are implemented after knowing the outcome of the random event. Second-stage decisions can be regarded as reactive and are often associated with operating decisions.

Second-stage decisions usually depend upon the first-stage decisions; therefore they are often used to model a response to the observed outcome. In recourse programming, a response should be modeled for each outcome of the random events that might occur. In general, this type of planning involves setting up responsive policies to adapt to the revealed outcome. For example, in water allocation models, the first-stage decisions correspond to water flow quantities from supply nodes to demand nodes, where demand might be modeled using random variables. When demand exceeds the amount of water supplied, policy may dictate that customer demand be backlogged at some penalty cost. The level of response (the amount backlogged) depends on the amounts supplied and demanded under uncertainty.

The following illustration of two-stage recourse programming is excerpted from Suvrajeet *et al.* (1999). For a generic two-stage formulation under recourse policy, the same notation used for deterministic linear programming (LP) can be applied. Generally, the constraints of the deterministic LP are written as:

$$Ax = b. \tag{3.6}$$

Under uncertainty, the sub-matrix A_1 (of A) and the sub-vector b_1 (of b) can be considered as rows that contain only deterministic parameters. Set R represents the remaining rows in A that contains at least one uncertain element. a_i is referred to as the i^{th} row vector in A, and use $\widetilde{a}$ to reflect the presence of random variables in the vector a. Let $g_i > 0$ denote the penalty cost for violating the target $\widetilde{b}_i$. y_i^+ and y_i^- are defined as the non-negative second-stage variables representing the surplus and shortfall used for compensating the violations caused by the randomness of demand $\widetilde{b}_i$. When the random vectors $\{\widetilde{a}_i, \widetilde{b}_i\}_{i \in R}$ are discrete random variables, let S_i denote an index set of all outcomes of the random vector $\{\widetilde{a}_i, \widetilde{b}_i\}_{i \in R}$ and let $p_{is} = P\{(\widetilde{a}_i, \widetilde{b}_i) = (a_{is}, b_{is})\}$ define the probability that $(\widetilde{a}_i, \widetilde{b}_i) = (a_{is}, b_{is})$. Thus, the following prototypical model allows a simple recourse policy:

$$\text{Minimize: } c'x + \sum_{i \in R} g_i \{ \sum_{s \in S_i} p_{is} (y_{is}^{+} + y_{is}^{-}) \} \quad (3.7)$$

$$\text{Subject to: } A_1 x = b_1, \quad x \geq 0 \quad (3.8)$$

$$a_{is} - y_{is}^{+} + y_{is}^{-} = b_{is} \qquad \forall s \in S_i \;\; \forall i \in R \quad (3.9)$$

$$L_i \leq x \leq U_i \quad (3.10)$$

where $\sum_{i \in R} g_i \{ \sum_{s \in S_i} p_{is} (y_{is}^{+} + y_{is}^{-}) \}$ is the expected recourse cost of choosing *x* in the first stage, L_i and U_i are the lower and upper bonds of *x* respectively and the penalty cost per unit y_{is}^{+} and y_{is}^{-} can be defined as g_i^{+} and g_i^{-} respectively.

This is the simple recourse formulation. More general recourse formulations which would give greater flexibility could be constructed in a similar way. By applying stochastic optimization methods to our water reuse model, more reliable and robust solutions can be obtained under the randomness of water demand involved in the system. The second stage variables and the corresponding penalty costs balance the violation caused by the outcome of the uncertain parameters. That is, the planning decisions can be obtained that would minimize the overall expected costs (or maximize the overall profits) under considerations of uncertainty with demands.

3.1.4 Chance-Constrained Stochastic Programming

Chance-constrained stochastic programming is another major approach for dealing with uncertain parameters in optimization problems in which chance constraints can be used for modeling uncertainty where degrees of compliances with the constraints are specified. In these models decisions need not be feasible for every outcome of the uncertain parameters, but the feasibility at some levels of probability is required (Henrion, 2004). In general, the chance-constrained programming method offers an efficient framework to model uncertainties in numerous applications in water resource management, energy production, circuit manufacturing, chemical engineering, telecommunications, and finance (Henrion, 2004)

In water reuse modeling, this method can be used to model the uncertainties with water quality. As discussed earlier, in the two-stage recourse model, the uncertainty is modeled by introducing penalty costs associated with the second stage variables to respond to the violations caused by the randomness. Suvrajeet (1999) concluded that such penalty costs are required by the philosophy of the recourse based modeling approach. In some applications, such as production and inventory models, obtaining the penalty costs is possible. However, in many applications, such as when safety relevant restrictions like levels of a water reservoir, water quality, etc. are modeled, this philosophy is not applicable or the penalty costs cannot be modeled practically. In such situations, chance constraints can be used to guarantee the feasibility of decisions at certain desired levels. In our water reuse model, for modeling water quality uncertainty, it is more appropriate to ensure a certain probability of quality compliance. In such a way, the risk of using reuse water can be controlled within the acceptable levels. The following section illustrates the chance-constrained model based on Gottfried and Weisman (1973).

In a general optimization problem with objective function *y* and inequality constraints $g_i(X) \le b_i$ assume that some of the technological coefficients, decision variables, or constraints include random correlations. With uncertainty in the constraints, it may be impractical to insist that b_i exceed $g_i(X)$ at all times. However, by employing chance-constrained programming, such constraints can be limited to a low level of probability of violation as follows. Let K_i be the desired minimum probability level of compliance, so that the constraints can be rewritten as:

$$P\{g_i(X) \le b_i\} \ge K_i \tag{3.11}$$

In this way the optimization problem is to optimize (maximize or minimize) the expected value of the objective function *Z*, that is, $E(Z)$ with constraints having the above form:

$$\textit{Optimize: } E(Z) \tag{3.12}$$

$$\textit{Subject to: } P\{g_i(X) \le b_i\} \ge K_i, \quad i = 1,2,\ldots,m. \tag{3.13}$$

This chance-constrained programming model was introduced by Charnes, *et al*. (1958). Charnes *et al*. also developed a procedure to evaluate the probabilities to save time on computation. Their method uses the *mean* and *standard deviation* of $g_i(X)$ to approximate $g_i(X)$, so that:

$$g_i(X) \cong \mu_{g_i(X)} + t_i \sigma_{g_i(X)} \tag{3.14}$$

where t_i is the number of standard deviations from the mean, often called the *standard normal variate*. Since

$$\mu_{g_i(X)} = E(g_i(X)) \tag{3.15}$$

the constraints can then be modeled as:

$$P\{E(g_i(X)) + t_i \sigma_{g_i(X)} \leq b_i\} \geq K_i, \quad i = 1,2,...,m. \tag{3.16}$$

Based on (3.16), when expressing the probability distribution function F in terms of t_i, i.e.,

$$K_i = F(t_i) \tag{3.17}$$

It is clear that given $E(g_i(X))$ and $\sigma_{g_i(X)}$, one can obtain t_i once K_i is set. In other words, specifying t_i is equivalent to specifying the desired probability level K_i using $K_i = F(t_i)$. As a result, the certainty equivalent of (3.13) is

$$E(g_i(X)) + t_i \sigma_{g_i(X)} \leq b_i. \tag{3.18}$$

So the deterministic equivalent optimization problem becomes:

$$\textit{Optimize:}\ E(Z) \tag{3.19}$$

$$\textit{Subject to:}\ E(g_i(X)) + t_i \sigma_{g_i(X)} \leq b_i, \quad i = 1,2,...,m. \tag{3.20}$$

Applied to our water reuse modeling study, the uncertainty issue with water quality is modeled with the chance-constrained stochastic programming method.

In the case where the coefficients of the objective function (*Z*) are uncertain, the uncertainty can be modeled using the mean-variance method developed by Markowitz (1992). The objective function is formulated as shown below:

$$\textit{Optimize:}\ E(Z) \pm \theta Var(Z) \tag{3.21}$$

where *Var*(*Z*) is the variance of the objective function (*Z*) and θ is the risk aversion parameter; "+" for minimization and "-" for maximization. Risk aversion is a measure of a decision maker's attitude towards risk. The risk aversion parameter indicates the willingness of paying money (or not to receive a high return) to reduce risk or avoid uncertainty in investment or planning (Baker, 2001). Applying to our water reuse modeling study, mathematically, the uncertainty with water price or water treatment cost can be modeled with this method since they are the coefficients of the total cost function, i.e., the objective function. Therefore, the general tendency to be afraid of taking risks can be modeled through different risk aversion parameters and reflected by the total costs obtained.

3.2 Geographic Information Systems (GIS)

3.2.1 Introduction

GIS is defined as "an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information" (ESRI, 1997). Simply used as a spatial database, GIS can assist in modeling applications through handling a special form of data that would otherwise be compromised or impossible to store in spatial or non-spatial databases (Scott *et al.,* 1999). Bennett (1997) states that GIS offers a virtual environment within which decision makers and scientists can explore theory and evaluate competing management strategies. In this section, general GIS data structure, data topology and applications are introduced.

3.2.2 GIS Functions and Applications

GIS contains map features' spatial information in topological data tables and descriptive information in attribute tables; the power of GIS lies in its link between this spatial and descriptive data (Nobel, 1998). Specifically speaking, GIS offers many sophisticated operations such as network analysis, spatial analysis, overlay processes, 3D operations, sub-basin delineation, network tracing, shortest path finding, travel routing, area computation, flow path length measurement, nearest distance determination, visualization and so on. All of these can be used to conveniently derive model-dependent parameters. Moreover, GIS can mathematically integrate spatial and non-spatial data by performing various operations. It is widely recognized that GIS analysis can provide crucial insight into geographical and environmental conditions, obtaining more accurate and appropriate solutions. In particular, GIS has been regarded and proven as an efficient and powerful tool in water resource management. According to the American Water Works Association, 90% of water agencies are now partially using GIS to assist in their daily operation.

GIS can be used for applications in water system management such as:

a) Water distribution system master planning;

b) Population and water demand projections;

c) Groundwater management/modeling;

d) Water quality monitoring;

e) Hazardous materials tracking/underground tank management;

f) Site analysis;

g) *Water flow analysis;*

h) *Water allocation, etc.*

A water reuse study usually involves the above applications of a), b), f), g) and h) where GIS could make great contributions. Specifically, in our water reuse and allocation case study, GIS and its powerful software could be used to:

1) project the various reuse water demands such as irrigation water demand based on population data, water use and land cover characteristics;

2) find the shortest path (or least cost route) for reuse water delivery based on street network data;

3) estimate the cost of water transportation from reuse water supply sites to demand sites. For such estimations GIS could be used for addressing the cost effects on the following issues as proposed by Labadie and Herzog (1999):

- *right of way issues;*
- *congestion problems during installation due to buried utilities;*
- *land use and development issues impacting installation costs, such as increased costs of pipe excavation in commercial districts due to business disruption and the need for traffic rerouting;*
- *spatially distributed soil characteristics impacting excavation costs, such as loose, sandy soils requiring more costly reinforcement of the site.*

For simplicity in the proposed case study, the GIS software package ESRI (Environmental Systems Research Inc.) *ArcGIS8.3* and *ArcView3.3* are used mainly to project the residential reuse water demand and find the shortest path (or least cost route) for reuse water delivery. Figure 3.2 illustrates the use of the Network Analyst extension in ArcView 3.3 for finding the least-cost paths (or shortest path) from supply sites to demand sites along the existing road networks.

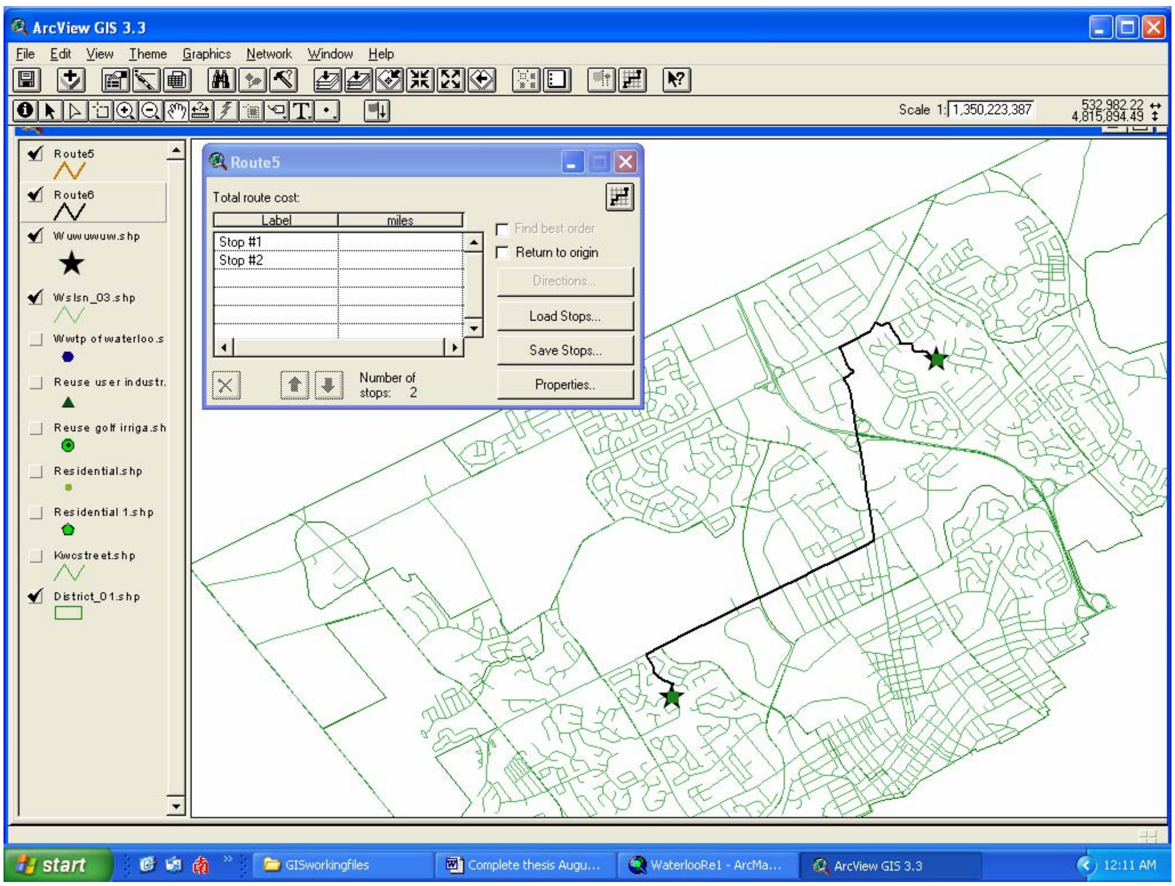


Figure 3.2 The use of the network analyst extension in ArcView 3.3

3.3 Summary

In this chapter, the network flow optimization model, stochastic programming methods and applications of GIS are introduced. The network flow optimization model offers an efficient node-arc structure which is very suitable for modeling urban water system: water can be treated as a commodity; water treatment facilities and water users can be modeled as nodes; the connections from water sources to sinks can be modeled as arcs. For such models, the objective is to minimize the overall cost of the network under constraints such as flow balance, capacity constraints and other societal and environmental constraints. Stochastic programming methods including two-stage stochastic recourse programming and chance-constrained methods can give such models the capability of addressing uncertainty associated with water demand, quality and water treatment cost. GIS is an efficient data processing and analysis tool which can be used for water demand projection, least-cost path finding and other data analyses in water reuse modeling.

Chapter 4

The Water Reuse Model

The three sections of this chapter present the development of the urban water reuse management model. The first section introduces the general procedures for implementing a water reuse project. The second section describes the optimization formulation, input parameters, decision variables, constraints, objective function, and the stochastic programming formulation. The various water system components and their relationships are modeled as nodes and corresponding attributes. The last section briefly illustrates the typical GIS applications used in the modeling process.

4.1 Steps of Water Reuse Project Implementation

Water reuse projects are generally complex projects. According to the US EPA (1992) and James and Liu (1999), the general approach for implementing a water reuse project involves several key steps:

i. The first step is to establish the boundary of the reuse system. Geographical boundaries for an urban water system are usually on a local to regional scale and include the municipality and its surroundings (Margar *et al*., 1999).

ii. The second step is the identification and characterization of potential demands for reclaimed water. As discussed in Chapter 2, this step may be carried out according to the category of urban water reuse applications and the corresponding water quality requirements.

iii. The next step is the identification and characterization of existing sources of reclaimed water to determine their potential for reuse water supply. In urban water systems, water sources include municipal water supply and reuse water supplies (i.e., reclaimed water from wastewater treatment facilities and large water users who could provide effluents for reuse). In some situations it may be necessary to design the treatment processes in order to produce safe and reliable reclaimed water that is suitable for its intended applications.

iv. The fourth step is the identification of the supplemental facilities required in operating a water reuse systems, such as conveyance and distribution networks, operational storage facilities, etc.

v. The last step is the estimation of the costs and the evaluations of the alternatives related to water reuse. The costs include infrastructural cost, such as piping, and treatment facility cost, operational and maintenance cost, such as pumping and energy cost, etc. Pumping cost in conveying reuse water from sources to sinks is closely related to the distance between them.

The primary objective in carrying out the water reuse model is cost effectiveness, which is determined by minimizing total resources costs to meet project constraints. In the modeling process, information about supply capacities and user demand, as well as their corresponding water quality are required as model input parameters. The model evaluates the potential reuse opportunities in terms of cost effectiveness under the restrictions of system capacity, user demand and water quality constraints and the uncertainty issues associated with them. The modeling procedure includes the construction of the water reuse optimization model and the formulation of the stochastic programming and GIS applications.

4.2 The Water Reuse Management Model

As discussed in the previous chapter, the optimization model was developed based on the network flow optimization model. Water users are modeled as sinks; water suppliers are modeled as sources; both sources and sinks are network nodes. The links interconnecting sources and sinks are arcs of the network. The amount of commodity transferred from source to sink is the flow rate on these arcs, which is the decision variable. The basic constraints of this model is adapted and revised from the model developed by Ocanas and Mays (1981). Their original model was refereed to as *OM model* in the rest of this chapter. *OM model* provided a suitable structure considering the possible components of urban water reuse system, as reviewed in Chapter 2, however the parameters and constraints were revised to better suit the objective of our water reuse model with consideration of uncertainties. In addition, the multi-levels of water treatment for water reuse are also incorporated into the revised model. As discussed in Chapter 3, two-stage stochastic recourse programming and chance-constrained programming methods are introduced into the model's constraints and objective function to allow for uncertain demands and water quality modeling. The model's variables, constraints and objective function are specified in what follows.

4.2.1 Model Decision Variables:

Decision variables include all flow rates between source nodes and sink nodes in the network system. Specifically, they can be defined as follows:

$XWT_{l,j}$ flow rate of treated water from water treatment plant (WTP) node *l* to user node *j*;

$XWWT_{h,j}$ flow rate of treated water from wastewater treatment plant (WWTP) node *h* to user node *j*;

$XWR_{j,r}$ flow rate of wastewater from user node *j* to receiving water body *r*;

$XTWWT_{j,l}$ flow rate of wastewater from user node *j* to WWTP node *l*;

$XST_{i,l}$ flow rate of fresh water from surface water source *i* to WTP *l*;

$XGT_{k,l}$ flow rate of fresh water from groundwater source *k* to WTP *l*;

$XWWTR_{h,r}$ flow rate of wastewater from WWTP *h* to receiving body *r*;

$X_{t,j}$ flow rate of water from user *t* to user *j* for reuse;

EXS_j flow rate of external water supply to user *j*.

where the units for flow rates are in 10^3 *gallons per day* (*kgpd*). The decision variables in this network flow model are the flow rate on each arc of the system.

4.2.2 Model Parameters and Required Input

For urban water reuse planning and management, the following parameters are required by the model:

US set of users;

SU set of surface water sources;

GR set of groundwater sources;

R set of receiving water bodies;

P set of pollutants;

WTP set of water treatment plants;

$WWTP$ set of wastewater treatment plants;

DEM_j water demand of user *j*;

NDL_j net demand of user *j*;

LT_l water losses at water or wastewater treatment plant *l*;

SWA_i maximum water available for withdrawal at surface water source *i*;

GWA_k maximum water available for withdrawal at groundwater source *k*;

$QR(P_n)_r$ maximum mass discharge of pollutant *n* acceptable by receiving water body *r*;

$CS(P_n)_i$ pollutant *n* concentration of surface water source *i*;

$CG(P_n)_k$ pollutant *n* concentration of groundwater source *k*;

$STD(P_n)_j$ maximum pollutant n concentration required by user j;

$CWT(P_n)_l$ pollutant n concentration leaving water treatment plant l;

$CWWT(P_n)_h$ pollutant n concentration leaving wastewater treatment plant h;

$C(P_n)_t$ pollutant n concentration leaving water user t;

CAP_l and CAP_h capacities of WTP l and WWTP h respectively.

where the units for pollutant concentrations are *mg/l* and the units of the mass discharge of pollutants are *kgd-mg/l*, and demand and capacity are in *kgd* as previously described.

4.2.3 Model Constraints

a) Demand constraints

The deterministic demand constraints which force the model to satisfy the demand for all users are given as:

$$\sum_{l\in WTP} XWT_{l,j} + \sum_{h\in WWTP} XWWT_{h,j} + \sum_{t\in US} X_{t,j} + EXS_j \geq DEM_j \qquad \forall j \in US \tag{4.1}$$

These constraints ensure that water supplied from all possible sources in the system to each user must be greater than or equal to their demand. To ensure that these constraints are satisfied in a situation of water shortage in the system an external supply source is added in addition to these constraints of the *OM model*. More importantly, this research models the uncertainty with demand as following.

Demand uncertainty modeling: When the user demands DEM_j are random and two-stage stochastic recourse programming (discussed in Chapter 3) is employed, second stage variables and penalty costs have to be introduced. The stochastic form of these demand constraints becomes:

$$\sum_{l \in WTP} XWT_{l,j} + \sum_{h \in WWTP} XWWT_{h,j} + \sum_{t \in US} X_{t,j} + EXS_j - SP_{s,j} + SF_{s,j} \geq DEM_j \qquad \forall j \in US,\ s \in S \tag{4.2}$$

where $SP_{s,j}$ and $SF_{s,j}$ are non-negative second stage variables denoting the surplus and the shortfall of case s (of the scenario set S) to the demand respectively. The corresponding total penalty cost which will augment the objective function is:

$$C_{penalty} = \sum_{j \in US} CP_j \{ \sum_{s \in S} p_{s,j} (SP_{s,j} + SF_{s,j}) \} \tag{4.3}$$

where CP_j denotes the unit penalty cost, $p_{s,j}$ denotes the probability of case s in the scenario set S.

According to probability theory, the scenarios can be generated once the characteristic of the distribution of the random variable (which is the demand in this case) becomes known. For example, if the expected value (or mean), the variance and the appropriate distribution of the random variable are known, a large number of scenarios can be generated to model the randomness of the variable. The number of constraints will increase proportionally to the number of scenarios, so the size of the optimization problem usually becomes large. Detailed explanation about scenario generation is illustrated through the example problem presented in Chapter 5.

b) Network flow balance constraints

Flow balance constraints sometimes are called conservation constraints in the network flow model which ensure that the flows are balanced at each node in the network. These constraints are modeled in a similar way with the *OM model*.

For users these constraints are:

$$\sum_{l \in WTP} XWT_{l,j} + \sum_{h \in WWTP} XWWT_{h,j} + \sum_{t \in US} X_{t,j} + EXS_j - \sum_{r \in R} XWR_{j,r} - \sum_{l \in WWT} XTWWT_{j,l} - \sum_{t \in US} X_{j,t} = NDL_j \quad \forall j \in US \tag{4.4}$$

which state that flows entering a node subtract flows leaving the node equals to its net demand. Net demands (or water losses) are defined as the amount of water actually consumed or lost at each node. These values are considered constant for each user and are assumed known. For water treatment plants these loses appear in the conservation constraints as follows:

$$\sum_{i \in SU} XST_{i,l} + \sum_{k \in GR} XGT_{k,l} - \sum_{j \in US} XWT_{l,j} = LT_l \qquad \forall l \in WTP \tag{4.5}$$

indicating that water treatment plants receive water only from surface and ground sources, and send water to users in the network system. For wastewater treatment plants flow conservation constraints become:

$$\sum_{j \in US} XTWWT_{j,h} - \sum_{r \in R} XWWTR_{h,r} - \sum_{j \in US} XWWT_{h,j} = LT_h \qquad \forall h \in WWT \tag{4.6}$$

indicating that wastewater treatment plants only receive water from the users and return treated water to users or discharge water to the surface and ground sources.

c) Capacity constraints

Capacity constraints limit the water entering a WTP or WWTP to the capacity of the corresponding plant. For water treatment plants these constraints are given by

$$\sum_{i \in SU} XST_{i,l} + \sum_{k \in GR} XGT_{k,l} \leq CAP_l \qquad l \in WTP \tag{4.7}$$

where CAP_l is the limit for water entering WTP l. Alternatively the capacity constraint can be used to limit the quantity of water supplied by WTP. In such cases these constraints are given by:

$$\sum_{i \in US} XWT_{l,i} \leq CAPOUT_l \qquad l \in WTP \tag{4.8}$$

where $CAPOUT_l$ is the supply capacity of WTP l. For WWTPs, the capacity constraints are:

$$\sum_{j \in US} XTWWT_{j,h} \leq CAP_h \qquad h \in WWTP \tag{4.9}$$

where CAP_h is the limit for water entering WWTP h. While the above capacity constraints are modeled in the same way as the *OM model*, in this research the multi-level wastewater processing is modeled as following.

Multi-level treatment process modeling: Figure 4.1 illustrates an example of leveled wastewater treatment processes, where three processes A, B, and C provide effluent class A, class B and class C for reuse water supplies. For this example, the treatment process can be modeled using the approach illustrated in Figure 4.2 and described in what follows.

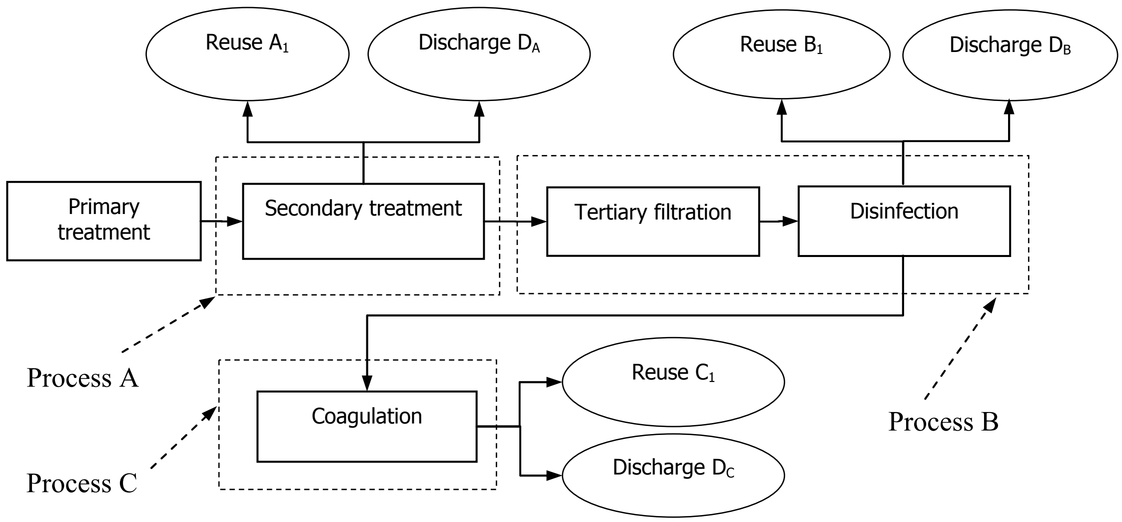


Figure 4.1 An example of wastewater treatment train with 3 levels of processes

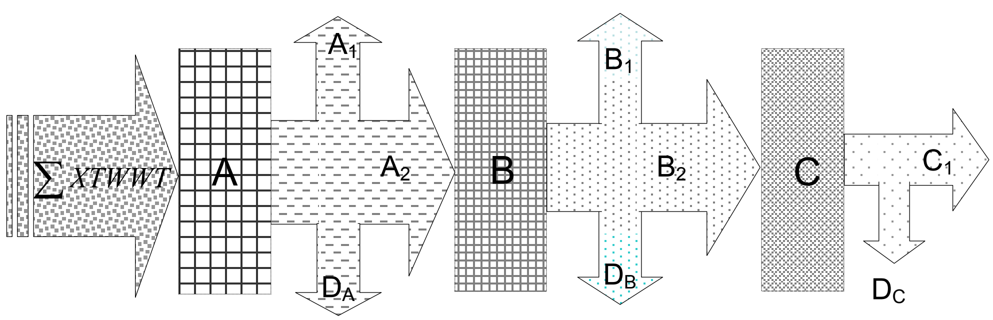


Figure 4.2 Wastewater treatment train with 3 levels of processes (*A,B,C*)

A,B,C represent the 3 levels of treatment processes, A_1,B_1,C_1 represent reuse water supplies from the corresponding process, and A_2,B_2 represent water entering the next treatment process for further treatment. The sum $\sum XTWWT$ represents the total amount of wastewater entering the WWTP whereas D_A, D_B, D_C represent the quantity of water discharged from each level. Using this notation the capacity constraints would be:

$$\sum_{j \in US} XTWWT_{j,h} \leq CAP_{h,A} \qquad \text{Capacity for level } A\text{, the same for WWTP}_h; \tag{4.10}$$

$$A_2 \leq CAP_{h,B} \qquad \text{Capacity for level } B; \tag{4.11}$$

$$B_2 \leq CAP_{h,C} \qquad \text{Capacity of level } C. \tag{4.12}$$

As well, for each process *A, B,* and *C*, represented as nodes in the network, there would also be a network flow balance constraint. They are:

$$\sum_{j \in US} XTWWT_{j,A} - A_1 - A_2 - D_A = LT_A \tag{4.13}$$

$$A_2 - B_1 - B_2 - D_A = LT_B \tag{4.14}$$

$$B_2 - C_1 - D_C = LT_C \tag{4.15}$$

Note that more general cases could be modeled in a similar fashion.

d) Water availability constraints

Water availability constraints limit the amount of water that can be withdrawn from each water supply source (similar with the *OM model*).

For surface water sources these constraints are given by

$$\sum_{l \in WTP} XST_{i,l} \leq SWA_i \qquad \forall i \in SU \tag{4.16}$$

whereas for ground water sources these constraints are given by

$$\sum_{l \in WTP} XGT_{k,l} \leq GWA_k \qquad \forall k \in GR \tag{4.17}$$

e) Quality requirement constraints

Quality requirements by users: These constraints force the flows in the system to satisfy the quality requirements of each user (i.e., that the pollutant concentrations are less than specified criteria). These constraints are derived from the assumption that the concentration of the water being delivered to the user is derived from the mixture of all flows entering that user node. Therefore the constraint requires that the resulting concentration of pollutants in the mixture be no more than the user's upper-bound. The deterministic form of these constraints is:

$$[\sum_{i\in SU} CS(P_n)_i\, XS_{i,j} + \sum_{k\in GR} CG(P_n)_k\, XG_{k,j} + \sum_{l\in WTP} CWT(P_n)_l\, XWT_{l,j} + \sum_{h\in WWTP} CWWT(P_n)_h\, XWWT_{h,j} + \sum_{t\in US} C(P_n)_t\, X_{t,j}] - STD(P_n)_j [\sum_{i\in SU} XS_{i,j} + \sum_{k\in GR} XG_{k,j} + \sum_{l\in WTP} XWT_{l,j} + \sum_{h\in WWTP} XWWT_{h,j} + \sum_{t\in US} X_{t,j}] \leq 0 \quad \forall j, n \tag{4.18}$$

The above quality constraints are a simplified version of the constraints of the *OM model* without modeling the quality changes produced by users and this research models the uncertainty issues with water quality.

Quality uncertainty modeling: Uncertain coefficients of water quality may include $CS(P_n)_i$, $CG(P_n)_k$, $CWWT(P_n)_h$, $CWWT(P_n)_h$, and $C(P_n)_t$. For simplicity denote the left hand side of the equation (4.18) by $g_j(X)$. According to the chance-constrained stochastic programming model discussed in Chapter 3, and assuming a desired quality compliance level of K_j and the corresponding risk factor t_j, the stochastic form of these quality constraints are:

$$E(g_j(X)) + t_j \sigma_{g_j(X)} \leq 0 \quad \forall j, n \tag{4.19}$$

where $E(g_j(X))$ is the expected value of the left hand side of expression (4.18), and $\sigma_{g_j(x)}$ is the standard deviation of the left hand side of expression (4.18). The generation of both $E(g_j(X))$ and $\sigma_{g_j(x)}$ is sometimes a complex process and the detailed explanation of the procedure is not included here. As an important stochastic programming method, chance-constrained programming offers a comprehensive strategy in modeling quality compliance in water reuse system based on various risk levels.

Maximum discharge to receiving water body: These constraints limit the quantity of pollutants which can be discharged to the receiving water bodies by requiring that the mass of pollutants being discharged be no more than the maximum discharge acceptable. These constraints are stated in a similar form with the ones in the *OM model*:

$$\sum_{h \in WWTP} CWWT(P_n)_h XWWTR_{h,r} \leq QR(P_n)_r \qquad \forall n, r \tag{4.20}$$

In addition to all the constraints described above, other technological, environmental and regulatory constraints can be added into the model as needed.

4.2.4 Objective Function

The objective of this water reuse optimization model is to determine the minimum cost solution to the problem of supplying water to every user in the system when water reuse is included. In order to proceed the costs incurred in implementing water reuse have to be estimated. These costs generally include the water and wastewater treatment costs, the transportation costs (represented by pumping costs), the infrastructural costs and penalty costs for modeling the uncertainty as discussed earlier. The objective of this model is written as:

Minimize:

$$C(X) = C_{(WTP)} + C_{(WWTP)} + C_{(pumping)} + C_{(Infrastructure)} + C_{(penalty)} \qquad (4.21)$$

where

$C_{(WTP)}$ is the municipal water treatment and distribution cost;

$C_{(WWTP)}$ is the costs for treating wastewater to certain quality level for discharge or reuse;

$C_{(pumping)}$ is the pumping cost due to energy consumption in transporting water; and

$C_{(Infrastructure)}$ is the cost involved with infrastructural construction.

These costs are further explained as follows:

Pumping cost: According to the literature, the cost of transporting water can be approximated by the pumping costs (i,e., energy costs). McCabe *et al.* (1993) and Nobel (1998) gave the following form of empirical pumping cost estimation:

$$C_{(pumping)} = (0.016\Delta z + 0.082L) \cdot R_E \qquad (4.22)$$

where Δz is the elevation change between the source and sink in *meters*; L is the distance between source and sink in meters and R_E is the electricity rate in *dollars/kwh*. The result is given in unit of *cost/10*^{3} *gallons/day*.

Municipal water treatment and distribution cost: This cost is defined as the fresh water treatment, delivery and storage cost for water supplied to the general public water supply system. It is best estimated using the local water pricing structure to account for maintenance and operational costs in treatment processes, ground water wells, storage, pumping station and the general water distribution network.

For the whole system, this cost is expressed as:

$$C_{(WTP)} = \sum_{l \in WTP} \sum_{j \in US} \left(XWT_{l,j} \times P_{(WTP_l)} \right) \tag{4.23}$$

where $C_{(WTP)}$ is the total cost of public water treatment and distribution, and $P_{(WTP_l)}$ is the price per *kgd* of public water supply at WTP *l*.

Wastewater treatment cost: Wastewater treatment costs generally occur in centralized wastewater treatment facilities such as WWTPs. The costs for treatment at different treatment levels (or processes of the treatment train) should be estimated. Higher prices apply to more advanced wastewater treatment processes for producing reuse water in higher quality for reuse applications with higher water quality requirements.

For the three level processes described in Section 4.2.3, this cost is expressed as:

$$C_{(WWTP)} = \sum_{h \in WWTP} \sum_{TL \in A,B,C} \sum_{j \in US} \left(XWWT_{h,j} \times P_{(WWTP)_{h,TL}} \right) \tag{4.24}$$

where $C_{(WWTP)}$ is the total cost of wastewater reclamation and distribution, and $P_{(WWTP)_{h,TL}}$ is the price per *kgd* of reuse water from WWTP $_h$ at treatment level *TL*.

Water resource infrastructural cost: This section describes how the capital investment costs of the water resource infrastructure, which may be considered if additional facilities are needed, are estimated. Typical capital cost equations for water resources infrastructures are shown in Table 4.1 which was adapted from the literature.

These cost functions for water and wastewater treatment plants are only a function of flow through the plants. Although infrastructural costs were not considered in the case study, where water transportation cost and water treatment costs were emphasized, these infrastructural costs could be used to evaluate budgetary feasibility based on the model results, e.g., the flow rates, if additional facilities need to be considered.

If uncertainty issues involved in the coefficients of the objective function, e.g., water treatment cost uncertainty, need to be considered, a new form of the cost objective function (see expression 3.21) is used to model these uncertainty issues with various risk aversion parameters.

Table 4.1 Capital Cost estimation functions for water system infrastructure (US EPA/600/R-99/029)

Facility	Units	1985 Cost Equation Capital Cost[1]	Range	Reference	Time
A. Conveyance					
1. Force main	$/ft	$C=6.97D^{1.19}$	$6 \le D \le 72$ in.	1	Fall, 1977
2. Gravity mains	$/ft	$C=5.08D^{1.19}$	$6 \le D \le 72$ in.	1	Fall, 1977
	$/ft-mgd	$C=150Q^{.46}$	$.13 \le Q \le 43$ mgd	1	Fall, 1977
3. Open channel	$/ft-mgd	$C=12.1Q^{41}$	$1200 \le Q \le 5800$ mgd	2	1985
4. Tunnel	$/ft	$C=4.44D^{1.14}$	$120 \le D \le 360$ in.	3	
B. Pump Station					
1. Well Pump	1000$	$C=72H^{64}Q^{.45}$	$10 \le Q \le 2000$ gpm	4	
	1000$		$100 \le H \le 1000$ ft		
2. Water Supply	1000$	$C=13H^{22}Q^{.44}$	$1 \le Q \le 10$ mgd	5	
			$30 \le H \le 100$ ft		
		$C=3.8H^{37}Q^{.76}$	$10 \le Q \le 100$ mgd	5	
			$30 \le H \le 100$ ft		
3. Wastewater	1000$	$C=27HQ^{.52}$	$.1 \le Q \le 100$ mgd	6	1976
			$10 \le H \le 20$ ft		
C. Storage facilities					
1. Reservoir	1000$	$C=160V^{.4}$	$10^4 \le V \le 10^6$ AF	7	1980
2. Covered concrete tank	1000$	$C=614V^{.81}$	$1 \le V \le 10$ mg	5	1976
3. Concrete tank	1000$	$C=532V^{.61}$	$1 \le V \le 10$ mg	5	1976
3. Earthen basin	1000$	$C=42V^{.76}$	$1 \le V \le 10$ mg	5	1976
4. Clearwell					
Below ground	1000$	$C=495V^{.56}$	$.01 \le V \le 10$ mg	5	1980
Ground level	1000$	$C=275V^{.43}$	$.01 \le V \le 10$ mg	5	1980
D. Water Treatment	1000$				
1. Package treatment	1000$	$C=580Q^{.64}$	$.1 \le Q \le 1$ mgd	5	
2. Conventional treatment	1000$	$C=680Q^{.74}$	$5 \le Q \le 130$ mgd	5	
3. Direct filtration	1000$	$C=640Q^{.62}$	$1 \le Q \le 100$ mgd	5	
4. Pressure filtration	1000$	$C=402Q^{.68}$	$1 \le Q \le 20$ mgd	5	
5. Reverse Osmosis	1000$	$C=1430Q^{.68}$	$1 \le Q \le 10$ mgd	5	
6. Ion exchange	1000$	$C=370Q^{.68}$	$1 \le Q \le 10$ mgd	5	
7. Lime softening	1000$	$C=1030Q^{.68}$	$10 \le Q \le 50$ mgd	5	
8. Corrosion cont.	1000$	$C=32Q^{.67}$	$1 \le Q \le 10$ mgd	5	
9. Activated carbon	1000$	$C=809Q^{.67}$	$2 \le Q \le 110$ mgd	5	
E. Wastewater treatment					
1. Primary	1000$	$C=2980Q^{.62}$	$1 \le Q \le 100$ mgd	6	1976
2. Secondary	1000$	$C=4375Q^{.68}$	$1 \le Q \le 100$ mgd	6	
3. Tertiary	1000$	$C=11400Q^{.72}$	$1 \le Q \le 100$ mgd	6	1976

References:
1. Dames and Moore (1978)
2. US Army Corps of Engineers (1979)
3. Merkle, C. (1983)
4. Benefield, L. D. et al. (1984)
5. Gummerman, R. C. et al. (1979)
6. US EPA (1976)
7. US Army Corps of Engineers (1981)

where D denotes pipe diameter in *inches*, Q denotes flow capacity in *mgd*, H denotes pipe length in *feet* and V denotes storage capacity in *million gallons*.

4.3 Applications of Geographic Information Systems

4.3.1 Water Demand Projection

In order to project urban water demand, GIS data layers are required zoning parcel layer, census data, enumeration area and land use layer are required. The GIS data processing steps shown in Figure 4.3 illustrate how urban residential reuse water demand might be projected.

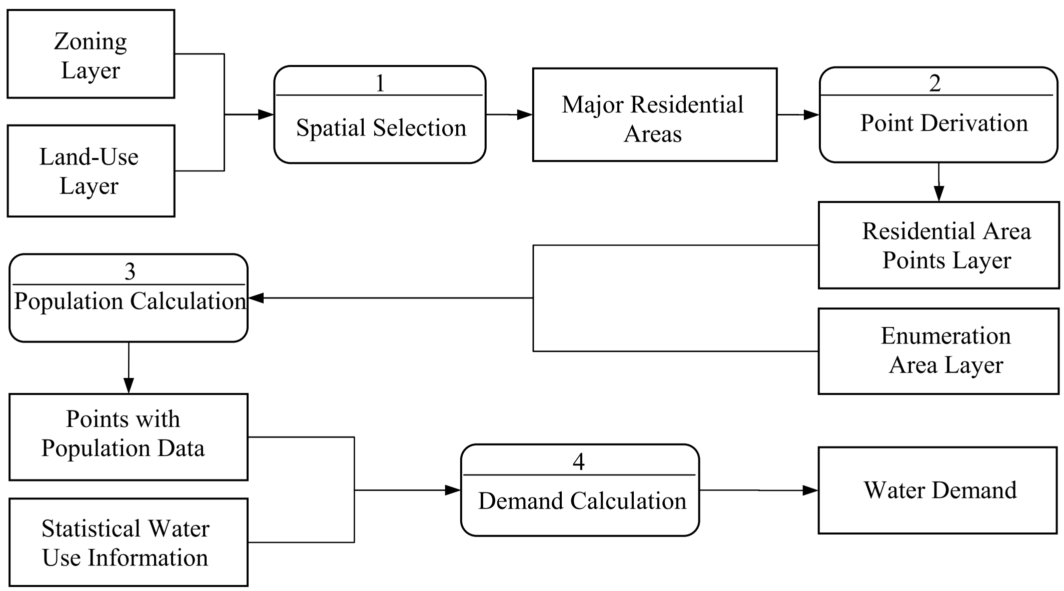


Figure 4.3 General procedures in water demand projection

Some key steps are described as follows:

1. From the zoning layer and land use layers, identify major residential areas;

2. Use a typical spatial derivation method (Table 4.2) to represent each residential area in the network model;
3. Use the enumeration area layer, calculate population data for each residential area;
4. Use average indoor and outdoor water use information, calculate water demands. For example, the average amount of water used for toilet flushing and outdoor irrigation is considered as the reuse water demand for residential areas.

Table 4.2 Types of nodes and derivation methods in GIS presentation

Node type	Coverage type	Derivation method
Receiving river	Arc	Taking the central point of an arc as a node.
Demand sites (irrigation site, i.e., golf course)	Polygon	Taking the central point of a polygon as a node.
Treatment plant (WTP and WWTP); Demand sites (single users)	Point	Taking the point as a node

4.3.2 Water Delivery Route Finding and Distance Measurement

The distances between reuse water supply sources and demand sites are important parameters in estimating the water transportation cost in the water reuse planning and management model. The GIS network functions of least-cost path or shortest path finding are used to generate the distance values from the street network data. The distances between water reuse source and destination pairs along the shortest street network are used to approximate the water conveyance line lengths in order to estimate the piping and pumping cost. These calculations are based on the fact that water distribution systems are generally installed in existing and planned road systems.

4.4 Summary

This chapter described the model's formulation. Key steps in conducting a water reuse project were discussed; the optimization formulations of the model, cost estimations and related GIS applications were presented. The addition of the two-stage recourse method and the chance-constrained stochastic programming method allows the water reuse model to account for uncertainty issues associated with water demand and quality. In order to illustrate the model's capability, an example problem is presented in next chapter.

Chapter 5

Model Application

In this chapter, a hypothetical example is presented in order to illustrate the urban water reuse modeling process with consideration of uncertainties. The example is based on data from the City of Waterloo, Ontario, Canada. Some assumptions were made to compensate for data that was not readily available such as data associated with water quality and treatment cost. The first part of the chapter briefly reviews the current water reuse status in Canada and the water environment in the Regional Municipality of Waterloo. The second part of the chapter discusses the modeling results and sensitivity analysis.

5.1 Introduction

5.1.1 Water Reuse Status in Canada

As discussed in previous chapters, the world is facing water shortage problems and water reuse is practiced in many parts of the world. However, the situation is different in Canada, where water reuse is practiced on a relatively small scale and in isolated cases. Some typical examples of water reuse include agricultural cropland irrigation, golf course and landscape irrigation, experimental housing, and reuse of wastewater at isolated facilities such as resorts, truck stops etc. It is well known that Canada has relatively abundant water resources, but with population growth and economic development on the rise in Canada there is a growing interest in wastewater reclamation and reuse, which is driven by some factors as mentioned in Marsalek (2002):

1) *steadily increasing water demands exerted against finite supplies, endangered by climate change;*
2) *opportunities to save on future expansion of the water supply infrastructure;*
3) *reducing or eliminating wastewater effluent discharge to sensitive receiving waters; and*
4) *opportunities for inexpensive provision of water services in isolated places, or single residential sites*

Based on these factors, the study of water reuse modeling is necessary and beneficial to Canada.

5.1.2 Waterloo Region's Water Resource and Water Reuse

The Regional Municipality of Waterloo (RMW) is located in the Grand River watershed at the southwestern part of the province of Ontario. There the integrated urban system supplies water to approximately 425,000 people in the region. The system consists of a complex network of 67 wells, reservoirs, pumping stations and trunk water mains. On average, the total amount of water supplied is about 171.5 million litres per day (MLD). The total water supply comes from two sources: approximately 75% of total water supply is from ground water, and 25% is from surface water. Eleven wastewater treatment plants are located within the region. The plants provide a minimum of secondary treatment for 164.1 MLD of wastewater. Treatment capacities for the individual plants vary from 0.13 MLD to 122.7 MLD (RMW, 2004).

As population and economic development grow rapidly in this area, the region is facing more stress on water sources, water supply, the wastewater treatment infrastructure, and the wastewater assimilation capacity of the Grand River (Region of Waterloo). Associated Engineering (1994) predict that the expected population growth for the Tri-City area of Kitchener, Waterloo, and Cambridge between 1991 and 2041 is 70%, 75% and 86%, respectively. This suggests that the total population for the Tri-City area, which was 346,000 in 1991, could reach 606,000 by 2041. Studies have shown that the water quality in the Grand River has been affected by waste loading, whether through wastewater treatment plants or agricultural practices (Associated Engineering, 1994). Thus, like many municipalities in the world, the Regional Municipality of Waterloo is faced with the challenge of providing water supply to their growing population, in competition with other sectors of the economy, relying on finite supplies, and controlling wastewater discharge into receiving waters.

The region's "Long Term Water Strategy (LTWS)" (RMW, 2000) has proposed several water supply options: more groundwater wells, an artificial recharge scheme, and long distant pipelines from one of the Great Lakes. Besides this long term water strategy plan, the region is continuously making efforts focusing on modifying or replacing water using efficient fixtures, etc.

As discussed before, worldwide water reuse has risen rapidly and has helped foster the sustainable development of urban water management. In addition to the region's LTWS, water reuse should be considered as an additional alternative, since it has been recognized that water reuse can not only facilitate the use of treated municipal effluents as a new source for beneficial uses to meet increasing water demands, but also reduce the discharge of polluted effluents into receiving waters (Asano *et al.*, 1996). As Marsalek (2002) emphasized, economic savings on delaying the expansion of water supply and wastewater treatment infrastructures could also be derived from water reuse. The many opportunities for water reuse discussed in Chapter 2 apply to this region. For example, there is a huge water reuse potential in the region's residential water use. Figure 5.1 shows the distribution of indoor residential water use in the region (RMW, 2003). Note that the 29% used for toilet flushing could be replaced by reuse water.

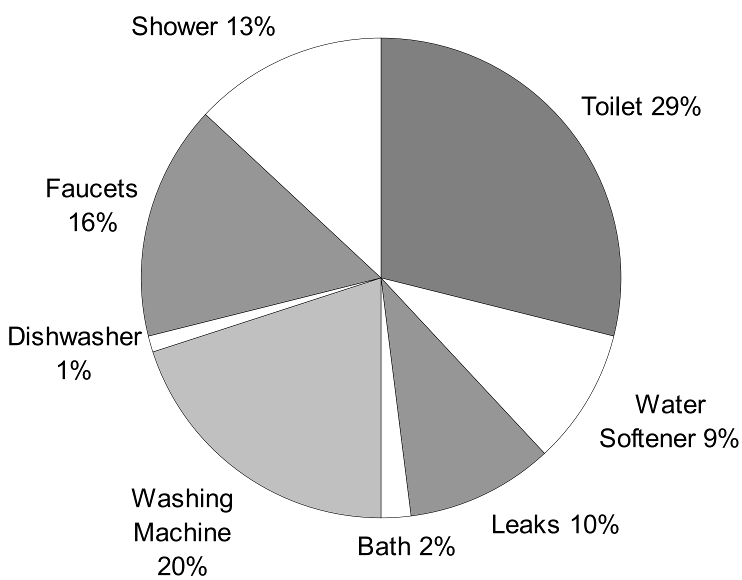


Figure 5.1 Percentage of indoor water use in Waterloo Region

Table 5.1 summarizes the amount of indoor and outdoor residential water use in the City of Waterloo which is located in the center of the region with a 2003 population of 103000. Outdoor water use generally consists of garden irrigation, car washing and recreational water use. From the table it is easy to see that water used for outdoor activities and toilet flushing account for 18% and 23% of total water use. If water reuse can be utilized for just these two categories, 41% of residential freshwater savings could be achieved.

Table 5.1 Summary of indoor and outdoor water use in the City of Waterloo

Category	Indoor and outdoor water use (gallons/capita/day)
Baths	1.35 (2%)
Clothes Washers	12.70 (17%)
Dish Washers	0.75 (1%)
Faucets	9.53 (13%)
Drinking Water	0.37 (<1%)
Leaks	6.20 (8%)
Showers	8.15 (11%)
Toilets	17.50 (23%)
Outdoor	13.40 (18%)
Total	75.20

Source: US EPA/600/R-99/029 (1999)

This strongly suggests that water reuse should be considered in the region's strategic plan for water and that further studies on water reuse in this region are necessary. In regard to water reuse studies, the uncertainty issues with water demand and quality should be addressed since the variations with these parameters cannot be ignored. To illustrate this point Figure 5.2 shows a plot of the daily water consumption information for the City of Waterloo (City of Waterloo, 2004) and highlights the variation with seasonal water consumption and the range of daily water use in the city.

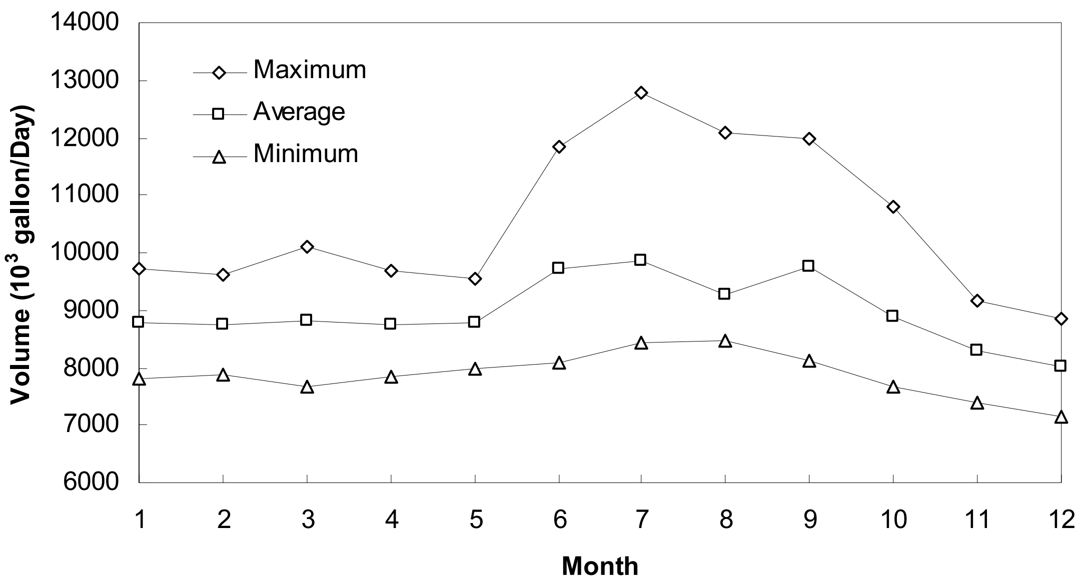


Figure 5.2 Daily water consumption of City of Waterloo in 2003

To illustrate the modeling process and demonstrate the capabilities in modeling uncertainty associated with water reuse, the proposed model was applied to a hypothetical problem in the City of Waterloo. For this problem, some data had to be fabricated due to the limitation of data currently available. The fabricated data are indicated in the following section.

5.1.3 Data Input and Model Implementation

Data required by the model includes GIS data and sophisticated information on water demand and quality, as well as data about water and wastewater treatment and costs. Some GIS data were provided by the City of Waterloo (2003) and the University Map and Design Library of the University of Waterloo. The following map (Figure 5.3) shows the locations of the major network elements used in this example. These elements include data associated with municipal water supplies and treatment plants, wastewater treatment plants with wastewater reclamation facilities and major water users.

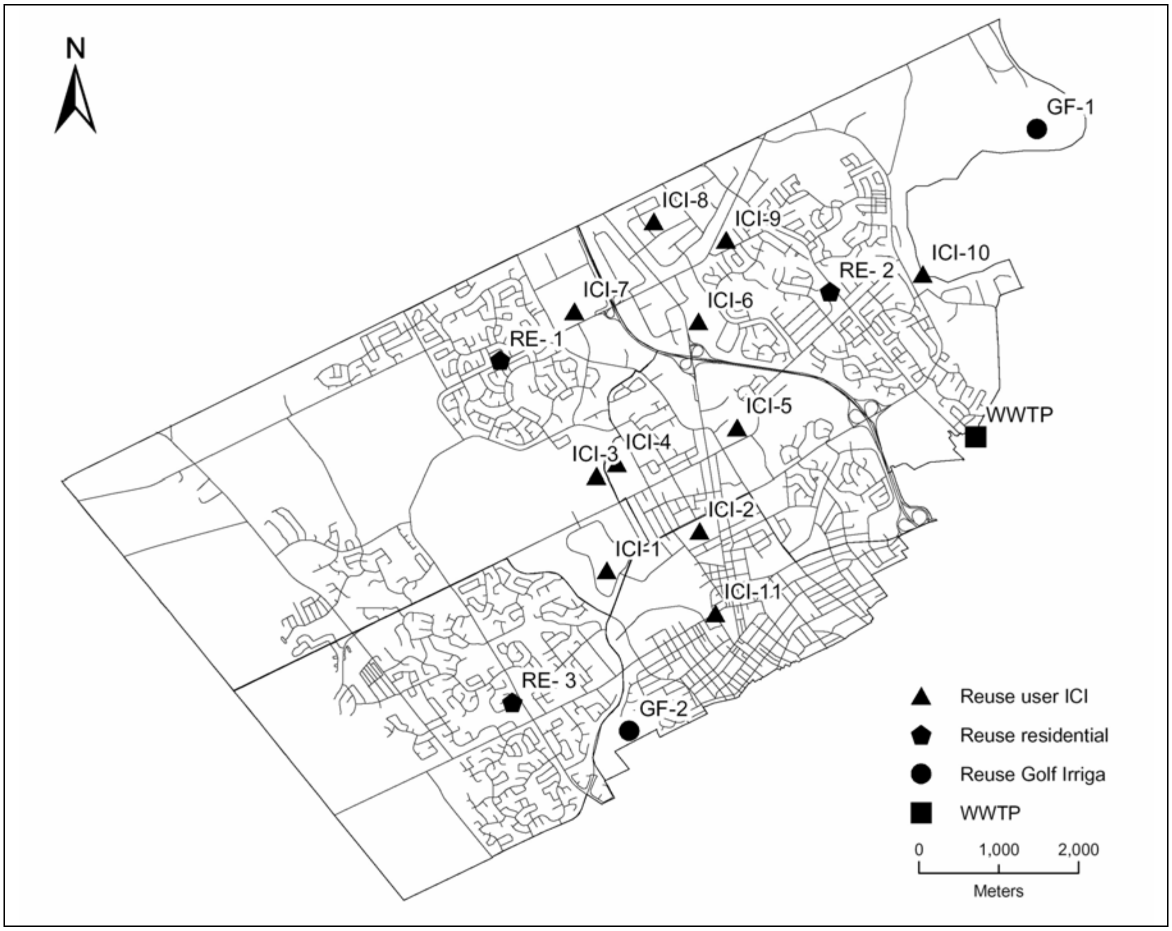


Figure 5.3 Water reuse elements in the system, one WWTP, 15 major users

Since the city's water is directly supplied by an integrated urban water supply system in the region, one theoretical water treatment plant was assumed in our model and all users in the system have direct access to municipal water through this water treatment plant. The one wastewater treatment plant located at the east end of the city is assumed to employ three levels of wastewater treatment processes with the basic level of treatment satisfying the wastewater discharge requirements and the other two levels of treatments generating reclaimed water for reuse. A total of fifteen major water users are assumed in this problem. Among them, ten ICI (Industrial, Commercial and Institutional) water users represent various industries such as chemical plants, paper industry, hydro power plants (cooling water demand), commercial malls and universities with reuse water demands having various quality requirements; three major residential areas were included to represent residential reuse water demand; and two golf courses were included as irrigation reuse water demand sites.

For water quality requirements, four common water quality parameters were considered, namely Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Organic Carbon (TOC). The influent quality requirements in terms of these parameters for the residential and irrigation users were estimated according to the types of water reuse discussed in Chapter 2. According to the Standard Industrial Classification (SIC) Code, recommended influent water quality values for different industries can be found in the literature. In this study, the influent water quality requirements and the effluent water quality parameters were estimated according to Nobel (1998). A complete list of the expected values of the demands and quality requirements for the users are listed in Table 5.2, where indices ICI-1 to ICI-10 represent the ten ICI users, RE-1 to RE-3 represent the three residential areas and GF-1 and GF-2 represent the two golf courses.

The residential areas' water demands were estimated using GIS through the general procedures found in the Appendix A. Table 5.3 presents the water quality and supply capacities data associated with the treatment facilities.

The costs of water reuse consist of two components: one is the cost of water treatment as given in Table 5.4, and the other is the transportation cost related to the distances between water sources and water users. The lengths of the shortest paths between any pair of source and sink in the network were calculated using the GIS and part of this data is given in Table 5.5.

Table 5.2 Water demand and quality data for the 15 water users considered

User Index	Demand* (kgpd**)	Influent (mg/l)				Effluent (mg/l)			
		TOC	TSS	BOD	COD	TOC	TSS	BOD	COD
ICI-1	424	50	100	20	20	137	220	180	150
ICI-2	127	50	100	20	20	240	147	100	250
ICI-3	122	50	100	30	30	160	106	100	140
ICI-4	101	20	50	20	20	22	66	100	140
ICI-5	79	5	10	10	20	18	72	100	100
ICI-6	160	60	100	30	50	224	350	600	1000
ICI-7	159	60	100	80	75	375	1619	600	1000
ICI-8	251	60	100	30	100	215	2657	600	1000
ICI-9	137	100	180	60	75	347	190	600	1000
ICI-10	134	80	180	60	75	3869	257	600	1000
RE-1	688	25	50	40	50	290	350	200	400
RE-2	825	25	50	40	50	160	220	300	500
RE-3	1155	25	50	40	50	160	220	400	600
GF-1	260	80	200	150	250	N/A	N/A	N/A	N/A
GF-2	130	80	200	150	250	N/A	N/A	N/A	N/A

* Average day demand for entire year; ** 10^3 gallon per day.

Table 5.3 Data for effluent quality and capacity of WTP and WWTPs

Facility	TOC (mg/L)	TSS (mg/L)	BOD (mg/L)	COD (mg/L)	Capacities* (kgpd)
WTP	2	0	0	0	3152
$WWTP_1$	80	200	600	800	6000
$WWTP_2$	20	50	100	100	1600
$WWTP_3$	10	20	20	60	800

* Scaled to suit the considered demands in this problem

Table 5.4 Input data for water treatment costs (City of Waterloo, 2004)

WTP water supply	User wastewater discharge	Water exchanged between users	Basic Reclaimed reuse water supply($wwtp_2$)	Advanced reclaimed reuse water supply($wwtp_3$)	Treated water discharge from wwtp to receiving waters
2.84	2.72	2.00*	1.00*	2.50*	1.00*

* Fabricated costs (Unit: $/$10^3$gal)

Table 5.5 Distances between source-sink pairs generated by the GIS network functions

Source	Sink	Distance* (m)	Source	Sink	Distance* (m)
WWTP	ICI-1	5738	ICI-1	ICI-8	6227
WWTP	RE-1	7318	ICI-1	RE-1	4703
WWTP	GF-1	5874	ICI-1	GF-1	9436

*generated according to the network elements' locations shown in Figure 5.3

The reuse network diagram for the case study is shown in Figure 5.4 (with incomplete arc connections). Connection rules used in the network are described as following: a WTP can supply any users; the dummy source can supply any users; some ICI users can supply other users; ICI users and Residential users discharge to $WWTP_1$; Golf courses' irrigation has no discharge; $WWTP_1$ only discharges to $WWTP_2$ and Receiving water body; $WWTP_2$ can supply $WWTP_3$, all users and the Receiving water body; $WWTP_3$ can supply all users and discharge to the Receiving water body. These rules can be realized by defining an appropriate node-arc incidence matrix in the network flow optimization model (see Appendix B). Specifically, in this network, the number of nodes is 22 and the number of all possible arcs connecting potential sources and sinks is 149.

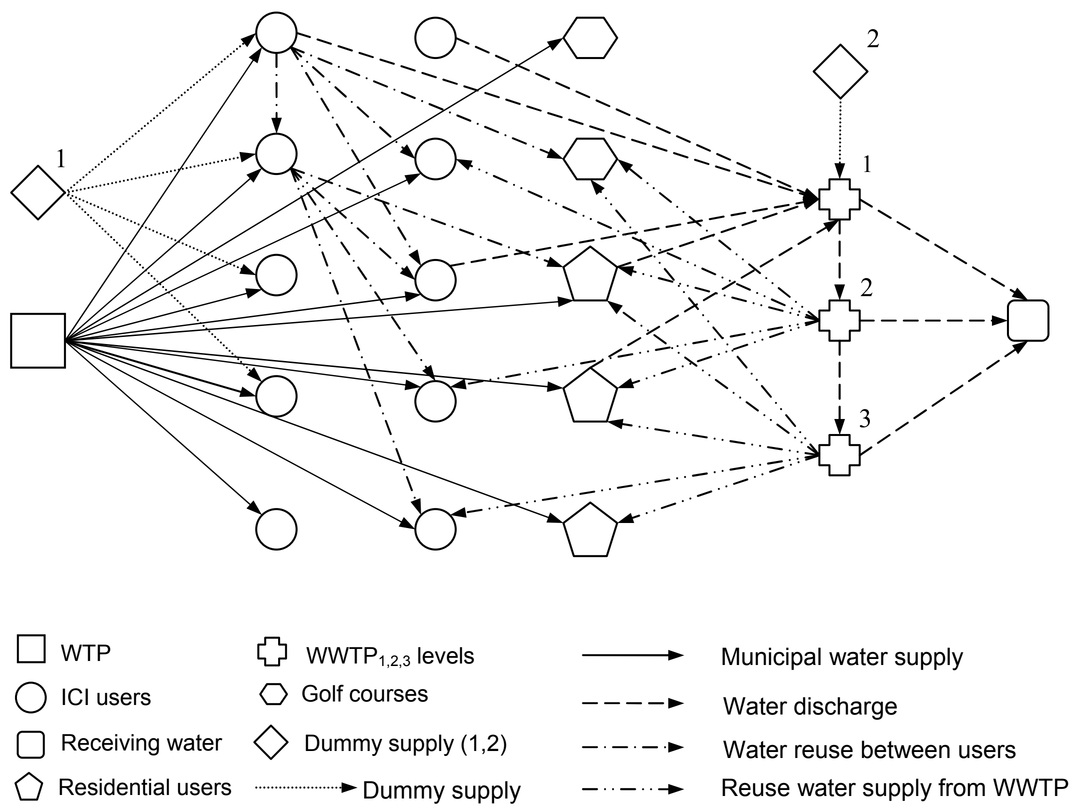


Figure 5.4 Network diagram of the case study system

The model was coded in MATLAB 6.1 and solved using MATLAB Optimization solver "fmincon" which is capable of solving general optimization problems with linear and non-linear constraints (general MATLAB input and solving statements and descriptions about “fmincon” and can be found in Appendix B). Uncertainty issues with demands and quality as well as discussions about the model results are presented in the next section.

5.2 Results and Discussions

This section discusses the results generated by the model coded in MATLAB. Firstly, as an urban water allocation and reuse management model, it is capable of obtaining the optimal allocation of urban water resources with consideration of water reuse in the given system. By considering water reuse, the water users’ demands are supplied by various water sources including municipal water supply and reuse water supplies. All these water sources are allocated to users under the condition that the overall costs of the system are minimized and water demands and quality requirements are satisfied. Secondly, by incorporating stochastic modeling methods, the model can help decision makers in making the best decisions regarding the uncertainty issues associated with water reuse planning and management. The following subsections discuss these two aspects of the modeling results. The first aspect is discussed by introducing the model results obtained from a deterministic case. The second aspect is discussed by comparing the impact of the results from cases with different levels of water demand and quality uncertainties.

5.2.1 The Optimal Allocation and Reuse of Urban Water Resources

This part of the discussion is addressed by examining the results obtained from the deterministic case (without uncertainties) using the expected values of water demands and quality as given in the last section. For discussion, the information elicited from the results are categorized into the following four parts, namely, the composition of water supplies from different sources; the water reuse activities between users; the comparison of water supplies of reuse water and WTP water; and the economic evaluation.

a) Composition of Water Supplies:

When water reuse is considered in urban water resource management, demanded water could be supplied by various sources including municipal water supply from WTP and reuse water supplies from WWTP wastewater reclamation facilities or other users. For the specific input information given to the model, the allocation of these various urban water resources can be optimized under various constraints such as demand, quality, capacity and network balance. Table 5.6 gives the model results using the expected values of the input data introduced in the previous section. From the result table, water reuse pathways (source and destination pairs) are quantitatively identified. For each user there are various water supplies blended to provide water with satisfactory quantity and quality (Figure 5.5). The demands of the entire system are satisfied with 40% of reuse water generated from within the system. In other words, a 40% reduction of fresh water can be achieved by implementing water reuse in this system.

The identified water reuse pathways provide essential information in planning water reuse. For example, basic reclaimed water from $WWTP_2$ can be supplied to users in larger flow rates such as users ICI-9, ICI-10 and GF-1. User GF-1 entirely depends on the basic reclaimed water supply, since the effluent quality of $WWTP_2$ satisfies this user's quality requirements. On the other hand, advanced reclaimed water from $WWTP_3$ is suitable to RE-2 with the larger quantity (619 kgpd) accounting for 75% of RE-2's total demand. Since this model accounts for the water price and delivery cost (calculated based on distance parameters as discussed in Chapter 4), distances between sources and sinks have a great impact on water allocation. In this example, advanced reclaimed water ($WWTP_3$) supplies a large amount of reuse water to RE-2, but does not supply to RE-1 and RE-3 with the same quality requirements because the location of RE-2 is much closer to WWTP than the other two residential areas. So the location of water reclamation facilities had a dramatic impact on the economic aspect of water reuse planning in this example.

Table 5.6 Optimal allocation of water resource involving water reuse

User Index	WTP Water Supply (kgpd)	Reuse Water Supply (kgpd)				
		Basic Reclaimed Water ($WWTP_2$)	Advanced Reclaimed Water ($WWTP_3$)	From Users	Total Reuse Water Supply	Percentage of total demand
ICI-1	363	-	-	61	61	14%
ICI-2	103	-	-	24	24	19%
ICI-3	97	-	-	25	25	20%
ICI-4	86	-	-	15	15	15%
ICI-5	71	7	-	-	7	10%
ICI-6	112	-	-	48	48	30%
ICI-7	78	-	-	81	81	51%
ICI-8	176	-	-	75	75	30%
ICI-9	55	69	-	14	82	60%
ICI-10	51	130	53	-	183	78%
RE-1	501	-	-	87	87	15%
RE-2	165	41	619	-	660	80%
RE-3	1024	-	-	131	131	11%
GF-1	-	260	-	-	260	100%
GF-2	-	21	-	109	130	100%
Total	2883	528	672	669	1869	65%

b) Water Reuse Opportunities between Users:

Water reuse opportunities also include water reuse between users. In this example, five users (ICI-1, 2, 3, 4, and 5) were defined as potential reuse water sources with the eligibility to provide reuse water to other users. Figure 5.6 shows the optimal allocation results of water reuse between users. The total amount of reuse water supply between users accounts for about 1/3 of the total water reuse in the system. Those supplies are in considerable quantities and indicate the promising water reuse opportunities between users.

c) Reuse Water Supply and Municipal (WTP) Water Supply:

Water supplied by WWTPs and eligible users is counted as reuse water supply. From the model results, the comparison between municipal (WTP) water supply and reuse water supply is given in Table 5.6 and illustrated in Figure 5.7.

Table 5.6 qualitatively compares municipal water supply with reuse water supply for each user by giving the percentage of reuse supply to each user. For users ICI-1 through ICI-5, reuse water supply accounts for between 10% and 20% of the demand, while for users ICI-6 through ICI-10, reuse water accounts for between 30% and 78% of the demand (because users ICI-6 through ICI-10 have lower influent quality requirements and their locations are closer to WWTP). The demands of users GF-1 and GF-2 are totally satisfied by reuse water supply because of their low water quality requirements and reasonable distances from WWTP. For residential users (RE-1, RE-2, RE-3), as discussed above, RE-2 receives 80% reuse water because of its proximity to WWTP and the advanced reclaimed water from WWTP satisfies its quality requirements. On the other hand, RE-1 and RE-3 depend mostly on the WTP water supply because the WTP water supply is more cost effective than the WWTP supplies due to the relative proximity of the WWTP.

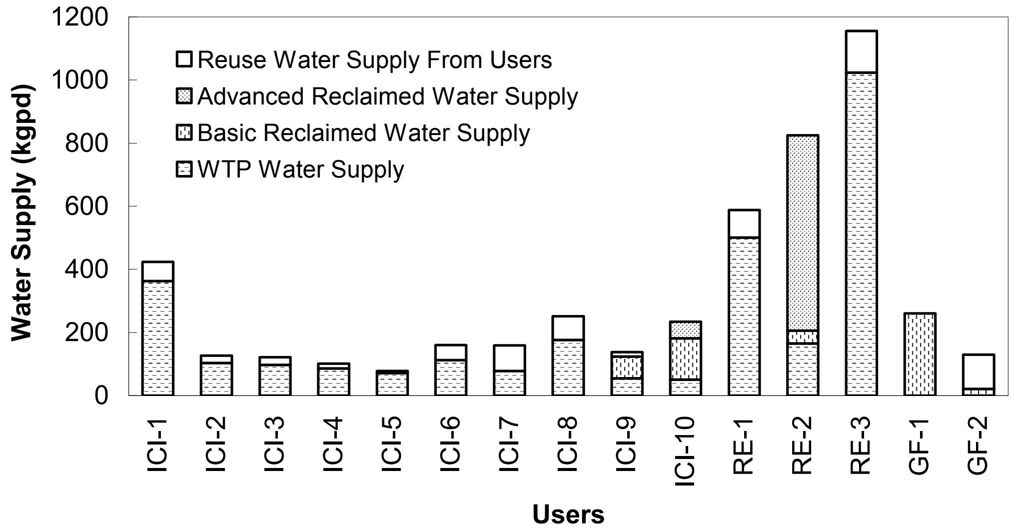


Figure 5.5 Composition of supplies

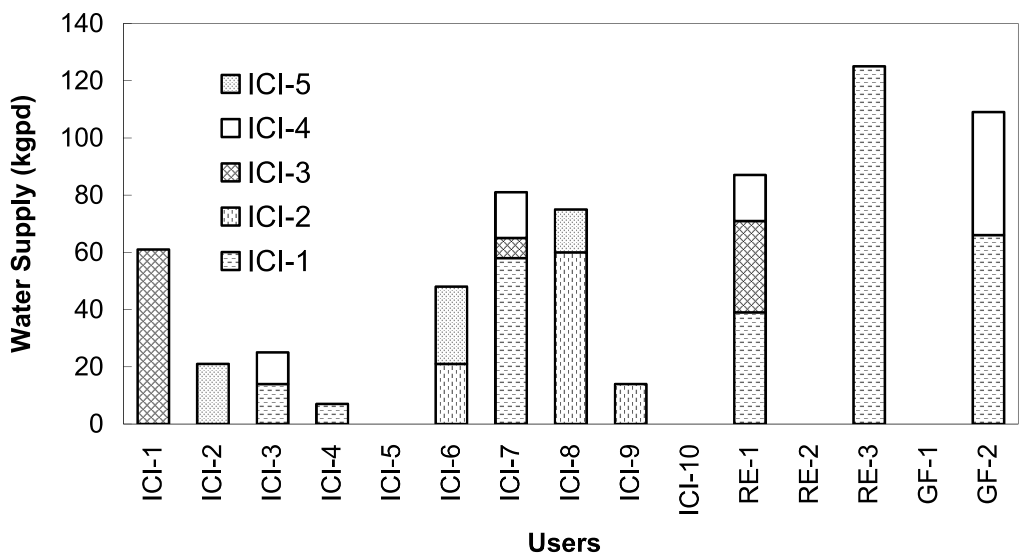


Figure 5.6 Distribution of reuse water supplied by users

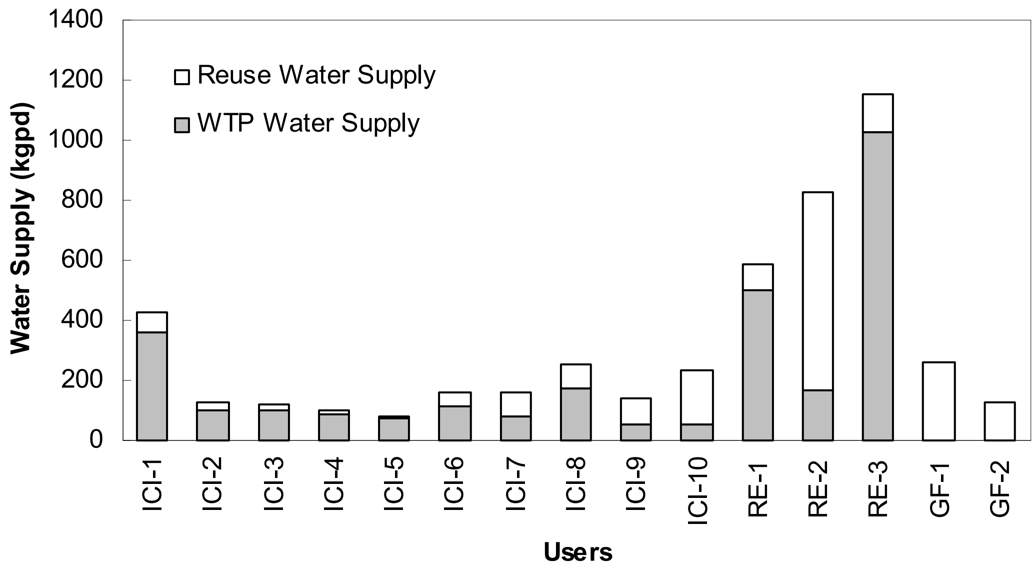


Figure 5.7 WTP supply and total reuse water supply

d) Economic Evaluation:

To further analyze the cost suitability of the water reuse opportunities identified by the model, an economic evaluation was also performed. Water treatment cost and water delivery cost associated with each reuse source-destination pair was considered in this model.

Table 5.7 summarizes the cost information from the model results. From this table, the economic suitability of each potential reuse water supply can be evaluated. Piping requirements for delivering reuse water from source to sink is listed in the table and a simple piping efficiency ratio (*PER*) was defined for each reuse water supply arc as:

$$PER = \frac{(Piping\ Length)_k}{(Flow\ Rate)_k} \qquad \forall \text{ water reuse arcs } k \tag{5.1}$$

Table 5.7 Economic evaluation of water reuse opportunities

User Index	WWTP Basic Reclaimed Water Supply					WWTP Advanced Reclaimed Water Supply					Water Reuse Between Users				
	Flow (kgpd)	Treatment cost	Energy cost	Piping length required (m)	Piping Efficiency Ratio	Flow (kgpd)	Treatment Cost	Energy Cost	Piping length required (m)	Piping Efficiency Ratio (*PER*)	Flow (kgpd)	Treatment Cost	Energy Cost	Piping length required (m)	Piping Efficiency Ratio
ICI-1											61	$121	$44	1728	29
ICI-2											24	$48	$20	1958	82
ICI-3											25	$50	$12	1131	45
ICI-4											15	$29	$9	1433	98
ICI-5	7	$7	$8	2401	322										
ICI-6											48	$96	$61	3025	63
ICI-7											81	$162	$136	3991	49
ICI-8											75	$151	$153	4852	64
ICI-9	69	$69	$73	2538	37						14	$27	$30	5180	378
ICI-10	130	$130	$72	1319	10	53	$133	$29	1319	25					
RE-1											87	$173	$143	3942	46
RE-2	41	$41	$23	1305	32	619	$1547	$339	1305	2					
RE-3											131	$261	$190	3459	26
GF-1	260	$260	$321	2937	11										
GF-2	21	$21	$34	3855	182						109	$218	$141	3080	28

* Treatment cost is calculated according to the water price setup; Energy cost is the transporting cost calculated by distance;

* Piping length required is the distance between source and sink along the road network.

The smaller the *PER* value is, the more economically suitable the potential reuse water supply would be. This ratio reflects the economy of scale which is important in infrastructural planning and investment. As well, the piping costs can be calculated by employing the estimation functions in Chapter 4, but they are omitted here for simplicity.

From this table, we investigate the cost suitability for each type of reuse water supply separately. In WWTP Basic Reclaimed Water supply, users ICI-5 and GF-2 do not yield good *PER* value due to their small supply of potential reuse water. For WWTP Advanced Reclaimed Water Supply, provision to users ICI-10 and RE-2 yield suitable *PER* value. For those who do not yield suitable *PER* value, WTP water supplies should be considered. An acceptable *PER* value needs to be determined by the planners.

Based on this analysis, we can derive the overall optimal water reuse planning decisions and by referring to the piping cost estimation functions discussed in Chapter 4, we can calculate the investment costs.

5.3 Discussions Regarding Uncertainties

Uncertainty in water demand and quality is modeled by incorporating two-stage stochastic recourse and the chance-constrained stochastic programming methods described in Chapter 3 and 4. In the following sections discussing uncertainties with demand and quality, we first introduce the data input for the uncertain parameters, then illustrate the experiments and scenario generation, and finally discuss the impact of the uncertainties.

5.3.1 Uncertainty with Demand

Table 5.8 lists the users (RE-1, RE-2, RE-3, GF-1 and GF-2) with uncertain water demands and the mean values of their water demands. We use the Coefficient of Variation (*CV*) to reflect the levels of variation of these demands. *CV* is defined as:

$$CV = \frac{\text{Standard Deviation}}{\text{Expected Value(Mean)}} = \frac{\sigma}{\mu}$$

$$\text{thus} \quad \sigma = CV \cdot \mu \tag{5.2}$$

The coefficient of variation *CV* is used to define the levels of the standard deviation (σ), e.g., the square root of the variance (σ^2) which measures the expected spread of the variable about the mean. For simplicity, a normal distribution was assumed for the uncertain variables in this research. In order to differentiate the levels of variability in demands, a set of *CV* was used, i.e., 0.05, 0.10, 0.20 and 0.50, corresponding to variability levels from low to high. The standard deviation and probability distribution corresponding to the demand of user RE-1 under this set of *CV* are shown in Table 5.9 and Figure 5.8.

For water demand modeling, it is necessary to consider the relationships between demands among the users in the system. For example, under similar weather conditions, the irrigation water demand of one golf course would reflect the demand of other golf courses, but this relationship would not hold between a golf course and an industry. Mathematically, these kinds of relationship between variables can be modeled by their correlation coefficients, a measure that determines the degree to which two variable's movements are associated. A strong correlation between variables means that the value of

Table 5.8 Mean values of uncertain demands

User Index	Mean Demands (kgpd)
RE-1	688
RE-2	825
RE-3	1155
GF-1	260
GF-2	130

Table 5.9 Different CVs and corresponding standard deviations of user RE-1

Coefficient of variation (CV)	Standard deviation (σ)
0.05	34.4
0.10	68.8
0.20	137.6
0.50	344

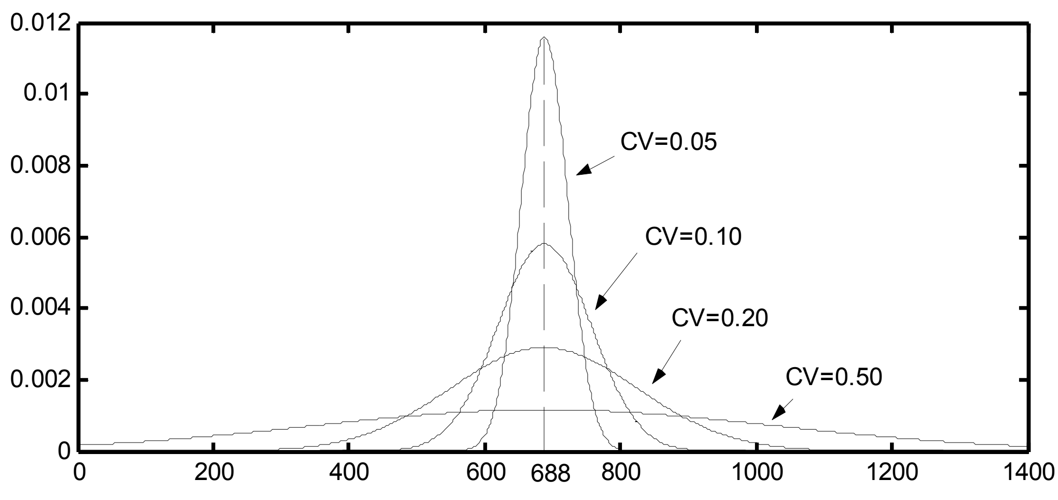


Figure 5.8 Distributions under different *CV*s for user RE-1

one variable can be predicted, to some extent, by the value of the other. The correlation coefficient is often denoted by r and is defined as:

$$r_{i,j} = \frac{Cov(x_i, x_j)}{\sigma_{x_i}\sigma_{x_j}} \tag{5.3}$$

where $r_{i,j}$ is the correction coefficient between random variable x_i and x_j, and $Cov(x_i, x_j)$ is the covariance of these two variables. The range of the correlation coefficient is from -1 to +1, with 1.0 indicating perfect positive correlation and -1.0 indicating perfect negative correlation. In our water reuse problem, the matrix of correlation coefficients with the demands of the five users is assumed to be:

$$r = \begin{bmatrix} 1 & 0.3 & 0.4 & 0.1 & 0 \\ 0.3 & 1 & -0.2 & 0.1 & 0.2 \\ 0.4 & -0.2 & 1 & 0.2 & 0.1 \\ 0.1 & 0.1 & 0.2 & 1 & 0.4 \\ 0 & 0.2 & 0.1 & 0.4 & 1 \end{bmatrix}.$$

In the matrix, the order of row and column corresponds to the five users with uncertain demands, namely RE-1, RE-2, RE-3, GF-1 and GF-2. The values in the matrix are corresponding to the correlation coefficients between demands of any two users. For example, the first row describes how the demand of user RE-1 correlates with demands of the other four users. Specifically, these correlation coefficients indicate that user RE-1 has a stronger demand correlation with RE-3 (r = 0.4) and RE-2 (r = 0.3), a weaker demand correlation with GF-1 (r = 0.1) and no correlation with GF-2 (r = 0). Thus, this demonstrates how demand correlation can be modeled.

Based on the covariance of the uncertain demands, a large number of scenarios can be generated to model the random variables, in this case, the uncertain water demands. The scenario generation process was done using MATLAB function “mvnrnd” with the mean, covariance, and number of scenarios as input parameters (more descriptions about function “mvnrnd” can be found in Appendix B). These scenarios are used in two-stage recourse stochastic programming to model the demand uncertainty. A portion of the scenarios generated for modeling the uncertain water demands is shown in Figure 5.9, 5.10 and 5.11 with different coefficients of variation.

Based on the generated scenarios for these water demands and the probability of each scenario’s occurrence, the demand uncertainty can be modeled by formulating the deterministic equivalent demand constraints using the two-stage programming method presented in Chapter 3 and Chapter 4. The number of scenarios generated in this analysis was 60 which gave reasonable results.

As discussed in Chapter 4, an initial recourse policy is needed to implement the two-stage stochastic method. For demonstration purposes, a unit penalty cost of $5 was assumed for shortfalls of the second-stage variables to compensate the noncompliance with demands. By minimizing expected costs an optimal water allocation policy can be reached for which the risk of demand noncompliance is minimized.

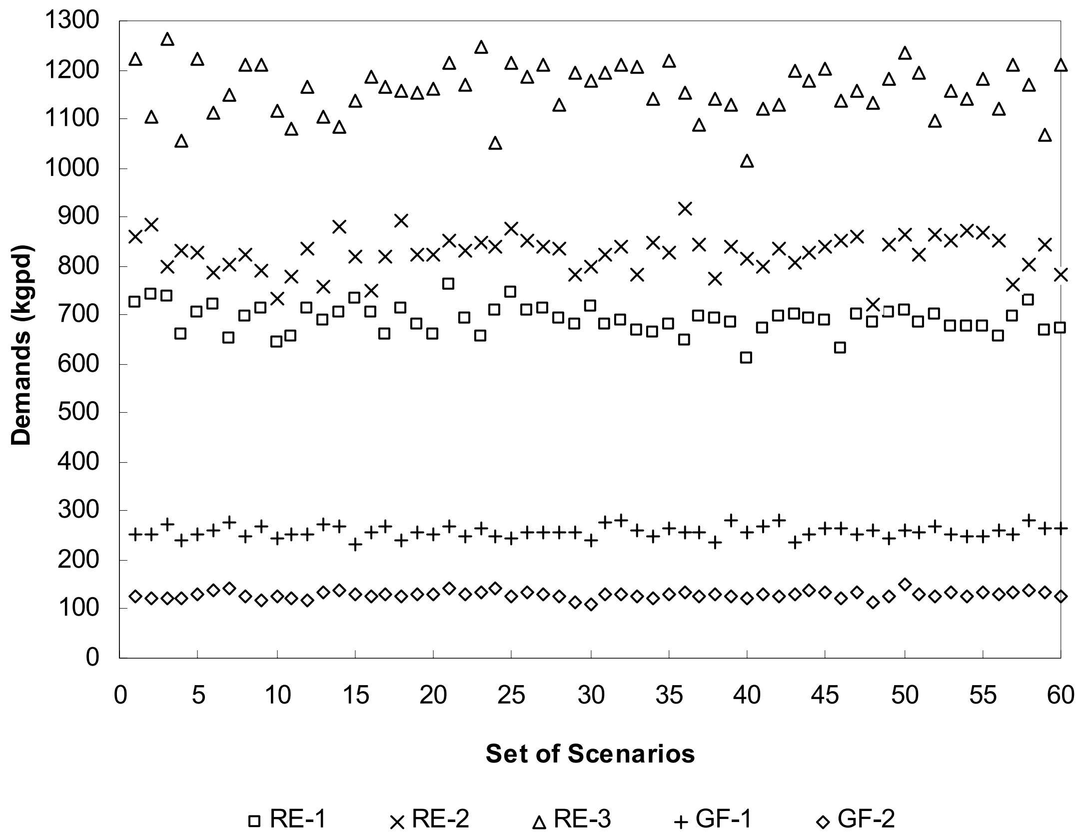


Figure 5.9 60 scenarios generated for modeling uncertain demands with *CV*=0.05

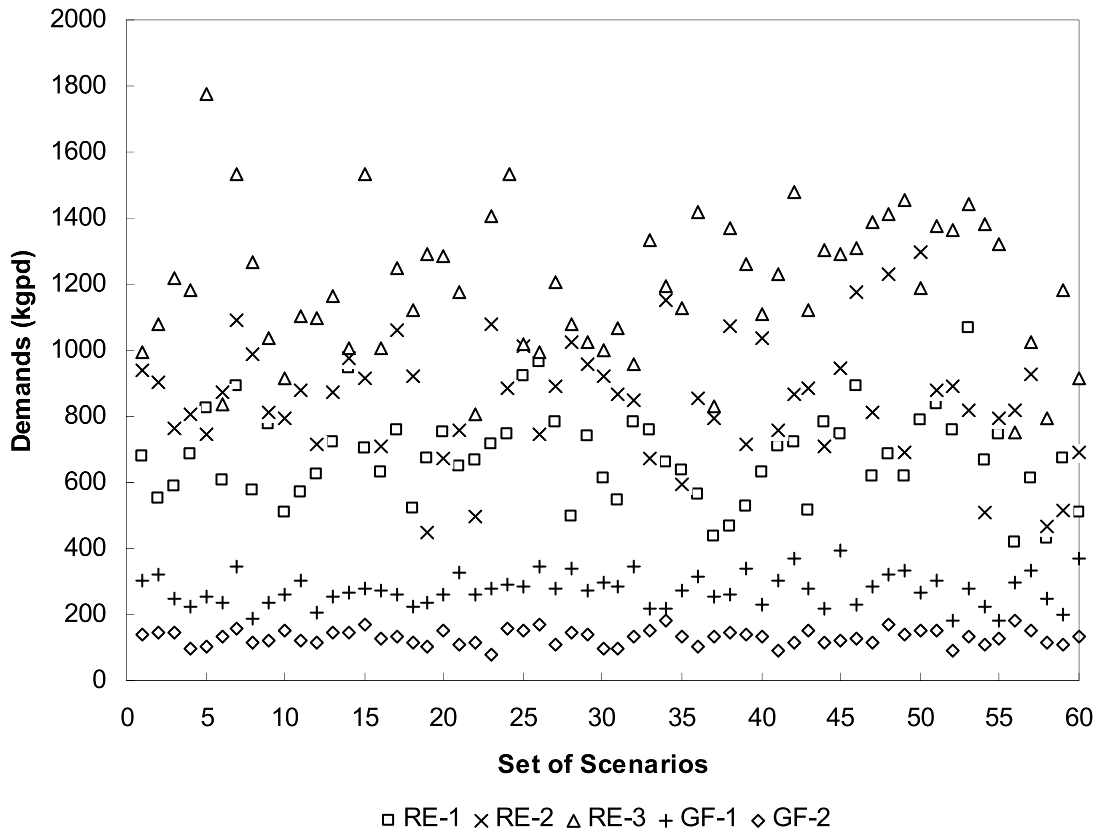


Figure 5.10 60 scenarios generated for modeling uncertain demands with *CV*=0.20

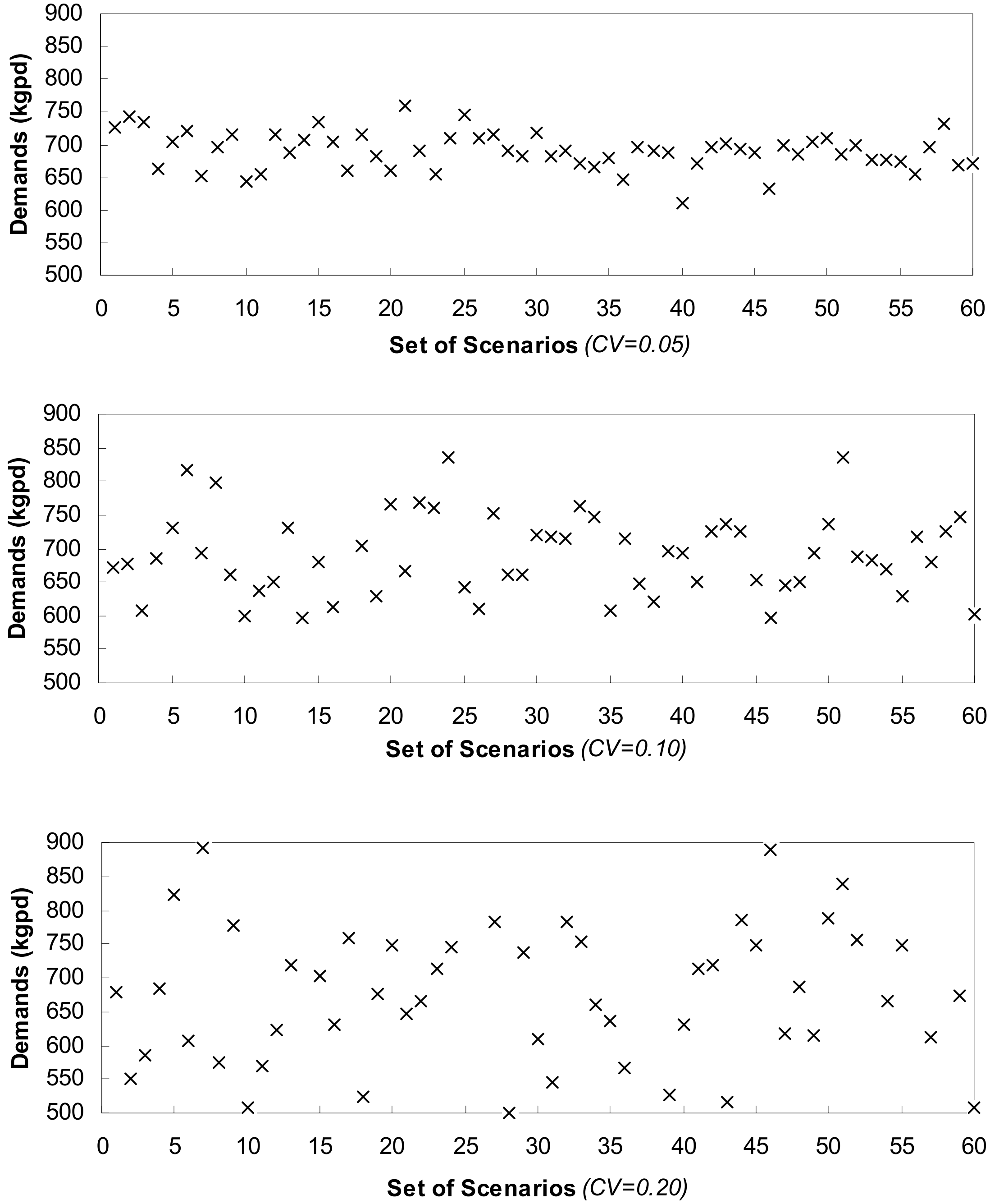


Figure 5.11 60 demand scenarios generated for RE-1 under different *CV*s

Figure 5.12 and 5.13 show the WTP (municipal water) supplies and the $WWTP_2$ (basic reclaimed) reuse water supplies under different levels of demand variation, that is, coefficients of variation: 0.05, 0.10, 0.20 and 0.50. As illustrated in Figure 5.8 (Distributions under different *CV*s for user RE-1), when the coefficients of variation increase, the distribution of the uncertain demands scatter. For the users with uncertain demands (RE-1, RE-2, RE-3, GF-1 and GF-2), their supplies tend to decrease as the level of demand variation gets higher. Meanwhile, the supplies for users with certain demands (ICI-1 through ICI-10) were not affected.

As we know, the smaller the coefficient of variation, the closer the uncertain variable behaves like a deterministic one. Figure 5.14 gives the objective function values, which are the costs to the overall water reuse system, optimized under cases with different demand *CV*s. By examining this figure, we can see the trade-off between cost and demand variation: the increase of the level of demand variation costs more to the system.

In regard to the uncertain water demands, the model is capable of predicting the expected costs to the overall system. The expected costs are also minimized by optimally allocating the water resources considered within the system. This is of great significance in making robust decisions when planning urban water reuse where demand uncertainty should be considered.

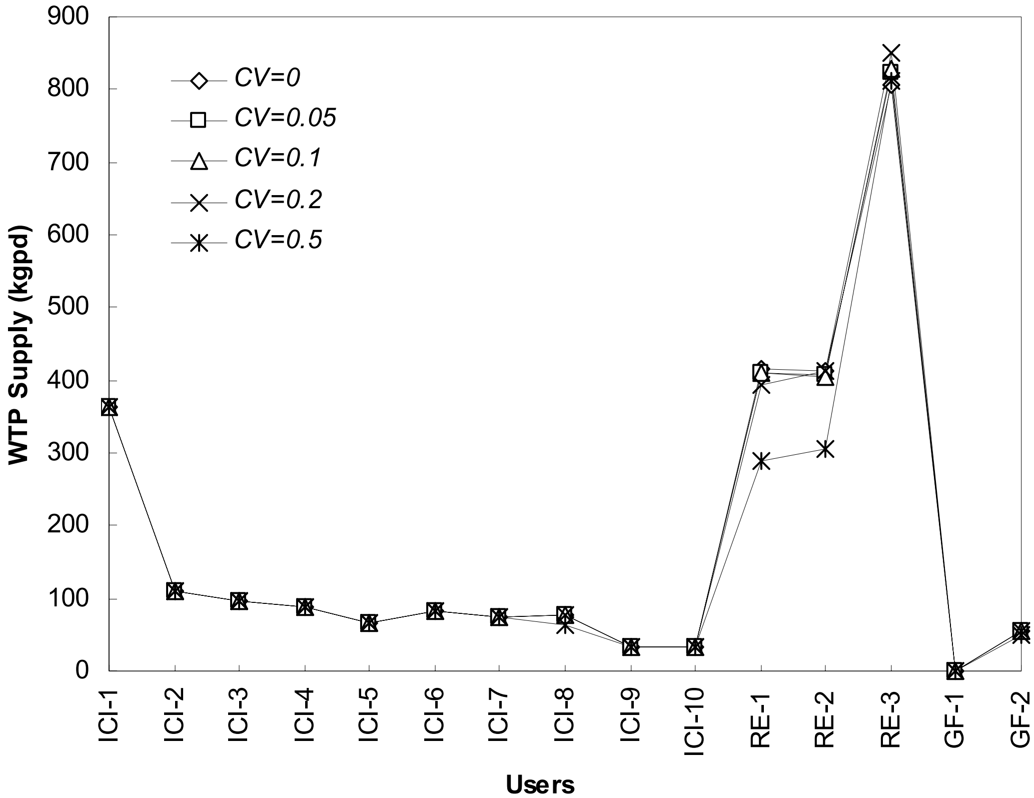


Figure 5.12 WTP supply with different coefficients of variation of demand

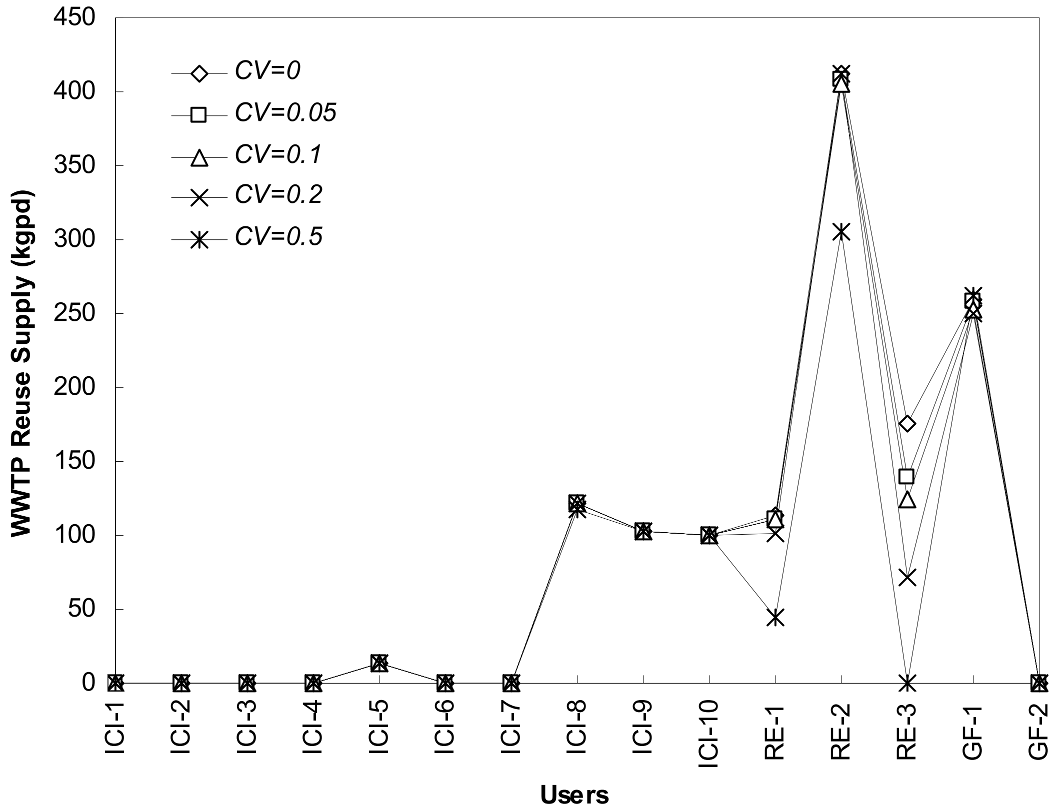


Figure 5.13 WWTP reuse supply with different coefficients of variation of demand

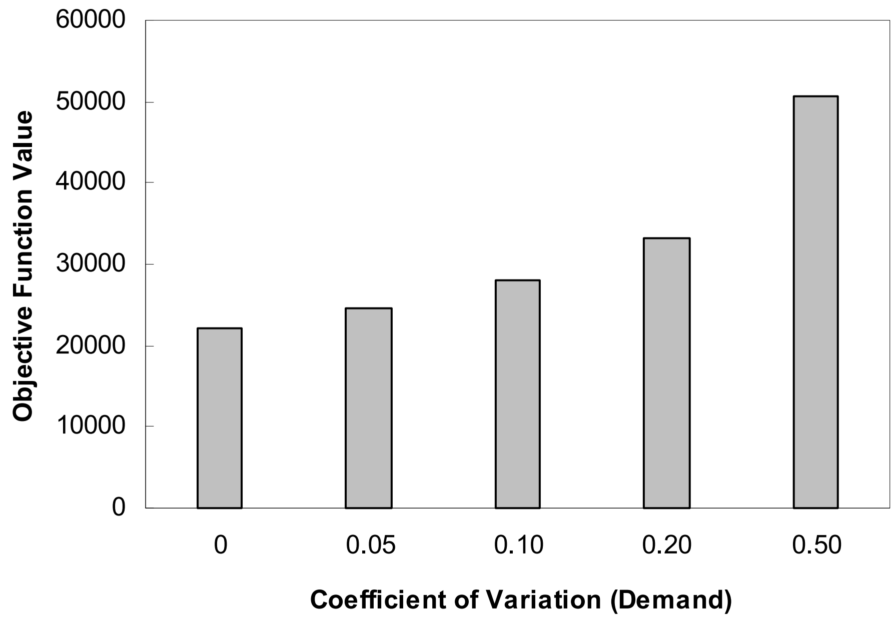


Figure 5.14 Cost-variation trade-off

5.3.2 Uncertainty with Quality

Water quality and water treatment stability are of great importance in water reuse management and modeling. Uncertainty with effluent quality from reuse water supply sources has been modeled using the chance-constrained programming method discussed in Chapter 3 and Chapter 4.

For modeling quality uncertainty in this study, the same set of coefficients of variation with quality is used as was used for demand uncertainty modeling; four levels of *CV*s are considered, namely, *CV* = 0.05, 0.10, 0.20 and 0.50. For implementing the chance-constrained programming method, the risk factors are set to 1.75, 1.28, 0.85 and -0.25, corresponding to probability levels, denoted by *p*, of quality compliance of 96%, 90%, 80% and 40% respectively. For simplicity, the quality of the WWTP basic reclaimed reuse water supply is considered uncertain and the mean values of the quality parameters are those listed in Table 5.10. Here we also assume that water quality changes are directly proportional among these four quality parameters and that the quality compliance based on TOC will guarantee the overall quality compliance with all other parameters. The coefficients of variation and their standard deviation are listed in Table 5.11, and the probability distributions are shown in Figure 5.15. The cases studied for modeling quality uncertainty are the sixteen possible combinations obtained using the 4 values of *CV* and the 4 quality compliance probability levels.

Table 5.10 Mean values of WWTP reuse water quality

Quality Parameters	**TOC**	**TSS**	**BOD**	**COD**
WWTP Basic Reclaimed Water (mg/L)	20	50	100	100

Table 5.11 *CVs* and standard deviations of TOC of WWTP reuse water quality

Coefficient of variation	Standard deviation (σ)
0.05	1
0.10	2
0.20	4
0.50	10

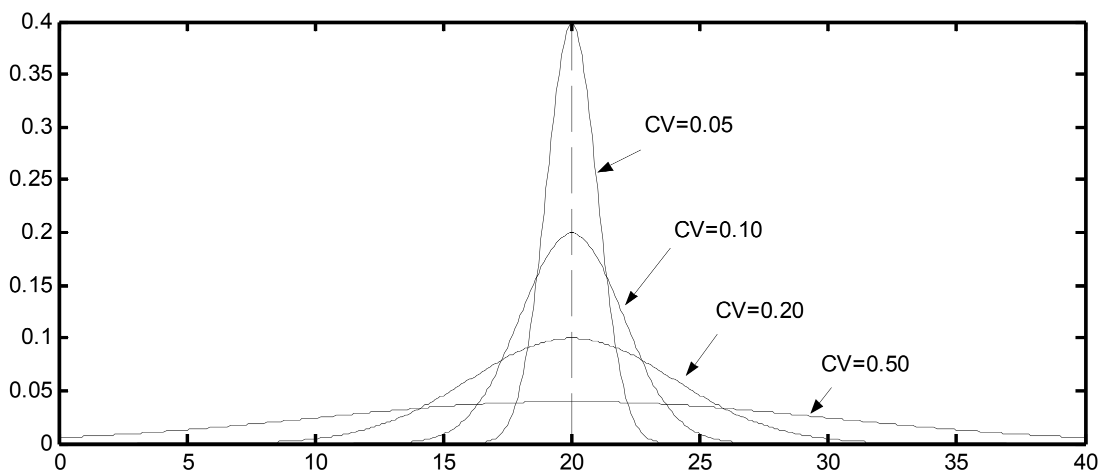


Figure 5.15 Distributions of parameter TOC with four levels of *CVs*

Figures 5.16 and 5.17 give the results of WTP and WWTP reuse water supplies respectively under the different quality chance-constraints with $CV = 0.05$.

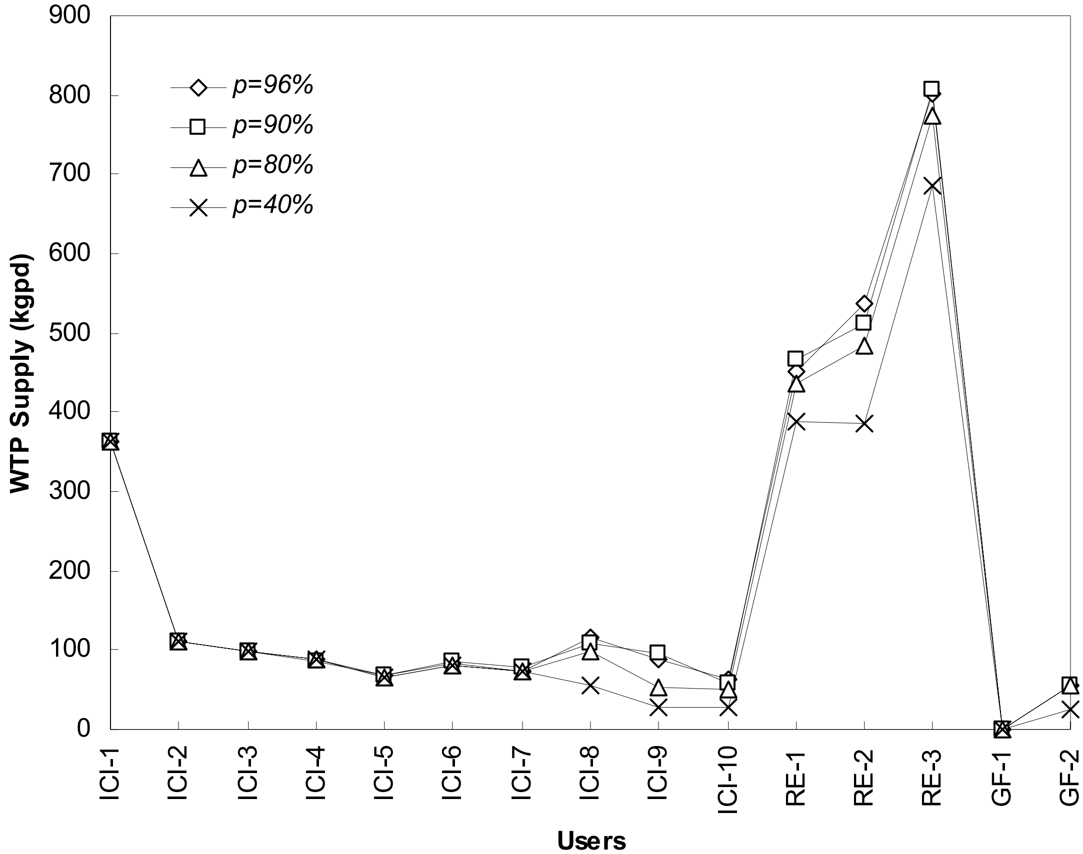


Figure 5.16 WTP water supplies under different chance-constraints with quality variability *CV*=0.05

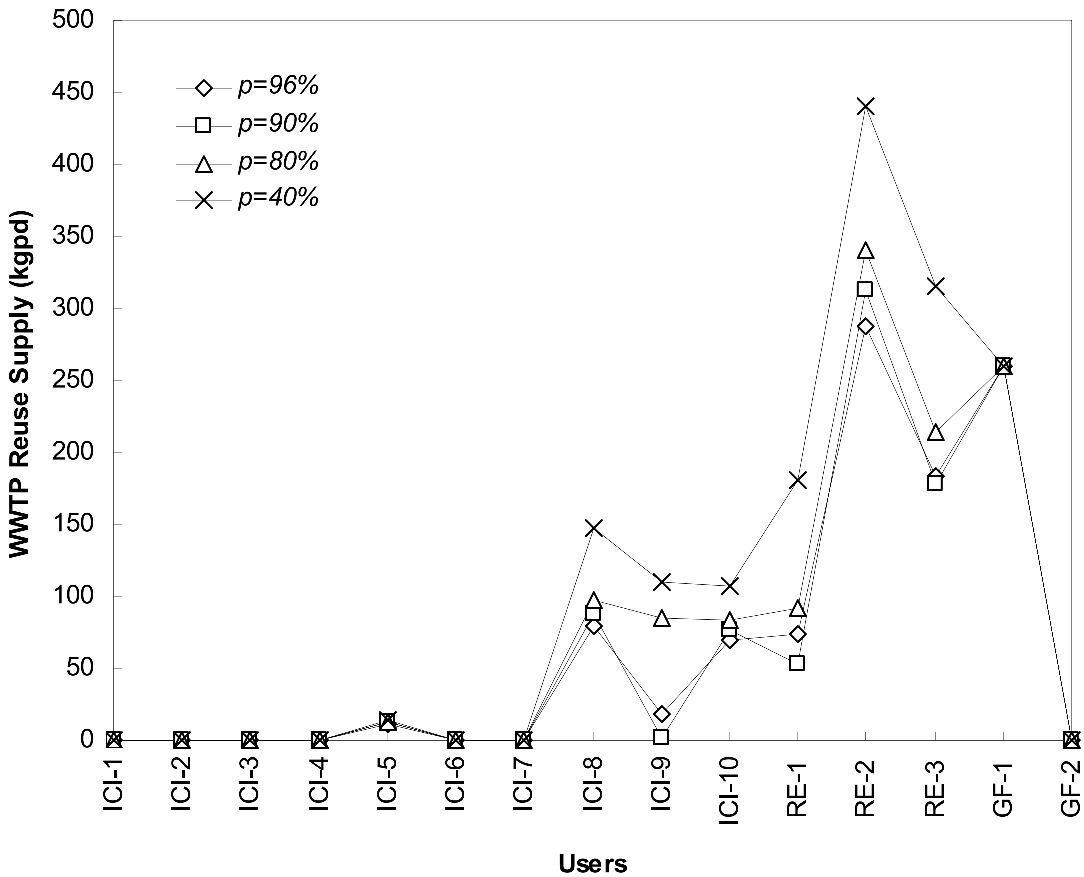


Figure 5.17 WWTP reuse water supplies under different chance-constraints with quality variability *CV*=0.05

These two figures illustrate that the higher quality chance-constraints require that more water be supplied from the WTP, which provides water with higher quality. As well, if we compare the results obtained when levels of quality variability are varied (using the coefficients of variation) under the same quality chance-constraint, the relationship between supplies and quality variability can be observed. These results are shown in Figure 5.18 and 5.19 under the quality chance-constraint of 96%.

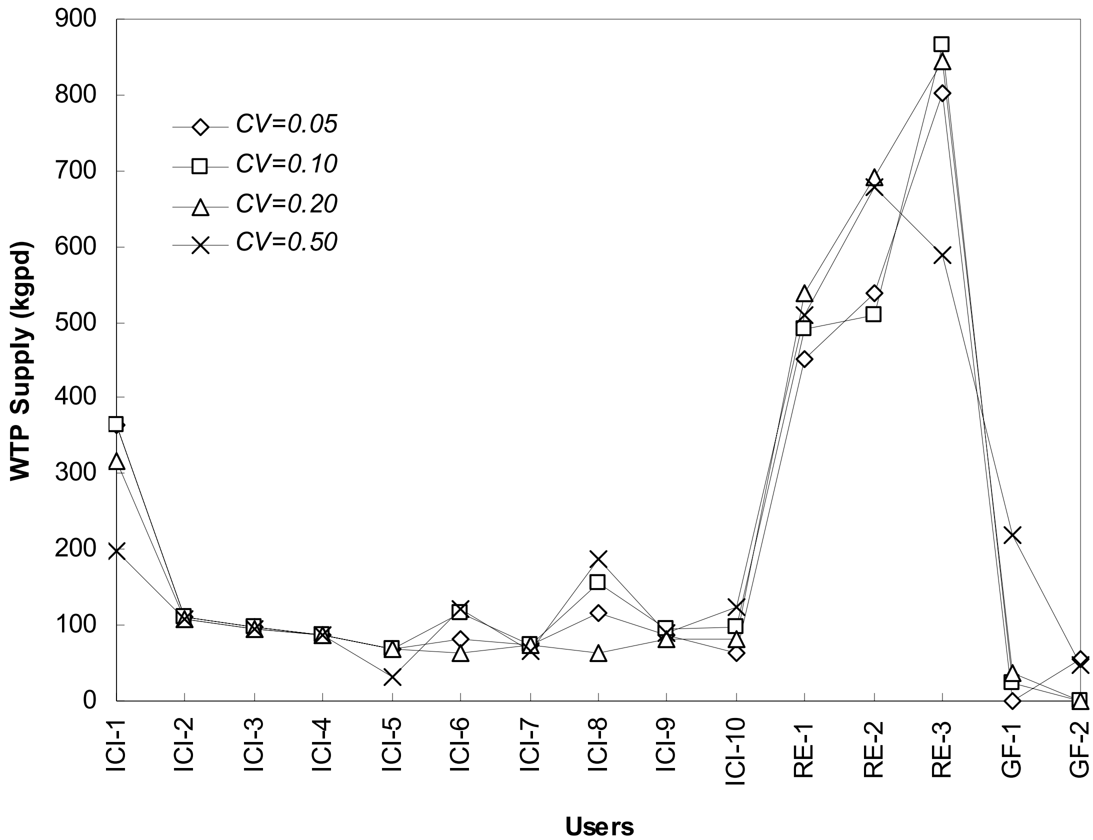


Figure 5.18 WTP water supplies under different levels of quality variability using the quality chance-constraint of 96%

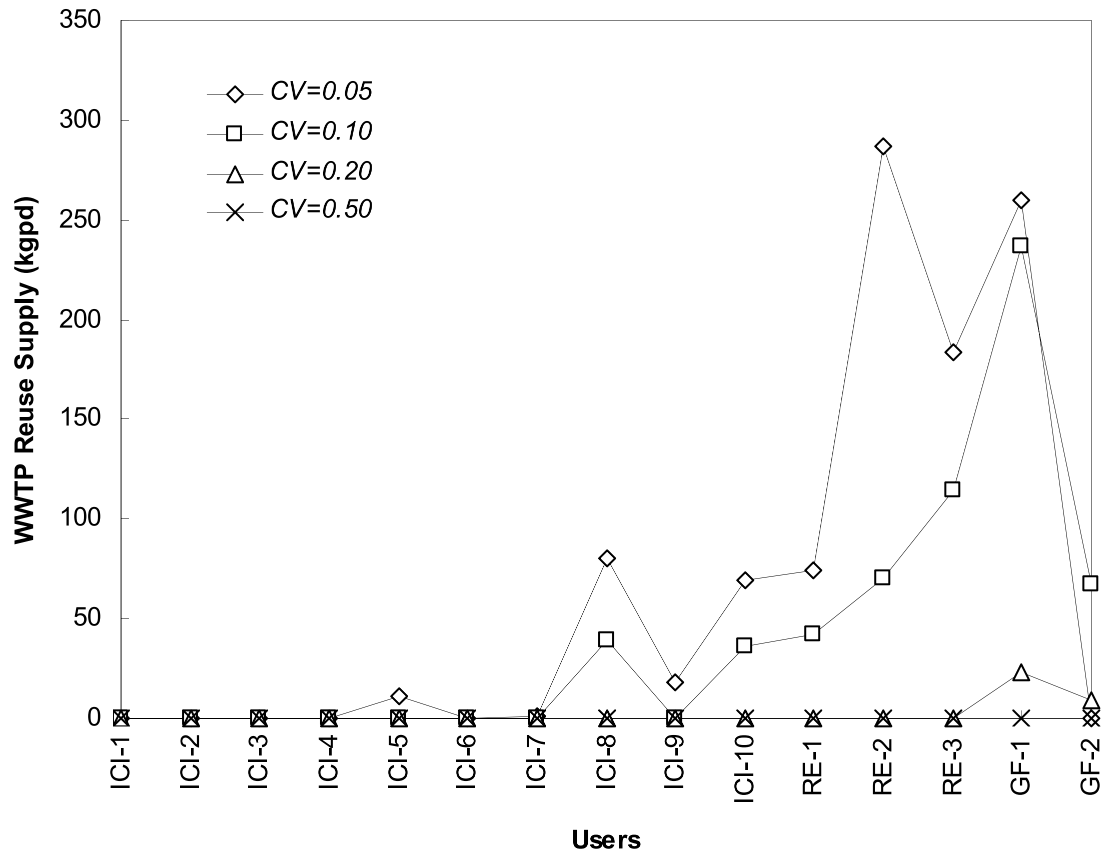


Figure 5.19 WWTP reuse water supplies under different levels of quality variability using the quality chance-constraint of 96%

Figure 5.18 illustrates, not surprisingly, that WTP water supplies tend to increase as the quality variability increases to ensure compliance of the required chance-constraints. Conversely, WWTP reuse water supplies tend to decrease, as illustrated in Figure 5.19, as quality variability increases. For example, Figure 5.19 indicates that for a *CV* value of 0.50, the WWTP supplies are reduced to zero. From these observations, we conclude that the reliability of water quality provided by reuse water sources determines the feasibility of their use for water reuse applications.

Figure 5.20 illustrates the cost and quality chance-constraint trade-off with the same quality variability level of CV = 0.05 and Figure 5.21 illustrates the trade-off of cost with various chance-constraints and different levels of quality variability.

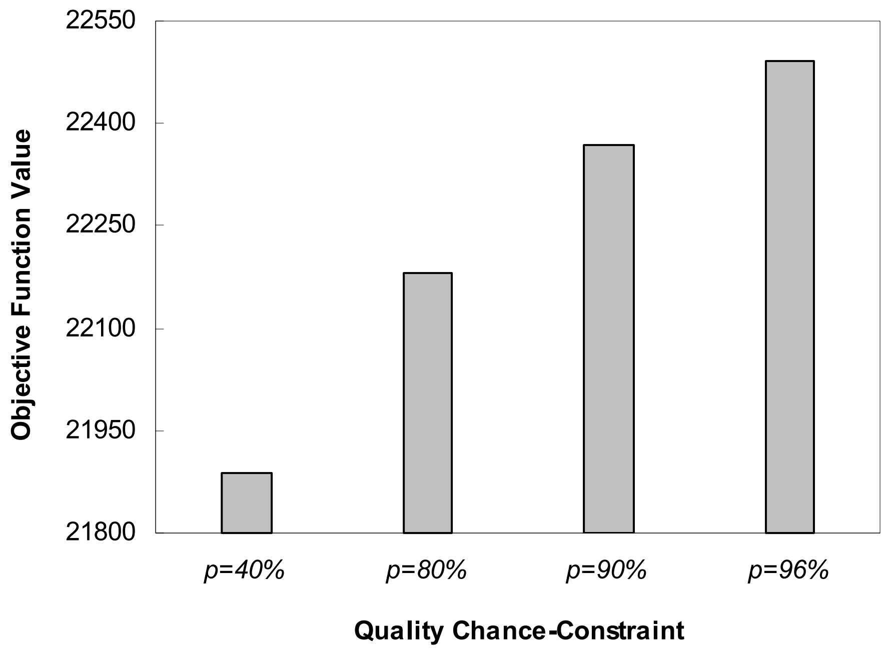


Figure 5.20 Cost and chance-constraint trade-off with quality variability *CV* = 0.05

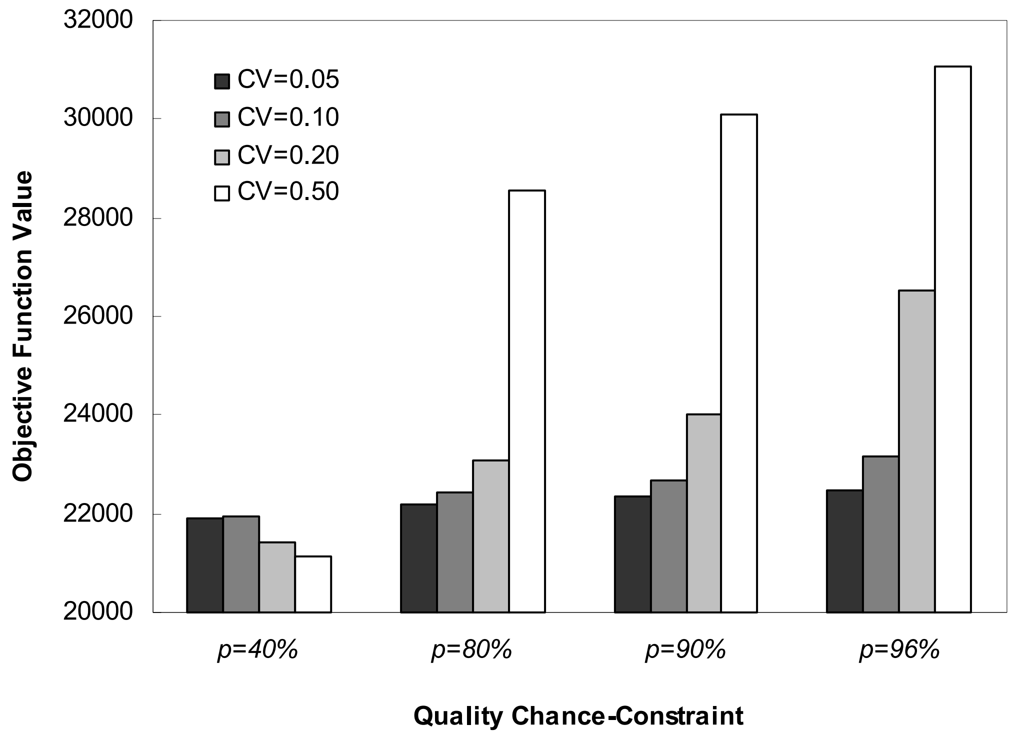


Figure 5.21 Trade-off of cost and quality chance-constraint and levels of quality variation (*CV*=0.05, 0.10, 0.20 and 0.50)

These plots show, again not surprisingly, that with the same level of quality variation (quality *CVs*), the higher quality chance-constraint (*p*) will cost more to the system. However more important observation is that when the level of quality variation gets sufficiently high, the cost to the system climbs dramatically if we want to achieve the same quality chance-constraint. The conclusion that can therefore be drawn is that for a water reuse system, the most significant aspect of cost effectiveness is the quality variability of the reuse water supplies or, in other words, the reliability of water treatment for reuse.

5.3.3 Uncertainties with Demand and Quality

In the preceding sections, we have discussed the cases with demand and quality uncertainty independently. However since demand and quality uncertainties typically occur at the same time, we now look at some cases where both uncertainties occur simultaneously. Table 5.12 lists the 4 cases that were investigated and Figure 5.22 shows the WWTP reuse water supplied under these cases. Figure 5.23 illustrates the corresponding costs for these four cases.

Table 5.12 Case specifications

Cases	Demand Uncertainty	Quality Uncertainty
I	deterministic	deterministic
II	deterministic	*CV*=0.05, chance-constraint=96%
III	*CV*=0.05	deterministic
IV	*CV*=0.05	*CV*=0.05, chance-constraint=96%

Figure 5.24 presents the WWTP reuse water supplies for 96% of quality chance-constraint with the five different levels of demand variability and Figure 5.25 indicates the costs from these five cases. Note that the WWTP reuse water supplies to each user reflect the specific characteristics of each case being investigated. Moreover, these results reveal the necessity of considering these uncertainty issues in water reuse planning and management.

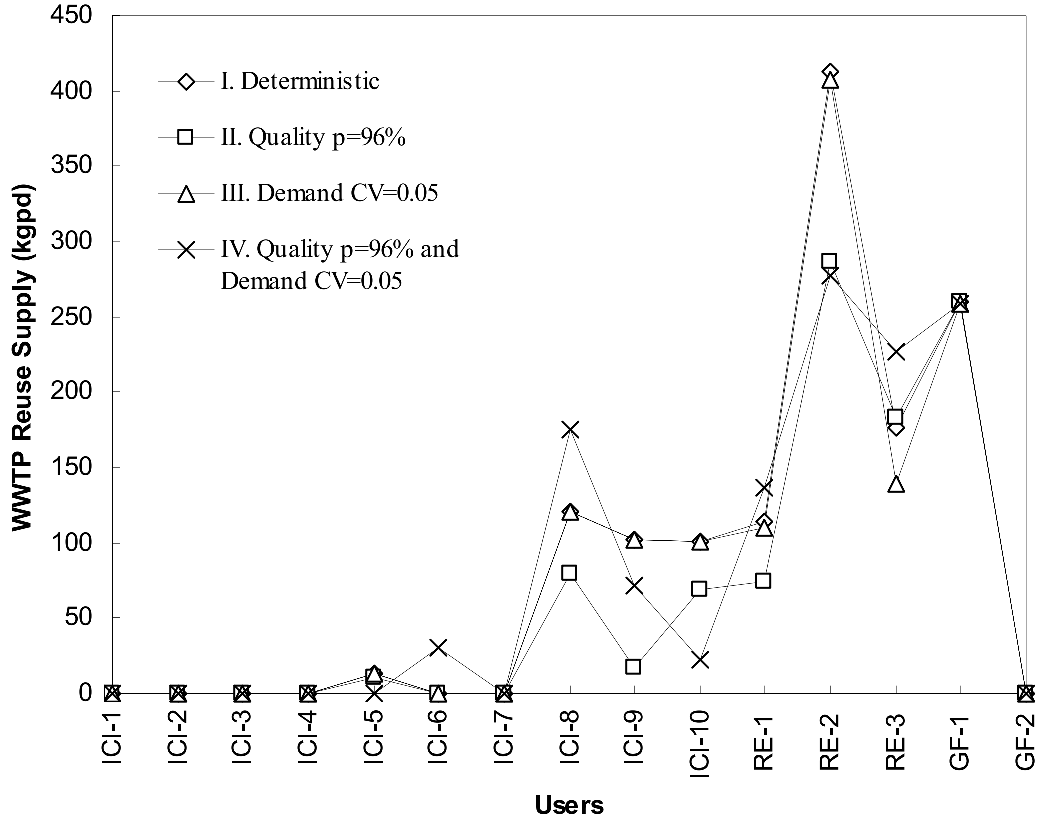


Figure 5.22 WWTP reuse water supplies under different cases of uncertainty with quality and demand

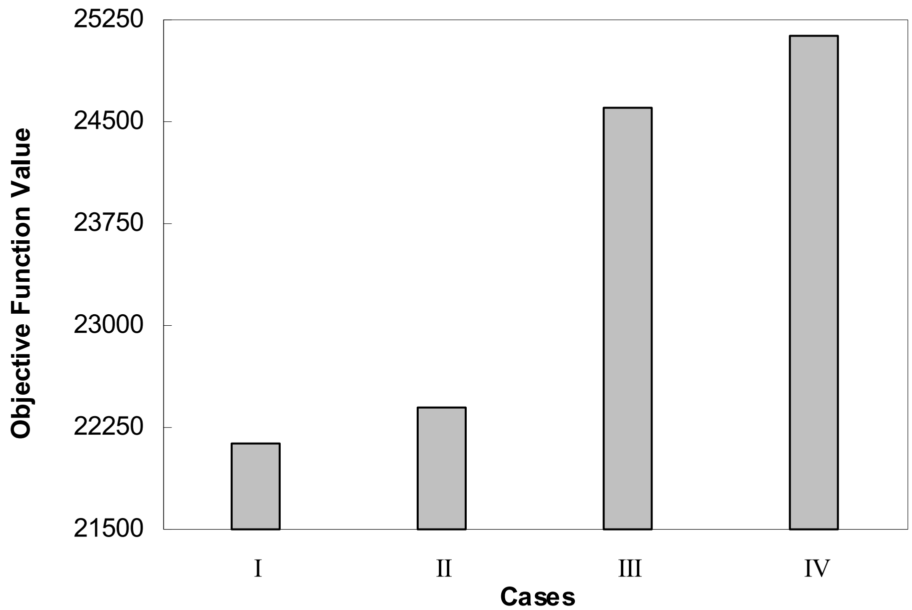


Figure 5.23 Cost for the four cases illustrated in Figure 30

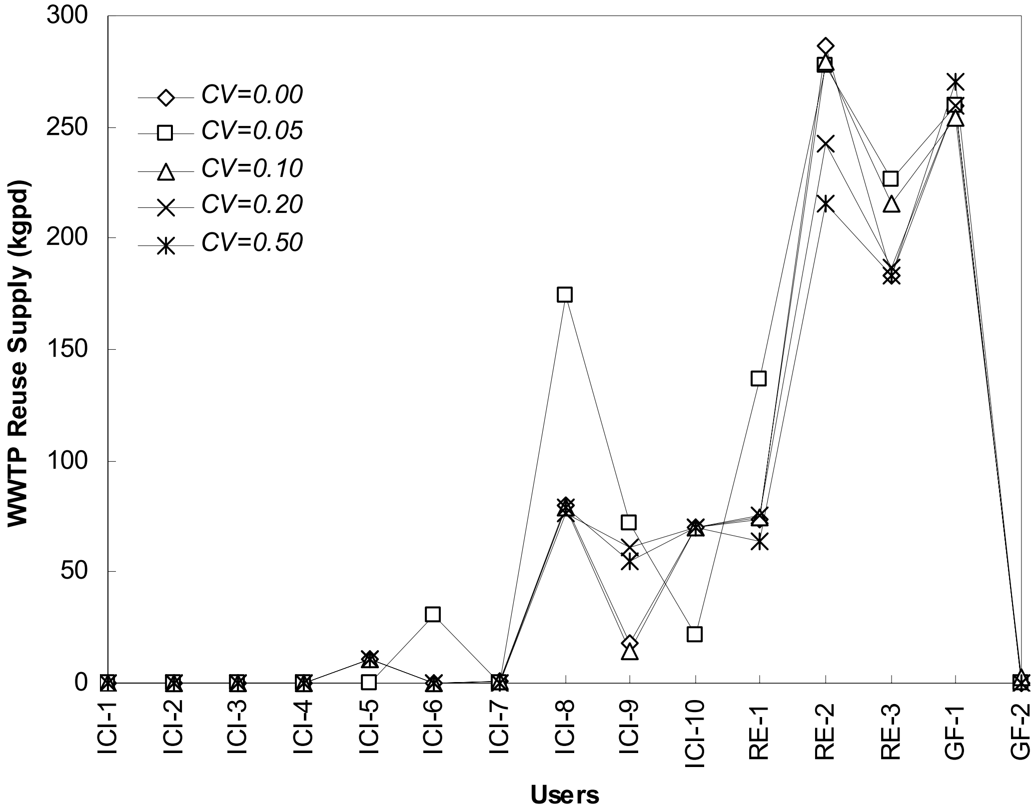


Figure 5.24 WWTP reuse water supplies under 96% of quality chance-constraint with different levels of demand variability (coefficient of variation *CV*)

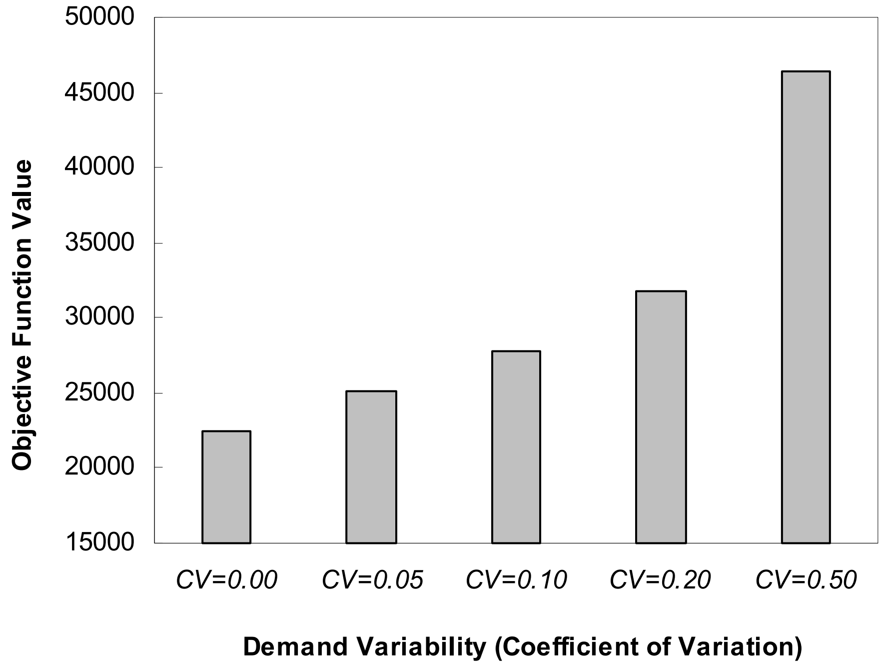


Figure 5.25 Cost and demand variability (coefficient of variation *CV*) trade-off under 96% of quality chance-constraint

5.3.4 Uncertainty with Price or Cost

In addition to modeling of uncertainties with demand and quality, this model is also capable of modeling uncertainty with water price or water treatment cost. Here, the modeling results from a simple case of uncertainty with the $WWTP_2$ reuse water treatment cost is presented with the assumption of normal distribution and the mean value of \$1.00. As introduced in Chapter 3, risk aversion is the tendency to be afraid of taking risks. In this case the cost risk aversion parameters (θ) were chosen to be 5e-10, 0.05 and 0.50

respectively. Figure 5.26 shows the comparison of the total costs for these risk aversion parameters based on the same condition of demand and quality uncertainties (demand *CV*=0.05, quality *CV*=0.05 and chance-constraint *p*=96%). From these results, the trade-off between risk aversion parameters and the total costs can be easily observed.

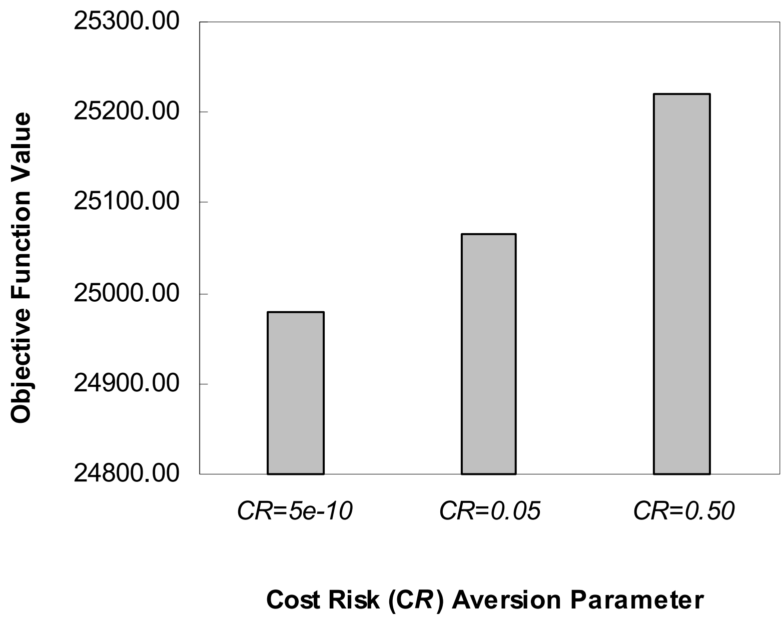


Figure 5.26 Trade-off between cost risk and total cost

5.3.5 Sensitivity Analysis to Price Parameters

Sensitivity analysis can be used to test the robustness of a model, that is, its ability to generate reasonable results with certain ranges of input data. Doing so allows us to identify which constraints are more important, which parameters are more sensitive to objective value, and so on. Besides the analyses discussed above, several experimental trails were performed to investigate the sensitivity of the proposed model to some input parameters.

Since the objective of this model is to minimize the overall system costs while implementing and promoting water reuse, water price input parameters are certainly very important in this cost-driven optimization model.

Table 5.13 presents the sensitivity analyses with changes of WTP water price. The values shown are percentages based on the outputs with the original input. As expected, the objective function value increases proportionally and the WTP supply decreases proportionally with increased WTP water price. For the effects with other supplies, observe that an increase of WTP price causes an increase of $WWTP_3$ (Advanced reclaimed water) supply and users' supply. This is because the $WWTP_3$ water supply (and users' supply) will have a competitive cost comparing with the increased WTP water price. The decrease of $WWTP_2$ (Basic reclaimed water) supply results when quality constraints force the optimization to use higher quality supplies in order to satisfy the quality requirements of users who receive less WTP water. In summary, the WTP water price has a major effect on water reuse, namely a higher WTP water price will definitely promote water reuse.

Table 5.14 presents the sensitivity analyses with changes of WWTP reclaimed water prices. These results demonstrate that reducing WWTP treatment costs has a positive effect on encouraging water reuse. The effects are subtle since the $WWTP_2$ price defined in the model was relatively small and the model includes reuse water transportation costs which do not change with these price changes. For $WWTP_3$, a cost decrease will provide lower cost high quality reuse water which would reduce WTP municipal water demands.

Table 5.13 Sensitivity analysis with changes of WTP water price

Parameters Level of original (%)		Obj. Value (%)	WTP Supply (%)	$WWTP_2$ Supply (%)	$WWTP_3$ Supply (%)	Reuse Between Users (%)
WTP Water Price	80	91	119	127	-	100
	90	96	101	110	92	97
	100	100	100	100	100	100
	120	109	99	93	105	103
	150	121	98	83	114	110

Table 5.14 Sensitivity analysis with changes of WWTP reclaimed water prices

Parameters Level of original (%)		Obj. Value (%)	WTP Supply (%)	$WWTP_2$ Supply (%)	$WWTP_3$ Supply (%)	Reuse Between Users (%)
$WWTP_2$ Price	80	100	101	110	92	97
	100	100	100	100	100	100
	120	100	99	93	105	103
	150	101	99	93	106	103
$WWTP_3$ Price	60	97	91	76	119	109
	80	99	99	93	106	103
	100	100	100	100	100	100
	110	101	101	116	87	96
	120	101	117	144	-	93

5.4 Summary

The main objective of this case study was to demonstrate the model's application and the process of modeling uncertainties associated with water demand and quality. By reviewing the current water reuse status in Canada and by considering the water environment of the Regional Municipality of Waterloo, the study area, we can conclude that water reuse should be considered as part of the region's water management strategy.

Through this study and analyses, many aspects of the model have been examined. It is established that the model is capable of providing essential information for urban water reuse planning and management. Water reuse opportunities, the supply-destination pairs, can be qualitatively and quantitatively identified and the economic feasibility of proposed reuse can be addressed.

By introducing the stochastic programming methods into the model, uncertainties associated with water demand and quality can be accounted for. In doing so, the robust planning and management options, which would minimize the expected costs and the risk of noncompliance to the system, can be derived from the model. In order to analyze the impacts of uncertainties with water demand and reuse water quality, various experiments with the levels of variations of demand and quality and the levels of probability with quality compliance (chance-constraints) have been investigated. By examining the optimal allocation of municipal and reuse water supplies and the overall costs to the entire system, one can concluded that the stability of reuse water treatment and quality has a most important impact both on the reliability of water quality compliance and on the cost effectiveness of the entire water reuse system.

Some sensitivity analyses to the input water price parameters have also been performed. The model is stable in providing reliable modeling outputs. At the same time, the analyses illustrate that technological advancement will promote water reuse by generating high quality reuse water with lowest cost.

GIS is a useful tool in processing and analyzing large amounts of spatial or non-spatial data for water resource studies. In this study, GIS applications were implemented for basic data processing and information gathering. Further use of GIS in an integrated water reuse management model will be beneficial, especially in data processing and model presentation.

Chapter 6

Conclusions, Contributions and Future Work

6.1 Conclusions and Contributions

Water reuse as one of the sustainable strategies in water resources management is increasingly attractive to communities around the world due to the great pressure on water resources posed by urbanization and population growth. A management model on water reuse will facilitate water reuse practices and promote economically and environmentally sound development.

This research work investigated water reuse management in the context of sustainable development. Some key aspects related to urban water resource management and water reuse were introduced and a review of previous research on water reuse management modeling was conducted. Prior to this study, uncertainty issues in water reuse modeling had not been fully addressed in the literature, so the focus of this study was stochastic modeling in water reuse systems.

An urban water allocation and reuse management model, which is capable of identifying and evaluating water reuse opportunities and analyzing the impact of uncertainties with water demand and quality, was developed. Specifically, the network flow optimization model, two-stage stochastic recourse programming and chance-constrained programming methods were integrated to form the basis of the model. The model was applied to an example problem to demonstrate its application. The impact of uncertainties with water demand and quality in water reuse system was extensively discussed. The modeling results exemplified the trade-off between expected costs to the system and the variations with demand and quality. The model is of great significance in evaluating water reuse management alternatives and deriving more robust decisions in regard to uncertain demand and quality.

The contributions of this research include the following aspects: the development of this comprehensive urban water reuse model in conjunction with the overall urban water system; the use of network flow optimization model for modeling urban water network; the modeling of multi-level wastewater treatment process for water reuse; and the employment of stochastic optimization methods to quantitatively model uncertainty issues in urban water reuse planning and management.

6.2 Future Work

Future research on water reuse modeling may be directed to: investigation on water treatment and transportation cost estimations, the optimal selection of wastewater treatment processes and the modeling of water quality changes; further investigation of system reliability and risk analysis associated with water reuse applications; investigation of stochastic modeling with consideration of more quality parameters and the accumulation of pollutants; investigation on computing issues for larger networks; and further incorporation of GIS techniques into the water reuse model.

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Appendix A

ArcGIS Application Procedures on Residential Reuse Water Demand Projection

The procedures are illustrated through the following figures aerated using ESRI ArcGIS 8.3. Referring to the land use map and zoning map of the City of Waterloo, 3 major residential areas were identified as shown in Figure A1 below after performing "Spatial Selection" Procedure, see Step 1 of Figure 4.3 (Page 54).

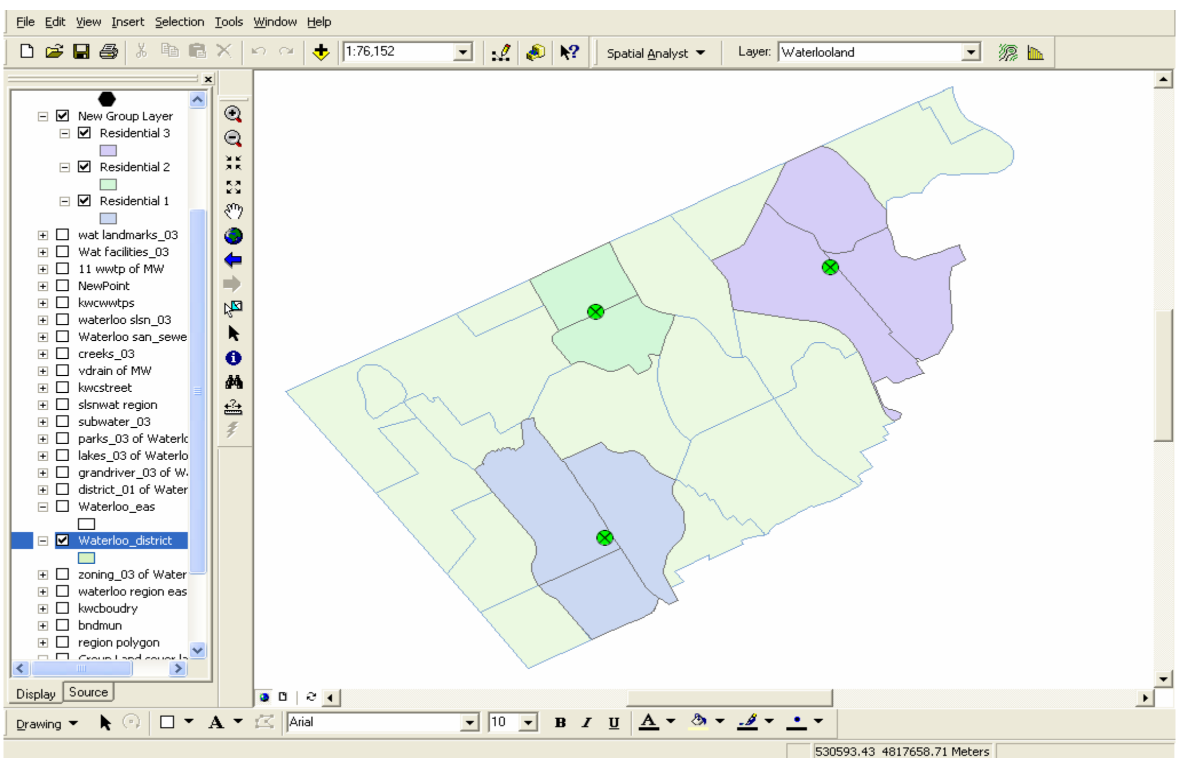

Figure A1: Map of three residential areas

The points in each of these 3 areas were generated (Step 2 of Figure 4.3) to represent these residential areas when computing their reuse water demands. See Table 4.2 (Page 55) for the introduction to the point derivation method.

Figure A2 shows the Enumeration Area (EA) map layer whose attribute table contains the population data listed in Figure A3. This layer was used to perform population calculation (Step 3 of Figure 4.3).

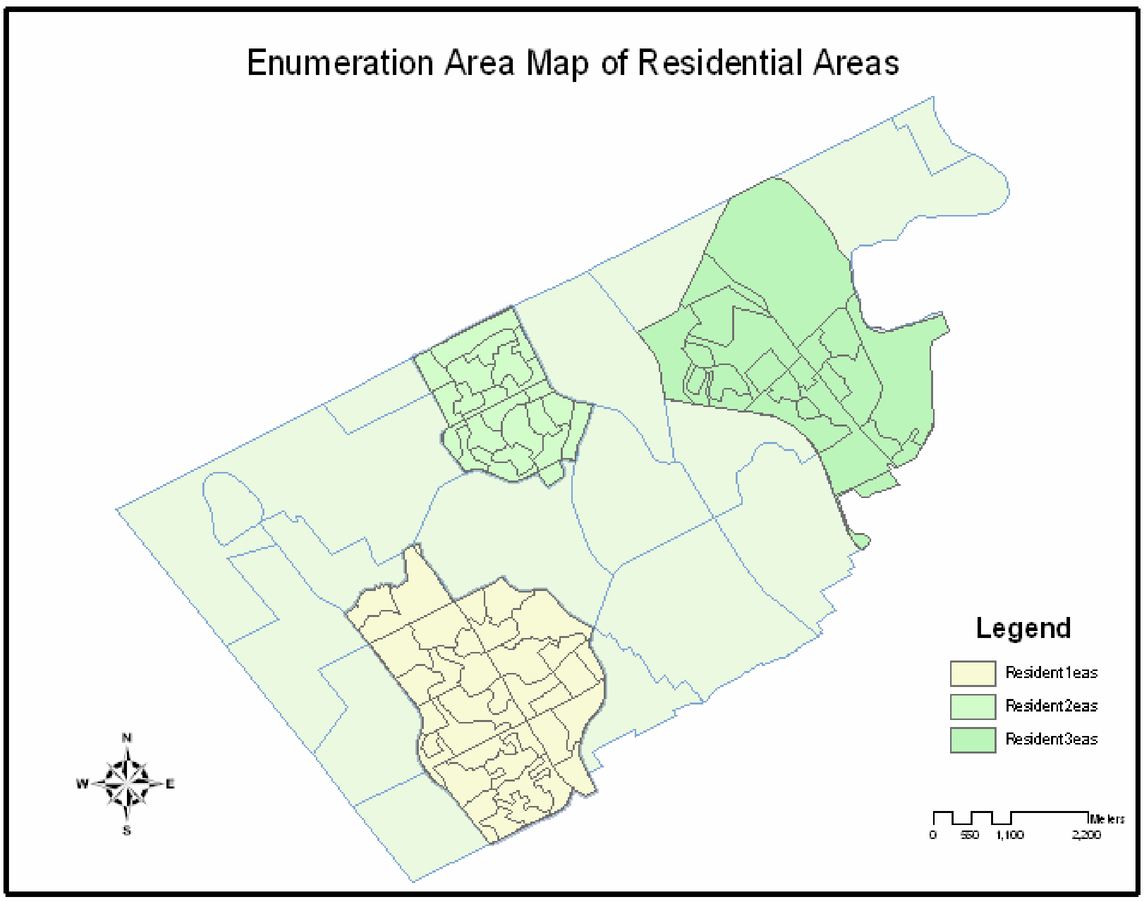

Figure A2: EA layer of selected residential areas

Attributes of Resident2eas

FID	Shape*	OBJECTID	DAUID	pop2001	pop2001as	pop_male	m
0	Polygon	40	35300040	349	350	225	
1	Polygon	40	35300040	349	350	225	
2	Polygon	40	35300040	349	350	225	
3	Polygon	40	35300040	349	350	225	
4	Polygon	40	35300040	349	350	225	
5	Polygon	296	35300297	456	455	230	
6	Polygon	41	35300041	541	540	270	
7	Polygon	42	35300042	478	475	235	
8	Polygon	593	35300596	0	0	0	
9	Polygon	596	35300599	520	520	250	
10	Polygon	58	35300058	1073	1075	525	
11	Polygon	595	35300598	318	315	160	
12	Polygon	597	35300600	550	550	280	
13	Polygon	60	35300060	624	620	300	
14	Polygon	43	35300043	504	505	260	
15	Polygon	59	35300059	585	585	285	
16	Polygon	57	35300057	431	430	220	
17	Polygon	56	35300056	644	645	330	

Record: 1 Show: All Selected Records (0 out of 34 Selected.)

Figure A3: Population data table of the enumeration layer of one of the residential areas

Figure A4 presents the zoning and street network layers for one of the residential areas. The zoning layer contains information about housing types and land property. Figure A5 shows the population statistics data of this residential area which was used to calculate water demand (Step 4 of Figure 4.3).

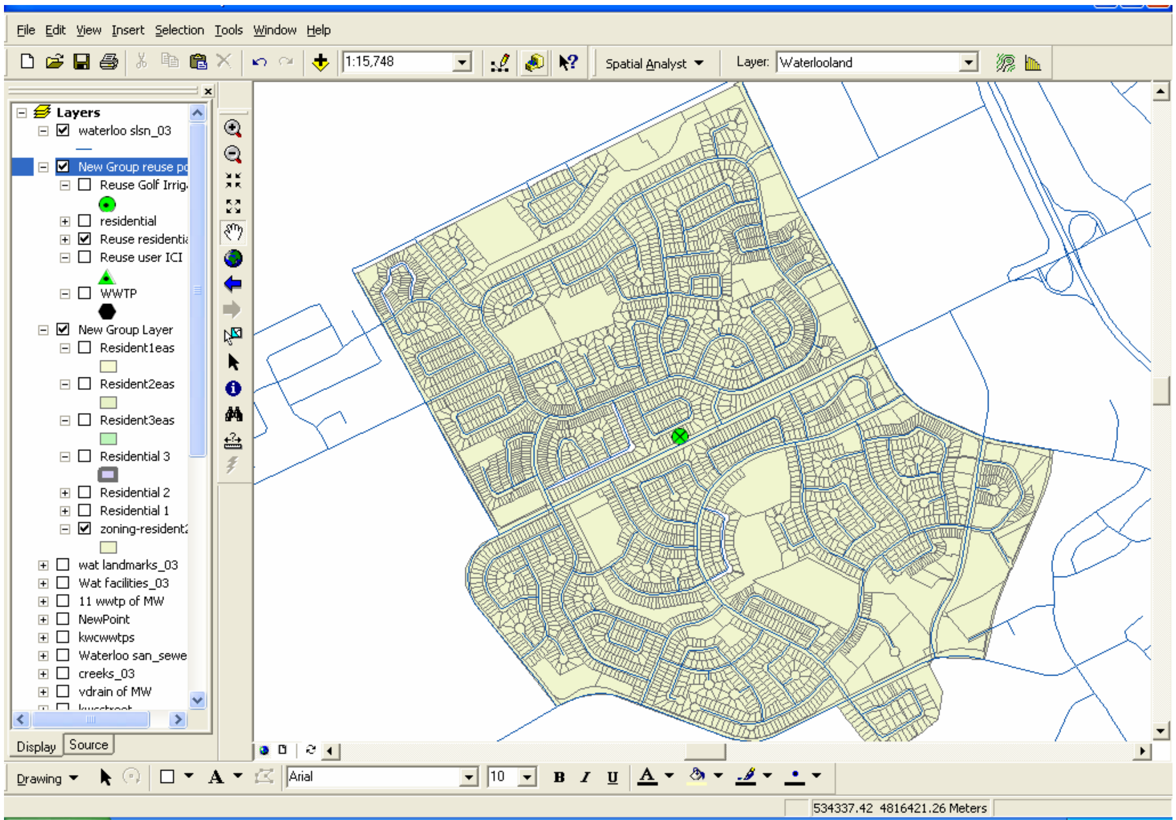

Figure A4: Zoning layer of the residential area 1

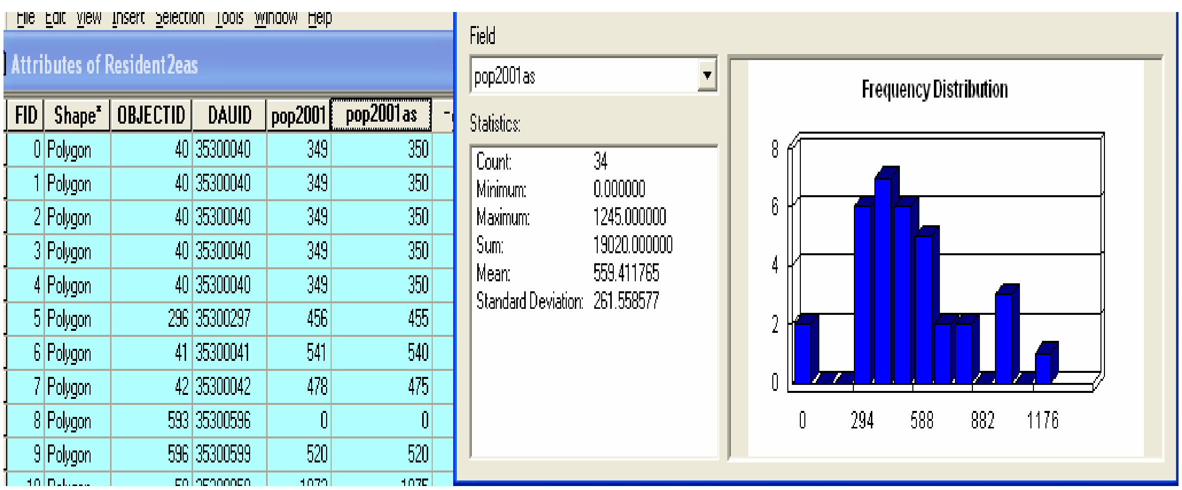

Figure A5: Population statistics data of the residential area

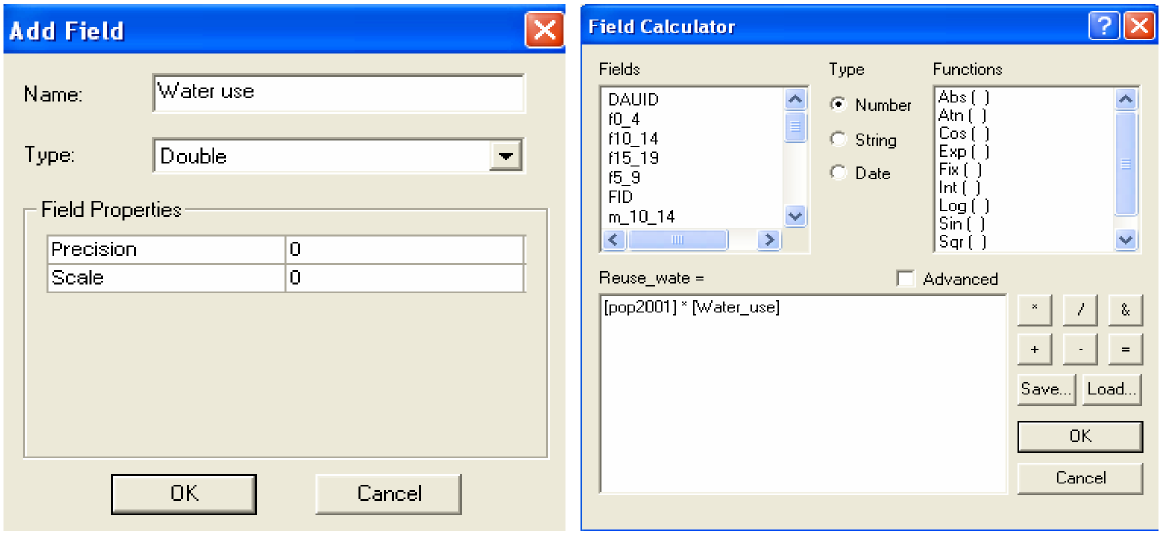

Figure A6: Add field and calculate values into the attribute table

GIS calculation tools (Figure A6) were used to compute the residential areas reuse water demands using water use statistical data presented in Table 5.1 in Chapter 5 of this thesis (Page 61). Figure A7 shows the reuse water demand result for one of the residential areas.

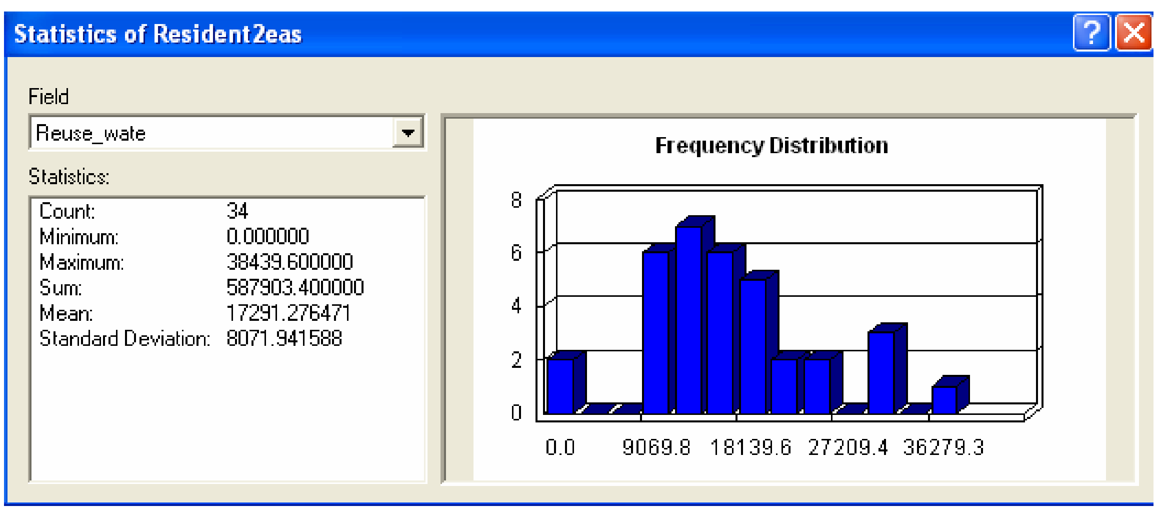

Figure A7: Reuse water demand data of residential area 1

After adding reuse demand values to the residential area point attribute table, a map can be created to show the results (Figure A8).

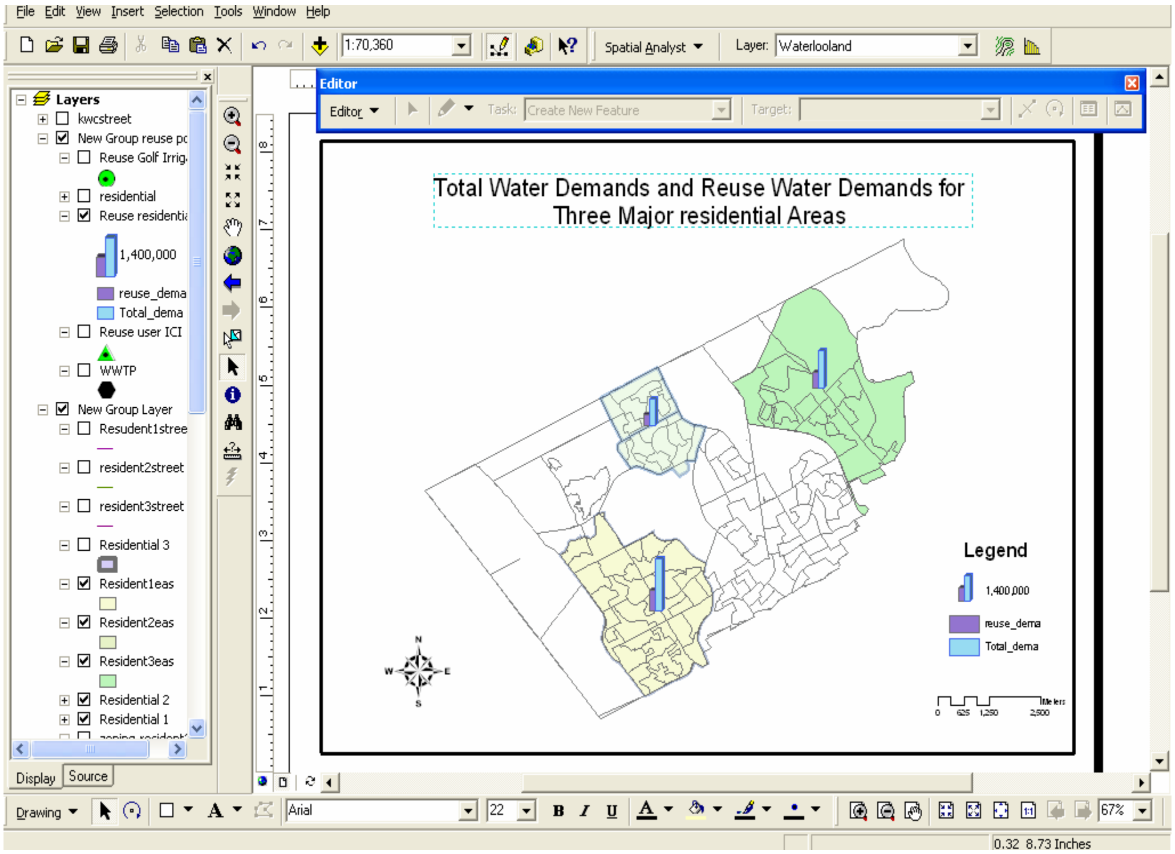

Figure A8: Example map showing the water demands for residential areas

Appendix B

1. Node-Arc Incidence Matrix

General definition of Node-Arc incidence matrix for $A \in R^{m\times n}$:

$$A_{i,j} = \begin{cases} -1 & \text{arc } j \text{ stars at node } i \\ 1 & \text{arc } j \text{ ends at node } i \\ 0 & \text{otherwise} \end{cases}$$

where $R^{m\times n}$ is network space with *m* nodes and *n* arcs.

For our example network:

Rows (nodes) are in the order of: WTP, DummyWTP, ICI-1, ICI-2, ICI-3, ICI-4, ICI-5, ICI-6, ICI-7, ICI-8, ICI-9, ICI-10, RE-1, RE-2, RE-3, GF-1, GF-2, $WWTP_1$, $WWTP_2$, $WWTP_3$, DummyWWTP, ReceivingWater

Connection rules used in the network are described as following: a WTP can supply any users; the dummy source can supply any users; some ICI users can supply other users; ICI users and Residential users discharge to $WWTP_1$; Golf courses' irrigation has no discharge; $WWTP_1$ only discharges to $WWTP_2$ and Receiving water body; $WWTP_2$ can supply $WWTP_3$, all users and the Receiving water body; $WWTP_3$ can supply all users and discharge to the Receiving water body.

The Node-Arc Incidence Matrix is a 22×149 matrix and is shown as a sparse matrix:

A =

(1,1)	-1	(3,1)	1	(1,2)	-1	(4,2)	1	(1,3)	-1	(5,3)	1	(1,4)	-1	(6,4)	1
(1,5)	-1	(7,5)	1	(1,6)	-1	(8,6)	1	(1,7)	-1	(9,7)	1	(1,8)	-1	(10,8)	1
(1,9)	-1	(11,9)	1	(1,10)	-1	(12,10)	1	(1,11)	-1	(13,11)	1	(1,12)	-1	(14,12)	1

(1,13)	-1	(15,13)	1	(1,14)	-1	(16,14)	1	(1,15)	-1	(17,15)	1	(2,16)	-1	(3,16)	1
(2,17)	-1	(4,17)	1	(2,18)	-1	(5,18)	1	(2,19)	-1	(6,19)	1	(2,20)	-1	(7,20)	1
(2,21)	-1	(8,21)	1	(2,22)	-1	(9,22)	1	(2,23)	-1	(10,23)	1	(2,24)	-1	(11,24)	1
(2,25)	-1	(12,25)	1	(2,26)	-1	(13,26)	1	(2,27)	-1	(14,27)	1	(2,28)	-1	(15,28)	1
(2,29)	-1	(16,29)	1	(2,30)	-1	(17,30)	1	(3,31)	-1	(4,31)	1	(3,32)	-1
(5,32)	1	(3,33)	-1	(6,33)	1	(3,34)	-1	(7,34)	1	(3,35)	-1	(8,35)	1
(3,36)	-1	(9,36)	1	(3,37)	-1	(10,37)	1	(3,38)	-1	(11,38)	1	(3,39)	-1
(12,39)	1	(3,40)	-1	(13,40)	1	(3,41)	-1	(14,41)	1	(3,42)	-1	(15,42)	1
(3,43)	-1	(16,43)	1	(3,44)	-1	(17,44)	1	(3,45)	1	(4,45)	-1	(4,46)	-1
(5,46)	1	(4,47)	-1	(6,47)	1	(4,48)	-1	(7,48)	1	(4,49)	-1	(8,49)	1
(4,50)	-1	(9,50)	1	(4,51)	-1	(10,51)	1	(4,52)	-1	(11,52)	1	(4,53)	-1
(12,53)	1	(4,54)	-1	(13,54)	1	(4,55)	-1	(14,55)	1	(4,56)	-1	(15,56)	1
(4,57)	-1	(16,57)	1	(4,58)	-1	(17,58)	1	(3,59)	1	(5,59)	-1	(4,60)	1
(5,60)	-1	(5,61)	-1	(6,61)	1	(5,62)	-1	(7,62)	1	(5,63)	-1	(8,63)	1
(5,64)	-1	(9,64)	1	(5,65)	-1	(10,65)	1	(5,66)	-1	(11,66)	1	(5,67)	-1
(12,67)	1	(5,68)	-1	(13,68)	1	(5,69)	-1	(14,69)	1	(5,70)	-1	(15,70)	1
(5,71)	-1	(16,71)	1	(5,72)	-1	(17,72)	1	(3,73)	1	(6,73)	-1	(4,74)	1
(6,74)	-1	(5,75)	1	(6,75)	-1	(6,76)	-1	(7,76)	1	(6,77)	-1	(8,77)	1
(6,78)	-1	(9,78)	1	(6,79)	-1	(10,79)	1	(6,80)	-1	(11,80)	1	(6,81)	-1
(12,81)	1	(6,82)	-1	(13,82)	1	(6,83)	-1	(14,83)	1	(6,84)	-1	(15,84)	1
(6,85)	-1	(16,85)	1	(6,86)	-1	(17,86)	1	(3,87)	1	(7,87)	-1	(4,88)	1
(7,88)	-1	(5,89)	1	(7,89)	-1	(6,90)	1	(7,90)	-1	(7,91)	-1	(8,91)	1
(7,92)	-1	(9,92)	1	(7,93)	-1	(10,93)	1	(7,94)	-1	(11,94)	1	(7,95)	-1
(12,95)	1	(7,96)	-1	(13,96)	1	(7,97)	-1	(14,97)	1	(7,98)	-1	(15,98)	1
(7,99)	-1	(16,99)	1	(7,100)	-1	(17,100)	1	(3,101)	-1	(18,101)	1	(4,102)	-1
(18,102)	1	(5,103)	-1	(18,103)	1	(6,104)	-1	(18,104)	1	(7,105)	-1	(18,105)	1
(8,106)	-1	(18,106)	1	(9,107)	-1	(18,107)	1	(10,108)	-1	(18,108)	1	(11,109)	-1
(18,109)	1	(12,110)	-1	(18,110)	1	(13,111)	-1	(18,111)	1	(14,112)	-1	(18,112)	1
(15,113)	-1	(18,113)	1	(3,114)	1	(19,114)	-1	(4,115)	1	(19,115)	-1	(5,116)	1
(19,116)	-1	(6,117)	1	(19,117)	-1	(7,118)	1	(19,118)	-1	(8,119)	1	(19,119)	-1
(9,120)	1	(19,120)	-1	(10,121)	1	(19,121)	-1	(11,122)	1	(19,122)	-1	(12,123)	1
(19,123)	-1	(13,124)	1	(19,124)	-1	(14,125)	1	(19,125)	-1	(15,126)	1	(19,126)	-1

(16,127) 1 (19,127) -1 (17,128) 1 (19,128) -1 (3,129) 1 (20,129) -1 (4,130) 1
(20,130) -1 (5,131) 1 (20,131) -1 (6,132) 1 (20,132) -1 (7,133) 1 (20,133) 1
(8,134) 1 (20,134) -1 (9,135) 1 (20,135) -1 (10,136) 1 (20,136) -1 (11,137) 1
(20,137) -1 (12,138) 1 (20,138) -1 (13,139) 1 (20,139) -1 (14,140) 1 (20,140) -1
(15,141) 1 (20,141) -1 (16,142) 1 (20,142) -1 (17,143) 1 (20,143) -1 (18,144) 1
(21,144) -1 (18,145) -1 (19,145) 1 (19,146) -1 (20,146) 1 (18,147) -1 (22,147) 1
(19,148) -1 (22,148) 1 (20,149) -1 (22,149) 1

2. General MATLAB inputs and solving statements

Inputs of demands and capacities

`DEM` = [424 127 122 101 79 160 159 251 137 134 688 825 1155 260 130]';

% mean demands of the 15 users

`CAPACITY` = [3152 100000 6000 1600 800 100000 100000]';

% capacities of WTP,DummyWTP,WWTPs(1, 2 and 3),DummyWWTP and receiving water

Inputs for demand uncertainty modeling

`Coefv =` 0.050; *% coefficients of variation as design parameters, e.g., 0.05, 0.10 etc.*

cases = 60; *% number of demand scenarios to be modeled*

`Corr` = [1 .3 .4 .1 .1; 0 1 -.2 .1 .2; 0 0 1 .2 .1; 0 0 0 1 .4; 0 0 0 0 1];

% the Correlation coefficients matrix, define the relationship between users' demands

`R = mvnrnd(MeanDemand,CovarDemand,cases);` *% MATLAB function "mvnrnd" is used to generate scenarios (see last part of this appendix for descriptions)*

`Pnt = 5`; *% the penalty cost per unit water*

Inputs of quality parameters for quality constraints and uncertainty modeling

% Qulaity requirements for users and receiving water body, four water quality parameters

`QSTD =` [50 100 20 20; 50 100 20 20; 50 100 30 30; 20 50 20 20; 5 10 10 20; 60 100 30 50; 60 100 80 75; 60 100 30 100; 100 180 60 75; 80 180 60 75; 25 50 40 50; 25 50 40 50; 25 50 40 50; 80 200 150 250; 80 200 150 250; 1500000 1500000 1000000 1000000];

% Effluent quality of WTP, DummyWTP, users,WWTPs(1, 2 and 3), DummyWWTP,

`Q =` [2 0 0 0; 2 0 0 0; 137 220 180 150; 240 147 100 250; 160 106 100 140; 22 66 100 140; 18 72 100 100; 224 350 600 1000; 375 1619 600 1000; 215 2657 600 1000; 347 190 600 1000; 3869 257 600 1000; 290 350 200 400; 160 220 300 500; 160 220 400 600; 0 0 0 0; 0 0 0 0; 60 100 600 1000; 20 50 100 100;10 20 20 60];

`Coefv` = 0.050; *% coefficients of variation of quality, e.g., 0.05, 0.10, etc.*

`Zalpha` = 1.75; *% quality chance-constraints, set to Z=1.75 for p=96%, Z=1.25 for p=90%, etc.*

Input water price and treatment cost information

`cwtp` = 2.84; *% WTP price*

`cdwtp` = 20; *% Dummy WTP price*

`cusers` = 2; *% User to user cost*

`cusertowwtp` = 2.72; *% discharge cost, from users to WWTP*

`cwwtp2` = 1.0; *% WWTP2 cost*

`cwwtp3` = 2.50; *% WWTP3 cost*

`cdwwtp` = 1.0; *% discharge from WWTPs to receiving water body*

Input distance parameters to calculate transportation cost

`ICI1` = [1807 1728 1835 3218 4609 4550 6227 6250 6843 4703 6205 3412 9436 2482];

% distances from ICI-1 to other user nodes, similiar below

`ICI2` = [1807 2420 2750 1942 3374 5433 5021 5180 5513 4833 5169 4567 8299 3720];

`ICI3` = [1728 2420 336 2781 4036 2396 4798 4750 6553 3226 7090 4694 8617 3820];

`ICI4` = [1835 2750 336 2732 3656 2703 4925 4800 6500 3521 7200 4820 8500 4000];

`ICI5` = [3218 1942 2781 2732 2745 4716 4182 4176 3944 5189 2951 6045 6321 6181];

`wwtp2user` = [5738 4383 6161 6333 4803 6028 6735 6104 5075 2638 7318 2610 7586 … 5874 7711]; *% distances from WWTP to user nodes*

Objective function

`function [FUNC] = FUN(x)` *% define a function of the optimization objective*

`FUNC = unitcost*x`; *% where unitcost is the vector of total unit cost including water price, treatment and transportation costs, etc.*

Optimization solving statements

```
x = fmincon(@FUN,x0,A,B,Aeq,Beq,vlb,vub,@qualitycon);
```

% where `FUN` *defines the objective function;* `x0` *is the initial vector to the decision variable* x*;* `A` *is the left hand side of inequality linear constraints;* `B` *is the right hand side of the inequality linear constraints;* `Aeq` *is the left hand side of the equality linear constraints;* `Beq` *is the right hand side of the equality linear constraints;* `vlb` *is the variables' lower bounds;* `vub` *is the variables' upper bounds; function* `qualitycon` *defines the non-linear equality and inequality constraints. For description of* `fmincon`*, see following part of this appendix.*

3. MATLAB function: fmincon

The following descriptions are excerpted from http://www.mathworks.com. For more information, please visit the site.

FMINCON finds a minimum of a constrained nonlinear multivariable function

$$\min_x f(x)$$

subject to

$$c(x) \le 0$$
$$ceq(x) = 0$$
$$A \cdot x \le b$$
$$Aeq \cdot x = beq$$
$$lb \le x \le ub$$

where *x, b, beq, lb,* and *ub* are vectors, *A* and *Aeq* are matrices, *c(x)* and *ceq(x)* are functions that return vectors, and *f(x)* is a function that returns a scalar. *f(x)*, *c(x)*, and *ceq(x)* can be nonlinear functions.

Syntax

```
x = fmincon(fun,x0,A,b)
x = fmincon(fun,x0,A,b,Aeq,beq)
x = fmincon(fun,x0,A,b,Aeq,beq,lb,ub)
x = fmincon(fun,x0,A,b,Aeq,beq,lb,ub,nonlcon)
x = fmincon(fun,x0,A,b,Aeq,beq,lb,ub,nonlcon,options)
[x,fval] = fmincon(...)
[x,fval,exitflag] = fmincon(...)
[x,fval,exitflag,output] = fmincon(...)
[x,fval,exitflag,output,lambda] = fmincon(...)
[x,fval,exitflag,output,lambda,grad] = fmincon(...)
[x,fval,exitflag,output,lambda,grad,hessian] =
fmincon(...)
```

Description

fmincon attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as *constrained nonlinear optimization* or *nonlinear programming*.

x = fmincon(fun,x0,A,b) starts at x0 and attempts to find a minimum x to the function described in fun subject to the linear inequalities A*x <= b. x0 can be a scalar, vector, or matrix.

`x = fmincon(fun,x0,A,b,Aeq,beq)` minimizes fun subject to the linear equalities `Aeq*x = beq` as well as `A*x <= b`. Set `A=[]` and `b=[]` if no inequalities exist.

`x = fmincon(fun,x0,A,b,Aeq,beq,lb,ub)` defines a set of lower and upper bounds on the design variables in x, so that the solution is always in the range `lb <= x <= ub. Set Aeq=[]` and `beq=[]` if no equalities exist.

`x = fmincon(fun,x0,A,b,Aeq,beq,lb,ub,nonlcon)` subjects the minimization to the nonlinear inequalities `c(x)` or equalities `ceq(x)` defined in nonlcon. fmincon optimizes such that `c(x) <= 0` and `ceq(x) = 0`. Set `lb=[]` and/or `ub=[]` if no bounds exist.

`x = fmincon(fun,x0,A,b,Aeq,beq,lb,ub,nonlcon,options)` minimizes with the optimization options specified in the structure options. Use optimset to set these options. Set nonlcon = [] if there are no nonlinear inequality or equality constraints.

`[x,fval] = fmincon(...)` returns the value of the objective function fun at the solution x.

`[x,fval,exitflag] = fmincon(...)` returns a value exitflag that describes the exit condition of fmincon.

`[x,fval,exitflag,output] = fmincon(...)` returns a structure output with information about the optimization.

`[x,fval,exitflag,output,lambda] = fmincon(...)` returns a structure lambda whose fields contain the Lagrange multipliers at the solution x.

`[x,fval,exitflag,output,lambda,grad] = fmincon(...)` returns the value of the gradient of fun at the solution x.

`[x,fval,exitflag,output,lambda,grad,hessian] = fmincon(...)` returns the value of the Hessian at the solution x.

Please visit http://www.mathworks.com for descriptions of input arguments and output arguments related to fmincon.

Examples

Find values of x that minimize $f(x) = -x_1 x_2 x_3$, starting at the point x = [10; 10; 10] and subject to the constraints

$$0 \le x_1 + 2x_2 + 2x_3 \le 72$$

First, write an M-file that returns a scalar value f of the function evaluated at x.

```
function f = myfun(x)
f = -x(1) * x(2) * x(3);
```

Then rewrite the constraints as both less than or equal to a constant,

$$-x_1 - 2x_2 - 2x_3 \le 0$$
$$x_1 + 2x_2 + 2x_3 \le 72$$

Since both constraints are linear, formulate them as the matrix inequality $A \cdot x \le b$ where

$$A = \begin{bmatrix} -1 & -2 & -2 \\ 1 & 2 & 2 \end{bmatrix} \qquad b = \begin{bmatrix} 0 \\ 72 \end{bmatrix}$$

Next, supply a starting point and invoke an optimization routine.

```
x0 = [10; 10; 10];   % Starting guess at the solution
[x,fval] = fmincon(@myfun,x0,A,b)
```

After 66 function evaluations, the solution is

x =

24.0000

12.0000

12.0000

where the function value is

fval =

    -3.4560e+03

and linear inequality constraints evaluate to be less than or equal to 0.

A*x-b=

    -72

      0

4. MATLAB function: mvnrnd

The scenario generation process was done using MATLAB function “mvnrnd” with the mean, covariance, and number of scenarios as input parameters. The following descriptions are excerpted from http://www.mathworks.com. For more information, please visit the site.

MVNRND Random matrices from the multivariate normal distribution

Syntax

```
R = mvnrnd(mu,SIGMA)
R = mvnrnd(mu,SIGMA,cases)
```

Description

`R = mvnrnd(mu,SIGMA)` returns an `n`-by-`d` matrix `R` of random vectors chosen from the multivariate normal distribution with mean `mu`, and covariance `SIGMA`. `mu` is an `n`-by-`d` matrix, and `mvnrnd` generates each row of `R` using the corresponding row of `mu`. `SIGMA` is a `d`-by-`d` symmetric positive semi-definite matrix, or a `d`-by-`d`-by-`n` array. If `SIGMA` is an array, `mvnrnd` generates each row of `R` using the corresponding page of `SIGMA`, i.e., `mvnrnd` computes `R(i,:)` using `mu(i,:)` and `SIGMA(:,:,i)`. If `mu` is a `1`-by-`d` vector, `mvnrnd` replicates it to match the trailing dimension of `SIGMA`.

`r = mvnrnd(mu,SIGMA,cases)` returns a cases-by-d matrix R of random vectors chosen from the multivariate normal distribution with a common `1`-by-`d` mean vector `mu`, and a common `d`-by-`d` covariance matrix `SIGMA`.

Reproducing the Output of mvnrnd

`mvnrnd` uses the MATLAB function `randn` to generate random numbers. When you call `mvnrnd`, you change the current state of `randn`, and thereby alter the output of subsequent calls to `mvnrnd` or any other functions that depend on `randn`. If you want to reproduce the output of `mvnrnd`, reset the state of `randn` to the same fixed value each time you call `mvnrnd`.

Example

```
mu = [2 3];
sigma = [1 1.5; 1.5 3];
r = mvnrnd(mu,sigma,100);
plot(r(:,1),r(:,2),'+')
```