Basin-wide Water Demand Management: Transfers and Compensation among Competing Users

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Water demand management is incorporated into a two-step water allocation process in order to motivate water users to implement water demand management strategies. In the first step, the initial allocation of water is based on existing water rights systems or agreements to form a baseline scenario for the next step involving the adoption of water demand management strategies. In the second step, two principles are identified for water demand management: either to increase aggregated benefits given the currently available water or to decrease aggregated water consumption while achieving benefits not less than the current ones. These two principles are considered in depth in this research in the development of various water demand management methodologies.

Within the first principle, a centralized basin-wide hydrologic-economic optimization model is designed to motivate certain users to conserve water in order to maximize the total net benefits of the river basin system, and then to allocate additional net benefits using cooperative game theory. The optimal aggregated net benefits with and without water demand management plans for various coalitions of users subject to physical, policy and water availability constraints are obtained. A modified cooperative reallocation game is developed to distribute additional net benefits such that positive economic gains are provided to users. From a decentralized viewpoint, agent-based modeling techniques are utilized to simulate water users' behavioral responses to water demand management strategies. Within the agent-based framework, each user individually decides whether or not to conserve water or to consume more water; water conservers are compensated while water consumers are charged. Incentive functions are introduced to calculate how much to compensate or how much to charge. Individual optimization problems are designed for each water user who considers the maximization of its own benefits as the primary objective. Coordination procedures are developed to reach the system-wide maximum net benefits objective.

To achieve the second principle, a centralized conservation-targeted hydrologic-economic optimization method is constructed to estimate the minimum water consumption requirement to produce the same amount of benefits in a river basin in order to better understand the present status of water use. Two formulations for representing different interpretations of water consumption are examined. The formulations take conservation limits and diverse characteristics of different users into consideration. The method is applied to the South Saskatchewan River Basin (SSRB) in southern Alberta, Canada, where water scarcity is a severe issue.

The foregoing approaches within each of the two principles are applied to illustrative case studies to facilitate a better understanding of the impact of water demand management on individual users and the overall system, and how to encourage water users to utilize water wisely. Meaningful insights are provided for achieving better water demand management to mitigate the stress brought by the dramatically increasing demand.

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$\alpha (k, t)$	scale parameter of water price-demand function
$\beta (k, t)$	price elasticity of water price-demand function
$\rho (k, t)$	level of water use efficiency improvement
$\theta (k, t)$	level of conservation limit
ε	discrepancy term in general water balance equations
ΔS	changes of storage volume in reservoirs or aquifer
Ω	feasible solution space
AGR	set of agricultural nodes
AGT	set of agents, $AGT = \{1, 2, \ldots, i, \ldots m\}$
$b_0, b_1, b_2, b_{3z}, b_{4z}, b_{5z}$	coefficients of the quadratic benefit functions
$bc (i, t)$	benefit or cost per unit of water conserved or consumed for agent i during period t
$C_z (k, t)$	concentration of pollutant z in the total inflow to node k during period t
C_{it}	cost of achieving water conservation for agent i during period t
E	water losses by evaporation
$e_N (k, t)$	consumption coefficients at node k during period t
$e_L (k_1, k, t)$	conveyance loss coefficients in link (k_1, k) during period t
$G (K, L)$	directed network of a river basin
$g_i(Q) \geq 0$	non-equality local constraints for agent i
$g(\lambda) \geq 0$	non-equality constraints
$h_i(Q) = 0$	equality local constraints for agent i
$h(\lambda) = 0$	equality constraints
i	index of agents
INC_{it}	incentive values of agent i during period t
j	index of stakeholders
K	sets of water demand nodes
k	index of water demand nodes
(k_1, k)	link from node k_1 to node k
L	sets of links of the network
MI	set of municipal and industrial nodes

N	set of stakeholders, $N = \{1, 2, \ldots, j, \ldots, n\}$
(N, v)	n-person cooperative game
$(N, \tilde{v})$	modified n-person cooperative game
NB_k	net benefits of node k during all planning periods
NB_{kt}	net benefits of node k during period t
NB_{kt}^{ini}	net benefits gained from initial water allocation of node k during period t
P	precipitation
$P\ (k, t)$	price of willingness to pay to retrieve water
$P_0\ (k, t)$	choke price of inverse water price-demand functions
Q_{SI}	surface inflow
Q_{GI}	groundwater inflow
Q_{SO}	surface outflow
Q_{GO}	groundwater outflow
Q_W	total water withdrawal
Q_C	total water consumed
$Q\ (k_1, k, t)$	water flow in link (k_1, k)) during period t
$Q\ (k, t)$	total inflow to demand node k during period t
$Q_0\ (k, t)$	choke quantity of inverse water price-demand function
$Q_{ini}\ (k, t)$	initial water allocation to demand node k during period t
$Q_{max}\ (k_1, k, t)$	maximum capacity of link (k_1, k) during period t
$Q_{min}\ (k_1, k, t)$	minimum requirement of link (k_1, k) during period t
$Q_l\ (k_1, k, t)$	conveyance losses of link (k_1, k) during period t
$Q_c\ (k, t)$	water consumed at node k during period t
$Q_D\ (k, t)$	water demand of node k during period t
$Q_a\ (k, t)$	adjustment flow from local small tributaries at node k during period t
RES	set of reservoir nodes
S	coalition of stakeholders
$S\ (k, t)$	storage volume of a reservoir (or aquifer) k during period t
$S_{max}\ (k, t)$	maximum storage volume of a reservoir (or aquifer) k during period t
$S_{min}\ (k, t)$	minimum storage requirement of a reservoir (or aquifer) k during period t
t	index of planning time periods

T	set of planning time periods
v	characteristic function relating coalition S to a real number $v(S)$
$v(\{1\}), v(\{2\}), \ldots, v(\{n\})$	benefits gained by individual stakeholder
$v(S)$	aggregated benefits gained by the members of coalition S
$v(N)$	aggregated benefits gained by the members of grand coalition N
$\tilde{v}$	modified characteristic function when a water demand management plan is implemented
$\tilde{v}(\{1\}), \tilde{v}(\{2\}), \ldots, \tilde{v}(\{n\})$	benefits gained by individual stakeholder when a water demand management plan is implemented
$\tilde{v}(S)$	aggregated benefits gained by the members of coalition S when a water demand management plan is implemented
$\tilde{v}(N)$	aggregated benefits gained by the members of grand coalition N when a water demand management plan is implemented
WP	water productivity
$wc(k, t)$	cost of water supply to node k during period t (\$/m^3)
$\boldsymbol{x}$	payoff vector of stakeholders, $\boldsymbol{x} = (x_1, x_2, \ldots, x_n)$
z	index of pollutant types, i.e. salinity

Chapter 1

Introduction

1.1 Background

Water is a paradox: scarce but often wasted. The supply of water is limited but the demand for water is increasing rapidly. The imbalance between water supply and demand is expected to greatly expand as water demand inexorably increases. Water scarcity has been a critical issue for many regions and has caused numerous water conflicts. Meanwhile, the value of water itself and the many services it provides has not been fully recognized and water has been utilized inefficiently in many places. The improvement in water use efficiency and productivity is widely considered as the best solution to ensure that future water demand does not exceed water availability, and this requires special attention on the demand side.

Water demand management has already received considerable attention and much effort has been expended to study this issue from technical, social, and legal aspects (Baumann et al., 1997; Renzetti, 2002; Butler and Memon, 2006; Kindler, 2010). Research and practice have demonstrated several unique advantages of water demand management:

- It can defer or even eliminate the construction of new water supply infrastructure. Historically, increasing water supply through the large-scale construction of new water supply infrastructure or inter-basin water transfer has been the main solution for solving the problem of water shortage. However, this supply-oriented approach often brings unanticipated adverse effects such as migration relocation, reduced runoff, and species extinction (Gleick, 2003a). These adverse effects could possibly be catastrophic to the ecosystem, and also cause many political conflicts. For instance, a downstream province or country would be against the construction of a new reservoir to keep water in an upstream province or country. In addition, the expenditures, including construction and operational costs, of a new water supply project sometimes could be greater than the cost of implementing initiatives on the demand side. Therefore, the implementation of water demand management strategies would become more viable, both economically and politically, in many parts of the world.

- Water demand management can improve the social welfare obtained from water utilization. The objective of water use is to provide a range of products and services to people. For some purposes water is indispensable, such as drinking and cooking, while for other uses water is one of the inputs and is manageable. People care about the quality of products and services, but may not be concerned about how much water is used or even whether water is used at all, as long as these products and services are provided in convenient, cost-effective, and socially acceptable ways (Gleick et al., 2011). Water demand management initiatives like the employment of advanced technologies enable higher production output with much less water input. In addition, preserved water could serve indirect purposes which are valuable for society, such as waste assimilation, even if the value of these indirect uses is often intangible.
- It can promote public awareness of the value of water. One of the main reasons why water is wasted is that people do not appreciate the true value of water. The adoption of economic tools and education methods can help people to recognize the real worth of water and to increase the awareness of water conservation, thereby promoting further voluntary water-saving practices.
- Water demand management can increase the resilience of human society and ecosystems. There is clear evidence that climate change has strong impacts on water systems, such as increasing uncertainties of water availability and high risks of droughts and floods (Bates et al., 2008), and affects almost every sector of human society including agriculture, industry, transport, energy, and recreation (Olmstead, 2014). People's behavioral changes towards water use would further affect the reliability and security of water systems. Being able to accomplish the same task with less water results in less risk of water cut-offs or shortages during drought periods. Having more water preserved in ecological systems also increases their adaptability to extreme situations, which is essentially beneficial to human society as a whole.
- It can support the sustainable development of water resources. The preserved water not only can be used for waste assimilation and increasing system resilience, but also can be

utilized for beneficial purposes by future generations. Moreover, less water usage by human society could induce less energy consumption and lower greenhouse gas emissions, which are also important contributions to the sustainability of human society.

Overall, the implementation of water demand management has a myriad of benefits, exceeding those mentioned above. However, there are also many barriers hindering the widespread adoption of water demand management initiatives.

- Many water authorities or agencies do not have official and clear guidelines for the implementation of water demand management, such as what goals and objectives should be achieved, what programs should be implemented, and what related issues about legislation should be addressed in a specific region. Without appropriate guidelines, managers and users are unaware or unable to make effective investments in water demand management programs. For example, clear standards regarding low-flush toilets for mandatory installation in new buildings and retrofitting programs in old buildings could significantly enhance water conservation objectives.

- The lack of knowledge and information is also one of the key barriers from the viewpoint of water users. They may know that water, especially clean drinking water, is valuable, but not fully realize how precious it is. Many users take for granted the availability of an abundance of clean water supplied at a reasonable price, and thus think nothing of using drinking water to wash cars or irrigate gardens. Knowledge of the real value or cost of water by users increases their awareness of water conservation. Public participation plays a significant role in the successful implementation of water demand management programs.

- The absence of incentives for users discourages them from taking the needed actions. People tend to be reactive in their habits, whether because of apathy or laziness or reluctance to accept new technologies. Even though consumers know that installing low-flush toilets can save water and reduce their water bills, many of them would not take the necessary actions if they bear all the costs of replacing old toilets. Providing rebates or subsidies to users could accelerate the adoption rate of new advanced technologies and thereby achieve better water demand management.

- There often exist conflicting objectives during the implementation of water demand management initiatives. For example, a policy aimed at reducing water use in irrigation for utilization for other purposes like increasing environment flows, is beneficial from a resources management perspective in the long term. However, the irrigator may suffer revenue losses because of crop production reductions, and thus be against the policy. In many cases, a large portion of the benefits garnered by water demand management, like deferring new water supply projects and enhanced ecosystem services, will not be immediately apparent or are intangible, but the costs would be generally noticeable. It is of great importance to take into account all of the potential costs and benefits, financial support, and public acceptability in the evaluation process.

Many other barriers can be identified for specific cases, such as the lack of effective communication mechanisms among management departments. To overcome these major or minor barriers, significantly more research is required.

1.2 Problem Statements

Municipal and industrial water demand are inexorably increasing because of population growth and economic development. According to a report published by the Organization for Economic Cooperation and Development (OECD), global water demand for water is expected to increase by 55% between 2000 and 2050, and water demand for manufacturing, electricity, and domestic purposes during the same time period are projected to increase by 400%, 144%, and 127%, respectively (Leflaive et al., 2012). Given that the absolute volume of urban demand is difficult to reduce without compromising the current quality of life, the key goal for the urban sector is to improve water use efficiency and promote water recycling.

The OECD report also indicated that 60% more food will need to be produced from irrigation in order to feed 9.7 billion people in 2050 (Leflaive et al., 2012; UNDESA, 2015). However, the water availability for irrigation purposes in 2050 will be reduced by 14% in comparison to the 2000 level. With the impacts of climate change, this availability may be even more uncertain. This emphasizes the urgent need for agriculture to use water more efficiently and productively.

This prediction points out one possible direction for solving water problems: encouraging water conservation in the irrigation sector and transferring the conserved water to the urban sector, with the urban sector providing adequate compensation to the irrigation sector such that the costs of water conservation can be fully or more than covered. Since irrigation is the largest water user, even a small amount of water conservation in irrigation may provide enough water for urban purposes and possibly also for environmental requirements.

With respect to water conservation in the irrigation sector, there is already ample scientific findings and practical experience available on the technical side. However, many investigations suggest that water conservation is more an issue of perception than of technology. In fact, the technological limitation for water demand management is modest while the conservation potential is significant (Mass, 2003; Blanke et al., 2007). The question is how do people regard water conservation, and do they have enough motivation to take advantage of these existing technologies?

As mentioned above, people normally do not voluntarily adopt advanced water-saving technologies. Sometimes external incentives are required to entice users to change their water use behavior, especially for users in sectors that possess great potential for water conservation. It is believed that every user has the capability to enhance his or her water use efficiency as long as proper incentives are offered. The problems of what incentives are needed, where do incentives come from, and how water users respond to the incentives under the context of water demand management need to be investigated.

1.3 Objectives of the Research

The overall objective of this research is to investigate the hydrologic and economic impacts of water demand management through water transfers among users and how to encourage water users to utilize water wisely by offering appropriate incentives. More specifically, various methodologies are developed based on two underlying principles: either to increase aggregated benefits given the currently available water or to decrease aggregated water consumption while achieving benefits that are no less than the current ones. Potential maximum benefits under the scenarios having water demand management are estimated using centralized and decentralized optimization techniques, and compensation values are determined to encourage water conservation. Minimum water requirements under different scenarios of conservation limits are assessed.

1.4 Organization of the Dissertation

The thesis is organized into seven chapters, as shown in Figure 1.1. The thesis begins with a general introduction in Chapter 1 stressing the importance and unique advantages of water demand management, and pointing out some key barriers to the widespread adoption of water demand management. The research problem and objectives are then described in this chapter. Chapter 2 reviews several aspects of water demand management starting from the classification of water demands and key characteristics of consumptive uses. The motivation, definitions, various measures, and potential costs and benefits of water demand management are discussed in depth. Water demand management at the basin level is a part of the water allocation problem, and objectives, approaches of water allocation are examined. Chapter 3 briefly reviews two initial water allocation methods and provides an example to show how the two methods work. Initial water allocation results obtained by using the methods constitute a baseline scenario in various water demand management methodologies in the following chapters.

Based on the first specified principle given on the left side in Figure 1.1, Chapter 4 describes how to incorporate a specified water demand management plan into a cooperative water allocation model to achieve better aggregated benefits, and then how to fairly share the additional benefits through a modified cooperative reallocation game. The economic impacts of the plan are evaluated using an illustrative case study. In Chapter 5, an agent-based model for water demand management based on the first principle is proposed to investigate the responses of different users in order to obtain individual maximum benefits and their impacts on the overall system. The same illustrative case study is utilized to test the new agent-based model.

Founded on the second principle, Chapter 6 puts forward two versions of a hydrologic-economic model to estimate the minimum water requirements to achieve at least the same level of benefit with various conservation limits consideration, as indicated on the right side of Figure 1.1. The model is applied to the South Saskatchewan River Basin. Chapter 7 summarizes the main contributions of this study, and lists some recommended future work, shown at the bottom of Figure 1.1.

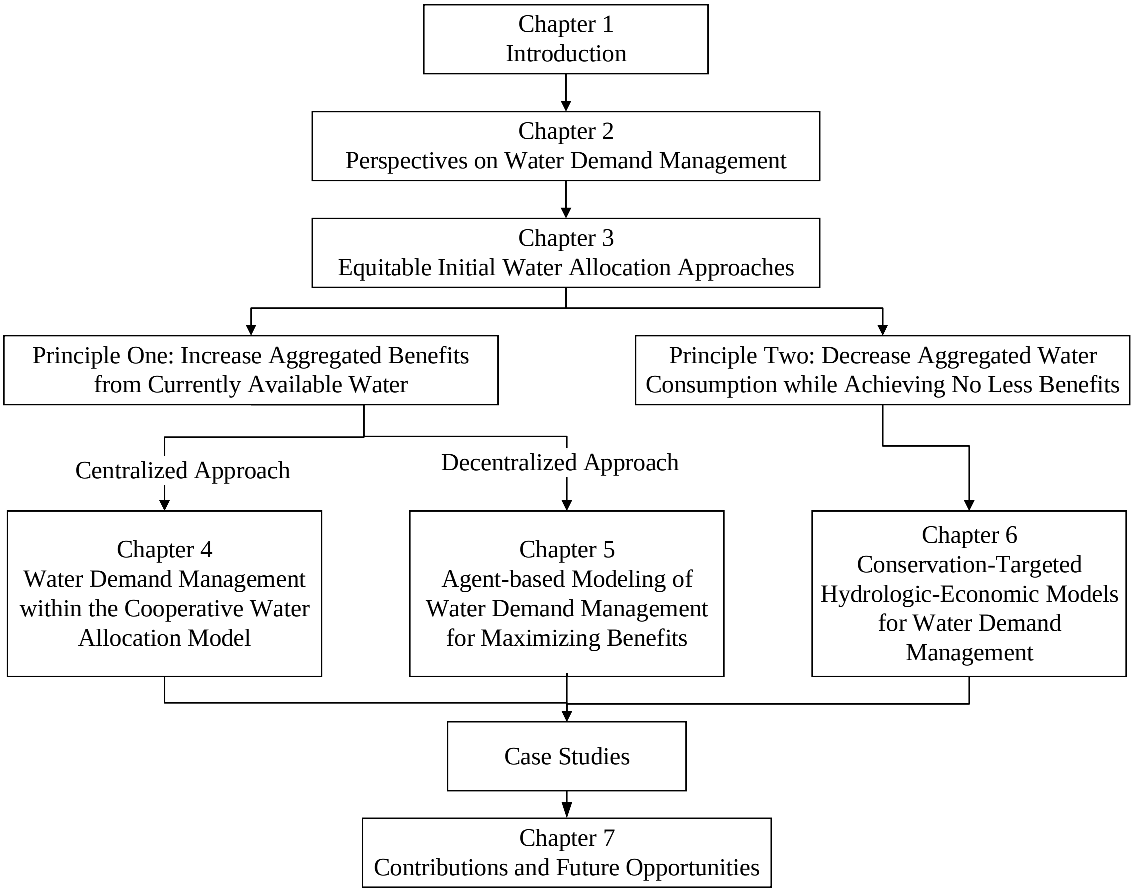


Figure 1.1 Organization of the dissertation

Chapter 2

Perspectives on Water Demand Management

The classification of water demand and the key characteristics of consumptive uses are firstly described in this chapter. How to manage the demand considering their different characteristics is a core question for water demand management. Two fundamental motivations, various definitions, a series of applicable measures, and the potential costs and benefits of water demand management are discussed in the second part. Lastly, water demand management at the basin level is an important part of water allocation. Hence, the objectives and approaches of water allocation at the basin level are reviewed.

2.1 Water Demand

Water is needed for various purposes by humanity. Firstly, people need drinking water for survival. Secondly, economic development requires water as one of its key inputs in order to satisfy people's various needs for goods and services. Thirdly, many water-related recreational activities are necessary for improvement in the quality of life. Last, but not least, ecosystem protection is crucial for the long-term evolution of human society. The need for water for a specified purpose is commonly referred to as *water demand* or *water use*. These two terminologies are utilized synonymously in this dissertation.

2.1.1 Classification of Water Demand

Based on different criteria, water uses can be categorized into various groups. For instance, according to the purpose of water use, there are residential, commercial, industrial, agricultural, hydropower, recreational, and environmental uses. Depending on their impacts on hydrologic cycle, water uses are classified into two main categories: consumptive and non-consumptive uses. Consumptive use refers to "water that is unavailable for reuse in the basin from which it was extracted due to evaporation, incorporation into plant biomass, transfer to another basin, seepage to a saline sink, or contamination" (Gleick et al., 2011). Consumptive use typically causes diminishment to water in quantity and/or quality, and thereby water availability is adversely affected. Non-consumptive use, on the other hand, means either no diversion from the water source, or water diversion is immediately returned to the source following its use in the same quantity and quality, such as hydropower generation, navigation, and recreational activities. A hierarchical classification of water uses in a basin is given in Table 2.1. In this table, consumptive use is indicated by "C", and non-consumptive use is marked by "NC".

It should be noted that consumptive and non-consumptive uses are not completely exclusive to each other. This is because consumptive use typically is not one hundred percent efficient, and there are always some return flows in the form of either surface runoff or groundwater recharge. For a non-consumptive use like storing water in a reservoir, there are always evaporation losses while maintaining the reservoir at a particular water depth. The evaporation losses of the reservoir are excluded from consumptive uses because this part of the water losses would normally transfer into clouds in the atmosphere, and subsequently fall to the ground in the form of rain or snow.

2.1.1.1 Consumptive Uses

As indicated in Table 2.1, municipal, industrial and agricultural uses are three main types of consumptive uses. Among these three major consumptive uses, municipal and industrial uses are commonly combined into one use named urban use. These sector-level consumptive uses can be further divided into individual level uses or be aggregated to the basin level and national level water uses, as depicted in Figure 2.1.

Table 2.1 Hierarchical classification of water uses (based on Gupta (2016))

Water uses			Objectives
Urban uses	Municipal uses (C)	Domestic	Use for cooking, washing, watering lawns, and air conditioning
		Public	Use in public facilities and for fire-fighting
		Commercial	Use in shopping centers, hotels, and laundries
		Small industries	Use for industrial production
		Conveyance loss	—
	Industrial uses (C)		Use for large water-using industries such as steel, paper, chemicals, textiles and petroleum refining
	Water dilution (NC)		Serve as the source for self-purification of the stream
Agricultural uses (C)	Irrigation		Use for raising crops
	Factory farm uses		Use for livestock
	Conveyance losses and waste		—
Hydropower use (NC)	Hydropower generation		Produce hydropower
Navigation uses (NC)	River regulation		Water release from upstream reservoirs to raise water depth
	Lock-and-dam		Increase water depth for navigation through ship locks and dams
	Artificial canalization		Use for artificially constructed channels with a number of ship locks
Other uses	Flood storage (NC)		Control floods
	Recreation (NC)		Provide a place for swimming, fishing and other recreational activities
	Water export (C)		Large diversion and export for commercial purposes
	Ecological uses (C & NC)		Conservation of endangered aquatic life, use for forestry, filling wetlands, etc.

C: Consumptive use; NC: Non-Consumptive use.

Municipal water use generally refers to water used for residential, commercial, public facilities, and some small industries not having a separate water supply system in a city. Residential use, also called household or domestic use, includes indoor appliances like toilets, showers, cooking facilities, and cloth washing machines, as well as outdoor activities such as landscape irrigation and car washing. The demand for water in this sector depends on several determinants like the number and density of population, income level, climate conditions, and cost of water supply (Baumann et al., 1997; Arbues et al., 2003). A simple equation to estimate municipal water demand is using population multiplied by per capita water usage. The per capita use differs from city to city. A survey in the United States indicated that in 2010 residential per capita use ranged between 51 and 167 gallons per day with a national average of 88 gallons per day (Maupin et al., 2014), while in Canada the average in 2011 was 66 gallons per day (Statistics Canada, 2013). In addition, the residential per capita water use shows a declining trend over the past few decades as a result of an increased availability of water-saving appliances and changes in water use behavior, as indicated by the decreasing dotted line in Figure 2.2.

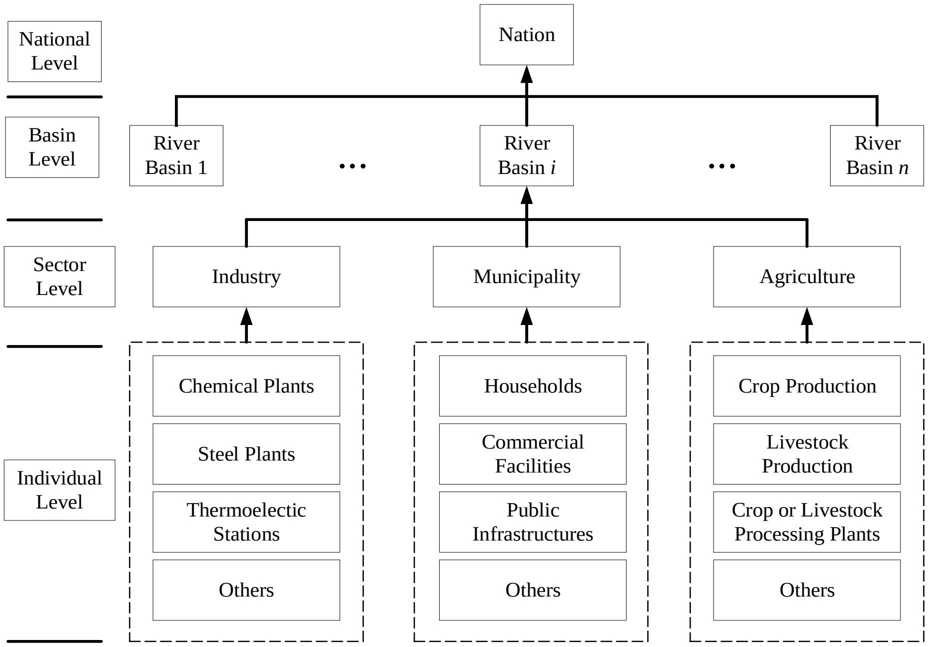
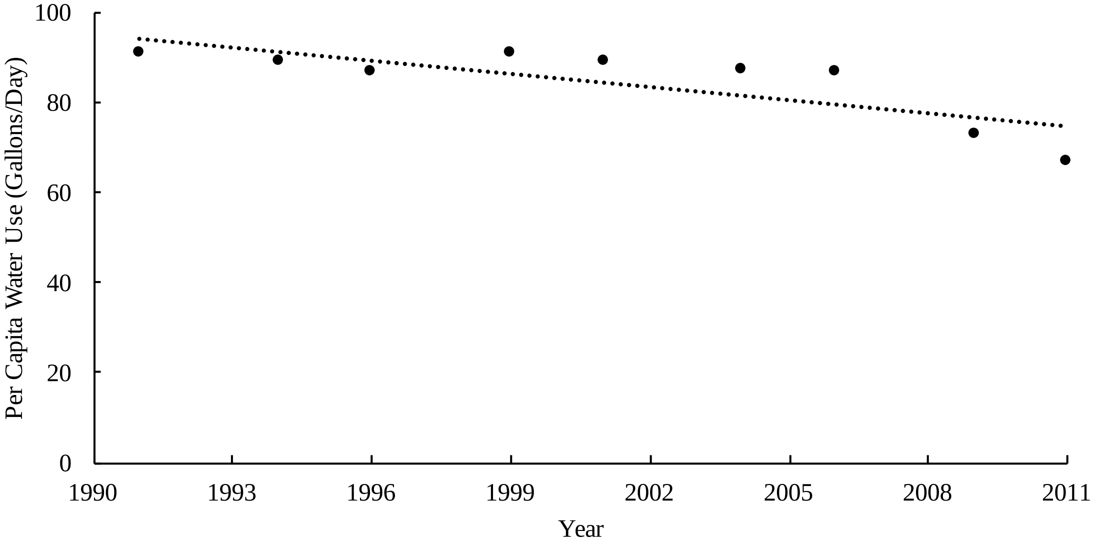


Figure 2.1 Different levels of consumptive uses (based on Kindler (2010))



Data Source: Environment Canada's Municipal Water and Wastewater Survey &
Statistics Canada's Survey of Drinking Water Plants

Figure 2.2 Residential per capita water use in Canada

Industrial use mainly includes thermoelectricity power plants and large water-consuming manufacturers, such as steel, paper, chemicals, textiles, and petroleum refining. Industrial use is affected by factors like types of production, technology used in processing. For example, oil sands production requires a large quantity of water (Xiao et al., 2015b), but specific requirements vary depending on the technologies utilized. By mining technology, about 3.1 barrels of water are required for each barrel of bitumen produced, while only 0.4 barrel of water is needed when in-situ technology is adopted (Kuang et al., 2014). The typical average water use of major industries are listed in Table 2.2. As can be seen in the table, average water use varies substantially by industry. A downward trend similar to municipal use is also observed for many industries. Figure 2.3 provides an example of the magnitude of each municipal and industrial use in a typical medium-size city. Of course, the percentages may be different according to various conditions of determinants mentioned above. About 80 to 90% of water withdrawal is returned to the river after treatment.

Table 2.2 Average water use of major industries (based on Gupta (2016), p.20)

Industry	Average Water Use
Thermoelectric power plants	19 gallons/kWh
Steel	62,000 gallons/ton
Paper	39,000 gallons/ton
Chemicals	55,000 gallons/ton
Woolens	140,000 gallons/ton
Petroleum refining	1,850 gallon/barrel

1 gallon = 3.785 litres

In agriculture, water use includes the need for water for raising crops (irrigation) and for breeding livestock (factory-farm). Irrigation is the dominant use in this sector, and also the heaviest use in a basin in most cases. Several factors could have impacts on irrigation water use, such as crop patterns, irrigation methods, soil and climatic conditions. Based on crop evapotranspiration and crop coefficient, one can determine the volume of water needed to be withdrawn from a river after the exclusion of effective rainfall. Livestock water use can be calculated by using the simple equation mentioned above: number of livestock multiplied by per capita water use. More details regarding characteristics of consumptive uses are discussed in Section 2.1.2.

2.1.1.2 Non-Consumptive Uses

Non-consumptive uses normally take place on-site and do not abstract water from water source. These uses may not provide substantial economic benefits, but still provide significant value for human society. The main types of non-consumptive uses include hydropower, navigation, recreation, and environmental uses.

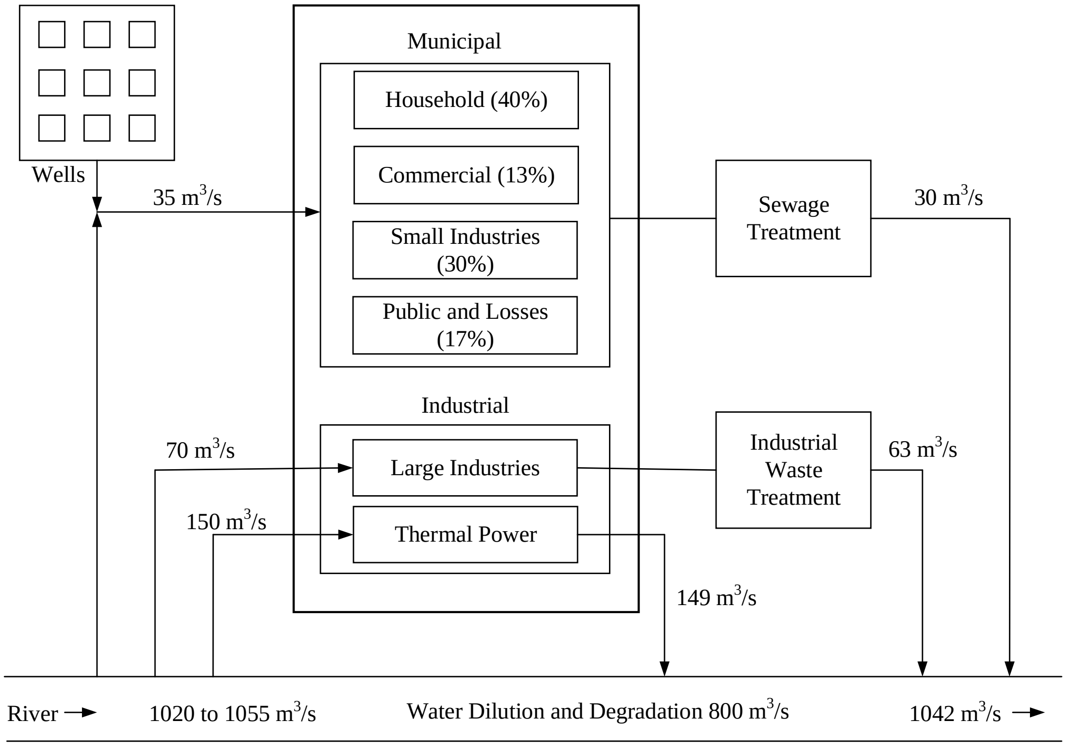


Figure 2.3 Water uses in a medium-size city (based on Gupta (2016), p.4)

Hydropower plants are normally attached to reservoirs or dams because they require a considerable size of water head and water flow to convert streamflow to electrical power. The economic evaluation of hydropower use is calculated by the amount of electrical power generated multiplied by the difference between electricity price and cost per unit of power. Hydropower is considered much cleaner and more sustainable than thermoelectricity power, but the construction of reservoirs or dams may cause conflicts between upstream and downstream users because it changes the water availability for downstream users.

Navigation in a river requires a minimum level of water depth depending on the size of the river and velocity of flow. This minimum requirement is roughly constant throughout the river and across seasons. For the situations in which the natural water depth at some sections of a river or some periods of a year is not sufficient for navigation purpose, some corrective actions are needed. For instance, water depth can be raised by water releases from upstream reservoirs, or by a series of dams and ship locks. When two different river systems need to be connected, new channels with a number of ship locks can be constructed to satisfy the needs of navigation.

From the environmental perspective, a certain amount of water needs to be preserved in a river for aquatic system protection and sewage purification purposes. In the past, raw waste from municipality and industry were directly discharged into the rivers without treatment. For this case, at least 40 times the amount of streamflow to wasteflow is often required to sufficiently dilute unsafe materials in the river system (Gupta, 2016). Even though nowadays direct dumping of raw waste is not allowed and waste treatment is normally performed before discharging waste into the rivers, there is still the need for an adequate level of streamflow. This is because the absolute volume of waste is significantly increasing due to the rapid pace of urbanization and industrialization, and also the distances between cities are shorter. In addition, forestry and wetland retain a sizable amount of water to maintain wildlife habitat. The evaluation of water for meeting environmental goals requires utilizing approaches such as the travel cost method and contingent valuation technique (Brown et al., 1991; Venkatachalam, 2004; Fleming and Cook, 2008). For modeling purposes, navigation water use and environmental use can typically be combined and implemented as a minimum flow requirement.

2.1.2 Key Characteristics of Consumptive Uses

The main typical consumptive uses possess distinguishable characteristics in terms of total demand, consumption ratio, sensitivity to price changes, productivity and seasonality. A better understanding of their diversified characteristics may provide greater opportunities for better managing these uses.

With respect to total water demand, agricultural demand is the largest globally whereas demand in the municipal and industrial sectors is increasing significantly (Shiklomanov, 2000). Almost 70% of the extracted fresh water is utilized for crop-raising activities globally (FAO, 2013), and more water is required in order to produce more food in the future. It is believed that if water is utilized effectively in agriculture, water will not be a bottleneck for future food production (De Fraiture and Wichelns, 2010). The demand for municipal and industrial uses is expected to increase rapidly in the near future due to burgeoning urbanization and industrialization. More specifically, the increases between 2000 and 2050 will mainly come from manufacturing (400%), electricity (144%), and domestic uses (127%) (Leflaive et al., 2012), as shown in Figure 2.4. Because of agriculture's large share in total water demand, a small contribution from agriculture may provide a substantial amount of water for other uses. A study in southern Alberta indicated that a 4.6% improvement in irrigation efficiency could conserve enough water to cover the annual demand of all municipalities in the basin (AIPA, 2010). Accordingly, agriculture is believed to have the most significant potential to free-up water for other uses.

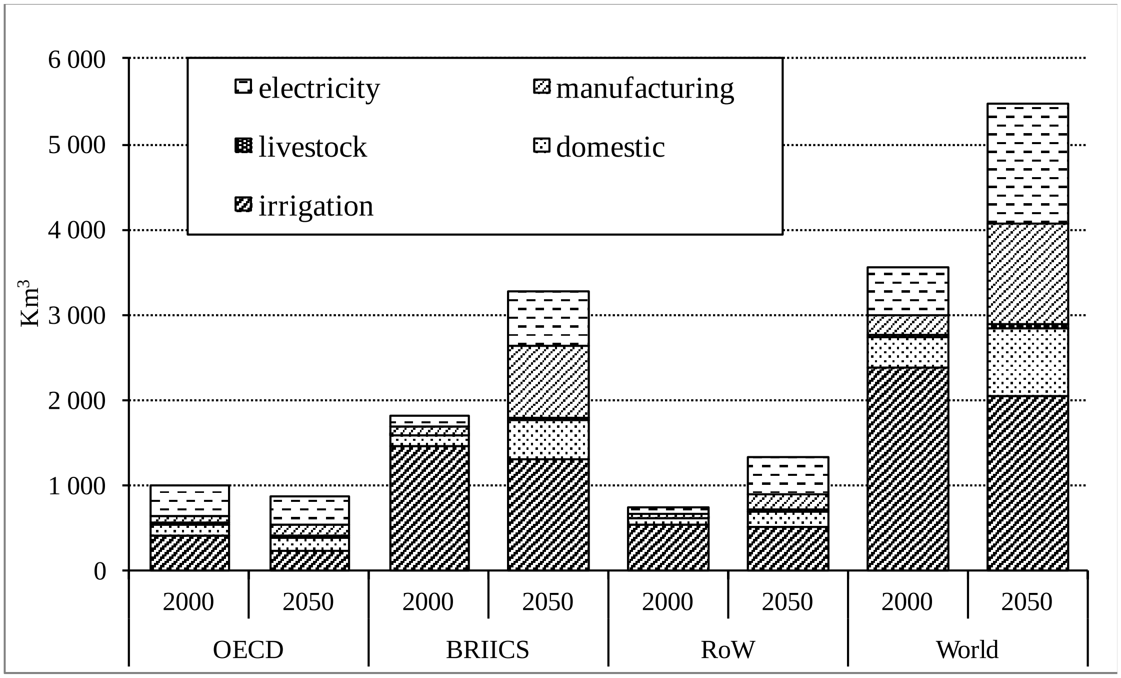


Figure 2.4 Global water demand in 2000 and 2050

(Note: BRIICS (Brazil, Russia, India, Indonesia, China, South Africa); OECD (Organization for Economic Cooperation and Development); RoW (rest of the world). This graph only measures 'blue water' demand and does not consider rainfed agriculture. Source: Leflaive et al. (2012))

Moreover, agriculture is also the largest water consumer in most regions, since it absorbs a majority of the water it takes. For instance, agriculture in Canada accounted for only five percent of total water withdrawal in 2013, but was still the largest water consumer (ECCC, 2017a). In contrast, most water withdrawn by municipal and industrial uses are returned to the water body, which means water consumed is much less than the water taken by them. It is reported that less than 10% of global water consumption comes from municipal and industrial sectors (Richter et al., 2013). Consequently, agriculture should be the first sector investigated in order to reduce overall water consumption in a region.

Because water is a scarce resource, economic instruments, such as pricing measures, are introduced for managing water demand like an economic good (Winpenny, 1994). Many studies have been conducted on estimating the price elasticity of water demand for the municipal, industrial (Arbués et al., 2003; Olmstead and Stavins, 2009) and agricultural sectors (Scheierling et al., 2006). Empirical studies suggest that elasticity in the municipal sector is relatively low, with an average value of -0.51, and normally varies from case to case (Espey et al., 1997). Industrial use is inelastic as well, with an average elasticity of -0.29 and ranging from -0.79 to -0.1, according to an investigation of 51 industrial plants in France (Reynaud, 2003). Agriculture water usage is also not very sensitive to price changes, with a mean value of price elasticity of -0.48 (Scheierling et al., 2006). With increasing competition for water, price signals play an important role in water demand management, but need to be evaluated carefully according to specific conditions in different cases.

Value of water utilization also varies from sector to sector. How much benefit can be generated by one user can be estimated by using statistical methods and optimization models. Benefit functions constitute an appropriate form to indicate the relationship between water consumption levels and benefits generation. The benefit functions can be represented by different structures like linear, quadratic, or inverse price-demand forms (Wang et al.,2008a, b). With respect to the benefits produced per unit of water, municipal and industrial uses generally perform better than agriculture uses. Consequently, many studies on efficient use of water resources suggest water transfer from low-value to high-value ones (Booker and Young, 1994; Mahan et al., 2002, Wang et al.,2008b).

Another important feature of consumptive use is its seasonality. Specifically, agriculture normally requires a sizable amount of water during the crop growing season, and much less water during the other months of the year; while municipal and industrial demand is generally evenly distributed throughout the year.

2.2 Water Demand Management

Water demand management is widely considered as a promising path towards the sustainable development of water resources (Tate, 1989; Gleick, 2003a; Brooks, 2006; Butler and Memon, 2006). During the past few decades, water management has witnessed a gradual shift from supply management towards demand management. The motivation, definitions, measures, and potential costs and benefits of water demand management are reviewed in this section.

2.2.1 Motivation for Water Demand Management

The development of water management techniques has gone hand-in-hand with the evolution of human societies, as illustrated in Figure 2.5. Two fundamental motivations are identified for the development of water demand management approaches.

The first motivation is the growing conflicts, in terms of both frequency and severity, caused by water scarcity. Earlier in human society, when the population was much smaller, all water needs could be satisfied because there was sufficient available water. As water demand has increased due to population growth and urban development in modern times, various supply-oriented practical efforts, such as expanding the construction of water infrastructure, have been made by water managers over the past century in order to increase water supply to meet the exponentially growing water demand, as shown in the middle part of Figure 2.5. These efforts have effectively alleviated water stresses facing humanity, and have provided massive benefits in terms of greater economic returns and fewer water-related disasters.

However, the methods to increase water supply are becoming much less viable as the marginal costs tend to be much more expensive economically, politically, and environmentally. The future demand will hardly be satisfied if the demand continues its exponential growth. In addition, with an increasing awareness of environmental conservation, the water availability for human use will be further restrained, as indicated by the dotted line of sustainable water available in Figure 2.5. Sharing of water among increasingly competing activities is becoming more challenging. Many water conflicts have arisen due to the imbalance between water supply and water demand (Wolf, 2002; Gleick and Heberger, 2014), and the situation can be aggravated if the imbalance cannot be managed properly.

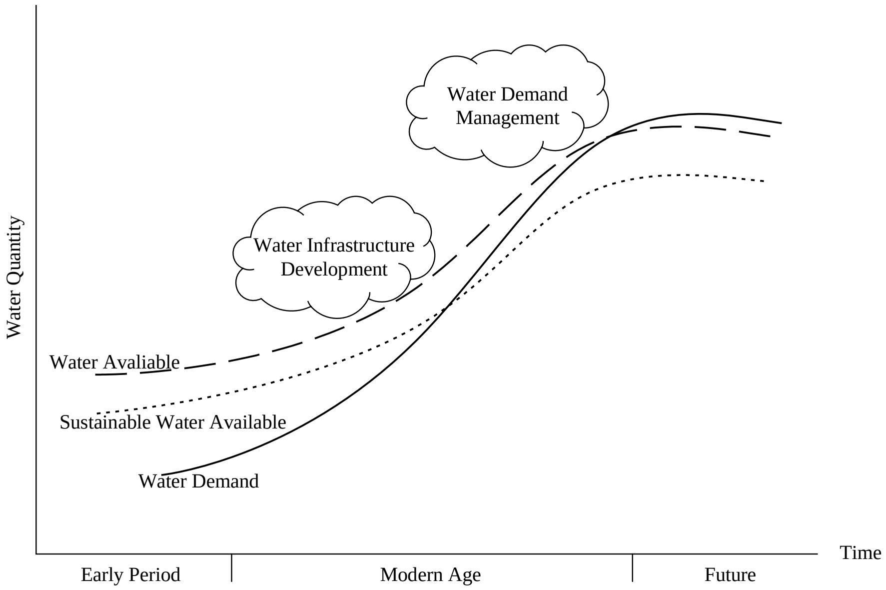


Figure 2.5 The evolution of water management techniques (based on Speed et al. (2013))

The second fundamental motivation for the development of water demand management approaches arises from the rethinking of the real purpose of water resources. Water has traditionally been viewed as an indispensable resource for activities like crop production and urban development. These activities compete for limited water resources. However, the essential purpose of water use is to produce a range of products and services to satisfy people's needs. As explained by Gleick et al. (2011), "people want to satisfy demands for goods and services, such as food, fiber, waste disposal, they may not care how much water is used - or even whether water is used at all - as long as these goods and services are produced in convenient, cost-effective, and socially acceptable ways".

A particular example is that about 100 to 200 tons of water was needed to produce a ton of steel in the 1920s, while less than four tons of water is required for each ton of steel produced nowadays (Gleick, 2003b). This example demonstrates the great potential for water demand management. A world water development report by the United Nations Educational, Scientific and Cultural Organization (WWAP, 2015) also indicates that the water crisis is not a problem of water resources itself, but rather a problem of water governance, and requires initiatives and cooperation from both the public and private sectors.

It should be noted that water demand management should be considered as being a valuable complement to, rather than a replacement of, traditional water supply management, because new water supply infrastructure will continue to be constructed if necessary, and there is ongoing research on desalination and recycling wastewater as new sources of water supply (Sahin et al., 2015; Ziolkowska, 2015). There is no definitive line between the two techniques; on the contrary, an overlap can be found between the two approaches. For example, is collecting rainwater for household use a supply or a demand management technique? It is hard to find a definitive answer to this question. Another illustration is that the reuse and recycling of water by individual users is normally viewed as a demand management technique; however, when it is conducted by a factory or company for the purpose of sale or transfer, it becomes a supply management technique. The two techniques - water demand management and water supply management - share the same purpose, which is to satisfy people’s needs for products and services; consequently, both approaches are important components within an integrated water management framework.

2.2.2 Definitions of Water Demand Management

Demand management was initially developed in the field of energy management in the 1970s when an energy crisis appeared, and particular attention was paid to the customer’s side. The idea of demand management emerged from debates among social scientists and analysts (Lovins, 1977; Gellings and Chamberlin, 1987). Since then, research on energy demand management has greatly flourished, and tremendous benefits have been gained, in terms of significant drops in energy demand and continually growing economic returns, from the successful application of energy demand management.

Water and energy share many similar characteristics: both are finite, both are used to satisfy human beings' various needs in daily life, and both resources have dramatically increasing demands. The idea of demand management in energy management is naturally extended to the area of water resources. However, there are also many differences between water management and energy management: energy is treated as an economic good while water is not; energy use can be metered more accurately than water use; and energy pricing system is considerably well-established while water pricing system is not. Many efforts are still required in the field of water demand management. Water demand management is a relatively new concept and still not completely definitive; consequently, a number of definitions can be found in the literature.

Tate (1989) defined water demand management as “any socially beneficial measure which reduces or reschedules average or peak water withdrawals or consumptive use from surface or groundwater, while maintaining or mitigating the extent to which return flows are degraded”. The term “socially beneficial” means the benefits produced by the adoption of a particular measure should outweigh the cost of adoption. Arlosoroff (1999) reported that demand management is “much more aggressive in its use of economics to influence the origin of water demands to provide incentives for satisfying given "ends" in the cheapest possible manner”. Renzetti (2002) defined water demand management as being "policies that are meant to contribute to the efficient allocation of water through the "management" of water demands".

Savenjie and van der Zaag (2002) described demand management as "the development and implementation of strategies aimed at influencing demand, so as to achieve efficient and sustainable use of a scarce resource". Brooks (2006) proposed an operational definition of water demand management consisting of the following five facets: (1) Reduce the quantity or quality of water required to achieve a specific task; (2) Adjust the nature of the task or the process it is undertaken so that it can be accomplished with less water or with lower quality water; (3) Reduce the loss in quantity or quality of water as it flows from source through conveyance systems and use to final disposal; (4) Shift the timing of use from peak to off-peak periods; and (5) Increase the ability of a water system to continue to serve society during times when water is in short supply.

Because water demand management involves hydrology, economics, legislation, and even psychology, whichever definition is adopted, the following facets need to be considered:

- Water demand management is not an objective but a strategy to achieve other desired objectives such as social equity and economic efficiency.
- Water demand management aims to promote efficiency and productivity of water use, and mainly focuses on consumptive uses.
- Water demand management is concerned with not only technology but also perceptual aspects. The technological capacity for water demand management is not a limitation in most cases (Mass, 2003; Blanke et al., 2007). The question is how do people think about water demand management, and do they have enough motivation to take advantage of these existing technologies?
- Water demand management can be implemented at different scales, like individual, sector, basin, and national levels.

At the basin level, the implementation of water demand management is more concerned with influencing water demand such that water is shared and utilized more efficiently and productively, than which specific technology is used. It is assumed that users already have the technical capacity to achieve a reasonable level of water conservation, and they will do so if proper incentives are provided such that the benefits gained are greater than the costs.

Water use efficiency is generally defined as the ratio of water consumed to water diverted for carrying out an activity (water efficiency = water consumed / water diverted). "Water consumed" stands for the amount of water that is unavailable for other activities in the same area in the short term, and it is calculated variously for different users. For instance, in irrigation, water consumed mainly refers to water depletion due to plant evapotranspiration (Jensen, 2007); and for manufacturing it normally implies the portion of water that has been incorporated into products. An improvement in water efficiency is achieved when the denominator decreases, such that less water is diverted to complete a specific activity by adopting new or advanced technologies or management practices.

However, even with a profound understanding of water balance for a particular activity, there are significant difficulties in accurately estimating the amount of water consumed in that process, and there commonly exists an underestimation of water efficiency using the classical definition, as examined by Seckler et al. (2003). Hence, a new concept called water productivity (WP) was proposed (Molden, 1997). This new idea is easier to measure than efficiency and reflects the ultimate objective of water utilization: provide goods and services to people. It is defined as the ratio of benefits gained from water utilization to the amount of water used to produce those benefits (Molden et al., 2010; Cai et al., 2011), as expressed by:

$$WP = \frac{Benefits\ gained\ from\ water\ use}{Water\ input} \tag{2.1}$$

The numerator, benefits gained from water use, can be expressed by physical outputs, economic values, or other feasible measurements; while the denominator, water input, can also consider several forms depending on the study objectives under consideration, such as gross/net inflow or evapotranspiration (Cai et al., 2011). Based on Equation 2.1, an improvement in water productivity can be achieved from two aspects: (1) by increasing benefits produced from water utilization given the current available water; and (2) by decreasing water input subject to achieving benefits not less than the current ones. Optimization problems can be formulated according to these two aspects: the former one implies maximizing benefits as the main objective subject to the constraints of water availability; while the latter indicates minimizing water consumption as the primary target constrained by physical requirements and benefit goals.

2.2.3 Measures of Water Demand Management

A great number of measures can be implemented for water demand management, depending on the study perspective, area, and objective. One can examine the potential of certain water saving technologies in an individual household, or specific farm, or the potential at the sector level; one can also evaluate the impacts of economic instruments on individual users or sectors. Many studies categorize water demand management measures into: technological improvements, economic instruments, regulatory policies, and educational programs.

2.2.3.1 Technological Improvements

A variety of technological measures can be taken in order to improve water use efficiency and productivity in each sector. The effectiveness of each technology and potential cost have been broadly studied.

In agriculture, Blanke et al. (2007) categorized water saving technologies into three groups: traditional, household-based, and community-based, and he estimated the water saving potential and the adoption level of these technologies in Northern China. Traditional technologies include border irrigation, furrow irrigation, and level fields; household-based technologies mainly consist of plastic sheeting, drought resistant crop varieties, retaining stubble/low till, and surface pipes; community-based technologies are underground pipes, lined canals, and sprinkler systems. Most technologies are able to save around 30% of water use, but their adoption level is quite low even though the types and availability of technologies were growing rapidly during the last two decades. Other measures like deficit irrigation (Fereres and Soriano, 2007), smart irrigation scheduling

(Pereira et al., 2007), and laser leveling (Larson et al., 2016) also show great potential in reducing water use.

In urban areas, relying on water distribution networks for water supply having large leakage losses constitutes a significant portion of water demand, and thereby leakage control is one of the most important measures to reduce water loss (Foxon et al., 2000; Marunga et al., 2006). The adoption of low-flow appliances (like toilets, showerheads, and washing machines) can effectively save household water usage (Lee et al., 2011; Carragher et al., 2012; Price et al., 2014). Inman and Jeffrey (2006) reported the saving potential of these indoor appliances in several countries. Among these appliances, toilet leakage is a major place to investigate for water conservation. Rainwater harvesting in regions having high levels of rainfall sometimes can also be an effective measure (Zhang et al., 2009; Assayed et al., 2013). In addition, greywater recycling systems could provide substantial amount of water to users who do not require the highest quality of water.

Overall, there exist plenty of currently available technologies. One of the common reasons hindering the adoption of the existing technologies is the lack of incentive. On the one hand, some technologies may need a great investment in the initial installation. On the other hand, the benefit from the adoption of the technology may not be obvious in the short term. Therefore, providing subsides or compensation to users could promote an increase in the adoption of existing technologies, as pointed in Ward (2014), providing subsidies to reduce financial cost for irrigators would help them to convert low-efficiency flood irrigation to high-efficiency drip irrigation technology, and offset some of the income losses in the face of a drought.

2.2.3.2 Economic Instruments

Among all of the economic instruments, price attracted the most attention, especially in the municipal sector (Baumann et al. ,1997; Nauges and Whittington, 2010). To what extent a price change can influence water usage level, which is called price elasticity, is the focus of research in this area. As indicated in Section 2.1.2, a consensus about price is that most consumptive uses are price inelastic, and the elasticity varies from place to place according to use type. In other words, price change can affect water use to some extent but may have limited effectiveness in some cases. For more comprehensive results on price elasticity, one can refer to the work of Epsey et al. (1997), Arbues et al. (2003), Dalhuisen et al. (2003), Worthington and Hoffman (2008) in the residential sector, and Scheierling et al. (2006) in the irrigation sector.

Price structure, particularly in the residential sector, has also been extensively studied (Nieswiadomy, 1992; Stevens et al., 1992; Hewitt and Hanemann, 1995; Kulshreshtha, 1996; Martins and Fortunato, 2007; Olmstead et al., 2007; Rosenberg, 2009; Monteiro and Roseta-Palma, 2011; Ghimire et al., 2015). Whether to adopt a uniform price or block price structure, and whether to utilize an average or marginal price, would result in different responses to price changes. Increasing-block price structures arguably increase elasticity more than a uniform structure does (Kulshreshtha, 1996; Olmstead et al., 2007). As examined by Olmstead et al. (2007), price elasticity under an increasing-block rate structure is -0.60 while the value is -0.19 under a uniform marginal price. However, there were also studies reporting that price structure may not significantly affect price elasticity (Stevens et al., 1992). The effects of average and that of marginal prices are also debatable: some studies reported that users react more to average price (Nieswiadomy, 1992; Kulshreshtha, 1996), while some others suggested that marginal price has a more significant impact on elasticity. This inconsistency may be due to several causes, like estimation technique, sample size, weather condition, cultural and historic reasons, and demographic factors. While the debate continues, one conclusion that can be drawn is that price elasticity is considerably site-dependent, so that the findings in one place may not be suitable for adoption in other places.

In addition, showing price information on water bills (Gaudin, 2006) and bill frequency (Stevens et al., 1992; Kulshreshtha, 1996; Fenrick and Getachew, 2012) may also significantly affect water users' reactions in regards to water use. To include price information on bills and to increase bill frequencies may enhance user's responsiveness to price and provide more motivation to conserve water.

Except for the municipal sector, economic instruments in agriculture have also received significant attention (Varela-Ortega et al., 1998; Berbel and Gómez-Limón, 2000; Johansson et al., 2002; Gómez-Limón and Riesgo, 2004; Tsur, 2005; Scheierling et al., 2006; Schoengold et al., 2006; Ohab-Yazdi and Ahmadi; 2015). As mentioned in Section 2.1.2, price inelasticity is observed in this sector as well. A general conclusion is that irrigation water demand needs to be priced, but what is the “right” price is debatable. A low price would not be effective in reducing irrigation water demand, but an effective price to reduce water demand may significantly affect farm income and employment (Berbel and Gómez-Limón, 2000; Huang et al., 2010). Different pricing policies in the same area may have distinct impacts on water demand, farmers’ income, and governments’ revenue (Varela-Ortega et al., 1998). Therefore, similar to the findings in the residential sector, price for irrigation water needs to be considered case by case, and one may not rely on experiences from other locations.

2.2.3.3 Regulatory Policies

Regulatory polices refer to any voluntary or mandatory actions taken by water users or administrative agencies to reduce water use. Fielding et al. (2013) estimated the long-term impacts of a series of voluntary strategies on urban water demand in Queensland, Australia, through an experimental study. The results showed that water consumption could greatly decrease for approximately 12 months, but would subsequently return to previous levels. This situation indicated that more actions other than voluntary strategies need to be taken to ensure the long-term effectiveness of water demand management. Water use restrictions can be temporary or permanently imposed to specific or all users in the face of water scarcity, such as restricting landscape irrigation during peak evapotranspiration hours (Renwick and Green, 2000). Mandatory allocation policies can also serve the purpose of reducing water consumption, but only with careful design and implementation. It is believed that mandatory policies perform more effective than voluntary methods in regard to water reduction (Renwick and Green, 2000; Maggioni, 2015), but the policy design process needs to take into account equity considerations, because the public’s support is one of the key factors in determining the successfulness of a given policy.

2.2.3.4 Educational Programs

Educational programs involve the use of printed, audio, and video materials in order to modify water use behavior in the long-term. Although their short-term effects might be limited in some regions, they are still worthy of investment as a promising approach (Thompson and Stoutemyer, 1991; Nieswiadomy, 1992; Syme et al., 2000; Lavee et al., 2013). Renwick and Green (2000) reported an average 8% reduction can be achieved through public information campaigns in the Western USA. The public participation rate is a key factor in the implementation of these programs, and sometimes targeted campaigns are employed.

2.2.3.5 Overview of Water Demand Management Measures

It should be noted that more than one kind of measure can be taken simultaneously. Thus, the effectiveness of different measures can be assessed and compared (Olmstead and Stavins, 2009; Tsai et al., 2011; Araral and Wang, 2013; Reynaud, 2013), in order to obtain valuable insights regarding the implementation of water demand management approaches. Extensive successful implementations of water demand management have been reported globally (Kreutzwiser and Feagan, 1989; Mwendera et al., 2003; Chen et al., 2005; Sharp, 2006; Brooks and Wolfe, 2007; Kenney et al., 2008; Adler, 2011; Zeitoun et al., 2012; Kampragou et al., 2011; Araral and Wang, 2013; Kishore, 2013; Tortajada and Joshi, 2013; Smith et al., 2015).

In summary, one finding from the literature review is that many measures are site-specific, especially economic instruments. Therefore, they should be adapted to be compatible with specific conditions (Sharma and Vairavamoorthy, 2009; Kampragou et al., 2011). The successful experiences in developed countries may not be directly applicable to developing countries (Sebri, 2014).

Another finding is that some measures may be technically achievable but politically infeasible, and public acceptability is of great importance. However, this categorization does not take into account the acceptability and participation level of individual users, which may result in unexpected outcomes in the implementation. For example, increasing the price of water is regarded as a tool to decrease water usage in households, but some users may use more water because they think they paid more for it. Another reason behind this phenomenon is that the water bill is only a small fraction of a household budget. Consequently, a different categorization is proposed by Mohamed and Savenije (2000), in which each type of water demand management measure is categorized according to positive and negative incentives, as well as water quota regulations. Positive incentives normally imply benefit being given to water users, like subsidies for adopting new technologies, while negative incentives generally mean benefits being taken from users, in the form of water prices or taxes. Both positive and negative incentives have their advantages and drawbacks, and should be selected according to specific circumstances, or sometimes be combined. However, because positive incentives are generally more acceptable to users, the participation rates and compliance levels to the water demand management measures are expected to be improved, thereby achieving better effectiveness of the measures. As a result, positive incentives receive special attention in this research.

2.2.4 Costs and Benefits of Water Demand Management

As mentioned earlier, positive incentives imply benefit being given to water users. More specifically, it means a surplus by subtracting cost from benefit obtained in the implementation of a specific water demand management program. To estimate the surplus, an in-depth understanding of potential cost and benefit regarding the program is required. Hence, cost-benefit analysis constitutes a systematic approach for consideration for employment in water demand management.

Water demand management costs mainly include implementation and operation costs. The implementation costs refer to the expenditures, such as labor, materials, and advertising, which occur during the design and evaluation of the implementation plan of a program and during the installation of the program. The operation costs mean the expenses required to maintain the full effectiveness of the program after its installation, such as the labor costs and economic incentives.

The benefits of water demand management consist of direct water use and indirect water use valuations. Direct valuation involves the value obtained from directly consuming water, like municipal, industrial, and agricultural uses, as well as hydropower electricity values. Indirect valuation includes recreational and environmental values provided by water savings from deferred construction of new infrastructure, reductions of wastewater treatment expenses resulting from less water discharge, and less electricity usage. Smith et al. (2015) also suggest the inclusion of the value of system resilience (less risk of water shortage and fire), value of less greenhouse gas emissions and energy requirements, value of public awareness (promoting further voluntary water-saving practices) and worth of good customer relationships. Even though these indirect values are intangible and require special estimation techniques, it is important to take these values into consideration.

The aforementioned costs and benefits are mostly of interest to administrative agencies or managers, while positive incentives are more related to individual users. An economic incentive is regarded as a benefit by the individual user, but may be viewed as a cost for agencies. Therefore, it is important to be clear about the point of view taken in a cost-benefit analysis, which is referred to as the “accounting perspective” (Baumann et al., 1997).

Individually, costs can be broken down into equipment investment, installation fee, maintenance cost, and sometimes learning expenses. The benefits can be divided into direct economic returns from water utilization, incentives from agencies, and indirect benefits such as reduced water bills, and sometimes aesthetic value. Note that the direct economic return from water utilization may drop due to the reduction in water usage. In this case, a compensation is necessary to cover the decline. This is also the key implication of having positive incentives.

2.3 Basin-wide Water Demand Management and Water Allocation

In the previous sections, water demand management issues at the individual and sector (municipal, industrial, and agricultural) levels have been discussed. Most existing studies focused on one particular sector to examine the effectiveness of one or more measures. There are extensive interactions among these sectors: the change of water demand in one sector may affect the water availability to other sectors, whether positively or negatively. In addition, water demand management beyond the sector level could provide more viable options by enabling the integration of demand-side and supply-side management for better water management. Therefore, it is of significant importance to investigate water demand management issues at the scale of inter-sectors, such as at the basin level.

Only a few studies have considered water demand management beyond one sector. Brinegar and Ward (2009) analyzed the basin impact of providing subsidies to agricultural users. Positive results are observed, such as more efficient use of water for crops, higher crop production, extra land irrigated, and increased basin-wide economic benefits. Sisto (2009) investigated the issue of compensating irrigators to free up more water for environmental purposes in the Rio Conchos River in Mexico, and estimated the required economic compensation values. Qureshi et al. (2010) examined two incentive policies, paying subsidies for water conservation efforts or buying water from irrigators in the water market, for increasing environmental flows in the Murray-Darling River Basin. They found that the water market method performs better than the subsidies approach alone in the basin, in terms of both additional environmental flows and cost savings. Ramires et al. (2011) explored the potential of water transfers from irrigators to urban users in the Mafraq Basin in Jordan. A sensitive price elasticity provides an economic opportunity for irrigators to conserve water and rent the conserved water to urban users.

At the basin level, water demand management becomes an important component of water allocation endeavors (Kindler, 2010), and the focus shifts from estimating future demand towards deciding the determinants of future demand and how these determinants can be managed to influence future demand. Water allocation is one of the central issues within integrated water management. Allocating scarce water resources in an efficient, fair and sustainable manner is one of the greatest challenges facing humanity around the globe.

2.3.1 Objectives of Water Allocation

Water allocation is the combination of actions which enable water users and water uses to take or to receive water for beneficial purposes according to a recognized system of rights and priorities

(Wang et al., 2003). The overall objective of water allocation is to maximize the benefits of water to society. This overall objective can further be divided into three specific goals: social equity, economic efficiency, and environmental sustainability.

2.3.1.1 Specific Goals

Equity means that water is shared in a fair and equitable manner among different users, among existing and future users, and between consumptive uses and the environment. Fairness is a complex concept perceived diversely by different people, but in general implies Pareto optimality, monotonicity, impartiality, consistency, priority, and envy-free (Young, 1994). Depending on the choice of these principles, various water allocation models can be formulated for solving different fair allocation problems (Wang et al., 2007a; Hipel et al., 2013). For instance, when the principles of priority and monotonicity are satisfied, a *priority equitable* allocation problem is formed (Wang et al., 2007a).

Efficiency means to achieve maximum benefits from water utilization, including both direct and indirect benefits. The valuation of water use substantially varies by types of use, and needs to be assessed carefully and thoroughly. The valuation of agricultural water use is normally estimated by a water-crop production function, and that of municipal and industrial water use can be measured as the consumer surplus derived from a demand function for water. However, for water use where there is no or little direct market-price measurement, and, hence, other valuation methods are needed (Brown et al., 1991; Gregory et al., 1993; Turner et al., 2001; Adamowicz et al., 2007; Stahl et al., 2007).

Sustainability implies that present water utilization should not jeopardize the water availability to meet future generations' needs, according to the most well-known definition made by the World Commission on Environment and Development in 1987 (WCED, 1987). Since then, a number of definitions have been proposed based on different understandings and interpretations of the concept. How to quantitatively measure this concept is still a challenging task, and requires great effort on identifying the long term possible impacts resulting from present water utilization

(Loucks and Gladwell, 1999; Loucks, 2000). Several specific requirements should be followed in the exercise of water management: guarantee a basic water supply for human health; guarantee a basic water need for sustaining the health of the ecosystem; maintain a certain minimum standard of water quality; collect and disclose data on water availability, water use, and water quality; and involve all affected parties in the water planning process (Mays, 2007).

The three specific objectives are normally in conflict with each other, and there exist trade-offs among them. When one objective is dominant over the others, additional objectives are normally considered as judgement-based constraints. However, when two or more objectives are equally important and non-commensurable, just like the three objectives mentioned above, a single optimum decision is extremely difficult to achieve (Haimes et al., 1975). The emphasis of one objective may undermine the achievability of other objectives, and that is when trade-offs come into effect. For instance, water markets can achieve the most efficient use of water, but may not be friendly to the environmental use and marginalized users. Failing to satisfy sustainability objectives might cause a new conflict, and the damage or cost of new conflict may be even higher than the benefits gained through the efficient use of water. Therefore, producing a widely socially acceptable water allocation plan is a process of finding a reasonable balance among these three objectives. To achieve multiple objectives simultaneously as much as possible, multiple-step water allocation methods are proposed. For instance, in the first step water is allocated following fairness principles, and then a second step is performed to achieve more efficient use of water by allowing temporary water transfer among users.

2.3.1.2 Transfer and Externalities

Water transfers among users normally have externalities regarding both physical and economic aspects. For example, if an upstream farmer transfers part of his or her water to an industrial user located downstream, there will be more streamflow in the section of river between the two users. Meanwhile, the farmer would experience a benefit loss due to a reduction in water utilization, while the industrial user could produce more benefit with the extra water. In this case, a fair compensation should be given to the farmer. The compensation could be provided by the industrial user or water agency.

2.3.2 Approaches of Water Allocation

Water allocation problems are essentially concerned with how to distribute limited water resources among competing activities to achieve the maximum social welfare. As a result, optimization methods are frequently utilized in terms of modelling techniques to find an optimal water allocation scheme. Many optimization methods have been proposed, including linear programming (Takama et al., 1981; Jacobs and Vogel, 1998; Devi et al., 2005; Kucukmehmetoglu and Guldmann, 2010), non-linear programming (Cai et al., 2003; Kilic and Anac, 2010; Yang et al., 2012; Xu et al., 2013), dynamic programming (Alaya et al., 2003; Luo et al., 2007; Jafarzadegan et al., 2014), genetic algorithms (Ahmed and Sarma, 2005; Nicklow et al., 2010), and any combination of these techniques (Cai et al., 2001; Reca et al., 2001; Huang et al., 2002; Ghahraman and Sepaskhah, 2004; Li et al., 2009).

One of the deficiencies of optimization techniques is that they assume every stakeholder is acting voluntarily to achieve optimal system-wide performance. However, an optimal system-wide outcome does not necessarily mean the best outcome for every individual stakeholder; sometimes the outcomes for certain stakeholders may be worse. For example, more water allocated to one stakeholder means less water for another stakeholder. In these cases, new conflicts might be triggered. It is important to provide motivation for every stakeholder, such as obtaining greater (or, at least, not any less) economic benefits, in order to achieve the best system performance.

Because water allocation is a problem involving multiple stakeholders, in which each stakeholder has different interests, conflicts usually arise among stakeholders. Negotiations among stakeholders are usually required to find a resolution to the conflict. Accordingly, game theory is a powerful tool for negotiation in many water management problems, particularly in water allocation (Madani, 2010).

Non-cooperative game theory, as a major branch of classical game theory, analyzes decision makers' moves and countermoves in a conflict situation, and derives stable outcomes as equilibria. This technique is suitable for carrying out a strategic analysis of a conflict in water management (Gopalakrishnan et al., 2005; Nandalal et al., 2007; Madani and Hipel, 2011; Hipel et al., 2014; Chu et al., 2015).

Cooperative game theory, on the other hand, which is another main branch of game theory, examines how the gains of cooperation can be shared within a coalition, thus making it more suitable than non-cooperative game theory for employment in the water allocation domain. Cooperative game theory has been successfully applied to many areas within water management such as cost allocation of water projects (Young et al., 1982; Dinar et al., 1992; Sechi et al., 2013) and waste load allocation (Kilgour et al., 1988; Okada and Mikami, 1992), but possesses limited application to water allocation.

A comprehensive water allocation framework based on cooperative game theory called the Cooperative Water Allocation Model (CWAM) was proposed by Wang et al. (2008a). In this structure, water allocation is carried out in two steps: initial allocation based on existing water rights systems or agreements, and cooperative reallocation involving water transfer and benefits sharing among water users. The second step is simulated as a cooperative game. Various coalitions can be formed, and the aggregated benefits associated with different coalitions can be estimated. The solution concepts of cooperative games such as core-based (nucleolus and its variations) (Young et al., 1982; Lejano and Davos, 1995; Owen, 1995) and non-core-based (Shapley value) (Shapley, 1953) can be utilized to solve the cooperative game.

2.4 Summary

As water demand is projected to expand in almost every sector, along with a growing awareness of the need for ecosystem maintenance and the uncertainties brought about by climate change, the competition for limited water will be increasingly intense. Proactive initiatives on the demand side are crucially required. Water demand management is playing an increasingly important role as a complement to supply management, and perhaps should be given higher priority over supply management in the near future. Although a variety of technologies for water demand management are available, how to motivate users to take advantage of these technologies is a key problem. Positive incentives have the potential to increase the participation rate and compliance level, thereby achieving better effectiveness of water demand management. Nonetheless, the costs and benefits in the implementation of water demand management alternatives need to be assessed carefully and thoroughly. To consider water demand management at the basin level provides more options to achieve enhanced water management.

Chapter 3

Equitable Initial Water Allocation Approaches

In this chapter, two main approaches for equitable initial water allocation proposed by Wang et al. (2007a) are briefly reviewed. This initial allocation is used as one of the inputs for a second main step in which water demand management is taken into account for improving the efficient use of water. The basic configuration of a basin-wide allocation model and hydrologic considerations are described. As mentioned in Section 2.3.1, equity is one of the most important principles but also a complex one for scarce resource sharing problems in which multiple stakeholders, each having different interests, are involved. Allocating water resources in an equitable manner provides an appropriate starting point for the implementation of various further operations such as water demand management strategies. The initial allocation results form a baseline scenario for the following chapters of water demand management methodologies.

3.1 Water Rights Systems

Water rights systems are established to define the ownership of water and how it can be distributed, utilized, and protected. Various systems are developed in different countries due to specific legal systems and historic reasons. Three most widely observed water rights systems are: prior, riparian, and public water rights system (Savenije and Van der Zaag, 2000).

Under the prior rights system, water is considered as a private property, and is allocated according to the principle of "first in time, first in rights". The first user can use an allocated quantity of water for beneficial purposes, and then subsequent users can use the remaining water for their beneficial purposes. In periods of water shortages, there is no sharing of shortage among users. Moreover, under this system water users may oppose a charge for obtaining water because they think water is their own property.

On the contrary, the public rights system considers water as a public property, and is mainly derived from the "civil law" doctrine. Thus, the ownership of water belongs to the state rather than individual users, and users only have the right to use water. Water is administratively distributed to users through water permits from the state. In periods of water shortages, the deficit is shared among users, and some users may share more than others.

The riparian rights system is normally derived from the “common law” doctrine. The ownership of water is connected to that of lands, and every riparian user can use a reasonable share of water as long as other riparian users are also able to obtain a fair share. This system is mainly developed in regions with abundant water resources. However, a pure riparian water system may cause the “tragedies of the commons” since the term “reasonable share” is hard to define without a proper regulatory management. Therefore, a riparian water system is commonly combined with various forms of regulation nowadays, and is treated similar to a public right system.

3.2 Initial Water Allocation Approaches

Initial water rights allocation is carried out in a basin based on its existing water rights systems or agreements. Optimization techniques are essentially utilized for initial water allocation. Based on the existing water rights systems, two multi-objective optimization methods, called the priority-based maximal multi-period network flow (PMMNF) approach and the lexicographic minimax water shortage ratios (LMWSR) approach, have been designed for initial allocation (Wang et al. 2007a; 2008a). Sequential and iterative solution algorithms to solve the three types of problems have been developed (Wang et al. 2007a), and various solvers in GAMS (GAMS, 2005) can be utilized to optimize these programs.

In the PMMNF method, water is allocated according to priority ranks. More specifically, each user is assigned to several priority ranks, and with each priority rank there is a maximum amount of water that can be withdrawn. For example, for a household user, half of his or her demand can be satisfied by the volume of water having the highest ranked priority, and the rest of the demand can be satisfied with the second highest ranked priority. Meanwhile, half of an industrial user’s demand can be satisfied with the highest priority, one fourth with the second highest priority, and one fourth with the third highest priority. In this method, water is firstly assigned to fully satisfy the highest ranked priority of the demand of all users, then the demand with the second highest priority, and so on, until all available water resources are allocated. For the situations in which water is not sufficient for satisfying all of the demand with a specific priority rank, water is allocated proportionally among all demands.

PMMNF is a very versatile method in which water users' priority ranks are the main principle for allocating water resources. Therefore, PMMNF is a *priority equitable* method for initial water allocation (Wang et al., 2007b). Water users with low priority will not receive water until water users with high priority are fully satisfied. Consequently, some "junior" users may not be able to receive any water during water shortage periods. PMMNF is applicable under the prior, riparian, and public water rights systems.

In contrast, LMWSR is designed for sharing water shortages among all users, every water user can receive a proportional share of water when water is limited, and the differences of water shortage ratios among all users are minimized. However, one may argue that, for example, domestic users have a higher degree of dependency on water than agricultural users, and thus need to be considered more preferentially. Hence, weight factors are utilized to distinguish the relative precedence of users. The LMWSR technique is applicable under the public rights system, and is considered as a *perfectly equitable* method for initial water allocation (Wang et al., 2007b).

3.2.1 Configuration of a Basin-wide Allocation Model

Water allocation involves an array of physical hydrological infrastructure such as reservoirs, dams, demand sites, rivers, and canals. To mathematically model a water allocation problem, all physical components can be described within an abstract network.

Consider a river basin represented by a node-link network $G\ (K, L)$ where $K = \{k_1, k_2, \ldots, k\}$ denotes a set of nodes representing physical components, such as reservoirs or demand sites, of the river basin, and $L = \{(k_1, k_2): k_1, k_2 \in K$ and $k_1 \neq k_2\}$ stands for a water conduit connecting two nodes. The overall planning period is defined as $T = \{1, 2, \ldots, t, \ldots, \tau\}$. Let $Q\ (k_1, k_2, t)$ be the water flow from node k_1 to node k_2 during time period t.

In a basin, there are typically various types of water uses, such as agricultural production, urban development, and environmental conservation, which must share the available water resources. Additionally, reservoirs are an essential part of water management operations as they can store water during periods of high flow to avoid flood disasters and release water to satisfy the needs of downstream water users during low flow periods. Therefore, the set of nodes can be further divided into several subsets according to node types, since different node types have different hydrological properties. For example, storage nodes and non-storage nodes should be treated differently in water balance equations. Specifically, the subsets include inflow nodes, outflow nodes, junction nodes, agriculture nodes, municipality and industry nodes, reservoir nodes, hydropower plants, and streamflow requirements.

3.2.2 Hydrologic Considerations for Water Allocation

In a water allocation problem, some basic hydrological considerations and constraints need to be incorporated into the process, mainly consisting of three categories: physical constraints, policy restrictions, and system control rules. The physical constraints mainly consist of water balance equations and capacity limits. Water balance equations normally are used to describe the flow of water in and out of a system, and are generally expressed as (Gupta, 2016, p.40):

$$P + Q_{SI} + Q_{GI} - E - Q_{SO} - Q_{GO} - \Delta S - \varepsilon = 0 \tag{3.1}$$

where P is precipitation; Q_{SI} and Q_{GI} represent inflow from outside of the system through surface water and groundwater, respectively; E means water loss by evaporation, including transpiration; Q_{SO} and Q_{GO} stand for outflow from the system in forms of surface water and groundwater, respectively; ΔS denotes the change of storage volume in reservoirs or aquifer; and ε is a discrepancy term. In practice, depending on the purpose of computation, various water balance formulations can be built. Figure 3.1 shows the water balance for a general node k in this study.

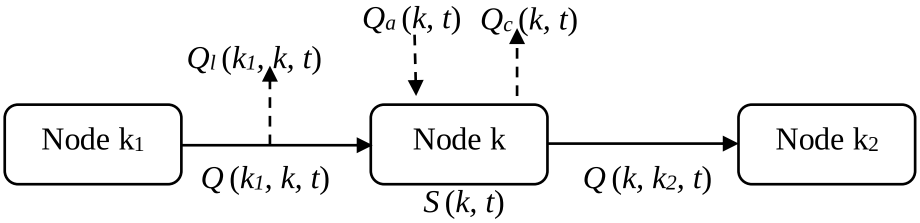


Figure 3.1 Water balance for a general node *k*

The general form of water balance equation for each node of the network during each period is written as:

$$\begin{aligned} S(k,t) - S(k,t-1) &= \sum_{(k_1,k)\in L} Q(k_1,k,t) - \sum_{(k,k_2)\in L} Q(k,k_2,t) \\ &- \sum_{(k_1,k)\in L} Q_l(k_1,k,t) + Q_a(k,t) - Q_c(k,t), \quad \forall k_1, k_2, k \in K \end{aligned} \tag{3.2}$$

where *S(k, t)* is the storage volume for storage node (reservoir or aquifer) k at the end of period t, and is equal to zero for non-storage nodes; $Q(k_1, k, t)$ means the water flow from node k_1 to k during period t, while $Q(k, k_2, t)$ is the outflow from node k to k_2, or is a return flow from node k if node k is a consumptive node; $Q_l(k_1, k, t)$ stands for water loss during transportation, due to evaporation, leakage, or seepage, from node k_1 to k during period t; $Q_a(k, t)$ represents water adjustment from local small tributaries to account for precipitation to node k during period t; and $Q_c(k, t)$ is used to denote the amount of water consumed at node k during period t due to economic activities. This equation can be modified accordingly based on the specific type of node for which it is describing. For example, for non-storage nodes S is equal to zero, and for non-consumptive nodes, Q_c can be omitted.

How much water can be diverted to a demand site is restricted not only by the maximum demand of that site but also by the capacity limit of conduits toward that site. Therefore, a capacity constraint is expressed as:

$$Q(k,\ t) \le min\left\{ Q_D(k,\ t),\ \sum_{(k_1,k)\in L} Q_{max}(k_1,\ k,\ t) \right\} \tag{3.3}$$

where $Q_D(k,\ t)$ represents the maximum demand of node k during period t; and $Q_{max}(k_1,\ k,\ t)$ indicates the maximum capacity of a conduit that is used to divert water to node k during period t. The smaller value of the demand volume and the sum of capacity of all conduits towards node k are the amount of water that can be diverted to that node.

Capacity limits for storage nodes and links also play an important role. For example, water flow in each link towards node k must not exceed the maximum capacity of the link, which can be written as:

$$Q(k_1,k,t) \le Q_{max}(k_1,k,t), \quad \forall (k_1,k) \in L \tag{3.4}$$

or for a storage node k:

$$S(k,t) \le S_{max}(k,t), \quad \forall k \in RES \tag{3.5}$$

Besides the physical constraints for each node, there are also policy considerations due to social-economic or political restrictions. An obvious example is that there is normally a minimum flow requirement for links, which can be expressed as:

$$Q(k_1,k,t) \ge Q_{min}(k_1,k,t), \quad \forall (k_1,k) \in L \tag{3.6}$$

Another example from the policy point of view is that the demand for node k during period t should be firstly provided by local tributaries, as water in local tributaries are typically accessible by local users only; then the deficit would be satisfied by water flows towards node k if necessary:

$$\sum_{(k_1,k)\in L} [Q(k_1,k,t) - Q_l(k_1,k,t)] \le max\{Q_D(k,t) - Q_a(k,t),\ 0\},\ \ \forall (k_1,k) \in L \tag{3.7}$$

In an abstract node-link network, a double-direction link or two opposite-direction links between two nodes represent that there exists water flow from a source node to a demand site and a return flow from that demand site to the source node. The return flow may cause an overestimation of water available at that source node during the same time period, because return flow only occurs after water is diverted to the demand site. However, water diversion is scheduled before a portion of water is returned to the source node. Therefore, return flow from one demand site is not available for diversion at that source node during the same time period. Assuming that node k is a source node, k_1 means a demand site that diverts water from and provides return flow to source node k, and k_2 stands for any node that has water flow, including return flow, towards the source node k, a system control constraint to reflect the exclusion of return flow from the available supply at source node k is written as:

$$\begin{aligned} \sum_{\substack{(k,k_1)\in L\\ and\\ (k_1,k)\in L}} Q(k,\, k_1,\, t) \le & \sum_{(k_2,k)\in L} [Q(k_2,\, k,\, t) - Q_l(k_2,\, k,\, t)] \\ & - \sum_{\substack{(k_1,k)\in L\\ and\\ (k_1,k)\in L}} [Q(k_1,\, k,\, t) - Q_l(k_1,\, k,\, t)] + Q_a(k,\, t), \end{aligned} \tag{3.8}$$

where the right side of the equation indicates that for a time period t, total effective return flow from demand site k_1 to source node k, represented by the term of $\sum_{\substack{(k_1,k)\in L\\ and\\ (k_1,k)\in L}} [Q(k_1,\, k,\, t) - Q_l(k_1,\, k,\, t)]$, should be subtracted from the total effective inflow towards source node k, represented by the term of $\sum_{(k_2,k)\in L} [Q(k_2,\, k,\, t) - Q_l(k_2,\, k,\, t)]$. Effective flow means water flow excluding water losses during transportation. The remaining flow plus local adjustment flow are the total available water at source node k during that period.

3.3 Initial Allocation Example

Without loss of generality, a hypothetical network, as depicted in Figure 3.2, is designed. The network has 2 inflow (IN1, IN2), 1 outflow (O1), 2 reservoirs (R1, R2), 2 agricultural (A1, A2), 2 domestic (D1, D2), 2 general (G1, G2), 2 industrial (I1, I2), and 2 instream flow requirements (S1, S2) demand nodes. The general demand refers to municipal, excluding domestic, demand, such as water use in commercial establishments and public infrastructures. The instream flow requirement indicates the minimum instream flow needed for the sake of the safety of aquatic ecology and recreational purposes. The water allocation problem is designed for a period of 12 months. The monthly supply and demand data are adapted from the South Saskatchewan River Basin (SSRB) case in a drought year in Wang et al. (2008b).

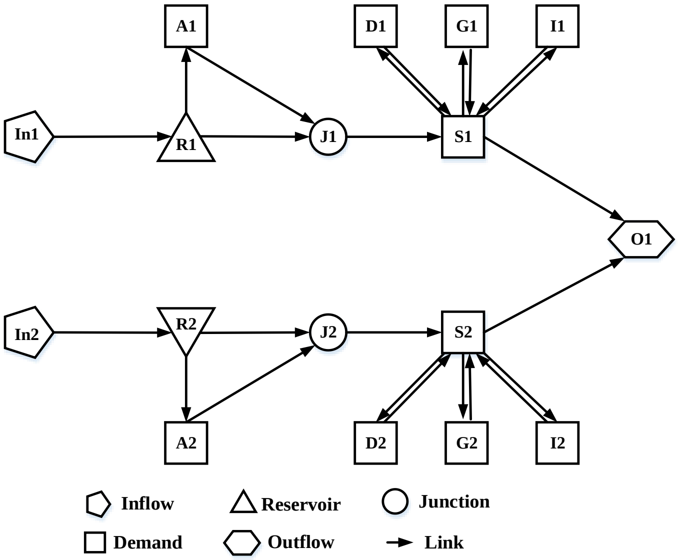


Figure 3.2 The network of the illustrative example

3.3.1 Water Demand and Supply Data

The monthly water supply, as shown in Table 3.1, consists of inflow, reservoir storage, and local adjustments from small tributaries. It should be noted that local adjustments only occurr at reservoir, junction, instream flow requirement, and outlet nodes. The water loss coefficient during transmission is set to 3% due to evapotranspiration. The return ratio from agriculture is 25%, while the return ratios from domestic and general users are 85% and 75%, respectively. Industrial users normally have higher return ratios than domestic or general users because of the higher degree of adoption of water recycling technologies, and their return ratios are 99.65% and 99.49% for I1 and

I2, respectively. The initial reservoir storages are set to 163.29 million m^3 and 317.06 million m^3 for R1 and R2, respectively.

On the demand side, agricultural users require water resources only during the crop growing season from May to September, and their water demand is assumed to be zero in other months. The demand of municipal and industrial users are evenly distributed throughout the year with small variances in each month, as reported in Table 3.2. In addition to the demand for consumptive users, there is also a minimum requirement at the outflow node, as shown in Table 3.3.

Table 3.1 Monthly water supply consisting of water inflows at two inflow nodes and water adjustments resulting from local tributaries (mcm*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IN1	0.864	0.773	0.836	1.155	5.005	9.753	8.504	5.960	3.645	2.344	1.288	1.000
IN2	2.260	1.927	2.098	2.169	7.284	15.611	13.309	8.479	5.221	3.611	2.697	2.460
J1	0.547	0.415	0.821	1.127	2.843	3.762	3.201	2.772	2.155	0.655	0.580	0.575
R1	0.271	0.154	0.241	0.322	0.797	1.311	1.326	0.998	0.705	0.282	0.227	0.244
S1	0.764	0.434	0.679	0.909	2.251	3.702	3.742	2.818	1.990	0.796	0.639	0.688
J2	1.106	0.839	1.658	2.278	5.747	7.605	6.471	5.604	4.355	1.325	1.172	1.163
R2	0.325	0.235	0.471	0.636	1.438	1.853	1.536	1.361	1.084	0.375	0.333	0.329
S2	0.304	0.230	0.455	0.626	1.578	2.088	1.777	1.539	1.196	0.364	0.322	0.319
O1	4.254	2.443	3.884	5.195	12.625	20.557	20.412	15.414	11.106	4.504	3.628	3.867

*1 mcm = 1 million cubic meters

Table 3.2 Monthly water demand of consumptive users (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	0.000	0.000	0.000	0.000	15.332	38.462	47.352	32.119	17.380	0.000	0.000	0.000
A2	0.000	0.000	0.000	0.000	27.221	147.970	209.984	118.812	38.340	0.000	0.000	0.000
D1	0.445	0.414	0.445	0.451	0.528	0.577	0.583	0.607	0.552	0.493	0.457	0.475
D2	11.424	10.109	11.129	11.277	12.887	12.887	15.385	14.942	13.626	11.720	11.129	11.277
G1	0.420	0.392	0.420	0.426	0.499	0.545	0.550	0.573	0.522	0.466	0.431	0.448
G2	6.152	5.444	5.993	6.073	6.940	6.940	8.285	8.047	7.338	6.311	5.993	6.073
I1	8.345	8.345	8.866	9.388	14.812	15.334	15.647	15.647	13.561	13.039	8.345	8.345
I2	9.209	9.209	9.785	10.361	16.347	16.922	17.268	17.268	14.965	14.390	9.209	9.209

Table 3.3 Monthly minimum outlet flow (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
O1	8.173	6.093	8.741	12.393	12.393	12.393	12.393	12.393	12.393	11.487	9.007	8.070

3.3.2 Initial Allocation Results

Under the PMMNF method, the priority ranks of demands are as listed in Table 3.4. Two domestic users' demands are ranked first, and other users' demands are satisfied with various priority ranks ranging from 2 to 6. The available water, including water supply as shown in Table 3.1 and return flows from upstream users, is distributed to users with the highest rank by the maximum amount of water which can be diverted, and then the second highest, until all available water is allocated. In this way, the initial allocation for each user can be obtained. By dividing one's allocation by his or her demand, a satisfactory ratio can be calculated. The results of the satisfactory ratios for users are displayed in Figure 3.3.

As can be seen from Figure 3.3, users A1, D1, and D2 are fully satisfied. This is because the demand of D1 and D2 are ranked the highest, and thereby are satisfied first. A1's demand can be fully satisfied with the amount of water provided in the second highest rank. Water shortages are observed for all other users in which G2 and I2 suffer the most. This is because water supply in the lower tributary of Figure 3.2 is far less than the total demand of users in that tributary. In fact, the demand of A2, G2, and I2 with second highest rank cannot be satisfied.

When the LMWSR approach is utilized, the weight factors of domestic users are set to 20 while the weight factors of all other users are set to 10. With the same water supply and demand data, initial water allocation for each user can be determined. The same method is employed to calculate each user's satisfactory ratio, for which the results are plotted in Figure 3.4. As can be seen from this figure, water shortages are shared among all users. However, the users in the lower tributary of Figure 3.2 possess lower satisfactory ratios than the same type of user in the upper tributary. The users of A2, G2, and I2 have the same shortage ratio. This implies that the competition in the lower tributary is more intense than that in the upper one.

Table 3.4 Priority ranks of consumptive users and annual withdrawal limits for PMMNF

Users	Annual demand (mcm)	Priority ranks	Annual water withdrawal limit (mcm)
A1	150.645	2	197.853
		5	31.939
A2	542.327	2	468.730
		5	86.346
		6	298.301
D1	6.027	1	6.027
D2	147.792	1	147.792
G1	5.692	2	4.212
		3	0.730
		4	0.339
		5	0.175
		6	2.563
G2	79.589	2	52.386
		3	3.891
		4	6.536
		5	5.060
		6	45.237
I1	139.674	2	74.821
		3	12.954
		4	5.997
		5	3.114
		6	145.334
I2	154.142	2	69.363
		3	5.152
		4	8.653
		5	6.703
		6	179.746

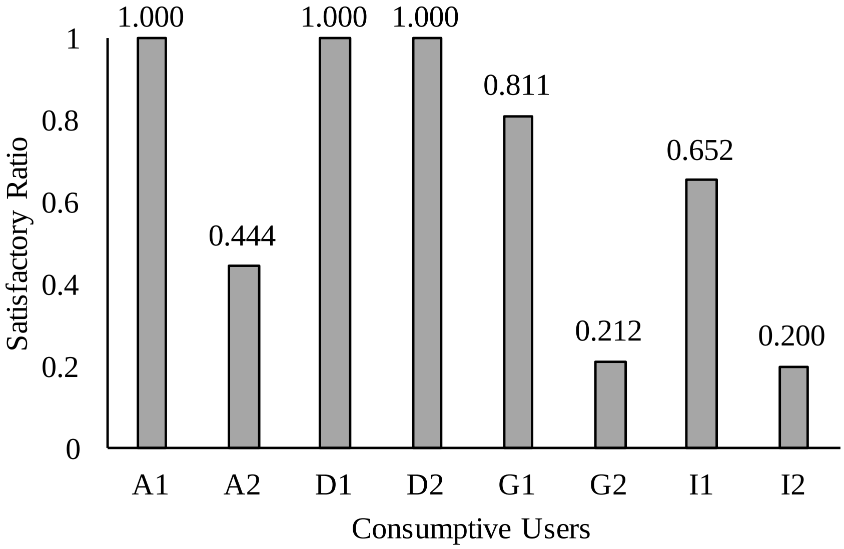


Figure 3.3 Annual satisfactory ratio of consumptive users using the PMMNF approach

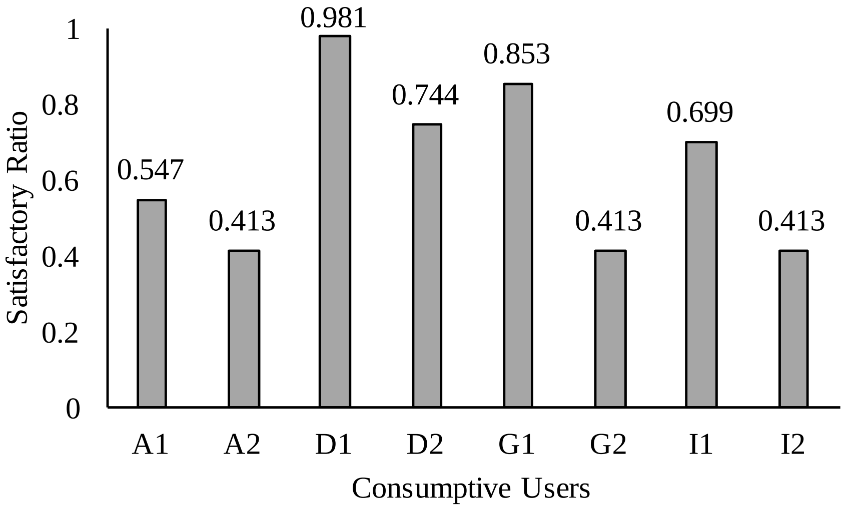


Figure 3.4 Annual satisfactory ratio of consumptive users using the LMWSR approach

3.4 Summary

Two main initial allocation approaches based on existing water rights systems are reviewed in this chapter. An illustrative example is utilized to show how these two methods work. The initial allocation results form a baseline scenario used in the following chapters in which water demand management strategies are implemented. Because the initial allocation indicates the actual amount of water under one's control with a given water availability, further operations based on this result would be more meaningful and realistic when one user interacts with other users.

Chapter 4

Water Demand Management within the Cooperative Water Allocation Model

The impact of a water demand management plan on a water system and its users is investigated within a comprehensive cooperative water allocation framework in this chapter. In particular, a demand management plan is incorporated into a two-step multi-period fair water allocation model. A modified cooperative game is designed for the sharing of additional net benefits under the scenario having water demand management. The results indicate that cooperation among water users can yield more net benefits, and a water demand management plan is able to lead to a further increase of the aggregated net benefits by means of water transfers from less productive users to more productive ones. By utilizing the modified cooperative game, fair sharing of additional net benefits ensures that every water user can expect to receive more net benefits and thereby water users are motivated by incentives to implement a water demand management plan which in turn improves water use efficiency. The results in this chapter are based on the findings of Xiao et al. (2016).

4.1 Cooperative Water Allocation Model

Conflicts among water users always exist in water resources allocation because each water user has its own interests, and these interests normally conflict with one another. Optimization approaches alone may not be able to provide an adequate solution to the conflict. The combination of optimization techniques and game theory could provide a proper path for better conflict resolution in assisting water policy makers and water managers. In this section, a comprehensive water allocation framework at the basin level called the Cooperative Water Allocation Model (CWAM), proposed by Wang et al. (2008a), will be described and then the water demand management plan will be incorporated into the CWAM.

The objective of the CWAM is to allocate limited water resources in an equitable, efficient, and environmentally sustainable manner. It involves two main steps: initial water allocation using priority-based or lexicographic techniques, as described in Chapter 3, and fair reallocation of net benefits (represented in monetary terms) using cooperative game theoretic approaches.

4.1.1 Basin-wide Optimization Model and Net Benefits Functions

Initial water allocation results are considered as inputs to the Hydrologic-Economic River Basin Model (HERBM), along with other inputs such as water demand and benefit functions of all types of uses, the set of stakeholders, coalitions and ownership. The purpose of the model is to estimate the net benefits of various coalitions and search for the water allocation schemes with the maximum net benefits in a basin. The HERBM, as a core component, is formulated as:

$$\max_{Q\in\Omega} \sum_k \sum_t NB_{kt} \tag{4.1}$$

where NB_{kt} represents the net benefits for demand site k during period t; and Ω is the feasible solution space subject to hydrologic and economic constraints. The net benefits function for agricultural (AGR) use is represented by a quadratic function form, while the net benefits function for municipal and industrial (MI) use can be derived from a water price-demand function with constant price-elasticity and choke price.

More specifically, the function for agricultural use is formulated as:

$$\begin{aligned}
NB_{kt} &= b_0(k,t) + b_1(k,t)Q(k,t) + b_2(k,t)Q(k,t)^2 \\
&+\sum_z [b_{3z}(k,t)\mathrm{C}_z(k,t) + b_{4z}(k,t)\mathrm{C}_z(k,t)^2 + b_{5z}(k,t)Q(k,t)\mathrm{C}_z(k,t)] \\
&-Q(k,t)wc(k,t), \\
&= b_2(k,t)[Q(k,t) + \frac{b_1(k,t)}{2b_2(k,t)}]^2 - \frac{b_1(k,t)^2}{4b_2(k,t)} + b_0(k,t) \\
&+\sum_z [b_{3z}(k,t)\mathrm{C}_z(k,t) + b_{4z}(k,t)\mathrm{C}_z(k,t)^2 + b_{5z}(k,t)Q(k,t)\mathrm{C}_z(k,t)] \\
&-Q(k,t)wc(k,t),\ \ \forall k \in AGR
\end{aligned} \tag{4.2}$$

where

$Q(k, t)$ is the total inflow to demand site k during period t (m^3),

$C_z(k, t)$ is the concentration of pollutant z in the total inflow to demand site k during period t,

$wc(k, t)$ is the water supply cost to demand site k during period t ($\$/m^3$),

b_0 to b_{5z} are coefficients derived from a regresion model.

The price-demand function with constant price-elasticity and choke price for MI use is shown as:

$$P(k,t) = \begin{cases} P_0(k,t), & 0 \le Q(k,t) \le Q_0(k,t) \\ [Q(k,t)/\alpha(k,t)]^{1/\beta(k,t)}, & Q(k,t) > Q_0(k,t) \end{cases} \tag{4.3}$$

where

$P(k, t)$ is the price of willingness to pay to retrieve water ($\$/m^3$),

$P_0(k, t)$ is the choke price of the price-demand function ($\$/m^3$),

$Q_0(k, t)$ is the choke quantity of the price-demand function (m^3),

$\alpha(k, t)$ and $\beta(k, t)$ are scale parameter and price elasticity for the water price-demand function, respectively ($\alpha(k, t)>0, \beta(k, t)<0$).

Based on the water price-demand function, the net benefits for MI use can be derived as:

$$\begin{aligned} NB_{kt} &= \int_0^{Q(k,t)} P(k,t)dQ(k,t) - Q(k,t)wc(k,t) \\ &= \int_{Q_0(k,t)}^{Q(k,t)} [Q(k,t)/\alpha(k,t)]^{1/\beta(k,t)} dQ(k,t) \\ &+ P_0(k,t)Q_0(k,t) - Q(k,t)wc(k,t) \\ &= \frac{(1/\alpha(k,t))^{1/\beta(k,t)}}{1+1/\beta(k,t)} [Q(k,t)^{1+1/\beta(k,t)} - Q_0(k,t)^{1+1/\beta(k,t)}] \\ &+ P_0(k,t)Q_0(k,t) - Q(k,t)wc(k,t), \quad \forall k \in MI \end{aligned} \tag{4.4}$$

4.1.2 Cooperative Reallocation Game

When the net benefits for different coalitions are obtained, they serve as the input of the Cooperative Reallocation Game (CRG). In a cooperative game, let $N = \{1, 2, ..., j, ..., n\}$ be the set of stakeholders, and a group of stakeholders working cooperatively is called a coalition and is denoted by S. Each individual stakeholder can be considered as a coalition which contains the individual stakeholder only, while the coalition that contains all stakeholders is called the grand coalition.

The reallocation of net benefits is viewed as a cooperative game (N, v), in which N is the set of stakeholders and v is the characteristic function on N. The notation $v(S)$ represents the maximum aggregated benefits produced by the members of coalition S through internal cooperation, and is calculated by:

$$v(S) = max\sum_{j}\sum_{t} NB_{jt} : j \in S \tag{4.5}$$

Accordingly, the benefits of individual stakeholders and the grand coalition can be expressed as $v(\{1\})$, $v(\{2\})$, …, $v(\{n\})$, and $v(N)$, respectively.

The benefits gained by stakeholders after the reallocation are denoted by a vector $\mathbf{x} = (x_1, x_2, ..., x_n)$. The vector is called an imputation or a solution to a cooperative game. The term $x_j - v(\{j\})$ represents the additional benefits that can be gained from participating in a coalition (also called participation value) for stakeholder j. The imputation must satisfy the conditions of individual rationality, group rationality, and joint efficiency (Young et al. 1982; Tisdell and Harrison 1992):

Individual rationality:

$$x_j \geq v(\{j\}) \quad \forall j \in N \tag{4.6}$$

Group rationality:

$$\sum_{j \in S} x_j \geq v(S) \quad |S| \geq 2 \tag{4.7}$$

Joint efficiency:

$$\sum_{j \in N} x_j = v(N) \tag{4.8}$$

The individual and group rationality conditions ensure that the benefits of a stakeholder or a coalition after reallocation will be no less than the benefits gained by acting on its own. The joint efficiency condition ensures that the solution is feasible for the grand coalition, and the benefits are shared among coalition members as much as possible.

Various solution concepts such as core-based (nucleolus and its variations) (Young et al. 1982; Lejano and Davos 1995; Owen 1995) and non-core-based (Shapley value) (Shapley 1953) concepts are utilized for solving the cooperative game in the CWAM (Wang et al. 2003). Since the computational complexity of solving a cooperative game can be exponentially high with an increase of stakeholder numbers, simplification is necessary to reduce the computational load to a reasonable level; thus, it is useful to classify some individual stakeholders into stakeholder groups based on their types (Wang et al. 2008a).

The water allocation schemes and benefits sharing solutions generated by these solution concepts can be used to facilitate better water allocation decision-making. However, the framework does not provide a mechanism to encourage water users to improve their water use efficiency and conserve water resources. Facing the expanding gap between water supply and demand, fair water allocation alone is not sufficient for future scenarios, and more efforts on the demand side need to be made. Therefore, a demand management plan is specified and incorporated into the CWAM framework, and its associated impacts are assessed.

4.2 Incorporation of Water Demand Management

4.2.1 Water Demand Management Plans

The basic idea of a water demand management plan is that every water user has the potential to improve its water use efficiency, such that certain tasks can be carried out with less water. For instance, less water is needed to irrigate a farm with a drip system or sprinkler technology compared to flood irrigation. Since water use can be reduced while the same level of outputs be maintained, the water demand of each user or user group can be adjusted by a different factor according to its capacities for adjustment, as well as the socioeconomic consequences arising from the changes (Xiao et al., 2014).

An example of a water demand management plan is reducing the demand of water for agricultural and industrial uses by 25% and 10%, respectively, while maintaining the water demand for hydropower, environmental, and domestic uses at the original levels, as depicted in Figure 4.1. The main reason underneath this plan is that there is a great opportunity to reduce water demand from agricultural use, whereas other uses such as municipal use also have potential to reduce their water demand, but the potential may not be as large as that of agricultural use (Xiao et al., 2015a). It is reported that almost 70% of the extracted freshwater is used for irrigation purposes globally (FAO 2013), and the number can be as high as 80% in some regions such as California (Christian-Smith et al. 2012). Irrigation is generally considered as the largest water consumer in a basin. Moreover, irrigation often has the highest priority in regions having a prior rights system based on the doctrine of "first in time, first in rights". Meanwhile, irrigation water use efficiency is generally low, especially when a flood irrigation method is still widely utilized. The conserved water from agricultural uses can be reallocated to meeting urban demands or environmental purposes. A case study in California indicated that 13% of agricultural water consumption is able to be conserved for reallocation to other uses even if its irrigation water use efficiency is already above 73% (Christian-Smith et al. 2012). One can assume that more water can be conserved in agriculture in regions having low water use efficiency.

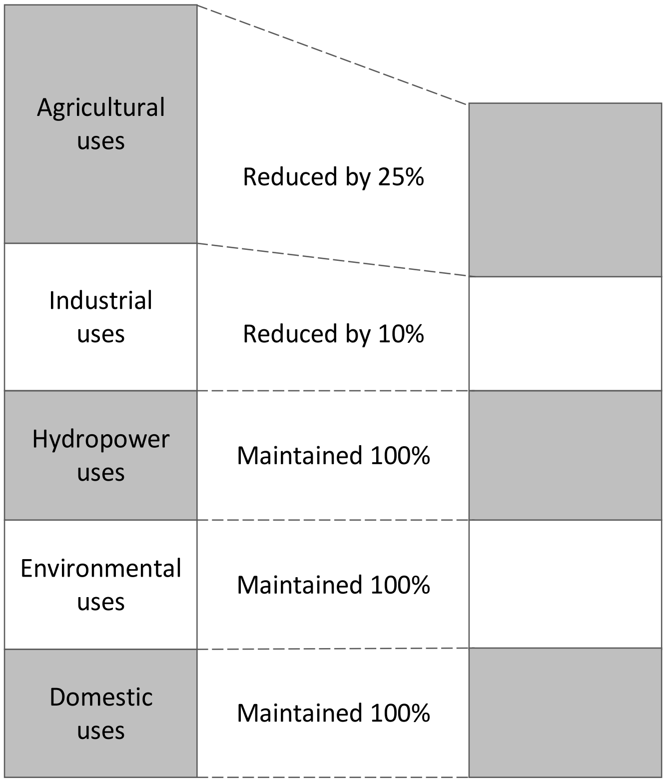


Figure 4.1 An example of a water demand management plan (based on Speed et al. (2013))

4.2.2 Modified Net Benefits Functions

The reduction of water use is the consequence of water use efficiency improvement. Meanwhile, the net benefits function of each user may change along with water use efficiency improvement, and its net benefits from the utilization of water may change accordingly. In this section, the net benefits functions with water use efficiency improvement of each user will be investigated.

A parameter $\rho\ (k, t)$ is used to denote the level of water use efficiency improvement at demand site k during period t. The relation between water use efficiency improvement and level of water reduction is assumed to be linear for the sake of computation load. Then, it can be incorporated into the net benefits function of each user. For agricultural users, its modified net benefits function with efficiency improvement can be formulated as:

$$
\begin{aligned}
NB_{kt} &= b_2(k,t)[Q(k,t)+\frac{b_1(k,t)}{2b_2(k,t)}(1-\rho(k,t))]^2+[b_0(k,t)-\frac{b_1(k,t)^2}{4b_2(k,t)}](1+\rho(k,t))\\
&+\sum_z[b_{3z}(k,t)\mathrm{C}_z(k,t)+b_{4z}(k,t)\mathrm{C}_z(k,t)^2+b_{5z}(k,t)Q(k,t)\mathrm{C}_z(k,t)]\\
&-Q(k,t)wc(k,t)(1+\rho(k,t)),\\
&=b_2(k,t)Q(k,t)^2+b_1(k,t)Q(k,t)(1-\rho(k,t))+b_0(k,t)(1+\rho(k,t))+\frac{b_1(k,t)^2}{4b_2(k,t)}(\rho(k,t)^2-3\rho(k,t))\\
&+\sum_z[b_{3z}(k,t)\mathrm{C}_z(k,t)+b_{4z}(k,t)\mathrm{C}_z(k,t)^2+b_{5z}(k,t)Q(k,t)\mathrm{C}_z(k,t)]\\
&-Q(k,t)wc(k,t)(1+\rho(k,t)),\quad \forall k\in AGR
\end{aligned}
\tag{4.9}
$$

An example of the comparison of agricultural user's net benefits functions under different scenarios of efficiency improvement is depicted in Figure 4.2. It can be seen from the figure that under the assumption of quadratic form for the net benefit function, when the ordinate representing net benefits is fixed, less water is needed with major improvement in comparison to minor or no improvement to produce the same amount of net benefits; while when the abscissa reflecting water consumption is fixed, more net benefits are produced with major improvement.

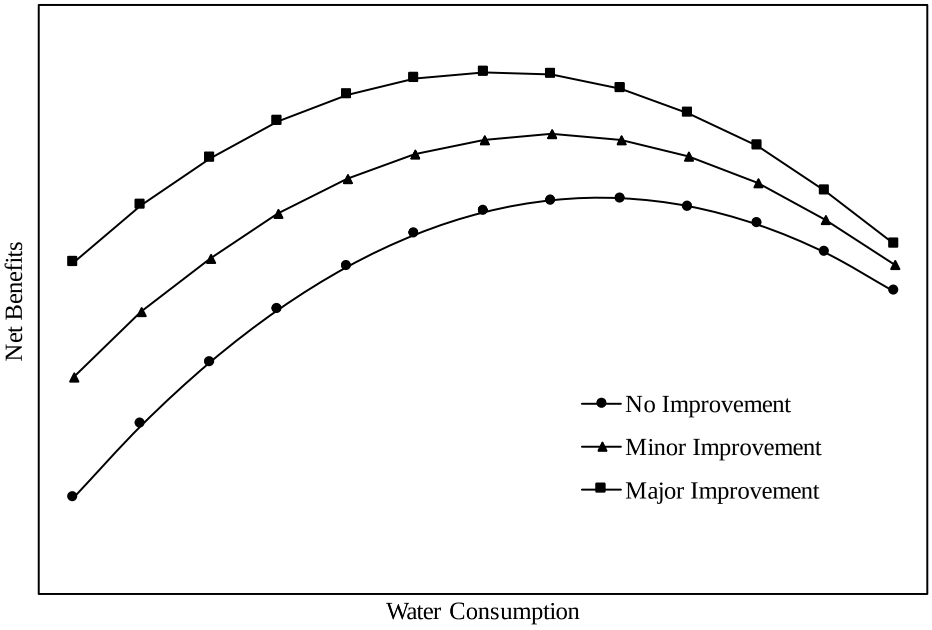


Figure 4.2 An illustrative example of quadratic net benefits functions under different levels of efficiency improvement for agricultural user

Similarly, when the parameter *ρ (k, t)* is taken into consideration for MI users, the modified water price-demand function can be formulated as:

$$\tilde{P}(k,t)=\begin{cases} P_0(k,t)(1+\rho(k,t))^{1/3}, & 0\le Q(k,t)\le Q_0(k,t) \\ [Q(k,t)(1-\rho(k,t))^{1/3}/\alpha(k,t)]^{1/\beta(k,t)}, & Q(k,t)>Q_0(k,t) \end{cases} \tag{4.10}$$

As an example, Figure 4.3 shows a plotting of the comparison of water price-demand functions under different scenarios of efficiency improvement. Accordingly, the modified net benefits function for MI use can be derived as:

$$\begin{aligned} NB_{kt} &= \int_0^{Q(k,t)} \tilde{P}(k,t)dQ(k,t)-Q(k,t)wc(k,t) \\ &= \int_{Q_0(k,t)}^{Q(k,t)} [Q(k,t)(1-\rho(k,t))^{1/3}/\alpha(k,t)]^{1/\beta(k,t)} dQ(k,t) \\ &+P_0(k,t)(1+\rho(k,t))^{1/3}Q_0(k,t)-Q(k,t)wc(k,t)(1+\rho(k,t)) \\ &= \frac{\left[(1-\rho(k,t))^{1/3}\big/\alpha(k,t)\right]^{1/\beta(k,t)}}{1+1\big/\beta(k,t)}[Q(k,t)^{1+1/\beta(k,t)}-Q_0(k,t)^{1+1/\beta(k,t)}] \\ &+P_0(k,t)(1+\rho(k,t))^{1/3}Q_0(k,t)-Q(k,t)wc(k,t)(1+\rho(k,t)), \quad \forall k\in MI \end{aligned} \tag{4.11}$$

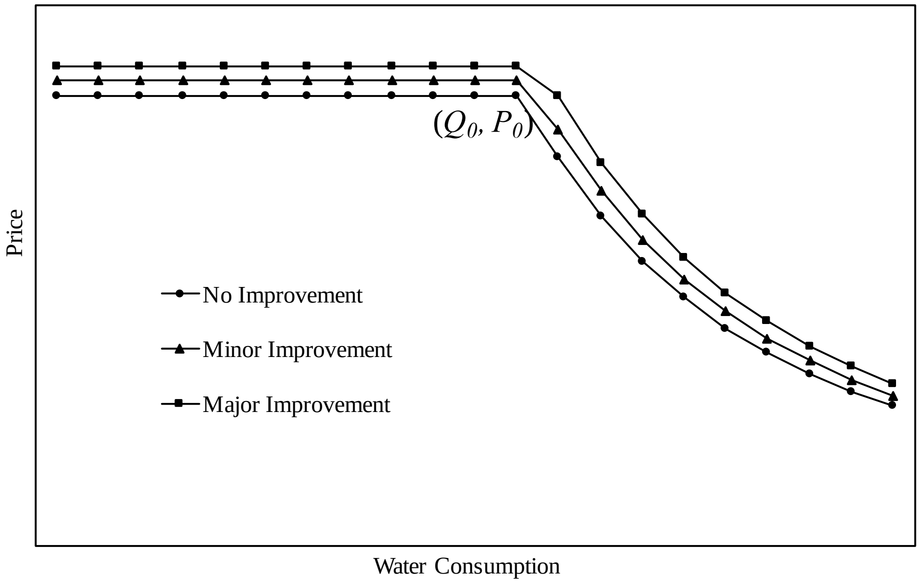


Figure 4.3 An illustrative example of water price-demand functions under different levels of efficiency improvement for MI user

4.2.3 Modified Cooperative Reallocation Game

When a demand management plan is implemented, it may have different impacts on different users. For example, the user who reduces its water use may gain less benefits from the utilization of water, while the user who receives more water may produce greater benefits. As a matter of course, the aggregated benefits of the coalitions may also change accordingly. The economic impact on a water reduced user might also be positive because of the efficiency improvement. The aggregated benefits of coalitions with a water demand management plan may be represented as $\tilde{v}(\{1\})$, $\tilde{v}(\{2\})$, …, $\tilde{v}(\{n\})$, $\tilde{v}(S)$, and $\tilde{v}(N)$. Then, a new cooperative game $(N, \tilde{v})$ is formed.

All three conditions of individual and group rationality and joint efficiency must still be satisfied for solving the new cooperative game. Moreover, it is necessary to ensure that no coalition will receive less benefits than the benefits gained from cooperative reallocation without a demand management plan; otherwise, some users may not have incentives to implement the water demand management plan. Therefore, the conditions of individual and group rationality should remain the same as equations (3.6) and (3.7), while the condition of joint efficiency is modified as:

$$\sum_{j \in N} x_j = \tilde{v}(N) \tag{4.12}$$

The core-based and non-core-based solution concepts are applied to the modified cooperative game, and new results can be obtained and be assessed. The structure of the Cooperative Water Allocation Model with a water demand management plan is shown in Figure 4.4.

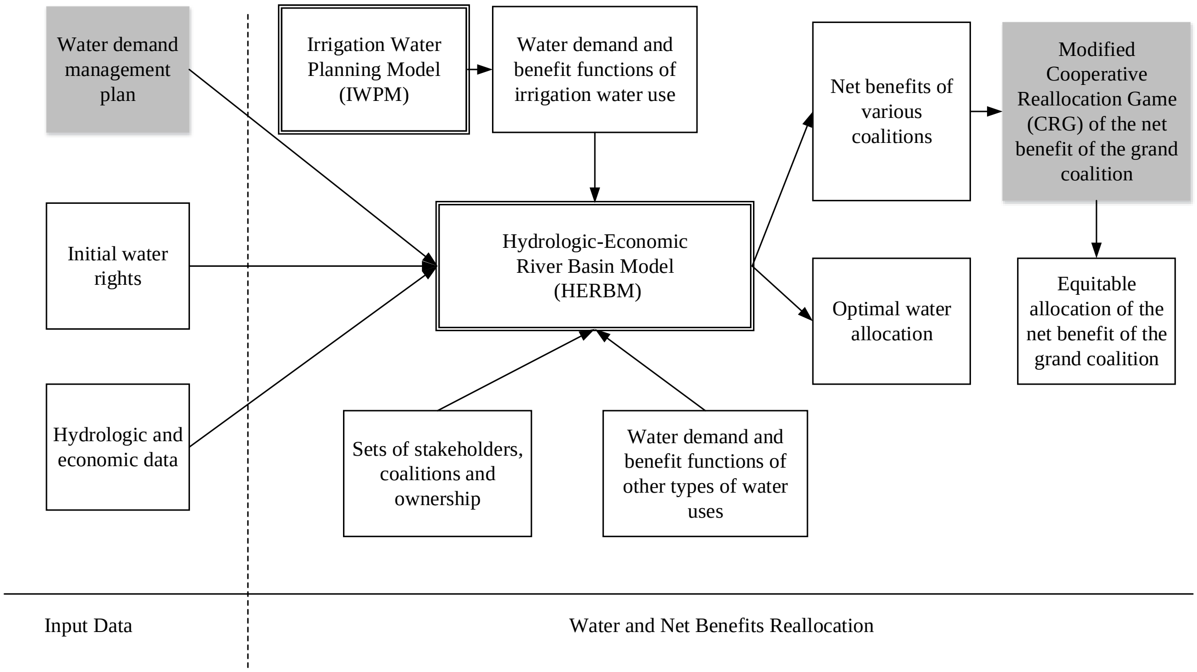


Figure 4.4 Structure of the Cooperative Water Allocation Model (CWAM) with a water demand management plan (based on Hipel et al. (2013))

4.3 Illustrative Case Study

In this section, the illustrative case described in Section 3.3 is used to evaluate the impact of a water demand management plan on the economic benefits for water users. The network is shown in Figure 4.5. The economic input data can be seen in Appendix A.

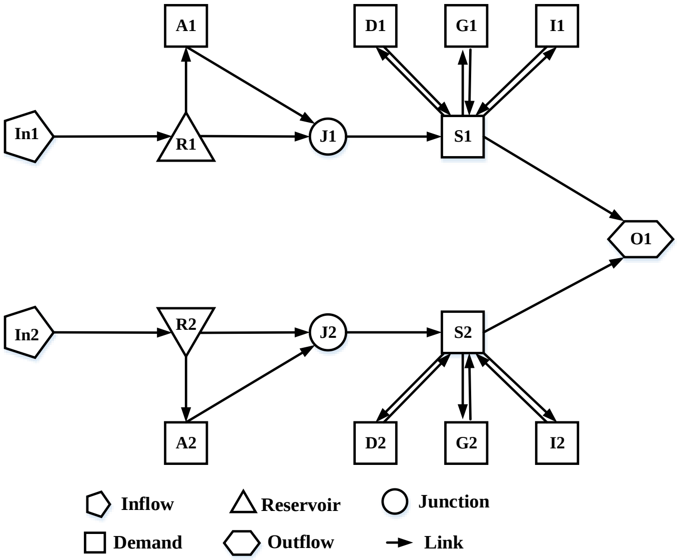


Figure 4.5 The network of the illustrative case study

4.3.1 Specification of Water Demand Management Plans

In this case, it is assumed that agricultural users' demand will be reduced by different percentages, such as 0% (baseline), 5%, and 10%, while other users maintain their original water demand. Once all the users are satisfied, then no user is willing to participate in a coalition; therefore, there will be no need to reduce agricultural users' demand further. It should also be noted that the results in this section are based on the original net benefit functions.

4.3.2 Results and Discussions

An uptrend can be observed for total net benefits from both initial water allocation and optimal reallocation as the level of reduction increases, as depicted in Figure 4.6. More specifically, when the PMMNF method is utilized for initial allocation, about 1,004 million dollars can be produced from initial allocation without any reduction, and it is increased to about 1,191 million dollars from optimal reallocation, which means an extra 187 million dollars can be produced through a grand cooperation. Along with the increased level of reduction, more net benefits can be generated, and it reaches up to about 1,284 million dollars when the level of reduction goes up to 30%. The increase demonstrates that not only is cooperation among water users more beneficial, but the demand management plan also is. Moreover, this increase gives incentives for water users to implement the demand management plan, as long as the additional net benefits are shared fairly among users so that everyone can receive more benefits.

It is also observed that the gaps between the total net benefits from initial allocation and from optimal reallocation become smaller along with the increased level of reduction. The main reason for this is the conserved water from agricultural users is distributed to city users located downstream during the initial allocation. Since city users have a higher productivity than agricultural users do, as is normally the case, the overall benefits from initial allocation for the entire basin is growing rapidly, while the growth of total net benefits from optimal reallocation is more moderate. When the level of reduction reaches a certain percentage, all agricultural, domestic, general, and industrial users are fully satisfied; thus, there is no need for reallocation. This result demonstrates that water transfer from low productive users to high productive users can generate more beneficial outcomes.

A similar uptrend can be observed for total net benefits from initial allocation and from optimal reallocation when the LMWSR method is utilized for initial allocation, as depicted in Figure 4.7. However, the increase is not as obvious as that from the PMMNF method. This is because the LMWSR method generates more evenly-spread water shortage ratios so that water is allocated in a more economically efficient manner.

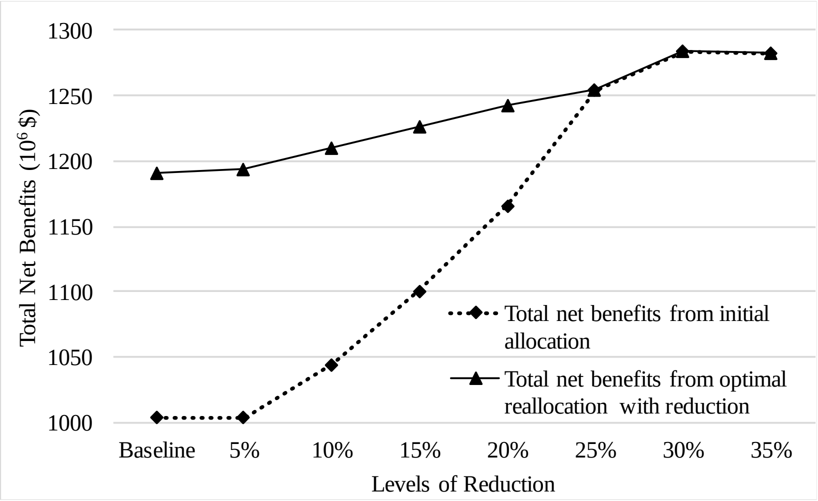


Figure 4.6 Total net benefits from initial water allocation and optimal reallocation for the grand coalition under different levels of reduction when initial water allocation is obtained from the PMMNF approach

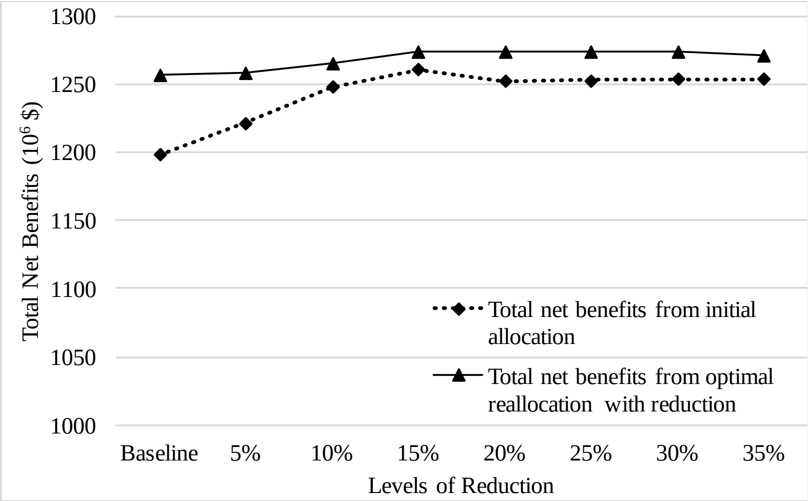


Figure 4.7 Total net benefits from initial water allocation and optimal reallocation for the grand coalition under different levels of reduction when initial water allocation is obtained from the LMMSR approach

The fact that cooperation is more beneficial is easy to understand. The key problems are how to fairly allocate the total net benefits among users, and how to evaluate the contribution of water users in implementing a demand management plan. For instance, the total net benefits without the plan are about 1,191 million dollars when the PMMNF method is utilized, as shown in Figure 4.6, and this is the total net benefits of the grand coalition. Similarly, the total net benefits of the grand coalition reach about 1,243 million dollars with a 20% reduction. Therefore, the question is how to share the 1,243 million dollars among stakeholders such that every stakeholder will get no less benefits than it can get without a 20% reduction.

By applying the aforementioned modified cooperative game, the sharing of net benefits (participation value) for each stakeholder in the grand coalition can be estimated by various solution concepts. It should be noted that domestic, general, and industrial users who share the same source of water are grouped into one single stakeholder, such as City 1, to reduce the computational complexity. Figure 4.8 shows an example of the participation value with a 20% water reduction and the PMMNF is utilized for initial allocation. As can be seen from Figure 4.8, A2 and City 2 are allocated more net benefits than A1 and City 1 under the solution concepts of nucleolus, weak nucleolus, and Shapley value. This is because A2 is the main conserver of water, while City 2 is the main contributor of additional net benefits.

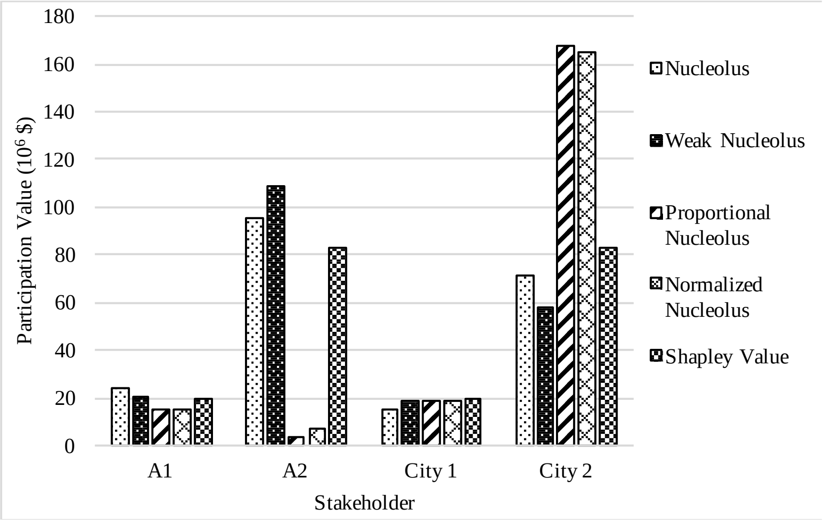
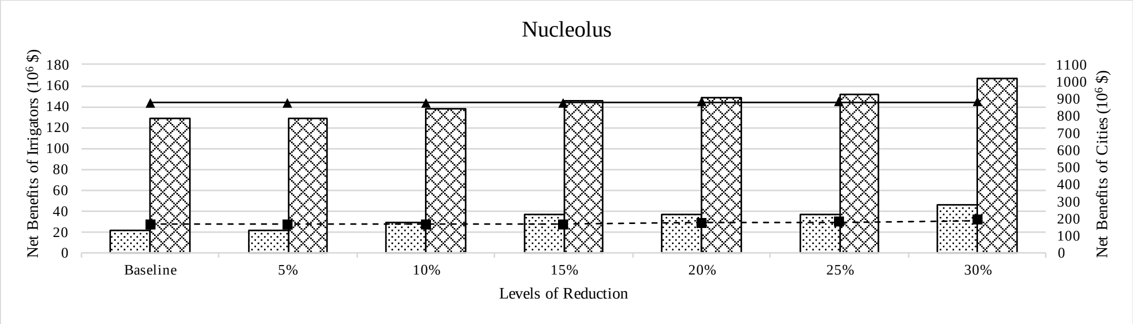
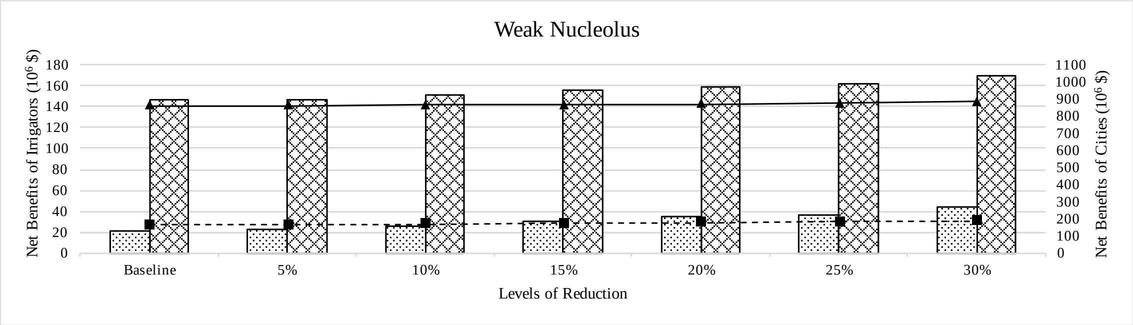
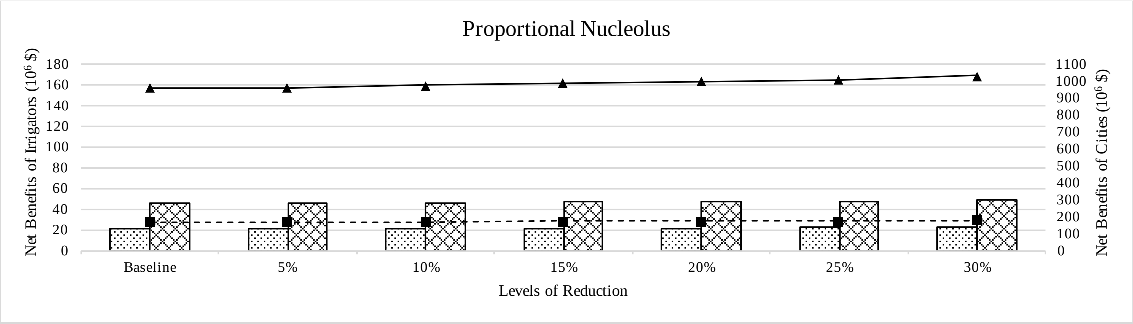


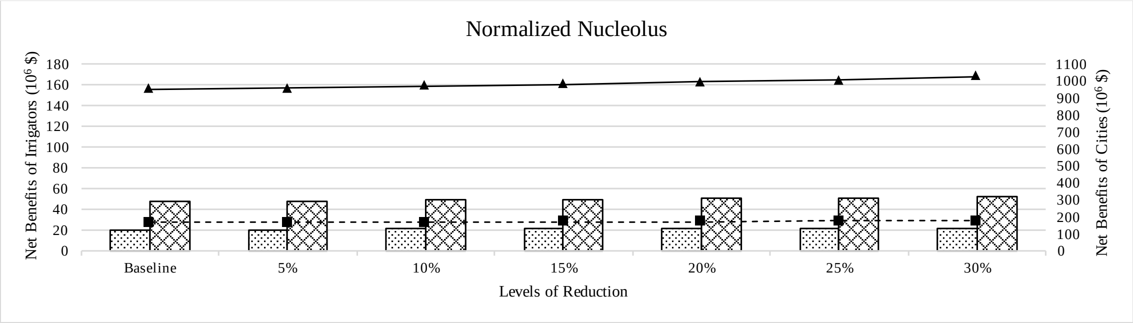
Figure 4.8 Participation value for stakeholders under various solution concepts for a 20% reduction scenario in which the PMMNF method is utilized for initial water allocation

It is important that no stakeholder will receive less net benefits with a plan than the net benefits it can get without a plan. A summary of the net benefits gained from the modified cooperative game for stakeholders with different levels of reduction under different cooperative solution concepts is depicted in Figure 4.9. The bar charts represent the total net benefits of irrigators (A1, A2), and line charts denote the total net benefits of city users (City 1, City 2). It can be seen that, compared to the baseline results, all stakeholders will receive more net benefits under the cases with water reduction. The more percentage of reduction, the more net benefits can be shared. It seems that under solution concepts such as nucleolus and weak nucleolus, more additional net benefits are shared by irrigators than by city users; while under proportional nucleolus and normalized nucleolus concepts, city users share more additional net benefits than irrigators. Under the concept of Shapley value, both irrigators and city users have a moderate growth in their net benefits. Overall, every stakeholder can expect an increase in net benefits when the demand management plan is carried out. The results also demonstrate the motivation for water users to implement the water demand management plan.


Nucleolus
Net Benefits of Irrigators (10^6 $)
180
160
140
120
100
80
60
40
20
0
Net Benefits of Cities (10^6 $)
1100
1000
900
800
700
600
500
400
300
200
100
0
Baseline
5%
10%
15%
20%
25%
30%
Levels of Reduction


Weak Nucleolus
Net Benefits of Irrigators (10^6 $)
180
160
140
120
100
80
60
40
20
0
Net Benefits of Cities (10^6 $)
1100
1000
900
800
700
600
500
400
300
200
100
0
Baseline
5%
10%
15%
20%
25%
30%
Levels of Reduction


Proportional Nucleolus
Net Benefits of Irrigators (10^6 $)
180
160
140
120
100
80
60
40
20
0
Net Benefits of Cities (10^6 $)
1100
1000
900
800
700
600
500
400
300
200
100
0
Baseline
5%
10%
15%
20%
25%
30%
Levels of Reduction


Normalized Nucleolus
Net Benefits of Irrigators (10^6 $)
180
160
140
120
100
80
60
40
20
0
Net Benefits of Cities (10^6 $)
1100
1000
900
800
700
600
500
400
300
200
100
0
Baseline
5%
10%
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25%
30%
Levels of Reduction

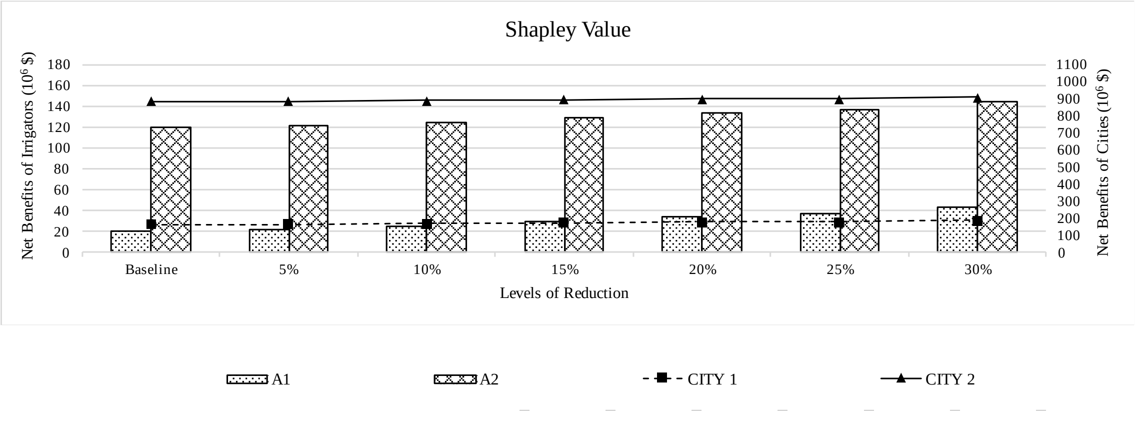

Figure 4.9 Comparison between total net benefits gained from the modified cooperative game for stakeholders with different levels of reduction and baseline results under various solution concepts when initial allocation is obtained from the PMMNF approach

When the net benefits functions with efficiency improvement are applied to the model, new allocation schemes and net benefits results can be obtained. The total net benefits will witness a further increase compared to the results with original net benefits functions, as shown in Figure 4.10. In terms of the total net benefits for each stakeholder after cooperative reallocation, its pattern is quite similar to the results shown in Figure 4.6. This outcome indicates that more net benefits can be produced and shared by stakeholders.

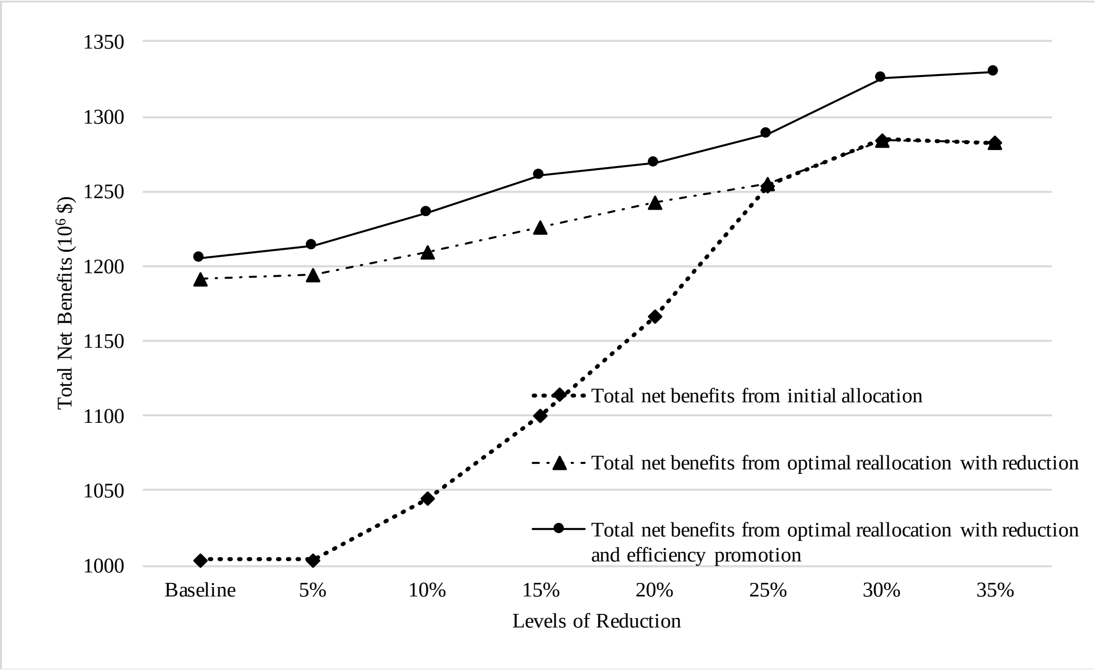

Figure 4.10 Total net benefits from allocation under different scenarios in which different levels of reduction and efficiency promotion are considered and initial allocation is obtained from the PMMNF method

4.4 Summary

In this chapter, a water demand management plan is specified and incorporated into the Cooperative Water Allocation Model (CWAM) to investigate its impact on water users. The results demonstrate several advantages of a water demand management plan. Firstly, more aggregated net benefits for the grand coalition can be yielded through water transfer from less productive users to more productive users and cooperation among water users. Secondly, every stakeholder is able to gain more net benefits by means of a modified cooperative game to fairly allocate the additional net benefits, which provides motivation for water users to carry out a demand management plan. Finally, water demand management can play an important role in alleviating water stress facing humanity in the near future, and prevent more water conflicts from happening. It can thus be of great assistance in some arid and semi-arid regions, especially areas with low water productivity.

Chapter 5

Agent-based Modeling of Water Demand Management for Maximizing Benefits

An agent-based modeling approach is proposed to simulate water users' behavior for water demand management in a river basin. In this procedure, each agent controls his or her own strategy regarding whether or not to conserve water or consume more water in order to achieve a better economic return based on an initial allocation scheme. The effects of agents' behaviors on their own economic returns and the aggregated impacts of individual behavior on the system are investigated. A positive incentive given to water conservers encourages agents to implement water demand management strategies, which in turn improve water use efficiency. A case study using this new agent-based approach reveals that agricultural users are the main contributors to water conservation. Compensation given to water conservers more than covers the benefit loss from less water consumption while other users gain benefits from the utilization of the conserved water. The results also indicate that the implementation of water demand management strategies is beneficial for the overall system from both economic and ecological perspectives. A comparison between the centralized approach in Chapter 4 and the decentralized method developed in this chapter is presented using the same case study.

5.1 Motivation for Agent-based Model

In Chapter 4, the incorporation of a specific water demand management plan into the cooperative water allocation model (CWAM) has demonstrated the advantages of the plan. However, there are several assumptions to the plan. Firstly, the capacities of agricultural users are assumed to be the same in the specified water demand management plan. In fact, each user may have different capacities to reduce its water demand because of the diversity of constraints. It is important to take the heterogeneity of capacities for water conservation into consideration in a water demand management problem. Secondly, a centralized process is utilized for the application of the specified water demand management plan, in which all users are assumed to comply with the plan willingly. However, the willingness for water conservation may vary from user to user. In addition, water users' willingness can be adaptive in a complex system. When water demand management studies on water consumption involves the perspective of users, it becomes more of a decentralized problem than a centralized one. Thirdly, perfect information exchange is assumed in the allocation process, which means that every user knows the water consumption and net benefits of itself as well as other users. In the real world, however, this assumption is very unlikely to be achieved.

Agent-based modelling techniques can partially relax these assumptions since they possess the following characteristics: (1) they are an individual-driven modelling approaches, in which each agent has its own behavioral rules. Therefore, they can handle the problem of heterogeneity; (2) they are adaptive because each agent can change its behavioral rules according to the information it receives from other agents and the environment; and (3) perfect information exchange is not a necessary requirement.

Water resources management is a relatively new field for ABM. However, because of the capability of ABM to investigate dynamic complex systems, a number of studies on the application of ABM can be observed. For example, Chu et al. (2009) utilized ABM techniques to evaluate the responses of different users in Beijing, China, in the face of a series of water supply and demand management policies such as financial rebate for replacing low-efficient appliances by high-efficient ones. Kanta and Zechman (2013) investigated the effectiveness of water conservation-based strategies using ABM methods in which users' water demand level is influenced by policy makers' selection of water conservation strategies and other users' choices. Giacomoni et al. (2013) examined dynamic interactions among water use, land use, and urbanization progress within a complex adaptive system framework in which ABM is utilized to simulate the water use behavior of each household. Other interesting research topics using ABM technique include: water demand estimation (Athanasiadis et al., 2005), water sharing problems (Yang et al., 2009; Yang et al., 2012; Guiliani and Castelletti, 2013; Giuliani et al., 2014), and common pool resources management (Schlüter and Pahl-Wostl, 2007; Bristow et al., 2014). Berglund (2015) provides a comprehensive review of the employment of ABM in water resources management.

However, very few studies of ABM can be found in water demand management, and significant research advances could be accomplished in this subdomain. Because of varying capacities and willingness to conserve water by different users, ABM constitutes a well-suited technique for simulating water users' actions regarding water conservation and their interactions within the context of water demand management. Accordingly, an agent-based model is proposed in this chapter to simulate changes in water users' behavior, and to investigate individual and aggregated impacts on the system as a whole. This work possesses the following novelties: (1) The proposed model is a more general framework for water demand management in comparison to the existing research on estimating demand-price elasticities, which normally have a site-specific dependence. (2) water demand management is studied from a decentralized perspective, which considers the willingness and capability of different users in different ways. The involvement of individual decisions can greatly promote public participation and acceptance. (3) water demand management is considered in the context of basin-wide planning and management, thereby enabling the integration of demand side and supply side management. Therefore, water efficiency and productivity are emphasized.

5.2 Agent-based Modeling for Water Demand Management

A typical agent-based model possesses four main components (Macal and North, 2010; Bristow et al., 2014): (1) a set of agents in which each agent having attributes to distinguish it from other agents; (2) an environment within which agents can interact with it as well as other agents; (3) methods that agents use to update their attributes; and (4) an interaction mechanism that controls when and how to interact, and with whom.

In an agent-based model for water demand management, each water user can be defined as an autonomous computational agent, structured as in Table 5.1. Each agent's strategy is to decide whether to conserve water or consume more water, and how much water to conserve or consume, based on the initial allocation this agent possesses.

Table 5.1 Agent structure of the agent-based model

Agent Type	Attributes	Decision Rules
Proactive agent	1. Level of water consumption; 2. Level of net benefits represented by net benefits functions.	1. After receiving a value of parameter given by the coordinator, each agent calculates the net benefits generated from water utilization and compensation or cost value; 2. An agent chooses to conserve water only if the compensation value is greater than net benefits losses, or selects to consume more water if the net benefits produced from extra water utilization are more enough to cover the cost charged; 3. An agent adjusts the level of water consumption to maximize his individual total economic returns by solving an individual optimization problem.
Reactive agent	1. Level of water consumption	1. Reactively respond to the actions of proactive agents.
Coordinator agent	1. Overall net benefits; 2. Total imbalance value.	1. For each given value of parameter, monitor the decisions of individual agents and calculate the system-wide net benefits and total imbalance between the compensation and cost values; 2. Update the value of parameter until the system-wide net benefits cannot be improved and total imbalance cannot be decreased.

If an agent decides to conserve water (hereinafter referred to as a water conserver), compensation will be provided to the agent; likewise, one has to pay a proper cost if he or she chooses to consume more water (called a water consumer). An agent will conserve water only if the compensation value is greater than the net benefits loss from water conservation; otherwise, his initial rights will be maintained. Similarly, an agent will retain his initial rights unless the net benefits gained from extra water consumption cover the paid cost. In other words, no agent will receive fewer net benefits than the net benefits from the initial allocation. In some situations, one agent's strategy could be affected by other agents' decisions. For instance, water consumers cannot obtain extra water if there is no water conserver. Therefore, one should monitor behavioral changes regarding water consumption of agents and estimate the corresponding economic returns for agents within an agent-based framework.

5.2.1 Individual Optimization Problem

Within an agent-based framework for water demand management, each water user is defined as an agent having two main attributes: water consumption and net benefit function. An optimization problem is presented for each agent as the method to update his or her attributes. In the optimization problem, an agent updates his water consumption based on the initial water allocation to maximize the economic returns from water usage over the planning periods. In addition to updating water consumption using the optimization problem, an agent's net benefit function will also be affected along with water use efficiency improvements resulting from the implementation of water demand management, as discussed in Section 4.2.2.

All water users in a basin are categorized into two main types of agents: proactive and reactive agents. Proactive agents are those who can update their water consumption actively, such as agricultural, domestic, and industrial users; on the other hand, reactive agents represent those who can only reactively respond to the actions of proactive agents, but their interests will be reflected in the constraints. For instance, a specified level of instream flow is considered as the minimum demand for ecological use.

5.2.1.1 Objective for Proactive Agents

As mentioned earlier, each agent's main objective in his or her own mind is to obtain economic returns over the planning periods as much as possible, either from extra water utilization or compensation. Let *AGT* be defined as a set of agents, and $AGT = \{1, 2, \ldots, i, \ldots, m\}$. For the *i*th agent, its individual optimization problem can be formulated as follows:

$$\max_{Q\in\Omega} \sum_{t} \left(NB_{it} + INC_{it} - C_{it} \right)$$

$$subject\ to\ \begin{cases} h_i(Q) = 0 \\ g_i(Q) \geq 0 \\ Q \geq 0 \end{cases} \tag{4.1}$$

where Q reflects water consumption; NB_{it} represents the net benefits produced from water utilization for agent *i* during period *t*, which is calculated by its net benefits function; INC_{it} refers to the incentive values for agent *i* during period *t;* C_{it} means the cost of achieving water conservation for agent *i* during period *t*; and $h_i(Q) = 0$ and $g_i(Q) \geq 0$ stand for the equality and non-equality local constraints for agent *i*, respectively. The symbol Ω is used to signify the feasible region of the optimization problem subject to applicable constraints.

The estimation of net benefit functions of agents should consider the different characteristics of agents, and can be represented using different forms, such as quadratic function form or derived from a water price-demand function. More details on net benefit functions for different agents are provided in Section 4.1.1 and 4.2.2.

The incentive value for each agent can be calculated by using an incentive function shown as:

$$INC_{it} = bc(i,t) * [Q_{ini}(i,t) - Q(i,t)] \tag{4.2}$$

where $bc(i, t)$ reflects the benefit or cost per unit of water conserved or consumed, respectively, for agent *i* during period *t*; and $Q_{ini}(i, t)$ refers to the initial water allocation for agent *i* during period *t*. The value of the incentive function is positive when an agent consumes less water than its initial allocation, and represents a compensation value to the agent. If the compensation value is greater than the net benefits loss and the cost, this agent is expected to obtain greater returns from water conservation. Therefore, it can be assumed that this agent will have incentives to implement water demand management strategies.

5.2.1.2 Constraints

Each agent seeks to maximize the economic benefits under certain hard constraints and/or soft restrictions. These constraints can be categorized into three main types: physical, policy, and system control constraints, as discussed in Section 3.2.1. However, not all constraints are applied to every agent. Only constraints related to a specific agent would be used to construct the solution space for that agent. For example, for an industrial agent, Equations (3.2) to (3.8) except Equation (3.5) are applicable.

5.2.2 Coordination Procedure

After specifying how each agent updates his or her behavior to achieve better economic returns individually, the next step is to design how they interact with one another or the environment. In this research, the agents interact in an indirect manner, whereby all agents respond to a parameter, which reflects the benefit or cost per unit water conserved or consumed, respectively, sent out by a coordinator (or policy maker) agent. A coordination procedure is required because without coordination some agents will attempt to obtain as much water as possible, which could result in a violation of the mass balance constraints in which the total allocated water to agents exceeds the available water supply. Although this violation can be interpreted as imported water from outside of the system or an indicator of water conservation objectives from a planning perspective, it should be avoided, or minimized as much as possible.

Yang et al. (2012) demonstrated that using water price as a signal for a water sharing problem could lead to an equilibrium status in which all available water is allocated and all users are satisfied with the allocation. In this work, a similar parameter reflecting the benefit or cost per unit water transferred is utilized as a signal to guide agents in making individual decisions. However, the objectives of this research are not only to redistribute water resources, but also to calculate the compensation needed for water conservers and the costs paid by water consumers. Then the imbalance of compensation and cost values is minimized to have a self-sustaining system. Moreover, in contrast to Yang et al.'s (2012) work, initial allocation schemes instead of water permits are used, because water permits only indicate how much water one should get, and not how much one actually obtains, especially under water shortage situations. The actual amount of water under one's possession provides a more realistic meaning for water demand management. In addition, more complicated and realistic constraints for agents are considered in this research. More specifically, water loss during the transportation from one node to another is commonly observed in reality, and this loss is taken into account in Equation 3.2; return flow at a particular node from which water supply is provided to demand sites is excluded from the available supply at that node in Equation 3.8.

The coordinator will monitor the behavior changes of each agent and the performance of the overall system arising from these individual alterations in behavior, and decide when to terminate the coordination. These behavior changes as expressed by changes in water consumption would have an effect on the net benefits produced from water utilization, and compensation or cost values for all of the agents. These changes can be further investigated in addition to the aggregated impact on the system.

The coordination procedure controlled by the coordinator, shown as a flow chart in Figure 5.1, starts by checking whether all the agents are fully satisfied during the initial allocation. If not, each agent makes individual decisions on whether or not to conserve water or consume more water and how much to conserve or consume under a given parameter *bc(i, t)*. After individual decisions have been taken, the coordinator will assess the overall system performance by calculating the total imbalance of compensation and cost values, total net benefits, and the net benefits increment in comparison to the results in the previous iteration. The total net benefits are compared to that from the initial allocation in the first iteration. If the benefit increment is larger than a predefined tolerance value (for instance, one thousandth of the total net benefits), then the system performance can still be improved, and another iteration is required with an updated parameter. Otherwise, the coordination process will be terminated, and the results of water allocation, net benefits, compensation or cost values for all of the agents, and the aggregated results for the system can be generated and interpreted.

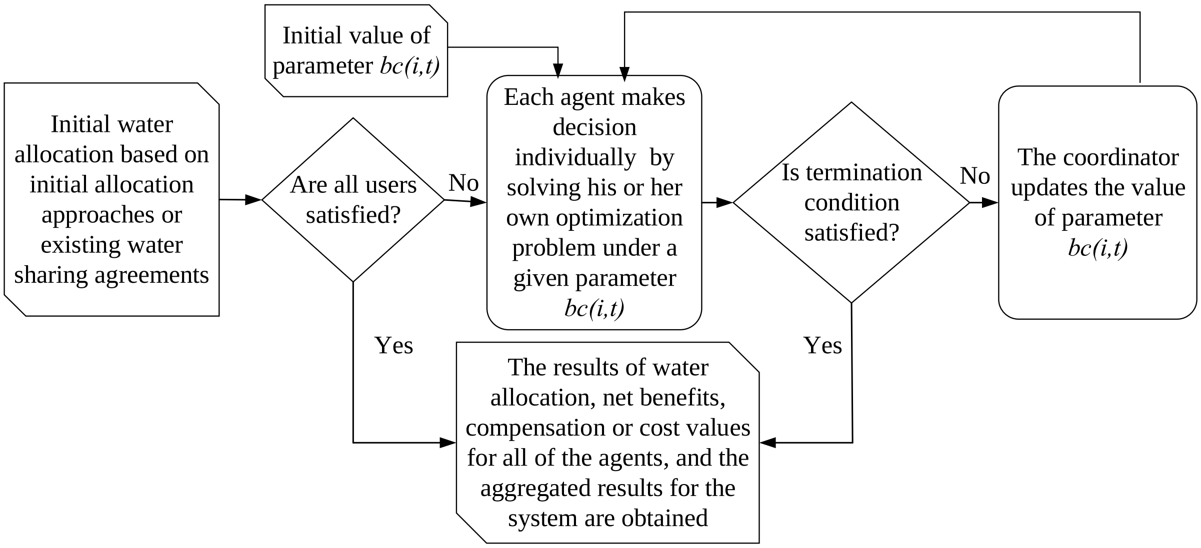

Figure 5.1 Coordination procedure

5.3 Illustrative Case Study

In this section, the behavior of different water users in a simplified basin network, reflecting an actual situation depicted in Figure 5.2, is simulated using the proposed agent-based model to investigate the impact of water demand management.

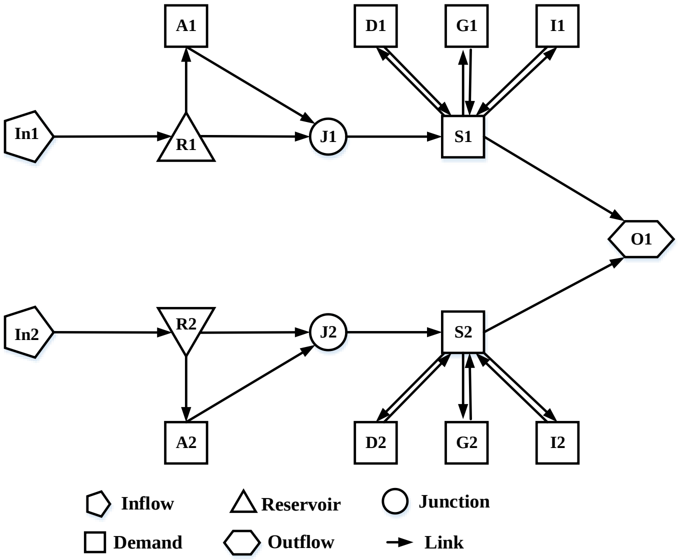

Figure 5.2 The network of the case study

5.3.1 Scenarios of Study

As aforementioned, an initial water allocation process is performed prior to the implementation of water demand management strategies to reflect social equity. The results of the initial allocation constitute a baseline case for this study in which no water demand management strategies are implemented. Therefore, the impact of different strategies can be observed, analyzed, and compared. It is assumed that different agents possess different water conservation limits due to technical and/or social-economic restrictions. For instance, an agent who decides to adopt drip irrigation will normally have greater potential than an agent who chooses to use flood irrigation. Therefore, a series of scenarios are designed based on conservation limits. More specifically, several percentages, such as 10%, 20%, and 30%, are specified as the maximum conservation an agent can achieve.

5.3.2 Impact Analyses

The impacts of the implementation of water demand management strategies can be analyzed from two perspectives: individual and aggregated viewpoints. The individual effects on each agent are discussed in Section 4.3.2.1 while the aggregated impacts on the system are explained in Section 4.3.2.2.

5.3.2.1 Individual Agent's Decisions and Economic Effects

With the implementation of water demand management strategies in a water system, the individual decisions made by different agents over different values of the parameter *bc* can be firstly observed. Figure 5.3 depicts the detailed water rights changes by agents under the scenario of a 20% conservation limit, while Figure 5.4 shows the net benefits changes by agents under the same scenario. It should be noted that the value of net benefits shown in Figure 5.4 are the sum of the net benefits gained from water utilization and compensation or cost. In fact, the patterns observed under other scenarios are similar to the results shown in Figure 5.3 and Figure 5.4.

Consider the case of agricultural use given as A1 in Figure 5.2. The water flow towards A1 from R1 minus the water loss in the conduit is the effective inflow or water available for utilization by A1, and should be no more than A1's demand during a particular time period. By subtracting the amount of water consumed by A1, the remainder is the return flow from A1 and is available to other downstream agents. Certainly, the water flow from R1 to A1 should not exceed the maximum capacity of the conduit, but should be more than a minimum requirement scheduled by policy makers or administration agents.

As can be seen in Figure 5.3, two agents (A1 and A2) choose to conserve water until they reach their limit at $bc = 0.1$. However, their net benefits are expected to grow along with the increase in the value of the parameter *bc*, mainly because of the increase of compensation value, as indicated in Figure 5.4. This increase results in the growth of a total imbalance between compensation and cost values as shown by the dotted line in Figure 5.5.

On the other hand, agents G2 and I1 are willing to consume extra water, as shown in Figure 5.3, and can expect more economic returns from the additional water utilization even though they have to pay a cost. As indicated in Figure 5.4, the maximum economic return for both agents occur at $bc = 0.1$, and thereafter starts to decrease due to the increase of cost. However, from Figure 5.3, one can see that I1 reduces its water consumption starting at $bc = 0.7$. This implies the benefits gained from additional water utilization are not enough to cover the cost. From the bottom plot in Figure 5.3, one can observe that agent G1 also prefers to consume more water but only by a slight amount. Other agents select to retain their initial water rights, and procure no extra net benefits. Among these agents, D1 and D2 choose not to consume more water because they are already fully satisfied during the initial allocation; therefore, their net benefits changes are omitted in Figure 5.4. It should be noted that since D1, I1, and G1 share the same supply node in the network, the return flow from one agent to the supply node is not available for other agents.

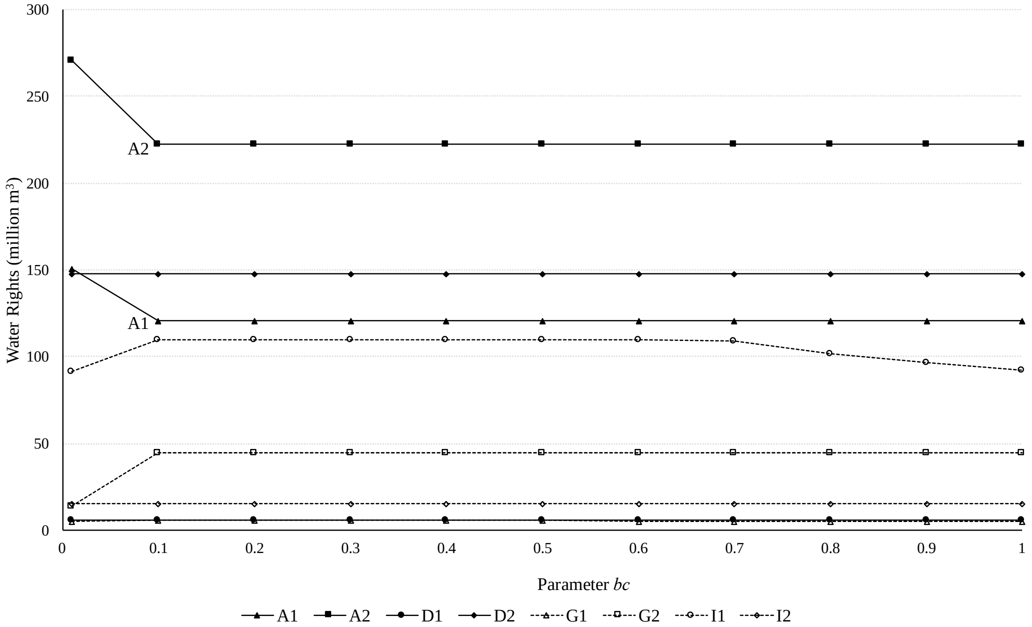

Figure 5.3 Water rights changes by agents over different values of the parameter *bc* under the scenario of a 20% conservation limit

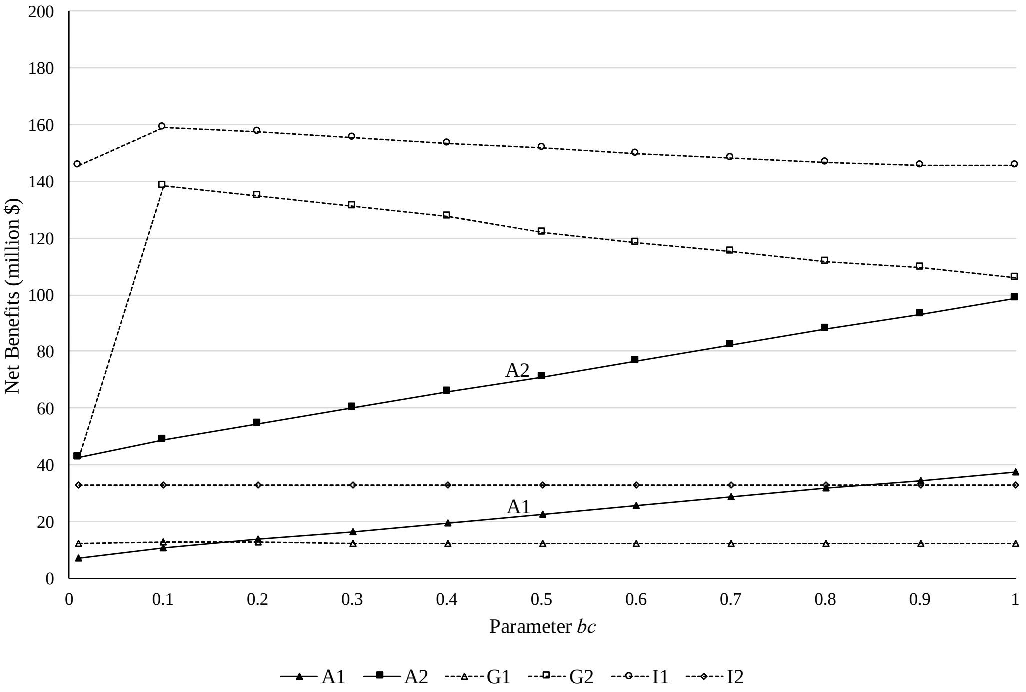

Figure 5.4 Net benefits changes by agents over different values of the parameter *bc* under the scenario of a 20% conservation limit

5.3.2.2 System Performance

The individual decisions made by agents may have different impacts on the system performance. One example is the increasing total imbalance resulting from the growing compensation to A1 and A2 even though they stop conserving water due to the conservation limit. The total imbalance of net benefits transferred is calculated by summing up all compensation values given to water conservers and all cost values paid by water consumers. A positive imbalance indicates that the compensation is larger than the cost, and can be interpreted as an infusion from outside of the system to make the strategies feasible. The infusion is expected to be as small as possible.

As affected by the increasing total imbalance, the total net benefits determined by adding up the individual net benefits of all agents are continuously growing as well, as shown by the top curve in Figure 5.5. If the infusion is deducted from the total net benefits, the remainder represents the economic benefits produced by all agents in the system. From Figure 5.5, one can see that the total net benefits produced by the system itself will reach its peak at *bc = 0.1*. This is also the point at which the coordination process stops, and the compensation to water conservers, cost paid by water consumers, net benefits for each agent, total infusion required, and total net benefit of the system itself are determined.

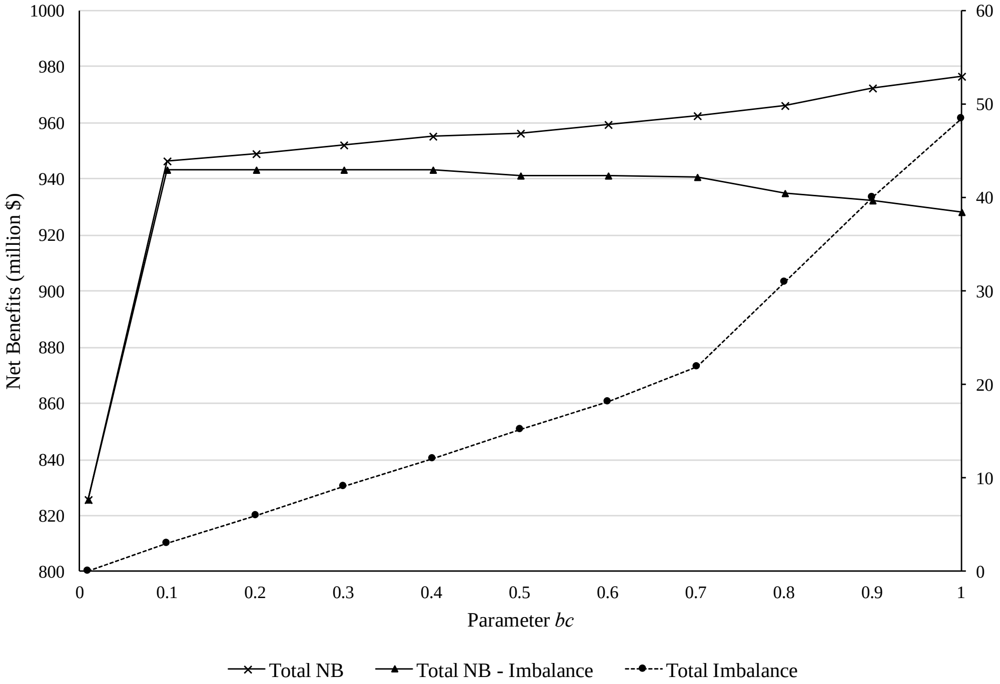

Figure 5.5 Total net benefits changes over different values of the parameter *bc* under the scenario of a 20% conservation limit

5.3.3 Discussions and Insights

The impact of water demand management on individual agents and the overall system under one scenario is explained in Sections 4.3.2.1 and 4.3.2.2. The optimal solution under different scenarios are compared and discussed in this section.

Figure 5.6 shows the changes in water consumption for each agent whereby the bar on the left above each agent gives the initial allocation for that agent. The remaining bars above each agent indicate the amount of water a given agent is going to withdraw under different scenarios. As can be seen in Figure 5.6, both A1 and A2 prefer to conserve water until they reach their limits under all scenarios, since each of the bars to the right of the baseline scenario is lower than the baseline. Notice that when there is no conservation limit, both A1 and A2 relinquish all of their initial allocation, which is reflected by the absence of a bar in Figure 5.6. This also demonstrates the necessity of having conservation limits because food production is still essential for agricultural agents. All other agents, except D1 and D2, tend to consume more water compared to their baselines as long as there is extra water available. G2 and I1 are the two main water consumers who utilize most of the conserved water under all scenarios, and I2 is not able to obtain extra water under scenarios having limits because of this, but is another main water consumer under the scenario of no limit, as plotted on the far right in Figure 5.6. D1 and D2 are already fully satisfied during initial allocation and they would not like to conserve water as indicated by all of the bars having the same level as the baseline. The more water agricultural users conserve, the more water available to water consumers.

In terms of an economic perspective, the net benefits for all agents, except D1 and D2, are projected to increase above the baseline, as depicted in Figure 5.7. Among these agents, A1 and A2 obtain more compensation to cover their benefit loss because of utilizing less water; conserving more water implies higher compensation. Although G2 and I1 are two main water consumers under all scenarios with limits, G2 produces greater benefits with additional water than I1 does. Furthermore, I2 is also able to generate massive benefits if there is extra available water as indicated by the bar on the far right in Figure 5.7. The fact that most agents are expected to gain more benefits and no one has less can encourage them to implement water demand management strategies.

The implementation of water demand management is also beneficial for the overall system. As can be seen in Figure 5.8, the total net benefits produced by the system under all scenarios are better in comparison to the baseline case, and the higher is the conservation limit, the greater are net benefits that can be produced. Even though the total imbalance is also higher under the scenario of a higher conservation limit, it is still a very small portion (less than 0.5% under all scenarios having limits) of the total net benefits produced.

In addition to the economic impact of water demand management on consumptive uses, it is also important to investigate its effect on non-consumptive uses, since these uses are modeled as reactive agents and will only respond to the decisions of proactive agents. As shown by the top plot in Figure 5.9, total water rights to consumptive uses are decreasing in comparison to the baseline scenario. In contrast to consumptive uses, the water flow through the two instream flow requirement nodes, which are labelled as S1 and S2 in the network, are increasing; higher conservation limits mean more water available to non-consumptive uses. The increasing instream water flow could be extremely useful for maintaining environmental standards. The findings indicate that besides economic gains, benefits can also be garnered from an ecological perspective as depicted in Figure 5.9.

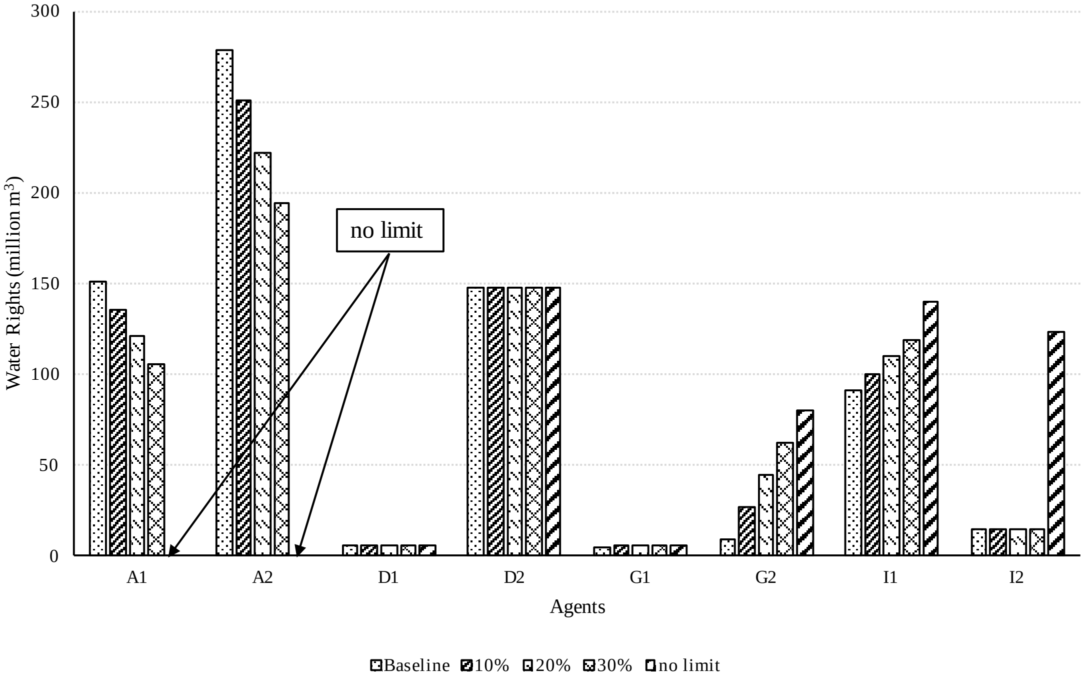

Figure 5.6 Comparison of water rights changes by agents under different scenarios

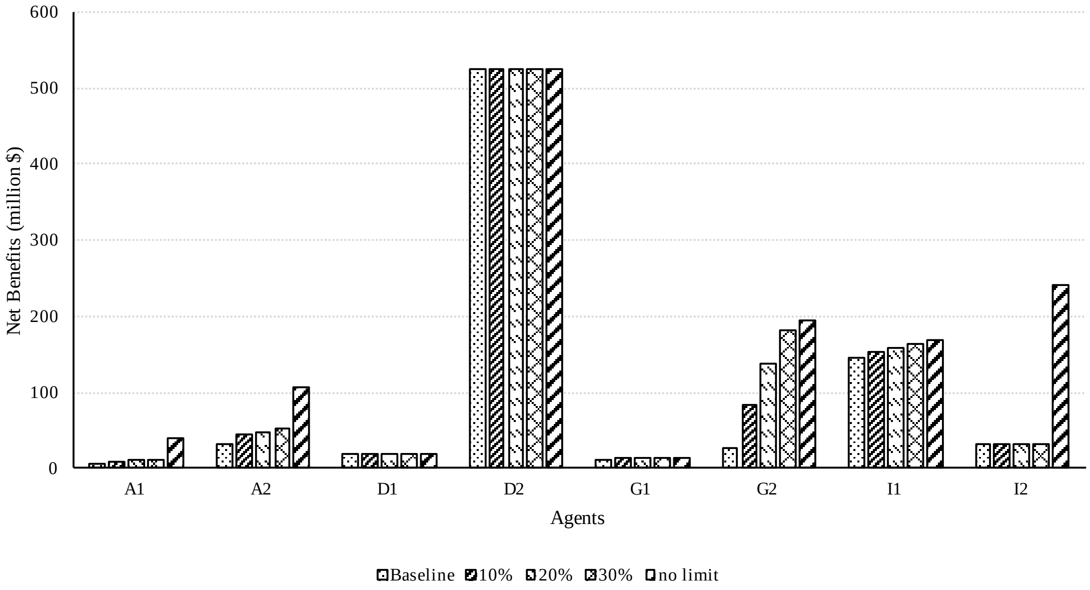

Figure 5.7 Comparison of total net benefits changes by agents under different scenarios

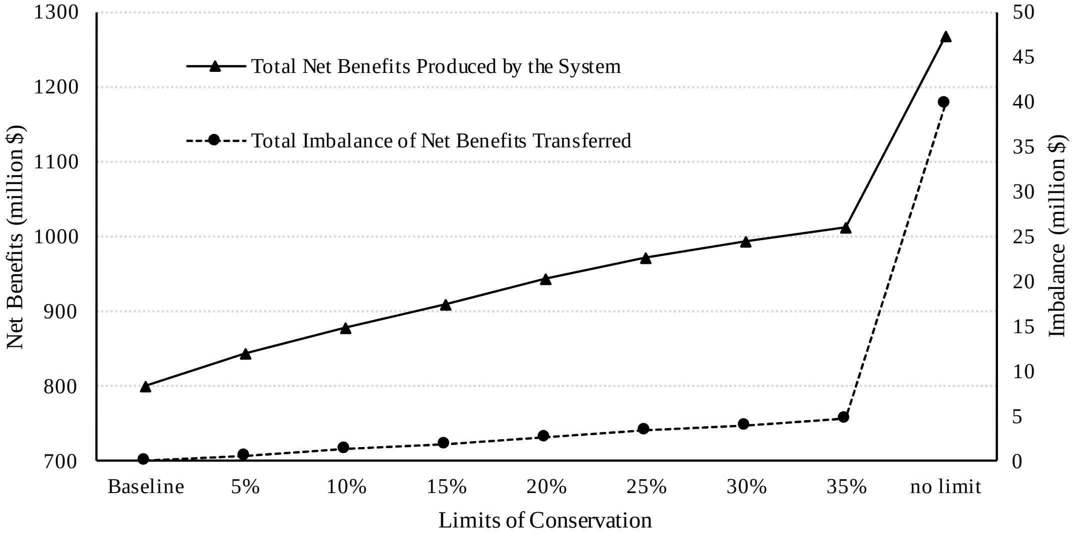

Figure 5.8 Overall net benefits in the basin from initial allocation and with water demand management

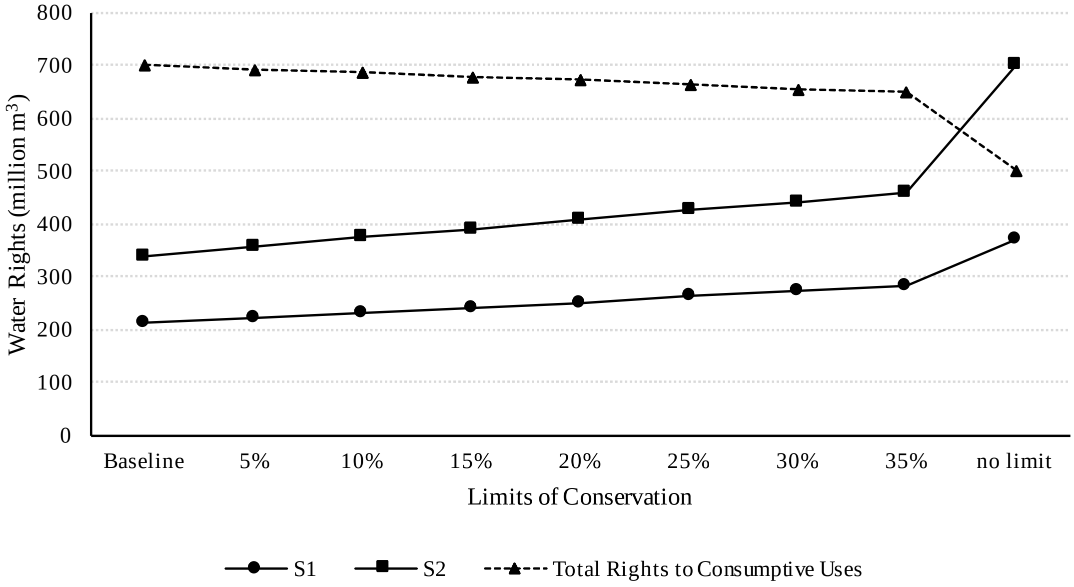

Figure 5.9 Comparison of water rights to consumptive uses and non-consumptive uses

5.4 Comparison between the Centralized and Decentralized Approaches

The methods developed in Chapter 4 and this chapter are based on the same principle of increasing the aggregated benefits from the currently available water from two perspectives. More specifically, the centralized method presented in Chapter 4 is normally referred to as a command and control approach in which all users act cooperatively and a central planner makes decisions for all users. The decentralized method described in this chapter, on the other hand, promotes individual decision-making. Centralized approaches are normally considered to be more economically efficient than decentralized methods, but may be difficult to apply to large-scale real world problems (Yang et al., 2009; Tedesco et al., 2016). A comparison between the two types of methods is presented in this section using the same case study to investigate their performance differences.

It should be noted that the water supply data used in this chapter are 25% of the supply data utilized in Chapter 4. However, in this section, the same set of input data, consisting of water supply and demand (Tables 3.1 and 3.2), and economic data (Appendix A) as used in this chapter, is utilized by each of the methods described in Chapters 4 and 5. The system-wide total net benefits and additional net benefits to users are determined for water demand management. Figure 5.10 presents the results for the total net benefits obtained for the two methods when the initial allocation is calculated for the priority-based approach (PMMNF). It can be seen that the total net benefits for optimal reallocation with a certain level of reduction are greater than that for the agent-based approach having the same level of conservation. This result is in accordance with the conclusion in the existing literature that centralized approaches perform better than decentralized ones from the aspect of economic efficiency.

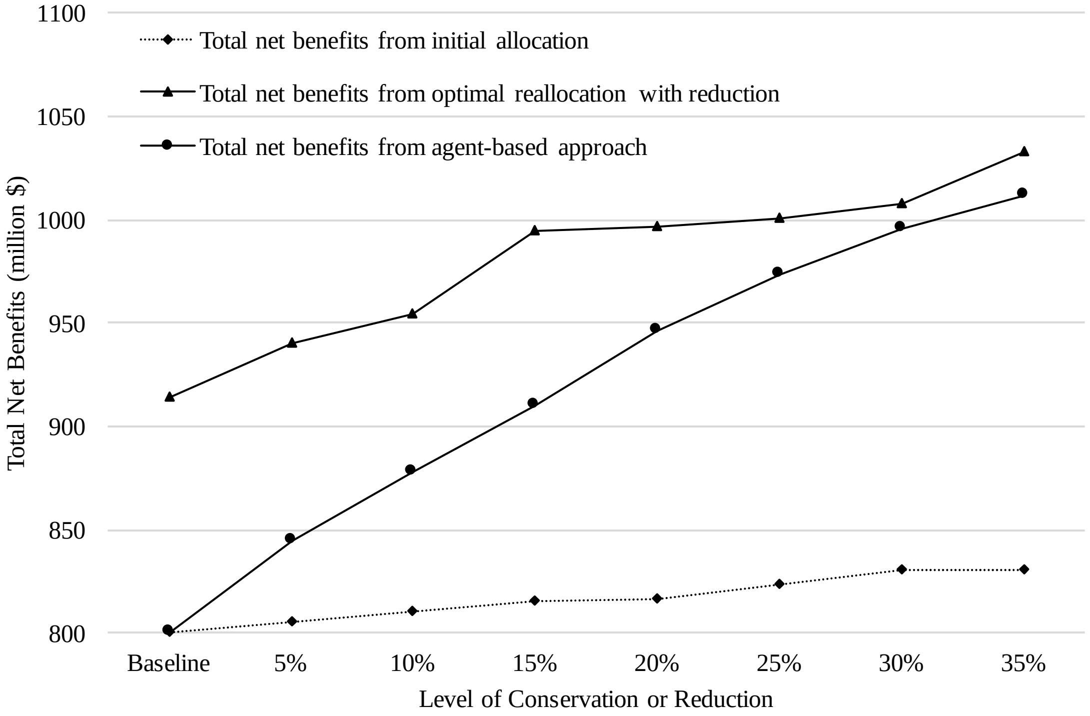

Figure 5.10 Comparison of total net benefits from initial water allocation, optimal reallocation, and agent-based approach under different levels of conservation when initial allocation is obtained from the PMMNF approach

In terms of the additional net benefits shared to users under various solution concepts in the modified cooperative reallocation game (Chapter 4) and within the agent-based approach (Chapter 5), Figure 5.11 shows the results of an example of 20% conservation. As can be seen in Figure 5.10, for the cooperative reallocation game with a 20% reduction, the total net benefits are 996 million dollars in comparison to the total net benefits in the baseline scenario for which 800 million dollars are obtained. Hence, there are 196 million dollars of additional net benefits which are shared across the four users in Figure 5.11. The calculation for the case of the agent-based approach is 145 million dollars of additional net benefits (obtained from Figure 5.10) which are shared by the four users in Figure 5.11. In addition, for the agent-based approach, the sharing of domestic, general, and industrial users within the same tributary are combined into one city user in order to compare this with the results of the cooperative reallocation game. The findings for the agent-based approach are displayed at the far right in Figure 5.11 for each user.

As can be seen from Figure 5.11, even though the total amount of additional net benefits in the agent-based approach is less than that in the cooperative reallocation game, the sharing of additional net benefits for certain users are greater than that for certain solution concepts in the cooperative reallocation game. For example, for user A1, the sharing in the agent-based approach is greater than that for the proportional and normalized nucleolus, but is less than that for the nucleolus, weak nucleolus, and Shapley value in the cooperative reallocation game. Under this situation, a certain user may prefer using certain solution concepts. For instance, user A1 would strongly prefer the results of the nucleolus because it can receive the most additional net benefits for this case, while user A2 prefers the weak nucleolus situation. Consequently, the selection of which solution sharing approach to adopt may require utilizing a bargaining and negotiation process. Various decision-making methods, such as the Graph Model for Conflict Resolution (GMCR) (Fang et al., 1993), could be useful for the negotiation process.

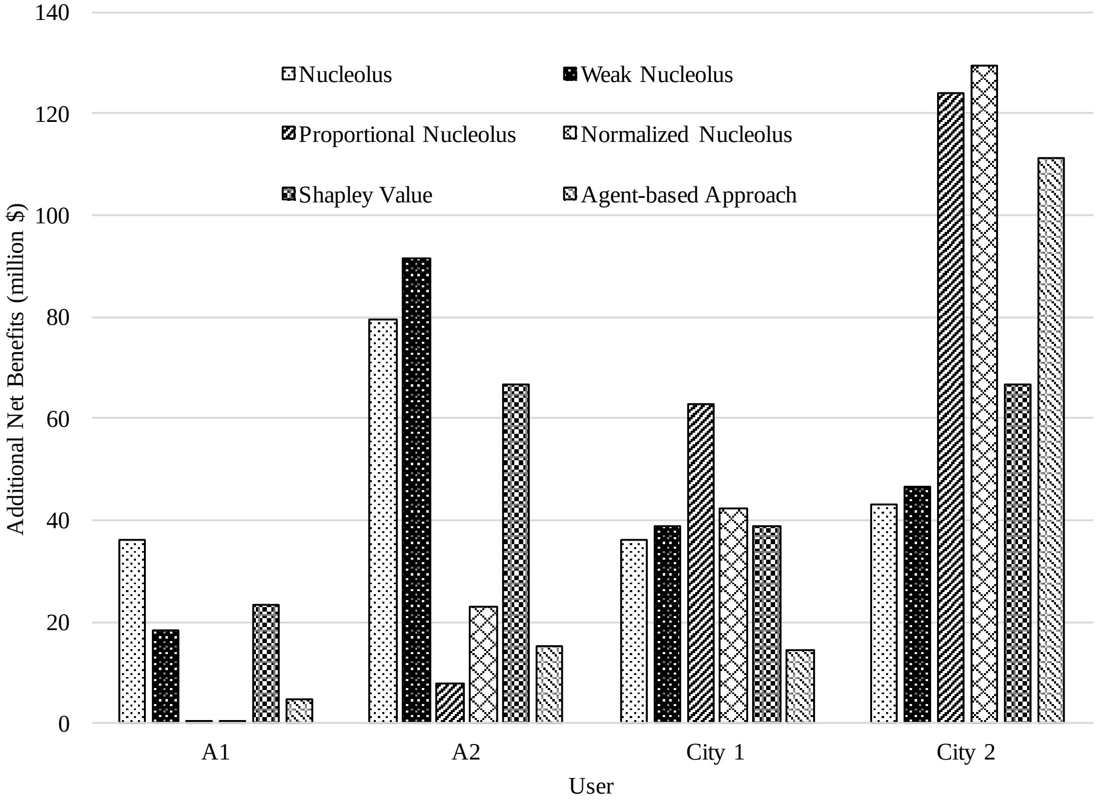

Figure 5.11 Comparison of additional net benefits by users among various solution concepts within cooperative game theory and the agent-based approach for a 20% conservation scenario

5.5 Summary

In this chapter, water users' responses to water demand management strategies are simulated within an agent-based framework in order to investigate the effect of water demand management on individual users and the overall system. The results indicate that agricultural users are more likely to conserve water, while the benefits loss from water conservation can be compensated so as to achieve a better economic return. The conserved water can be distributed to other users to produce more economic benefits, but a portion of the extra benefits must be transferred in order to obtain the additional water. By implementing water demand management, positive incentives are provided to water conservers and other users could also benefit. The system performance is projected to be improved as well from both economic and ecological perspectives. Finally, the economic performance of the methods developed in Chapter 4 and this chapter is compared.

Chapter 6

Conservation-Targeted Hydrologic-Economic Models for Water Demand Management

A basin-wide hydrologic-economic optimization model is presented to estimate how much water consumption can be conserved while maintaining the same level of economic output. Water consumption is interpreted as either water diverted to consumptive users or water consumed by all users. Two different formulations for representing the two interpretations of water consumption are examined. The two formulations take into consideration the characteristics of different users, such as the consumption ratio and productivity. The model is applied to the South Saskatchewan River Basin (SSRB) in southern Alberta, Canada, where water scarcity is a severe issue. It is found that: a substantial amount of water can be conserved without sacrificing economic output; irrigation is the largest contributor while municipal and industrial users make a small difference in terms of water conservation; MI users make major economic contribution in order to retain the same level of system-wide aggregated benefits, and thereby overall water productivity can be considerably improved; and MI users' reactions are diversified depending on the specified conservation targets: either water diverted to consumptive users or water consumed by all users. The implication of results can be used to facilitate a better understanding of present water usage and guide policy makers to make informed decision for water demand management.

6.1 Conservation Targets

Conservation normally means promoting the efficient use of water resources and reducing unnecessary water consumption such that more water can be preserved in reservoirs or aquifers for the purpose of environmental protection or other beneficial uses. Traditionally, water conservation is measured by the reduced amount of water diverted to a user. However, one may argue that most of the water diversions are returned to the water source, and only a small part is depleted. Conservation efforts among different users may not be evaluated fairly because of a skewed distribution of the consumption ratio. In addition, water loss during the transportation process may constitute a considerable portion of water demand, and is ignored most times.

Based on this argument, two different interpretations of water consumption are specified. One is the amount of water diverted to a user, and the other one is the volume of water consumed by a user. For basin-wide water demand management, consumptive users are the main focus. The conservation endeavours would be targeted at them under the traditional approach in which total amount of water diversion is calculated. However, if one only takes into account the portion of water not available for reuse, water loss during transportation should also be included.

6.2 Hydrologic-Economic Optimization Model

In this model, the main objective is to estimate the minimum requirement of total water consumption during all planning periods, subject to various physical and policy constraints. Based on the two different interpretations of water consumption specified for water demand management: water withdrawal by consumptive users or water consumed by all users, two different formulations are developed. The former with the minimum water withdrawal objective (refers to "minimum withdrawal formulation" hereafter) is expressed as:

$$min\ Q_W = \sum_t \sum_k Q(k,t) : k \in C$$

$$subject\ to \begin{cases} h(Q) & = & 0 \\ g(Q) & \geq & 0 \\ Q & \in & \Omega \end{cases} \tag{5.1}$$

where Q_W indicates total water withdrawal by consumptive users, and means the sum of all flows toward node k describing a consumptive user during period t; $h(Q) = 0$ and $g(Q) \geq 0$ represent the equality and non-equality constraints respectively; and Ω is used to denote the feasible solution space of the problem. The latter with minimum water consumed objective (refers to "minimum consumed formulation" hereafter) is shown as:

$$min\ Q_C = \sum_t \left(\sum_k Q(k,t) * e_N(k,t) + \sum_{(k_1,k) \in L} Q(k_1,k,t) * e_L(k_1,k,t) \right)$$

$$subject\ to \begin{cases} h(Q) = 0 \\ g(Q) \geq 0 \\ Q \in \Omega \end{cases} \tag{5.2}$$

where Q_C implies total water consumed by all users, including water loss during transportation. $e_N(k, t)$ means the consumption coefficient (the ratio of water that is not returned to the water source) of node k during period t, and $e_L(k_1, k, t)$ is the water loss coefficient during transportation due to evaporation or seepage in the link (k_1, k) during period t. These coefficients are considered as given parameters in this paper.

The constraints considered in this model include physical constraints, policy restrictions, and system control rules, as described in Section 3.2.1.

In addition to the constraints mentioned in Section 3.2.1, there are also some other restrictions in this model. For example, one may want to relinquish all its water obtained from initial allocation, but this is not likely to happen in reality because some economic activities are required to maintain a certain level or because a high level of reduction is hard to achieve due to technological difficulties. A parameter $\theta(k, t)$ is introduced to indicate this conservation limit. Therefore, water diverted to node k during period t should be no less than its initial allocation minus the amount of water one can conserve, and this restriction is shown as:

$$Q(k,\ t) \geq Q_{ini}(k,\ t) * (1 - \theta(k,\ t)) \tag{5.3}$$

where $Q_{ini}(k, t)$ represents the initial water allocation to node k during period t.

Furthermore, a reduction of water consumption should not jeopardize the performance of the system. As indicated in Equation 2.1, the benefits gained from water utilization and its associated water productivity are main indicators of system performance. The benefits are measured using benefit functions in monetary terms here. To indicate that benefits would not become worse, a system control rule is specified as:

$$\sum_{k}\sum_{t} NB_{kt} \geq \sum_{k}\sum_{t} NB_{kt}^{ini} \tag{5.4}$$

where NB_{kt} and NB_{kt}^{ini} represent the net benefits obtained from water utilization, and initial net benefits produced by using initial water allocation for node *k* during period *t*, respectively.

6.3 Case Study

The foregoing optimization model is applied to the South Saskatchewan River Basin (SSRB) in southern Alberta, Canada, as shown in Figure 6.1. The SSRB includes four major municipalities: Calgary, Lethbridge, Red Deer and Medicine Hat, and thirteen irrigation districts, which account for 13% and 75% of total water allocation, respectively, in the basin (Alberta Environment, 2003; 2007). The SSRB adopts a priority-based water right system in which a water license is required for water diversion except for the predetermined statutory right for traditional agricultural users (6,250 cubic meters/year) and household users (1,250 cubic meters/year). The application of license follows the principle of “first in time, first in right”, and hence some recent (junior) users may not be able to receive any water during water shortage periods.

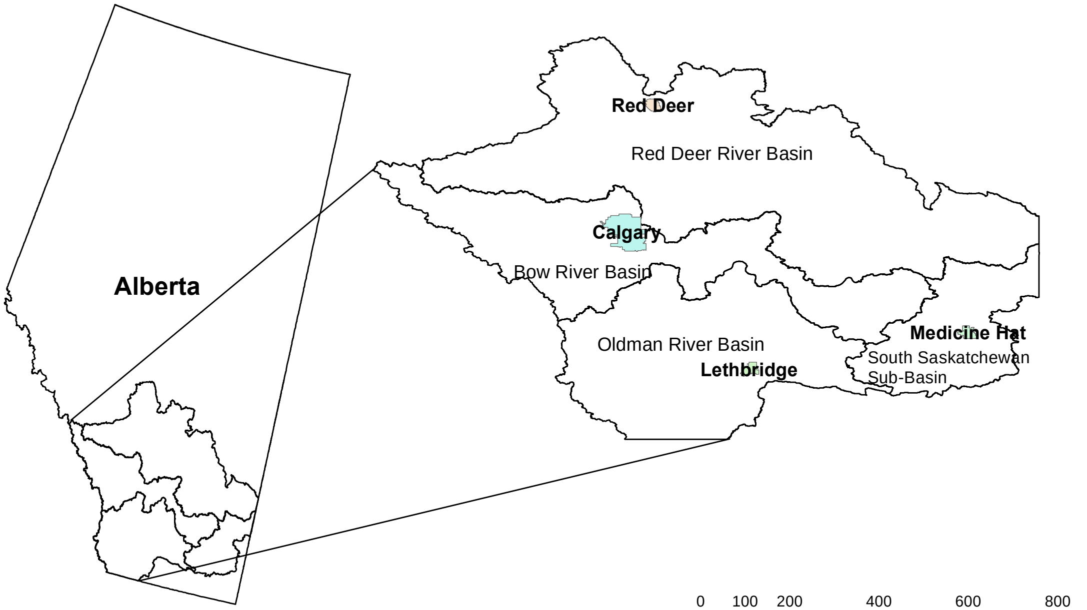

Figure 6.1 Location of the SSRB within Alberta, Canada

6.3.1 Network and Input Data

As shown in Figure 6.1, the SSRB is comprised of four river sub-basins: Red Deer, Bow, Oldman river basins and the portion of the South Saskatchewan River sub-basin located within Alberta. An abstracted node-link network of the SSRB is depicted in Figure 6.2, which includes 9 irrigation, 4 domestic, 4 general, 4 industrial, 10 inflow, 1 outflow, 2 hydropower plants, 17 reservoirs, and 4 instream flow requirement nodes. In this study, 13 irrigation districts are aggregated into 9 irrigation regions according to the source of water diversion and agroclimatic conditions. The irrigation districts of Mountain View, Aetna, United, and Leavitt are considered as one demand node, as are the Raymond and Magrath districts. General demand refers to municipal excluding domestic need, such as the demand of water for commercial, institutional and public infrastructural purposes. Irrigation, domestic, general and industrial users are categorized as consumptive users, and the remaining are non-consumptive users. Note that even though reservoirs and instream flow requirements are considered as non-consumptive users, there still is a specified demand for each of them in order to maintain a certain water depth for fisheries, recreation and ecosystem protection considerations. The name of those consumptive users and their representing nodes in the network are summarized in Table 6.1,. Their projected annual water demand in millions cubic meter (mcm) is listed in the rightmost column of the table, and total annual demand of all consumptive users is about 3.88 billion cubic meters. More detailed hydrological and economic data are provided in Appendix B.

Table 6.1 Name and annual water demand of consumptive users in SSRB

Node	Name of Consumptive Users	Annual Demand (mcm)
A1	Western Irrigation Region	150.65
A2	Bow River Irrigation Region	542.33
A3	Eastern Irrigation Region	861.51
A4	Lethbridge Northern Irrigation Region	381.64
A5	Mountain View, Aetna, United, Leavitt Irrigation	55.58
A6	Raymond and Magrath Irrigation Region	81.26
A7	St. Mary River - West Irrigation Region	362.09
A8	Taber Irrigation Region	224.87
A9	St. Mary River - East Irrigation Region	575.83
D1	City of Red Deer - Domestic	6.03
D2	City of Calgary - Domestic	147.79
D3	City of Lethbridge - Domestic	14.15
D4	City of Medicine Hat - Domestic	7.04
G1	City of Red Deer - General	5.69
G2	City of Calgary - General	79.59
G3	City of Lethbridge - General	16.77
G4	City of Medicine Hat - General	8.35
I1	City of Red Deer - Industrial	139.67
I2	City of Calgary - Industrial	154.14
I3	Eastern Industrial Region - Industrial	15.38
I4	City of Medicine Hat - Industrial	50.99

mcm: million cubic meters.

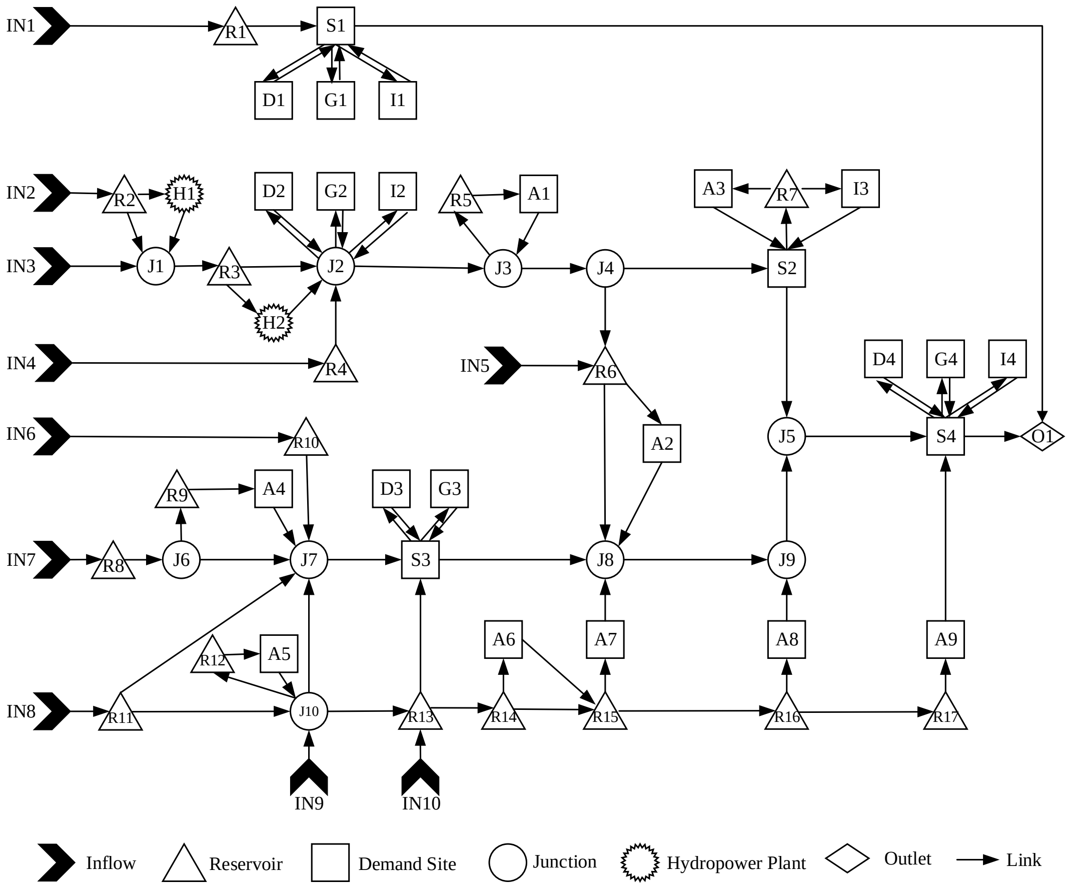

Figure 6.2 Network of the SSRB (based on Wang et al. (2008b))

Monthly water supply consists of inflow from outside of the basin and adjustment flow from small local tributaries for accounting in precipitations. Based on the work of Wang et al. (2008b) and data from the Water Survey of Canada's HYDAT database (ECCC, 2017b), the long term averaged annual flow of the ten inflow nodes is about 4.4 billion cubic meters, and inflows during crop growing season (May to September) is higher than those during winter season. In this study, the monthly supply data of a dry year is selected, with an annual total inflow volume of 2.19 billion cubic meters and total adjustment flow of 2.31 billion cubic meters. It should also be noted that at least 50% of the annual natural flow must be passed to the downstream province Saskatchewan according to the *1969 Master Agreement on Apportionment* (Alberta Environment, 2003).

Consequently, the annual outflow at outflow node O1 shall be no less than 2.25 billion cubic meters, which makes the water available for users in the SSRB to be more restrained. In other word, a total demand of 3.88 billion cubic meters from consumptive user needs to be satisfied with 2.25 billion cubic meters of water availability.

Water is consumed during economic activities at consumptive sites with different percentages. For irrigation, it is reported that about 10% to 30% of water diverted to farms in the SSRB are returned to the water system (Alberta Environment, 2003; Adamowicz et al., 2010). In this study, the consumption coefficient for irrigation is set as 75%. For municipal users, consumption ratios are 15% and 25% for domestic and general users, respectively. An industrial user consumes about 5% of its water diversion. In addition, water evaporated during transportation is set to be 3%, and could potentially be up to 7% (AIPA, 2010).

6.3.2 Results and Discussions

The results obtained from minimum withdrawal and minimum consumed formulations under a series of conservation limit scenarios are discussed and compared in this section. It is worthwhile to mention that even though the scenario of no conservation limit is also examined, but it is unlikely for one user to reduce water usage by too much in the short term. Therefore, it is more meaningful to focus on the results under low conservation limit scenarios. In fact, the consumption level change of different users can be clearly observed within a 50% conservation limit. The baseline scenario is obtained from a priority-based initial allocation method proposed by Wang et al. (2007a). In the baseline scenario, the irrigation districts of Western (A1), Eastern (A3), Mountain View, Aetna, United, and Leavitt (A5), and Raymond and Magrath (A6) are able to divert water to their maximum demand, and all MI users except general and industrial demand in the city of Calgary (G2 and I2) are fully satisfied. Return flow is considered under both formulations. The total amount of water diverted to all consumptive users is 3,467.6 mcm, and irrigation accounts for 2,927.3 mcm, which is 84.4% of the total diversion.

6.3.2.1 Results under the Minimum Water Withdrawal Formulation

Under the minimum withdrawal formulation in Equation 5.1, the system performance considering different conservation limits are summarized in Table 6.2. For the scenario of having a 50% conservation limit in Table 6.2, the total water withdrawal by all consumptive users can be reduced to 1967.5 mcm from 3467.6 mcm in the baseline scenario, which is a 43.3% conservation. The irrigation's water withdrawal accounts for 1463.7 mcm, which is 74.4% of the total water withdrawal. However, irrigation contributes 97.6% of the total water conservation. The remaining 2.4% conservation comes from the MI users, whose withdrawal reduces to 503.8 mcm from 540.3 mcm in the baseline scenario. The aggregated economic benefits of consumptive users under all scenarios are equal to the value in the baseline scenario. These findings imply that the same level of economic benefits can be produced by utilizing much less water, with conservation from both the irrigation and MI sectors. Irrigation contributes a majority of the total water usage reduction, whereas the MI usage seems hard to be significantly reduced. In an extreme scenario of having no conservation limit, the MI users even take more water than their initial allocation, thereby making irrigation's contribution more than 100%. An important indicator for system performance is the overall water productivity. As can be seen from the last row in Table 6.2, the overall productivity increases from 0.44 $\$/m^3$ to 0.77 $\$/m^3$, a 75% improvement, between the scenarios of baseline and 50% limit, and can increase more under higher conservation limit scenarios.

In terms of the water consumption level of each individual user, Figure 6.3 depicts the change patterns of irrigation users. As major conservation contributors, irrigation's water consumption level change with respect to water conservation limit is obvious, as indicated in Figure 6.3. Specifically, all irrigation users are reducing their water usage, including the unsatisfied ones in the baseline scenario, until they reach their conservation limits under all scenarios. After the limit of 80%, the consumption level for each irrigation user remains the same because there is a minimum demand requirement equivalent to 20% of one's maximum demand. However, the water productivity of each irrigation user shows an upward trend, as depicted in Figure 6.4. For example, A3's productivity increases from 0.05 $\$/m^3$ in the baseline to 0.07 $\$/m^3$ under the 50% limit scenario, and to 0.10 $\$/m^3$ under no limit scenario.

Table 6.2 System performance under the scenarios of different conservation limits and minimum withdrawal formulation

Scenarios:	Baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
Total Water Withdrawal (mcm)	3467.6	3151.9	2842.4	2543.9	2251.8	1967.5	1688.3	1411.9	1192.7	1192.7	1192.7
Irrigation Water Withdrawal (mcm)	2927.3	2634.6	2341.9	2049.1	1756.4	1463.7	1170.9	879.1	647.1	647.1	647.1
MI Water Withdrawal (mcm)	540.3	517.3	500.5	494.8	495.4	503.8	517.4	532.8	545.6	545.6	545.6
Irrigation Withdrawal Percentage (%)	84.4%	83.6%	82.4%	80.6%	78.0%	74.4%	69.4%	62.3%	54.3%	54.3%	54.3%
Total Water Conservation (%)	-	9.1%	18.0%	26.6%	35.1%	43.3%	51.3%	59.3%	65.6%	65.6%	65.6%
Irrigation Conservation Contribution (%)	-	92.7%	93.6%	95.1%	96.3%	97.6%	98.7%	99.6%	100.2%	100.2%	100.2%
Overall Productivity ($\$/m^3$)	0.44	0.48	0.53	0.59	0.67	0.77	0.90	1.07	1.27	1.27	1.27

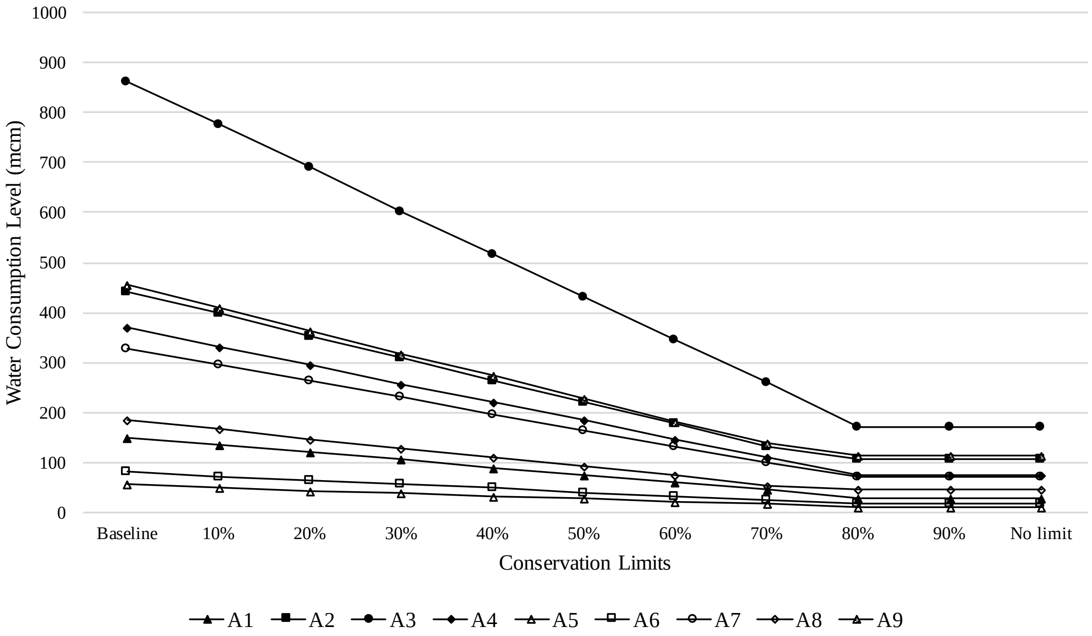

Figure 6.3 Water consumption level of irrigation users under the scenarios of different conservation limits and minimum withdrawal formulation

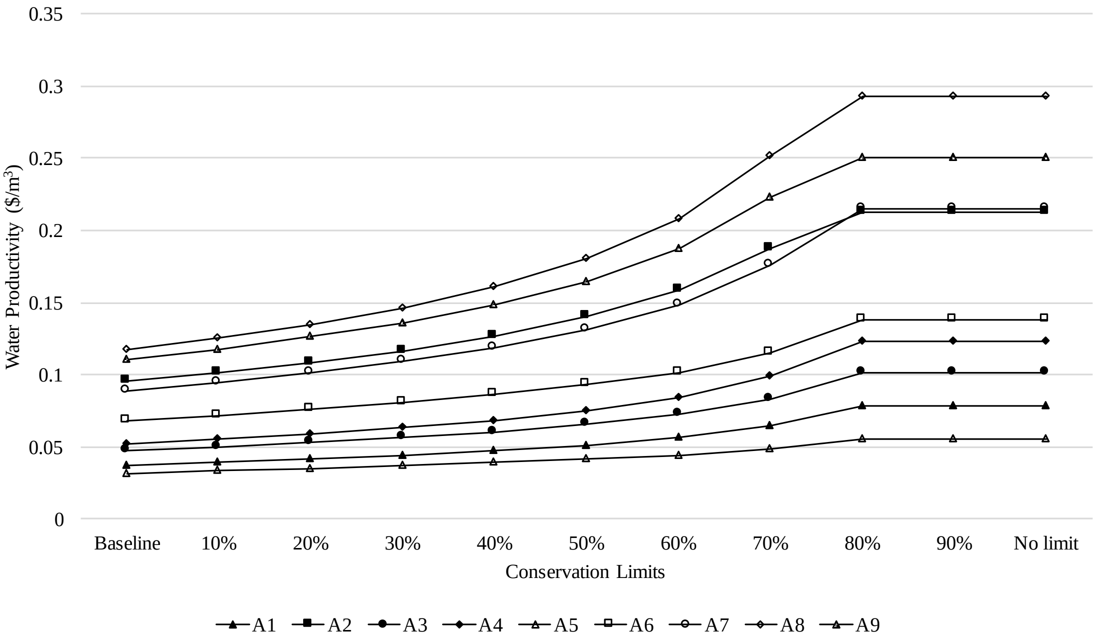

Figure 6.4 Productivity of irrigation users under the scenarios of different conservation limits and minimum withdrawal formulation

In contrast, the responses of MI users are quite diversified. As can be seen in Figure 6.5, more water is utilized by G2 and I2 along with the increase of the conservation limit, whereas other MI users reduce their water usage to a certain level and then start to increase their usage. It is believed that marginal net benefit is the key factor influencing all MI users' responses, as clearly indicated in Figure 6.6 that all MI users' marginal net benefits are merging to the same value.

As portrayed in Figure 6.6, in the baseline scenario, G2 and I2 possess higher marginal values than the other MI users. The values are 2.09 $\$/m^3$ for G2 and 1.92 $\$/m^3$ for I2, whereas the values of the other MI users range from 0.36 $\$/m^3$ to 0.83 $\$/m^3$. Consequently, all other MI users are reducing their water usage and their marginal values are increasing. G2 and I2's marginal values merge the earliest under the 10% limit scenario with a merged value of 1.92 $\$/m^3$. For the other MI users, if one user's marginal value is still less than the merged value, the user will continue to reduce its water usage until its marginal value grows to the same as the merged value. It can be seen that all MI users' marginal values become identical under the 50% limit scenario and afterwards. This implies that after the 50% limit scenario all MI users are equally efficient in terms of benefit generation. In other words, they are able to produce the same amount of net benefit with every additional unit of water, and they would increase their water usage in a proportional manner if more net benefits need to be produced.

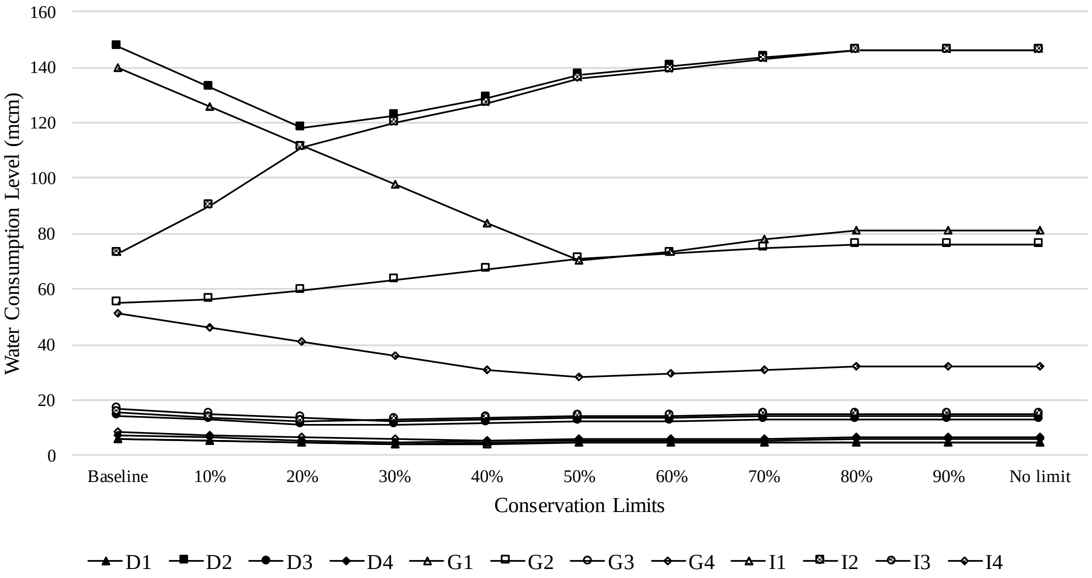

Figure 6.5 Water consumption level of MI users under the scenarios of different conservation limits and minimum withdrawal formulation

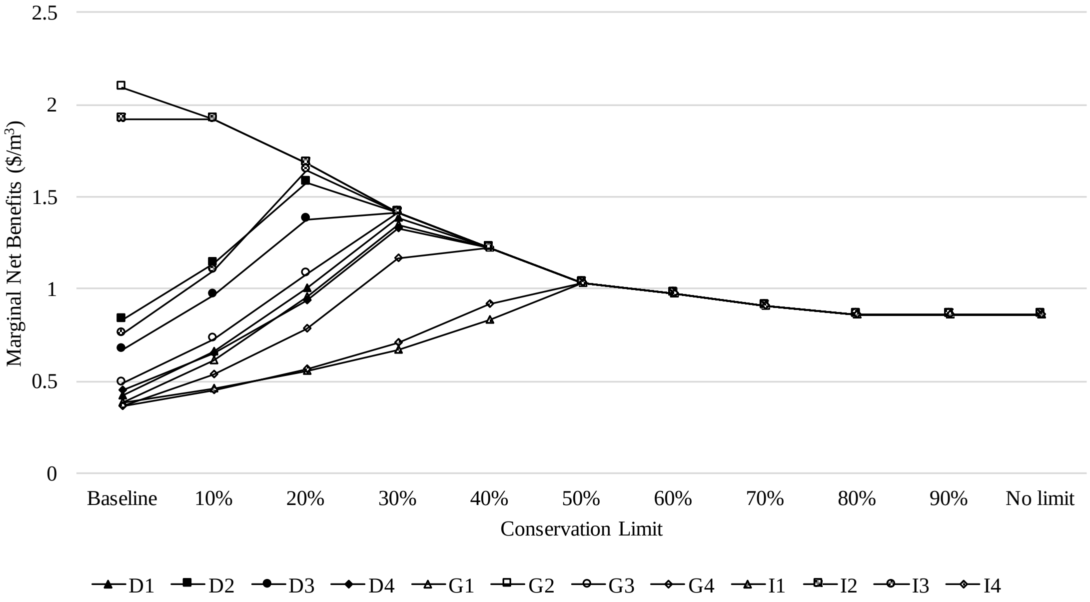

Figure 6.6 Marginal net benefit of MI users under the scenarios of different conservation limits and minimum withdrawal formulation

6.3.2.2 Results under the Minimum Water Consumed Formulation

When minimum water consumed by all users is set as the objective function following Equation (5.3), the resulting system performance under different conservation limit scenarios are summarized as in Table 6.3. Again, consider a 50% limit scenario as an example, for which the total water consumed by all users can be reduced from 2254.3 mcm in the baseline scenario to 1153.0 mcm, which is a 48.9% water conservation. Water consumed by irrigation accounts for 1097.7 mcm, and 55.3 mcm is consumed by MI users. The share of irrigation in the total water consumed is 95.2%, but irrigation contributes 99.7% of the total water conservation. These two high percentages imply that irrigation is not only the dominant water consumer but also the major water contributor in the basin, whereas the MI users make a very minor difference in terms of water conservation. This finding is in accordance with the implication in the previous formulation, but irrigation is much more influential in this case. Since the same level of economic benefits are produced under all scenarios, it can be calculated that the overall productivity increases from 0.67 $\$/m^3$ to 1.31 $\$/m^3$ between the scenarios consisting of baseline and 50% limit, as shown in the last row in Table 6.3, which makes a 95.5% improvement.

Table 6.3 System performance under the scenarios of different conservation limits and minimum consumed formulation

Scenarios:	Baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
Total Water Consumed (mcm)	2254.3	2030.5	1808.3	1589.1	1371.1	1153.0	934.7	717.4	544.7	544.7	544.7
Irrigation Water Consumed (mcm)	2195.5	1975.9	1756.4	1536.8	1317.3	1097.7	878.2	659.3	485.4	485.4	485.4
MI Water Consumed (mcm)	58.8	54.6	51.9	52.3	53.8	55.3	56.5	58.1	59.3	59.3	59.3
Irrigation Consumed Percentage (%)	97.4%	97.3%	97.1%	96.7%	96.1%	95.2%	94.0%	91.9%	89.1%	89.1%	89.1%
Total Water Conservation (%)	-	9.9%	19.8%	29.5%	39.2%	48.9%	58.5%	68.2%	75.8%	75.8%	75.8%
Irrigation Conservation Contribution (%)	-	98.1%	98.5%	99.0%	99.4%	99.7%	99.8%	99.9%	100.0%	100.0%	100.0%
Overall Productivity ($\$/m^3$)	0.67	0.74	0.84	0.95	1.10	1.31	1.62	2.11	2.78	2.78	2.78

At the individual level, the water consumption levels of the irrigation users are identical as drawn in Figure 6.3. The irrigation users' water productivities also show a similar upward trend in this case as in the previous formulation. This indicates that the only effective constraint for irrigation users is the conservation limit constraint. However, there are substantial difference with respect to the reactions of MI users, as depicted in Figure 6.7. More specifically, I2 is the only one who consumes more water under all scenarios, and reaches its maximum demand under the 60% limit scenario. In contrast, G2, which shares the same pattern as I2 in the previous formulation, reacts differently. G2 only starts to increase its water usage when the limit is larger than 20%. The industrial users I1, I2 and I4 start to increase their consumption levels at the scenarios of 50%, 20% and 40% limits, respectively. All of the other MI users are generally reducing their water usage to a certain level and then turn to growing their water usage.

Meanwhile, the differences among MI users can also be observed in their various marginal net benefit as shown in Figure 6.8. Unlike the result that same marginal value shared for all MI users after the 50% limit scenario in the previous formulation, marginal values in this case tend to merge based on the types of users. The general users possess the highest average marginal value, domestic the second highest, and industrial the lowest in this formulation. This is because more water is distributed to industrial users, as industrial users have the lowest consumption ratio and general users the highest. The fact that the industrial users have a favorable position is very sensible in the formulation which is targeted on minimizing water consumed by all users, because industrial users consume the least of its water diversion among all users.

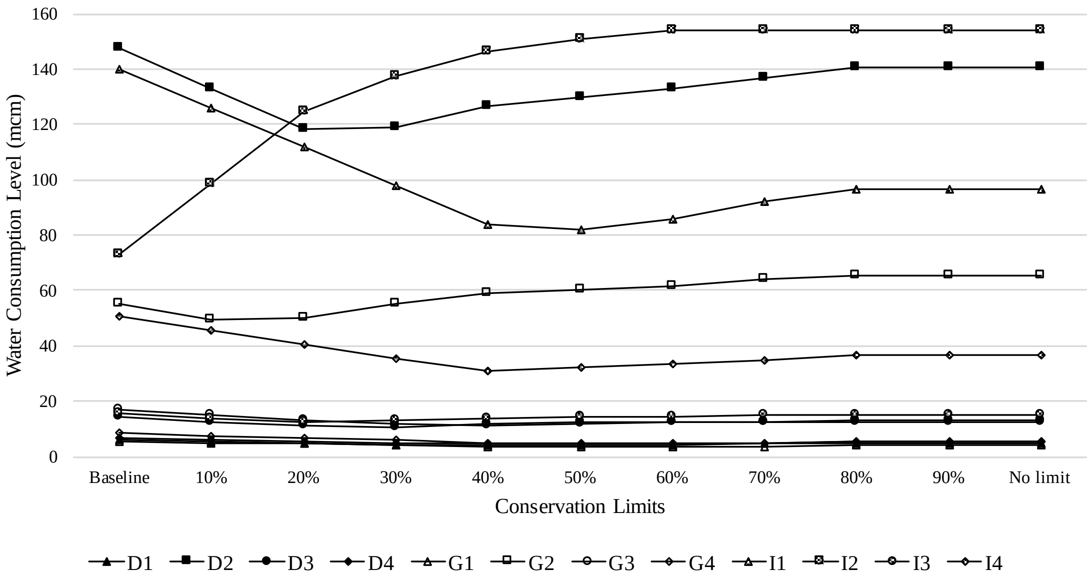

Figure 6.7 Water consumption level by MI users under the scenarios of different conservation limits and minimum consumed formulation

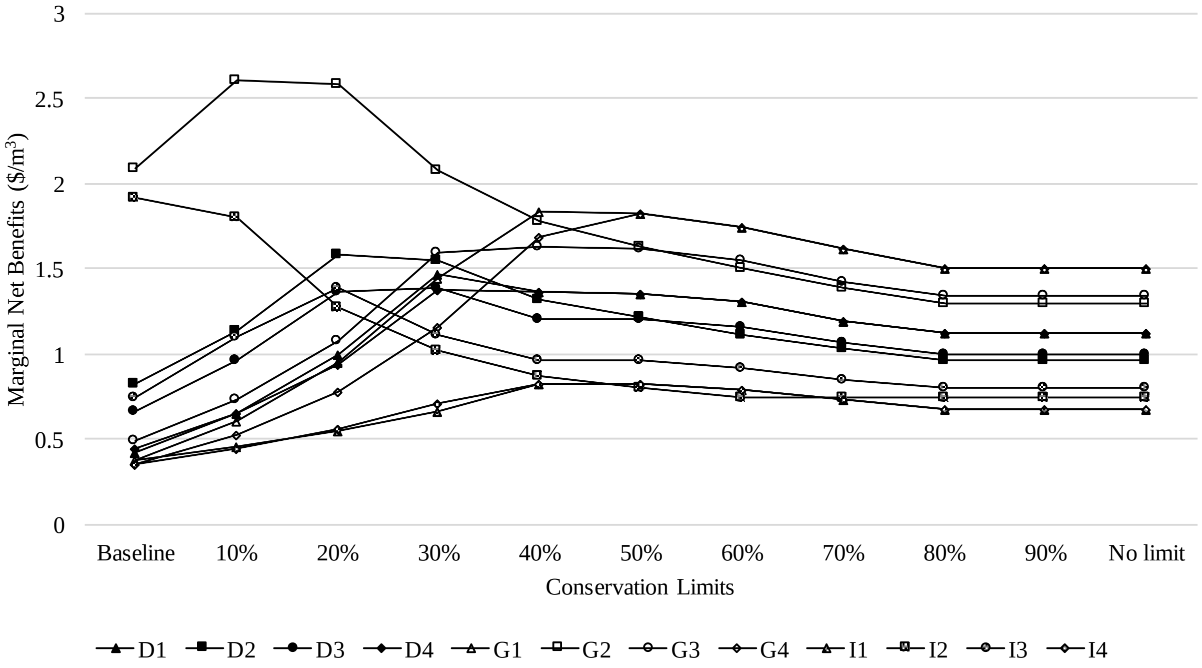

Figure 6.8 Marginal net benefits of MI users under the scenarios of different conservation limits and minimum consumed formulation

6.3.2.3 Comparisons and Insights

The results of the two formulations provide some similar findings and also some different outcomes. Similar findings include: a substantial amount of water can be conserved while producing the same level of economic benefits; irrigation is the largest water contributor while MI users make a small difference in water conservation; MI users make economic contributions in order to maintain the same level of aggregated benefits, and thereby overall water productivity can be considerably improved.

The water consumption levels of the MI users are different between the two formulations. These differences are calculated by using the results of the minimum consumed formulation minus that of minimum withdrawal formulation, and are summarized in Table 6.4. These findings indicate that more water is distributed to industrial users. I2 is the largest water consumer followed by I1. Other MI users, especially G2, tend to consume less water under the minimum consumed formulation.

Table 6.4 A comparison of water withdrawal by municipal and industrial users between two formulations (mcm)

Scenarios:	Baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
D1	0.00	0.00	0.00	-0.08	-0.17	-0.41	-0.44	-0.42	-0.40	-0.40	-0.40
D2	0.00	0.00	0.00	-3.91	-3.60	-7.44	-6.99	-6.35	-5.78	-5.78	-5.78
D3	0.00	0.00	0.00	-0.05	-0.02	-0.64	-0.72	-0.66	-0.61	-0.61	-0.61
D4	0.00	0.00	0.00	-0.05	-0.22	-0.53	-0.57	-0.55	-0.53	-0.53	-0.53
G1	0.00	0.00	0.00	-0.08	-0.55	-0.77	-0.80	-0.78	-0.77	-0.77	-0.77
G2	0.00	-6.75	-9.85	-8.64	-8.73	-10.86	-10.73	-10.51	-10.29	-10.29	-10.29
G3	0.00	0.00	0.00	-0.38	-1.25	-1.97	-2.06	-2.02	-1.97	-1.97	-1.97
G4	0.00	0.00	0.00	0.00	-0.57	-1.17	-1.22	-1.21	-1.20	-1.20	-1.20
I1	0.00	0.00	0.00	0.00	0.00	13.72	12.89	14.28	15.47	15.47	15.47
I2	0.00	8.33	13.83	17.08	18.19	14.39	14.67	10.97	7.95	7.95	7.95
I3	0.00	0.00	0.63	0.92	0.91	0.27	0.20	0.26	0.31	0.31	0.31
I4	0.00	0.00	0.00	0.00	1.90	4.20	3.93	4.33	4.68	4.68	4.68

It is interesting to note that a large portion of the conserved water from irrigation is not utilized by MI users, because MI users are also reducing their usage in most scenarios. This portion of water is stored in reservoirs or instream flows, and can be used to meet the requirement of ecosystem protection, fisheries or recreation. In addition, if more benefits are required from the system, the stored water can be released to consumptive users as well. It is estimated that total net benefits can be improved by 11% when all MI users consume water to their maximum demand.

Nevertheless, this finding may raise another question: is it necessary to involve irrigation users if their conservation is not utilized by MI users? To address this question, another case, in which only MI users are involved, is built and tested by using the two formulations. Water conservation percentages under both formulations are as listed in Table 6.5. As can be seen in the table, if only the MI users are involved, at most 2.4% of the water withdrawal can be conserved under the minimum withdrawal formulation, and 0.4% of water consumed under the minimum consumed formulation. As a result, it is necessary to include irrigation users because both percentages are much less than those in the cases that all users are involved. This conclusion can also be supported by the finding in the previous sections that MI users only make a small contribution to water conservation.

Table 6.5 A comparison of water conservation percentages among different formulations

Scenarios:		10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
Min Withdrawal Formulation	All Users	9.1%	18.0%	26.6%	35.1%	43.3%	51.3%	59.3%	65.6%	65.6%	65.6%
	MI Only	0.8%	1.4%	1.8%	2.1%	2.3%	2.4%	2.4%	2.4%	2.4%	2.4%
Min Consumed Formulation	All Users	9.9%	19.8%	29.5%	39.2%	48.9%	58.5%	68.2%	75.8%	75.8%	75.8%
	MI Only	0.2%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%

A publication on investigating water available for future growth and economic development in southern Alberta was recently published. Specifically, by using a statistical method, Bennett et al. (2017) explored the amount of unused water from irrigation districts, major urban and rural communities, and transferred water. They found that on average 54.5% of the licensed allocation of irrigation districts, and 56.1% of the licensed allocation of major urban and rural communities have not been utilized during the last decade. The total volume of transferred water has been 35.3 mcm since 2003, which is relatively low in comparison to an annual mean diversion of 1,611 mcm for irrigation and an annual mean use of 304 mcm for urban areas. Hence, it was concluded that there is sufficient water for meeting future increasing demand.

However, there are two major distinctions between this study and that of Bennett et al. (2017). Firstly, their study was carried out based on licensed allocation and this investigation is founded based on initial allocation. It is argued that the initial allocation under a given water availability constitutes a more sensible baseline scenario for water demand management because initial allocation indicates the actual amount of water under one's control while licensed allocation only implies the maximum amount of water one can withdraw. In water shortage cases, a user with high licensed allocation may not be able to obtain any water since there are other senior users possessing higher priority for water diversion. Therefore, an initial allocation step is necessary before the implementation of water demand management. Secondly, hydrological considerations are not entertained in their study, which may lead to an overestimation or underestimation of water availability for future needs. For instance, water in one tributary (sub-basin) is physically unavailable for users in another tributary (sub-basin) if there is no connecting conduit, and failing to consider this may result in an overestimation. In addition, return flows from upstream users can be a source of water for downstream users, and an underestimation may occur if return flow is not taken into account.

6.4 Summary

Two versions of a basin-wide hydro-economic optimization model are developed to estimate the minimum water requirement to produce no less net benefits under different conservation limit scenarios. The minimum requirement with a given conservation limit can be considered as an achievable conservation target for water demand management. It is found that for the SSRB case irrigation is the largest water consumer and can be the greatest contributor in water conservation, and should be the first place to investigate. MI users' main contribution is on the economic side rather than water side, even though their reactions regarding conservation limit are diversified depending on the formulation used. It is important to involve both the irrigation and MI users for the basin-wide water demand management, because without irrigation users, MI users have limited effectiveness in reducing overall water withdrawal or water consumed without sacrificing overall net benefits. Therefore, it can be argued that any attempt of water demand management strategies in a basin without considering irrigation user could hardly be successful to alleviate water stress faced by water managers and users. By the implementation of basin-wide water demand management, the overall water productivity is considerably improved on account of the significant water conservation from the irrigation sector and the economic benefits produced from MI sectors.

Overall, this study presents a hydrologic-economic perspective to estimate conservation potential in a basin, and can be utilized to assist in designing better strategies for water demand management. Even though great conservation potential is observed in the SSRB case, relatively low level of successful water transfer demonstrates that converting the potential to real exercises is not easy. There are still many obstacles that need to overcome for promoting water transfer among users in a basin, especially within a prior water right system. Most importantly, proper incentive is necessary to be in place in order to motivate certain users to conserve water.

Chapter 7

Contributions and Future Opportunities

7.1 Summary of Contributions

The overall contribution of this dissertation is the development of various water demand management methodologies based on two principles: one is to increase the aggregated benefits given the current water availability; another is to decrease the aggregated water consumption while maintaining at least the same level of benefits. The specific original contributions in this thesis are summarized in Table 7.1 and explained in more detail below.

Table 7.1 Summary of main contributions to the development of water demand management methodologies

Chapter	Main Contributions
2 & 3	A comprehensive review of various aspects of water demand management provides a better understanding of the advantages and barriers for water demand management. Equitable initial allocation methods are introduced to obtain a baseline scenario for various water demand management methodologies.
4	A modified cooperative game is presented for fairly sharing additional net benefits under the cases when water demand management plans are implemented.
5	An agent-based model is proposed for investigating the responses of different users regarding water conservation and compensation.
6	A hydrologic-economic model is presented for estimating the minimum water requirements without compromising benefits based on two formulations.

An in-depth analysis of several aspects of water demand management is provided in Chapter 2. The analysis of key characteristics of consumptive uses furnishes a better understanding of how they can be managed, which is fundamental to water demand management. The comprehensive review of water demand management definitions and measures emphasizes the well-established technological capacity and the importance of positive incentives in the implementation of water demand management. Water demand management at the basin level has rarely been studied, but when it is integrated as a component into a basin water allocation framework, it can provide more options for water management. Two equitable initial water allocation models are introduced in Chapter 3 to obtain the initial water rights under one's control with a given water availability. This initial allocation constitutes a baseline scenario for various water demand management methodologies.

Based on the characteristics of different consumptive uses, a water demand management plan is specified and incorporated into a fair water allocation model in Chapter 4 in which its associated impacts on individual users and the overall system are assessed. A modified cooperative reallocation game is put forward to fairly redistribute the additional benefits among users under various scenarios having a water demand management plan. A range of core-based and non-core-based solution concepts within cooperative game theory are incorporated into the modified cooperative reallocation game. The results of an illustrative case study demonstrate that under all solution concepts, the net benefits of the overall system and individual users are improved in comparison to the scenario without a water demand management plan. These additional net benefits may provide positive incentives for individual users to implement water demand management and improve the benefits further more.

An agent-based model is proposed for water demand management in Chapter 5 to take into account the heterogeneity of capacities and willingness levels of different users. The decision rule of each agent is converted to an individual optimization problem in which each agent aims to maximize his or her own net benefits, either from water utilization or compensation, without violating hydrologic and socio-economic constraints related to this agent. The interaction mechanism among agents and the environment is expressed by a coordination procedure. The decisions made by individual agents and the impacts of these individual decisions on the overall system are monitored by a coordinator. The system performance serves as a termination criterion for the coordination procedure, and the coordination stops when the aggregated net benefits of the overall system reaches its maximum. The results of an illustrative case study demonstrate that water is transferred from agricultural agents to municipal and industrial agents, and compensation is given to agricultural agents. All agents can be motivated to implement water demand management because of the accruement of more net benefits.

According to the second principle: “to decrease aggregated water consumption while achieving at least the same level of benefit”, two formulations representing two different interpretations of water consumption are proposed in Chapter 6 to estimate the minimum water requirement. The case study in the South Saskatchewan River Basin (SSRB) demonstrates that great conservation potential is observed, but requires the cooperation of the irrigation, and municipal and industrial users.

In summary, a useful array of possible solutions consisting of several methodologies on demand management is put forward for alleviating water stress facing society from a systems management perspective. The results of several illustrative case studies demonstrate the usefulness and advantages of incorporating water demand management into a basin water allocation framework. Meaningful insights and implications on how to encourage water users to utilize water wisely are obtained and can be used to support more informative water management.

7.2 Future Opportunities

As summarized in the previous section, this research in thesis includes several original methodologies for water demand management purposes, which can be further expanded. In addition, water demand management involves more aspects than what have been presented in this dissertation, and, hence, more work can be executed in the future. Worthwhile future research opportunities are now explained.

In Chapter 4, only water reduction by irrigators is investigated. However, domestic, general, and industrial users also have a huge potential for using less water, as indicated by a case study in California that found that about 30% of its urban water use can be conserved (Gleick et al. 2003). Consequently, the positive impacts of incorporating the water conservation of urban users into a water demand management plan can be further investigated.

In Chapter 5, the value of benefit or cost per unit of water conserved or consumed is assumed to be the same for all agents. However, the presence of diverse values for different agents may reflect real situations more realistically. Therefore, these cases can be further examined using empirical data.

In Chapter 6, the value of conservation limit parameter is assumed to be the same for all users. However, in the short term, some municipal or industrial users may not be able to conserve a significant amount of water. In this case, different conservation limits of different users can be taken into consideration and tested through scenario analyses.

The second principle of decreasing aggregated water consumption while achieving no less benefits than the current ones can also be investigated from a decentralized perspective. Therefore, one can explore how to best coordinate users such that both the individual and system benefits are at least the same as current levels whereas aggregated water consumption is minimal.

Valuable insights are obtained by using illustrative case studies; however, more complex real world case studies can be further tested. Additionally, water demand management can also be studied from other perspectives, such as institutional and legal viewpoints.

The approaches developed in this dissertation are deterministic. However, uncertainty often exists in both hydrologic and economic aspects of water demand management problems, and may play an important role in affecting users' decisions. Hence, uncertainty could be incorporated into the approaches developed in this thesis in the future.

In this research, water transfers from agricultural users to city users are considered as a way to improve basin-wide productivity. However, the decrease of water consumption in agriculture may have an impact on food production. The specific impacts could be investigated within the food-water-energy nexus.

Three overarching goals are emphasized in this two-stage planning procedure, in which social equity is addressed in the initial allocation step, economic efficiency is improved through transfers among users in the second step, and environmental sustainability is taken into account in both steps. Assessing how well all three goals are considered within an overall framework is an interesting problem to investigate. A systematic evaluation of the improvements of the three goals by using a series of indexes, such as conservation target achieved, net benefits reached, joint efficiency obtained, and productivity met, could be a worthwhile direction for future research following the contributions put forward by Joyce et al. (2017).

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Appendix A

Economic Input Data for Case Study in Chapters 4 and 5

This appendix A provides the economic input data used in the case study in Chapters 4 and 5.

Table A.1 Choke quantity (Q_0) of the monthly water demand function for MI nodes (mcm*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	0.233	0.217	0.233	0.236	0.235	0.257	0.259	0.270	0.246	0.258	0.239	0.248
D2	6.582	5.825	6.412	6.497	6.469	6.469	7.723	7.501	6.840	6.753	6.412	6.497
G1	0.249	0.232	0.249	0.253	0.260	0.284	0.287	0.299	0.272	0.276	0.256	0.266
G2	3.955	3.500	3.853	3.904	3.995	3.995	4.770	4.632	4.225	4.058	3.853	3.904
I1	2.608	2.608	2.771	2.934	4.629	4.792	4.890	4.890	4.238	4.075	2.608	2.608
I2	6.273	6.273	6.665	7.057	11.135	11.527	11.762	11.762	10.194	9.802	6.273	6.273

*1 mcm = 1 million cubic meters

Table A.2 Choke price (P_0) of the monthly water demand function for MI nodes ($\$/m^3$)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
D2	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
G1	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
G2	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
I1	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500
I2	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500

Table A.3 Scale parameter $\alpha\ (k, t)$ of the monthly water demand function for MI nodes

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	0.443	0.413	0.443	0.449	0.526	0.574	0.580	0.604	0.550	0.491	0.455	0.473
D2	12.531	11.088	12.207	12.369	14.466	14.466	17.270	16.772	15.296	12.855	12.207	12.369
G1	0.412	0.384	0.412	0.417	0.487	0.531	0.536	0.559	0.509	0.456	0.423	0.439
G2	6.529	5.777	6.360	6.444	7.475	7.475	8.924	8.666	7.903	6.698	6.360	6.444
I1	7.846	7.846	8.336	8.827	13.927	14.417	14.711	14.711	12.750	12.259	7.846	7.846
I2	9.919	9.919	10.539	11.159	17.606	18.226	18.598	18.598	16.118	15.498	9.919	9.919

Table A.4 Price elasticity *β (k, t)* of the monthly water demand function for MI nodes

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
D2	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
G1	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
G2	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
I1	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202
I2	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500

Table A.5 Water cost for water withdrawal and diversion to municipal and industrial demand nodes ($\$/m^3$)

	Water treatment	Water distribution	Wastewater treatment	Total cost
D1	0.1404	0.1092	0.2028	0.4524
D2	0.0673	0.0659	0.1426	0.2758
G1	0.1404	0.1092	0.2028	0.4524
G2	0.0673	0.0659	0.1426	0.2758
I1	0.1404	0.1092	0.2028	0.4524
I2	0.0673	0.0659	0.1426	0.2758

Table A.6 Water cost for water withdrawal to agricultural demand nodes ($\$/m^3$)

	Pumping cost
A1	0.0177
A2	0.0177

Appendix B

Hydrologic and Economic Input Data for Case Study in Chapter 6

This appendix B provides the input data used in the SSRB case study in Chapter 6.

Table B.1 Monthly water supply from surface runoff at inflow nodes (mcm*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IN1	6.910	6.181	6.683	9.240	40.042	78.019	68.031	47.676	29.160	18.749	10.303	7.995
IN2	12.053	9.870	10.298	13.608	68.701	163.296	143.294	89.592	50.803	31.471	18.662	14.062
IN3	13.794	11.467	10.231	5.754	6.227	10.498	10.874	9.415	7.089	6.803	10.485	13.526
IN4	3.817	3.411	4.312	6.104	19.418	31.493	20.892	12.455	10.212	8.531	5.962	4.634
IN5	0.469	0.943	3.134	3.447	2.772	2.864	2.397	1.594	1.503	1.339	0.850	0.581
IN6	3.254	2.830	4.111	11.223	52.229	64.282	27.454	11.798	8.178	7.178	5.314	3.924
IN7	0.147	0.151	0.364	1.309	4.486	4.147	1.714	0.943	0.674	0.570	0.334	0.214
IN8	5.343	4.342	5.156	14.386	66.290	97.848	44.595	15.133	10.666	11.490	9.746	6.455
IN9	2.518	2.286	2.812	7.944	29.328	39.398	21.829	9.455	6.247	6.522	4.977	3.227
IN10	5.879	5.189	7.151	17.366	63.880	94.738	49.818	22.766	18.014	17.142	12.519	7.700

*1 mcm = 1 million cubic meters

Table B.2 Monthly water supply of flow adjustments from local tributaries for accounting for precipitations (mcm). Water adjustments only occur at junction, reservoir, instream flow, and outflow nodes.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
J1	4.375	3.319	6.563	9.014	22.743	30.097	25.609	22.177	17.236	5.242	4.639	4.601
J2	0.669	0.508	1.004	1.379	3.480	4.605	3.918	3.393	2.637	0.802	0.710	0.704
J3	0.669	0.508	1.004	1.379	3.480	4.605	3.918	3.393	2.637	0.802	0.710	0.704
J4	3.130	2.374	4.695	6.449	16.270	21.532	18.321	15.865	12.331	3.751	3.319	3.292
J5	5.852	4.439	8.778	12.057	30.420	40.258	34.254	29.664	23.055	7.012	6.205	6.155
J6	1.030	0.679	1.405	1.833	3.132	3.689	2.781	2.681	2.318	1.107	0.989	0.978
J7	2.148	3.060	2.446	4.848	5.309	10.042	2.000	6.299	4.942	1.651	2.099	1.418
J8	0.710	0.468	0.968	1.263	2.159	2.542	1.917	1.848	1.598	0.763	0.682	0.674
J9	4.393	2.895	5.990	7.812	13.354	15.725	11.856	11.432	9.884	4.717	4.218	4.168
J10	1.869	1.343	0.748	0.328	0.090	0.443	0.009	0.499	0.802	0.052	0.135	0.069
R1	2.164	1.230	1.925	2.574	6.378	10.490	10.603	7.984	5.638	2.255	1.811	1.948
R2	0.644	0.489	0.966	1.327	3.348	4.431	3.770	3.265	2.538	0.772	0.683	0.677
R3	0.644	0.489	0.966	1.327	3.348	4.431	3.770	3.265	2.538	0.772	0.683	0.677
R4	0.033	0.025	0.050	0.069	0.174	0.230	0.195	0.169	0.132	0.040	0.035	0.035

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R5	0.019	0.014	0.028	0.038	0.096	0.128	0.109	0.094	0.073	0.022	0.020	0.019
R6	0.921	0.607	1.256	1.638	2.800	3.297	2.486	2.397	2.072	0.989	0.884	0.874
R7	0.335	0.254	0.502	0.689	1.740	2.302	1.959	1.696	1.318	0.401	0.355	0.352
R8	2.508	1.653	3.420	4.460	7.623	8.977	6.768	6.526	5.643	2.693	2.408	2.380
R9	0.131	0.086	0.179	0.233	0.398	0.469	0.353	0.341	0.295	0.141	0.126	0.124
R10	0.710	0.468	0.968	1.262	2.158	2.541	1.916	1.847	1.597	0.762	0.682	0.674
R11	0.497	0.764	0.545	1.152	1.172	2.392	0.316	1.472	1.141	0.355	0.483	0.303
R12	0.018	0.012	0.025	0.033	0.056	0.066	0.050	0.048	0.041	0.020	0.018	0.017
R13	0.532	0.818	0.584	1.233	1.255	2.562	0.339	1.577	1.222	0.380	0.517	0.324
R14	0.090	0.059	0.123	0.160	0.273	0.322	0.243	0.234	0.202	0.097	0.086	0.085
R15	0.089	0.058	0.121	0.158	0.269	0.317	0.239	0.230	0.199	0.095	0.085	0.084
R16	0.064	0.042	0.088	0.114	0.196	0.230	0.174	0.167	0.145	0.069	0.062	0.061
R17	0.111	0.073	0.151	0.197	0.337	0.397	0.299	0.288	0.249	0.119	0.106	0.105
S1	6.110	3.473	5.434	7.267	18.007	29.616	29.937	22.541	15.917	6.367	5.113	5.499
S2	2.428	1.842	3.642	5.003	12.622	16.704	14.213	12.308	9.566	2.910	2.575	2.554
S3	7.834	5.738	7.005	10.444	10.728	19.655	4.733	13.009	13.448	4.653	4.171	3.835
S4	6.355	4.314	8.489	11.505	21.340	29.040	18.834	15.448	16.793	8.582	7.330	6.819
O1	34.029	19.540	31.069	41.558	101.002	164.451	163.296	123.312	88.844	36.031	29.025	30.933

Table B.3 Monthly water demand of consumptive uses (mcm). Agricultural uses require water resources only in the crop growing season from May to September, and their water demand is assumed to be zero in other months.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	0	0	0	0	15.332	38.462	47.352	32.119	17.380	0	0	0
A2	0	0	0	0	27.221	147.970	209.984	118.812	38.340	0	0	0
A3	0	0	0	0	77.054	228.020	291.392	178.108	86.933	0	0	0
A4	0	0	0	0	33.971	101.871	127.641	79.743	38.417	0	0	0
A5	0	0	0	0	6.353	12.338	18.648	11.852	6.384	0	0	0
A6	0	0	0	0	2.443	22.287	45.180	9.623	1.729	0	0	0
A7	0	0	0	0	21.768	89.185	155.901	69.427	25.805	0	0	0
A8	0	0	0	0	12.851	59.718	80.034	51.842	20.424	0	0	0
A9	0	0	0	0	34.537	150.904	216.540	131.288	42.559	0	0	0
D1	0.445	0.414	0.445	0.451	0.528	0.577	0.583	0.607	0.552	0.493	0.457	0.475
D2	11.424	10.109	11.129	11.277	12.887	12.887	15.385	14.942	13.626	11.720	11.129	11.277
D3	0.893	0.825	0.934	0.989	1.263	1.538	1.648	1.951	1.374	0.989	0.866	0.879
D4	0.409	0.368	0.396	0.444	0.673	0.763	0.958	0.985	0.694	0.541	0.402	0.409

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G1	0.420	0.392	0.420	0.426	0.499	0.545	0.550	0.573	0.522	0.466	0.431	0.448
G2	6.152	5.444	5.993	6.073	6.940	6.940	8.285	8.047	7.338	6.311	5.993	6.073
G3	1.058	0.978	1.107	1.172	1.498	1.823	1.954	2.313	1.629	1.172	1.026	1.042
G4	0.485	0.436	0.469	0.527	0.798	0.905	1.135	1.168	0.822	0.641	0.477	0.485
I1	8.345	8.345	8.866	9.388	14.812	15.334	15.647	15.647	13.561	13.039	8.345	8.345
I2	9.209	9.209	9.785	10.361	16.347	16.922	17.268	17.268	14.965	14.390	9.209	9.209
I3	0.919	0.919	0.976	1.034	1.631	1.689	1.723	1.723	1.493	1.436	0.919	0.919
I4	3.046	3.046	3.237	3.427	5.407	5.598	5.712	5.712	4.950	4.760	3.046	3.046
H1	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000
H2	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000
S1	17.503	17.503	17.503	17.503	35.006	35.006	35.006	35.006	35.006	17.503	17.503	17.503
S2	75.526	75.526	75.526	75.526	151.050	151.050	151.050	151.050	151.050	75.526	75.526	75.526
S3	33.354	33.354	33.354	33.354	66.708	66.708	66.708	66.708	66.708	33.354	33.354	33.354
S4	37.655	37.655	37.655	37.655	75.310	75.310	75.310	75.310	75.310	37.655	37.655	37.655

Table B.4 Monthly storage demand of reservoir nodes (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R1	163.292	163.292	163.292	163.292	163.292	163.292	163.292	163.292	163.292	163.292	163.292	163.292
R2	60.792	60.792	60.792	60.792	60.792	60.792	60.792	60.792	60.792	60.792	60.792	60.792
R3	210.206	210.206	210.206	210.206	210.206	210.206	210.206	210.206	210.206	210.206	210.206	210.206
R4	18.833	18.833	18.833	18.833	18.833	18.833	18.833	18.833	18.833	18.833	18.833	18.833
R5	10.460	10.460	10.460	10.460	10.460	10.460	10.460	10.460	10.460	10.460	10.460	10.460
R6	381.420	381.420	381.420	381.420	381.420	381.420	381.420	381.420	381.420	381.420	381.420	381.420
R7	375.156	375.156	375.156	375.156	375.156	375.156	375.156	375.156	375.156	375.156	375.156	375.156
R8	392.144	392.144	392.144	392.144	392.144	392.144	392.144	392.144	392.144	392.144	392.144	392.144
R9	76.508	76.508	76.508	76.508	76.508	76.508	76.508	76.508	76.508	76.508	76.508	76.508
R10	51.979	51.979	51.979	51.979	51.979	51.979	51.979	51.979	51.979	51.979	51.979	51.979
R11	135.537	135.537	135.537	135.537	135.537	135.537	135.537	135.537	135.537	135.537	135.537	135.537
R12	9.432	9.432	9.432	9.432	9.432	9.432	9.432	9.432	9.432	9.432	9.432	9.432
R13	316.478	316.478	316.478	316.478	316.478	316.478	316.478	316.478	316.478	316.478	316.478	316.478
R14	117.038	117.038	117.038	117.038	117.038	117.038	117.038	117.038	117.038	117.038	117.038	117.038
R15	152.264	152.264	152.264	152.264	152.264	152.264	152.264	152.264	152.264	152.264	152.264	152.264
R16	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000
R17	99.272	99.272	99.272	99.272	99.272	99.272	99.272	99.272	99.272	99.272	99.272	99.272

Table B.5 Monthly minimum outlet flow (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
O1	72.649	54.157	77.695	110.160	110.160	110.160	110.160	110.160	110.160	102.109	80.058	71.730

Table B.6 Water loss (consumption) ratios at agricultural uses (return flow ratio = 1 − loss ratio)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A2	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A3	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A4	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A5	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A6	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A7	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A8	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
A9	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Table B.7 Water loss (consumption) ratios at municipal and industrial uses

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
D2	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
D3	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
D4	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
G1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
G2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
G3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
G4	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
I1	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
I2	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051
I3	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
I4	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035

Table B.8 Choke quantity (Q_0) of the monthly water demand function for municipal and industrial uses (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	0.233	0.217	0.233	0.236	0.235	0.257	0.259	0.270	0.246	0.258	0.239	0.248
D2	6.582	5.825	6.412	6.497	6.469	6.469	7.723	7.501	6.840	6.753	6.412	6.497
D3	0.503	0.465	0.526	0.557	0.616	0.750	0.804	0.952	0.670	0.557	0.488	0.495
D4	0.200	0.179	0.193	0.217	0.274	0.311	0.390	0.401	0.283	0.264	0.196	0.200
G1	0.249	0.232	0.249	0.253	0.260	0.284	0.287	0.299	0.272	0.276	0.256	0.266
G2	3.955	3.500	3.853	3.904	3.995	3.995	4.770	4.632	4.225	4.058	3.853	3.904
G3	0.639	0.590	0.668	0.707	0.797	0.970	1.039	1.230	0.866	0.707	0.619	0.628
G4	0.258	0.231	0.249	0.280	0.362	0.410	0.515	0.530	0.373	0.341	0.253	0.258
I1	2.608	2.608	2.771	2.934	4.629	4.792	4.890	4.890	4.238	4.075	2.608	2.608
I2	6.273	6.273	6.665	7.057	11.135	11.527	11.762	11.762	10.194	9.802	6.273	6.273
I3	0.700	0.700	0.744	0.788	1.243	1.287	1.313	1.313	1.138	1.094	0.700	0.700
I4	1.113	1.113	1.182	1.252	1.975	2.045	2.087	2.087	1.808	1.739	1.113	1.113

Table B.9 Choke price (P_0) of the monthly water demand function for municipal and industrial uses ($\$/m^3$)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
D2	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
D3	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
D4	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
G1	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
G2	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
G3	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
G4	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500	3.500
I1	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500
I2	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500
I3	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500
I4	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500

Table B.10 Scale parameter $\alpha (k, t)$ of the monthly water demand function for municipal and industrial uses

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	0.443	0.413	0.443	0.449	0.526	0.574	0.580	0.604	0.550	0.491	0.455	0.473
D2	12.531	11.088	12.207	12.369	14.466	14.466	17.270	16.772	15.296	12.855	12.207	12.369
D3	0.957	0.884	1.001	1.060	1.378	1.678	1.798	2.128	1.499	1.060	0.928	0.942
D4	0.380	0.341	0.367	0.412	0.613	0.696	0.873	0.898	0.632	0.502	0.373	0.380
G1	0.412	0.384	0.412	0.417	0.487	0.531	0.536	0.559	0.509	0.456	0.423	0.439
G2	6.529	5.777	6.360	6.444	7.475	7.475	8.924	8.666	7.903	6.698	6.360	6.444
G3	1.054	0.974	1.102	1.168	1.490	1.814	1.944	2.301	1.620	1.168	1.022	1.037
G4	0.425	0.382	0.411	0.462	0.677	0.768	0.963	0.991	0.698	0.562	0.418	0.425
I1	7.846	7.846	8.336	8.827	13.927	14.417	14.711	14.711	12.750	12.259	7.846	7.846
I2	9.919	9.919	10.539	11.159	17.606	18.226	18.598	18.598	16.118	15.498	9.919	9.919
I3	0.969	0.969	1.029	1.090	1.719	1.780	1.816	1.816	1.574	1.513	0.969	0.969
I4	2.335	2.335	2.481	2.627	4.145	4.291	4.379	4.379	3.795	3.649	2.335	2.335

Table B.11 Price elasticity $\beta (k, t)$ of the monthly water demand function for municipal and industrial uses

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D1	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
D2	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
D3	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
D4	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
G1	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
G2	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
G3	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
G4	-0.400	-0.400	-0.400	-0.400	-0.500	-0.500	-0.500	-0.500	-0.500	-0.400	-0.400	-0.400
I1	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202	-1.202
I2	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500	-0.500
I3	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354	-0.354
I4	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809	-0.809

Table B.12 Coefficient (b_0) of the quadratic benefit function for agricultural uses

b_0	May	Jun	Jul	Aug	Sep
A1	0.229384	0.229384	0.229384	0.229384	0.229384
A2	2.809884	2.809884	2.809884	2.809884	2.809884
A3	1.759267	1.759267	1.759267	1.759267	1.759267
A4	1.147782	1.147782	1.147782	1.147782	1.147782
A5	0.036077	0.036077	0.036077	0.036077	0.036077
A6	0.201897	0.201897	0.201897	0.201897	0.201897
A7	1.939695	1.939695	1.939695	1.939695	1.939695
A8	1.841638	1.841638	1.841638	1.841638	1.841638
A9	3.672924	3.672924	3.672924	3.672924	3.672924

Table B.13 Coefficient (b_1) of the quadratic benefit function for agricultural uses

b_1	May	Jun	Jul	Aug	Sep
A1	0.053980	0.062118	0.065583	0.059591	0.057122
A2	0.066166	0.106401	0.121373	0.102598	0.079602
A3	0.059480	0.073461	0.078915	0.068518	0.063009
A4	0.058646	0.070739	0.072021	0.071412	0.068277
A5	0.055329	0.057303	0.066217	0.058034	0.055630
A6	0.062923	0.090661	0.108761	0.090815	0.062056
A7	0.072605	0.096342	0.124205	0.094469	0.077132
A8	0.074814	0.111429	0.123685	0.112607	0.093616
A9	0.077378	0.113501	0.128939	0.115394	0.088426

Table B.14 Coefficient (b_2) of the quadratic benefit function for agricultural uses

b_2	May	Jun	Jul	Aug	Sep
A1	-0.000667	-0.000366	-0.000332	-0.000401	-0.000674
A2	-0.000430	-0.000202	-0.000175	-0.000239	-0.000481
A3	-0.000144	-0.000077	-0.000069	-0.000086	-0.000149
A4	-0.000333	-0.000174	-0.000125	-0.000208	-0.000375
A5	-0.001723	-0.000967	-0.000877	-0.001036	-0.001745
A6	-0.004599	-0.000938	-0.000647	-0.002687	-0.007299
A7	-0.000640	-0.000293	-0.000255	-0.000360	-0.000680
A8	-0.001104	-0.000531	-0.000468	-0.000614	-0.001143
A9	-0.000454	-0.000216	-0.000184	-0.000253	-0.000501

Table B.15 Water cost for water withdrawal and diversion to municipal and industrial demand nodes ($/m^3)

	Water treatment	Water distribution	Wastewater treatment	Total cost
D1	0.1404	0.1092	0.2028	0.4524
D2	0.0673	0.0659	0.1426	0.2758
D3	0.0898	0.1197	0.1684	0.3779
D4	0.0662	0.0691	0.1403	0.2756
G1	0.1404	0.1092	0.2028	0.4524
G2	0.0673	0.0659	0.1426	0.2758
G3	0.0898	0.1197	0.1684	0.3779
G4	0.0662	0.0691	0.1403	0.2756
I1	0.1404	0.1092	0.2028	0.4524
I2	0.0673	0.0659	0.1426	0.2758
I3	0.0898	0.1197	0.1684	0.3779
I4	0.0662	0.0691	0.1403	0.2756

Table B.16 Water cost for water withdrawal to agricultural demand nodes ($/m^3)

	Pumping cost
A1 to A9	0.0177

Table B.17 Initial reservoir storage (mcm)

R1	163.292
R2	60.792
R3	210.206
R4	18.833
R5	10.460
R6	381.420
R7	375.156
R8	122.545
R9	76.508
R10	51.979
R11	84.711
R12	9.432
R13	98.899
R14	117.038
R15	152.264
R16	15.000
R17	99.272