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Thema

The Water Situation of the Future Mega City "Urumqi" (NW-China) – Resources, Risk, Conservation and Management

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Summary

Urumqi is located in the remote center of the Eurasian continent. It is a future mega-city with rapid economic development and high population density in China's western interior. Urumqi's water resource problems are the main research objects in this thesis. Several models have been put forward to predict water demand in Urumqi and useful suggestions have been gathered to reduce water scarcity.

In 2010, the average annual water resources of Urumqi were at 939.22 million m^3 and the average per capita water resources were 387 m^3, meaning that water resources are inadequate in Urumqi. The water consumption in Urumqi already exceeded the total amount of water resources. Furthermore, almost half of the wastewater is discharged directly into rivers and wasteland in Urumqi and as such, both surface water and groundwater are seriously polluted. Since there is also no reasonable water price system, the price of water is relative low which leads to weak awareness of water conservation. In addition, the high leakage rate of the pipe network and the backward technology of agricultural irrigation have resulted in serious water losses.

In order to alleviate the scarcity of water resources and instead increase the number of resources, while at the same time improving water quality, wastewater in Urumqi and how it is reused of Urumqi was analyzed. Some suggestions about Urumqi's sewage and water reuse system were put forward. Moreover, various water scarcity assessment indexes were used to evaluate the water scarcity risk in Urumqi. Based on the results of a water scarcity risk assessment, the water scarcity decision model was built up by adopting the advanced Analytic Hierarchy Process (AHP) methodology. The measures to reduce water scarcity include a.o. adjusting industrial structures, water conservation, using unconventional water resources, implementing economic regulation measures, controlling environmental safety, improving urban functions, and the interbasin transfer of water. According to the results of the analysis of water scarcity decisions, major solutions to resolve the problem of water scarcity were identified, with water conservation as the most important step in reducing water scarcity in Urumqi. In addition, a water conservation index system was set up based on the water-saving evaluation standard in China to change the present situation of serious wastage of water resources in Urumqi. This index system can be used to reflect the problems (e.g. high leakage rate of the water supply pipe network, low water price, low conveyance efficiency of irrigation canal system, low rate of recycled industrial water and water conservation awareness) and the potentials of water conversation in each sector (agriculture, industry and domestic). The results of the index system show that there is a large potential of agricultural water conservation, and it can be achieved by several measures, such as improving the water efficiency of the canal system, promoting the usage of advanced water conservation irrigation techniques and increasing the water price for agricultural irrigation.

In addition, the "quota method" and the "grey model" (used to analyze the system, which related to time includes both certain and uncertain information) were used to predict water demand. The "quota method" predicts the water demand based on indicators of socio-economic development and the water use quota in each sector. The "grey model" was constructed according to the time series of agricultural, industrial, domestic and total water consumption in Urumqi from 2003 to 2010 by creating a sequence of first-order accumulated generating operation and differential equations. The predictions that were calculated by using the grey model show that agriculture will still be the biggest user of water in 2015. Therefore, changing the agricultural system and improving the efficiency of agricultural water use are the best ways to realize the rational allocation and sustainable use of water resources in Urumqi. In order to effectively manage Urumqi's water resources and to integrate the water demand prediction model and the water scarcity decision model, the water resources management and information system for Urumqi was built up by using various technologies (database, Web and GIS server). This system not only reflects the current situation of Urumqi's water resources but also helps users to make decisions for reducing water scarcity.

Zusammenfassung

Die Stadt Urumqi befindet sich im Zentrum des Eurasischen Kontinents. Sie ist aufgrund des rapiden wirtschaftlichen Wachstums und der hohen Bevölkerungsdichte eine zukünftige Megastadt in Chinas westlichen Hinterland. Urumqis Wasserressourcen und damit zusammenhängende Probleme sind Hauptuntersuchungsgegenstand dieser Arbeit. Modelle zur Analyse der Situation der Wasserressourcen werden verwendet, um den Wasserbedarf für Urumqi vorherzusagen und sowie hilfreiche Vorschläge vorgebracht, um die Wasserknappheit zu reduzieren.

In 2010 betrug die durchschnittliche Menge an Wasserressourcen in Urumqi 939,22 Millionen m^3 und die durchschnittliche Verfügbarkeit pro Kopf 387 m^3. Die Wasserverfügbarkeit in Urumqi ist daher unzureichend, außerdem überschreitet der Wasserverbrauch die insgesamt verfügbare Menge an Wasser. Desweiteren fließt fast die Hälfte des Abwassers direkt in Flüsse und Brachland in Urumqi und daher sind sowohl Oberflächenwasser als auch Grundwasser ernsthaft verschmutzt. Da der Wasserpreis nicht den Produktions- und Entsorgungskosten entspricht und ziemlich niedrig ist, ist auch das Bewusstsein für das Wassersparen sehr gering. Zusätzlich verursachen die hohe Leckagerate der Wasserleitungen und die rückständige Technologie in der Bewässerungslandwirtschaft ernsthafte Wasserverluste.

Um die Wasserknappheit zu verringern und stattdessen die Menge an verfügbarem Wasser zu erhöhen, während gleichzeitig die Wasserqualität verbessert wird, wurde die Abwassersituation und die Nutzung geklärter Abwässer in Urumqi analysiert. Einige Vorschläge zur Verbesserung des System für Abwasser und Abwassernutzung in Urumqi werden vorgestellt. Weiterhin wurden verschiedene Indizes zur Bestimmung der Wasserknappheit verwendet, um das Risiko einer Wasserknappheit in Urumqi zu evaluieren. Basierend auf den Ergebnissen der Untersuchung wurde ein Entscheidungsmodell entwickelt, welches die Analytic Hierarchy Process (AHP)-Methode verwendet und die Auswirkungen verschiedener Maßnahmen und Entscheidungen analysiert. Die betrachteten Maßnahmen umfassen u. a. die Anpassung der industriellen Strukturen, Wassersparen, Nutzung unkonventioneller Wasserressourcen, Einführung

wirtschaftlicher Regulationsmechanismen, Überwachung der Umwelt, Verbesserung städtischer Funktionen und Wassertransfer zwischen Einzugsgebieten. Laut den Analyseergebnissen zu Entscheidungen bezüglich der Wasserressourcen wurden die wichtigsten Lösungsvorschläge für das Problem der Wasserknappheit identifiziert: Wassereinsparung und eine höhere Nutzungseffizienz sind die wichtigsten Schritte um die Wasserknappheit in Urumqi zu reduzieren. Zusätzlich wurde ein Indexsystem für Wassereinsparungen aufgesetzt basierend auf den Evaluationsstandards zum Wassersparen in China, um die aktuelle Situation und ernsthafte Verschwendung von Wasserressourcen in Urumqi zu reduzieren. Dieses Indexsystem kann verwendet werden, um die Probleme und Potenziale von Wassereinsparungen im Bezug auf Leckagerate, Wasserpreis, Transporteffizienz des Bewässerungssystems, Recyclingrate der geklärten Abwässer und Bewusstsein für das Wassersparen in den drei Sektoren Landwirtschaft, Industrie und Haushalte zu reflektieren. Die Ergebnisse des Indexsystems zeigen, dass großes Potenzial für Wassereinsparungen in der Landwirtschaft liegt. Die Einsparungen können erreicht werden durch verschiedene Maßnahmen wie die Verbesserung der Kanalsystems, Verwendung und Verbreitung fortschrittlicher wassersparender Bewässerungstechniken und Anpassung des Wasserpreises für die Bewässerungs landwirtschaft.

Zusätzlich wurden die "Quoten-Methode" und ein "grey model" verwendet, um den Wasserbedarf vorherzusagen. Die "Quoten-Methode" basiert auf Indikatoren für die sozio-ökonomische Entwicklung sowie die Wassernutzungs-Quote in jedem Sektor. Das "grey model" wird verwendet um Systeme zu analysieren, für welche im Bezug zur Zeit sowohl sichere als auch unsichere Informationen vorhanden sind. Anhand der Zeitreihe für den Wasserverbrauch in Urumqi durch Landwirtschaft, Industrie und Haushalte und Gesamtwasserverbrauch für die Jahre 2003 bis 2010 wurden eine Reihe von Accumulated Generating Operations (AGOs) erster Ordnung und Differenzialgleichungen entwickelt. Die Vorhersagen, die mit dem "grey model" berechnet wurden, besagen, dass auch im Jahr 2015 die Landwirtschaft der größte Wasserverbraucher sein wird. Daher stellen Veränderungen des Agrarsystems und Verbesserungen der landwirtschaftlichen Wassernutzungseffizienz die besten Möglichkeiten dar, eine rationale Allokation und nachhaltige Nutzung der Wasserressourcen in Urumqi zu erreichen. Um ein effektives Management der Wasserressourcen in Urumqi zu ermöglichen, wurden die Modelle zur Vorhersage des Wasserverbrauchs und das Entscheidungsmodell zur Analyse der Wasserknappheit kombiniert und ein Management und Informationssystem für die Wasserressourcen in Urumqi mit Hilfe verschiedener Methoden (Datenbanken, Web- und GIS-Server) aufgebaut. Das System repräsentiert nicht nur die aktuelle Situation der

Wasserressourcen in Urumqi, sondern unterstützt seine Nutzer dabei, nachhaltige Entscheidungen zur Reduzierung der Wasserknappheit zu treffen.

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1 Introduction

Water resources are the most valuable natural resource in the world. It is not only the foundation for human living, but also a lifeline for the economy, society and ecosystems. Fresh water makes up only 2.53 % of the total reserves of water on earth, and the available fresh water for humans makes up only 0.77 % of the global water reserves (ZHENG 2010). Meanwhile, the distribution of fresh water is uneven and water scarcity is a common regional phenomenon (SHAH 2001). Water resources can be affected by human activities, since human activities can disrupt water cycles in several ways, such as the emission of carbon dioxide (which alters ocean temperatures), dams (which alter the flow of waterways), and pollution (which impacts on water quality and usability) (DING 2008, 21).

At present, over 100 nations and states are confronted with water scarcity (average per capita water resources is less than 1000 m^3 per year), and 28 of them have been classified as nations or states with serious water scarcity (average per capita water resources is less than 500 m^3 per year) (ZHANG et al. 2001b, 35). With the continuous growth of population, more and more people will be under water stress conditions due to the limited water resources. By 2025 there will be 1.8 billion people living in regions with water scarcity (FAO 2012). In addition, water scarcity becomes an important factor that restricts the sustainable development of the economy and society. It is projected that water demand will exceed water supply by 56 % by the year 2025, due to the increasing water demand from domestic use, agriculture and industry (LEADERSHIP GROUP ON WATER SECURITY IN ASIA 2009, 7; WWO 2010). Therefore, the gap between water supply and water demand becomes increasingly prominent worldwide, especially in the regions already experiencing water scarcity. Urumqi, in the Northwest of China, is one of the water scarcity regions with the problem of increasing the gap between water demand and water supply.

Concentrating on these problems, this chapter is divided into the following sub-chapters: the main research fields of water resources (section 1.1), the research area of water resources (section 1.2), the problems of water resources in the research area (section 1.3), and research goals and approaches (section 1.4).

1.1 The main research fields of water resources

Water resources are the foundation for sustainable economic development. Water scarcity, water supply and water demand, water reuse, water conservation, and water resources management are the main research fields of water resources in the arid regions (including Urumqi).

1.1.1 Water scarcity

There are two kinds of water scarcity, physical water scarcity and economic water scarcity. Physical water scarcity means that water supply cannot meet all demands (such as the demands of production, living and ecology). Economic water scarcity is caused by a lack of economic investment in water management, or because water cannot be effectively extracted from the water resources (MOLDEN 2007). Water scarcity on a regional scale concerns lots of factors (such as water quantities and their spatial distribution, climatic conditions and economic structure) (LI et al. 2010, 1041). According to the analysis and assessment of regional water scarcity, water scarcity risk can be regulated by using a variety of risk-control measures such as water conservation and the adjustment of water price (RUAN et al. 2005, 906; HAN & XU 2007b, 81). In this way, the optimal solutions for reducing or solving water scarcity can be achieved.

1.1.2 Water supply and water demand

Water demand is growing because of the rapid development of population, the economy and urbanization. Due to the limited availability of water resources, water pollution and the unreasonable allocation of water resources, the gap between water supply and demand is intensified (TIEP 2002). However, based on variations of water consumption, a water demand prediction model can be built and the predicted results can provide a scientific and reliable basis for water resources planning and allocation (DONG 2009, 33; DU et al. 2011, 143).

1.1.3 Water reuse

Wastewater reclamation and reuse is one of the most effective ways to reduce water pollution, improve the ecological environment and reduce water scarcity (FRIEDLER & LAHAV 2006, 423; ABUDUSHATAER et al. 2007, 675). Treated wastewater can be used for agriculture irrigation, industry, urban applications, environmental water enhancement and groundwater recharge. The National Academy of Sciences of the United States reported that wastewater reuse would directly augment available water resources and the potential water resources from wastewater by 6 % of the estimated water use for United States (NAS 2012). In the United States, treated wastewater has been used for more than 40 years (MCKENZIE 2005, 51).

In Urumqi, however, most wastewater is not treated and directly discharged into rivers and wasteland. Indiscriminate disposal of untreated sewage and industrial effluents can pollute the environment, which can reduce the available water resources. In light of the successful experience of water reuse in the United States, there is great potential to increase the amount of reused water in Urumqi.

1.1.4 Water conservation

Besides water reuse, water conservation is another effective measure to reduce water scarcity. Water conservation can be realized by implementing conservation measures, such as high-efficiency plumbing programs, high-efficiency showerheads, water reclamation facilities and leak detection and repair programs (EPA 2002; XIAO et al. 2005, 143). Many countries have adopted such water conservation measures. In Germany, the government was required to consider water conservation within environmental politics (LAWA 1996). In the United States, water conservation methods and techniques have been developed and used for agricultural water conservation, industrial water conservation and domestic water conservation (DOI 2011). Although the standardization of water conservation technology in China began to be propagated in the 1980s, water conservation is still below expectations, especially in inland water scarcity regions (YANG et al. 2007, 2). Therefore, potential water conservation should be assessed using reasonable measures.

1.1.5 Water resources management

There is a lot of information on water resources that needs to be managed. The basic information about water resources can be divided into seven parts (WILLIAMS 1989; BOXER 2001; JANOSOVA et al. 2006, 269; RAHM et al. 2006; KANG 2011) (see Figure 1-1):

1. The information about principles, policies, strategies, planning, laws, and regulations of water resources
    - → The function of water resources management is to ensure water resources are rationally developed and utilized.
2. The information about water use, water allocation, water supply, water demand, water assessment and flood assessment

   → The function of water resources management is to provide guidance for water management.

3. The information about implementation supervision, water protection plans, water capacity of pollutant load, wastewater discharge, guidance for drinking water, groundwater exploitation and use
   → The function of water resources management is to protect water and water infrastructures.
4. The information about flood control, drought relief, emergency water allocation and emergency plans
   → The function of water resources management is to provide guidance on emergency treatment of water resources.
5. The information about water conservation and policies, water-saving plans, water recycling and water reuse
   → The function of water resources management is to provide the relevant standards and directions for the development of water resources.
6. The information about hydrological data, the management of hydrological stations and water resource information
   → The function of water resources management is to guide hydrological work and investment.
7. The information about the construction of farmland water facilities, water-saving irrigation and development of water-energy
   → The function of water resources management is to provide information about irrigation and drainage.

The common method of managing the information on water resources is to use a water information system. Such a system can integrate all the information about the water resources and realize the above-mentioned functions. For example, water can be treated as a multi-product economic commodity in the water management information system in order to analyze water quantity, water supply, water pricing and public policy (SPULBER & SABBAGHI 1998, 343). An information system-based integrating visualization software (GIS or MapX) was developed to manage the amounts of spatial data and to ensure water resources rational utilization (FENG et al. 2003, 226; MA et al. 2005, 176; ZEILHOFER et al. 2008, 23; GUO et al. 2011, 173). The system can also represent the present situation of water resources and show the quality and the movement of water.

A decision support system (DSS), which is commonly used in water resources management and information systems, is a common method to assist users in making decisions for water allocation and prediction (GU & TANG 2000, 59).

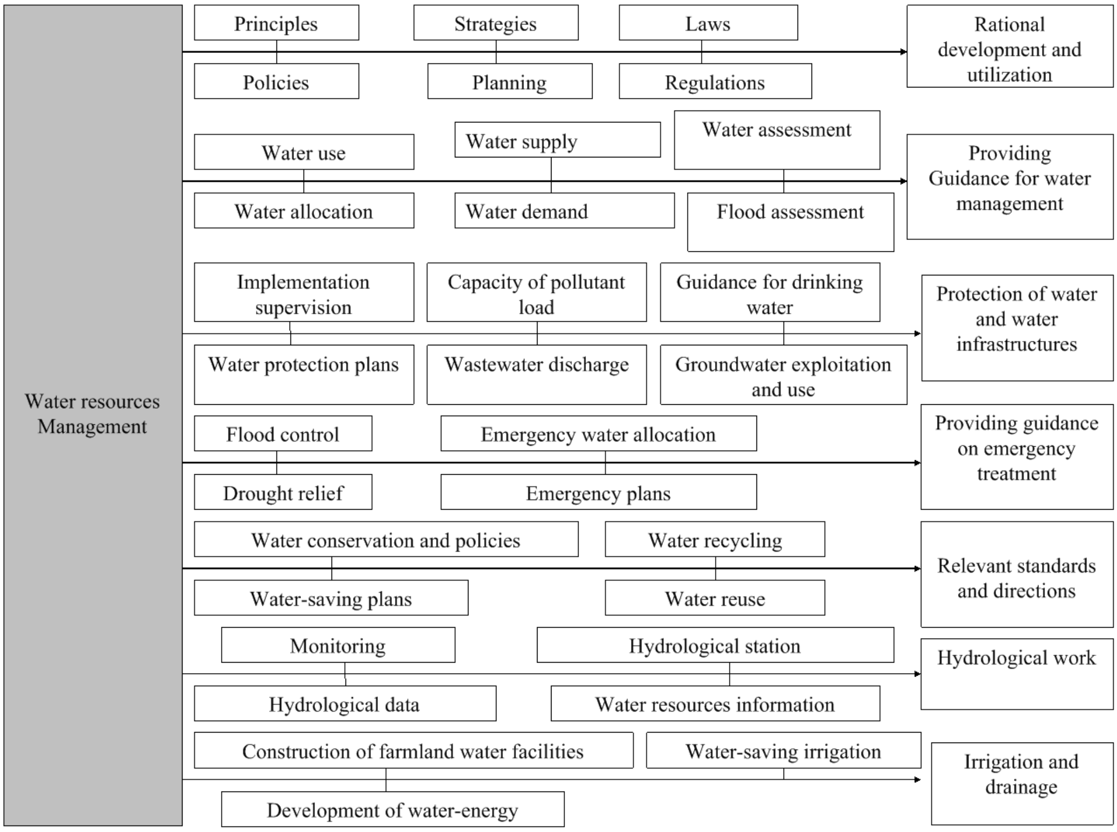

Figure 1-1 Basic information about water resources in water resources management (source: own design according to WILLIAMS 1989, BOXER 2001, JANOSOVA et al. 2006, RAHM et al. 2006 and KANG 2011).

1.2 Research area

The research area in this thesis is Urumqi (Wūlǔmùqí) in the northwest of China. It is situated in the center of Xinjiang Uyghur Autonomous Region (Xīnjiāng Wéiwú'ěr Zìzhìqū) of the People's Republic of China. It is located from 86°37'33"-88°58'24" east longitude to 42°45'32"-45°00'00" north latitude (see Figure 1-2).

Urumqi is the capital of Xinjiang Uygur Autonomous Region. It is the political, economic, cultural, scientific and technological center of Xinjiang as well as the second west bridgehead of the Eurasian Continental Bridge. It is the farthest away city from an ocean among all the inland cities in the world (LI et al. 2006c, 115). It is also a future mega-city with rapid economic development and a high population density in China's western interior (LI & TURSUN 2001, 12).

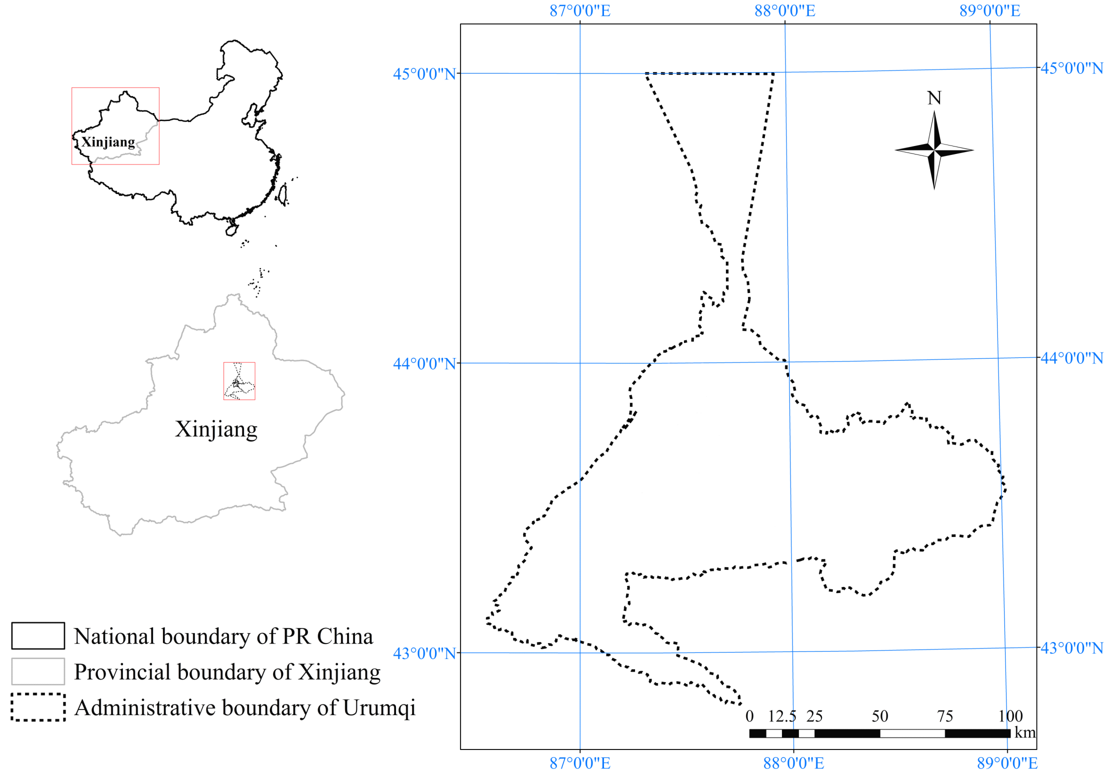

Figure 1-2 The location of Urumqi in China (source: AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; own design).

Urumqi is comprised of 7 districts (Xinshi District, Saybagh District, Tianshan District, Shuimogou District, Toutunhe District, Midong District, and Dabancheng District) and 1 county (Urumqi County). The central districts are Tianshan District, Saybagh District, Xinshi District and Shuimogou District (see Figure 1-3). The administrative area of Urumqi stretches 153 kilometers from North to South and 190 kilometers from East to West (WANG et al. 2012b, 878). It is adjacent to the middle region of the Tianshan Mountain and surrounded by mountains on three sides (East, South and West) (also see Figure 1-3).

The northwestern part of this region slopes down to the Junggar Basin (ZHANG 2008, 62). The elevation is high in the East and South, and low in the West and North. The natural slope is 12 ‰-15 ‰ (YIN et al. 2011, 1011). The altitude range is 450 meter to 4800 meter above the sea level. The mean elevation of Urumqi downtown is about 800 meters above sea level and the mountain areas comprises more than 50 % of the total area of Urumqi (PU & ZHANG 2011, 243) (also see Figure 1-3).

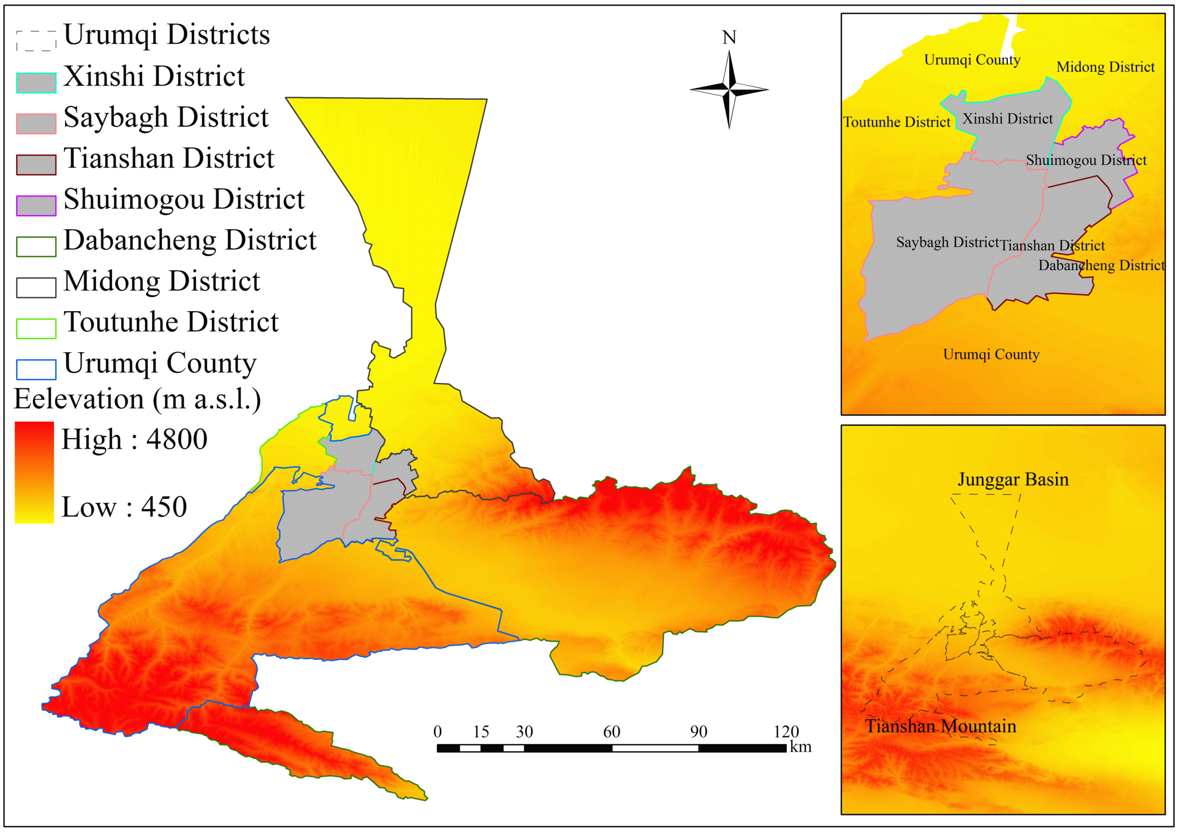

Figure 1-3 Urumqi's districts, the distribution of central districts and topographical features (source: SRTM-3; AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; own design).

The administrative area of Urumqi was 10,800 km² before 2007 (CHEN & YANG 2008, 13). In 2007, the government agreed to merge Miquan City of Changji Hui Autonomous Prefecture (Chāngjí Huízú Zìzhìzhōu) and Dongshan District of Urumqi to establish Midong District. Finally, the administrative area of Urumqi grew to 148,900 km² (ZHANG et al. 2012b, 818). For almost 20 years, Urumqi has experienced rapid expansion. Land use/cover has changed significantly. The growth of urban construction land reached 44.73 % in the central area and suburban area from 1990 to 2009 (WANG et al. 2012b, 878).

1.3 The problems of the water resources in Urumqi

In China, the average annual amount of total renewable freshwater resources is about 2.8 trillion m³ and the per capita water resources is about 2200 m³ which is only 25 % of the average world level. China is one of 13 countries with the highest water scarcity in the world (SHI et al. 2011, 50). Additionally, the spatial and temporal distribution of water resources in China is uneven and the pollution of water resources is becoming more and more serious. Furthermore, the water deficit (the gap between water demand and water supply) is about 30 to 40 billion m³ per year (SHANG & ZHANG 2007, 71). This amount of water is almost equal to the total water used (32 billion m³) by industry and private households in 2007 in Germany (FEDERAL MINISTRY FOR THE ENVIRONMENT NATURE CONSERVATION AND NUCLEAR SAFETY 2011).

About 400 Chinese cities experience water scarcity (average per capita water resources is less than 1000 m³ per year), of which 110 cities are suffering a more serious scarcity of water (average per capita water resources is less than 500 m³ per year) (ZHANG et al. 2009a, 118). In Urumqi the quantity of total water resources was 939.22 million m³ in 2010. The amount of usable water resources was 824 million m³ (ZHENG 2009, 232). The average per capita water resources was 387 m³ per year in Urumqi, which was 17.6 % of the average per capita water resources of China and 4 % of the world's average value (WATER AFFAIRS BUREAU OF URUMQI 2003-2010; SHI et al. 2011, 50). Urumqi was facing serous scarcity of water. In Urumqi, the water is used for agriculture, industry and domestic purposes. Since the development of the economy and population, agriculture and industry, is proceeding rather dynamically, more and more water resources are needed. In 2010, the total water consumption was 1089.31 million m³ and more than 60 % of it was used for agriculture. The total water consumption already exceeded the total water resources of 939.22 million m³ by far (WATER AFFAIRS BUREAU OF URUMQI 2010, 18). This means that about 150 million m³ of the consumed water had to be imported from other regions.

The main recharge sources of water resources in Urumqi are precipitation and snow-ice melt water (ZHANG 2008, 62). The average annual precipitation was about 304 mm (the average value of annual precipitation from 2003 to 2010). The average annual potential evaporation was 2300 mm, which is about 7 times higher than the annual precipitation. In addition, more than 70 % of the groundwater quality in the plain area was poor due to the indiscriminate discharge of untreated wastewater (ABUDUSHATAER et al. 2007, 675). The self-purification abilities of the rivers are low because most of the rivers in Urumqi are inland rivers with short waterways. This means that there is not enough water to dilute the polluted water (PAN 1999, 70; GUO 2005, 20). Runoff consumption is much greater than runoff production in the urban area, because the distribution of main recharges (precipitation and glacier melt water) of runoff is mainly determined by elevation. The further downstream, the worse the self-purification abilities of the rivers will be. The overall anti-pollution efforts with respect to water resources are poor in Urumqi (LI & TURSUN 2001, 14).

1.4 Research goals and approaches

In order to solve the problems mentioned in section 1.3, effective solutions (including suitable integrated water management on water supply and water consumption) for water scarcity and reasonable allocation of water resources for different sectors are crucial. In addition, controlling water consumption within the total availability of water resources is a core issue to achieve the sustainable economic development (YAO et al. 2002, 111). The sustainable use of limited water resources has become one of the major challenges of the world, especially in water scarcity regions. Urumqi can be regarded as a representative example of water scarcity regions with a rapidly developing economy and a large population. Corresponding to this challenge, the goals of this thesis are to assess water scarcity and explore solutions, predict future water demand and achieve an integrated management of water resources.

Due to the special location of Urumqi (the farthest inland region away from oceans and surrounded by mountains on three sides), the recharge of water resources, as well as the classification and distribution of water resources are different from other inland regions (chapter 2).

Treating wastewater as an additional water source (the first water source is natural water resources) is the first step that should be carried out to increase the amount of available water resources (ABUDUSHATAER et al. 2007, 675). According to the analysis of the current wastewater system and problems of water reuse in Urumqi, effective methods for improving the efficiency of water reuse and relieving water scarcity are suggested (chapter 3).

The severity of water scarcity can be determined by comparing water demand and water supply. Based on the analysis of water scarcity in Urumqi, water scarcity risk is comprehensively evaluated to determine the solutions which can reduce the water scarcity in Urumqi. By using water scarcity risk assessment indexes and adopting the Analytic Hierarchy Process methodology, the water scarcity decision model is built (HAN & XU 2007b, 81). The solutions derived from this decision model can provide important suggestions for water resource planning and management in Urumqi to ensure a sustainable use of water resources (chapter 4).

In all solutions for reducing water scarcity, water conservation is a direct and effective way to reduce the water scarcity crisis in Urumqi. In order to reflect the relationship between the development of Urumqi and water conservation, a very efficient way is to assess the potential of water conservation in each sector by building an integrated water conservation index system (ZHANG et al. 2008a, 1; JIA & LIU 2011, 73). Part of the important indexes can be used as standards to guide the future allocation of water resources in different sectors in Urumqi (chapter 5).

Water demand prediction plays an important role in water resources planning and managing for the future water demand and allocation (HE et al. 2007, 61). It is a vital reference for allocating water resources in each sector. Water demand prediction is also important for promoting the reasonable utilization of water resources and sustainable economic development in Urumqi. According to data requirement, accuracy of models, difficulty of parameter determination and complexity of water resource prediction models (e.g. artificial neural networks, fuzzy mathematical prediction model, support vector machine (SVM) prediction model, quota method, grey model), the "quota method" and the "grey model" are chosen to predict the water demand in Urumqi. Based on the water conservation indexes (chapter 5) and current utilization of water resources, short-term water demand is predicted (chapter 6).

In order to literately manage information about water resources (chapter 2 and 3), as well as integrating the water demand prediction models (chapter 6) and the water scarcity decision model (chapter 4), a water resources management and information system is developed. This management and information system contains two main parts in order to manage data and to make decisions. One part is the information system which is used to manage a large number of data about Urumqi's water resources. The second part is the decision support system (DSS) which can be used to analyze and extract data from the database. By analyzing the results of models, it can provide a feasible strategy for the rational allocation of water resources and implement the sustainable water resource management in Urumqi (SUN et al. 2006, 9) (chapter 7).

2 Water resources in Urumqi

In 1988, The United Nations Educational, Scientific and Cultural Organization and The World Meteorological Organization defined water resources as the sources of water which are useful or potentially useful (UNESCO & WMO 1988). The distribution and recharge of water resources have regional differences due to the impact of various factors, such as terrain topography, soil and vegetation. Meanwhile, because of regional socio-economic development and the different water demand for ecological protection, there are also regional differences in water supply and consumption (LIU et al. 2009a, 1247). In this chapter, the classification and the distribution of water resources, as well as the characteristics of water cycle, water supply and water consumption in Urumqi are summarized and analyzed.

2.1 Precipitation in Urumqi

In Urumqi, the main recharge source for water resources is precipitation (SU et al. 2007, 343). Therefore, the change of precipitation can directly affect water resources (ZHANG 2008, 62). Humidity, as the main source for the precipitation in Urumqi, originates from the Atlantic Ocean and the Arctic Ocean. The long distance of the water vapor from these oceans to Urumqi determines the small amount of precipitation in Urumqi. Therefore, the future mega-city in the center of the Eurasian continent has a semi-arid climate. The average annual precipitation was about 304 mm from 1988 to 2010 (STATISTICS BUREAU OF URUMQI 1989-2011). The precipitation in the mountain areas is abundant; therefore, the runoff in these areas is the source of Urumqi's rivers (WATER AFFAIRS BUREAU OF URUMQI 2010, 6). In contrast, precipitation in the plain area is scarce and evaporation is high (LI 2009, 22). The inter-annual precipitation and the annual precipitation can be seen to reflect the characteristics of precipitation of a region (LENG et al. 2007, 64; WANG et al. 2012a, 509). Therefore, the inter-annual precipitation and the annual precipitation of Urumqi are analyzed.

2.1.1 Inter-annual variation of precipitation

The inter-annual variation of precipitation is usually measured by the coefficient of variation which is a statistical measure to express the variability of inter-annual precipitation for regions (VANMAERCKE et al. 2012, 605). The higher the value of the coefficient of variation, the greater the inter-annual variation of precipitation will be. The coefficient of variation can be used to measure the relative change of the data in time and space (FANG et al. 2001, 1723; CHEN et al. 2005, 638). The coefficient of variation (C_v) is defined as the ratio of the standard deviation (σ) to the average precipitation during several years ($\bar{P}$) [mm]. The average precipitation ($\bar{P}$), the standard deviation (σ) and the coefficient of variation (C_v) can be expressed as follows:

$$\bar{P} = \frac{1}{n}\sum_{i=1}^{n} P_i \;\; (i = (1, 2, \ldots, n)) \tag{2.1}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(P_i - \bar{P})^2}{n}} \;\; \text{(WONG et al. 2009, 5479)} \tag{2.2}$$

$$C_v = \frac{\sigma}{\bar{P}} \times 100\% \;\; \text{(XIA et al 2007, 411)} \tag{2.3}$$

where P_i is the precipitation for the i-th year [mm], $\bar{P}$ is the average precipitation during several years [mm] and n is the length of time.

According to the equations (2.1), (2.2) and (2.3), the coefficient of variation (C_v) and the standard deviation (σ) were calculated with the scenario for annual precipitation from 1988 to 2010. The value of the standard deviation (σ) is 71.57 and the coefficient of variation (C_v) is 25.25 %. The coefficient of variation (C_v) is higher than the mean value of Xinjiang (19 %), which means the inter-annual precipitation varies greatly (ZENG et al. 2003, 459).

In order to get an overall view of the inter-annual deviation in annual average precipitation, the anomaly rate of precipitation (P_a) is used to reflect the ratio of the precipitation in a certain period and the average value for several years and is expressed as follows:

$$P_a = (P_i - \bar{P}) / \bar{P} \;\; \text{(FAN et al. 2009, 536)} \tag{2.4}$$

where P_a is the anomaly rate of precipitation [%], P_i is the precipitation for the i-th year [mm] and $\bar{P}$ is the average precipitation over several years [mm].

The time series of total annual precipitation (P_i) are the input values for the equations (2.1) and (2.4). Then the anomaly rate of precipitation can be calculated (see Table A-3 in Appendix A.2). Figure 2-1 showed that the anomaly rate of precipitation fell in the range of -0.5 to 0.4 and the deviation was extreme in 1998 and 2007 during the period of 1988 to 2010. In 2007, precipitation was about 419.50 mm, which was 2.6 times higher than that of 1997 with the lowest precipitation (159.8 mm). It is impossible to predict which year will be dry, normal or wet, since the anomaly rate of precipitation from 1988 to 2010 did not exhibit regularity. It seems there will be a reverse cycle every eight years, for example 1996-1998 (wet – dry - wet) and 2006-2008 (dry – wet - dry).

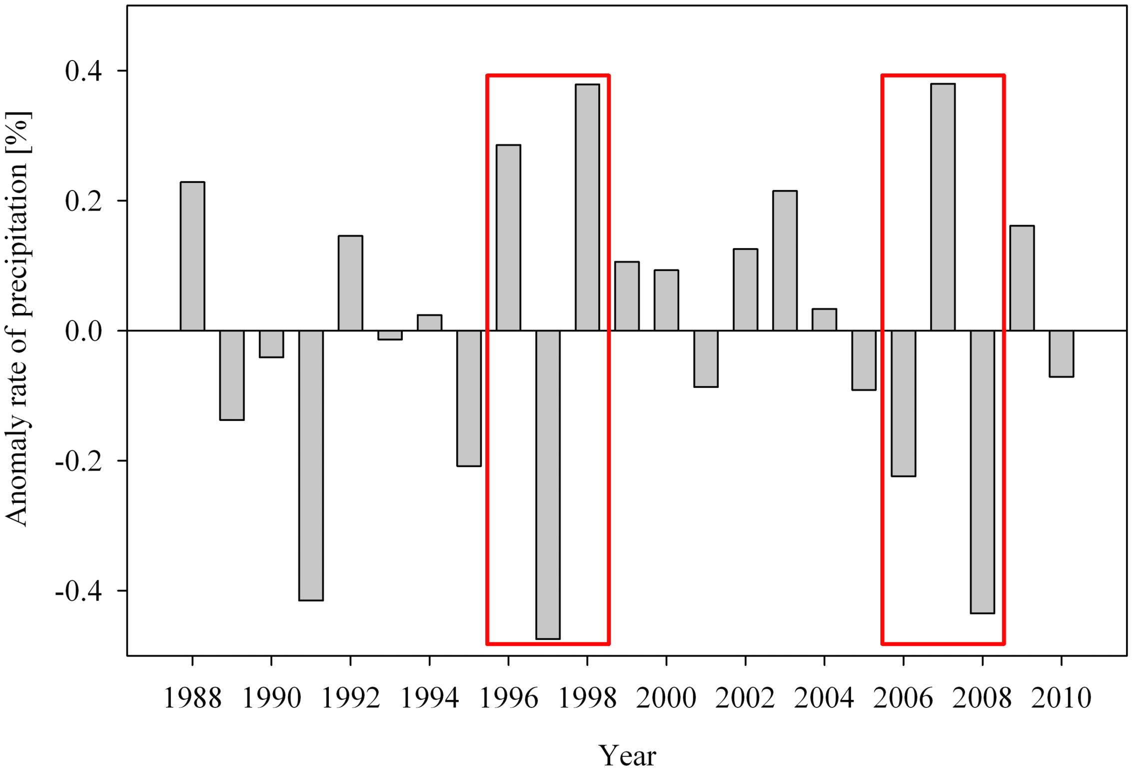

Figure 2-1 Time series of the anomaly rate of precipitation (Red line: the reverse cycle) (source: own calculations)

2.1.2 Intra-annual distribution of precipitation

The most commonly used index for measuring a region's inter-annual variation of precipitation is the traditional drought monitoring index (monthly precipitation anomaly percentage) (LIU et al. 2003, 14; JIANG et al. 2006, 83). The precipitation anomaly percentage can also reflect the ratio of the deviation of intra-annual precipitation in a certain period.

The input values are the monthly precipitation levels from 1988 to 2010. According to the equations (2.1) and (2.4), the average monthly precipitation and the ratio of the monthly precipitation can be calculated. The monthly precipitation can be evaluated according to the Chinese national standard of the classification of meteorological drought (AQSIQ & SAC 2006a; YANG et al. 2010b, 62). Based on the value of the anomaly rate of precipitation (P_a), the meteorological drought during a year can be divided into five types, such as no drought, light drought, moderate drought, high drought and extremely high drought (see Table 2-1). According to the calculation results of monthly precipitation anomaly percentage (P_a) (see Table A-4 in the Appendix A.2) and the classification of meteorological drought, the frequencies of monthly droughts are obtained (see A-5 in the Appendix A.2).

Table 2-1 The Chinese national classification of meteorological drought (source: AQSIQ & SAC 2006a, 3).

Type	The anomaly rate of intra-annual precipitation [%]
	Monthly
No drought	$-40 < P_a$
Light drought	$-60 < P_a \leq -40$
Moderate drought	$-80 < P_a \leq -60$
High drought	$-95 < P_a \leq -80$
Extremely high drought	$P_a \leq -95$

Although there are relatively large amounts of precipitation in the summer, the total drought frequencies are highest in July and August due to the extremely high temperatures. Because of the low precipitation, the highest frequency of drought also appears in December. The change in the frequency of extremely high drought is small and the peak value appears in April and October. The change in the moderate drought frequency is relatively large (see Figure 2-2).

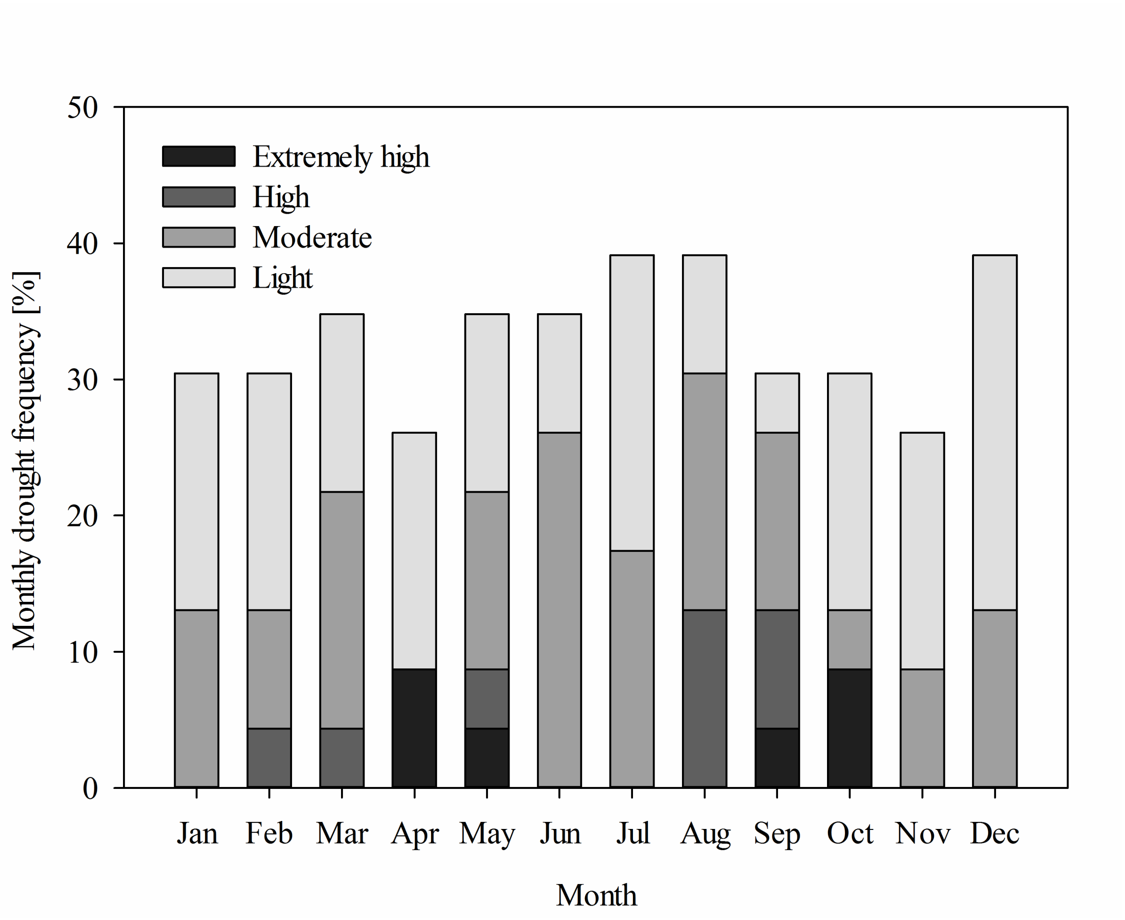

Figure 2-2 Drought frequency in each month (source: own calculations).

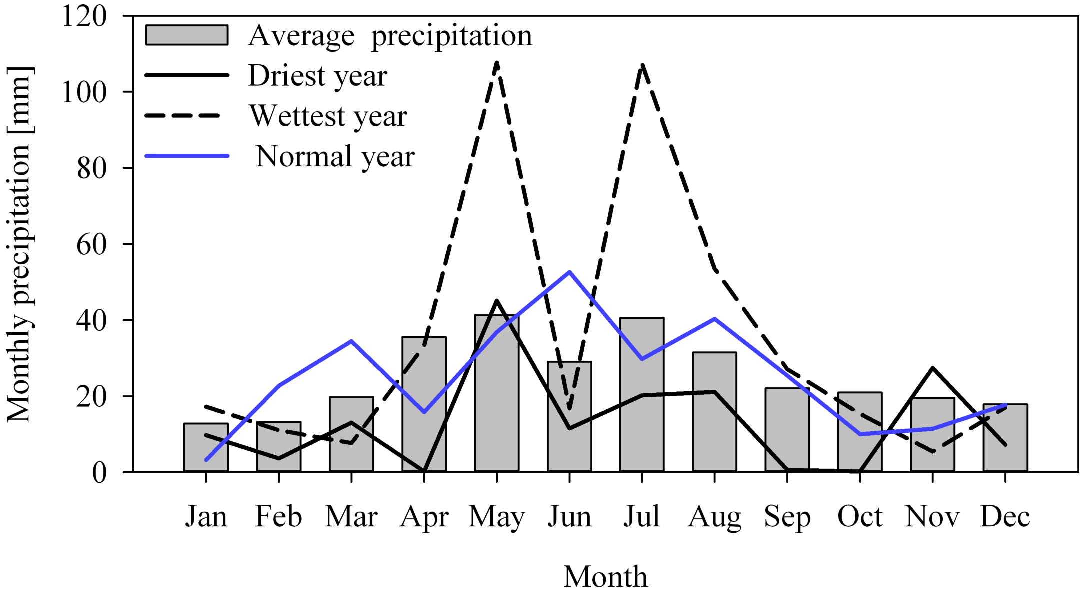

Figure 2-3 The average monthly precipitation distribution for the time period from 1988 to 2010 and the monthly precipitation distribution for the driest year, the wettest year and the normal year (source: STATISTICS BUREAU OF URUMQI 1989–2011; own design).

The differences in monthly precipitation vary a lot from one year to the next, for example the driest year (1997), the normal year (1993) and the wettest year (2007) (see Figure 2-3). However, according to the ratio of the average monthly precipitation to the average annual precipitation over 23 years, the monthly precipitation increases from January to May, which can be determined as the wettest month. Between 1988 and 2010, the maximum monthly precipitation in May was at 41.25 mm on average, which was 13.58 % of the average annual precipitation. The secondary peak appeared in July, with a monthly precipitation of 40.57 mm, or 13.36 % of the annual precipitation. From the months of April to September the total precipitation was 199.9 mm, or 65.8 % of the annual precipitation (also see Figure 2-3). This period is also the peak water use (including agricultural water use and ecological water use) period (JIANG et al. 2006, 85).

2.1.3 The distribution of precipitation in Urumqi

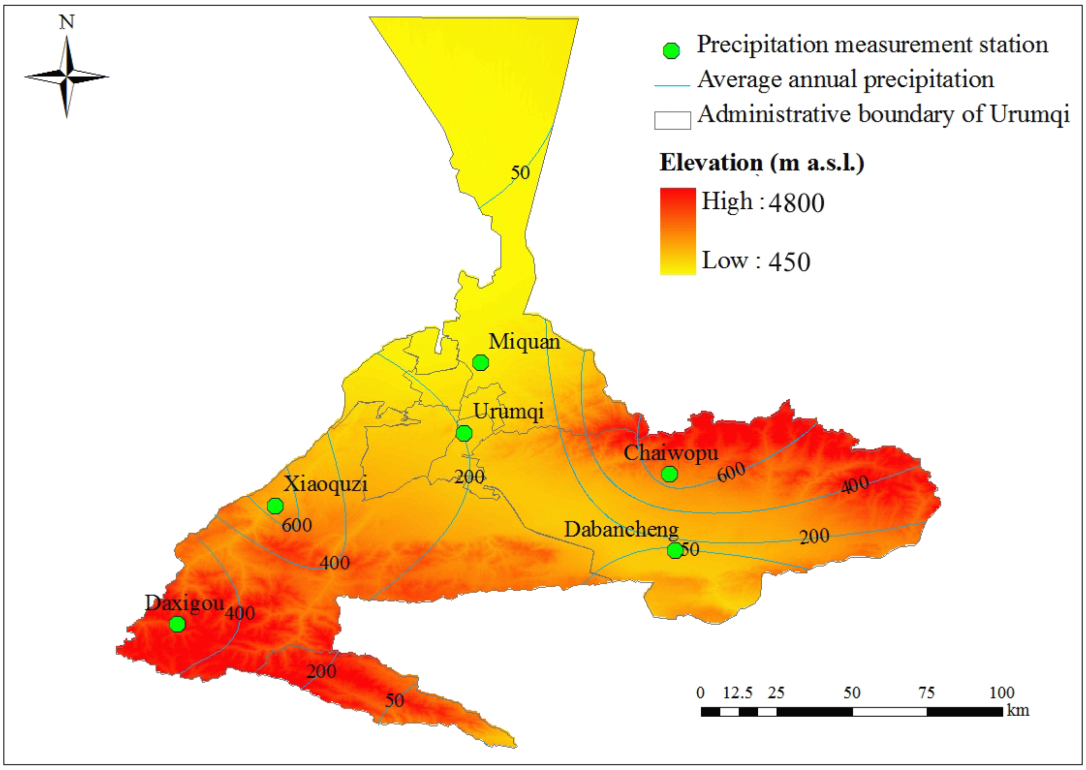

Figure 2-4 Average annual precipitation distribution in 2010 according to the elevation of Urumqi (source: WATER AFFAIRS BUREAU OF URUMQI 2010, 7; SRTM-3; AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; own design).

Urumqi is surrounded by mountains on three sides (East, South and West), while the northern part is covered by a plane. With the westerly circulation and winds, the wet cold air from the Atlantic Ocean and the Arctic Ocean drifts into Xinjiang province. Therefore, the precipitation of Urumqi is mainly affected by the humidity from the Northwest and the distribution of precipitation in Urumqi depends on the changes in elevation and exposition. The amount of precipitation is higher in mountain, western and windward slope areas and less in plain, eastern and leeward areas (WATER AFFAIRS BUREAU OF URUMQI 2010, 6) (see Figure 2-4).

2.2 Surface water in Urumqi

There are many small rivers in Urumqi, which belong to five basins, the Urumqi River Basin, the Toutun River Basin, the Baiyang River Basin, the Chaiwopu Basin and the Alagou Basin (ZHANG & QIAN 2004, 54) (see Figure 2-5).

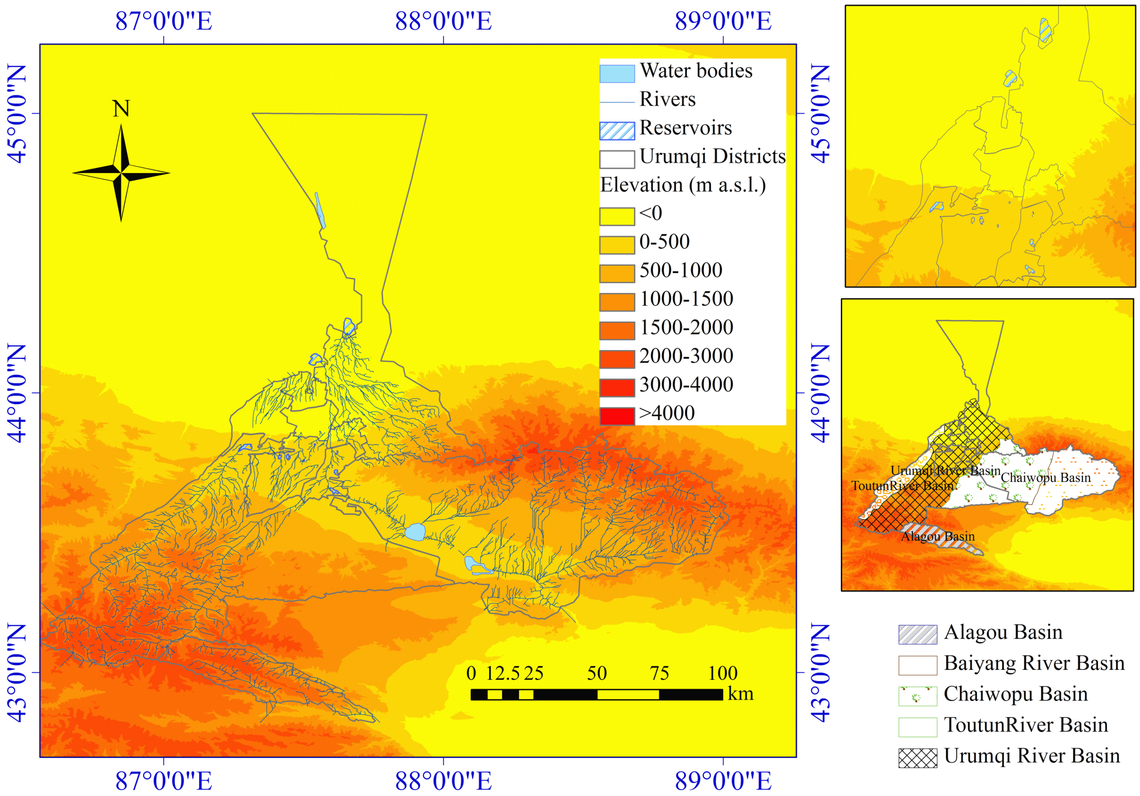

Figure 2-5 Five basins, water system and topography of Urumqi (m a.s.l.: Meters above sea level) (source: SRTM-3; AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; XIE et al. 2005, 374; own design).

The Urumqi River Basin (including Urumqi River, Banfanggou River and Shuimo River) is located around the main built-up area of Urumqi Region. Urumqi River supplies a large amount of water for agriculture, urban life and industrial production (ABUDUKADIR & JIANG 2005, 78). The main stream (200 km long) of Urumqi River originates from Glacier No.1 in the North of Tengeer Mountain and flows down along the northern slope of the hillside towards the Wulabo reservoir. From the Wulabo reservoir, the main stream flows towards the North and through Urumqi. This main stream finally vanishes in the Gurbantunggut desert (YAO & ZHANG 2006, 78). There are four reservoirs (Wulabo reservoir, Hongyangchi reservoir, Mengjin reservoir, and Bayi reservoir) connected to Urumqi river with a total capacity of 180 million m^3 (ZHANG 2008, 62). The annual surface water of Urumqi River Basin was 339.47 million m^3, which was 36 % of the total surface water in Urumqi in 2010 (WATER AFFAIRS BUREAU OF URUMQI 2010, 12) (also see Figure 2-5).

The Toutun River Basin includes Toutun River, Xiaoquzi River, Heijiagou River and Qingshui River. The terrain of Toutun River slopes from West to East (KONG et al. 2006, 36). Toutun River is the boundary river for Urumqi and Changji, therefore half of the river quantity belongs to Urumqi (CHEN 1992, 32). The total length of the main stream of Toutun River is 190 km, and the Toutun River Basin covers an area of 2885 km^2. In 2010 the annual surface water of the Toutun River Basin was 111.42 million m^3 (WATER AFFAIRS BUREAU OF URUMQI 2010, 12). The source of Toutun River is at an altitude of 4562 meters. The upstream area of Toutun River high in the mountains (1700 to 3500 meters above sea level) is the main runoff area, because the precipitation is abundant there and the drainage density is high in this area (LI et al. 2006b, 40) (also see Figure 2-5). Due to the impact of zonal atmospheric circulation, air humidity for precipitation comes from westerly circulation and the precipitation increases with the elevation. There is less precipitation in the hilly area (800 to 1700 meters), downstream of Toutun River (LI et al. 2006b, 40). In the alluvial plain area (less than 800 meters above sea level), there is less precipitation and surface runoff cannot occur (LIU 2011, 10).

The Chaiwopu Basin, whose annual surface water was about 105.85 million m^3 in 2010, originates from several small rivers (including Tiechanggou River, Shuimogou River and Baiyanggou River) and is located at the northwest hillside of Bogeda Mountain. The Chaiwopu Lake was formed because of two big protruding obstacles (Sangezhuang, Xigeda) obstructing the water from the rivers so that the water is pooled in the low-lying land. In addition, Wushenchenggou (river) from the northern hillside of the middle Tianshan Mountains also enters into the low-lying land and therefore also belongs to the Chaiwopu Basin (CHEN 1992, 31) (also see Figure 2-5).

Chaiwopu Basin is one of the main water resources for domestic water, and 30 % of domestic water in Urumqi comes from this basin (HOU 2011, 9).

The Baiyang River Basin is constituted by Baiyang River and Kujiayigou River (including Heigou, Aksu and Gaoyazigou which belong to southern slope rivers). The rivers close to Dabancheng converge into the Baiyang River which occupies 24 % of the total surface water in Urumqi. Most of Baiyang river water flows into the Turpan Basin (also see Figure 2-5). The intra-annual precipitation in the Baiyang River Basin greatly fluctuates (summer (38.7 %) > spring (27.6 %) > autumn (24.1 %) > winter (9.5 %)). The recharges for runoff of the Baiyang River Basin are glacial melt water, rain, snow and groundwater. The ranking of the seasonal runoff is summer > autumn > spring > winter (DING & ZHANG 2009, 98). The total annual surface water of the Baiyang River Basin was 274.95 million m³ (WATER AFFAIRS BUREAU OF URUMQI 2010, 12).

The Alagou Basin includes many small rivers (including Banfanggou, Shuixigou, Dadonggou, Xiaodonggou, Banjiegou and Yangquangou) and is located at the northern slope of the middle Tianshan Mountains (also see Figure 2-5). The amount of annual surface water of the Alagou Basin was 23.73 million m³ (WATER AFFAIRS BUREAU OF URUMQI 2010, 12).

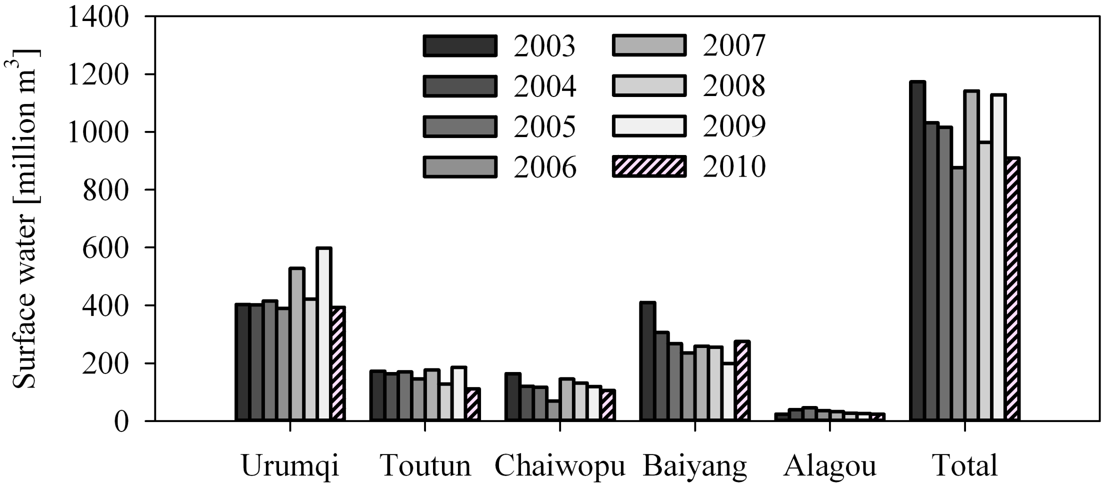

Figure 2-6 Surface water of different basins in Urumqi 2003-2010 (Urumqi: Urumqi River Basin; Toutun: Toutun River Basin; Chaiwopu: Chaiwopu Basin; Baiyang: Baiyang River Basin; Alagou: Alagou Basin; Total: total surface water in Urumqi) (the data for 2006 was calculated and obtained according to the WATER AFFAIRS BUREAU OF URUMQI 2007) (source: WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; own design).

Figure 2-6 summarizes the amount of surface water in the five main basins. The amount of surface water in the Urumqi River Basin accounts for almost half of the total surface water in Urumqi. From 2003 to 2006 there was an obvious decreasing tendency of surface water for Chaiwopu Basin and Baiyang River Basin. From 2006 to 2007, the surface water in Urumqi River Basin, Toutun River Basin and Chaiwopu River Basin had apparently increased, because precipitation amounts over these three basins were relatively larger in 2007. The surface water of Chaiwopu Basin, Baiyang River Basin and Alagou Basin had decreased from 2007 to 2010. Because surface water is replenished by precipitation, the total surface water can respond to the changes in precipitation.

In addition, there are lots of reservoirs in Urumqi that are used for water storage, flood retention, flow regulation, irrigation, water supply and power generation (ZHANG 2010b, 80). The Wulabo reservoir, Hongyanchi reservoir and Hongyan reservoir are the three largest reservoirs in Urumqi (also see Figure 2-5). The design capacity of the Wulabo reservoir is 70 million m³ and it is used for flood retention, urban water supply and irrigation. The Hongyanchi reservoir is used for irrigating as well as for supplying water for some industrial enterprises. Its design capacity is 54.2909 million m³. The Hongyan reservoir is used for drinking water and urban greening (see Table 2-2). There are also several small reservoirs, such as 104 Tuan big reservoir, 104 Tuan small reservoir, Shipao reservoir, Jiujiawan reservoir, Santunbei reservoir, and Shiqihu reservoir.

Table 2-2 The three medium-sized reservoirs in Urumqi (source: WATER AFFAIRS BUREAU OF URUMQI 2010, 15).

Reservoir	Design capacity [million m³]	Application
Wulabo	70	Flood retention, urban water supply and irrigation
Hongyanchi	53	Irrigation and water supply for several industrial enterprises
Hongyan	36	Drinking water for residents and urban greening

The surface water resources have two characteristics in Urumqi. The first one is that all the rivers in Urumqi are inland rivers. They arise from the hills and vanish in the semi-desert in the North of Urumqi (also see Figure 2-5). The second one is that different rivers have different sources of recharge because of their various geographical locations. For example, precipitation and melt water are the main sources of recharge for Urumqi River Basin and Toutun River Basin, while the main sources of recharge for Chaiwopu Basin are springs around the lake and shallow groundwater (see Table 2-3) (ZHANG 2008, 62).

Table 2-3 The different recharge sources for five basins in Urumqi (source: ZHANG 2008, 62; KONG et al. 2006, 36; LI & TURSUN 2001, 12; own design).

Basins	Recharge sources
Urumqi River	Precipitation and melt water
Toutun River	Seasonal melt water and precipitation
Chaiwopu	Precipitation and in the higher mountains glacier melt, summer rainfall, seasonal melt water and groundwater
Baiyang River	Springs around the lake and shallow groundwater
Alagou	Precipitation and glacier melt water

The inter-annual variability of runoff is small in Urumqi, but the distribution of runoff during the year is uneven. In spring the river runoff accounts for 10 %-20 % of the annual water, for 50 %-70 % in summer, for 10 %-20 % in autumn and less than 10 % in winter. The river runoff is characterized by drought in spring and winter, by flood in summer, and by shortage in autumn. The rivers are short and the flow rate of the runoff is slow (WANG 2001, 86).

In Urumqi, the quality of 10 % of the surface water cannot be treated by conventional purification technologies (e.g. flocculation, sedimentation, filtration and disinfection) to meet the quality of drinking water (ABUDUSHATAER et al. 2007, 676). Furthermore 8 % of the surface water has been seriously polluted, especially from the Shuimo River (WATER AFFAIRS BUREAU OF URUMQI 2010, 27). Due to the limited amount of surface water, the poor quality of the water and the increasing water demand, new strategies should be used to exploit groundwater to meet the needs for industrial production and domestic use (HUO et al. 2010, 1).

2.3 Groundwater in Urumqi

Groundwater is part of a recharge cycle and is generated by the infiltration of precipitation and surface water (including rivers, lakes, reservoirs, channels and irrigation water on the ground) (WATER AFFAIRS BUREAU OF URUMQI 2007, 10). According to the report of the analysis of groundwater by Xinjiang's Hydrology and Water Resources Bureau, the Urumqi Water Resources Management Committee and the Water Affairs Bureau of Urumqi in 2010, the main type of groundwater in mountainous areas of Urumqi is bedrock fissure water. This kind of water is recharged in hilly areas by precipitation, snow-ice melt water and pore water in clastic rocks. In the plain area, the main sources of groundwater are recharged by riverbed seepage and the inlet channel, field irrigation water infiltration, piedmont streams, and rainfall/snow infiltration. The groundwater bodies on the plain are mainly distributed within Chaiwopu Basin and North plain area of Urumqi River (LI & TURSUN 2001, 12).

In 2010, the total amount of groundwater (including the water exchange between surface water and groundwater) was decreased to 403.4 million m³ which was 58.65 % of that of 2007 (687.9 million m³) (WATER AFFAIRS BUREAU OF URUMQI 2010, 14). Although the total area of Urumqi is larger than before 2007 (Miquan City was merged into Urumqi in 2007), the total amount of groundwater has decreased in absolute figures (see Figure 2-7). The changes in groundwater can be caused by natural phenomena (reduced precipitation, snow and ice melt) and human activities (over-exploitation) (PENG et al. 2003, 667). Water over-exploitation occurs when the groundwater is directly pumped for urban agriculture, industry and domestic use in Urumqi (CHEN et al. 2007b, 312). The groundwater extraction rate is more than 85 % in Urumqi (YAN 2009a).

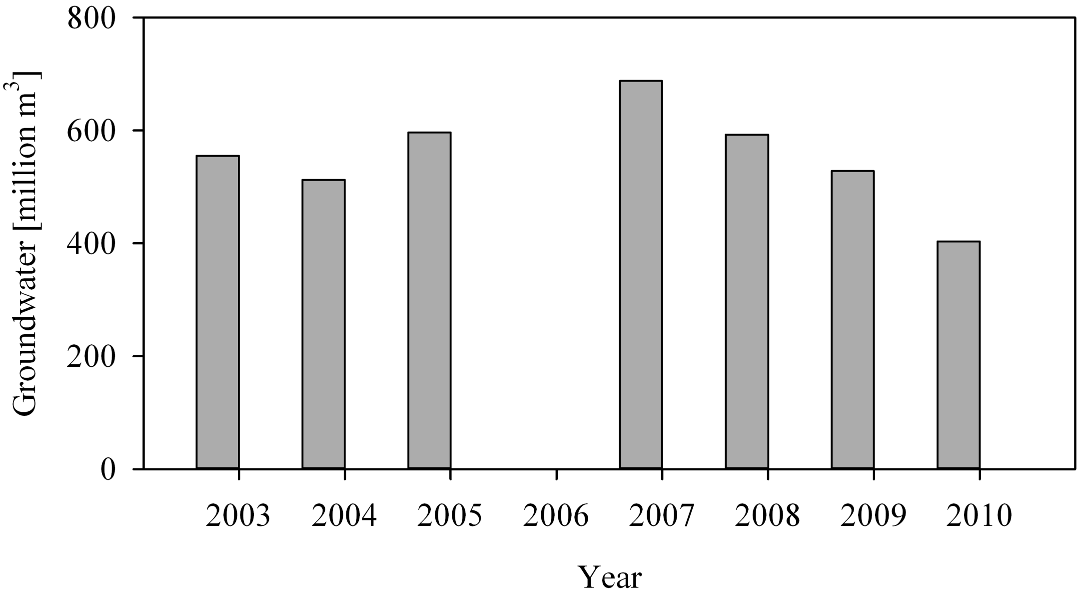

Figure 2-7 Total amount of groundwater (including the water exchange between surface water and groundwater) in Urumqi 2003-2010 (missing data for 2006) (source: WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; own design).

In Urumqi, the main source of water supply is ground water, and five water plants are extracting groundwater all year around (LV et al. 2002, 34). With the development of Urumqi, the exploitation of groundwater increases year by year. The groundwater level decreases drastically (the groundwater level is declining at rate of 0.54 m/year) (XI et al. 2011). In some parts of the region the groundwater was evacuated completely, and the underground funnel appears after the groundwater was taken away (LV et al. 2002, 33).

In addition, because of the wastewater discharge, 70 % of groundwater in the plain area has been polluted (ABUDUSHATAER et al. 2007, 676). The pollution of surface water and groundwater is having a negative effect on the living environment in Urumqi. Water pollution not only decreases the amount of accessible water, thereby increasing the gap between water supply and water demand, but also heavily affects the sustainable socio-economic development.

2.4 Total water resources in Urumqi

The total volume of regional water resources is the yield of surface water and ground water, which was recharged by precipitation. Groundwater and surface water are linked to each other through the hydrological cycle. But groundwater resources and surface water are often calculated separately. Thus, an overestimation of the total water resources can be caused by a simple addition of groundwater and surface water due to the water exchange between surface water and groundwater. The water exchange between surface water and groundwater refers to the difference between the groundwater drainage into rivers and the seepage from rivers into aquifers. Therefore, the total amount of water resources should be the difference between the sum of total surface water and total groundwater and the water exchange between surface water and ground water (total water resources = (total surface water + total groundwater) – water exchange between surface water and groundwater) (FAO 2003, 12).

Figure 2-8 shows that the total water resources, surface water and groundwater follow roughly the same trend as the annual precipitation. There were two years with high values for the total amount of water resources in Urumqi. The first peak value and the second peak value appeared in 2003 and 2007, because of a large amount of rainfall in those years. This indicates that climate change can affect water resources through its quantity. The average total water resources were about 39.85 % of the average annual precipitation, including about 38.6 % of the precipitation, which replenished surface water, and 1.25 % of the precipitation which replenished groundwater. More than 60 % of precipitation was released by the evapotranspiration of vegetation and open surfaces or absorbed by the ground.

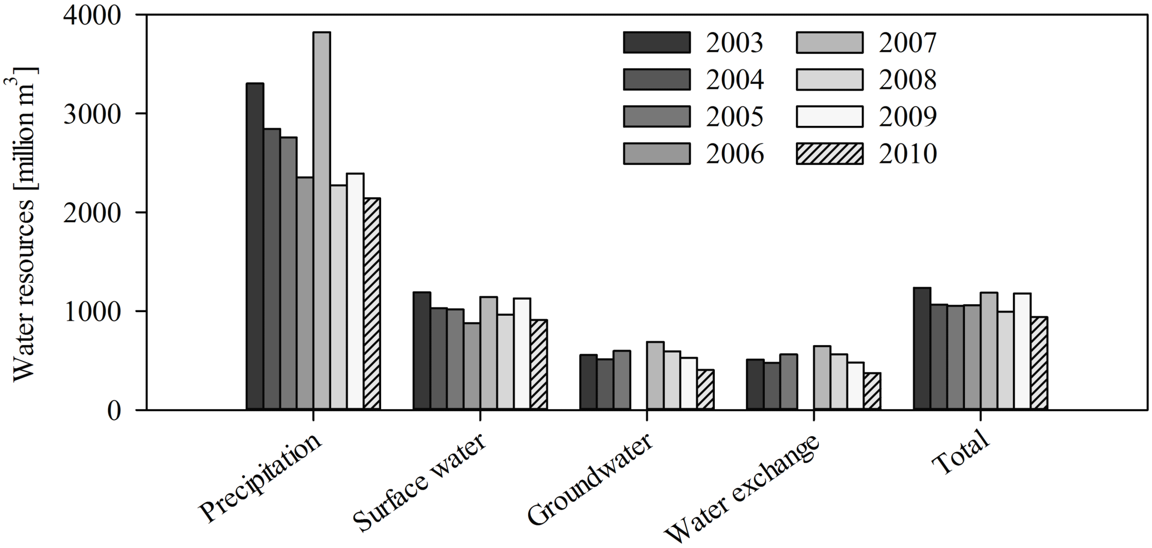

Figure 2-8 Comparison of annual precipitation, surface water, groundwater extraction and total water resources in Urumqi 2003-2010 (Water exchange: water exchange between surface water and groundwater) (missing data about groundwater and water exchange for 2006) (source: WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; STATISTICS BUREAU OF URUMQI 2007; own design).

In order to understand the water resources in a region, the attributes of water resources should be studied and the relationships between the different recharge sources should be identified. In Urumqi, the water resources are rivers, lakes, groundwater and glacier melt water. The main recharge source of water resources is precipitation. The main part of consumed water is biowater, which refers to the different states of water existing in a variety of biological systems. All of the water resources, water recharges and water consumptions are interrelated with each other. For example, groundwater and surface water from rivers and lakes can be exchanged depending on the hydraulic head (KALBUS et al. 2006, 873). When the groundwater table is close to the surface, it will recharge rivers and lakes. And when the water table drops, the surface water (rivers, lakes and glaciers) can recharge the groundwater. Biological systems can also obtain water from rivers, lakes, glaciers and groundwater and discharge sewage to rivers and lakes (YAO 2010, 144) (see Figure 2-9).

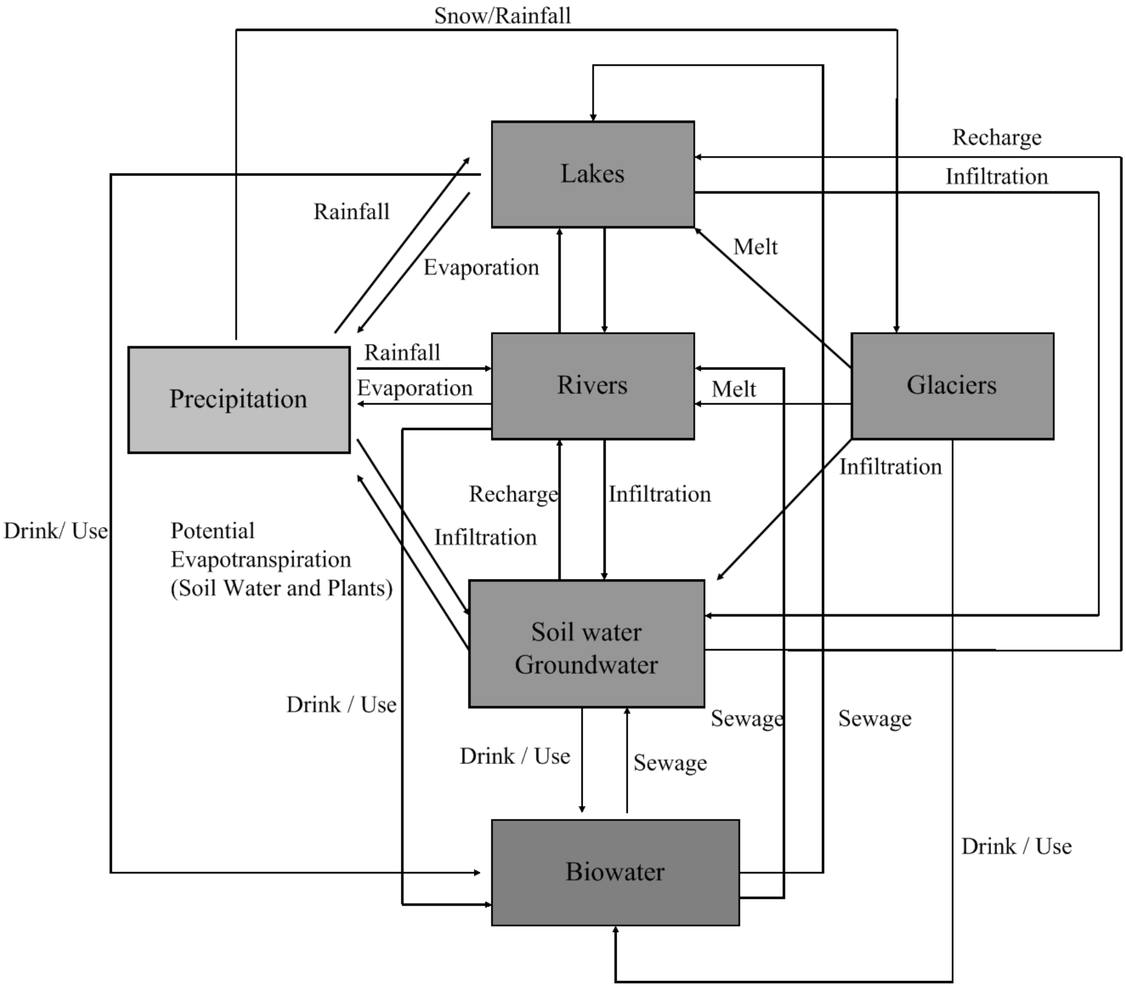

Figure 2-9 The relationships among different water resources (source: YAO 2010, 144).

2.5 Classification of the water resources in Urumqi

Water resources on the regional level refer to the overall water in the regional water circle, including surface water and groundwater which are controlled by humans and used for irrigation, power generation, farming, living, as well as for rivers, lakes, wells and springs (XU & SINGH 2004, 592). Based on the definition and the distribution of the water resources in nature, there are different kinds of water resources in Urumqi. The water resources in Urumqi are related to three spheres according to the spatial attribution (see Figure 2-10):

1. The first sphere is the atmosphere. In the lowest layer of atmosphere, atmospheric phenomena such as, rain, fog, dew, snow, hail and sleet occur. Air humidity is also included in the atmosphere and it falls on the earth in the form of precipitation.

2. The second sphere includes rivers, lakes and glaciers, as well as the biosphere. The biosphere contains the water used for human living, plants and animals. For human living it is composed of the water used for agriculture, industry, households and environment as well as the wastewater and sewage. Human activities can affect the water resources in the biosphere.
3. The third sphere includes groundwater, the pedosphere and the lithosphere. The pedosphere contains rainfall and snow infiltration, the water seepage through riverbeds, the seepage from inlet channels and groundwater infiltration. The lithosphere contains bedrock fissure water, clastic rock crack pore water and old groundwater (LI & TURSUN 2001, 12).

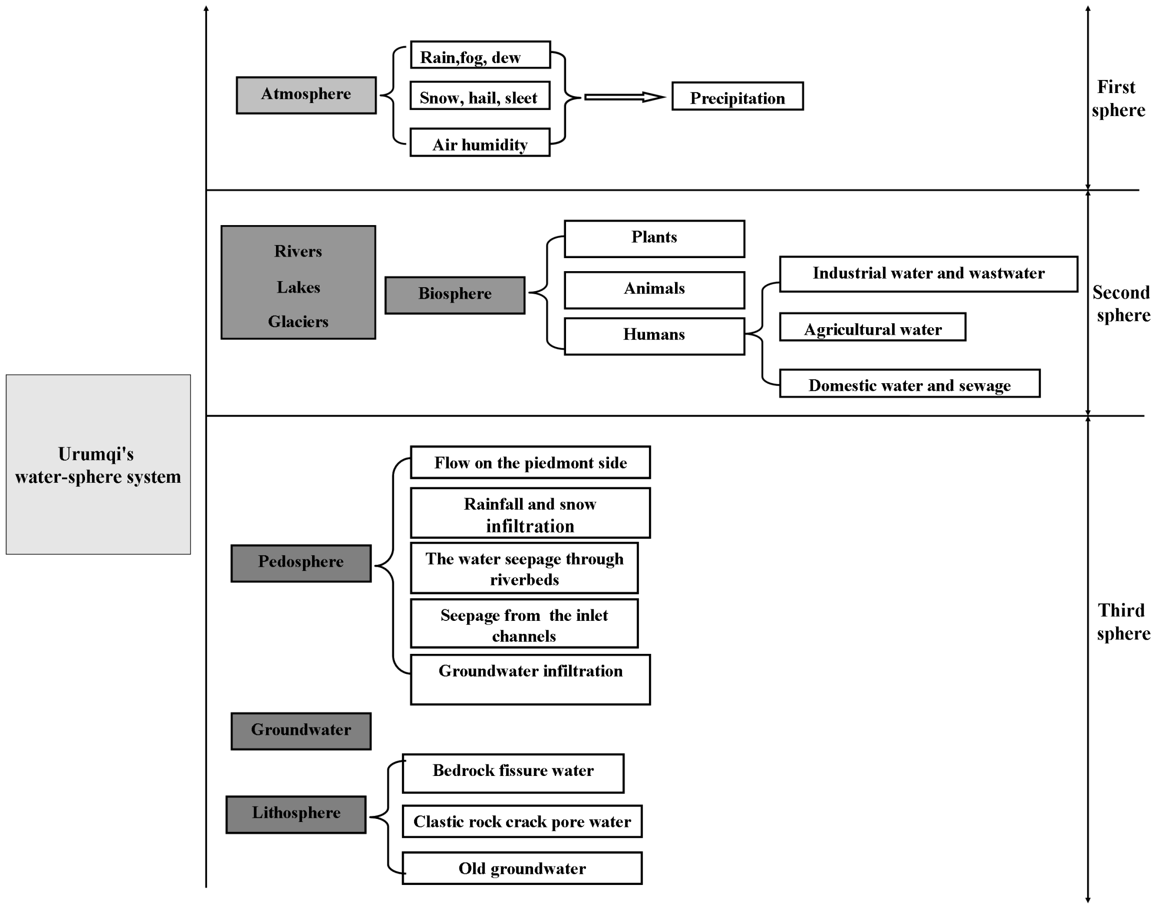

Figure 2-10 Urumqi's water-sphere system (source: own design).

2.6 Water cycle in Urumqi

The water cycle means the continuous movement of water on, above and below the surface of the earth (USGS 2012). According to the definition of water cycle and water utilization in inland regions in China (including Urumqi), the water cycle includes two parts, one of which is the terrestrial water cycle which belongs to the natural cycle, and the other is the anthropogenic water utilization cycle (CHEN 2006).

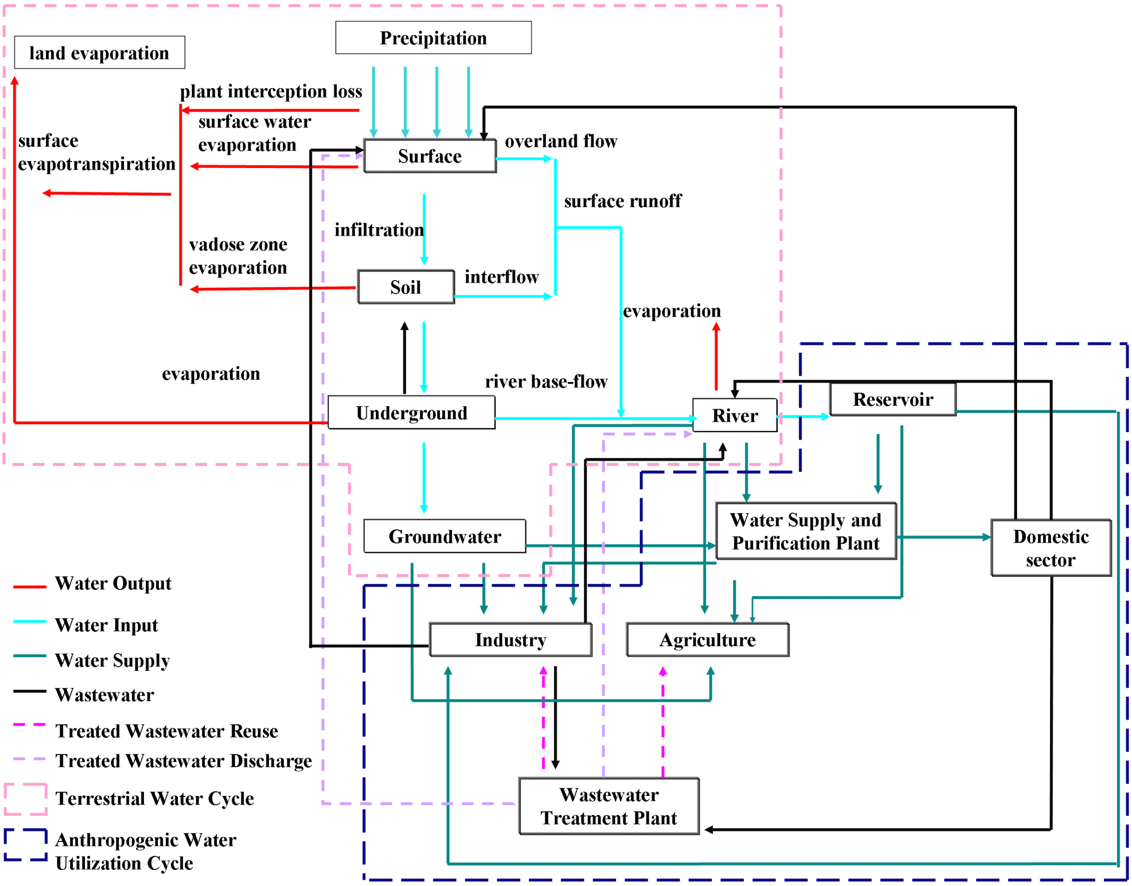

Figure 2-11 The terrestrial water cycle and the anthropogenic water utilization cycle in Urumqi (Domestic: domestic water use and sewage; Industry: industrial water use and wastewater; Agriculture: agricultural water use) (source: own design).

The terrestrial water cycle is a process which involves the transformation among precipitation, surface runoff, underground runoff and evaporation. It plays a critical role in the climate, ecology, and biogeochemistry of the planet (VÖRÖSMARTY & SAHAGIAN 2000, 753). Due to the plant interception losses, surface water evaporation, vadose zone evaporation and groundwater evaporation, water turns back into air (see Figure 2-11).

The anthropogenic water utilization cycle includes water resources exploitation, water usage and the wastewater cycle. It is not a closed loop, since wastewater is discharged and leaves the anthropogenic system (also see Figure 2-11).

2.7 Water supply and water consumption in Urumqi

The amount of water supply refers to the total amount of water supplied by various water programs and also includes water losses in the distribution system. The sources of water supply in Urumqi are surface water, groundwater and other sources which include reused wastewater (see Figure 2-12).

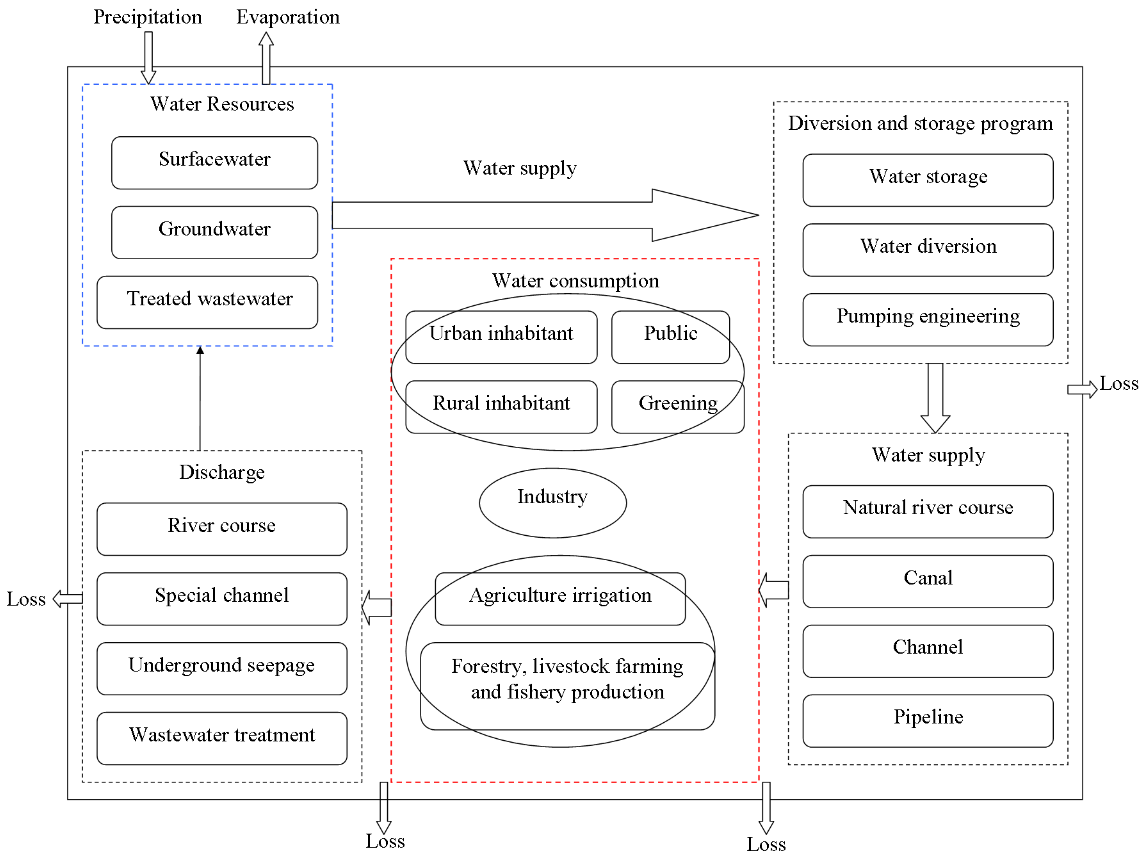

Figure 2-12 Urumqi's water supply and consumption flow (Red line zone: water used for agriculture, industry and the domestic sector) (source: own design according to WATER AFFAIRS BUREAU OF URUMQI 2010).

Water supply has gone up year by year. For the years from 2003 to 2010 the total water supply already increased from 805.02 million m³ to 1089.31 million m³, which had exceeded the total water resources. More than 50 % of the supplies came from surface water. But the proportion of surface water supply had decreased from 65 % to 52 % and the proportion of groundwater supply had increased from 30 % to 45.6 % (see Figure 2-13). That means the groundwater extraction was increasing.

Water consumption refers to the amount of water allocated to households (including water conveyance loss), but also to the water used for agriculture and industry. Agricultural water consumption includes water consumed by agricultural irrigation, forestry, animal husbandry and fishery production. Domestic water consumption includes water consumed by urban and rural inhabitants, public water use and greening (also see Figure 2-12). The total water resources are decreasing, but water consumption has increased year by year. The total water consumption had increased from 805.02 million m³ to 1089.31 million m³ during 2003 to 2010. Compared with the total water resources, water consumption has already exceeded the total water resources in 2010 (also see Figure 2-13).

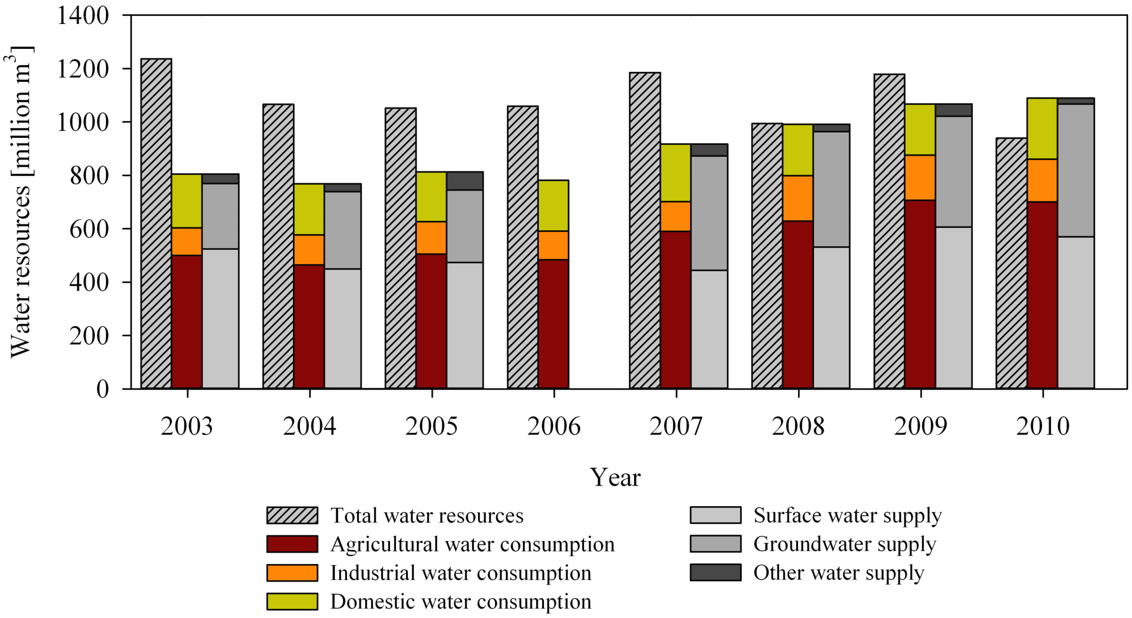

Figure 2-13 The comparison of the total amount of water resources, the total water supply with different supply sources and the total water consumption with different consumption sectors in Urumqi 2003-2010 (missing data about water supply in Urumqi for 2006) (source: WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; own design).

Figure 2-14 shows that domestic water consumption mostly centers on Xinshi District, Tianshan District, Saybagh District and Shuimogou District, since these districts form the central business district and are the most densely populated. Toutunhe District and Saybagh District are industrial areas, thus industrial water consumption is high in these two districts. The agricultural water consumption is also high in Xinshi District, since the Agriculture Division No.12 (a big agricultural area) of Xinjiang Production and Construction Crops is located in Xinshi District. There are high values of total water consumption in Midong District, Urumqi County and Xinshi District. The amount of water consumption in these three regions occupies more than 50 % of the total water consumption in Urumqi due to the agricultural water consumption.

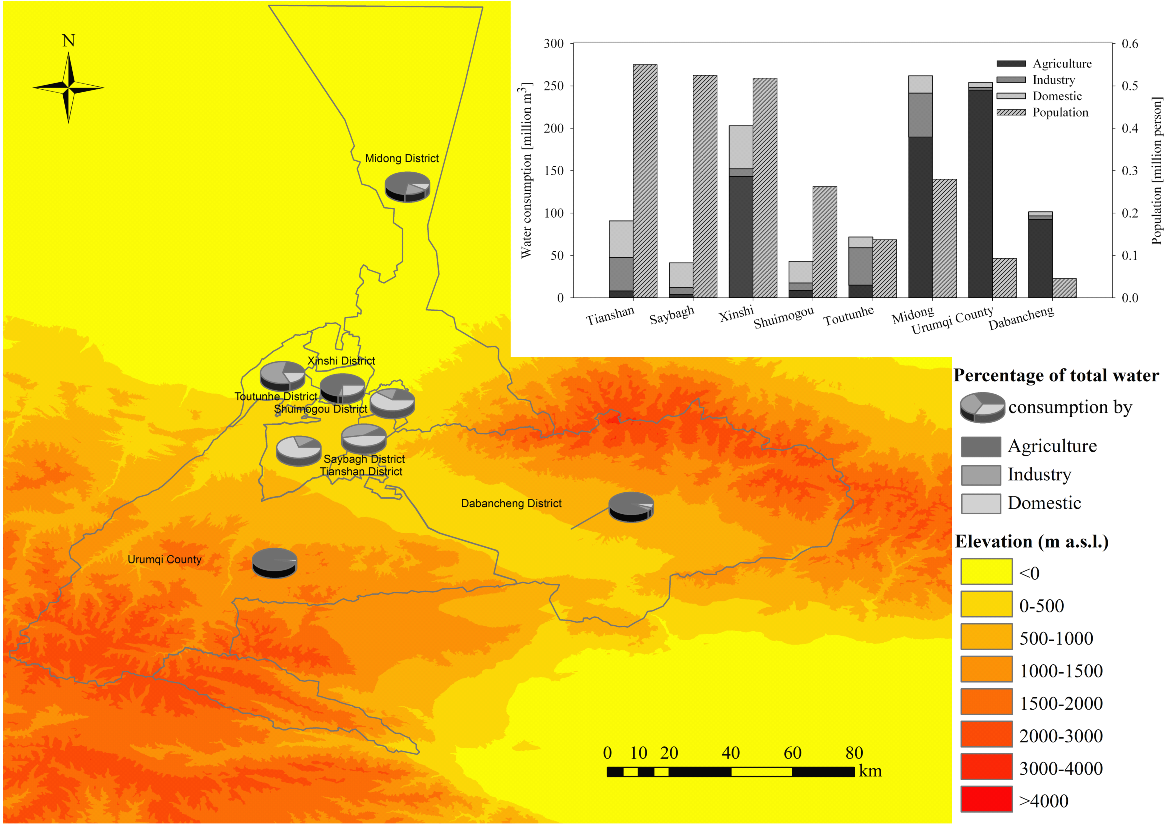

Figure 2-14 Water consumption sectors and population in Urumqi's districts in 2009 (source: SRTM-3; AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; WATER AFFAIRS BUREAU OF URUMQI 2009, 17; STATISTICS BUREAU OF URUMQI 2010, 93; own design).

Overall, Urumqi's water using region centers on the urban area and plain agricultural area. But a large amount of water still exists in the mountain areas (because precipitation occurs frequently and melting snow appears in the mountain areas). It means there is a spatial distance between the water-using region and the water-rich region. The best way to solve this problem is to transfer the water from mountain areas to urban areas and agricultural areas of the plain.

In the medium and long run, water consumption must be less than the total amount of water resources in one region. According to the survey on water resources in northwest China, the amount of water consumption should not exceed 70 % of the total water resources in that region, otherwise the water used to maintain the natural environment will be diverted, and that will bring about serious consequences for the environment because of the over-exploitation of surface and ground water (DENG 2001, 19; ZHANG 2010a, 179). Due to the continuing growth of the population and the expansion of industrial activity in Urumqi, water consumption has increased year by year and it has exceeded 100 % of the total water resources. It means water scarcity has become a vital factor restricting socio-economic development.

3 Wastewater and water reuse in Urumqi

In order to improve the quality of water, relieve water scarcity, and decrease the gap between water supply and water demand, the second water resource should be developed in Urumqi. Wastewater as the second water source is a fundamental and strategic measure to solve the problems of Urumqi water resources, since other kinds of water resources are not adequate. The water from the wastewater, with reasonable treatment, not only increases the amount of available water to alleviate the scarcity of water resource, but also plays an important role in securing the water supply with much less pressure on environmental sources (ABUDUSHATAER et al. 2007, 675). Treated wastewater (domestic sewage and industrial wastewater) is a renewable water resource, which can be used in many useful ways, such as irrigation, industrial uses and for city greening (HAERING 2009, 1). In addition, water reuse has many economic benefits. By reusing treated wastewater, the costs of water will be decreased for several purposes, because there is no necessity to use the highest water quality available for irrigation, most of the industrial use as well as city greening (DILLON 2000, 101). However, treated wastewater involving biological and chemical compounds may injure human health and the environment (SALGOT et al. 2006, 30). In wastewater, all the potential pathogens can cause infection diseases. Contaminations (nutrients, organics and heavy metals), which are not properly treated, can pollute the environment (SNOW et al. 1999, 27; WEN et al. 2008, 1442). In considering the positive and negative aspects of water reuse, treated wastewater can be reused under the premise of the national reclaimed water reuse standard (i.e. the former wastewater that is treated, recycled and reused is called reclaimed water).

In this chapter, the wastewater discharge pipe system will be introduced. The wastewater treatment rate in wastewater treatment plants, the current situation of treated wastewater reuse and the water reuse price mechanism will be analyzed. The purpose of these analyses is to study the wastewater resource and its potential, and to put forward some constructive suggestions to improve the water reuse rate.

3.1 The wastewater system and the drainage pipe systems in Urumqi

For a long time in the past, the use of water resources followed the rule of "exploitation-utilization-sewage disposal" without considering reuse or the further consequences of disposal (MENG et al. 2009, 89). In fact, wastewater discharge has significant effects on the water resources, because water pollution occurs when wastewater is directly discharged without any treatment. In Urumqi, the government has categorized wastewater into six groups (URUMQI DEVELOPMENT AND REFORM COMMISSION 2002a).

1. Domestic sewage coming from residents, enterprises, cultural and educational institutions (e.g. schools and kindergartens) as well as institutions for public health (e.g. hospitals).
2. Industrial wastewater coming from food and beverage industries, chemical and pharmaceutical production, spinning and dyeing industries, printing and papermaking, mechanical engineering, electronics and instrument manufacturing, metal repairs and founding, building material manufacturing, transportation, power generation, brewing and breeding.
3. Business services wastewater coming from hotels, restaurants, cosmetics industry, public bathhouses, markets and outlets, places of recreation, commercial storages and all kinds of services for public works.
4. Greening, sanitation and firefighting wastewater coming from environmental sanitation, public latrines, firefighting, public greening for roads, gardens, squares, residential area greening and barren mountains greening.
5. Construction projects wastewater coming from construction for new buildings, building reconstruction, extensions and maintenance.
6. Special wastewater coming from saunas, foot baths, car washing and swimming pools.

According to the rule for the design of wastewater reclamation and reuse and the integrated wastewater discharge standard, the entire structure of the wastewater system should enable wastewater reuse: domestic sewage includes two parts, the fecal sewage and washing/kitchen sewage (SEPA & STSA 1996; MCC & AQSIQ 2002). The fecal sewage is discharged into septic tanks and is added to the washing and kitchen sewage after treatment and discharged into sewer systems.

On the premise of wastewater meeting the discharge standard of the wastewater treatment plant, the industrial wastewater is discharged into the sewer system, otherwise it would have to be pretreated by the industries in interim tanks. The wastewater coming from business services, greening, sanitation, firefighting, construction projects and the special wastewater is also discharged through sewer pipes into the sewer system (FAN et al. 2005, 252). All of the wastewater in the sewer system is mixed together, one part is discharged directly into rivers and wasteland, and another part is discharged into plants and treated with secondary treatment (i.e. after the removal of settleable and floatable material (primary treatment), biological or chemical processes are used to substantially remove dissolved, suspended and colloidal organic materials) (WANG et al. 2009b, 1090) (see Figure 3-1).

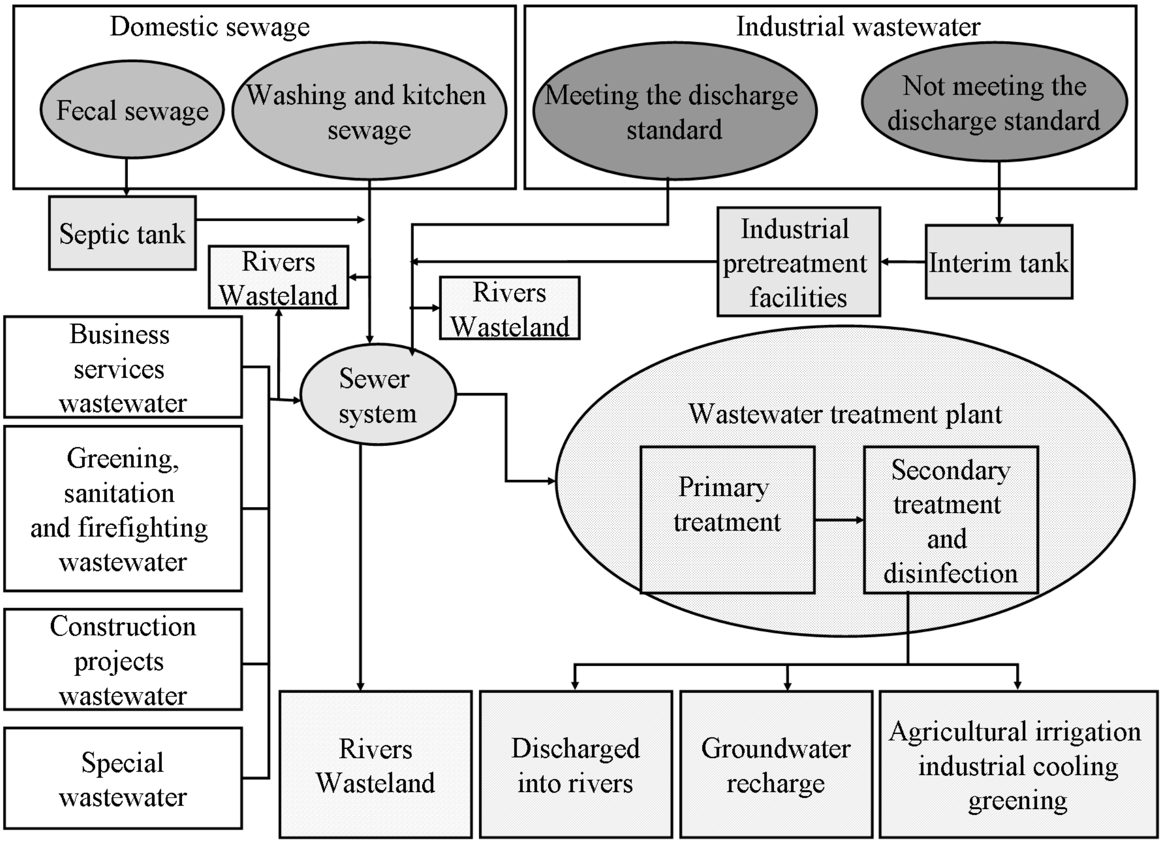

Figure 3-1 The structure of the wastewater system in Urumqi (source: own design).

However, two problems exist in the current wastewater system in Urumqi. The first one is that domestic sewage and industrial wastewater are mixed with each other in the sewage system and directly discharged into the sewage treatment plant, which causes secondary contamination of sewage and causes some problems for its treatment in the wastewater treatment plant. The second one is that the domestic sewage and industrial wastewater are directly discarded into rivers or wasteland without any monitoring, which contaminates rivers and groundwater.

The government of Urumqi is aware of these problems. The future urban sewage system is currently under regional planning. Based on the Urumqi Urban Master Planning, there are six drainage pipe systems (URUMQI URBAN PLANNING BUREAU 2011). The Hedong system includes the Tianshan District, the Saybagh District and the eastern part of the Xinshi District pipe networks. The Hexi system includes the western part of the Xinshi District and the airport pipe networks. The Shuimogou system includes the Shuimogou District and Jianquanjie pipe networks. The Sanping farm system includes the Toutunhe Industrial District, the West/North stations and the Wangjiagou pipe networks. The Shihua system and the Bagang system are the independent pipe networks for enterprises.

3.2 Wastewater treatment plants and wastewater reuse in Urumqi

From 1997 to 2010, the total amount of wastewater and the domestic sewage had been increasing year by year. In 2010, the total amount of wastewater was 1.6 times higher than that in 1997 and the domestic sewage in 2010 was twice as high as that in 1997. Industrial wastewater first showed a decreasing trend and then increased. The average annual total wastewater discharge amount was 150.85 million m^3, which made up roughly 16 % of the total water resources in 2010 (939.22 million m^3). Domestic sewage had increased from 54.44 million m^3 to 108.2516 million m^3 since 1996 (STATISTICS BUREAU OF URUMQI 1997-2011) and it showed a rising tendency as a whole (see Figure 3-2).

With the development in population, urbanization, industry and agriculture, more and more urban wastewater is generated in Urumqi. It is particularly important to consider whether wastewater treatment plant capacities can meet the demand of wastewater growth.

Table 3-1 shows the ten wastewater treatment plants of Urumqi. Before 2007 five main wastewater treatment plants were built, Hedong plant, Hongqiao plant, Qidaowan plant, Yashan plant and Toutunhe plant (ABUDUSHATAER et al. 2007, 677). Since 2007, another five wastewater treatment plants have been built (MEPC 2010b). In January 2009, the government extended the Hedong plant and the estimated treatment capacity is now twice as large as its originally designed capacity.

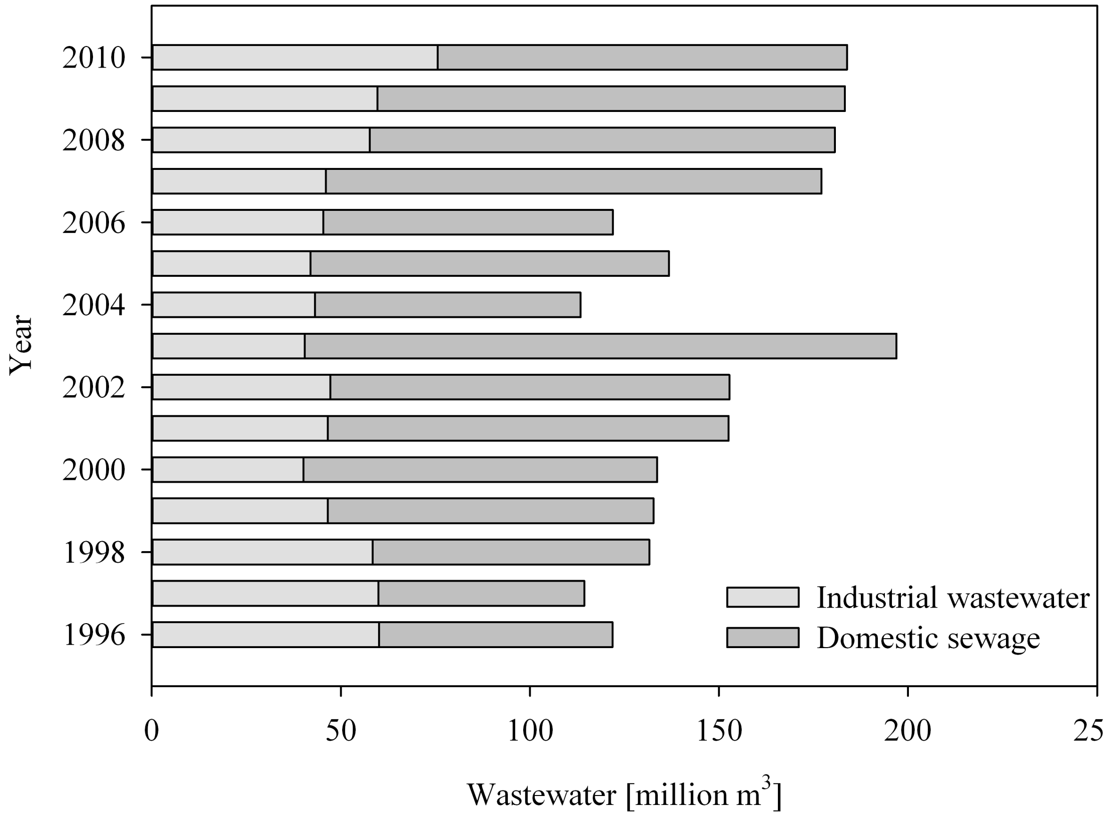

Figure 3-2 The discharges of industrial wastewater and domestic sewage from 1996-2010 in Urumqi (source: STATISTICS BUREAU OF URUMQI 1997–2011; own design).

The total estimated wastewater treatment capacity of all the wastewater treatment plants was 0.7353 million m^3 per day (MEPC 2010b) (also see Table 3-1). In Urumqi, 0.7 million m^3 of wastewater was produced each day by the residents and industries (LI et al. 2006c, 114). This means that every day the total wastewater treatment capacity of all the plants must be greater than or equal to 0.7 million m^3. This also means that the processing capacity of the wastewater treatment plants fully meets the requirements of all wastewater treatment. However, only a limited amount of wastewater was discharged into treatment plants probably because of the deficient sewer pipe systems. In reality, the average amount of treated wastewater for these plants was 0.1912 million m^3 per day, which is only 25 % of the installed treatment capacity. Most of the wastewater treatment plants are centralized plants, except the plant in Urumqi County, which was supported by a "Sino-Japanese decentralized wastewater treatment cooperation project" (MEPC 2010b; UEPB 2010).

Table 3-1 Wastewater treatment plants in different districts of Urumqi (source: ABUDUSHATAER et al. 2007, 678; UEPB 2010; own design).

Name	Time	Design capacity [million m^3/day]	District	Average treatment capacity [million m^3/day]	Types of reuse for the treated wastewater
Hedong (Chuangwei)	1997	0.20	Xinshi District	0.099	Agricultural irrigation, barren mountains greening and sand wash
Hedong (second phase)	2009	0.20	Xinshi District		Agricultural irrigation, greening in summer and discharge into wasteland in winter
Hongqiao	2002	0.03	Shuimogou District	0.03	Barren mountains greening
Qidaowan (Shuiwu)	2003	0.07	Shuimogou District	0.042	Agricultural irrigation and river recharge
Yashan	2003	0.05	Saybagh District	0.0092	Barren mountains greening
Toutunhe	2003	0.015	Toutunhe District	0.011	Agricultural irrigation, greening and groundwater recharge
Midong (Miquan)	2009	0.04	Midong District	-	Greening, agricultural irrigation and river recharge
Hexi	2010	10	Urumqi County	-	Agricultural irrigation and barren mountains greening
Wangjiagou	2010	0.5	Toutunhe District	Inflow< 0.0005	Agricultural irrigation and barren mountains greening
Bagang (Domestic sewage)	2010	2.5	Toutunhe District	-	Agricultural irrigation and greening
Decentralized plant	2010	0.03	Urumqi County	-	Agricultural irrigation and barren mountains greening

Concerning the location of the wastewater treatment plants, the majority was located in Urumqi's central districts (Xinshi District, Saybagh District and Shuimogou District), Toutunhe District and Midong District, where more than 70 % of the residents lived. Due to the natural slope in Urumqi, the main sewage treatment plants were built up in the downstream of the region, which limited the spatial extent of water reuse options (see Figure 3-3).

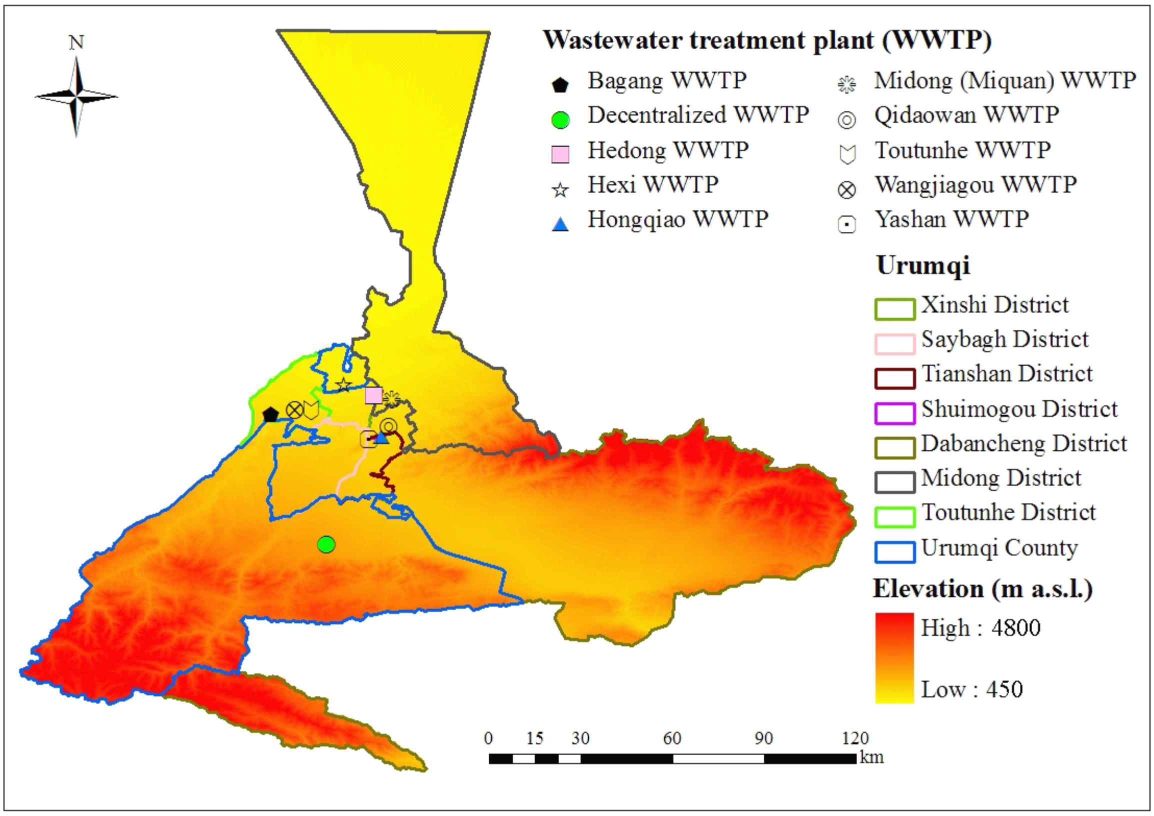

Figure 3-3 Distribution of the wastewater treatment plants in Urumqi (source: SRTM-3; AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; own design).

According to the Chinese national secondary discharge standard of pollutants for wastewater plants (national standard II), in the final effluent a maximum chemical oxygen demand (COD) is 100 mg/l, biochemical oxygen demand (BOD) must not be greater than 30 mg/l, suspended solids (SS) must not be greater 30 mg/l, nitrogen from ammonia (NH_3-N) must fall between 25 and 30 mg/l and a maximum total phosphorus is 3 mg/l (SEPA & AQSIQ 2002). According the Chinese national first grade discharge standard of pollutants for wastewater plant (national standard I), there are two levels, level A and level B. For the B in first grade discharge standard, in the final effluent a maximum chemical oxygen demand (COD) is than 60 mg/l, biochemical oxygen demand (BOD) must not be greater than 20 mg/l, suspended solids (SS) must not be greater than 20 mg/l, total nitrogen (total N) must not be greater than 20 mg/l, nitrogen from ammonia (NH_3-N) must fall between 8 and 15 mg/l, and a maximum total phosphorus (total P) is 3 mg/l (SEPA & AQSIQ 2002) (see Table 3-2). In Urumqi, the quality of the final effluent in six wastewater treatment plants (Hedong, Qidaowan, Yashan, Toutunhe, Wangjiagou, Decentralized plant) has reached the Chinese national secondary discharge standard (national standard II) and there were four plants (Hongqiao, Midong, Hexi, Bagang) where the quality of the effluent reached the B in first grade discharge standard (national standard I) (ABUDUSHATAER et al. 2007, 675; UEPB 2010) (also see Table 3-2). The quality of the treated wastewater is high, but not all the sectors require high-quality water. The wastewater treatment effluent only needs to meet certain requirements of water quality.

Table 3-2 Chinese national discharge standard of pollutants for wastewater plant and the quality of final effluent in the wastewater treatment plants in Urumqi (WWTP: wastewater treatment plant) (source: SEPA & AQSIQ 2002; UEPB 2010; own design).

Name	Standard	COD [mg/l]	BOD [mg/l]	SS [mg/l]	NH_3-N [mg/l]	Total N [mg/l]	Total P [mg/l]	Urumqi's WWTP
Chinese national standard	National standard I B	≤ 60	≤ 20	≤ 20	8-15	≤ 20	≤ 1	Hongqiao, Midong, Hexi and Bagang
	National standard II	≤ 100	≤ 30	≤ 30	25-30	-	≤ 3	Hedong, Qidaowan, Yashan, Toutunhe, Wangjiagou, Decentralized plant

In the wastewater treatment plants, there were only 0.001 % of pollutants in the secondary wastewater treatment effluent (ABUDUSHATAER et al. 2007, 677). The standards of wastewater treatment plants are high but the wastewater treatment rate is low (not all of the sewage is treated). Furthermore, not all of the treated wastewater (claimed water) is reused. According to the statistical data of 1997 to 2010, wastewater treatment plants in Urumqi treated approximately 74.96 million m³ per year and the average wastewater treatment rate in the urban area was 59 %, which means almost half of the wastewater was not treated and discharged directly into rivers and wasteland each year (STATISTICS BUREAU OF URUMQI 1998-2011). In 1998, the wastewater treatment rate reached 90.64 % since the Hedong wastewater treatment plant was built, but after that it showed an overall decline, because wastewater was not completely discharged into the treatment plants. The numbers and treatment capacity of wastewater treatment plants increased from 1997 to 2010, but the overall tendency of wastewater treatment rate was on the decline (see Figure 3-4).

There are two reasons for this phenomenon. The first one is that most of the wastewater is not discharged into treatment plants due to the faulty drainage pipes and weak environmental awareness. The second one is the increasing amount of wastewater. In 2010 the water reuse rate in Urumqi was 24.5 %, which had reached the domestic top-level (≥ 20 %), but it was half of the international top-level (≥ 40 %) (GUO 2009, 94). In addition, the water reuse rate was only 10.52 % due to the high reclaimed water fee, and the treated wastewater was reused for agricultural irrigation, greening and industrial cooling.

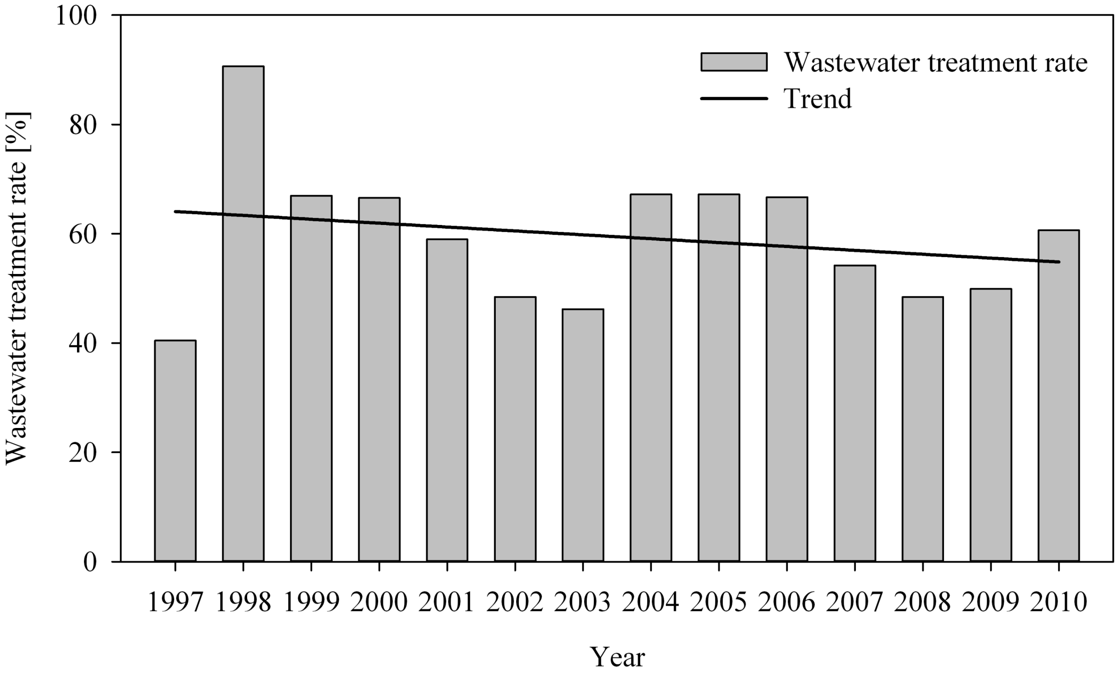

Figure 3-4 Wastewater treatment rate in Urumqi 1997-2010. The black line represents the trend of the wastewater treatment rate in Urumqi (source: STATISTICS BUREAU OF URUMQI 1998–2011; own design).

3.3 Government strategies to support wastewater reuse in Urumqi

In order to improve the reuse of wastewater the government of Urumqi has planned wastewater reuse projects. For example, wastewater treatment plants were expanded (e.g. Hedong wastewater treatment plant in 2009) (MEPC 2010b). 100 million Yuan[1] were invested to build 54 kilometers of an urban drainage network in 2007 that can effectively collect urban sewage. Major industrial enterprises were urged to complete wastewater treatment systems and improve the operational rate of sewage treatment facilities (STATISTICS BUREAU OF URUMQI 2011). In 2009 the municipal government invested 190 million Yuan in the advanced treatment processes of reclaimed wastewater. The government also prepared to build a wastewater treatment plant in Houxia to control environmental pollution and protect the Urumqi River (ABUDUSHATAER et al. 2007, 678).

Although water reuse projects have made some success, it is difficult to widely promote water reuse projects. The main reason behind this is that the reclaimed water resource

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[1] Yuan: Unit of currency of PR China, Renminbi.

market is a kind of policy market which depends on policies/laws that are different from other markets (QIAN & WANG 2003, 28).

3.4 The pricing mechanism and reclaimed water charge in Urumqi

In a market economy, price is a powerful segment to guide the consumer. In Urumqi, water supply prices in urban areas contain three parts: water tariff, wastewater treatment charge and water resource fee (an administrative cost levied by the government from entities or individuals that directly draw water resources) (URUMQI DEVELOPMENT AND REFORM COMMISSION 2005).

The data in Table 3-3 shows the development of water prices in Urumqi. From June 1st 2002, the water tariff was raised by the Urumqi government to twice the level it had been before. At the same time, the Urumqi government actively promoted a graded water price plan for urban water supply except agriculture, which contained three levels with a differential proportioning of 1:1.5:2 (URUMQI DEVELOPMENT AND REFORM COMMISSION 2005). The first price class, namely basic price, is relevant for residential water consumption (A) which is less than 4 m^3 per person per month ($A \leq 4$ m^3/person and month). The second price class, which is 1.5 times higher than the basic price, is for residential water consumption between 4 m^3 and 6 m^3 (4 m^3 $< A <$ 6 m^3/person and month). The third price class, which is twice the basic price, is for residential consumption of more than 6 m^3 ($A \geq 6$ m^3/person and month).

From 2005 to 2010, the water price for domestic usage (the sum of water tariff (paid to the water supply plant), wastewater treatment charge (paid to the wastewater treatment plant) and water resource fee (paid to the government) for domestic use) was 2.1 Yuan/m^3, which was much lower than that of Tianjing City with the highest domestic water price (3.5 Yuan/m^3) in China (HE & WANG 2012, 151).

The industrial water price (the sum of water tariff (paid to the water supply plant), wastewater treatment charge (paid to the government) and water resource fee (paid to the government) of industrial use) was 2.22 Yuan/m^3, which was 19 % of the value in Shaoyang City with the highest industrial water price (11.68 Yuan/m^3) (URUMQI DEVELOPMENT AND REFORM COMMISSION 2005; LI et al. 2007, 230; HE & WANG 2012, 151). The proportion of household expenditure on water supply is 0.09 % of the average disposable income of 14,402 Yuan per year in Urumqi (STATISTICS BUREAU OF URUMQI 2011). It is much lower than the suggested value by the World Bank (5 %) (CESIA 2010, 19).

The wastewater treatment charge (0.7 Yuan/m³) is much lower than the cost (3.4 Yuan/m³) in Urumqi, leading to a lower operation rate of the wastewater treatment facilities (LIU 2009, 112).

In addition, there is no reasonable pricing for reclaimed water and the reclaimed water fee is high. The reclaimed water fee for agricultural irrigation (0.1 Yuan/m³) is 2.5 times the water price in agriculture (the water resource fee, 0.04 Yuan/m³) (YAO 2002, 32; URUMQI DEVELOPMENT AND REFORM COMMISSION 2002b and 2005).

Table 3-3 Development of the water tariffs and the wastewater treatment charge in Urumqi city compared with the relatively stable reclaimed water charge from 2001 until 2010 (source: URUMQI DEVELOPMENT AND REFORM COMMISSION 2002b and 2005; WATER AFFAIRS BUREAU OF URUMQI 2010; own design).

Price [Yuan/m³]	Types	Time			
		2001	Jun.01.2002	Nov.01.2005	2010
Water tariff	Domestic sector	0.7	1.2	1.36	1.36
	Industry	0.8	1.2	1.48	1.48
	Business services	1.3	2.00	2.44	2.44
	Greening, sanitation and firefighting	0.5	0.9	0.9	0.9
	Construction projects	1.9	2.90	3.54	3.54
	Special uses	4.85	7.13	8.7	8.7
Wastewater treatment charge	Domestic sector	0.15	0.3	0.7	0.7
	Industry	0.15	0.3	0.7	0.7
	Business Services	0.15	0.3	0.7	0.7
	Greening, sanitation and firefighting	0.1	0.1	0.1	0.1
	Construction projects	0.1	0.1	0.1	0.1
	Special uses	0.15	0.3	0.7	0.7
Water resource fee	Water resource	-	0.03	0.04	0.04
Reclaimed water charge	Agricultural irrigation	0.05	0.05	0.1	0.1
	Industry	0.05	0.05	0.4	0.4
	Greening	0.1	0.1	0.1	0.1

3.5 Reasons for the low wastewater reuse rate

All of the wastewater treatment plants in Urumqi are secondary treatment plants, and the quality of effluents is up to the secondary standard (national standard II). All the wastewater discharged into these plants can be treated, but only 59 % of the total wastewater was discharged into treatment plants and the wastewater reuse rate was only 24.52 % in 2010. According to the analysis of the wastewater system, treatment plants and the pricing mechanism in Urumqi, the causes of the low wastewater reuse rate are:

1. The construction of the sewer pipes was deficient. Based on the analysis of the wastewater system only a small part of the wastewater was discharged into wastewater treatment plants, most of the wastewater was directly discharged into the streams and wasteland. At the same time there were no separate sewer pipes for rain, domestic sewage and industrial wastewater and many types of wastewater were mixed and discharged, which led to low internal efficiency of the wastewater treatment plants.
2. Basic measures for wastewater recycling were inadequate. The implementation of the basic measures lagged behind urban development, because the central treatment for sewage started later (from 1997) than urban construction (LIU 2009, 112). As the construction of infrastructural facilities for wastewater recycling lagged behind, there was no wastewater to treat.
3. The wastewater treatment plants were lacking economic profitability. As all of the plants were built with government funds, the managers regarded wastewater treatment as a public service (DONG & FU 2008, 41). Most of the treatment plants have made gigantic losses due to their lack of economic profitability, for example the Yashan wastewater treatment plant. In 2009 the wastewater treated in total was 1.6 million m^3, and the total cost was 5.5 million Yuan excluding the depreciation for the equipment. Thus the average cost per cubic meter was 3.4 Yuan. According to the national wastewater treatment fee, the wastewater treatment charge was only 0.8 Yuan/m^3, hereby resulting in a loss of 2.6 Yuan/m^3, which amounted to a total of 4.16 million Yuan to treat the total wastewater (1.6 million m^3) (LIU 2009, 112). The main reason for this development is that nobody felt responsible for the deficit because the wastewater plants are mandated by the government.

4. Industrial wastewater severely exceeded the discharge standard of the wastewater treatment plants. In Urumqi, about 22 % of industrial wastewater did not meet the discharge standards (STATISTICS BUREAU OF URUMQI 2011). Quality and quantity of industrial wastewater are different from domestic sewage. The composition of industrial wastewater is complex and industrial wastewater contains a lot of toxic materials. Industrial wastewater could not be clarified by one step treatment technology (HU 2004, 5). If industrial wastewater and domestic sewage are mixed in a sewage system, then the water can cause secondary contamination of domestic sewage. In order to meet the high standard of receiving water bodies (such as rivers, lakes) and reuse for industry, the reclaimed water must be processed to remove pollutants which cannot be completely removed by secondary treatment (FAN et al. 2005, 252; PU 2012, 237).

Currently, only 24.5 % of the wastewater is reused for agricultural irrigation, industry and greening (WATER AFFAIRS BUREAU OF URUMQI 2010, 21). In Urumqi the main plants are fiber crops and upland grain (STATISTICS BUREAU OF URUMQI 2011). According to the Chinese national standard on urban recycling water used for farmland, the treated wastewater can be used for fiber plant irrigation (chemical oxygen demand (COD) ≤ 200 mg/l, biochemical oxygen demand (BOD) ≤ 100 mg/l and suspended solids (SS) ≤ 100 mg/l) and upland grain (chemical oxygen demand (COD) ≤ 180 mg/l, biochemical oxygen demand (BOD) ≤ 80 mg/l and suspended solids (SS) ≤ 90 mg/l) (AQSIQ & SAC 2007) (see Table 3-4).

Table 3-4 Differences between the major indexes' values of the national standard on urban recycling water used for farmland and the treated wastewater from the wastewater treatment plants (the quality of the final effluent of the treatment plants reached national standard II or national standard I B) (source: AQSIQ & SAC 2007; UEPB 2010; own design).

Name	Standard	COD [mg/l]	BOD [mg/l]	SS [mg/l]	NH_3-N [mg/l]	Total N [mg/l]	Total P [mg/l]
Treated wastewater	National standard I B	60	20	20	8-15	20	1
	National standard II	100	30	30	25-30	-	3
Chinese national standard	Fiber plant	200	100	100	-	-	-
	Upland grain and oil crops	180	80	90	-	-	-
	Paddy field grain	150	60	80	-	-	-
	Open ground vegetables	100	40	60	-	-	-

In Urumqi, the quality of effluent of treatment plants has reached the Chinese national secondary standard (national standard II) (chemical oxygen demand (COD) ≤ 100 mg/l, biochemical oxygen demand (BOD) ≤ 30 mg/l and suspended solids (SS) ≤ 30 mg/l)) or the B in first grade discharge standard (national standard I) (chemical oxygen demand (COD) ≤ 60 mg/l, biochemical oxygen demand (BOD) ≤ 20 mg/l and suspended solids (SS) ≤ 20 mg/l) (UEPB 2010) (also see Table 3-4). Therefore the quality of the treated wastewater has already met the farmland irrigation standards. However, only a small portion of treated wastewater was used for agricultural irrigation due to the high price of reclaimed water for agricultural irrigation. There are three reasons for treated wastewater to be the prime candidate of agricultural irrigation. The first reason is that agriculture is the major water user in Urumqi, while agricultural irrigation requires less stringent quality water, and the water reuse rate can be greatly improved if treated wastewater is used in agriculture irrigation. The second reason is that the sewage contains some plant nutrients such as nitrogen, phosphorus, and potassium, which may increase agricultural production. The third reason is that most of the municipal sewage treatment plants are built in the outskirts of the city, which can shorten the distance of the water supply to the surrounding farmland.

In addition, reclaimed water from treatment plants in Urumqi also can be used for miscellaneous purposes (e.g. toilet flushing, firefighting, landscape irrigation and car washing) (HAO & ZHANG 2006, 8). According to the Chinese national standard for urban miscellaneous water consumption, if the treated wastewater can meet the different standards of major indexes, the reclaimed water can be used for toilet flushing (biochemical oxygen demand ≤ 10 mg/l, 6 ≤ pH ≤ 9, nitrogen from ammonia ≤ 10 mg/l, anionic surfactant ≤ 1 mg/l, turbidity ≤ 5 NTU, total coliforms ≤ 3 no./l, chlorine (contact 30 minute) ≥ 1.0 mg/l and chlorine (end of the network) ≥ 0.2 mg/l), roads and firefight (biochemical oxygen demand ≤ 15 mg/l, 6 ≤ pH ≤ 9, nitrogen from ammonia ≤ 10 mg/l, anionic surfactant ≤ 1mg/l, turbidity ≤ 10 NTU, total coliforms ≤ 3 no./l and chlorine (contact 30 minute) ≥ 1.0 mg/l and chlorine (end of the network) ≥ 0.2 mg/l), landscape irrigation (biochemical oxygen demand ≤ 20 mg/l, 6 ≤ pH ≤ 9, nitrogen from ammonia (NH_3-N) ≤ 20 mg/l, anionic surfactant ≤ 1mg/l, turbidity ≤ 10 NTU, total coliforms ≤ 3 no./l and chlorine (contact 30 minute) ≥ 1.0 mg/l and chlorine (end of the network) ≥ 0.2 mg/l), car washing (biochemical oxygen demand ≤ 10 mg/l, 6 ≤ pH ≤ 9, nitrogen from ammonia ≤ 10 mg/l, anionic surfactant ≤ 0.5 mg/l, turbidity ≤ 5 NTU, total coliforms ≤ 3 no./l and chlorine (contact 30 minute) ≥ 1.0 mg/l and chlorine (end of the network) ≥ 0.2 mg/l) and construction (biochemical oxygen demand ≤ 15 mg/l, 6 ≤ pH ≤ 9, nitrogen from ammonia ≤ 20 mg/l, anionic surfactant ≤ 1mg/l, turbidity ≤ 20 NTU, total coliforms ≤ 3 no./l and chlorine (contact 30 minute) ≥ 1.0 mg/l and chlorine (end of the network) ≥ 0.2 mg/l) (see Table 3-5).

Currently, the high quality tap water is used as urban miscellaneous water in Urumqi, which is wasteful. The quality of effluent of treatment plants in Urumqi is slightly lower than the Chinese national standard of water for miscellaneous use (also see Table 3-5). Therefore, the effluent of treatment plants can be treated by advanced treatment (e.g. membrane separation technologies and advanced oxidation technologies) (CIARDELLI et al. 2001, 189; COMNINELLIS et al. 2008, 769). Then the treated wastewater can be used for toilet flushing, firefighting, and car washing.

Table 3-5 Differences between the values of major indexes of the Chinese national standard on urban miscellaneous water consumption and the treated wastewater of the wastewater treatment plants (the quality of the final effluent of the treatment plants reached National standard II or national standard I B) (source: AQSIQ 2002; UEPB 2010; own design).

Name	Standard	BOD [mg/l]	pH	NH_3-N [mg/l]	Anionic surfactant [mg/l]	Turbidity [NTU]	Total coliforms [no./l]	Cl_2 [mg/l]
Treated wastewater	National standard I B	20	6-9	8-15	1	-	10^4	-
	National standard II	30	6-9	25-30	2	-	10^4	-
Chinese national standard	Toilet flushing	10	6-9	10	1	5	3	Contact 30 minute ≥ 1.0, end of the network ≥ 0.2
	Roads and firefighting	15	6-9	10	1	10	3	
	Landscape irrigation	20	6-9	20	1	10	3	
	Car washing	10	6-9	10	0.5	5	3	
	Construction	15	6-9	20	1	20	3	

3.6 Conclusion and suggestions

In order to alleviate the scarcity of water resources, urban sewage can be used as a potential water resource to meet the water demand. Sewage as a resource has a very important practical significance in arid regions. Sewage treatment is technically feasible. Water reuse can effectively save water resources, improve water utilization and control environmental pollution. According to the actual conditions and current problems in Urumqi, there are several suggestions about how to improve the ratio of water reuse (see Figure 3-5).

1. Establish a reasonable price system of water. According to the current situation (the price of water is low and the price of reclaimed water is high for agricultural irrigation)

it is a good measure for Urumqi to raise the water tariff to reduce water consumption and to improve the water reuse rate by the low reclaimed water charge for agricultural irrigation.

2. Increase the use of reclaimed water. Up to now, all the wastewater treatment plants have used secondary treatment in Urumqi. The reclaimed water is only used for agricultural irrigation, industrial cooling and greening. By improving treatment technologies (tertiary treatment, special treatment and advanced treatment) for wastewater treatment plants, the quality of effluent can be improved and wastewater can be reused for toilet flushing and car washing.
3. Heighten the enterprises' sense for environmental protection and strengthen the supervision and administration. That means the government needs to continuously improve administrative oversight and carry out rectification with respect to enterprises that fail to meet the requirements for pollutant discharge.
4. Adopt a managerial responsibility system of contracting. The government can sign a contract through public bidding with either an individual or a unity, with the profits going to the contractors. Thereby water treatment and reuse can be commercialized and motivate wastewater treatment plants to improve reclaimed water reuse.
5. Closely monitor the directly discharged sewage for persons or businesses and carry out a system of reward and punishments. If the directly discharged sewage cannot comply with the integrated wastewater discharge standard (SEPA & AQSIQ 2002), the government will apply measures of punishment in order to reduce the directly discharged sewage.
6. Improve the sewer pipe systems. Separate sewage pipes for domestic sewage, industrial wastewater and rain are necessary, as the pollution components for semester sewage, industrial wastewater and rain are different. If all of them are discharged into wastewater treatment plants through the same pipe, cross-contamination will occur.
7. Popularize small decentralized wastewater treatment plants. The long distance transfer of wastewater may cause pollution because of pipeline leakage. In residential areas all of the sewage is discharged into small scale sewage treatment systems and treated (MCC & AQSIQ 2003). The system also supplies reclaimed water for residents to establish a system of production and reuse of domestic sewage.

8. Design wastewater reservoirs to store the treated wastewater. In spring, summer and autumn with a high rate of water consumption a large amount of wastewater is produced and a lot of wastewater is discharged into wastewater treatment plants. The wastewater can be stored in the reservoir after it is treated and it can be used in winter when there is a lack of water.
9. Optimize the position of water reuse facilities. Water reuse facilities can be built close to population concentrated areas. The treated wastewater can be used for greening and ground washing.

The suggestions of improving wastewater recycling rate in Urumqi can be provided as references for the work of water conservation, wastewater reclamation and reuse in other cities of China. They also have significance in realizing the sustainable use of urban water resources.

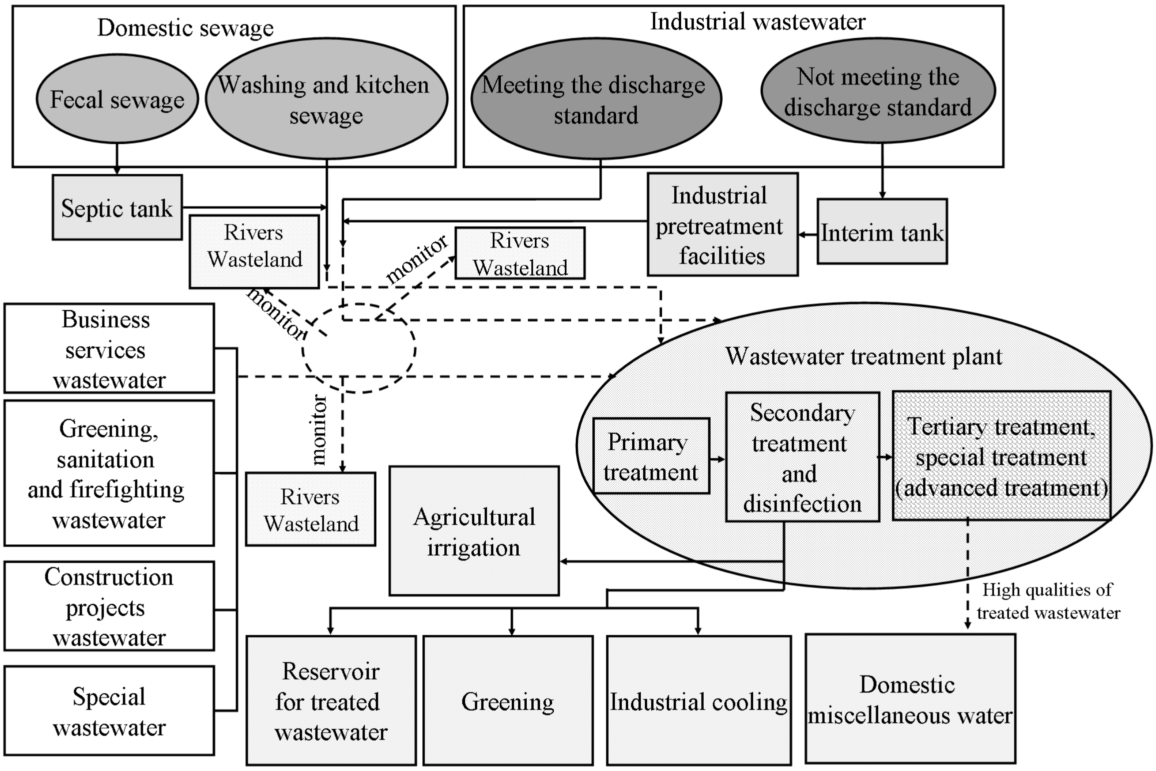

Figure 3-5 Advanced wastewater system of Urumqi (source: own design).

4 The water scarcity decision model

The fresh water cycle usually remains in a state of equilibrium in a region over a long period of time. But some influencing factors can disturb this equilibrium. These influencing factors are classified into two main types: natural factors (climate change, natural calamities) and human factors (excessive development and utilization, wasting water resources, water pollution) (JOHNSON & WEAVER 2009). These influencing factors could damage the water cycle and lead to water scarcity in a region.

Under specific environmental conditions, water scarcity risk refers to the unwanted events in water systems and the probability of occurrence of these unwanted events in water systems (insufficient water to meet basic needs), as well as the consequences which arise from this situation (e.g. political and business instability or lost economic opportunities) (RUAN et al. 2005, 906; ORR et al. 2009, 4). Being aware of water scarcity (section 4.1), water scarcity assessment indexes can be used to reflect the local water stress in Urumqi (section 4.2). Then, the water scarcity risk assessment indexes are chosen to identify and evaluate water scarcity risk in Urumqi (section 4.3). Meanwhile, by analyzing the methodologies used for decision-making, the methodology for decision-making and the tackling of water scarcity in Urumqi are found out (section 4.4). Afterward, the water scarcity decision-making model can be set up (section 4.5). This model could be used for providing some strategic decision-making advices (section 4.6).

4.1 Water scarcity

A water resource system is a sophisticated system with many sorts of elements, which are related to each other (POSTEL 2000, 941). The stability of this system can be affected by the natural circulation of a water system and human activity, as well as urbanization, pollution, and capital investment (MA et al. 2009, 2). A water resource system has its own characteristics, such as persistence (for sustainable human development, the relative stability of the water resources system must be maintained through various ways), natural attributes (following the natural processes, for example precipitation, runoff, groundwater, soil water, and evaporation), social attributes (domestic water consumption, water for production and ecological water consumption), economic attributes (water resources are the backbone of the national economy and abundance of water resources can accelerate socio-economic development) and vulnerability (ecological environment damage and water pollution) (HOLLING 1973; KUNDZEWICZ 1997). Water resources, society, the economy and the ecological environment are intimately interrelated and interdependent (JIANG et al. 2004, 32). Water resources are the basis of socio-economic development and the maintenance of the ecological environment. However, the development of society and the economy calls for increasing allocations of water resources for domestic use, agriculture and industry and causes a deterioration of the eco-environment (e.g. increases in sewage disposal and water pollution), it further intensifies the pressure on water resources, leading to conflicts among water users and excessive pressure on the ecological environment (JIANG et al. 2004, 32; CHENG 2005, 9) (see Figure 4-1). When the availability of water resources cannot meet the demand for socio-economic development and for maintaining healthy ecosystems, the imbalances between availability and demand (water scarcity) occur.

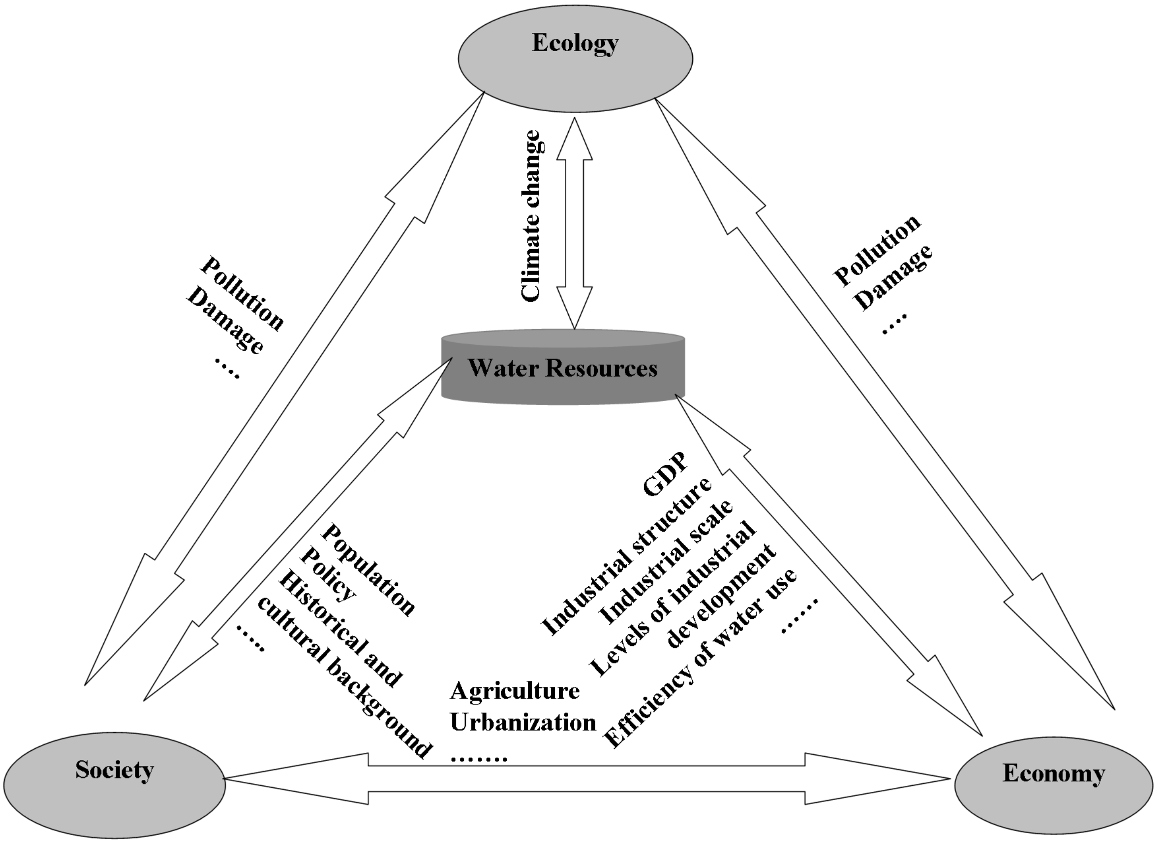

Figure 4-1 The relationship between water resources, society, the economy and ecology (source: own design according to POSTEL 2000, JIANG et al. 2004 and MA et al. 2009).

Since the 1980s, the international community has carried out lots of studies on water scarcity. The possible performance of water scarcity had been evaluated and classified by three criteria, namely reliability, resiliency and vulnerability (HASHIMOTO et al. 1982a, 1982b). These criteria were applied in the risk analysis of planning and operating a water supply system (JINNO et al. 1995, 187; XU et al. 1998, 21; MERABTENE et al. 2002, 2189). The characteristics of risk analysis for sustainable water resources were discussed according to the higher complexity of water resource management and uncertainty factors (LATINOPOULOS et al. 1997, 263; ZHANG et al. 2000b, 81). The demand satisfaction index, the demand reliability index, the rate of water resources utilization and the water-use efficiency were used to assess water scarcity risk and establish a decision-making system (LI et al. 2010, 1043).

4.2 Water scarcity assessment in Urumqi

Water scarcity describes the gap between available water resources and water demand. Water scarcity is related to many factors, such as the richness of water resources, water resources' spatial and temporal variability, the difficulty in the development and utilization of water resources, the level of socio-economic development, the degree of regional drought, regional water use habits, as well as the water conservation level. Water scarcity in Urumqi could be assessed by using the following methods.

4.2.1 Water stress index (*WSI*)

FALKENMARK et al. (1989) calculated the water usage per person in each economy in order to measure the water stress. Afterwards, FALKENMARK & ROCKSTRÖM (2004) modified the calculation method and used average per capita water resources (water stress index) to measure water scarcity. It means that water scarcity can be defined by annual per capita water availability. Since this index is simple, the method was widely used to describe water availability.

By 2010 2.43 million people were living in Urumqi, and the average per capita water resources accounted for 387 m^3, which is 17.6 % of the national per capita (2200 m^3). According to the thresholds and degrees of water scarcity, Urumqi was experiencing extreme water scarcity, and water scarcity has been a main constraint to life (see Table 4-1).

Table 4-1 Thresholds and degrees of water stress with explanatory remarks (*WSI*) (source: FALKENMARK et al. 1989; SHIKLOMANOV 2000; FALKENMARK & ROCKSTRÖM 2004; ARNELL 2004).

Category	Index [m^3 of water resources per capita and year]	Remark
Sufficient	> 1,700	Water scarcity occurs only irregularly or locally
Water stress	1,000-1,700	Water scarcity appears regularly
Scarcity	500-1,000	Water scarcity is a limitation to economic development, human health and well-being
Extreme scarcity	< 500	Water availability is a main constraint to life

4.2.2 Water poverty index (*WPI*)

The water poverty index defined by SULLIVAN (2002) is a composite index used to provide a better understanding of the relationship between water availability and measures of people's capability to access water. It combines many components which can be used to measure water poverty. It is normally used to analyze the relative scarcity of water resources among different regions or countries. There are five key components identified which can be used to measure water scarcity: resources (*R*) is used to identify the physical availability of water (how much water is available), access (*A*) is used to identify the access of water to human use, including domestic water consumption, taking into account basic water and sanitation needs for agriculturally-based regions, capacity (*C*) is used to identify the capacity and efficiency of management of water resources and it can provide information about socio-economic variables which can impact on access to water, use (*U*) is used to identify different ways and efficiency of water resources utilization and environment (*E*) is used to identify the environmental integrity of related water resources (MLOTE et al. 2002, 30; SULLIVAN & MEIGH 2003; SULLIVAN et al. 2006, 415). Each component contains subcomponents. According to the comprehensive analysis of Urumqi, 13 subcomponents are selected (see Table 4-2).

Table 4-2 Data selected based on water poverty index (*WPI*) component variables in Urumqi (source: own design).

WPI Component	Subcomponent	
R (Resource)	R_1	Total water resource [million m^3]
	R_2	Total population [person]
A (Access)	A_1	% of water demand by agriculture [%]
C (Capacity)	C_1	Per capita GDP [Yuan]
U (Use)	U_1	Per capita urban domestic water consumption [l/person and day]
	U_2	Per capita rural domestic water consumption [l/person and day]
	U_3	Per capita industrial water consumption [m^3/person]
	U_4	Per capita agricultural water consumption [m^3/person]
E (Environment)	E_1	Comprehensive drinking water pollution index [%]

A balanced approach is used to calculate *WPI*. Because the unit of each subcomponent is different, the values of the subcomponents need to be standardized. According to the different variables, the calculation method of the subcomponent is also different. When the value of the subcomponents for variables is greater, the status of the variables is better. The equation of the subcomponent can be written as follows:

$$y_j = (x_j - x_{\min})/(x_{\max} - x_{\min}) \text{ (SHAO \& YANG 2007, 867)} \tag{4.1}$$

where x_j is the value of variable j, $x_{\max}$ is the maximum value in the j data series, $x_{\min}$ is the minimum value in the j data series, y_j is the value of the subcomponent for the variable j and it falls between 0 and 1.

When all the values of subcomponents for all the variables are obtained, the mean values of the subcomponents for each variable multiply by 20, then the value of components for each variable can be calculated and the equation is expressed as below:

$$c_i = 20\overline{y_{ik}} \text{ (SHAO \& YANG 2007, 867)} \tag{4.2}$$

where k is the number of the subcomponents for each variable i, $\bar{y}_{ik}$ is the mean value of average value of the subcomponents for the variable i and c_i is the score of component for the variable i. The score of components falls between 0 and 20.

The *WPI* can be obtained by summing up the scores of components. The value of *WPI* falls between 0 and 100 because of the five different variables and the equation is written as follows:

$$WPI = \sum c_i \text{ (SHAO \& YANG 2007, 867)} \tag{4.3}$$

WPI can not only emphasize the vulnerability of communities to physical water scarcity, but also can consider the impacts of social, economic and political determinants. Therefore, it is suitable to be used to measure water scarcity in Urumqi.

In order to determine the overall score of *WPI* for Urumqi, the scores of *WPI* in seven districts and one county are calculated respectively. Taking into account the information accessibility in the districts of Urumqi, the variable of total water resource in resource component is substituted by surface water in 2010. The value of access (C_1) is calculated based on the proportion of water demand by agriculture in total water consumption in 2010. The score of capacity is calculated according to the per capita GDP (Yuan) in 2010. The comprehensive drinking water pollution index (the comprehensive evaluation of pH, dissolved oxygen, permanganate index, biochemical oxygen demand, ammonia nitrogen, phenol, mercury, lead and petroleum) for the surface water sources was 0.26 in 2010 in Urumqi (due to a relatively clear water which can serve as a drinking water after filtration) (WATER AFFAIRS BUREAU OF URUMQI 2010, 27). The variables and the subcomponents in districts and Urumqi County are showed in Table 4-3.

Table 4-3 Variables and subcomponents corresponding to the *WPI* in Urumqi (for the explanation of R_1, R_2, A_1, C_1, U_1, U_2, U_3, U_4 and E_1, refer to Table 4-2) (source: STATISTICS BUREAU OF URUMQI 2011; WATER AFFAIRS BUREAU OF URUMQI 2010, 27; own design).

Districts (variables)	*WPI* Subcomponent								
	R_1 [surface water resources in million m^3]	R_2 [no. of persons]	A_1 [%]	C_1 [Yuan]	U_1 [l/person and day]	U_2 [l/person and day]	U_3 [m^3/person]	U_4 [m^3/person]	E_1 [%]
Tianshan District	3.9	552799	0.12	38200	178	56	68.74	20.13	0.26
Saybagh District	9.86	522371	0.23	33782	143	373	21.04	30.04	
Xinshi District	2.28	534571	0.67	58216	239	39	30.16	250.46	
Shuimogou District	9.29	266166	0.22	35616	198	424	36.93	41.74	
Toutunhe District	7.67	138764	0.19	56751	221	59	330.20	114.80	
Midong District	31.38	44730	0.77	304985	157	117	728.82	3825.62	
Dabancheng District	365.61	276379	0.91	6089	196	428	32.06	486.04	
Urumqi County	479.43	94535	0.97	19167	453	47	25.39	2237.48	

The seven districts and one county are the variables. The minimum value ($x_{\min}$) and the maximum value ($x_{\max}$) for seven districts and one county are 2.28 and 479.43, separately (also see Table 4-3). According to equation (4.1), the values of subcomponent R_1 for the each district can be calculated. The values of subcomponent R_2 for the seven districts and one county also can be calculated using the same method. Then the average value of subcomponent R_1 and subcomponent R_2 for each district can be obtained. According to equation (4.2), the score of component R each district can be calculated (see Table 4-4). The score of components A, C and U can also be calculated by using equations (4.1) and (4.2). Due to the limited available data resources for the subcomponent E_1, the component E can be calculated by using equation (4.2). After the calculations for the components R, A, C, U and E, the *WPI* for each district can be obtained according to equation (4.3) (also see Table 4-4).

The lower the scores of the various components, the greater the problem of water scarcity. The score of R reflects how much of the water resource is available. The score of A reflects how important crops are for consumer products and what percentage of water is obtained for crop production. The score of C reflects how the socio-economy influences water extracting. The score of U reflects the water consumption status in the district and the use efficiency. The score of E reflects the environmental index of water supply. The high *WPI* score and A score indicate crops as the main consumer goods in this region (Midong District, Urumqi County, and Dabancheng District). The lower C score of Urumqi County and Dabancheng District means the socio-economic development of this region causes some restrictions on water extraction (see Table 4-4).

Table 4-4 The scores of components and *WPI* in districts in Urumqi (each component score ranges from 1-20; the *WPI* score ranges from 1-100) (for the explanation of R, A, C, U and E, refer to Table 4-2) (source: own calculations).

Districts	The score of components					*WPI*
	R	*A*	*C*	*U*	*E*	
Tianshan District	10.03	2.33	2.15	1.12	5.2	20.83
Saybagh District	9.56	4.53	1.85	4.31		25.45
Xinshi District	9.64	13.36	3.49	1.92		33.60
Shuimogou District	4.51	4.41	1.98	5.98		22.07
Toutunhe District	1.96	3.71	3.39	3.82		18.08
Midong District	0.61	15.49	20.00	11.23		52.52
Dabancheng District	12.17	18.12	0.00	6.54		42.04
Urumqi County	10.98	19.39	0.88	8.05		44.49

According to the scores of components and *WPI* in the districts, the overall score of component and *WPI* in Urumqi Region can be determined by the mean scores of components and *WPI* in the districts. When comparing the scores of *WPI* between Urumqi Region and three inland basins (Heihe, Shulehe and Shiyanghe) in the Hexi Corridor, the score of *WPI* for Urumqi is the lowest, which means that the water resources management in Urumqi is unreasonable integrated (see Table 4-5). The lower score of resource (*R*) means that the amount of water resources is insufficient in Urumqi compare to the three inland basins. The lowest score of capacity (*C*) in Urumqi mean that the capability and efficiency of water management must be improved. The relatively high score of component *A* means more efforts had been put in to improve agricultural production in Urumqi and most of the available water resources were used to meet the demand of agricultural production. The relatively low score of component *E* indicates there are great risks in water resources security and water pollution is very serious in Urumqi compared to the three inland basins (also see Table 4-5).

Table 4-5 The scores for each component and *WPI* for Urumqi Region and three inland basins in the Hexi Corridor (source: Urumqi: own calculations; data source for Heihe basin, Shulehe basin and Shiyanghe basin: ZHANG et al. 2012a, 44).

Region/Basin	Components					*WPI*
	R	*A*	*C*	*U*	*E*	
Urumqi	7.43	10.17	4.22	5.37	5.2	32.39
Heihe	9.0	3.1	11.2	5.2	10.9	39.4
Shulehe	8.5	2.7	20	8.0	26.8	66
Shiyanghe	7.2	2.7	8.1	5.3	13.3	36.6

4.2.3 Water availability index (*WAI*)

The water availability index is used to measure available water for socio-economic development (SHIKLOMANOV 1991, 1998). SHIKLOMANOV & RODDA. (2003) made some comparisons between available water (surface water and groundwater) and the water demands from various sectors. Here, water availability index was improved according to available water resources (ALCAMO et al.1997). Afterwards, this improved index was applied in many areas (MEIGH et al. 1999, 85; ALCAMO et al. 2003; ALAMARAH et al. 2007; TAMIMI et al. 2007). Since this index could directly reflect the gap between available water resources and the ability to meet the water demands for socio-economic development, this index can also be applied in Urumqi to assess water scarcity.

The value of the index falls in the range of -1 to 1. The index is zero when the availability and demands of water are equal (TAMIMI et al. 2007, 333) (see Table 4-6). The water availability index can be expressed as follows:

$$WAI = \frac{S_r + W_g - WC_T}{S_r + W_g + WC_T} \quad \text{(TAMIMI et al. 2007, 333)} \qquad (4.4)$$

where S_r is surface runoff, W_g is groundwater resources and WC_T is total water consumption by all sectors.

In 2010, the surface water was 909.42 million m³ and the safe yield of groundwater was 29.80 million m³ (WATER AFFAIRS BUREAU OF URUMQI 2010, 14). The total water consumption was 1089.31 million m³ (WATER AFFAIRS BUREAU OF URUMQI 2010, 18). According to the equation (4.3), the *WAI* value is -0.07, which is less than 0 (also see Table 4-6). Therefore the water availability is not sufficient to meet water demand in Urumqi, which highlights the gap between water supply and demand of water resources in this region.

Table 4-6 Degrees of water scarcity for the water availability index (*WAI*) (source: TAMIMI et al. 2007, 333).

Category/Condition	Index
Availability > demands	1-0
Availability = demands	0
Availability < demands	-1-0

4.2.4 Water supporting index (*WSPI*)

According to the amount of water resources and water withdrawal, the water supporting index was invented by LI & LI (2012) and used to measure water scarcity in China. The water supporting index describes the ability of water resources to support regional socio-economic development. It is important for decision-making on water resources, regional development planning, function divisions and the evaluation of urban development.

The utilization rate of water resources is the proportion of water withdrawal compared to total water resources and it was calculated using the following equation:

$$WRU = \frac{(TWS - W_T - UW)}{R_1} \quad \text{(LI \& LI 2012, 412)} \qquad (4.5)$$

The research area was divided into several small evaluation units. For one evaluation unit the overall water utilization rate can be represented by the flowing equation:

$$WRU_n = \frac{\sum (TWS_n - W_{Tn} - UW_n)}{\sum R_{1n}} \text{ (LI \& LI 2012, 412)} \tag{4.6}$$

The degree of water resources utilization (WRU_d) was presented by the minimum of WRU and WRU_n. The standardized water supporting index ($WSPI$) was expressed as below:

$$WSPI = \frac{1}{1 + WRU_d} \text{ (LI \& LI 2012, 412)} \tag{4.7}$$

According to the data accessibility in Urumqi, the water resources utilization rate (WRU) can be modified and rewritten as follows:

$$WRU = \frac{(TWS - UW)}{R_1} \tag{4.8}$$

where WRU is the water resources utilization rate [%], TWS is the total water supply [million m³], UW is the unconventional water resources (treated wastewater and precipitation) [million m³] and R_1 is the total water resources [million m³].

With Urumqi as the evaluation unit, therefore, the degree of water scarcity can be presented by the WRU. The standardized water supporting index ($WSPI$) can be modified and rewritten as follows:

$$WSPI = \frac{1}{1 + WRU} \tag{4.9}$$

The $WSPI$ value falls in the range of 0 to 1. If the value is less than 0.6, the extreme scarcity will occur. When the score falls in the range of 0.92 to 0.1, it implies that this region has abundant water resources (see Table 4-7).

Table 4-7 Degrees and characteristics of water scarcity for the water supporting index ($WSPI$) (source: LI & LI 2012, 413).

Category	Index	Remark
No water scarcity	0.92-0.1	-
Low	0.82-0.92	Water stress occurs under extreme drought
Medium	0.74-0.82	Periodic water scarcity, poor ability to respond to drought
High	0.6-0.74	Periodic water scarcity, water scarcity caused by drought
Extreme scarcity	<0.6	Persistent water scarcity, normal water demand cannot be effectively guaranteed.

In Urumqi, the total water supply and the total water resources were 1089.31 million m³ and 939.22 million m³ in 2010. The unconventional water resource was only treated wastewater, about 22.63 million m³ (WATER AFFAIRS BUREAU OF URUMQI 2010, 17). According to the equations (4.8) and (4.9), a *WSPI* score can be obtained. The value is 0.4682, which is less than 0.6, meaning that a persistent water scarcity occurs and the available water resources cannot meet the normal water demand.

In addition, there are lots of other methods used to measure water scarcity, such as the water resources vulnerability index (*WRVI*) (RASKIN et al. 1997) and the IWMI (International Water Management Institute) model (SECKLER et al. 1999, 39). According to the analysis of water scarcity of the international water management institute (SECKLER et al. 1999, 39; MOLDEN 2007, 11), Urumqi is an example of a region in which more than 75 % of river flows are assigned to agriculture, industries and residents.

Overall, Urumqi suffers under the effects of physical water scarcity, which means the per capita water resource is low. In addition, unreasonable management and allocation of water resources and water pollution increase the gap between water supply and water demand, further exacerbating the risk of water scarcity.

4.3 Water scarcity risk assessment indexes

Because of an uneven distribution of water resources and water pollution, water scarcity and ecological deterioration has gone from bad to worse and has become an important factor that restricts the sustainable development of Urumqi. Water scarcity has caused an increasingly serious conflict between water supply and demand. In the meantime, water scarcity can also be affected by water demand and water supply. The random distributions of water supply, water demand, precipitation, and runoff also bring about a serious risk in water scarcity. If the amount of available water resources cannot meet the demand of socio-economic development, then it will bring economic losses. If the water scarcity is prolonged, an especially serious aspect of which is the lack of domestic water, then it will cause further social problems.

The impact factor and index of water scarcity risk assessment must reflect the water scarcity risk in the water scarcity region, measure the water scarcity risk, and reflect the affordability of the water resources system after the water scarcity risk in solving the water scarcity problem (HUANG et al. 2007, 256; WANG et al. 2009a, 32; HAN et al. 2011, 398). The rational exploitation, efficient utilization, optimal allocation, comprehensive conservation, effective protection and scientific management of water resources can be proposed based on the analysis of water scarcity risk.

Various common water scarcity risk assessment indexes are introduced in section 4.3.1. The water scarcity risk assessment indexes for Urumqi are presented in section 4.3.2.

4.3.1 Common water scarcity risk assessment indexes

A risk assessment index involves using an index to measure the risk level. The higher the index, the higher the risk (WANG et al. 2010c, 70). Water scarcity risk assessment refers to the probability of undesired events and the resulting economic and non-economic losses in specific time-space environmental conditions (WANG et al. 2009a, 31). The most commonly used water scarcity risk assessment indexes are risk rate, vulnerability, recoverability and risk level.

4.3.1.1 Risk rate

Risk rate refers to the probability of fatal accident (water supply cannot meet water demand). It can be expressed by the number of accidents per unit of time. If the fatal accident of water resources is F € $(\lambda > \rho)$, the risk rate of water resources can be written as follows:

$$\tau = P(\lambda > \rho) = P\{\eta_t \in F\} \text{ (WANG et al. 2010c, 70)} \qquad (4.10)$$

where ι is the risk rate of the water system, η_t is the state variable of water resource system.

4.3.1.2 Vulnerability

Vulnerability is an important index to describe the average loss severity due to fatal accident (water supply cannot meet water demand). Supposing the i-th severity of the loss is ψ_i, and its respective probability of occurrence is π_i, then the vulnerability of the system can be represented by the following equation:

$$\zeta = E(s) = \sum_{i=1}^{TNF} \pi_i \psi_i \text{ (WANG et al. 2009a, 31)} \qquad (4.11)$$

where ζ is the vulnerability of the water system, TNF is the total number of fatal accident, ψ_i is the i-th severity of loss of the system and π_i is the i-th probability of occurrence of such a loss.

4.3.1.3 Recoverability

Recoverability is used to describe the possibility of the system returning to its normal state after a fatal accident (water supply cannot meet water demand). The higher recoverability shows that the system can recover to the normal state from fatal accident. It can be represented by the conditional probability as follows:

$$\theta = P(\eta_t \in \gamma | \eta_{t-1} \in F) \text{ (ZHANG et al. 2005, 1140)} \tag{4.12}$$

where θ is recoverability of water system, γ is the normal state of water resource system, F is the fatal accident (water supply cannot meet water demand), η_t and η_{t-1} are the t-th and (t-1)-th state variables of water system.

4.3.1.4 Risk level

Risk level is used to describe the variability of risk magnitude by mathematical characteristics of probability distribution. The greater the risk level means the probability distribution is more dispersed and the probability of deviation between the actual results and the expected value is greater. Risk level is expressed commonly by using standard deviation (σ) and it can be represented by the following equation:

$$\sigma = (D(\eta))^{1/2} = \left(\sum_{i=1}^{n} \frac{(\eta_i - E(\eta))^2}{n-1} \right)^{1/2} \text{ (WANG et al. 2010c, 70)} \tag{4.13}$$

where η_i is the i-th state variable of water resource system and $E(\eta)$ is the average of the state variable of water resource system for several years.

In addition, there are lots of other indexes used to assess water scarcity risk, such as reliability, resilience, reproducibility and acceptability (HASHIMOTO 1982b, 19).

A single risk assessment index cannot reflect all the information for water scarcity due to the complex influencing factors of water scarcity (the characteristics of water resources, climatic conditions, facilities of water supply and water consumption, and policies of water management). Therefore, the combination of several indexes is adopted to evaluate water scarcity risk. In 1982, three water scarcity indexes (reliability, resilience and vulnerability) were used to evaluate water resources and concluded that the risk rate is the rate that water supply cannot meet water demand (HASHIMOTO et al. 1982b, 19). A drought risk index system was built to reflect the water scarcity by using a reliability index (the extent of the water supply system to meet the water demand), a recovery index (the possibility of the return from a dry state to a normal water supply state in the system when water scarcity occurs) and a vulnerability index (the measure of the water scarcity) (XU et al.1998, 21; ZHANG et al. 2005, 1140). WANG et al. (2009a) built a SPV-VFS (Set Pair Analysis-Variable Fuzzy Set) model to evaluate water scarcity risk according to the risk rate, vulnerability, recovery and risk level.

All these methods can only describe performance indexes which contain less information and these indexes cannot be used in a regional scale due to the different assessment goals and the different time-scale of the data.

4.3.2 Water scarcity risk assessment indexes for Urumqi

Water resources are related to society, the economy and ecology, therefore lots of factors can cause water scarcity, such as the development level of a region, the allocation of water resources, water quality, water regulation and management, and socio-economic structure (ZHANG et al. 2000b, 81). The selected water scarcity risk assessment indexes should reflect the probability and potential impact of water scarcity which are caused by the factors on a regional scale (Urumqi).

MARTIN-CARRASCO & GARROTE (2007) used a demand satisfaction index, demand reliability index, resources use index and reliability increase index to assess water scarcity risk in Spain's Ebro River Basin. These indexes were modified (demand satisfaction index, demand reliability index, the rate of water resources utilization and water-use efficiency) and used to establish a water scarcity risk assessment and decision-making system in Beijing-Tianjing-Tangshang region by LI et al. (2010). These indexes are easy to understand and can be used in many regions. Therefore, according to the available data of water resources in Urumqi, the rate of water resources utilization and water-use efficiency are selected and modified as the indexes to make decisions.

4.3.2.1 Rate of water resources utilization

The rate of water resources utilization (*RWU*) is used to assess water scarcity and is computed as follows:

$$RWU = \frac{WC_T}{R_1} \text{ (LI et al. 2010, 1043)} \qquad (4.14)$$

where WC_T is the total water consumption [million m^3] and R_1 is the total water resources [million m^3] in this area. It can be affected by economic development. According to the evaluation of global water resources, if the rate of water resources utilization is more than 0.4, water scarcity occurs in that area (LI et al. 2010, 1042). In northwest China, the amount of water consumption must not exceed 0.7 of the total water resources, otherwise it will bring about serious consequences for the environment because of the over-exploitation of surface and ground water ((DENG 2001, 19). According to the degree of the regional water scarcity, some measures for solving this situation can be taken, such as unconventional water resources, economic regulation measure, controlling environmental safety, improving urban functions and the interbasin transfer of water ((DENG 2001, 19; RUAN et al. 2005, 912; LI et al. 2010, 1042).

4.3.2.2 Water-use efficiency

Water-use efficiency (WUE) is used to describe the level of water use and reflect the water conservation in the region. LI et al. (2010) used the level of water used for agriculture and industry to measure the level of water use in the whole Beijing-Tianjing-Tangshang region and the water-use efficiency was expressed as below:

$$WUE = \frac{\alpha_i WC_{AP} + \beta WC_{IP}}{WC_{AP} + WC_{IP}} \quad \text{(LI et al. 2010, 1043)} \tag{4.15}$$

In Urumqi, water is used for agricultural, industrial and domestic purposes and agricultural and domestic actors are major water users. Water-use efficiency originates in the economic concept of productivity (cf. HAMDY 2007, 10), therefore, the proportion of the agricultural economy is used to evaluate the agricultural water-use efficiency due to the high agricultural water consumption and low agricultural GDP in Urumqi. In addition, the leakage losses in the pipe network can drastically increase domestic water consumption which can directly affect the domestic water-use efficiency. Thus, the index can be modified and computed with the equation as below:

$$WUE = \frac{\alpha_i \varpi WC_{AP} + \beta WC_{IP} - \chi_l WC_{DP}}{WC_{AP} + WC_{IP} + WC_{DP}} \tag{4.16}$$

where α_i is the average conveyance efficiency of the irrigation canal system [%], $\bar{\omega}$ is the proportion of the agricultural economy (agriculture, forestry, animal husbandry and fishery) [%], β is the industrial water recycle rate [%] and χ_l is the leakage rate of the city pipe network [%]. WC_{AP} is the proportion of agricultural water consumption to the total water consumption in Urumqi. WC_{IP} is the proportion of industrial water consumption to the total water consumption in Urumqi. WC_{DP} is the proportion of domestic water consumption to the total water consumption in Urumqi. The value of water-use efficiency depends on the parameters α_i, $\bar{\omega}$, β, χ_l, WC_{AP}, WC_{IP} and WC_{DP}. If sustainable water resources development is considered, the value of water use-efficiency must be improved in the region with a high level of economic development and water scarcity by improving α_i, $\bar{\omega}$ and β, reducing χ_l and adjusting the proportion of water consumption for each sector. The improvement of α_i,$\bar{\omega}$ and β, and reduction of χ_l can be realized by taking water conservation measures. And the reasonable allocation of water consumption can be realized by adjusting industrial structures. In order to evaluate the water-use efficiency status in Urumqi, water-use efficiency is compared with the national average value (0.46) (cf. MA et al. 2012, 797). If the value of water-use efficiency is less than the national average value, the conservation program and industrial structure need to be strengthened in the region.

4.4 Decision-making methodologies for tackling the problems of water scarcity

The decision-making strategies for reducing the problem of water scarcity could be obtained through appropriate methodologies for decision-making in water scarcity according to the water scarcity risk assessment indexes mentioned in section 4.3.2. Based on the analysis of the advantages and the disadvantages of water scarcity decision-making methodologies (section 4.4.1), the suitable method used in Urumqi is introduced in section 4.4.2.

4.4.1 Common decision-making methodologies for tackling the problem of water scarcity

As a premise of integrated water scarcity risk assessment indexes, it is important to analyze and evaluate water scarcity risk by using proper methods. The common methodologies used for making decisions to solve water scarcity are the Monte Carlo method, the statistics of extremes, the fuzzy risk analysis, and the maximum entropy risk analysis.

4.4.1.1 The Monte Carlo method

The Monte Carlo method is a stochastic simulation method. It is a method based on a probability and statistics theory method (LANDAU & BINDER 2000, 4). There are lots of complex mechanisms among risk variables in water resources risk assessment. The Monte Carlo method can be used to obtain random changes of some decision-making indexes and it can be expressed as follows:

$$\begin{cases} Y = f(X) \\ X = (X_1, X_2, \ldots, X_n) \end{cases} \quad \text{(HAN et al. 2003, 43)} \tag{4.17}$$

where X is a multi-dimensional random variable of a probability distribution and $f(X)$ is an unknown function.

According to the physical nature of the system, the Monte Carlo method is used to describe the characteristics of the system and the probability density function of certain feature quantity can be exported. Then some simulation results of the characteristics can be obtained by random sampling. Some characteristics of the system can be predicted based on the summary analysis of the simulation results (WANG et al. 2010c, 70). The results of this methodology show diversity, but it needs more computational space and a huge amount of calculation. It also requires prior experience and detailed data (KWAK & INGALL 2007, 50). It is therefore not suitable for the case of Urumqi with its limitations in the availability of information.

4.4.1.2 Statistics of extremes

Extreme value theory is used to analyze the probabilistic and statistical questions related to very high or very low values (SMITH 2003, 4). Statistics of extremes is a branch of mathematical statistics, dealing with the maximum and minimum of a certain sample (FU et al. 2001, 8).

Let X be the initial random variable with a cumulative distribution function $F_X(x)$. The maximum risk is Y_n in an n year period and it can be expressed as follows:

$$Y_n = \max(X_1, X_2 \ldots, X_n) \quad \text{(OLSEN et al. 1998, 498)} \tag{4.18}$$

where X_1, X_2,..., X_n are independent of each other and have identically distributed variables with random variable X.

Let X_i be the maximum risk in year i. Each X_i has a cumulative distribution function $F_{X,i}(x)$. The cumulative distribution function of Y_n can be given by (OLSEN et al. 1998, 499):

$$F_{Y,n}(y) = P(Y_n \le y) = P(X_1 \le y, X_2 \le y, \ldots, X_n \le y) = \left[F_{X,1}(y)\right]\left[F_{X,2}(y)\right]\ldots\left[F_{X,n}(y)\right] \tag{4.19}$$

When $n \to \infty$, F belongs to either Type I distribution (Gumble-distribution), Type II (Frechet-distribution) or Type III (Weibull-distribution) (FU et al. 2001, 9).

Extreme value theory is widely used in decision-making for water scarcity. The statistics of extremes can simulate and monitor water scarcity risk under random event, such as droughts and floods. But it is of poor division of scope and intensity of risk and therefore, is also not suitable for Urumqi.

4.4.1.3 Fuzzy mathematics

Fuzzy mathematics is a mathematic approach to researching and processing the uncertainty of objects based on people's subjective understanding and judgment. Risk includes the set of scenario identification, the probability of that scenario and the evaluation measure of that scenario (KAPLAN & GARRICK 1981, 13). Things are affected by many factors from different aspects in their development and evolution, which make them embody an unstable, fuzzy, disorder or chaotic phenomena (Han et al. 2003, 43). The fuzzy of water resources system can be divided into two classifications: random uncertainty described by stochastic analysis method, and fuzzy uncertainty described by fuzzy mathematics (HAN et al. 2003, 44). Water scarcity was assessed by using fuzzy mathematics based on the indexes such as risk rate, vulnerability, recovery, recurrence interval and risk level (RUAN et al. 2005, 906). However, there are many influencing factors in this method and the weight of each factor is very small. Therefore, it is impossible to get reliable predictions using this method. Thus, fuzzy mathematics is not suitable for the decision-making to reduce Urumqi's water scarcity with its many influencing factors.

4.4.1.4 Maximum entropy risk analysis

The entropy is the parameter to describe the disorder of things. The entropy of a system is the degree of disorder. Information is used to eliminate or reduce uncertainty. The degree of uncertainty in a system is information entropy (SHANNON 1948). In information theory, practical problems contain three types of information (objective information, subjective information and mixture information). Objective information associates with the results of tests and it can be ensured by information entropy. Subjective information associates with judgment, experience and understanding. It can be measured by fuzzy entropy. Mixture information includes both objective information and subjective information. It can be described by fuzzy random variables (HAN et al. 2003, 44). Maximum entropy can be used to set the prior distribution. The probability characteristics of risk variables can be analyzed based on the prior distribution. Then the risk analysis can be made based on the probability characteristics of risk variables (HAN et al. 2011, 397). When modeling, the user only needs to select features, and does not need to consider how to use these features. However, the data spare problem exists in maximum entropy model which is why this method is not suitable for Urumqi.

In addition, there are many other methodologies used to make decisions to solve water scarcity, such as the grey risk analysis methodology, the JC methodology, and the Analytic Hierarchy Process (AHP) methodology. A suitable methodology plays a key role in creating a correct water scarcity decision model.

4.4.2 Decision-making methodology for Urumqi

Methodology for decision-making in areas with (potential) water scarcity is the core of a water scarcity decision model. Since decision-making is based on multiple levels of factors and complex indexes (mentioned in section 4.3.2) in Urumqi, the multi-target method has been chosen and modified to calculate the relationship between various factors and decisions in Urumqi.

4.4.2.1 Multi-objective methodology

Analytic Hierarchy Process (AHP) methodology is a multi-objective decision-making methodology, which is one of the most effective methodologies to calculate the weight of decisions and factors in a complex system (YANG et al. 2008, 125). The Analytic Hierarchy Process introduced by SAATY in the 1970s is also known as level weight analysis. It is a systematic and hierarchical analysis method, which combines quantitative and qualitative analysis and has been used in various areas (SAATY 2008, 95). As one of the methodical tools in system analysis, the Analytic Hierarchy Process can express and process the subjective judgment of people in the form of quantity (WANG et al. 2012c, 126). It transfers complex problems into various factors and establishes a hierarchy structure with various factors. It is commonly adopted to make decisions for solving regional water scarcity because of some specific advantages which are described below (ZHAO & DAN 2000; REN & LI 2000, 318; ZHU et al. 2003, 46; WANG & HE 2004, 6; RUAN et al. 2005, 906; LI et al. 2006a, 49; ZHAO & DAN 2008):

1. Systematic analysis method

   The Analytic Hierarchy Process takes the research subject as a system. It can make decisions according to decomposition, comparative judgment and comprehensive thinking. It has become the most important analysis tool after mechanism analysis and statistical analysis.

2. Practical decision-making method

   The Analytic Hierarchy Process combines qualitative and quantitative methods. It can solve lots of practical problems. Its application is widespread.

3. Simple method

   Using a simple mathematical calculation, decision-makers can easily understand the results.

4. Less required quantitative data

   The Analytic Hierarchy Process requires more qualitative analysis and judgment than normal quantitative approaches.

Urumqi's water scarcity decision model is a multi-objective decision-making model. Therefore, it should be built based on the Analytic Hierarchy Process. The development Steps of the Analytic Hierarchy Process for a decision model are as follows (see Figure 4-2):

1. To establish a hierarchical model

   Based on the detailed analysis of the relationship among the various components in the system, the relevant factors can be layered in a top-down form, including three layers: target layer, factor layer and decision layer.

2. Pairwise comparison matrix, single priority ranking and consistency ratio

   According to the subject experience, the scores can be given to each factor in the factor layer against goal layer and each decision in the decision layer against each factor. The scores must fall from 1 to 9. The n-factor pairwise comparison matrix can be constructed against the target layer. And the n-decision pairwise comparison matrix can be constructed against each factor in the factor layer. The priorities of factors and decisions can be obtained. The consistency ration is used to check the consistency of the pairwise comparison matrix.

3. Overall priority ranking and the overall consistency of hierarchy

   Combining the priorities of each factor against target and the priorities of each decision against each factor, the final priorities of decisions against the target can be obtained. The overall consistency of hierarchy can be used to check the overall judgment.

4. Final decision

   In accordance with the overall priority ranking of decisions, optimal selection can be generated.

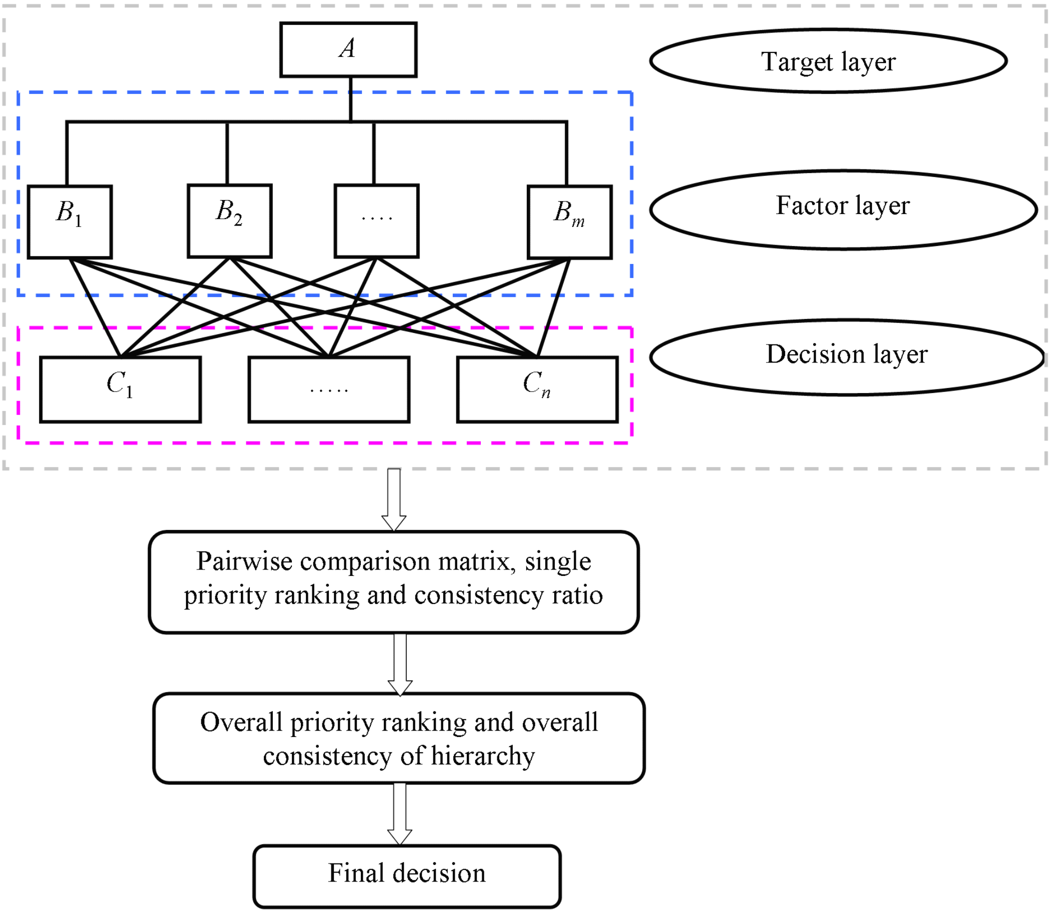

Figure 4-2 The development steps of the Analytic Hierarchy Process methodology for the decision model (source: own design).

4.4.2.2 Advanced multi-objective methodology

However, the Analytic Hierarchy Process also has some disadvantages, such as that only one original option is obtained and subjective factors have large impacts on the entire process. In order to reduce subjectivity, correlation analysis is a commonly used method to measure the relationship between two variables (TAYLOR 1990, 35; LI et al. 2006a, 47; ZHAO & DAN 2008, 114). It can be used to identify the associations between each factor and target.

By combining a correlation coefficient with the Analytic Hierarchy Process, the accuracy of the decision-making model is improved. The development steps of the advanced water scarcity decision model are shown as below (see Figure 4-3):

1. Make sure of different factors according to the target layer.
2. Make sure the decision layer according to the indexes to find out many options.

3. Use correlation analysis to determine the correlation coefficient and make sure the score of each factor has a high, moderate and low correlation with the target layer.
4. According to the score, the n-factor pairwise comparison matrix can be constructed against the target layer. And the *n*-decision pairwise comparison matrix can be constructed against each factor in factor layer. The priorities of factors and decisions can be obtained. The consistency ratio is used to check the consistency of the pairwise comparison matrix.
5. Overall priority ranking and overall consistency of the hierarchy.
6. Find out the final decisions according the overall priority ranking.

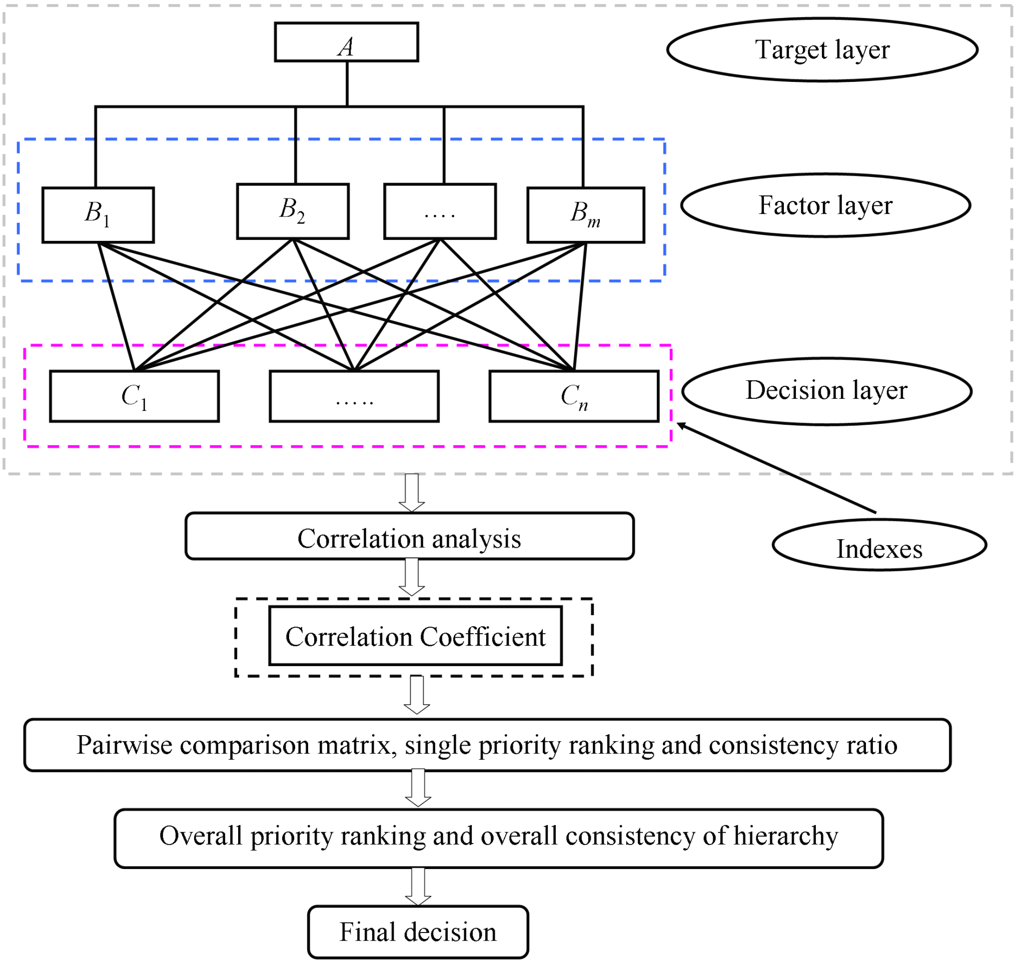

Figure 4-3 Advanced development steps of the Analytic Hierarchy Process methodology for water scarcity decision model in Urumqi (source: own design).

4.5 Water scarcity decision model for Urumqi

The decision model can be used to elevate the implications of uncertainty in the water system, which focus on system risk decision-making (LATINOPOULOS et al. 1997, 263). It also can be used to analyze the risks of the sustainable management of water resources and decision-making characteristics according to the comparison of the complexities and uncertainties of the existing water resources management (ZHANG et al. 2000b, 80; ZHANG et al. 2010b, 1855). Urumqi's water scarcity decision model is built based on the selected water scarcity risk assessment indexes and the selected methodology (mentioned in section 4.4.2), which can provide water resource management strategies for decision-makers. According to the assessment indexes, the decisions can be made (section 4.5.1). Based on the decisions, all the connected factors which can cause water scarcity in Urumqi can be obtained (section 4.5.2). Not all the factors have a strong or moderate correlation with water consumption in Urumqi. Some factors contain duplicated information with others. Correlation analysis can measure the correlation coefficient between each factor with water consumption in Urumqi (section 4.5.3). Based on the correlation coefficient, the score of the factors can be determined. The comprehensive solutions for water scarcity in Urumqi can be made using advanced Analytic Hierarchy Process methodology (section 4.5.4 and 4.5.5).

4.5.1 Water scarcity decision layer for Urumqi

According to the assessment results by using the rate of water resources utilization index and the water-use efficiency index (mentioned in section 4.3.2.1 and section 4.3.2.1), the corresponding decisions can be obtained. The decisions used to describe the measures for solving water scarcity risk are adjusting industrial structures (C_1), water conservation (C_2), using unconventional water resources (precipitation, treated wastewater reuse) (C_3), implementing economic regulation measures (C_4), controlling environmental safety (C_5), improving urban functions (C_6), and the interbasin transfer of water (C_7) (WANG et al. 2004, 48; RUAN et al. 2005, 907; HAN et al. 2008, 3; LI et al. 2010, 1044)) (see Table 4-8).

In Urumqi the total water consumption and total water resources were 1089.31 million m^3 and 939.22 million m^{3}in 2010. According to equation (4.14), the rate of water resources utilization (RWU) can be obtained and the value is 1.16 which is larger than 0.7 (mentioned in section 4.3.2.1).

Table 4-8 The decisions for solving water scarcity according to the water scarcity risk assessment indexes (*RWU*: the rate of water resources utilization; *WUE*: water-use efficiency; '*RWU-*': the value of *RWU* is less than 0.70; '*RWU=*': the value of *RWU* is equal to 0.70; '*RWU+*': the value of *RWU* is larger than 0.70; '*WUE-*': the value of *WUE* is less than 0.46 (the national average value); '*WUE=*': the value of *WUE* is equal to 0.46; '*WUE+*': the value of *WUE* is larger than 0.46) (source: own design).

Index		Decision	Description
RWU-	*WUE-*	C_1 and C_2	Index values +high =neutral -low Decisions: C_1: adjusting industrial structures C_2: water conservation C_3: using unconventional water resources C_4: implementing economic regulation measures C_5: controlling environmental safety C_6: improving urban functions C_7: interbasin transfer of water *RWU*>0.70 → + *RWU*=0.70→ = *RWU*<0.70 → - *WUE*>0.46 → + *WUE*=0.46→ = *WUE*<0.46 → -
	WUE=		
	WUE+		
RWU=	*WUE-*	C_1 and C_2	
	WUE=		
	WUE+		
RWU+	*WUE-*	C_1, C_2, C_3, C_4, C_5, C_6 and C_7	
	WUE=	C_3, C_4, C_5, C_6 and C_7	
	WUE+	C_3, C_4, C_5, C_6 and C_7	

The parameters (a_i, β, $\bar{\omega}$, χ_l, WC_{AP}, WC_{IP} and WC_{DP}) can be determined by using the data of the average conveyance efficiency of irrigation canal systems (0.62), the proportion of the agricultural economy (agriculture, forestry, animal husbandry and fishery) (1.49 %), the industrial water recycle rate (98 %), the leakage rate of the city pipe network (17.9 %) (including the losses of water for public supply), the total water consumption (1089.31 million m^3), the agricultural water consumption (701.11 million m^3), the industrial water consumption (159.09 million m^3) and the domestic water consumption (139.33 million m^3) in Urumqi in 2010 (STATISTICS BUREAU OF URUMQI 2011; WATER AFFAIRS BUREAU OF URUMQI 2010). According to the equation (4.16), the water-use efficiency index (*WUE*) can be calculated and it is 0.165 which is less than the national average value (0.46) (also see Table 4-8).

According to the high value of *RWU* and low value of *WUE*, seven main decisions can be obtained, such as adjusting industrial structures, water conservation (agricultural water conservation, industrial water conservation and domestic water conservation), using unconventional water resources (precipitation, treated wastewater reuse), implementing economic regulation measures, controlling environmental safety, improving urban functions and the interbasin transfer of water (also see Table 4-8).

4.5.2 Water scarcity factor layer for Urumqi

On account of the water consumption by all sectors and the potential water consumption, the factors in the factor layer should be the main influencing elements. All the factors should be closely related to the distribution of water resources in a water resource-ecology-society-economy system. Each factor should describe the characteristic of the water resource-ecology-society-economy system from different viewpoints. At the same time these factors can reflect the actual situation of the industrial structure, water conservation, and environmental safety (REN & LI 2000, 318; ZHU et al. 2003, 46; WANG & HE 2004, 6; LI et al. 2006a, 49). In summary, the factors related to total water consumption in Urumqi are as follows: per capita GDP (gross domestic product) [Yuan] (B_1), proportion of primary industry output-value [%] (B_2), average conveyance efficiency of irrigation canal systems [%] (B_3), the average irrigation water per mu[2] [m^3/mu] (B_4), cultivation index (the proportion of farmland area to the total area in Urumqi) [%] (B_5), industrial water recycle rate [%] (B_6), water consumption per value added by industry [m^3/10^{4}Yuan] (B_7), per capita daily domestic water use [l/person and day] (B_8), total resident population [person] (B_9), treated wastewater reuse rate [%] (B_{10}), annual average precipitation [mm] (B_{11}), wastewater treatment rate [%] (B_{12}), ratio of wastewater to total water resources [%] (B_{13}), annual average temperature [°C] (B_{14}), rate of industrial wastewater up to the discharge standards (the proportion of volume of industrial wastewater up to the standards with the total volume of industrial wastewater discharged) [%] (B_{15}), urban green coverage rate in built-up areas [%] (B_{16}) and urban population [person] (B_{17}). These factors can integrally reflect water consumption in Urumqi and all of them could be easily quantified. However, all of these factors are obtained based on subjective judgment and some factors have only a weak correlation with water consumption, therefore. In order to objectively select the factors, the relationship between these factors and water consumption must be evaluated by correlation analysis. Then the major factors can be obtained for the water scarcity decision model in Urumqi.

4.5.3 Correlation analysis for factors

Correlation analysis is used to quantitatively measure the relationship between two variables. Liner correlation analysis is to determine a liner association between two variables. It is a statistical method to study the correlation between random variables. The characteristics of the correlativity are embodied by two types. One is the direction, such as

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[2] mu: Chinese unit of land measurement. 1 mu=666.67 m^2.

positive correlation, negative correlation or no correlation. Another is the strength of a relationship. Positive correlation means a correlation in the same direction ($\kappa > 0$). Negative correlation means a correlation in the opposite direction ($\kappa < 0$) (COHEN 1988; BUDA & JARYNOWSKI 2010). Table 4-9 shows the six strengths of the relationship between two variables according to the value of the correlation coefficient.

Table 4-9 The standard for the strength of the correlation between two variables (source: YANG & FANG 2009).

Correlation coefficient	Relationship
$\lvert\kappa\rvert > 0.95$	Significant correlation
$\lvert\kappa\rvert \geq 0.8$	Strong correlation
$0.5 \leq \lvert\kappa\rvert < 0.8$	Moderate correlation
$0.3 \leq \lvert\kappa\rvert < 0.5$	Weak correlation
$\lvert\kappa\rvert < 0.3$	Very weak correlation
$\kappa = 0$	No linear relationship

There are three methods to get κ, such as the Pearson correlation coefficient, the Spearman correlation coefficient and the Kendall correlation coefficient. The Pearson correlation coefficient is a commonly used measure of the correlation between two variables, because it can avoid grade inflation (HALL & KO 2008). It is also called the Pearson product-moment correlation coefficient. It was developed by PEARSON (1896) and used to measure the correlation between two continuous variables (MUDELSEE 2003, 651; PAN & ZHAO 2006, 53). The Pearson correlation coefficient is expressed with the equation as follows:

$$\kappa = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right]\left[\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2\right]}} \text{ (BUDA \& JARYNOWSKI 2010)} \qquad (4.20)$$

where κ is the correlation coefficient, x and y are two variables, $\bar{x}$ and $\bar{y}$ are the mean values of the two variables.

Most of the data for the factors come from the Urumqi Statistical Yearbooks (STATISTICS BUREAU OF URUMQI 2004-2011) (see Table A-1 in Appendix). The data about average irrigation water per mu (B_4) and water consumption per value added by industry (B_7) come from Urumqi Water Reports (WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010) (also see Table A-1 in Appendix). The time scale is selected from 2003 to 2010.

Table 4-10 The correlation coefficient between each factor and total water consumption in Urumqi (B_1: per capita GDP (gross domestic product) [Yuan]; B_2: proportion of primary industry output-value [%]; B_3: average conveyance efficiency of irrigation canal systems [%]; B_4: the average irrigation water per mu [m^3/mu]; B_5: cultivation index (the proportion of farmland area to the total area in Urumqi) [%]; B_6: industrial water recycle rate [%]; B_7: water consumption per value added by industry [$m^3/10^4$Yuan]; B_8: per capita daily domestic water use [l/person and day]; B_9: total resident population [person]; B_{10}: treated wastewater reuse rate [%]; B_{11}: annual average precipitation [mm]; B_{12}: wastewater treatment rate [%]; B_{13}: ratio of wastewater to total water resources [%]; B_{14}: annual average temperature [°C]; B_{15}: rate of industrial wastewater up to the discharge standards (the proportion of volume of industrial wastewater up to the standards with the total volume of industrial wastewater discharged) [%]; B_{16}: urban green coverage rate in built-up areas [%]; B_{17}: urban population [person]) (source: own calculations).

Factors	Correlation coefficient ($\lvert\kappa\rvert$)	Relationship
B_1	0.9413	Strong correlation
B_2	0.9417	Strong correlation
B_3	0.9072	Strong correlation
B_4	0.5706	Moderate correlation
B_5	0.4887	Weak correlation
B_6	0.1458	Very weak correlation
B_7	0.6538	Moderate correlation
B_8	0.4116	Weak correlation
B_9	0.9063	Strong correlation
B_{10}	0.0966	Very weak correlation
B_{11}	0.0409	Very weak correlation
B_{12}	0.2952	Very weak correlation
B_{13}	0.3370	Weak correlation
B_{14}	0.1118	Very weak correlation
B_{15}	0.0778	Very weak correlation
B_{16}	0.8171	Strong correlation
B_{17}	0.9320	Strong correlation

The correlation coefficients for 17 factors with total water consumption in Urumqi can be obtained by the Pearson correlation coefficient using the existing function in Matlab 2010b (corer = corr(WC_T, YE)). WC_T is the total water consumption from 2003 to 2010 in Urumqi. YE is the value of each factor. Table 4-10 shows the correlation coefficient between each factor and total water consumption in Urumqi according to the Pearson correlation coefficient. Per capita GDP (gross domestic product) (B_1), the proportion of primary industry output-value (B_2), the average conveyance efficiency of irrigation canal systems (B_3), the total resident population (B_9), the urban green coverage rate in built-up areas (B_{16}) and the urban population (B_{17}) have a strong correlation with the total water consumption in Urumqi. The average irrigation water per mu (B_4) and water consumption per value added by industry (B_7) have a moderate correlation with total water consumption. The cultivation index (B_5), per capita daily domestic water use (B_8) and ratio of wastewater to total water resources (B_{13}) show a weak correlation with total water resources (see Table 4-10).

4.5.4 The Analytic Hierarchy Process for a water scarcity decision model in Urumqi

Based on the decision layer and factor layer mentioned in section 4.5.1 and 4.5.2, the comparison matrix for factors and decisions could be built and the consistency test of the comparison matrix can be made by using the Analytic Hierarchy Process methodology (section 4.5.4.1).According to the overall priority ranking of factors and decisions, the overall weight of the decisions can be calculated (section 4.5.4.2).

4.5.4.1 Comparison matrix and consistency

Because there is a subjectivity involved in the Analytic Hierarchy Process, the number of evaluation elements in each layer is not more than nine (LIN et al. 2006, 57). According to the results of Pearson correlation coefficient, eight factors with strong and moderate correlation with total water consumption are selected. They are per capita GDP (gross domestic product) (B_1), the proportion of primary industry output-value (B_2), the average conveyance efficiency of irrigation canal systems (B_3), the average irrigation water per mu (B_4), the water consumption per value added by industry (B_7), the total resident population (B_9), the urban green coverage rate in built-up areas (B_{16}) and the urban population (B_{17}) (also see Table 4-10). Based on the sequence of the correlation coefficient, the factors can be scored with values from 1 to 9. The score signifies the relative importance for each factor by comparison with others (see Table 4-11).

Table 4-11 The saaty rating scale (source: SAATY & VARGAS 2001).

Intensity of importance	Definition
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

If factor *A* is absolutely more important than factor *B* according to their values of correlation coefficient, it is rated at 9 and *B* must be absolutely less important than *A* and it is rated at 1/9. The pairwise comparisons are carried out for all factors. According to the correlation coefficient of the factors, a comparison matrix can be constructed. In the matrix, according to the value of correlation coefficient of the 6 factors, b_{ij} can be obtained, and $b_{ij} = 1$ when $i = j$ and $b_{ji} = 1/b_{ij}$. The pairwise comparison matrix is *B*.

$$B = \begin{bmatrix} 1 & 1/2 & 3 & 8 & 6 & 4 & 5 & 2 \\ 2 & 1 & 4 & 9 & 7 & 5 & 6 & 3 \\ 1/3 & 1/4 & 1 & 6 & 4 & 2 & 3 & 1/2 \\ 1/8 & 1/9 & 1/6 & 1 & 1/3 & 1/5 & 1/4 & 1/7 \\ 1/6 & 1/7 & 1/4 & 3 & 1 & 1/3 & 1/2 & 1/5 \\ 1/4 & 1/5 & 1/2 & 5 & 3 & 1 & 2 & 1/3 \\ 1/5 & 1/6 & 1/3 & 4 & 2 & 1/2 & 1 & 1/4 \\ 1/2 & 1/3 & 2 & 7 & 5 & 3 & 4 & 1 \end{bmatrix}$$

The eigenvectors (λ_i) can be calculated by square root method. M_{ij} multiplies together the entries in each row of the comparison matrix. λ_i is the n-th root of M_i. The equations for M_{ij} and λ_i are written as follows:

$$M_{ij} = \Pi_1^n b_{ij} \quad (i, j = 1, 2, ..., n) \text{ (ZHANG et al. 2009b,592)} \tag{4.21}$$

$$\lambda_i = \sqrt[n]{M_i} \text{ (the } n\text{-th root) } (i = 1, 2, ..., n) \text{ (ZHANG et al. 2009b,592)} \tag{4.22}$$

The priority vector (ω) can be developed using the equations as follows:

$$w_i = \frac{\lambda_i}{\sum_1^n \lambda_i} \text{ (LIAO 2010, 125)} \tag{4.23}$$

$$\omega = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \text{ (ZHANG et al. 2009b,592)} \tag{4.24}$$

The maximum eigenvalue $\lambda_{\max}$ of the comparison matrix can be calculated by the following equation:

$$\lambda_{\max} = \frac{\sum_1^n (\mathrm{B}\omega)_i}{n\omega_i} \text{ (LIAO 2010, 125)} \tag{4.25}$$

According to the equations (4.21), (4.12), (4.23) and (4.24), the weight vector can be obtained and it is $\omega = [0.2322\ 0.3277\ 0.1073\ 0.0189\ 0.0339\ 0.0721\ 0.0489\ 0.1591]'$.

Based on the equation (4.22), the maximum eigenvalue ($\lambda_{\max}$) can be calculated and its value is 8.3427.

The consistency index (CI) and consistency ration (CR) are used to test the consistency of the comparison matrix. The equations for consistency index and consistency ration are written as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \text{ (LIAO 2010, 126)} \tag{4.26}$$

$$CR = \frac{CI}{RI} \text{ (LIAO 2010, 126)} \tag{4.27}$$

where n is the number of factors being compared, RI is the random consistency index. It is the consistency index of a randomly generated pairwise comparison matrix. Its value depends on the size of pairwise comparison matrix:

Table 4.12 shows the value of RI corresponding to the size of pairwise comparison matrix (e.g. if the size of the pairwise comparison matrix is 5, the value of RI will be 1.12) (see Table 4-12). When CR is less than 0.1, the inconsistency of the comparison matrix is acceptable. When CR is greater than 0.1, the comparison matrix needs to be revised.

Table 4-12 The random consistency index (RI) (source: SAATY 2008).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0	0	0.58	0.90	1.12	1.26	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.58

The size of the pairwise comparison matrix is 8 and the maximum eigenvalue $\lambda_{\max}$ is 8.3427. According to equation (4.27), the consistency index (CI) can be obtained and the value is 0.0490. The random consistency index (RI) for $n = 8$ is 1.41, and then the consistency ration (CR) is 0.0347, which is smaller than 0.1, meaning that the comparison matrix is acceptable (also see Table 4-12).

The same method with the factor layer is used to construct the comparison matrix according to each factor in the upper layer. Each factor is used to compare the elements in the decision layer. Then the comparison matrix for decisions against each factor can be constructed (C_1, C_2, C_3, C_4, C_7, C_9, C_{16} and C_{17}) (see A.4 in Appendix). Therefore, the ranks of the decisions in the decision layer can be obtained. In Table 4-13 the rankings of the decisions are given against the 8 factors.

Table 4-13 The priority ranking of decisions against each factor in factor layer (source: own calculations).

k	1	2	3	4	5	6	7	8
ω_{k1}	0.3787	0.3102	0.033	0.033	0.3886	0.0534	0.0372	0.0369
ω_{k2}	0.0773	0.3102	0.5391	0.5391	0.0943	0.3976	0.1552	0.2473
ω_{k3}	0.0391	0.0443	0.0572	0.0572	0.036	0.0359	0.0593	0.0589
ω_{k4}	0.1831	0.1477	0.0572	0.0572	0.2468	0.2905	0.0958	0.0952
ω_{k5}	0.1167	0.0654	0.1146	0.1146	0.058	0.0799	0.2639	0.1541
ω_{k6}	0.1831	0.0985	0.1418	0.1418	0.1533	0.1176	0.3692	0.3885
ω_{k7}	0.0220	0.0237	0.0572	0.0572	0.0229	0.0249	0.0194	0.0192
λ_k	7.2756	7.2550	7.4697	7.4697	7.6486	7.2951	7.6384	7.7001
CI_k	0.0459	0.0425	0.0783	0.0783	0.1081	0.0492	0.1064	0.1167
RI_k	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
CR_k	0.0348	0.0322	0.0593	0.0593	0.0819	0.0373	0.0806	0.0884

4.5.4.2 Overall priority ranking and consistency

The priority ranking of each factor against the target layer is b_1, b_2,..., b_m, and the priority ranking of decisions against each factor is c_{1j}, c_{2j},..., c_{nj} (j = 1, 2, ..., m). The overall priority ranking of each decision against the target layer can be calculated by the following equation (4.28) (cf. SAATY 1990, 18). The values for the overall priority ranking of decisions are showed in Table 4-14.

$$\sum_{j=1} b_j c_{1j} = c_1', \sum_{j=1} b_j c_{2j} = c_2', \ldots, \sum_{j=1} b_j c_{nj} = c_n' \tag{4.28}$$

Table 4-14 The overall priority ranking of decisions in the decision layer (source: own calculations).

Factor Decision	B_1	B_2	B_3	B_4	B_7	B_9	B_{16}	B_{17}	Overall priority
	0.2322	0.3277	0.1073	0.0189	0.0339	0.0721	0.0489	0.1591	
C_1	0.3787	0.3102	0.033	0.033	0.3886	0.0534	0.0372	0.0369	0.2185
C_2	0.0773	0.3102	0.5391	0.5391	0.0943	0.3976	0.1552	0.2473	0.2664
C_3	0.0391	0.0443	0.0572	0.0572	0.036	0.0359	0.0593	0.0589	0.0469
C_4	0.1831	0.1477	0.0572	0.0572	0.2468	0.2905	0.0958	0.0952	0.1473
C_5	0.1167	0.0654	0.1146	0.1146	0.058	0.0799	0.2639	0.1541	0.1081
C_6	0.1831	0.0985	0.1418	0.1418	0.1533	0.1176	0.3692	0.3885	0.1862
C_7	0.0220	0.0237	0.0572	0.0572	0.0229	0.0249	0.0194	0.0192	0.0267

The overall consistency of hierarchy (CR') can be calculated by summing all levels, with weighted consistency index (CI) in decision layer and weighted random consistency index (RI) in decision layer (cf. SULTAN et al. 2012). It is expressed as follows:

$$CR' = \frac{\sum_{i=1}^{m} b_i CI_i}{\sum_{i=1}^{m} b_i RI_i} \tag{4.29}$$

When CR' is smaller than 0.1, the consistency is acceptable. According to the values of the consistency index in the decision layer, the overall consistency can be calculated according to the equation (4.29). The value of the overall consistency is 0.0496 which is smaller than 0.1. The consistency is thus acceptable. The overall priority ranking can be used as the final basis for decision-making.

4.5.5 Comprehensive decisions for water scarcity in Urumqi

According to the weights of decisions against the target layer, the priority order for solving water scarcity in Urumqi is water conservation (C_2), adjusting industrial structures (C_1), improving urban functions (C_6), implementing economic regulation measures (C_4), controlling environmental safety (C_5), using unconventional water resources (precipitation, treated wastewater reuse) (C_3) and interbasin transfer of water (C_7).

1. Water conservation (C_2)

   Water conservation includes agricultural water conservation, industrial water conservation, and domestic water conservation.

   Agriculture needs a lot of water. In 2010, the average farmland water consumption per mu was 639 m³, a figure that was 1.55 times higher than the water consumption of the national farmland irrigation area per mu (421 m³) (WATER AFFAIRS BUREAU OF URUMQI 2010, 24; MWRC 2010). It means there are a lot of potentials for agricultural water conservation. There are many ways to improve the efficiency of agricultural water consumption: strengthen agricultural science and technology, develop agricultural infrastructure, improve the utilization coefficient of irrigation canal, develop water conservation facilities in agriculture, promote the changing of agricultural planting strategy and speed up the transformation of agricultural production (GAO et al. 2002, 27; YAO 2002, 32).

   For industrial water conservation, people should establish and improve the water recycling system, improve the industrial water recycling rate, develop and promote the steam condensate recycling technology, and develop efflux wastewater reuse technology and "zero-emission" technology (XIE et al. 2008, 3; ZHANG et al. 2008a, 2; ZHANG et al. 2011b, 540).

Residents' habits also play a decisive role in domestic water conservation (CHEN et al. 2004b, 125). Some good habits can greatly reduce domestic water consumption. The water should be multi-used and water conservation appliances should be introduced into everyday family life. The living water recycling rate must be improved. The leakage in the water supply network must be reduced. The leakage losses in the pipe network have drastically increased water supply in Urumqi. Therefore, reducing the leakage rate of the pipe network must be considered as one of important solutions for water scarcity in Urumqi.

2. Adjusting industrial structures (C_1)

The industrial water sectors have exacerbated the water resource scarcity in Urumqi. Heavy industry is the main industry in Urumqi. In 2010, the output value of heavy industry accounted for 91.96 % of the total industrial output value (172 billion Yuan) (STATISTICS BUREAU OF URUMQI 2011). The heavy industry has eight sectors (the petroleum industry, the textile industry, the metallurgical industry, the machinery industry, the electric power industry, the chemical industry, food industry, and the coal industry). According to the classification of products, the main products of heavy industries are raw coal, crude salt, steel, cement, power generation and crude oil. The main products of light industries are wool, sand, cloth, drinks and shoes (LI & TURSUN 2001, 15; AILI & ABULIZI 2005, 21). All of these industries need a huge amount of water to function. In addition, the tertiary industry accounted for 62 % of the regional GDP (STATISTICS BUREAU OF URUMQI 2011). The service sectors (including transportation, warehousing, post and telecommunications, wholesale and retail, accommodation and catering) consume lots of water (ZHANG et al. 2011b, 540). Therefore, tasks such as increasing industrial integrated water resources, recycling, unified allocating and metering of water withdrawals, no new industrial building or expansion, new construction or expansion of industries with lower recycle rates of industrial water (e.g. beverage industry), reducing the industries with high water consumption must be performed in adjusting industrial structures.

Adjusting industrial structures can be realized by the following measures: (1) development of high standards of environmental protection requirements in order to limit or control the discharge of industrial wastewater, (2) development of high-tech industries and advanced technology to improve traditional industries, transferring the labor-capital intensive industry with high water consumption to the technology-knowledge intensive industry with low water consumption, (3) raising the price of fresh water withdrawals and the costs of wastewater discharges according to water quality resentments in different industries and contents in industrial wastewater in order to promote the upgrading of industrial structure and improve the efficiency of industrial water use by the reform of the market economy, (4) improving industrial facilities and implementing advanced measures (e.g. closed loop reuse, closed loop recycling with treatment, reuse of wash water) can improve the industrial water efficiency rate.

3. Improving urban functions (C_6)

   Gathering populations speed up urbanization. The increasing population in the city raises the consumption of urban water. Sometimes, the fast expansion of the city results in a shortage of the water supply, which affects industrial production and people's daily lives. Urumqi already has some seriously environmental and geological problems because of the overdraft of groundwater. The expanding of the urban population and the building scale in the city change the local climatic conditions in urban areas, which affects the city's precipitation conditions and leads to the "urban heat island effect" (LI et al. 2006c, 117).

   Meanwhile, the layout of the city has been changed, many big houses have been built, and a lot of roads have been paved that increase the impermeable layers under the surface. Therefore, infiltration and evaporation have been reduced, the surface runoff and runoff volume have increased, something which directly changes the convergence characteristics of the runoff in its natural state. The boundaries of the urban scale development urgently need to be determined according to the carrying capacity of water resources, and new materials should quickly be implemented to avoid urban construction changing the urban landscape.

4. Implementing economic regulation measures (C_4)

   The reasonable water price is an effective economic measure, which can ensure the balance of water supply and demand. The water price has a function that can guide the use of water resources from low efficiency to high efficiency. The water resources could be reasonably distributed by improving the water fee collection standards through the market regulation, reforming of water price system, and specifying reasonable water price.

   In Urumqi, there are no complete water rights, water pricing or water market mechanisms for water resource allocation (ZHANG & CHEN 2002, 484; LIU et al. 2005, 284). A long time ago, people focused too much on natural properties and social services of water and too little on the commodity of water, water rights management and paid use. From 2005 until now, the water resource fee has only been 0.04 Yuan per cubic meter, which is one third of the national value (0.12 Yuan/m^3) (URUMQI DEVELOPMENT AND REFORM COMMISSION 2005; WATER AFFAIRS BUREAU OF URUMQI 2010). Since 1998, the water pricing for irrigation has only been 0.04 Yuan/m^3 in southern suburbs in the irrigation area of Urumqi (YAO 2002, 32). Due to low agricultural water pricing, the crop irrigation technique is flood irrigation. Therefore, another effective economic measure to reduce water consumption would be to improve agricultural water pricing. At the same time, a more stringent classification of agricultural water pricing should be established. For example, for the crops with higher water consumption and the crops with lower unilateral water efficiency, the price of water should be raised and water rights should be limited.

5. Controlling environmental safety (C_5)

   In 2010, the total discharged sewage was 215.10 million m^3, and only 66.3 % of the sewage was processed. If the treated sewage meets the national standards, then it can be used for agricultural irrigation, greening and industry.

   However, only 52.76 million m^3 of the treated sewage was used for agricultural irrigation, greening and industrial cooling, which accounts for 24.5 % of the total amount of sewage (WATER AFFAIRS BUREAU OF URUMQI 2010, 21). As mentioned in section 3.2, nearly half of the sewage is directly discharged to the river without treatment in Urumqi, which causes serious pollution of rivers and other surface water. Wulabo reservoir is an important drinking water source protection area in Urumqi (WANG et al. 2010a, 22). According to the 2010 Urumqi Water Resources Communique, the overall water quality of Wulabo reservoir is worse than Class V water, which means it was heavily polluted (WATER AFFAIRS BUREAU OF URUMQI 2010). The downstream of Urumqi River is seriously contaminated, and cannot achieve the requirements of agricultural irrigation water. One of the best ways to solve the water scarcity problem in Urumqi is to utilize wastewater resources. People could construct wastewater reuse projects and find a second water source to save the clean water resources and control pollution of water resources (ZENG & TAYIER 2007, 42).

6. Using unconventional water resources (C_3)

   Urumqi has developed unconventional water resources, such as treated wastewater. In addition to the treated wastewater, other unconventional water resources also should be encouraged in Urumqi, such as the utilization of rainwater. Rainwater resourcing means rain could be transformed into available water resources (XU et al. 2000, 32). The traditional urban rain water is separated into two parts: one part is directly conducted into the river, and another part is conducted into the sewage treatment plant with the sewage. The rain water could be recycled in the sewage treatment plant. The urban rainwater utilization should follow the rule that comprehensive utilization is more important than emission, so that rainwater could be transformed to resourced water.

7. Interbasin transfer of water (C_7)

   The potential water resources in this region should be found. The water from other basins could be transferred to Urumqi.

4.6 Summary

Water scarcity risk reflects to what extent social development can be supported by the maximum available water resources, and it is restricted by many kinds of factors, such as population, the economy and the environment (JING & CHEN 2006, 11). Urumqi is a water scarcity region. The average per capita water resources was 387 m^3 in 2010 (WATER AFFAIRS BUREAU OF URUMQI 2010). Normal water demand cannot be effectively guaranteed. Due to the natural factors and social factors, water resource has become one of the important elements restricting the social and economic development of the region. By selecting and analyzing water scarcity risk assessment indexes and calculation method, Urumqi's water scarcity decision model is established.

According to the indexes and the current situation of the total amount of water supplied in Urumqi, the rate of water resources utilization and water-use efficiency are selected as the indexes to make decisions. According to the values of these two indexes, the decisions for solving water scarcity in Urumqi are made. Using the Pearson correlation coefficient, 8 factors (per capita GDP (gross domestic product), the proportion of primary industry output-value, the average conveyance efficiency of the irrigation canal systems, the average irrigation water per mu, the water consumption per value added by industry, the total resident population, the urban green coverage rate in built-up areas and the urban population) with high and moderate correlation with total water consumption in Urumqi are selected from 17 factors. Based on the decisions, three layers of the decision model are built. By using the Analytic Hierarchy Process, the overall priority of decisions is obtained.

Figure 4-4 shows the integrated structure of the water scarcity decision model for Urumqi.

The priorities to solve water scarcity in Urumqi are water conservation (C_2), adjusting industrial structures (C_1), improving urban functions (C_6), implementing economic regulation measures (C_4), controlling environmental safety (C_5), using unconventional water resources (precipitation, treated wastewater reuse) (C_3) and interbasin transfer of water (C_7). The sum of the weight of water conservation (C_2) and adjusting industrial structures (C_1) is more than 48 % which means the two methods are an urgent priority for solving water scarcity in Urumqi. Furthermore, water conservation is the most important step for reducing water scarcity.

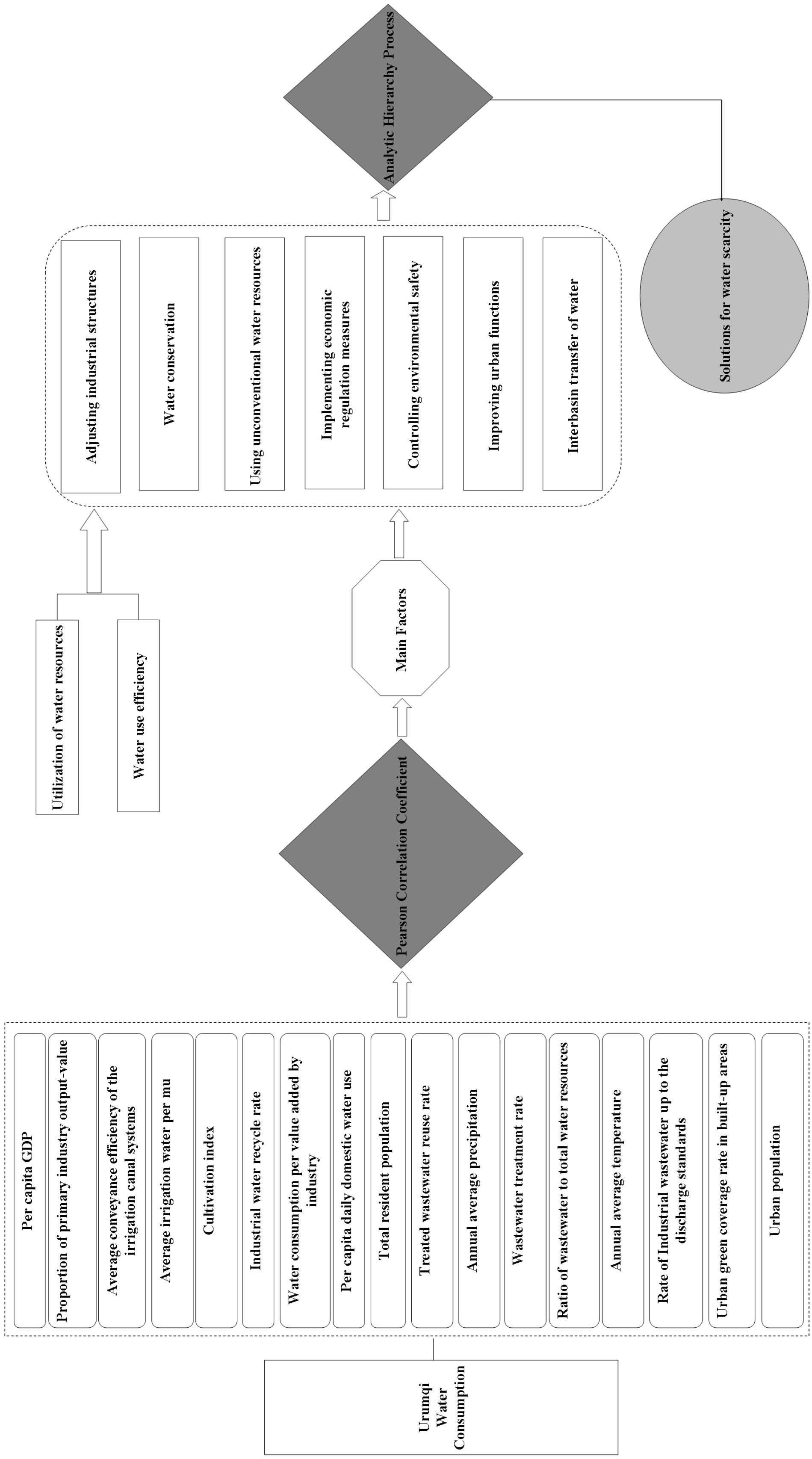


Figure 4-4 The structure of the water scarcity decision model for Urumqi (source: own design).

5 Water conservation in Urumqi

There are three methods to address the water scarcity problem, firstly, by using engineering measures to manage surface water and groundwater to meet water requests; secondly, by utilizing 'unconventional' water resources such as waste water, rainwater harvesting and desalinized seawater; thirdly, by raising awareness about how important water is, improving technology for water utilization and reforming the pricing system to promote water conservation (LIU 2002, 19; ZHANG et al. 2009a, 120). The construction of a water conservation society is the fundamental way to solve the water scarcity problem. The present common problems of water conservation (section 5.1), the water conservation index (section 5.2), and the integrated measures for water conservation (section 5.3 and section 5.4) in Urumqi are analyzed and summarized in this chapter.

5.1 Present common problems of water conservation

The purpose of water conservation is to ensure water use for industrial and agricultural production, domestic water demand and water ecosystem (ABU-ZEID et al. 2004, 270; WANG & MA 2006, 59). It can be achieved by improving the efficiency of water usage, reducing water consumption, increasing the recycling of wastewater, and reducing the waste of water (YAO 2001, 3). According to the existing problems with the utilization of water resources in Urumqi, water conservation will be one of the most effective ways to relieve water scarcity (mentioned in chapter 4). When the quantity of water is kept constant, water conservation can realize reasonable and effective water usage (LIU 2001, 3).

Using current technology, the agricultural water demand can be reduced by 10 %-50 % (YANG & NIE 2002, 77; SHAN & LIU 2007, 5902). For example, if the techniques of surge irrigation or micro-irrigation were used, then 10 %-30 % or up to 50 % water could be saved respectively (GAO et al. 2002, 27; YAO 2002, 32). Industrial water demand can be reduced by 40 %-90 % and domestic water demand in urban areas can be reduced by up to 30 % without any effect on the economy or the quality of life in China (YANG & NIE 2002, 77). The potential of industrial water conservation is related to industrial water use efficiency. There are different water use efficiencies in various provinces of China. For example, the water use efficiency in Shandong province is 439.7 %, which is the highest one in China. The water use efficiency in Guizhou (25.4 %) is the lowest one in China. In the regions with low water use efficiency, the industrial water efficiency potential can be promoted by up to 94.2 % (ZHU 2007, 49). Currently, the water recycling rate of industry in China is about 50 %-60 %. The average industrial water consumption per ten thousand Yuan is 225 m^3, which is 2.25 times that of a developed country (WANG 2010a, 131). Since the water recycling rate directly determines the water use efficiency, the latest techniques must be used to improve the water recycling rate. Through these technological innovations, a decrease in the industrial water demand by between 40 % and 90 % can be achieved. The average leakage rate of pipe networks in China is up to 21.5 %, while the leakage rate in Japan is lower than 10 %, the leakage rate in the United States is lower than 8 %, and the leakage rate in Germany is about 4.9 % (LUO & TAO 2010, 95). Therefore, there is a great potential to reduce the leakage rate in China. In addition, by popularizing water conservation appliances and changing water use habits, it is possible to reduce domestic water consumption in China by 30 % (YANG & NIE 2002, 77).

5.1.1 Domestic water consumption and conservation

With the rapid development of urbanization and population growth, water appliances and water heating systems (such as bathing facilities, washing machines, and dishwashers) are increasingly contributing to the growth of domestic water consumption. Urban domestic water consumption refers to the water consumption of households in daily life, the water consumption for city greening and the water consumption of public welfare facilities, including the consumption of restaurants, hotels, hospitals, barber shops, public bathhouses, laundries, swimming pools, shops, schools, institutions, army units and other units. In 1990, the urban domestic water consumption of Urumqi was 55.64 million m^3, but in 2010 it rose to 122.55 million m^3 due to a growth in population (average annual growth rate of population is 4.1 %) and an increase of living standards (urban per capita disposable income growth rate is 12 %) (STATISTICS BUREAU OF URUMQI 2011). From 1990 to 2006, the overall urban domestic water consumption rose steadily. Since there was less rainfall in 2001 and 2002, the water supply was relatively low in these two years. However, 2003 experienced such a high level of rainfall that water supply was relatively high in this year. After Miquan City was merged into Urumqi, there was a sharp increase in urban water consumption in Urumqi. Because of the popularization of water conservation appliances, the urban domestic water supply had been greatly reduced in 2009 and 2010 (see Figure 5-1).

Urban daily water consumption is related to population, temperature and urban water supply. Therefore, urban daily water consumption shows irregularities. However, the overall trend was relatively stable and maintained at 150 to 200 l/person and day from 1990-2010 (also see Figure 5-1).

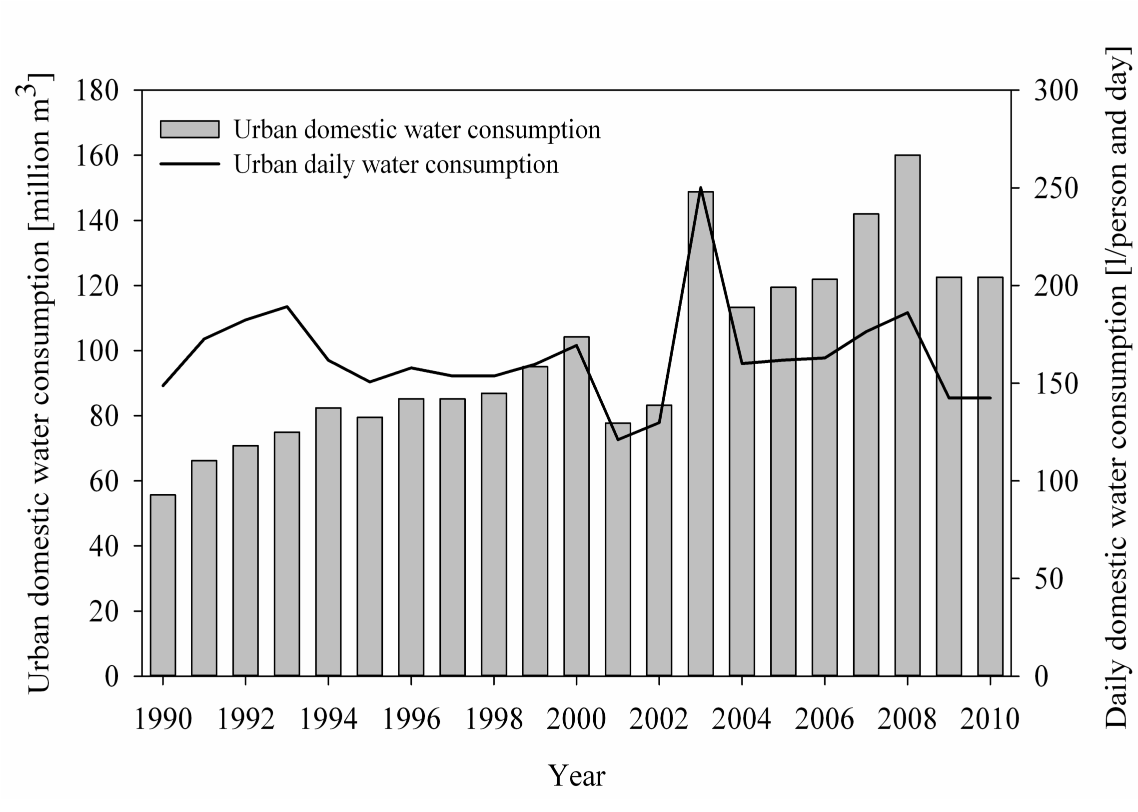


Figure 5-1 Urban domestic water consumption and daily domestic water consumption 1990-2010 (source: STATISTICS BUREAU OF URUMQI 2011; own design).

Table 5-1 The Chinese national standard of water quantity for the city's residential use (source: MCC & AQSIQ 2002).

Daily water use [l/person and day]	Province
80-135	Helongjiang, Jilin, Liaoning, Neimenggu
85-140	Beijing, Tianjing, Hebei, Shandong, Henan, Shanxi, Ningxia, Gansu
120-180	Shanghai,Jinagsu, Zhejiang, Fujiang, Jiangxi, Hubei, Hunan, Anhui
150-220	Guangxi, Gunagdong, Hainan
100-140	Chongqing, Sichuan, Guizhou, Yunnan
75-125	Xinjiang, Xizang, Qinghai

According to the national standard of water quantity for the city's residential use (MCC & AQSIQ 2002), the per capita urban domestic water consumption is 75-125 l/person and day in the Northwest region (see Table 5-1). Therefore, the practical urban daily water use was almost twice as high as the national standard. The water used for public greening was about 7.5 million m³ in 1980, and in 2006 it was 66.41 million m³ which was 8.85 times higher than that in 1980 (XIE et al. 2008, 2).

The water demand for flushing, cleaning, greening and other miscellaneous functions is covered with high quality water. In addition, the losses of water were about 17.83 million m³ in 2010 due to the high leakage rate of the water supply pipe network (WATER AFFAIRS BUREAU OF URUMQI 2010, 18).

5.1.2 Agricultural water consumption and conservation

The geographical position and the nature of Urumqi's climate (located in an arid and semi-arid region) determine the typical irrigation style of agriculture. More than 60 % of the total water consumption was used for agriculture in Urumqi, while the proportion of the agricultural economy (agriculture, forestry, animal husbandry and fishery) was less than 2 % of the gross regional product in 2010. The tendency of water consumption for agriculture (irrigation water and the water used for forestry, animal husbandry and fishery) was on the rise from 2003 to 2010, while the proportion of agricultural GDP in gross regional product had been declining (see Figure 5-2). The main reason for agricultural production value accounting for small proportion of the total output value is the unreasonable structure of agriculture. In 2010, food crops accounted for half of the total acreage and other economic crops accounted for another half (STATISTICS BUREAU OF URUMQI 2011).

In 2010, the farmland area was about 994,500 mu (mu: Chinese unit of land measurement. 1 mu = 666.67 m²) (STATISTICS BUREAU OF URUMQI 2011). The mean value of overall irrigation water consumption was 639 m³/mu, which was far higher than the mean value of other countries (479 m³/mu). Specifically, irrigation water consumption for paddy fields was 1037 m³/mu, irrigation water consumption for irrigated land was 534 m³/mu, and irrigation water consumption for vegetable fields was 1355 m³/mu (WATER AFFAIRS BUREAU OF URUMQI 2009, 19; ZHANG et al. 2009a, 118). The dominant irrigation method for all farmlands was flood irrigation through canals for most of the cultivated land. With this method, the canal seepage rate was high and the irrigation quota could not be adjusted appropriately according to the growth of the crops (YAO 2002, 32). The average conveyance efficiency of irrigation canal systems was about 0.62 in Urumqi in 2010 (WATER AFFAIRS BUREAU OF URUMQI 2010, 22). If the efficiency of China's conveyance efficiency can reach the level of Israel's conveyance efficiency (0.9), then nearly 30 % of water used for agriculture can be saved (LIU 2001, 1). In addition, due to the low water price of agricultural irrigation, the waste of agricultural water is very serious (LIU et al. 2005, 283).

In summary, agricultural water conservation potential depends on agricultural reform and structural adjustment, expansion of water-saving in the irrigation area, improvement of the conveyance efficiency of irrigation canal system and improvement of the water price system for agricultural irrigation.

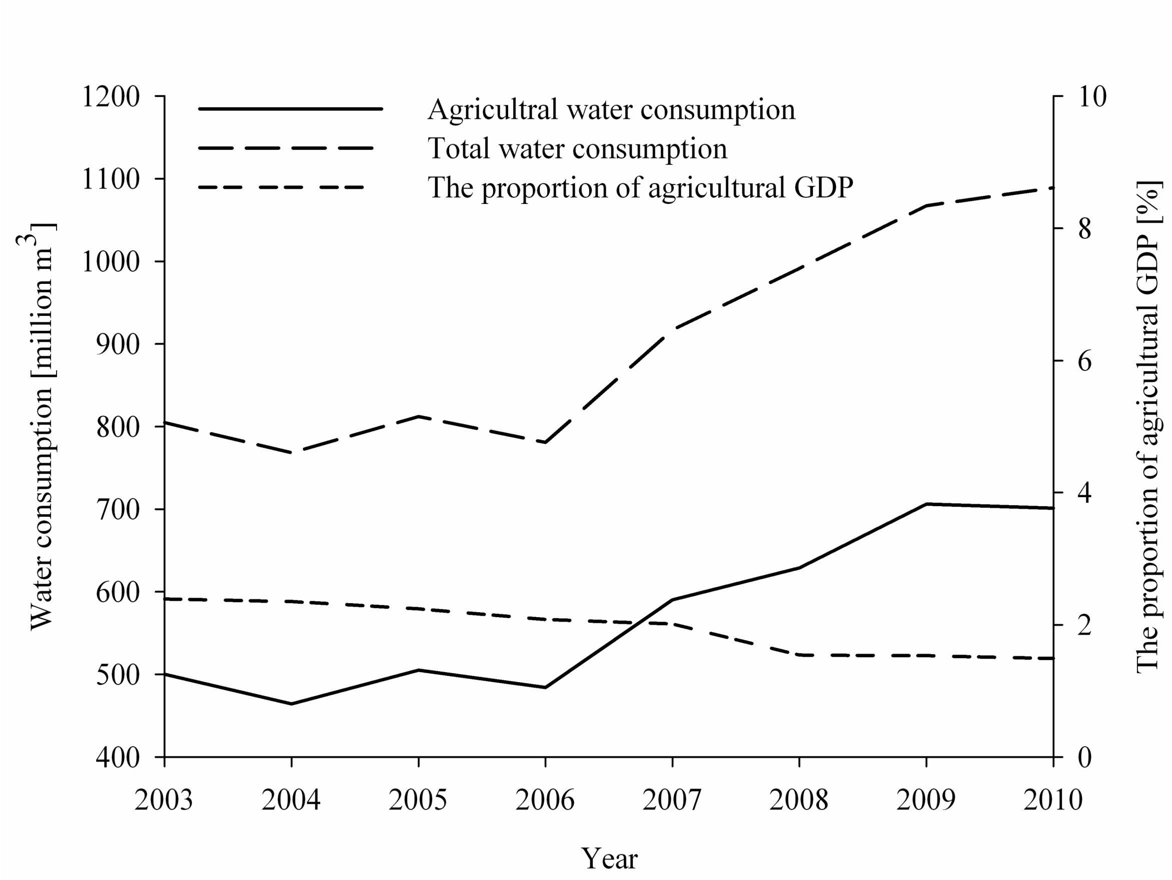


Figure 5-2 Agricultural water consumption and the proportion of agricultural GDP with respect to the total regional GDP 2003-2010 in Urumqi (source: XIE et al. 2008, 1; WATER AFFAIRS BUREAU OF URUMQI 2003, 2005, 2004, 2005, 2007, 2008, 2009 and 2010; STATISTICS BUREAU OF URUMQI 2011; own design).

5.1.3 Industrial water consumption and conservation

With the rapid socio-economic development, industry also developed very quickly. From 2003 to 2010, the gross industrial output value grew from 38.1 billion Yuan up to 172.45 billion Yuan. The average annual growth rate of the gross industrial output value was

21.7 % and the industrial water consumption, which means fresh water withdrawals, was increasing as well. In 2003, the industrial water consumption was 103.67 million m³, about 12.9 % of the total water consumption (805.02 million m³ in 2003). In 2010, industrial water consumption was up to 159.09 million m³, which was 14.6 % of the total water consumption (1089.31 million m³ in 2010) and about 1.5 times higher than that in 2003 (see Figure 5-3).

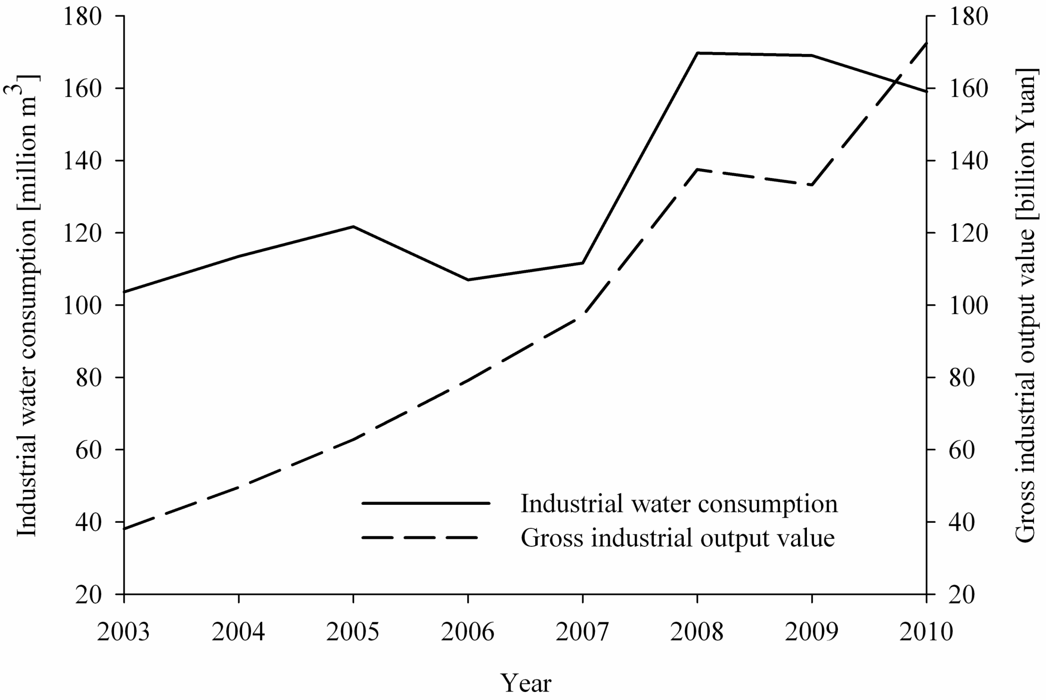


Figure 5-3 Industrial water consumption and gross industrial output value 2003-2010 (source: STATISTICS BUREAU OF URUMQI 2011; XIE et al. 2008, 1; WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; own design).

Industrial water consumption only includes the fresh water withdrawals and not the internally reused water (recycled water) (XIE et al. 2008, 2). In 2010, the rate of recycled industrial water was 70 %, which was lower than the level of the developed countries (more than 80 %) (JIA 2001, 57; WATER AFFAIRS BUREAU OF URUMQI 2010, 22). Therefore, the best way to help the task of water conservation is to improve the industrial water recycling rate.

5.2 Water conservation index

The total amount of available water resources in Urumqi cannot meet the demand of increasing economic development. Constructing a water conservation city is the best way to ensure the sustainable development of the economy and society in Urumqi. The establishment of a water conservation city is complicated because of the numerous influencing factors, such as society, production and the ecosystem (FANG 2009). In order to carry out a comprehensive evaluation of the urban water conservation level, the Chinese Ministry of Water Conservation developed a water conservation index system in 2005. This evaluation system included a comprehensive index, an agricultural water conservation index, a domestic water conservation index, an industrial water conservation index and a water ecology and environment index (CHEN et al. 2004a, 84; CHEN et al. 2004b, 127; MWRC 2005b; WANG 2010b, 34). The water conservation index system uses the quantified indexes to assess the efficiency of urban water use and the degree of utilization of water resources. Actually, this system is a scale parameter to measure the level of water consumption or water conservation and reflects the level of the water conservation potentials (CHEN et al. 2004b, 125). Therefore, the water conservation index system is used as a measure to understand and change the patterns of water consumption. In 2004, the economy development index was introduced into the water conservation index system. The economy development index can be used to find the problems of the relationship between water resources and socio-economic development. It is also conducive to resolve the problem of water resources development and utilization management (CHEN et al. 2004b, 127). Since this index system is related to water resources, the economy, society and ecology, it needs large amounts of statistical data. In 2005, on the basis of sustainable development of urban water resources, XIAO et al. (2005) used the principle of system dynamics to improve the water conservation index system. This method took into account the degree of abundance or shortage of water resources, but it did not consider the impact of economic development on water conservation. In 2010, regulations and institutional indexes, as well as promotion and protection indexes were introduced into the water conservation index system by ZHANG et al. (2010a). This improved system was used to provide a theoretical basis for the development of water conservation. Overall, the establishment of the water conservation index system should be based on the actual situation of regional socio-economic development (WEN et al. 2007, 37; ZHANG et al. 2008a, 3).

The water conservation index system for Urumqi is built in accordance with the national water conservation index system. Considering the current allocation of water resources and the potential of water conservation, the water conservation index system contains a comprehensive index, an agricultural conservation index, an industrial conservation index, a domestic index, and a water ecology and environment index.

5.2.1 Comprehensive index

The comprehensive index is used to reflect the achievements of a water conservation society, including the reflection of economic development and the sustainable use of water resources. In order to better reflect the sustainable use of water resources, and the impact of economic development on water use efficiency and water conservation in Urumqi, according to the water-saving evaluation standard in China in 2012, the water consumption amount per ten thousand Yuan GDP and the proportion of unconventional water (e.g. treated wastewater and rain) use to water supply are selected as composite indexes (AQSIQ & SAC 2012).

The water consumption amount per ten thousand Yuan GDP can be used to measure the efficiency and the benefit of water consumption. The water consumption amount per ten thousand Yuan GDP can better reflect macro water use efficiency. In the meantime, the water consumption amount per ten thousand Yuan GDP also can be used to estimate the amount of water resource utilization and predict future water demand. If the value of the water consumption amount per ten thousand Yuan GDP is high, it means the efficiency and the benefit of water consumption is low. In 2000, the water consumption amount per ten thousand Yuan GDP was less than 60 m^3 in developed countries: in America it was 58 m^3, in France it was 36 m^3, and in Britain it was 8 m^3. In China the water consumption amount per ten thousand Yuan GDP was four times than that of the word average (144 m^3) (MA et al. 2007, 7). The values of the water consumption amount per ten thousand Yuan GDP of India, China, and Russia were very high comparing to the other 9 countries, meaning that the water consumption efficiency and benefit of these three countries are very low (see Figure 5-4).

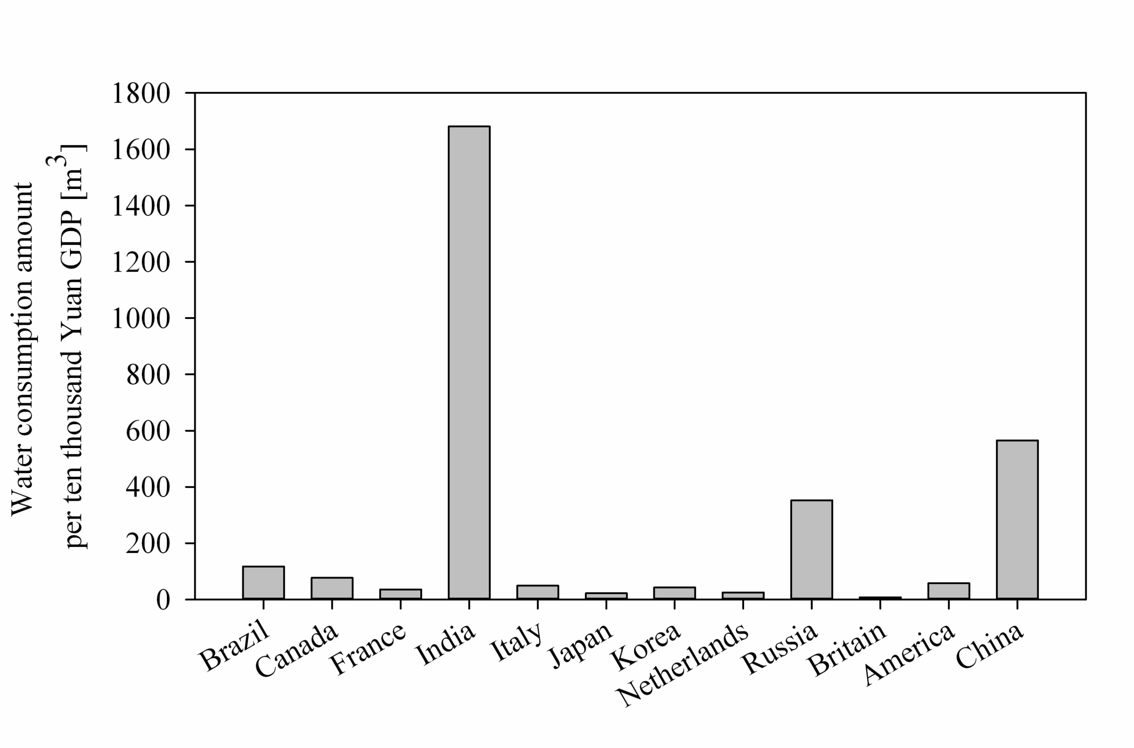


Figure 5-4 Water consumption amount per ten thousand Yuan GDP in many Countries (source: MA et al. 2007, 7; own design).

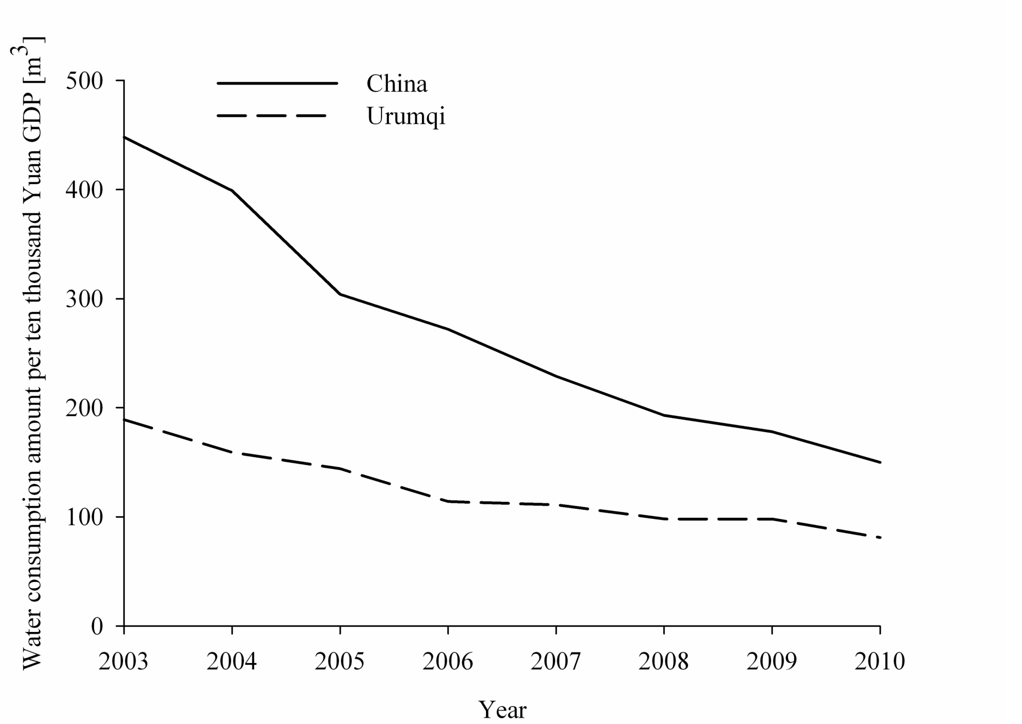


Figure 5-5 Water consumption amount per ten thousand Yuan GDP 2003-2010 in China and Urumqi (source: MWRC 2003, 2004, 2005a, 2006, 2007, 2008, 2009 and 2010; WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; STATISTICS BUREAU OF URUMQI 2007; own design).

From 2003 to 2010 the water consumption amount per ten thousand Yuan GDP in China and Urumqi had been declining due to industrial structure adjustment and water conservation. In Urumqi, the water consumption amount per ten thousand Yuan GDP was lower than the national value, since Urumqi's average annual GDP growth rate (18 %) was higher than the national average annual GDP growth rate (7 %) (STATISTICS BUREAU OF URUMQI 2011; ZHANG 2011, 17) (see Figure 5-5).

The water consumption amount per ten thousand Yuan GDP from 2003 to 2010 dropped significantly, but it was still higher than the world average. In 2010, Urumqi's water consumption amount per ten thousand Yuan GDP was 81 m^3, which was almost twice the world average (45.3 m^3 in 2001) (ZHU & QIN 2003, 32). According to the criterion of a national water conservation city, a city is a water conservation city if the water consumption amount per ten thousand Yuan GDP in the city is less than 50 % of the national average value (150 m^3) (MWRC 2010). The water consumption amount per ten thousand Yuan GDP has still not reached the criterion of a water conservation city (75 m^3) (WATER AFFAIRS BUREAU OF URUMQI 2010; MHURDC & NDRCC 2012). This means water efficiency and effectiveness need to be improved and there is a great potential for water conservation in Urumqi. If the water consumption amount per ten thousand Yuan GDP in Urumqi reaches the average level of high income countries in the world (45.3 m^3 in 2001), more than 40 % of the total water consumption can be saved based on the GDP in 2010 (ZHU & QIN 2003, 32).

The second index, the proportion of unconventional water use to water supply, can reflect the sustainable use of water resources in the region. Since there is currently no rainwater collection and use device in Urumqi, treated wastewater is the only unconventional water resource. However, the low wastewater treatment rate and the low treated wastewater reuse rate lead to a situation in which hardly any unconventional water resources are used in Urumqi. In 2010, unconventional water resources only occupied 2.1 % of the total water supply (1089.31 million m^3), of which only 10.52 % of the total was wastewater (215.1 million m^3) (WATER AFFAIRS BUREAU OF URUMQI 2010). If the water reuse rate in Urumqi can reach the domestic top-level (≥ 20 %), 20.39 million m^3 fresh water can be saved (GUO 2009, 93).

To achieve the aim above, the pattern of water consumption would have to be changed and the utilization rate would have to be improved. Therefore, adjusting of water allocation, increasing the use of unconventional water resources and improving of the efficiency of water use could improve the water conservation efficiency.

5.2.2 Domestic water conservation index

The changes of domestic water consumption are impacted by socio-economic development, water conditions, and the construction of public facilities. The focus of domestic water conservation is to promote water conservation appliances and to reduce water supply network dropout (ZHANG et al. 2008a, 2). Per capita urban domestic water consumption and per capita rural domestic water consumption can directly reflect domestic water use quota. In addition, penetration of water conservation appliances and urban water supply network management dropout rate directly affect the total domestic water supply. Therefore, according to the water-saving evaluation standard in China in 2012, the domestic water conservation index contains four different parameters (AQSIQ & SAC 2012):

1. The per capita urban domestic water consumption which contains the acquired running water for day to day life per person per day in urban areas and the public water consumption for construction, service and greening.
2. The per capita rural domestic water consumption including the acquired running water for day to day life per person per day in rural areas and the water consumption for the rural environment.
3. The popularization of water conservation appliances.
4. The leakage rate of the water supply pipe network.

Since living standards, lifestyles and water supply facilities are different, the per capita urban domestic water consumptions of various regions are also different (YUAN *et al.* 2007a, 51). However, the trend of per capita urban domestic water consumption (including public water consumption) in China was relatively stable from 2004 to 2009. Due to the continuous improvement of China's urban water supply capacity, total water consumption of urban life had been basically stable (QIU 2011, 9) (see Figure 5-6 A). With the increase of urban population in China, the decline in per capita urban domestic water consumption in 2010 was 193 l/person and day, which was 1.6 times that of German per capita urban domestic water consumption (121 l/person and day) (MWRC 2010; STATISTISCHES BUNDESAMT 2012). The per capita urban domestic water consumption in Urumqi showed a downward trend (an average annual decline of 0.29 %) from 2004 to 2010 (also see Figure 5-6 A). Except 2009 (the proportion of urban population growth was greater than the proportion of the urban water supply growth in 2009), the per capita urban domestic water consumption in Urumqi was higher than the national level (also see Figure

5-6 A). In 2010, the per capita urban domestic water consumption in Urumqi was 1.38 times higher than the national level. The main reason for the high per capita urban domestic water consumption in Urumqi is that Urumqi's urban domestic water price is relatively low, which results in residents' water conservation consciousness being weak. As for the expected expansion of urban population, more water will be needed for domestic use. In addition, the continued growth of public water use and environment water use (average annual growth rate is 29 %) also increased the amount of domestic water use (ZAN et al. 2006, 177; XIE et al. 2008, 3). According to China's water consumption standards of urban residents, the per capita urban domestic water consumption should reach 270 l/person and day (MCTC & MCC 2006). By reducing the leakage rate of water supply pipe networks, improving the awareness of water conservation and raising the water price, a reduction in the water quota of urban domestic use is achievable. Therefore, the per capita urban domestic water consumption is envisaged to be at 270 l/person and day (including public water consumption) in Urumqi in 2015.

During the same time period, the per capita rural domestic water consumption (including livestock water consumption) was between 100 and 150 l/person and day (see Figure 5-6 B). According to the criterion of water supply in rural areas of Xinjiang, the maximum per capita domestic water consumption is 120 l/person and day (BEIJING MUNICIPAL INSTITUTE OF DESIGN AND RESEARCH 1996; WATER RESOURCES DEPARTMENT OF XINJIANG UYGUR AUTONOMOUS REGION 2006). Therefore the per capita rural domestic water consumption is envisaged to be at 120 l/person and day in 2015.

In accordance with the appraisal standards for a water conservation city, the urban sewage treatment rate must be greater than or equal to 80 % in provincial capitals, 70 % in prefecture-level cities and 50 % in county-level cities. The leakage percentage in the pipe network must be less than or equal to 12 % (MCC 2002). The popularization of water conservation appliances is envisaged to reach 100 % in 2015 in Urumqi based on the implementation program of water conservation in Urumqi (URUMQI MUNICIPAL GOVERNMENT 2005). According to the Urumqi Water Resources Report in 2007, the leakage rate of the pipe network for urban water supply (not including the loss of public water supply) was 15 % and it had reached 12.8 % in 2010 (WATER AFFAIRS BUREAU OF URUMQI 2005 and 2010). This means that water supply facilities are being improved in order to reduce losses of water. According to the Urumqi Urban Master Planning the leakage rate of pipe network (not including the loss of public water supply) is envisaged to reach 8 % in 2015 (URUMQI URBAN PLANNING BUREAU 2011).

However, the leakage rate of the pipe network for urban water supply which includes the losses of public water supply was 17.9 % in 2010 due to the lack of public awareness on water conservation.

In summary, domestic water conservation efficiency can be improved by four measures, namely the improvement of water prices for public water consumption, the reduction of the leakage rate of the pipe network, the improvement of the popularization of water conservation appliances and the promotion of public awareness on water conservation.

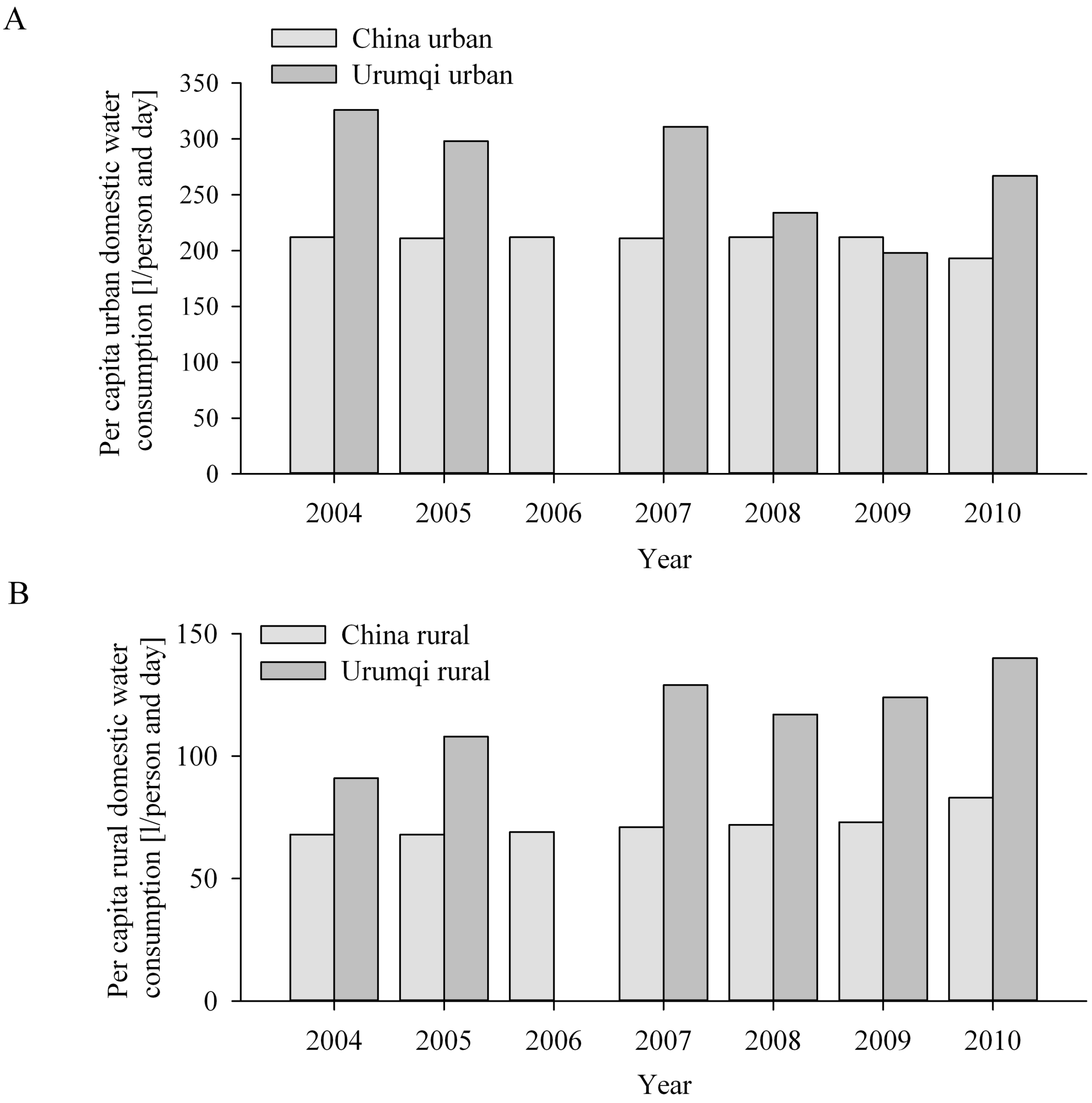


Figure 5-6 Comparison of per capita urban domestic water consumption and per capita rural domestic water consumption in China and Urumqi. A. per capita urban domestic water consumption; B. Per capita rural domestic water consumption (missing data in Urumqi for 2006) (source: MWRC 2004, 2005a, 2006, 2007, 2008, 2009 and 2010; WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; own design).

5.2.3 Agricultural water conservation index

ZHANG et al. (2008a) suggested that agricultural water conservation can be improved by adjusting the crop planting system, reconstructing the large size irrigation districts, expanding farmland with an effective irrigation system, improving the effective utilization coefficients in water canals, optimizing the irrigation schedule and adjusting the price of agricultural water supply. Agriculture includes five kinds of sectors, i.e. farming, forestry, animal husbandry, fishery and side-line occupations (WATER AFFAIRS BUREAU OF URUMQI 2010, 18). The major water users are farming and animal husbandry. Therefore, based on the water-saving evaluation standard in China in 2012, the agricultural water conservation index contains average irrigation water per mu, average livestock water use (water use per head and day) and the conveyance efficiency of the irrigation canal system, which is the ratio of the effective water use for agriculture compared to the total agricultural water supply (AQSIQ & SAC 2012). All these indexes can be used to reflect agricultural water conservation potential.

Because the positive anomaly of precipitation (mentioned in section 2.1.1) has influence on the amount of water used for irrigation, the average irrigation rate should be low in the wettest year. However, the wettest year (2007) was the one with the second highest average irrigation rate due to the expansion of the irrigated area (Miquan City was merged into Urumqi in 2007). Meanwhile, due to the use of new techniques for agricultural irrigation and the structural adjustment of farmland cultivation (reduce paddy filed area), the average irrigation water per mu showed an insignificant downward trend both in China and Urumqi from 2004 to 2010. But in Urumqi the average irrigation water per mu was still almost 1.5 times the national value. In 2010, the average irrigation water in Urumqi was 639 m^3/mu, which was 81 m^3/mu less than the average irrigation water in 2004 (see Figure 5-7). However, it was still larger than the average irrigation water (500 m^3/mu) of the United States (FENG 2010, 43).

According to the standard of irrigation water quota for different crops in China, the irrigation water is divided into three categories according to the water demand conditions of crops, including paddy, upland and vegetables. The irrigation water quota for paddy (containing rice) is 800 m^3/mu and for upland (containing wheat, corn, and cotton,) is 300 m^3/mu (AQSIQ & SAC 1992) (see Table 5-2). In Urumqi, the main crops are food crops (rice, wheat) and vegetable crops. Therefore, the average irrigation water quota in Urumqi will be 500-550 m^3/mu in 2015, with the cultivated land being constant.

Table 5-2 The standard of irrigation water quota for different crops in China (source: AQSIQ & SAC 1992).

Categories	Irrigation water per mu [m³/mu]	Description
Paddy	800	Rice
Upland	300	Wheat, corn and cotton,
Vegetable	200-500	Cabbage, leeks and onions

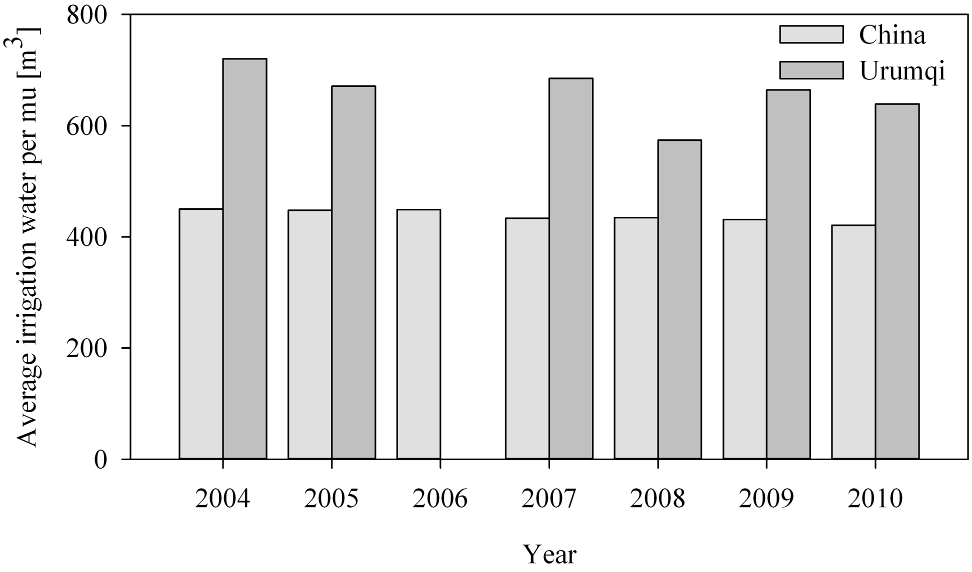


Figure 5-7 Comparison of irrigation water quota in China and Urumqi (average irrigation water per mu) (mu: Unit of area of PR China) (missing data in Urumqi for 2006) (source: MWRC 2004, 2005a, 3006, 2007, 2008, 2009 and 2010; WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; own design).

The conveyance efficiency of the irrigation canal system depends on three components. These are the conveyance from the water source to fields (integrated canal system utilization factor), the irrigation methods and techniques, and the field water use for crops (water use efficiency). In China, most of the irrigation canals for are earthen channels, making water conveyance losses (water seepage and evaporation) a serious problem. Furthermore, some irrigation canals are old, therefore the average conveyance efficiency of an irrigation canal system is 0.5 which lags fairly far behind when compared with countries with advanced agricultural systems where the water efficiency of irrigation is 0.7-0.8 (PEI 2003, 19; PENG & AI 2012, 81). In addition, the agricultural irrigation water price is relatively low and a lot of agricultural irrigation water is wasted (YAO 2002, 35). By transforming irrigation canal systems (impermeable lining of the channels accounted for

45.74 % of the total length of the channels), the average conveyance efficiency of irrigation canal systems had reached 0.62 in 2010 in Urumqi (WATER AFFAIRS BUREAU OF URUMQI 2010). By adopting seepage control for the canals, the average water efficiency of the canal system for agricultural irrigation could be improved up to 75 % and it may be possible to increase this figure up to 85 %-90 % by using sprinkler irrigation system through pipelines (LIU et al. 2005, 283). Meanwhile, water conservation irrigation techniques will be promoted, such as drip irrigation and micro-irrigation in the future (YAO 2002, 32). Thus, a large amount of agricultural water could be saved.

In addition to irrigation water, the water consumption for livestock is another large water user in agriculture water consumption. The livestock has continued to grow and needed more water in Urumqi. The average livestock water consumption was 12 l/head and day from 2004 to 2010. Based on the criterion of rural water use for livestock, different kinds of livestock have different water use quota, for sheep it is 5-10 l/head and day, for pigs it is 20-90 l/head and day (BEIJING MUNICIPAL INSTITUTE OF DESIGN AND RESEARCH 1996) (see Table 5-3). The main livestock category in Urumqi is sheep. Therefore, in 2015, the average livestock water use in Urumqi will stay at around 10 l/head and day according to the Chinese national standard of water supply for livestock (BEIJING MUNICIPAL INSTITUTE OF DESIGN AND RESEARCH 1996).

The analysis above shows that the potential for agricultural water conservation is large and that agricultural water consumption decline can be achieved by improving irrigation water prices and improving the conveyance efficiency of irrigation canal systems.

Table 5-3 Specifications on rural water use for livestock in China (source: BEIJING MUNICIPAL INSTITUTE OF DESIGN AND RESEARCH 1996).

Type	Water use [l/head and day]
Horse	40-50
Cow	50-120
Pig	20-90
Sheep	5-10
Chicken	0.5-1.0
Duck	1.0-2.0

5.2.4 Industrial water conservation index

Industrial water conservation is closely related to water resources, economic and social development, scientific and technological levels, and water prices. According to the water conservation evaluation standard in China in 2012, the industrial water conservation index contains recycling rates of industrial water and water consumption per value added by industry (AQSIQ & SAC 2012). The low recycle rate of industrial water results in the high water consumption per ten thousand Yuan added value of industry. China's recycling rate of industrial water in 2000 was 53 %, lower than the mean recycling rate of industrial water of developed countries (75 % to 85 %), that was only equivalent to the recycling rate of the United States in the 1960s and Japan in the early 1970s (HE et al. 2004, 169). The water consumption per value added by industry in China was 288 m^3 in 2000, 3 times higher than the world average, 2.6 times that of the United States (its water recycling rate is 90 %) and 23 times than that of Japan (its water recycling rate is 78.1 %) (NDRCC, MWRC & MCC 2006; MA et al. 2007, 9) (see Figure 5-8).

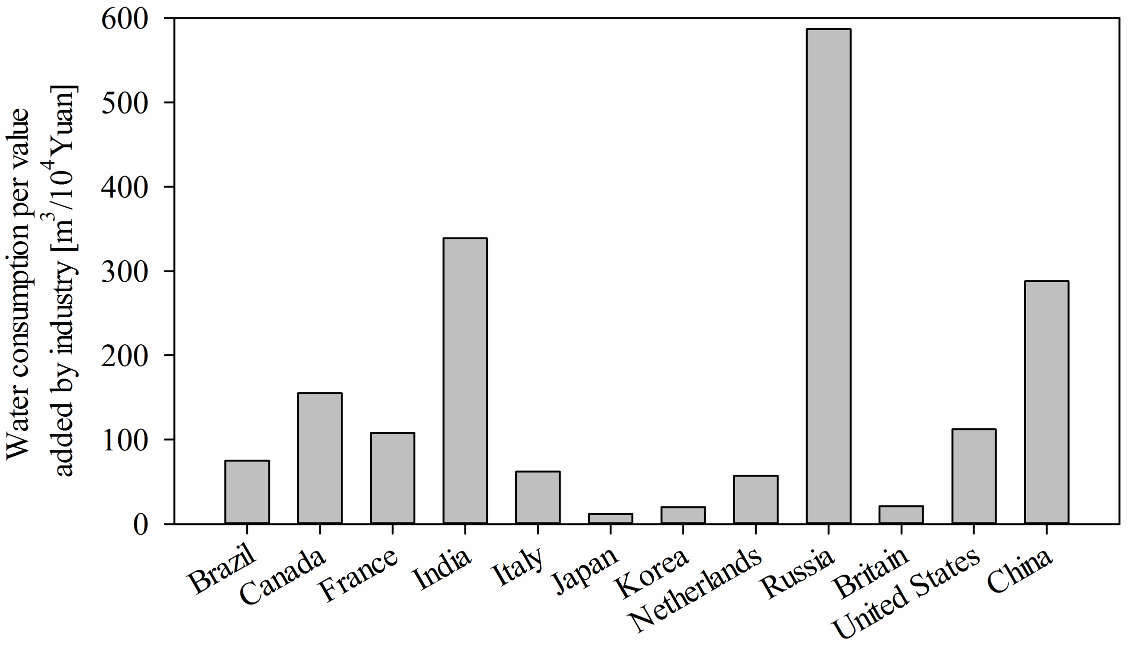


Figure 5-8 Water consumption per value added by industry in different countries in 2000 (source: Ma et al. 2007, 7; own design).

With the improvements of water conservation awareness in industry and industrial techniques, water consumption per value added by industry in China is on the decline. There is also a less pronounced downward trend for Xinjiang and Urumqi. In 2010, water consumption per value added by industry was 30 $m^3/10^4$Yuan in Urumqi, which is 63 % lower than the value in 2004 (see Figure 5-9). According to the Energy Conservation and Emission Reduction Plan in China, water consumption per value added by industry will be decreased by 25 % of that in 2010 during the twelfth five-year period (2011-2015) (SCC 2012). Therefore, the water consumption per value added by industry in Urumqi will be 22.5 $m^3/10^4$Yuan in 2015.

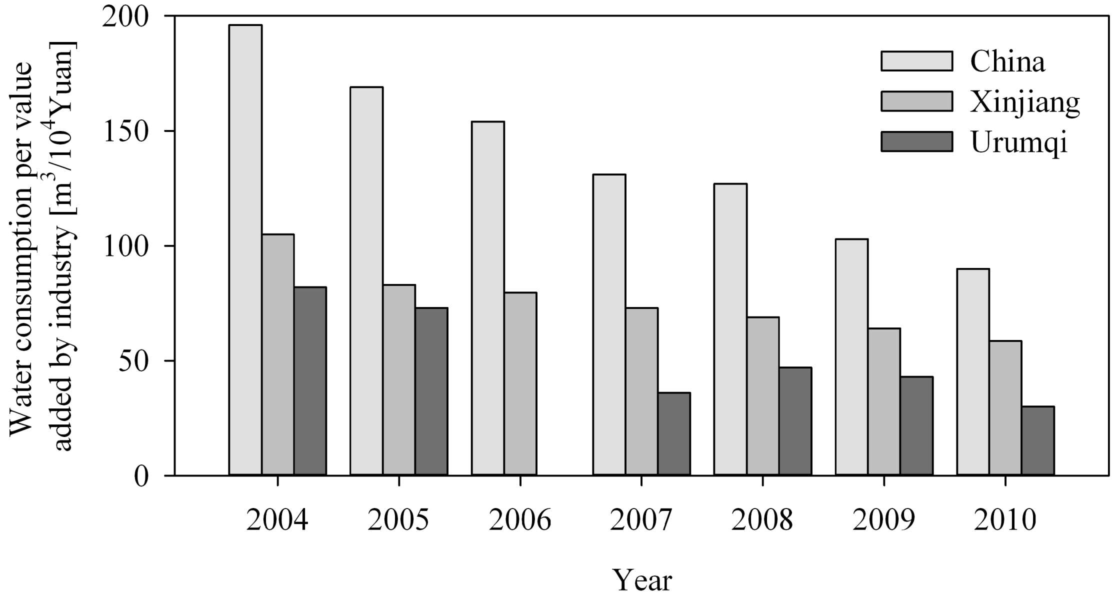


Figure 5-9 Water consumption per value added by industry 2004-2010 (missing data in Urumqi for 2006) (source: MWRC 2004, 2005a, 2006 2007, 2008, 2009 and 2010; DEPARTMENT OF WATER RESOURCES OF XINJIANG UYGUR AUTONOMOUS REGION 2004-2010; WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; own design).

The source of industrial water includes fresh water withdrawals and recycled water (ZHANG et al. 2001a, 79). Fresh water withdrawals mean fresh water supplied by the public water supply sector. Recycled water is the water reused with or without water treatment in industries. The recycle rate of industrial water is the ratio of the recycled water and the total industrial water (the sum of the recycled water and industrial water withdrawals). It is an important indicator to reflect the efficiency of industrial water use (SUN 2008, 55).) In 2010 it was 70 %, which was lower than the developed countries (WATER AFFAIRS BUREAU OF URUMQI 2010, 22).

According to the twelfth five-year plan of economic and social development in Urumqi, the recycle rate of industrial water must be higher than or equal to 98 % in the future (URUMQI DEVELOPMENT AND REFORM COMMISSION 2011). Hence, the industrial water conservation potential is great since the water recycling rate is still lower than the value of the twelfth fiver-year plan.

5.2.5 Water ecology and environment index

The water ecology and environment index is a key index to reflect the situation of ecology and the environment. Indiscriminate discharge of domestic sewage and industrial wastewater are two main sources which cause environmental pollution of the Urumqi's water (LUO & LI 2007, 18). Based on the water-saving evaluation standard in China in 2012, water ecology and the environment index contains the criterion of industrial wastewater meeting the discharge standards and centralized treatment rate of domestic sewage (AQSIQ & SAC 2012).

In Urumqi, the total industrial wastewater was 58.22 million m^3 in 2010, and 53.54 million m^3 of the industrial wastewater met the discharge standard (STATISTICS BUREAU OF URUMQI 2011). This means the rate of industrial wastewater meeting the discharge standard (91.96 %) was lower than the national industrial wastewater discharge standard (95.3 %) (MEPC 2010a). According to the twelfth five-year plan of economic and social development in Urumqi, 100 % of industrial wastewater will be up to the discharge standards in 2015 (URUMQI DEVELOPMENT AND REFORM COMMISSION 2011).

In 2010, the total domestic sewage was 118.43 million m^3 in Urumqi, while only 60.65 % of domestic sewage was treated because of the incomplete urban drainage network (STATISTICS BUREAU OF URUMQI 2011). The sewage treatment rate in Urumqi was lower than the national domestic sewage treatment rate (65.12 %) (MEPC 2010a). By contrast, in the developed countries the centralized treatment rate domestic sewage had reached 80 % as early as the 1980s (YAN et al. 2003, 72). In order to improve the centralized treatment rate of domestic sewage, the government of Urumqi already developed a plan to improve the wastewater system (URUMQI URBAN PLANNING BUREAU 2011). According to the national twelfth five-year environmental protection plan, in 2015, Urumqi's centralized treatment rate of domestic sewage will increase by as much as 85 % (SCC 2011).

5.3 Integrated water conservation analysis

A water conservation index system can reflect the current situation of water conservation in Urumqi. It can be used as the basis for the establishment of a water conservation society. According to the status of water conservation and the utilization of water resources, as well as based on the aim of government and the principle of efficiently using water resources, the water conservation measures of various departments are analyzed and summarized.

5.3.1 Domestic water conservation

Due to the growing population and the increase in public water consumption, the domestic water consumption will also increase. Domestic water consumption is closely related to the process of urbanization and living standards. According to the analysis of domestic water consumption and conservation, three problems (the high leakage rate of the pipe network, poor public water conservation awareness, and serious wasters of public water) have been discovered. Several suggestions are provided to improve domestic water conservation.

1. Water conservation appliances could be popularized in normal households.

   Water conservation appliances include water saving faucets, a water saving toilet system, water saving flushing for water closets, water saving showers, and water saving washing machines. For example, for the residence in Urumqi which was constructed before 2000, the average capacity of toilets is 9 liters (WU 2007a, 38). According to the requirements of the Chinese national standard for water-saving sanitary, the household toilet must be switched to 3/6 liter double capacities with two separate tanks for different purposes (AQSIQ & SAC 2006b).

2. Change the residents' habits of water use.

   Water conservation could also be achieved by changing the residents' water use habits. Residents should avoid long shower times, control the flow of the faucet when washing fruits and vegetables, change uninterrupted rinses for intermittent flushing, and turn off the tap in time when washing hands and face. Concentrated washing of clothes, the right amount of detergent, reuse of the sewage coming from bath, laundry and washing fruits and vegetables are very important for saving water (ZHANG 2007, 621). For example, bath water can be used to flush the toilet, laundry water can be used for cleaning, and the sewage coming from washing fruits and vegetables can be used to water flowers and gardens.

3. Inter-floor reuse of domestic sewage (the sewage generated between floors in the same building) is an effective measure to improve the efficiency of water usage. The domestic sewage of a whole building is collected and the treated domestic sewage can be used for agricultural irrigation and industry according to the national standard.
4. Reduce the leakage rate of the pipe network to improve urban water supply. The leakage rate of the pipe network (including the losses of public water supply) was about 17.9 % in 2010 and the losses of water was about 17.83 million m^3 of high quality water resources which could be saved (WATER AFFAIRS BUREAU OF URUMQI 2010, 18).
5. Due to the poor public awareness of water conservation, the waste of public water is most serious, for example in public toilets, schools, hospitals and hotels. Water conservation works depend on understanding the need for conservation and public awareness.

If the above suggestions can be implemented, the per capita urban domestic water consumption (including public water consumption) can be reduced to 125 l/person and day and the leakage rate of the pipe network can be reduced to 8 % according to the analysis in section 5.2.2. Based on this assumption and when the population base has been maintained, about 2 % of the urban domestic water consumption in 2010 could be reduced due to the reduced leakage rate of pipe network for urban water supply.

5.3.2 Agricultural water conservation

In contrast to the domestic water consumption, the agricultural water conservation has a larger potential to decrease water consumption. The overall aim for modern agricultural water conservation is to meet the requirement of water-efficient agriculture and to promote the development of agricultural water conservation technologies along quantitative, standardized, modular, integrated lines according to the current situation in Urumqi (KANG et al. 2004, 4). This goal can be achieved through decreasing the leakage losses in canals by better pavements, the use of new techniques and the adjustment of the structure of farmland cultivation (reduce paddy-filled area) to reduce the irrigation water quota, control the ineffective water losses to evapotranspiration, and enhance the efficiency of water resources utilization (DUAN et al. 2002, 50; GAO et al. 2002, 26; LI & YANG, 2003, 38). Unconventional water resources such as rainwater and wastewater can be used for agricultural irrigation when paying special attention to the influence of treated wastewater irrigation on soil and groundwater, soil pollution regulations and the self-purification capacity of the soil, the degree of tolerance of different crops and the quantitative indexes system of wastewater irrigation security (INDELICATO et al. 1993, 57; GUO 2009, 93). In addition, improvement of the water price system for agricultural irrigation also plays a regulatory role in agricultural water conservation.

Although agricultural water consumption has shown a descending tendency since the 1990s, agricultural irrigation is still the major water user in Urumqi. If the average irrigation water quota is reduced by 500-550 m^3 according to the analysis in section 5.2.3, the water resource for agricultural irrigation can be reduced by 14 %-22 % of the agricultural water consumption.

5.3.3 Industrial water conservation

Although the water consumption per value added by industry has been decreasing, the total industrial water consumption has been increasing every year due to the continuous expansion of industry in Urumqi (ZHANG 2008, 63). In the meantime, the water consumption amount per ten thousand Yuan gross industrial output value is still high, since industries with high water consumption (petroleum refining and coking, electricity, architecture materials papermaking, and black metal smelting industry) are quite common in Urumqi (LI & TURSUN 2001, 15; ZHANG et al. 2011b, 540).

As the water consumption per value added by industry and the recycling rate of industrial water in Urumqi were still lower than that of the developed countries, the method for industrial water conservation is mainly to reduce the proportion of industry with intensive water use, develop water recycling system, take measures to reuse industrial wastewater and promote zero-emission (refers to the industrial wastewater achieves all-around micro-emission) technology. Meanwhile, it is also important to change the industrial structure from labor and capital intensive industries to technology and knowledge based industries (JIA 2001, 51).

5.4 Summary

Urumqi is a region with absolute water scarcity where the total water resources cannot meet the development of society and the economy. People live in water-stressed conditions. Therefore, present water consumption patterns must be changed. The indexes of water conservation should be applied and the water conservation index system should be built to reflect the problems in rational water use, water consumption and water allocation. The water conservation index system is an intuitive and straightforward way to reflect the potential of water conservation in different sectors.

Figure 5-10 shows Urumqi's water conservation index system according to the water-saving evaluation standard of China. All the indexes in the water conservation index show a variety of water conservation potential in Urumqi.

Based on the integrated analysis for water conservation in Urumqi, domestic water consumption will become a big water user due to the growth of population and the rising living standards. However, by reducing the leakage rate of pipe networks for domestic water supply and public water supply, controlling the urban population and promoting public awareness on water conservation, domestic water conservation can be realized. Moreover, population growth and the leakage rate of the pipe network are the direct determinants of water conservation.

As mentioned in section 5.1.2, agricultural water consumption occupies more than 60 % of the total water consumption. There is a large potential in agricultural water conservation by several measures, such as improving the water efficiency of the canal system, using advanced water conservation irrigation techniques (e.g. surge irrigation and micro-irrigation), increasing the water-saving irrigation area and improving the water price for agricultural irrigation.

In addition, with the rapid industrial development, industrial water consumption will continue to increase. Due to the lower recycling rate of industrial water in comparison with developed countries, water conservation potential for industry is also great. As mentioned in section 4.5.5, by taking appropriate measures (e.g. improving industrial facilities and implementing advanced measures, raising the price of fresh water withdrawals and the costs of wastewater discharges) to adjust industrial structures in order to reduce the industrial water consumption quota, industrial water conservation can also be realized in Urumqi.

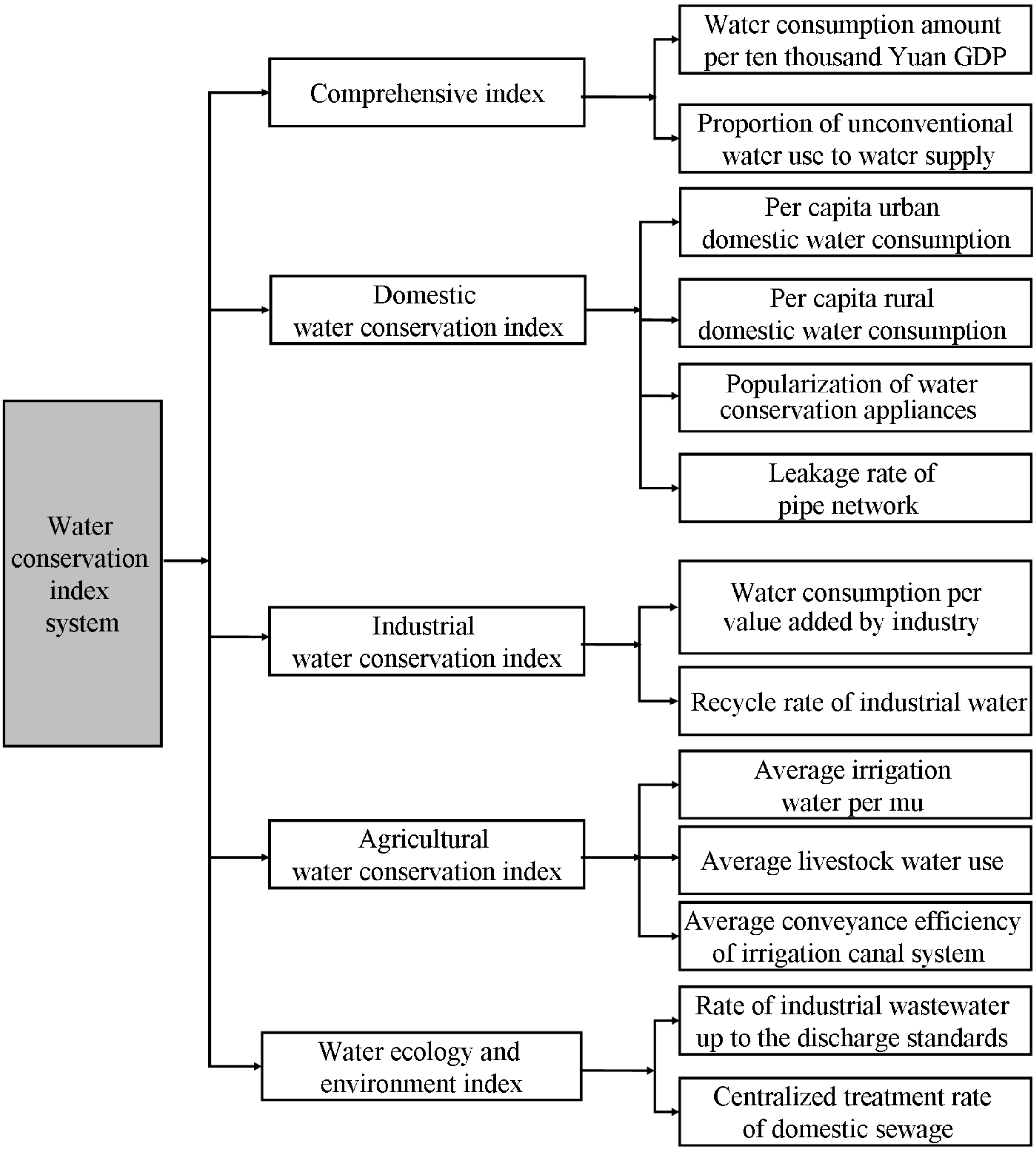


Figure 5-10 Urumqi's water conservation index system (source: own design).

6 Study on simulating and predicting water demand

Water demand is the amount of water required for a given purpose (NIELSEN 2004). For a given region, water demand can be affected by population, climate, industry, and commercial conditions (FIRAT et al. 2009, 618).

There are different classifications of water demand, which emphasize different aspects:

1. In accordance with the application of the required water, water demand can be divided into natural ecological water use and water used for human society (SONG & WANG 2006, 155).
2. Based on water rights, water demand can be divided into basic demands, which refer to the amount of water needed to meet human survival and development, the requirements of ecosystems, which refer to the quantity of water needed to maintain functions of the ecosystem and the environment, as well as the needs of the economy which refer to industrial water demand and agricultural water demand (JIANG 2000, 13; LEI et al. 2006, 20; LI 2008, 14).
3. According to water demands in different areas, it can be divided into rural water demand (including water demand for irrigation, rural living, industry and farming, forestry, animal husbandry, side-line production and fishery) and urban water demand (including urban industrial water demand, urban domestic water demand and water demand for construction industry, tertiary industry and the ecological environment) (YUAN et al. 2007b, 405; WORTHINGTON 2010, 238).
4. On the basis of the time period, water demand can also be divided into two classes (BILLINGS & JONES 2008, 302):

A. The water demand of the status quo

The reasonable volume of water is demanded for current economic and social development and for maintaining ecological conditions of the target region.

B. The short-term water demand and long-term water demand

The water is used for maintaining certain ecological objectives for the short-term use and long-term use according to the planned economic development.

In order to predict water demand in the future, the gap between water supply and water demand must be analyzed. Water demand is steadily increasing because of many factors, such as population growth, industry expansion and urbanization. With the increase of water demand, the water supply has to be raised to ensure residents' normal life and socio-economic development. The total water supply (1089.31 million m³) in Urumqi was 1.16 times the total water resources (939.22 million m³) in 2010. It was 3.2 times the total water supply in Karamay (343 million m³), which was also an inland water scarcity region (WATER AFFAIRS BUREAU OF URUMQI 2003-2010; STATISTICS BUREAU OF XINJIANG UYGUR AUTONOMOUS REGION 2011). The total water supply in Urumqi is increasing and it has exceeded the total amount of water resources which can only be explained by an import of water from other regions. Water demand prediction should be used to determine water supply in the future and serve as a guide for the current adjustment of water allocation.

The models for predicting water demand are compared with each other in this chapter (section 6.1). According to the analysis of advantages and disadvantages of the water demand prediction models, two models are selected and used to predict the short-term water demand in Urumqi (section 6.2 and section 6.3). Finally, the predicted results of the two models are discussed in section 6.4.

6.1 Selection of prediction method

The selection of a reasonable model is very important for providing credible results and the selected water demand prediction model should be suitable for the various characteristics of water consumption in Urumqi (LI et al. 2001, 104). There are many factors which should be considered when the prediction model is selected, such as data requirements, the purposes of the prediction, the prediction accuracy, the limitation of the prediction and the cost of the prediction model as well as the level of difficulty and complexity of the prediction model.

The common water demand prediction models are the quota method, the time series method, the grey model, the per capita comprehensive prediction model, the regression analysis, the artificial neural networks (ANN), the fuzzy mathematical prediction model, and the support vector machine (SVM) prediction model. All these water demand prediction models are built on the basis of historical data, therefore most of the models (e.g. the time series method and ANN) need a large amount of data. However, considering the availability of the data, the selected model has to comply with the limited water resources data of Urumqi. On the other hand, Urumqi's water demand is influenced by many factors, such as the socio-economy, water conservation projects, water price, water conservation and water resources management. Therefore, the designed model should be able to deal with all these factors. Finally, the selected model should be able to adapt to fluctuant water resources data (see Table 6-1).

Table 6-1 Comparison of different prediction models ('Yes' means the model is suitable for use in Urumqi, 'no' means the model is not suitable for use in Urumqi) (source: own design).

Method	Description	Feature	Suitability for Urumqi
Quota method	Used to predict social development indexes and the householder water consumption quota (HE et al. 2007, 63; LIU 2011, 10).	It combines the actual local conditions of water consumption and water demand.	Yes (The method is simple and can easily measure the changes of various factors and policy adjustments)
Water mechanism prediction method	According to the internal mechanism of water demand, the growth law of water demand is found out to establish a water balance model (HE et al. 2007, 63).	Requires a thorough understanding of the water sector and its future evolution and water supply and demand mechanism.	No (It is difficult to quantitatively describe the internal water demand mechanism)
Time series method	The analysis of historical water data, the smoothing method and the trend extrapolation are used to predict the future water demand (SUN 2005, 12; LIU 2011, 10).	The application of the method is relatively wide, but the mechanism is not clear for water demand (HE et al. 2007, 62).	No (Heavy workload and low prediction accuracy)
Grey model	Accumulates the original data to look for the overall law of/relations in the system and construction exponential growth model (SUN 2005, 13; ZHANG & CHEN 2006, 10; REN 2007, 51).	According to the different characteristics of the original data, constructs different forecasting models which are suitable for long-term or short-term forecasts.	Yes (The required amount of data is limited and it is very effective when lacking data)
Regression model	Determines the relationship between the amount of water consumption and the influencing factors to build a regression model (TSAUR 2008, 1105; YAN 2009b, 76)	When the system changes greatly, the predicted value can be corrected according to the corresponding variables.	No (It is generally not used for the data volatility of water consumption and its complex influencing factors)
Artificial neural networks (ANN)	A mathematical model using the connected structure which is similar to neural networks to process the information (JAIN et al. 2001, 299; LIU et al. 2001, 233; JAIN & ORMSBEE 2002; LIU et al. 2002).	It is suitable for short term forecasting and dynamic prediction (FIRAT et al. 2009, 617; BABEL & SHINDE 2011, 1653).	No (Requires a certain amount of historical data)
Fuzzy theory	Uses a precise mathematical method to deal with the fuzzy variables which could not be described by mathematics in the past (SUN 2005; LIU et al. 2009b).	Imperfect system analysis technique and uncertain stability of the model.	No (This model is very complex and it is difficult to determine the parameters of the model)
Support vector machine (SVM)	Seeks structured risk minimization to improve the generalization ability of the learning machine and to minimize the empirical risk and confidence range (DONG et al. 2007; ZHANG et al. 2008b).	A good method to resolve the problems of small sample, nonlinear, high dimensional and local minimum values	No (The relatively large computational complexity increases the difficulty of determining parameters.

The parameters of some models (e.g. water mechanism prediction method, Fuzzy theory and Support vector machine) are difficult to determine. Furthermore, the prediction results cannot quantitatively describe water demand, therefore these models are not suitable for predicting water demand in Urumqi (also see Table 6-1).

The quota method and the grey model are two models suitable for predicting the water demand in Urumqi, since they can deal with a limited amount of data, process many factors and adapt to fluctuant data. In addition, the quota method and the grey model have other useful characteristics. The quota method can analyze various factors' changes and policy adjustments and it can also be improved according to the real time status of water resources in Urumqi. The grey model can be built easily according to the input data.

6.2 The quota method

The quota method predicts water demand based on the development of socio-economic indexes and the corresponding water quota. It uses the statistical data of the last few years to establish a mathematical model for future water demand prediction. The steps involved in the quota method of water demand prediction are the "design of the quota method" (section 6.2.1), "parameter determination for the quota method" (section 6.2.2), and "water demand results of the quota method" (section 6.2.3).

6.2.1 Design of the quota method

The quota method predicts water demand in three steps. Firstly, the water consumption quota corresponding to water consumption in all sectors is selected. Secondly, the selected water consumption quota is determined according to the national standards and the historical water data. Thirdly, the prediction model is built according to the trend of water consumption. There are two kinds of quota methods, the comprehensive quota method and the subitem quota method (YUAN et al. 2007b, 405; HE et al. 2007, 63; LIU 2011, 10).

The comprehensive quota method determines the total water demand by per capita comprehensive water consumption. It can be expressed by the following equation: (WANG et al. 2003, 27; HE et al. 2007, 63):

$$WD_T = WC_{pc} \times R_2 \quad \text{(WANG et al. 2003, 27)} \qquad (6.1)$$

where WD_T is the total water demand [million m^3], WC_{pc} is the per capita comprehensive water consumption [m^3/person and year] and R_2 is the total population [million people].

This method only uses one comprehensive water use quota (per capita comprehensive water consumption), which determines the accuracy of the predicted results. On the other hand, this method cannot determine the water consumption in each sector and adapt to socio-economic development. Therefore, this method is not suitable for use in Urumqi with its unreasonable distribution of water resources.

The subitem quota method predicts water demand by determining the water use quota in each sector. It can be expressed by the following equation (YUAN et al. 2007b, 405; GONG et al. 2008, 171; LI & LI 2009, 6499; LIU 2011, 10):

$$WD_T = W_D + W_I + W_A = Q_D \times R_2 \times 365 + Q_I \times I_O + Q_A \times f_a \tag{6.2}$$

where WD_T is the total water demand [million m³], W_D is the water used for domestic purposes [million m³], W_I is the water used for industry [million m³], W_A is the water used for agriculture (million m³), Q_D is the water use quota for the domestic sector [l/person and day], R_2 is the total population [person], Q_I is the water use quota for industry [m³/Yuan], I_O is the industrial output [billion Yuan], Q_A is the average irrigation water quota [m³/mu] and f_a is the farmland area [mu]. Since this method can deal with many factors and determine water consumption in each sector, it could help to make plans for the improvement of water resources.

Considering the nature of water users and data accessibility in Urumqi, the subitem quota method can be applied to predict water demand in Urumqi and build the allocation of water resources in each sector (e.g. domestic, agriculture and industry) by modifying the parameters of this model.

In Urumqi, water use can be divided into three categories: domestic, agricultural and industrial, according to the various water sectors (WATER AFFAIRS BUREAU OF URUMQI 2010; DU et al. 2011, 143) (see Figure 6-1). Water used for domestic purposes (including city greening and water used for public welfare facilities) includes urban residential use, and rural residential use. Agricultural water use includes agricultural irrigation, forestry, animal husbandry and fishery production. Industrial water use includes the water used for industry and the construction industry, the commercial and drinks industries and the service industry (WATER AFFAIRS BUREAU OF URUMQI 2010; STATISTICS BUREAU OF URUMQI 2011). Therefore, water demand can be divided into domestic water demand, agricultural water demand and industrial water demand according to the water use groups (also see Figure 6-1).

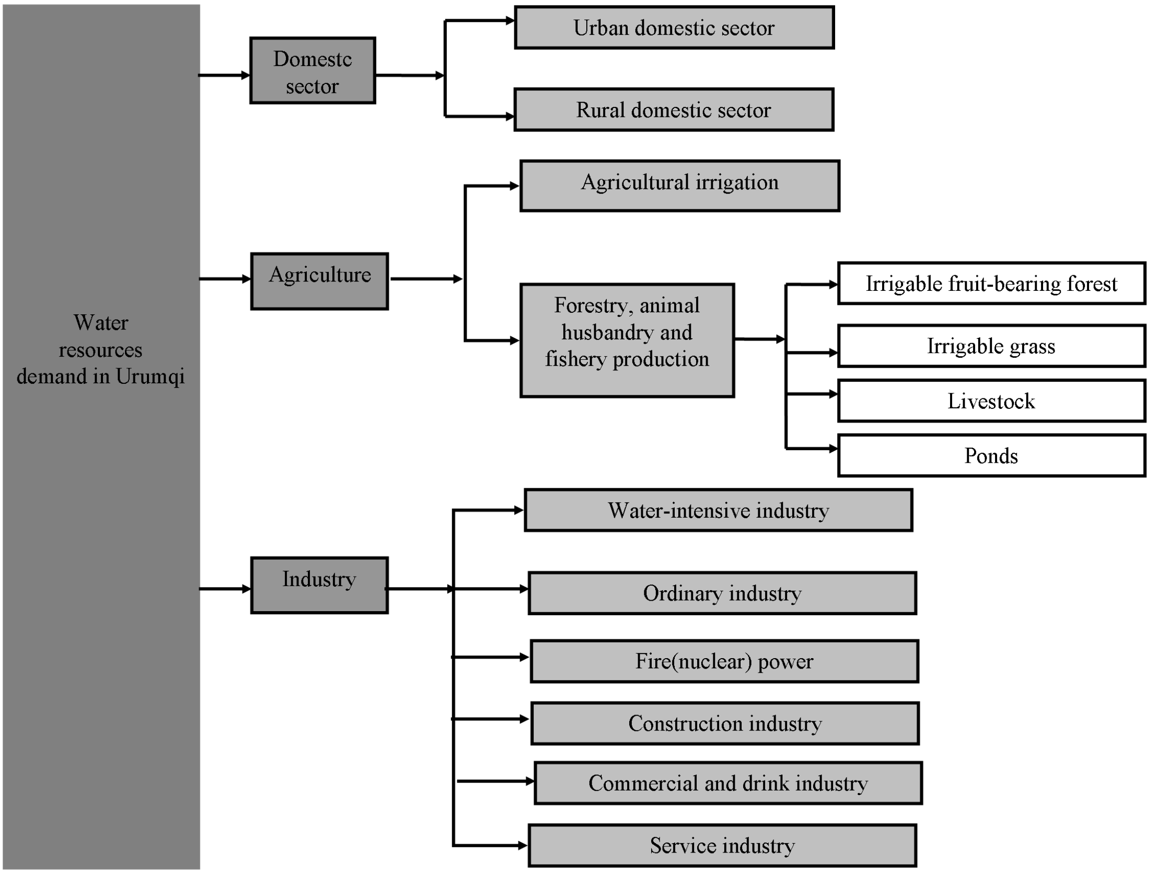


Figure 6-1 Water demand classification according to water use groups in Urumqi (source: own design).

Water demand is the sum of water used for agricultural, industrial and domestic purposes in Urumqi (see Figure 6-2). It is expressed as follows:

$$WD_T = W_A + W_D + W_I \tag{6.3}$$

where WD_T is the total water demand [million m^3], W_A is the water used for agriculture [million m^3], W_D is the water used for domestic purposes [million m^3] and W_I is the water used for industry [million m^3].

Water used for domestic purposes (W_D) including urban domestic water and rural domestic water (also see Figure 6-2). It can be written as follows:

$$W_D = U_1 \times N_{ru} \times 365 + U_2 \times N_{rr} \times 365 \tag{6.4}$$

where U_1 is the per capita urban domestic water consumption (including public water use, such as water used for construction and landscaping) [l/person and day], U_2 is the per capita rural domestic water consumption (including water used for rural greening) [l/person and day], N_{ru} is the total population in urban areas [person] and N_{rr} is the total population in rural areas (including the floating population) [person].

Water used for agriculture (W_A) includes water used for agricultural irrigation, forestry, animal husbandry and fishery in Urumqi. Because of the limited data about water used for forestry and fishery production, water demand for agriculture can be counted as water used for agriculture irrigation and livestock (also see Figure 6-2). It can be expressed as follows:

$$W_A = Q_A \times f_a + T_{nl} \times Q_L \times 365 \tag{6.5}$$

where W_A is the water used for agricultural purposes, Q_A is the average irrigation water quota [m^3/mu], f_a is the farmland area [mu], T_{nl} is the total number of livestock [head] and Q_L is the quota of water demand for livestock [l/head and day].

Water used for industry includes water consumption by the water-intensive industry, ordinary industry, fire power, the construct industry, the commercial and drinks industries and the service industry (MINISTRY OF URBAN AND RURAL CONSTRUCTION AND ENVIRONMENTAL PROTECTION 1999). Because of the limited available data on water use for the construct industry, the commercial and drinks industries and the service industry in Urumqi, the total water used for industry is replaced by the water used for the water-intensive industry, ordinary industry and fire power. It equals the value added by industry multiplied with the water consumption per value added by industry. The equation can be rewritten as follows (also see Figure 6-2):

$$W_I = I_{va} \times WC_{Iva} \tag{6.6}$$

where W_I is the water used for industry, I_{va} is the value added by industry [10^4Yuan] and WC_{Iva} is the water consumption per value added by industry [m^3/10^4Yuan].

The total population (R_2) can be divided into the urban population and rural population and can be calculated as follows (also see Figure 6-2):

$$R_2 = N_{ru} + N_{rr} = R_2 \times r_u + R_2 \times (1 - r_u) \tag{6.7}$$

where R_2 is the total population [person], N_{ru} is the population in urban areas [person], N_{rr} is the population in rural areas [person] and r_u is the urbanization rate [%].

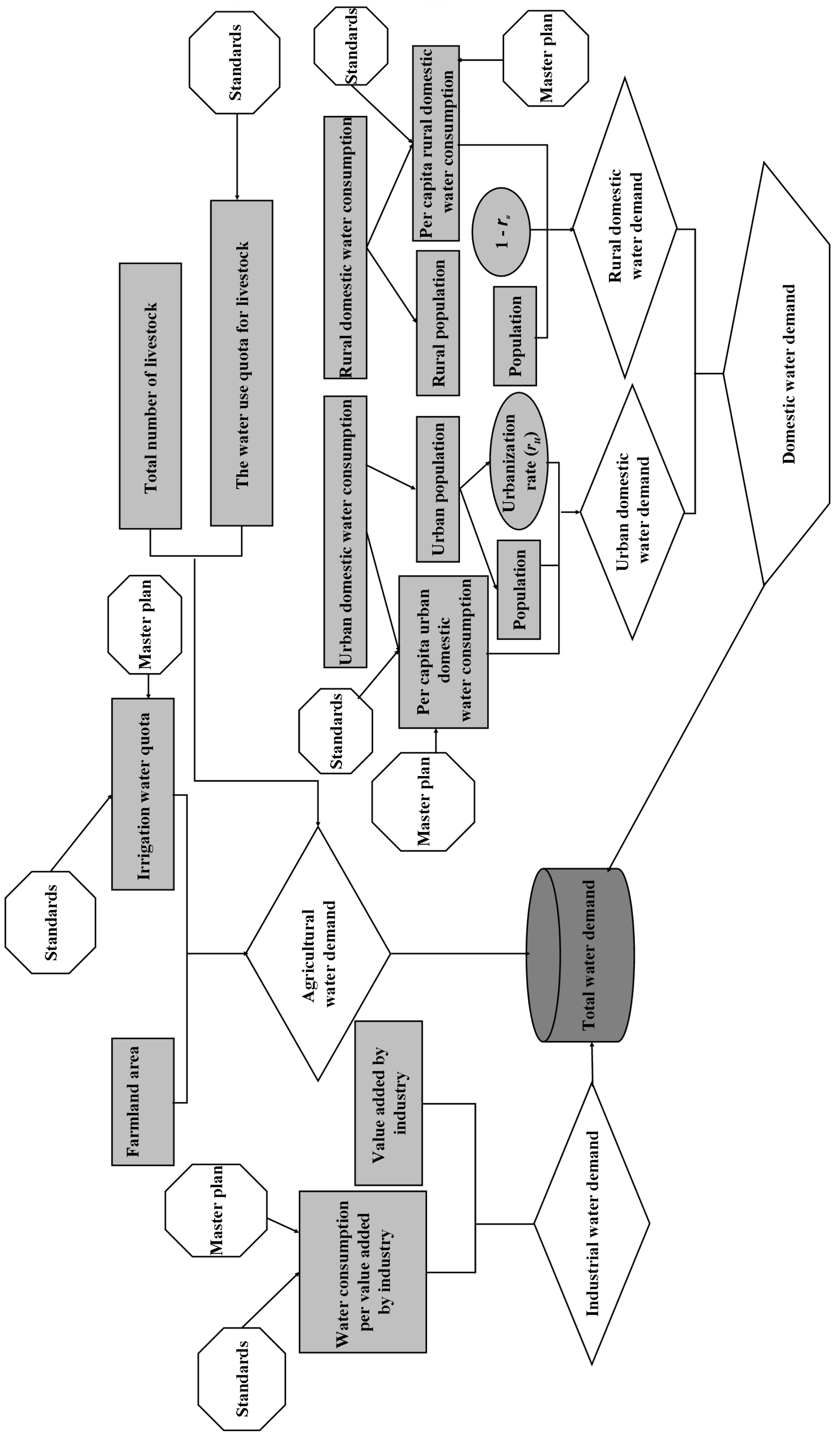


Figure 6-2 Overview of the quota method for water demand prediction in Urumqi (source: own design).

Based on the equations (6.1), (6.2), (6.3), (6.4), (6.5), (6.6) and (6.7), the total water demand prediction model in Urumqi can be built and expressed as follows (also see Figure 6-2):

$$WD_T = Q_A \times f_a + T_{nl} \times Q_L \times 365 + I_{va} \times WC_{Iva} + U_1 \times R_2 \times r_u \times 365 + U_2 \times R_2 \times (1 - r_u) \times 365 \quad (6.8)$$

where Q_A is the average irrigation water quota [m³/mu], f_a is the farmland area [mu], T_{nl} is the total number of livestock [head], Q_L is the quota of water demand for livestock [l/head and day], I_{va} is the value added by industry [billion Yuan], WC_{Iva} is the water consumption per value added by industry [m³/10⁴Yuan], U_1 is the per capita urban domestic water consumption (including public water use, such as water used for construction and landscaping) [l/person and day], U_2 is the per capita rural domestic water consumption (including water used for the rural environment) [l/person and day], R_2 is the total population [million people] and r_u is the urbanization rate [%]. In order to obtain all of the parameters of water consumption for all sectors, the standards, planning and investigated values are compared with national standards and the local master plan (also see Figure 6-2).

6.2.2 Parameter determination for quota method

Having designed the quota method for water demand prediction in Urumqi, the parameters must be determined. The water use quota for each sector (the average irrigation water quota, the quota of water demand for livestock, the water consumption per value added by industry, the per capita urban domestic water consumption and the per capita rural domestic water consumption) can be obtained by analyzing the historical water data. The socio-economic development parameters (the farmland area, the value added by industry, the total number of livestock, the total population and the urbanization rate) can be obtained by analyzing the historical data and summarizing the national and regional standards and plans.

6.2.2.1 The average irrigation water quota (Q_A) and farmland area (f_a)

Because of the uneven temporal and spatial distribution of water resources in Urumqi, the spatial distribution of the arable land and agricultural production are characterized by the irrigated oasis agriculture (LI & YU 2008, 76). Agricultural water mainly refers to farming irrigation, forestry, animal husbandry, fisheries and rural drinking water (URUMQI SCIENCE & TECHNOLOGY BUREAU 2009). Agriculture is the largest water user with more than 60 % of the total water consumption in Urumqi and farming irrigation accounting for more than 90 % of the water consumption of agriculture.

The irrigation canals have become aged and badly damaged in the suburbs of Urumqi, therefore, the irrigation canals have a very high permeability (seepage loss) which has led to a low water efficiency of the canal system. Northern outskirts and districts are irrigation areas and the water efficiency of the canal system is up to 0.7. But it is only about 0.55 in Banfanggou and Shuixigou in southern outskirts, and is especially low in the Dabancheng District (ZHANG 2008, 62; WU & ZHOU 2011, 93). In addition, most of the agriculture is still using traditional and extensive flood irrigation methods because of the inefficient adjustment, single growth mode of agriculture and the low rate of application of water conservation irrigation technology. The highest irrigation quota even can reach up to 800-1000 m^3 /mu (YAO 2002, 32).

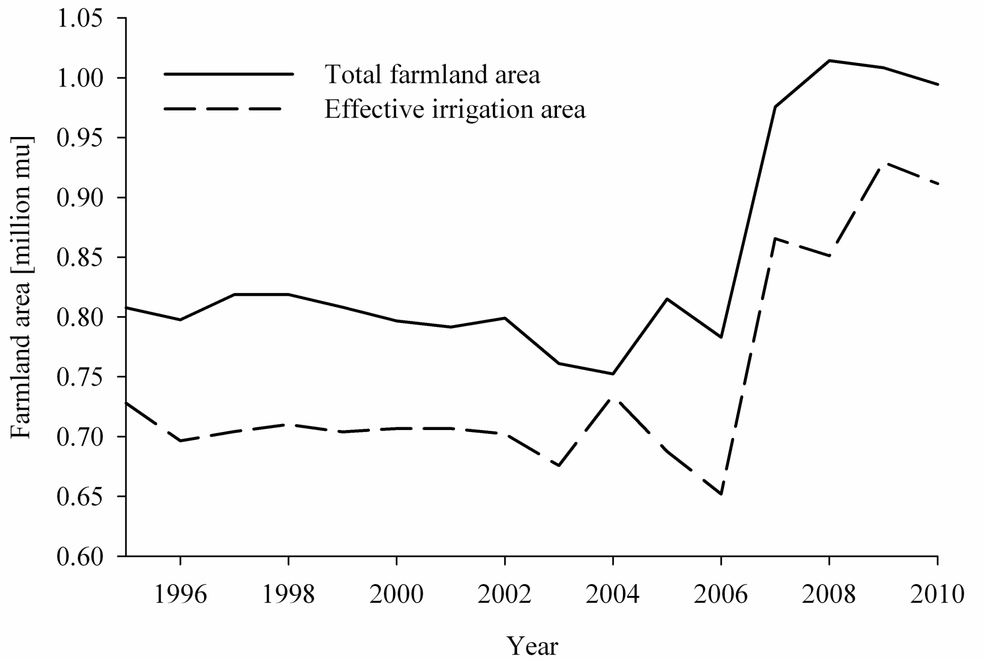


Figure 6-3 Farmland area and effective irrigation area in Urumqi 1995-2010 (source: STATISTICS BUREAU OF URUMQI 1996-2011; own design).

In the early stages of economic growth, the farmland area was decreasing (CHEN & GAO 2006, 2583). Indeed, the farmland area and effective irrigation area showed a declining trend from 1995 to 2006. With the maturation of socio-economic development, Urumqi's government vigorously implemented efficient agricultural water conservation projects; therefore, farmland area was on the increase from 2006 and then showed a tendency towards stabilization (see Figure 6-3). Based on the development trend of the farmland area, it will remain around 975,000 mu in 2015.

According to the predicted results in section 5.2.3, the average irrigation water quota (Q_A) will be 500-550 m³/mu. The maximum value (550 m³/mu) is selected as the average irrigation water quota in 2015 in order to determine the maximum water demand for agriculture.

6.2.2.2 Livestock water use quota (Q_L) and total number of livestock (T_{nl})

Forestry, animal husbandry and fishery water use includes water consumption for irrigable fruit-bearing forests, irrigable grasses, livestock and ponds (also see Figure 6-1). Only the water demand for livestock is considered in this thesis, since the water for livestock occupies the great majority of the water consumption of forestry, animal husbandry and fishery. In Urumqi the main animals are cows, horses, pigs and sheep. Sheep accounted for a relatively large proportion and showed an increasing trend, while the others tend to stay fairly stable (see Figure 6-4). Since the number of sheep is more than other livestock, the standard of the water consumed by sheep can be used to represent the average livestock water use quota. As mentioned in section 5.2.3, the average livestock water use quota (Q_L) will still stay around 10 l/head and day in 2015. The annual growth rate of livestock is 2.2 %. Therefore, in 2015 the total number of livestock (T_{nl}) will be 893,618 heads in Urumqi (STATISTICS BUREAU OF URUMQI 2011).

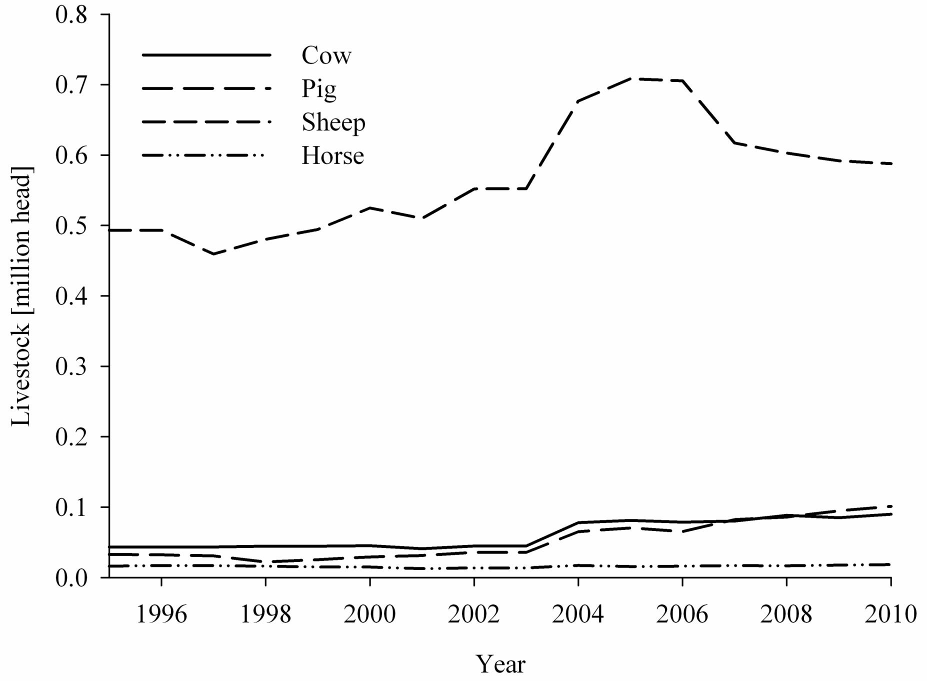


Figure 6-4 The species and number of livestock in Urumqi 1995-2010 (source: STATISTICS BUREAU OF URUMQI 1996-2011; own design).

6.2.2.3 Value added by industry (I_{va}) and water consumption per value added by industry (WC_{Iva})

As with the rapid development of China's western region, the economy of Urumqi has also increased significantly in recent years. Urumqi has a unique advantage in the quick opening-up and development of new industries. Government policies promote advanced manufacturing and modern services to foster the development of strategic emerging industries and upgrade traditional industries (URUMQI URBAN PLANNING BUREAU 2011). In Urumqi the value added by industry has accelerated exponentially. In 2010, the value added by industry was 50.8 billion Yuan, 12 % higher than in 2009. The average growth rate was 11 % from 1998 to 2010 (see Figure 6-5). According to the Urumqi Urban Master Planning, the value added by industry will be 122 billion Yuan in 2015 (URUMQI URBAN PLANNING BUREAU 2011). Water consumption per value added by industry has been analyzed in section 5.2.4 and it is predicted to be 22.5 $m^3/10^4$Yuan in 2015.

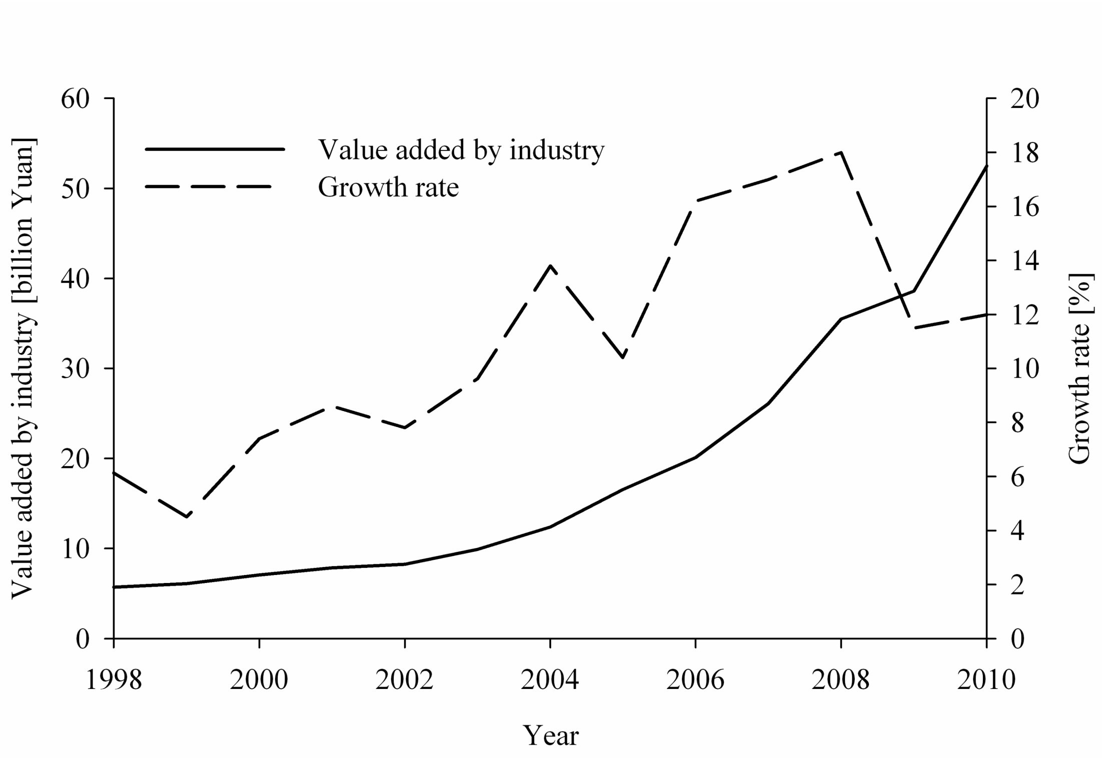


Figure 6-5 Value added by industry and its growth rate in Urumqi 1998-2010 (source: STATISTICS BUREAU OF URUMQI 1997–2011; own design).

6.2.2.4 Per capita urban domestic water consumption (U_1) and per capita rural domestic water consumption (U_2)

Per capita urban domestic water consumption (U_1) is the amount of water used in urban areas per person per day. It includes public water use, such as water used for construction and landscaping. Per capita rural domestic water consumption (U_2) is the amount of water used in rural areas per person per day. It includes water used for the rural environment. The tendency of per capita urban domestic water consumption (including water used for construction and landscaping) was not clear from 2004 to 2010. Per capita rural domestic water consumption (including rural environmental water use) increased year by year (see Figure 6-6).

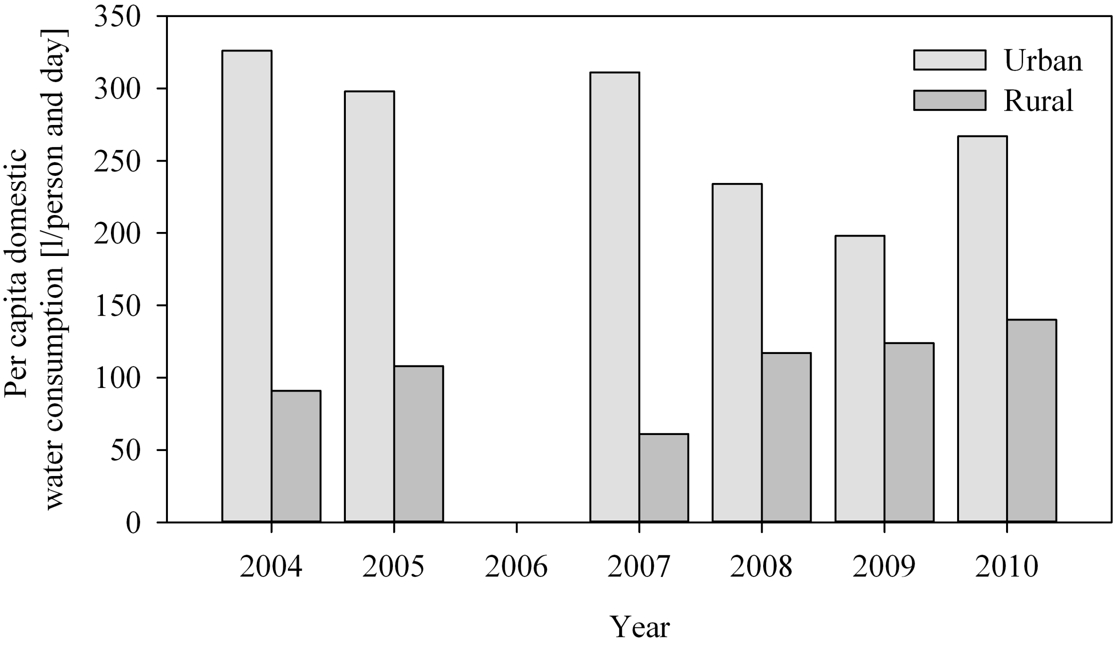


Figure 6-6 Urban and rural per capita domestic water consumption in Urumqi 2004-2010 (missing data for 2006) (source: WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; own design).

With more water being used in the public and environmental sectors, as well as the expansion of the urban population, the urban domestic water consumption will increase (section 5.2.2.2). Meanwhile, with the improvement of living conditions in rural areas, domestic water consumption in rural areas will also increase. However, due to plans to improve the water price for public water consumption, reduce the leakage rate of the pipe network, improve the popularization of water conservation appliances and promote public awareness on water conservation, the water quota of domestic use will decrease. According to the analysis results in section 5.2.2, the per capita urban domestic water consumption (including the public water consumption for construction and landscaping) will be 270 l/person and day and 120 l/person and day for rural areas.

6.2.2.5 The total population (R_2)

Due to a growing population, water is one of the relatively decreasing natural resources (FALKENMARK & WIDSTRAND 1992; ESCOS et al. 2008, 276; RAYER et al. 2009, 774). As the total population (R_2) continues to grow in Urumqi, domestic water consumption and industrial water consumption are increasing (see Figure 6-7).

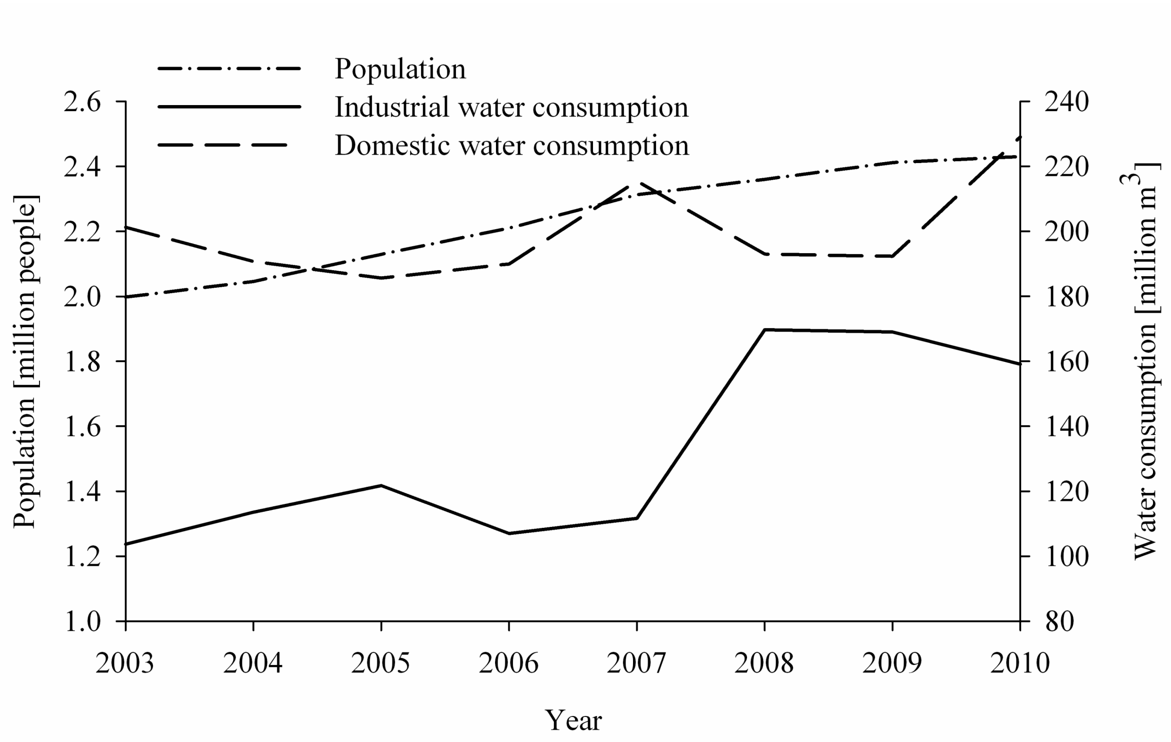


Figure 6-7 The total population and water consumption for domestic and industry in Urumqi 2003-2010 (source: STATISTICS BUREAU OF URUMQI 2011; WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; XIE et al. 2008, 1; own design).

Population is an important parameter for predicting the domestic water demand. According to the available data, the population could be analyzed and predicted by using mathematical models. The prediction results can directly determine the accuracy of water demand prediction. The common models for population prediction are the polynomial regression model, the malthusian growth model and the logistic model.

1. The polynomial regression model

Population changes are related to a variety of factors, such as natural resources, socio-economic development and urban infrastructure (ZHENG 2007, 78). All these factors are interrelated with each other. The polynomial regression model simply predicts population by studying the correlations between population and these factors. In the polynomial regression model, there is only one dependent variable and several independent variables. The changes of the dependent variable can be explained by several independent variables and the polynomial regression equation is expressed as follows:

$$Y = a_0 + a_1 X + a_2 X^2 + \cdots + a_i X^i + \varepsilon \quad \text{(FARAWAY 2002, 100)} \tag{6.9}$$

where Y is the dependent variable, X is the independent variables, a_i (i = 1, 2, ..., n) is the regression coefficient and ε is the error variable. Using the least square method to make polynomial fitting for the total population in Urumqi from 1949 to 2010, the expression of total population with time (R^2 (the goodness of fit) = 0.9928) is as follows:

$$Y = 1.77*10^{-9}X^5 + 7.725*10^{-8}X^4 - 1.782*10^{-5}X^3 + 4.935*10^{-4}X^2 + 0.0332X + 0.00338 \tag{6.10}$$

2. The malthusian growth model

The malthusian growth model was introduced by MALTHUS (1798). It is an exponential growth model and assumes that the population growth rate is a constant. The equation of malthusian growth model is written as follows:

$$x(i) = x_0 e^{\varphi_i} \quad \text{(JIN et al. 2012, 91)} \tag{6.11}$$

where x_0 is the initial population, φ is the growth rate and i is the time.

The input data is the total population from 1949 to 2010. Using Matlab, the equation of the malthusian growth model can be rewritten below:

$$x(i) = e^{-59.4872+0.0301\mathrm{i}} \tag{6.12}$$

3. The logistic model

The logistic model is a restricted growth model. It is an improved Malthusian growth model and was first proposed by VERHULST (1845). In this model, the environment can restrict population. Population will not grow to an unlimited size, but will eventually slow towards a constant (TSOULARIS 2001, 23). The logistic model is expressed as follows:

$$y = \frac{x_m}{1 + (\frac{x_m}{x_0} - 1)e^{-U_r t}} \quad \text{(WANG 2012, 202)} \tag{6.13}$$

where $x_0 = x(0)$, x_m is the maximum population allowed by environment, t is the time and U_r is an unknown parameter.

The analytical solution of logistic equation is shown below:

$$y = \frac{1}{\frac{1}{x_m} + e^{(a_a + b_b t)}} \tag{6.14}$$

where a_a and b_b are unknown parameters, and t is the time.

The input data is the total population from 1949 to 2010. When the maximum population allowed by the environment in Urumqi is assumed as 5 million, the logistic model for the total population can be rewritten as follows with Matlab (URUMQI URBAN PLANNING BUREAU 2011):

$$y = \frac{1}{5^{-1} + e^{-75+0.038t}} \tag{6.15}$$

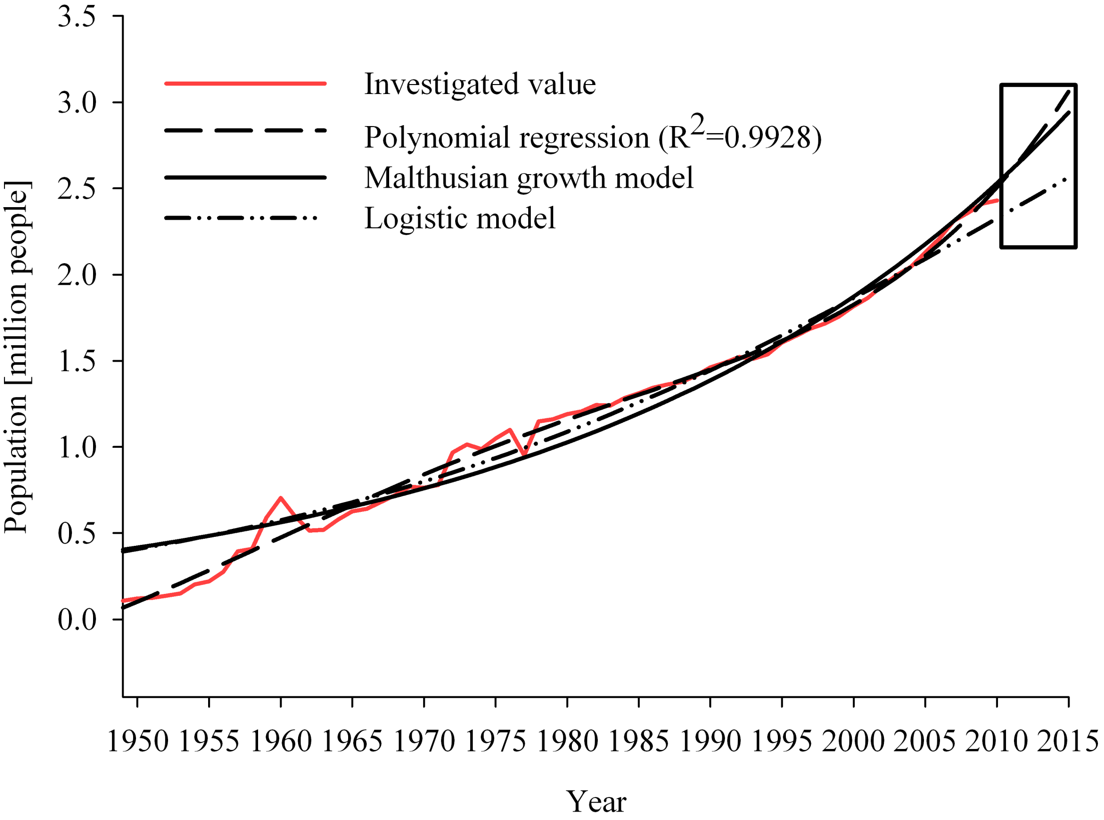


Figure 6-8 The investigated values and predicted values for the total population with three models (source: own calculations; investigated values: STATISTICS BUREAU OF URUMQI 2011).

According to equations (6.10), (6.12) and (6.15), the total population in Urumqi can be simulated and predicted (see Table A-6 in Appendix A.2). In the black box of Figure 6-8, the predicted values of the three models for the total population after 2010 are shown. Because the growth of the predicted results of the polynomial regression model is too fast and the growth of the predicted results of the logistic model is too slow, the predicted results for the malthusian growth model is in the confidence interval. Therefore, there would be a population of more than 2.9 million in 2015.

6.2.2.6 Urbanization rate (r_u)

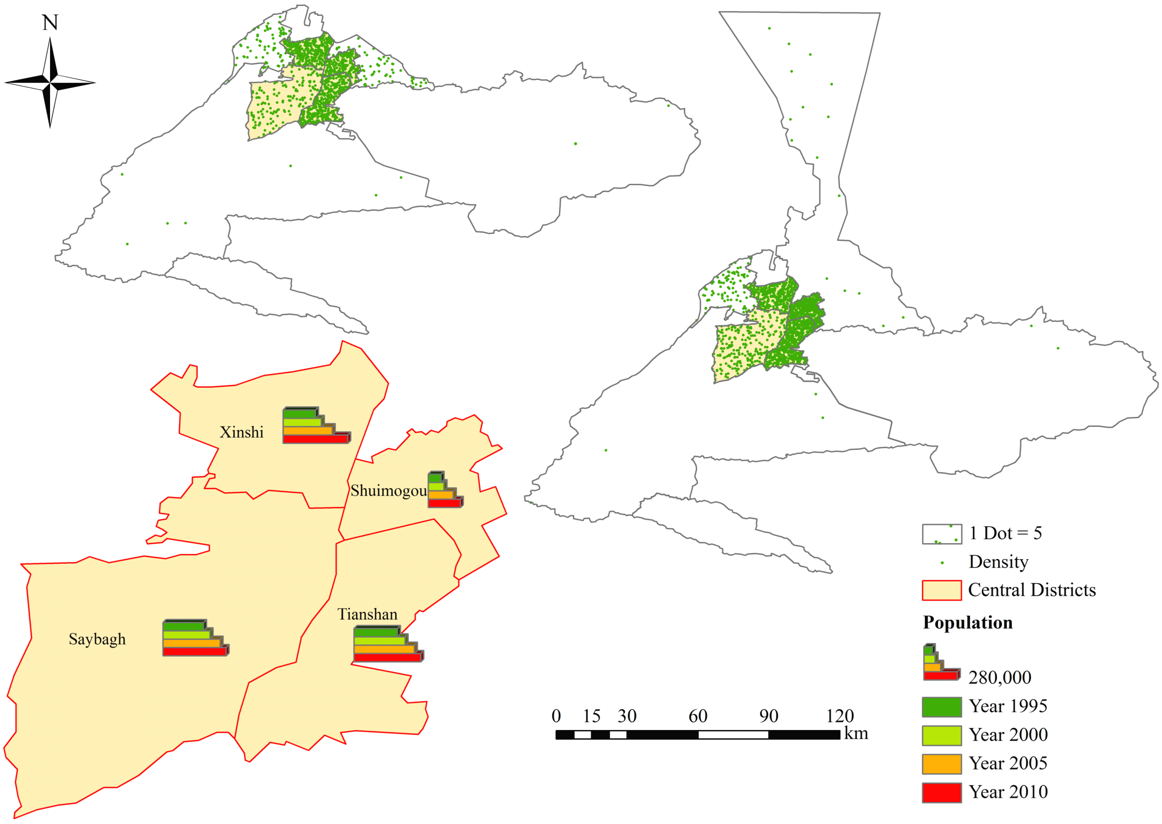


Figure 6-9 The development of the districts' population 1995-2010 (In 2007, Miquan City and Dongshan District were united and now make up Midong District, which belongs to Urumqi) (source: AUTONOMOUS REGION BUREAU OF SURVEYING AND MAPPING 2004; STATISTICS BUREAU OF URUMQI 1996, 2001, 2006 and 2011; own design).

The urbanization rate is the ratio of the urban population to the total population (XU et al. 2009, 23). It can be used as an urbanization index. It is an important symbol of the economic development of a region (NIU & WANG 2012, 86). It is also used to reflect the aggregation of population moving to the cities. From 1995 to 2010, there was an obvious change in population in each district in Urumqi. The change in population density in 1995 and 2010 showed the true nature of population concentration in central districts (Xinshi District, Shuimogou District, Tianshan District and Saybagh District). Furthermore, the populations in these districts showed a stepwise growth from 1995 to 2010 (see Figure 6-9). The increase of the urban population will lead to an increase in residential water consumption. Urbanization is a complex dynamic process, which may influence the amount of domestic water consumption and water quality (WANG & WU 2009, 177). NORTHAM (1979) put forward the theory that the urbanization process could be divided into three stages. The first stage is the initial stage of urbanization, in which the urbanization rate is low and the development of urbanization is slow. The second stage is the acceleration phase of urbanization, in which the population flocks to the city much faster than in the first stage and the urbanization rate is high. The third stage is the mature stage of urbanization, where the level of urbanization is very high and urban populations increase slowly or even stagnate. The rate of urbanization in Urumqi showed two stages between 2003 and 2010 (see Figure 6-10).

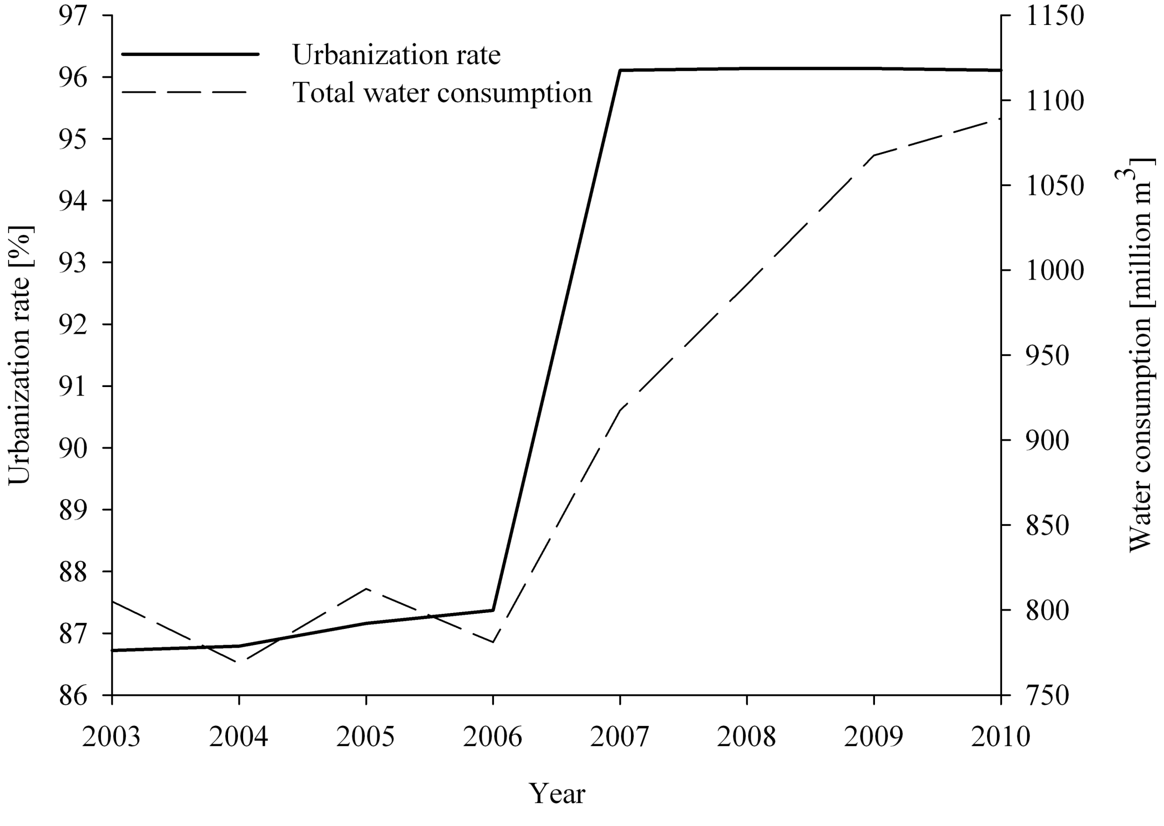


Figure 6-10 The relationship between the urbanization rate and total water consumption from 2003 to 2010 (urbanization rate: the ratio of the urban population to the total population) (source: STATISTICS BUREAU OF URUMQI 2004-2011; WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; XIE et al. 2008, 1; own design).

The first stage was from 2003 to 2006, in which the urbanization rate was about 87 % and showed an upward trend. The second stage was from 2007 to 2010, in which the average urbanization rate was about 96 %. The main reason for this phenomenon is that Miquan City was merged into Urumqi to form Midong District in 2007. Overall, the urbanization rate of Urumqi was relatively high and has increased slowly since 2007, which means Urumqi's urbanization has entered a mature stage (NI & YANG 2005, 17). According to the Urumqi Urban Master Planning, the urbanization rate in 2015 will be 94.5 % (URUMQI URBAN PLANNING BUREAU 2011). In addition, with the change in the urbanization rate, the total water consumption increased from 2003 to 2010. The tendency of total water consumption is roughly the same as the trend of the urbanization rate (also see Figure 6-10). The total water consumption will increase due to the higher rate of urbanization. However, there is a relationship not only between total water consumption and the urbanization rate, but also with water supply facilities, public awareness for water conservation, water resources and climate change. Therefore, although the urbanization rate will decline, the total water consumption will increase due to the increasing total population, the unimproved water supply facilities and the poor public awareness for water conservation (mentioned in section 5.3.1).

6.2.3 Water demand results of the quota method

After determining the water use quota for each sector (the average irrigation water quota, the quota of water demand for livestock, the water consumption per value added by industry, the per capita urban domestic water consumption and the per capita rural domestic water consumption) and the socio-economic development parameters (the farmland area, the value added by industry, the total number of livestock, the total population and the urbanization rate), the water demand was calculated using Matlab according to the equation (6.8) and presented in Table 6-2. Based on the prediction results, from 2004 to 2015 Urumqi's water demand increased from 768.55 million m^3 to 1095.94 million m^3. Agriculture will still be the major water user, but the proportion of agricultural water demand in relation to the total water demand will be reduced. As mentioned in section 5.2.3, there is a great potential for making water saving in the agricultural sector. By improving the water efficiency of the canal system, using advanced water-saving irrigation techniques, increasing water-saving in the irrigation area and improving the water price for agricultural irrigation, it is possible to decrease the proportion of the agricultural water demand. Because of population growth, the continued growth of public water use and environmental water use, domestic water demand will increase and become the second largest water user. Meanwhile, due to the continuous expansion of industry in Urumqi, industrial water demand will also increase. However, the value added by industry is higher and the water consumption per value added by industry is lower, meaning that there is a great industrial cost-efficiency. By adjusting industrial structures, which can be achieved by developing high standards of environmental protection requirements to limit or control the discharge of industrial wastewater, developing high-tech industries and advanced technology to improve traditional industries, raising the price of fresh water withdrawals and the costs of wastewater discharges according to water quality resentments in different industries and contents in industrial wastewater, improving industrial facilities and implementing advanced measures (mentioned in section 4.5.5), the industrial efficiency of water consumption in 2015 will be greatly improved.

The results for the predicted water demand as calculated by the quota method are compared with the results predicted by the grey model under the premise of the current water conservation facilities in section 6.4.

Table 6-2 The investigated water demand of Urumqi 2004-2010 and the predicted water demand of Urumqi in 2015 (source: 2004, 2005, 2007, 2008, 2009 and 2010: WATER AFFAIRS BUREAU OF URUMQI 2004, 2005, 2007, 2008, 2009 and 2010; 2006: XIE et al. 2008, 1; 2015: own calculations according to the investigated values from 2004 to 2010).

Year	Water demand						
	Agriculture		Industry		Domestic sector		Total
2004	464.27	60.4%	113.51	14.7%	190.77	24.8%	768.55
2005	505.11	62%	121.70	15%	185.63	23%	812.45
2006	484	62%	107	13.7%	190	24.3%	781
2007	590.15	64%	111.65	12%	215.41	24%	917.27
2008	628.87	63%	169.71	17%	193.05	20%	991.63
2009	706.18	66%	169.04	16%	192.35	18%	1067.57
2010	701.11	64.4%	159.09	14.6%	229.11	21%	1089.31
2015	539.51	49.23%	275.5	25.14%	280.93	25.63%	1095.94

6.3 The grey model

When a system related to time includes both certain and uncertain information within a certain range, the grey model could be used to analyze this system (HAN & XU 2007a, 18). The characteristics of the grey model are introduced in section 6.3.1. When the grey model is used for water demand prediction, the influencing factors of water demand and the relationship among the influencing factors in the water demand system do not need to be considered. The useful information can be obtained from water consumption time sequences (total water consumption, agricultural water consumption, industrial water consumption and domestic water consumption).

The grey model for water demand is designed according to the useful information (section 6.3.2), which is used to predict total water demand and the individual water demands of agriculture, industry and the domestic sector (section 6.3.3).

6.3.1 Introduction of the grey model

The grey system theory was proposed by DENG (1988), which was then further developed and used as the key theory to build the grey model (DENG et al. 1999). The grey model (GM) can be used to make predictions and decisions, as well as for making evaluations, control planning and system analyses. It has been applied in different domains, such as airline city traffic (HSU & WEN 2000, 47), lifetime (CHIAO & WANG 2002, 127), output values (LIN & YANG 2003, 177), power demand (HSU & CHEN 2003, 2241), urban water consumption (LOU et al. 2005,11), urban water demand (REN 2007, 52), social security levels (DUAN & LIN 2007, 13), pore pressure (MOHAMMED et al. 2010, 1523) and wireless communication (AMANNA et al. 2011, 259). The grey model is especially well suited to systems which have short time series, and in which information is not complete.

The grey model (1, 1) is one of the most common grey models and is known as the "Grey model First Order One Variable" (KAYACAN et al. 2010, 1785). It consists of a one-order differential equation which contains only a single variable based on the short time series (LOU et al. 2005, 12; REN 2007, 53; TSAUR 2008, 1106; MILOJKOVIC et al. 2011, 184). JIANG & FU (1990) used water demand for a ten thousand Yuan output value to establish the grey model (1, 1) and to predict industrial water consumption. LOU et al. (2005) built a grey model (1, 1) to forecast urban water consumption according to the annual water supply, GDP and population. The grey model (1, 1) can also be used to predict the annual water demand directly by using annual water consumption (REN 2007, 51; CHEN 2007, 17; WU 2007b, 90; JIANG et al. 2011, 50). The grey model (1, 1) has also been used to forecast domestic water demand, industrial water demand and agricultural water demand, respectively. The advantage of this method is that the predicted value can be compared with the actual data. The results can reflect the trends of domestic, industrial and agricultural water demand and provide possible solutions for decision-makers (WANG et al. 2010b, 9; DA et al. 2010, 19).

The characteristics of the grey model are as follows (YANG 2000, 1):

1. The modeling requires less information and it can process less data.
2. It is necessary to know the priori characteristics of the distribution of the original data.
3. The model is highly accurate as it can maintain the characteristics of the original system and reflect the actual situation of the system.

   The grey model can identify different tendencies of development (association analysis) among system factors and also find out the law of the system by processing the original data. Based on the generated regulatory sequence and differential equation, the grey model can be used to predict the development trend of water demand in Urumqi.

6.3.2 Design of the grey model

The grey model makes predictions based on the law of the development of time series data (JIANG et al. 2011, 50). Supposing there is a sequence of time-dependent data $X^{(0)} = \{X^{(0)}(1), X^{(0)}(2),..., X^{(0)}(n)\}$ (n is the size of the sequence) (cf. DA et al. 2010, 19), there are four steps to designing the grey model (see Figure 6-11).

1. Creating a sequence of first-order accumulated generating operation (AGO)

   $X^{(1)}$ is defined as $X^{(0)}$'s first-order accumulation generating operation and it is can be written as follows (KAYACAN et al. 2010, 1786):

$$X^{(1)} = \{X^{(1)}(1), X^{(1)}(2), \ldots, X^{(1)}(n)\} = (\sum_{k=1}^{1} X^{(0)}(k), \sum_{k=1}^{2} X^{(0)}(k), \cdots, \sum_{k=1}^{n} X^{(0)}(k)) \quad (6.16)$$

   Where

$$X^{(1)}(1) = X^{(0)}(1) \text{ (KAZEMI et al. 2011, 14)} \quad (6.17)$$

$$X^{(1)}(2) = X^{(0)}(1) + X^{(0)}(2) \text{ (KAZEMI et al. 2011, 14)} \quad (6.18)$$

$$X^{(1)}(i) = \sum_{n=1}^{i} X^{(0)}(n) \text{ (KAYACAN et al. 2010, 1786)} \quad (6.19)$$

   where $X^{(0)}(i)$ is the i-th data in the original sequence and $X^{(1)}(i)$ is the i-th data in the accumulated sequence.

2. Mean sequence and differential equation

$Z^{(1)}(i)$ is the mean value of adjacent data and it can be written with the following equation:

$$Z^{(1)}(i)=\frac{X^{(1)}(i)+X^{(1)}(i-1)}{2} \quad (i=(1,2,\ldots,n)) \text{ (DENG 1988)} \qquad (6.20)$$

The difference equation of the grey model (1, 1) is defined as follows:

$$X^{(0)}(n)+aZ^{(1)}(n)=u \text{ (KAYACAN et al. 2010, 1786)} \qquad (6.21)$$

where a and u are grey parameters requiring determination, a is a system developing parameter and u is grey action quantity, while i is the independent variables in the system.

Therefore the whitening equation is written as a function:

$$\frac{dX^{(1)}}{di}+aX^{(1)}=u \text{ (KAYACAN et al. 2010, 1786)} \qquad (6.22)$$

$\hat{a}$ *is* a parameter vector to be estimated and it can be expressed as follows:

$$\hat{a}=\begin{pmatrix} a \\ u \end{pmatrix} \text{ (DA et al. 2010, 20)} \qquad (6.23)$$

The values of a and u can be determined by the ordinal least square estimate sequence of the difference equation (6.22) as follows:

$$\hat{a}=\left(M^{T}M\right)^{-1}M^{T}X=\begin{bmatrix} a \\ u \end{bmatrix} \text{ (HAN \& XU 2007a, 19)} \qquad (6.24)$$

Furthermore, the accumulated matrix M and the constant vector X are expressed as below:

$$M=\begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(1)}(n) & 1 \end{bmatrix} \text{ (KAYACAN et al. 2010, 1786)} \qquad (6.25)$$

$$X=\begin{bmatrix} X^{(0)}(2) \\ X^{(0)}(3) \\ \vdots \\ X^{(0)}(n) \end{bmatrix} \text{ (SUN \& LIN 2009, 356)} \qquad (6.26)$$

If the data set starts at time $i = 1$, then the equation (6.23) can be expressed as follows:

$$\begin{bmatrix} X^{(0)}(2) \\ X^{(0)}(3) \\ \vdots \\ X^{(0)}(n) \end{bmatrix} = \begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(1)}(n) & 1 \end{bmatrix} \begin{bmatrix} a \\ u \end{bmatrix} \text{(WANG et al. 2010b, 10)} \qquad (6.27)$$

According to the equations (6.20), (6.21), (6.22), (6.23), (6.24), (6.25), (6.26) and (6.27), the solution of $X^{(1)}(i)$ at time k is expressed as follows:

$$\hat{X}^{(1)}(k+1) = \left[X^{(0)}(1) - \frac{u}{a} \right] \times e^{-ak} + \frac{u}{a} \; (k = 1, 2, ..., n) \text{ (WANG et al. 2010b, 10)} \qquad (6.28)$$

3. Model test

The accuracy of the model can be tested in three different ways (the residual test, the relational coefficient test and the posteriori error test).

(1) Residual test

According to the equation (6.28), $\hat{X}^{(1)}(i)$ is calculated and the IAGO (inverse accumulated operation) is obtained $\hat{X}^{(0)}(i)$. The absolute error sequence ($\Delta^{(0)}(i)$) and the relative error sequence ($\varnothing(i)$) of the original sequence $X^{(0)}(i)$ and the IAGO $\hat{X}^{(0)}(i)$ are as follows:

$$\Delta^{(0)}(i) = \left| X^{(0)}(i) - \hat{X}^{(0)}(i) \right| \; (i = 1, 2, \ldots, n) \text{ (cf. SUN \& LIN 2009, 357)} \qquad (6.29)$$

$$\phi(i) = \frac{\Delta^{(0)}(i)}{X^{(0)}(i)} \times 100\% \; (i = 1, 2, \ldots, n) \text{ (cf. SUN \& LIN 2009, 357)} \qquad (6.30)$$

The average relative error can be expressed as follows:

$$\phi(avg) = \frac{1}{n} \sum_{i=1}^{n} \left| \phi(i) \right| \text{ (ZHAO et al. 2011, 129)} \qquad (6.31)$$

According to the average relative error, the model accuracy can be obtained. The smaller the average relative error, the better the accuracy of the model. When the average relative error is less than 10 %, then the accuracy of the model is larger than 90 % (see Table 6-3).

Table 6-3 The average relative error and the accuracy of the grey model (source: SHEN 2007, 34).

Level	$\varnothing(avg)$
Good	<20 %
Best	<10 %

(2) Relational coefficient test

The association coefficient of the original sequence $X^{(0)}(i)$ and the IAGO $\hat{X}^{(0)}(i)$ can be expressed as follows:

$$\vartheta(i)=\frac{\min\min\left|\hat{X}^{(0)}(i)-X^{(0)}(i)\right|+\rho\max\max\left|\hat{X}^{(0)}(i)-X^{(0)}(i)\right|}{\left|\hat{X}^{(0)}(i)-X^{(0)}(i)\right|+\rho\max\max\left|\hat{X}^{(0)}(i)-X^{(0)}(i)\right|}\quad \text{(ZHANG et al. 2011a, 925)(6.32)}$$

where min min $|\hat{X}^{(0)}(i)$ - $X^{(0)}(i)|$ is the minimum variance, max max $|\hat{X}^{(0)}(i)$ - $X^{(0)}(i)|$ is the maximum variance, $|\hat{X}^{(0)}(i)$ - $X^{(0)}(i)|$ is the absolute error for $X^{(0)}$ and $\hat{X}^{(0)}$ at time i. ρ is called the distinguished coefficient and falls between 0 and 1; it is thus generally taken as 0.5.

The relational degree (τ) of $X^{(0)}(i)$ and $\hat{X}^{(0)}(i)$ can be deformed as below:

$$\tau=\frac{1}{n}\sum_{i=1}^{n}\vartheta(i)\quad \text{(FENG 1998, 346)} \qquad (6.33)$$

When τ is greater than or equal to 60 %, the accuracy of the model is credible. When τ is greater than or equal to 50 %, the model is reliable.

(3) Posteriori error test

The standard deviation of the original sequence (S_1) and the standard deviation of the absolute error sequence (S_2) can be calculated and expressed as follows:

$$S_1=\sqrt{\frac{\sum\left[X^{(0)}(i)-\overline{X}^{(0)}\right]^2}{n-1}}\quad \text{(SHEN 2007, 34)} \qquad (6.34)$$

$$S_2=\sqrt{\frac{\sum\left[\Delta^{(0)}(i)-\overline{\Delta}^{(0)}\right]}{n-1}}\quad \text{(SHEN 2007, 34)} \qquad (6.35)$$

where $\Delta^{(0)}(i)$ is the absolute error sequence of the original sequence $X^{(0)}(i)$ and the IAGO $\hat{X}^{(0)}(i)$, and $\dot{\Delta}^{(0)}(i)$ is the relative error sequence of the original sequence $X^{(0)}(i)$ and the IAGO $\hat{X}^{(0)}(i)$.

The variance ratio (V_r) is the ratio of the original sequence (S_1) and the standard deviation of the absolute error sequence (S_2). The variance ratio (V_r) and the error probability ($Ø(prob)$) can be expressed as follows:

$$V_r=\frac{S_2}{S_1}\quad \text{(HUI et al. 2009, 524)} \qquad (6.36)$$

$$\phi(prob)=P\left\{\left|\Delta_{(i)}^{(0)}-\overline{\Delta}^{(0)}\right|<0.6745S_1\right\}\text{(HUI et al. 2009, 524)} \qquad (6.37)$$

where $e_i = |\Delta^{(0)}(i)$ - $\dot{\Delta}^{(0)}(i)|$ and $S_0 = 0.6745S_1$.

If the variance ratio is less than 0.35 and the error probability is greater than 0.95, the accuracy of the model is best. If the variance ratio is equal to or greater than 0.65 and the error probability is equal to or less than 0.7, this means that the accuracy of the model is bad (see Table 6-4).

Table 6-4 The criteria for the variance ratio (V_r) and the error probability (*Ø*(*prob*)) of the grey model (source: SHEN 2007, 34).

Ø(*prob*)	V_r	Model accuracy
> 0.95	< 0.35	Best
> 0.80	< 0.50	Better
> 0.70	< 0.65	Good
≤ 0.70	≥ 0.65	Bad

4. Residual modification

If the accuracy of the grey model (1, 1) is bad, it can be corrected using residual modification. According to equation (6.28), the predicted value of $X^{(1)}$ can be obtained. The residual series can be thus defined as:

$$e^{(0)}(j) = X^{(1)}(j) - \hat{X}^{(1)}(j) \quad \text{(MOSTAFAEI \& KORDNOORI 2011, 97)} \qquad (6.38)$$

If $j = i$, i+1, ..., n, the corresponding residual series can be written as follows:

$$e^{(0)}(k) = \left\{e^{(0)}(1), e^{(0)}(2), \ldots, e^{(0)}(n)\right\} \quad \text{(MOSTAFAEI \& KORDNOORI 2011, 97)} \qquad (6.39)$$

Where

$$\varepsilon^{(0)}(k) = \left|e^{(0)}(k)\right| \quad \text{(HSU \& CHEN 2003, 2244)} \qquad (6.40)$$

According to the equations (6.16)-(6.28), a grey model (1, 1) of the generated residual sequence can be established as:

$$\overset{\wedge}{\varepsilon}^{(1)}(k) = (1 - e^{a_\varepsilon})\left[\varepsilon^{(0)}(1) - \frac{u_\varepsilon}{a_\varepsilon}\right] e^{-a_\varepsilon(k-1)} \quad \text{(HSU \& CHEN 2003, 2244)} \qquad (6.41)$$

where a_ε, u_ε can be estimated by using the method of least square.

If the value of the k-th data residual of the model is positive, the sign of k-th data residual is in state 1. Otherwise, the sigh of k-th data residual is in the state 2. Assuming that H is a one-step transition probability which is associated with each possible transition for state i to state j (i, j = 1, 2), H can be estimated using the following equation:

$$H_{ij} = N_{ij} / N \quad \text{(MOSTAFAEI \& KORDNOORI 2011, 97)} \qquad (6.42)$$

where N_i is the number of years whose residuals are in state i, N_{ij} is the number of transitions from state i to state j that have occurred.

These one step transition probabilities (H_{ij}) can be expressed using the transition matrix HH as follows:

$$HH = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \text{ (HSU \& CHEN 2003, 2244)} \tag{6.43}$$

The initial state distribution is expressed by the vector $TP^{(0)} = [TP^{(0)}{}_1, TP^{(0)}{}_2]$, where $TP^{(0)}{}_1$ is the transition possibility of state 1 and $TP^{(0)}{}_2$ is the transition possibility of state 2.

The state possibility vector of the (i+1)-th step of transformation after the initial state can be calculated by using the following equation:

$$TP^{(i+1)} = TP^{(0)} HH^{(i+1)} \text{ (MOSTAFAEI \& KORDNOORI 2011, 98)} \tag{6.44}$$

where $TP^{(i)}$ are the k-th step residual state probabilities.

A correction of the grey model can be rewritten as follows (MOSTAFAEI & KORDNOORI 2012, 100):

$$\hat{X}_r^{(1)}(k) = \hat{X}_0^{(0)}(k) + \delta(k)(1 - e^{a_\varepsilon})\left[\hat{\varepsilon}^{(0)}(1) - \frac{u_\varepsilon}{a_\varepsilon}\right] e^{-a_\varepsilon(k-1)} \tag{6.45}$$

where $\delta(k)$ is the correction parameter. When $TP^{(i+1)}{}_1$ is greater than $TP^{(i+1)}{}_2$, $\delta(i+1)$ is equal to 1. When $TP^{(i+1)}{}_1$ is less than $TP^{(i+1)}{}_2$, $\delta(i+1)$ is equal to -1.

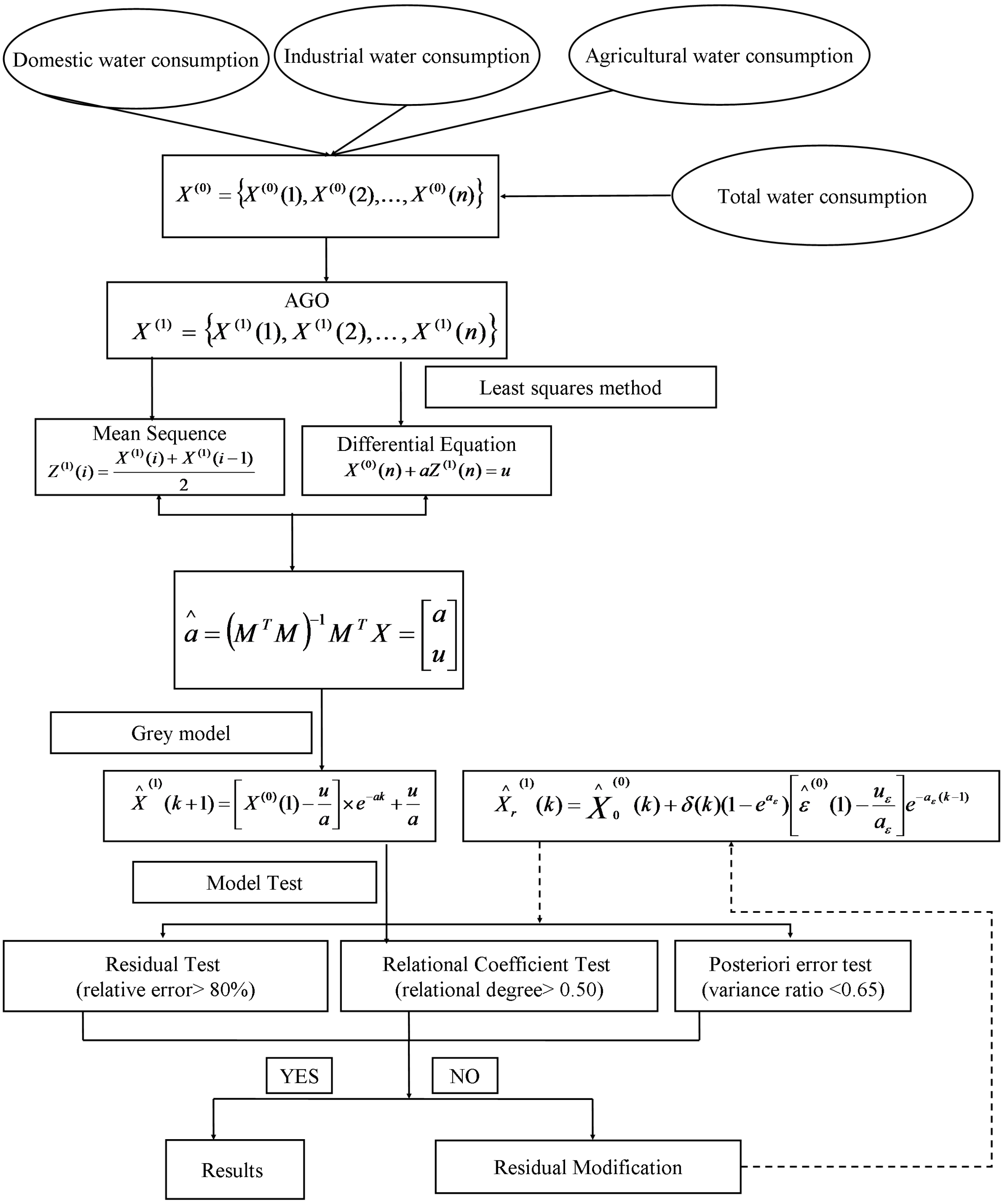


Figure 6-11 The grey model process for water demand prediction in Urumqi (source: own design).

6.3.3 Water demand results of the grey model

This research uses the data from the Water Affairs Bureau of Urumqi City (WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010) and XIE et al. (2008). The data include total water consumption, agricultural water consumption, industrial water consumption and domestic water consumption from 2003 to

2010, which are used as the original sequence. Water demand for agriculture, industry and the domestic sector can be predicted by the grey model (1, 1). After the accumulated generating operation the following sequence $X^{(1)}$ can be obtained and shown in Table 6-5.

Table 6-5 The original sequences and the sequences of first-order accumulated generating operation for agricultural water consumption, industrial water consumption, domestic water consumption and total water consumption ($A^{(0)}$: the original sequence for agricultural water consumption; $I^{(0)}$: the original sequence for industrial water consumption; $D^{(0)}$: the original sequence for domestic water consumption; $T^{(0)}$: the original sequence for total water consumption; $A^{(1)}$: the sequences of first-order accumulated generating operation for agricultural water consumption; $I^{(1)}$: the sequences of first-order accumulated generating operation for industrial water consumption; $D^{(1)}$: the sequences of first-order accumulated generating operation for domestic water consumption; $T^{(1)}$: the sequences of first-order accumulated generating operation for total water consumption) (source: $A^{(0)}$, $I^{(0)}$, $D^{(0)}$, $T^{(0)}$: XIE et al. 2008, 1; WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010; $A^{(1)}$, $I^{(1)}$, $D^{(1)}$, $T^{(1)}$: own calculations).

Year	$A^{(0)}$ (Agriculture)	$A^{(1)}$ (Agriculture)	$I^{(0)}$ (Industry)	$I^{(1)}$ (Industry)	$D^{(0)}$ (Domestic sector)	$D^{(1)}$ (Domestic sector)	$T^{(0)}$ (Total)	$T^{(1)}$ (Total)
2003	500.1	500.1	103.67	103.67	201.25	201.25	805.02	805.02
2004	464.27	964.31	113.51	217.18	190.77	392.02	768.55	1573.57
2005	505.11	1469.48	121.70	338.88	185.63	577.65	812.44	2386.01
2006	484	1953.48	107	445.88	190	767.65	781	3167.01
2007	590.15	2543.63	111.65	557.53	215.47	983.12	917.27	4084.28
2008	628.87	3172.5	169.71	727.24	193.05	1176.17	991.63	5075.91
2009	706.18	3878.68	169.04	896.28	192.35	1368.52	1067.57	6143.48
2010	701.11	4579.79	159.09	1055.37	229.11	1597.63	1089.31	7232.79

According to the equation (6.28), the system developing parameter (a) and the grey action quantity (u) for agricultural water demand, industrial water demand, domestic water demand and total water demand can be obtained separately as follows:

a(Agriculture) = -0.0772, u(Agriculture) = 400.5280

a(Industry) = -0.0784, u(Industry) = 93.8282

a(Domestic sector) = -0.0239, u(Domestic sector) = 178.4222

a(Total) = -0.06597, u(Total) = 668.987

Therefore, the time response sequence for agricultural water demand, industrial water demand, domestic water demand and total water demand can be written as follows:

$$\hat{A}^{(1)}(k+1) = 5686.2982 \times e^{0.07723k} - 5186.1982 \tag{6.46}$$

$$\hat{I}^{(1)}(k+1) = 1300.7742 \times e^{0.078379k} - 1197.1042 \tag{6.47}$$

$$\hat{D}^{(1)}(k+1) = 7661.9751 \times e^{0.023915k} - 7460.7251 \tag{6.48}$$

$$\hat{T}^{(1)}(k+1) = 10945.8358 \times e^{0.065597k} - 10140.8158 \tag{6.49}$$

After the prediction models for agricultural water demand, industrial water demand, domestic water demand and total water demand have been built, the model accuracy can be tested by residual tests, relational coefficient tests and posteriori error tests according to equations (6.31), (6.33), (6.36) and (6.37), respectively. Then the average absolute error ($\varnothing(avg)$), the relational degree (τ), the variance ratio (V_r) and the error probability ($\varnothing(prob)$) can be obtained.

Table 6-6 The average absolute error ($\varnothing(avg)$) and the corresponding model accuracy for agricultural water demand, industrial water demand, domestic water demand and total water demand in Urumqi (source: own calculations).

Parameters	$\varnothing(avg)$ [%]			
	Agriculture	Industry	Domestic sector	Total
Values	3.26< 10	9.60 < 10	4.49 <10	2.64 < 10
Model accuracy	Best	Best	Best	Best

Table 6-7 The relational degree (τ) and the corresponding model accuracy for agricultural water demand, industrial water demand, domestic water demand and total water demand in Urumqi (source: own calculations).

Parameters	τ [%]			
	Agriculture	Industry	Domestic sector	Total
Values	63.50 ≥ 60	55.07 ≥ 50	54.70 ≥ 50	66.32 ≥ 60
Model accuracy	Credible	Reliable	Reliable	Credible

The value of the average absolute error ($\varnothing(avg)$) of the prediction models for agricultural water demand, industrial water demand, domestic water demand and total water demand l is less than 10 %, which means the accuracy of the three models is best (see Table 6-6). The value of the relational degree (τ) of prediction models for industrial water demand and domestic water demand is larger than 50 %, which means the model accuracy is reliable. For agricultural water consumption and total water demand it is larger than 60 %, which means the model accuracy is credible (see Table 6-7). The value of the variance ratio (V_r) for agricultural water demand, industrial water demand and total water demand is less than 0.35, which means the model accuracy is best. For domestic water demand it is less than 0.5, which means the model accuracy is better (see Table 6-8).

Table 6-8 The variance ratio (V_r), the error probability (Ø($prob$)) and the corresponding model accuracy for agricultural water demand, industrial water demand, domestic water demand and total water demand in Urumqi (source: own calculations).

Parameters	V_r				Ø($prob$)			
	Agriculture	Industry	Domestic sector	Total	Agriculture	Industry	Domestic sector	Total
Values	0.17<0.35	0.29<0.35	0.435<0.50	0.16<0.35	100>0.95	100>0.95	100>0.95	100>0.95
Model accuracy	Best	Best	Better	Best	Best	Best	Best	Best

The model tests prove that the grey model for agriculture, industry and the domestic sector is very precise and the predicted value can be obtained. The total water demand in 2015 is predicted to be 1542.23 million m³. The predicted agricultural water demand is 1067.67 million m³, the predicted industrial water demand is 251.17 million m³ and the predicted domestic water demand is 241.25 million m³.

However, the growth of the predicted values for total water demand and agricultural water demand is faster than the investigated values. Therefore, the original sequence needs to be adjusted according to the sequence of stepwise ratio. The sequence of stepwise ratio ($\lambda(k)$) is expressed as follows:

$$\lambda(k)=\frac{X^{(0)}(k-1)}{X^{(0)}(k)} \quad (k=(2,3,\ldots,n)) \text{ (YANG \& ZHANG 2003, 21)} \qquad (6.50)$$

In order to obtain a desired prediction value, all the stepwise ratios of the original sequence must fall in $(e^{-2/(n+1)}, e^{2/(n+2)}) = (0.8807, 1.2214)$ (YANG & ZHANG 2003, 21).

According to the calculation, the stepwise ratio of total water demand falls between 0.8414 and 1.047 and the stepwise ratio of agricultural water demand falls between 0.979 and 1.007. Although all the stepwise ratios fall between 0.8807 and 1.2214, some stepwise ratios in the original sequence are small. Therefore according to the translation adjustment, the stepwise ratios of the new sequence will be better than that of the new original sequence. The new sequence can be obtained by adding together the original sequence with a constant c and it can be rewritten as follows:

$$X^{(0)}(k) = X^{(0)}(k) + c \tag{6.51}$$

Set c is the sum of the variables in the original sequence.

According to the equation (6.28), the system developing parameter (a) and grey action quantity (u) for agricultural water consumption and total water consumption can be obtained:

a(Agriculture) = -0.0087, u(Agriculture) = 4.9626

a(Total) = -0.00738, u(Total) = 7.8828

The time response sequence for agricultural water demand and total water demand can be written as follows:

$$\hat{A}^{(1)}(k+1) = 575069.3373 \times e^{0.0087k} - 569989.4473 \tag{6.52}$$

$$\hat{T}^{(1)}(k+1) = 1075544.7625 \times e^{0.00738k} - 1067506.9525 \tag{6.53}$$

After building the advanced models for agricultural water demand and total water demand, the advanced model accuracy can be obtained by residual tests, relational coefficient tests and posteriori error tests. The values of the average absolute error ($\varnothing(avg)$) for agricultural water demand and total water demand are less than 10 % and the model accuracy is the best. The value of the relational degree (τ) for agricultural water demand and total water demand is larger than 60 % and the model accuracy is credible. The values of the variance ratio (V_r) for agricultural water demand and total water demand are less than 0.35, and the value of the error probability ($\varnothing(prob)$) is larger than 0.95, which means the model accuracy is the best (see Table 6-9). Therefore, the predicted results for agricultural water demand and total water demand are credible.

Table 6-9 The average absolute error ($\varnothing(avg)$), the relational degree (τ), the variance ratio (V_r), the error probability ($\varnothing(prob)$) and the corresponding model accuracy of the advanced model for agricultural water demand and total water demand in Urumqi (source: own calculations).

Parameters	Agriculture				Total			
	$\varnothing(avg)$ [%]	τ [%]	V_r	$\varnothing(prob)$	$\varnothing(avg)$ [%]	τ [%]	V_r	$\varnothing(prob)$
Values	0.3<10	67.54≥60	0.18<0.35	100>0.95	0.27< 10	71.127≥60	0.19<0.35	100>0.95
Model accuracy	Best	Credible	Best	Best	Best	Credible	Best	Best

The predicted total water demand is 1413.29 million m³ and the agricultural water demand is 954.34 million m³. Contrary to the predicted values of the quota method, the predicted agricultural water demand of grey model still occupied more than 60 % of the total water demand in 2015. Compared with industrial water demand and domestic water demand, the increased magnitude of agricultural water demand is much higher. The growth trend of total water demand is the same as that of agricultural water demand. If the agricultural structure is not adjusted, agriculture will still be the major water user in 2015. Industrial water demand and domestic water demand show continuous growth, and the growth rate of industrial water demand is higher than that of domestic water demand in 2015 due to the industrial expansion (see Figure 6-12).

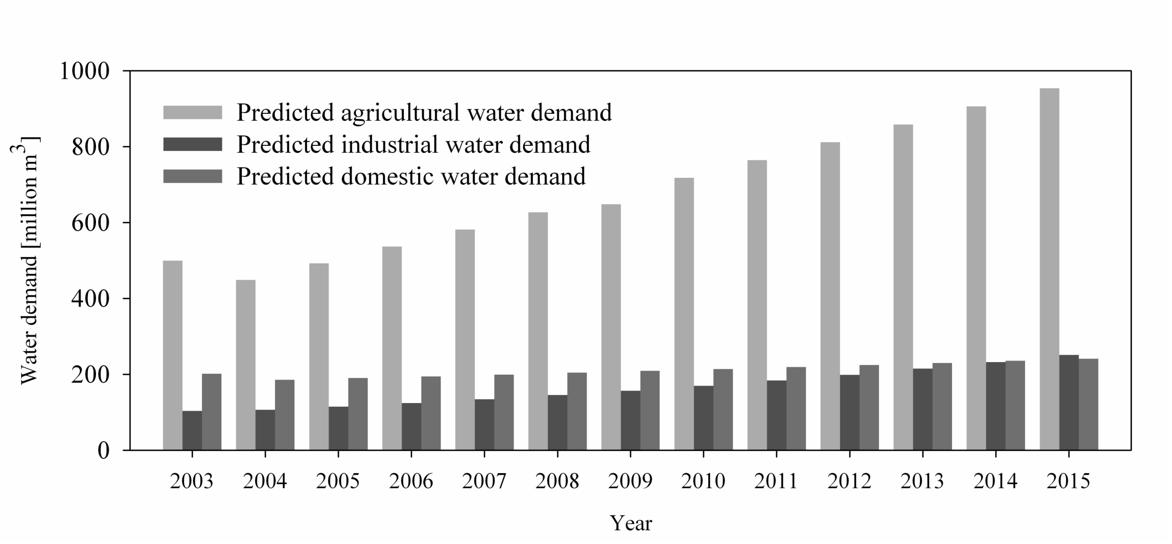


Figure 6-12 The predicted values for agricultural water demand, industrial water demand and domestic water demand from 2003 to 2015 in Urumqi (source: own calculations).

The grey model predicts water demand based on the data of existing water conversation facilities. The future water conservation measures, the socio-economic development plans, and the increases of water consumption of greening were not considered when building this model. Therefore, the predicted values of agricultural water demand should be larger than the investigated values and the predicted values of domestic and industrial water demand should be smaller than the investigated values.

6.4 Summary

Water demand prediction is an interdisciplinary subject, involving disciplines of water resources, macroeconomics, microeconomics, eco-environmental science and so on. The most important question is how to improve the accuracy of the forecast model. All the prediction models have many characteristics in common, such as requirements for historical data collection, inadequacy forecasts for ecological water demand, and lack of attention to the connection between water resources supply capacity. The average relative error of the quota method and the grey model are 1.19 % and -0.12 %, respectively, which means the accuracy of both models is reliable (see Table 6-10).

The quota method is accurate and convenient. Factor changes and policy adjustment can be analyzed more easily by this method. Since a water consumption quota must be determined according to the national and regional economic development, water consumption quotas varies with economic development. The water demand for forestry, animal husbandry and fishery is not considered in the quota method. Therefore, the water demand predicted by the quota model should be less than the actual water demand and it can be considered as the minimum water demand in Urumqi.

The grey model is concise due to its algorithms, which are based only on the input data on water consumption. It therefore requires less data. The water demand predicted by the grey model is under the premise of the current water conservation facilities, without considering possible water conservation measures that could be adopted in the future. Therefore, the value of the water demand predicted by the grey model should be larger than the value of the actual water demand and it can be considered as the maximum water demand.

Therefore, the total amount of water demand in Urumqi in 2015 should fall between the results of the quota method and the grey model. The water scarcity in Urumqi can be calculated as the difference between the predicted values of the quota method and the grey model with the value of the total water resources (939.22 million m^3) in 2010, with the gap being reduced from 474.07 million m^3 to 156.72 million m^3. This means that 317.35 million m^3 of total water demand can be saved by improving the water efficiency of the canal system, using advanced water-saving irrigation techniques, increasing the water-saving irrigation area and improving the water price for agricultural irrigation. The predicted results of these two models indicate that water scarcity is inevitable in Urumqi, but that it can be reduced by water conservation. This conclusion is consistent with the conclusion reached in chapter 4. This also means that the gap between water supply and demand can be reduced by adopting water conservation measures.

Meanwhile, by taking other appropriate measures mentioned in section 4.5.5 (e.g. adjusting industrial structure by developing the high standards of environmental protection requirements to limit or control the discharge of industrial wastewater, developing the high-tech industries and advanced technology to improve traditional industries, raising the price of fresh water withdrawals and the costs of wastewater discharges, improving industrial facilities and implementing advanced measures), a balance could be achieved between water demand and water supply in Urumqi.

Table 6-10 The comparison of the predicted values and the relative error of the quota method and the grey model (source: own calculations).

Year	Models			
	Quota method		Grey model	
	Predicted value	Relative error	Predicted value	Relative error
2003	-	-	805.02	0
2004	854.80	-11.22%	738.76	3.88%
2005	799.42	1.60%	797.84	1.80%
2006	-	-	857.36	-9.78%
2007	947.90	-3.34%	917.32	-0.01%
2008	949.11	4.29%	977.73	1.40%
2009	958.86	10.18%	1038.58	2.72%
2010	1028.34	5.60%	1099.89	-0.97%
2015	1095.94		1413.29	

7 Water resources management and information system for Urumqi

Due to the growing population, expanding irrigation areas and accelerated industrialization, the gap between water supply and demand increased dramatically and led to an over-exploitation of surface and ground water resources in Urumqi (FRICKE et al. 2009). Water resources have largely affected the socio-economic development of the Urumqi Region and have become a constraining factor for its sustainable socio-economic development. Therefore, it is necessary to strengthen the effective management of water resources through optimized allocation in order to meet the needs of economic and social development (CHEN 2006, 6; ZUO & CHEN 2007, 83).

Water resources information includes data collected from both the managed water resources and the protected water resources. It can reflect the transport, utilization and management status of water resources (CHEN 2006, 3). Based on a computer technology and geographic information system technology, water resources management together with an information system could effectively process water resources information (ZHU et al. 2006, 109; ZOU & CHEN 2007, 93).

This system could be used to store water resources information (basic database), display the graph (geo-database), utilize expert knowledge (knowledge database), and predict water demand according to the quota method and the grey model which are mentioned in section 6.3, as well as making decisions according to the water scarcity decision model (Analytic Hierarchy Process) which is mentioned in section 4.5.4 (model database). Its purpose is to provide technical support services for the scientific management of water resources (see Figure 7-1).

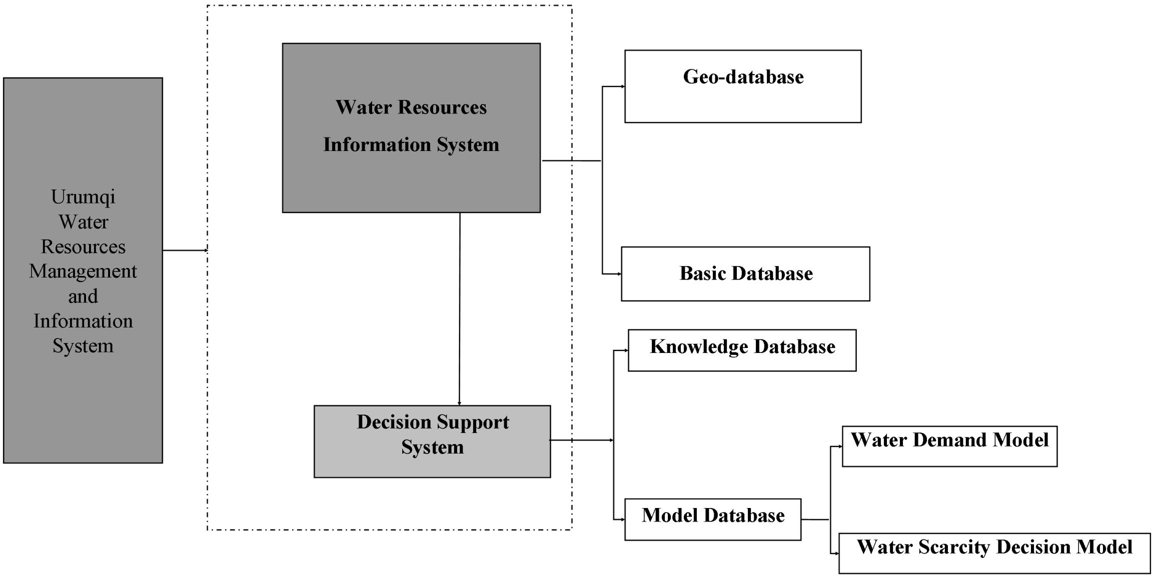


Figure 7-1 The overall structure of the water resources management and information system for Urumqi (source: own design according to YAO 2010).

In this chapter, the requirement analysis of the system (section 7.1) and the system design (section 7.2) are introduced. The water resources management and information system for Urumqi is developed, which contains the water resources information system (section 7.3) and the water resources decision support system (section 7.4).

7.1 Requirement analysis of the system

The requirements of this system, which are needed in order for it to be built, are analyzed, for example, it's applicability, reliability and how efficient it is. Water resource management and information system requirement analysis form the basis of the design and development of water resources management and information systems (CHEN 2006, 13). The initial requirements of the users of the software features are determined according to users' requirements. There are various requirement analyses for the development of different systems. The common requirement analysis includes information requirement analysis and functional requirement analysis (WANG et al. 1993). Information requirement analysis ensures all users obtain the necessary information. For water resource management and information systems, information requirement analysis is based on water resources planning and theory management (LIU & WEI 1997, 43). The aim of this information requirement analysis is to provide information for the rational allocation of water resources and the sustainable development of the socio-economy by analyzing water resources data and users' demands (HAO & ZHANG 2001, 40; MAGUIRE & BEVAN 2002, 134;).

Functional requirement analysis is based on the analysis of users' requirements of the system (YAO 2004, 28; MACIASZEK 2007). The system not only has a scientific management function, but can also help users make decisions. According to the problems and the characteristics of the water resources, the quantitative decision-making model could also be built by using a prediction method and decision-making analysis.

In order to meet the standards of the above information requirement analysis and functional requirement analysis, the water resources management and information system must contain two main functions. Firstly, the system should be able to collect, process, query, create statistics, analyze, publish, output and maintain the spatial and thematic data and the attribute data. Secondly, the system should support scientific decisions for water management by integrating the water resources prediction model into the knowledge base to meet the functional requirement of users.

7.2 System design

The system design is the physical design stage of the system (ZHU et al. 2006, 111). System design must follow some basic principles which are explained in section 7.2.1. The design method (section 7.2.2), the architectural design of the system (section 7.2.3) as well as the development tools and the development environment of the system (section 7.2.4) are key factors for its establishment. A well running system should have excellent design of the functional modules (section 7.2.5). In addition, users will feel more comfortable when they are using a user interface designed according to their needs (section 7.2.6).

7.2.1 System design principles

System construction is based on the principles of overall planning, unified management, rational use of funds, and sustainable development (CHEN 2006, 47; BAHILL & BOTTA 2008, 9). The system should meet hardware requirements, but also possible escalating demand and flexible expansion (ZHU et al. 2006, 111). The system should adapt to the database project increment and the modification in the decision-making model. In the initial phase of constructing a system, it is very difficult to meet the all requirements due to the constraints of funding, current application requirements, and the development of information technology (CHEN 2006, 47). Therefore, the system is constructed under the consideration of existing conditions. In the early stage of system construction, the urgent common function should be built first (ZUO & CHEN 2007, 84). Then, the system could be extended by more functions step-by-step. Finally, the fully functioning system could serve as a useful tool for decision-making.

System building should involve computer technology, database technology, communications technology, geography information system (GIS) technology and network technology (LI et al. 2003, 111). From a long-term perspective, overall and sustainable developments, the advanced technology of the system and open-source character are very important. Therefore, the GIS platform must follow internationally accepted standards (e.g. network protocol standards (Transmission Control Protocol/Internet Protocol (TCP/IP) standard, HTTP) and Web standards (XML, GML)), and this platform should be combined with the most advanced IT technology. This system is not a project that led to the economic benefits of a single unit. But it can generate more benefits for the ecology sector as a whole, as well as for society. Once the system is under construction, its public welfare character and its special user group should be considered (CHEN 2006, 47). The data is the principal component of such a system and as a system for servicing data, data security is very important. Because of the uncertainty of the on-line user, the permissions of query and modification must be strictly defined. It will ensure that legitimate users can easily access the data and use the system, while being able to deny access illegal users. In addition, the system's automatic backup and manual backup ensure maximal data security.

7.2.2 System design method

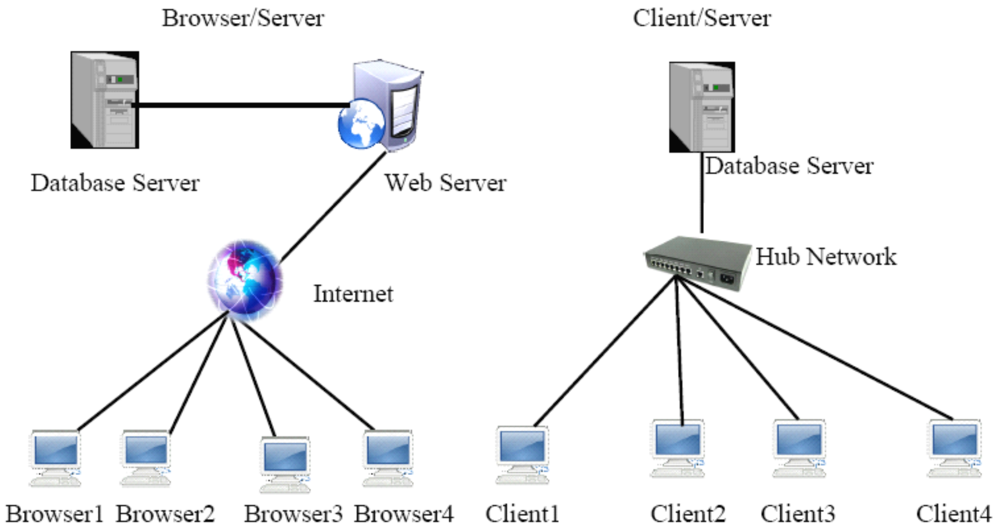


Figure 7-2 Browser/Server architecture and Client/Server architecture (source: own design according to YANG et al. 2009).

The water resources management and information system for Urumqi was developed using the object-oriented design method. The system features a combined architecture of a Browser/Server architecture combined with a Client/Server architecture, which is of great advantage. The Browser/Server (B/S) architecture is a network structure mode with the access to the World Wide Web. A web browser (such as Internet Explorer) is the main application software and needs be installed by the clients. The database (such as SQL Server) needs be installed on the server. According to the Web Server, the browser can interact with the database (YANG et al. 2009, 74) (see Figure 7-2).

The Client/Server (C/S) architecture depends on the system architecture software. It refers to the network architecture where one or more computers are connected with a server. It is generally oriented towards relatively fixed users and has a strong control ability of the information security (GRAY et al. 2001, 1). If the database contains highly confidential information, the system will use C/S architecture (HÖPFNER 2007, 773). Some functions are executed by the client and others are executed by the Server in C/S architecture (also see Figure 7-2).

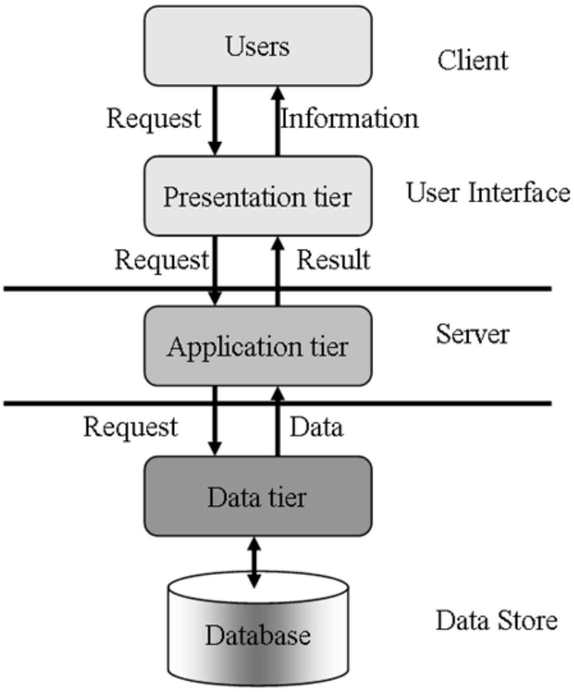


Figure 7-3 Three-tier architecture (source: own design according to SANDHU & FEINSTEIN 1994 and YANG et al. 2009).

The design of the system adopts a three-tier structure for presentation, application and data. The presentation tier is used to respond to and manage interaction between the user and the system. The application tier is used to receive requests from the presentation tier and return the results from the data tier to the presentation tier. The data tier provides access to the database and sends the data to the application tier when requested (MICROSOFT 2012) (see Figure 7-3).

7.2.3 Architectural design of the system

For Client/Server architecture, the server requires high-performance computers and a large database system, such as Oracle, Sybase, Informix or SQL Server (CHEN et al. 2007a, 219). The users need to install the client software. For Browse/Server architecture, the users only need to install one browser on the client workstation for to make full use of all the functions of the system. The server also requires high-performance computers to supply the Web data services. These services can be supplied by one or two servers.

The system intended to be built involves a large number of data input, data modification and data deletion. The data are of diverse formats. The system should be able to handle frequent queries and publications of information to meet the needs of different users and data updates. Therefore, the management and information system is developed with a hybrid architecture of Browse/Sever (B/S) and Client/Server (C/S) to ensure the security of sensitive data and improve the access efficiency and network utilization efficiency in Client (YANG et al. 2010a, 103). Function interface which needs Web to meet the users request is built using B/S architecture. Background functions, which are needed by a small number of people is built using C/S architecture. Components are located in the Web application. Client issues a request for HTTP to use the Web application. The web application then sends the request to the database server. The database server sends the data back to the Web application. Then the Web Server sends the data back to the client (YAO 2010, 146) (see Figure 7-4).

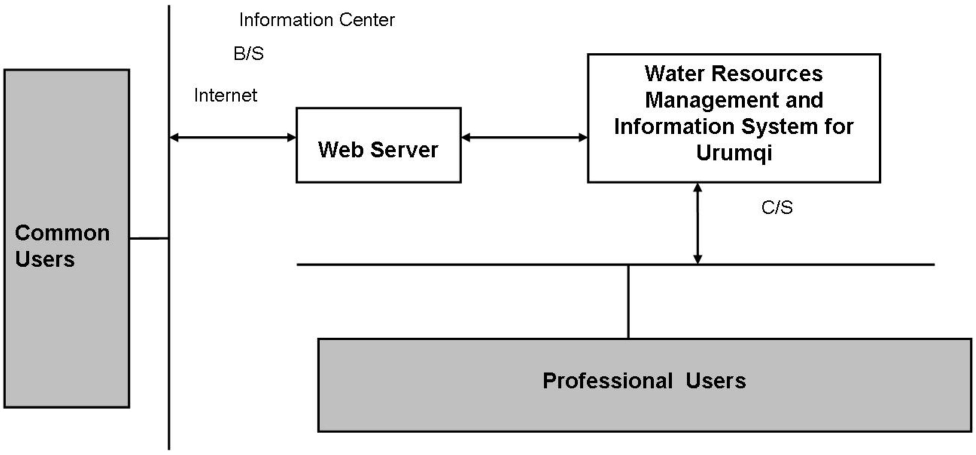


Figure 7-4 The hybrid architecture of the Client/Server C/S) and the Browser/Server (B/S) (source: YAO 2010, 146).

7.2.4 System development tools and development environment

System development tools and the development environment are the technological basis for the development of the system and their selection directly affects the quality of the system development. According to the architectural design of the system, development tools (section 7.2.4.1) and the development environment (section 7.2.4.2) are introduced.

7.2.4.1 Development tools

According to the design principles of the management and information system, the development tools of the water resources management and information system for Urumqi must be easy to be integrate with other systems, their interfaces should be simple, they must be able to support structured and unstructured data and should be easily expandable (CHEN et al. 2007a, 219). The management and information system in this thesis is developed based on .Net Framework 2.0, the development tool is Visual Studio 2005 and the programming language is C#. The Web interface is developed using Asp.net 3.0, while the database is created using SQL Server 2005. ActiveX data objects (ADO) is used to access the database from the Web pages. The map results are the published on the web using ArcGIS Server.

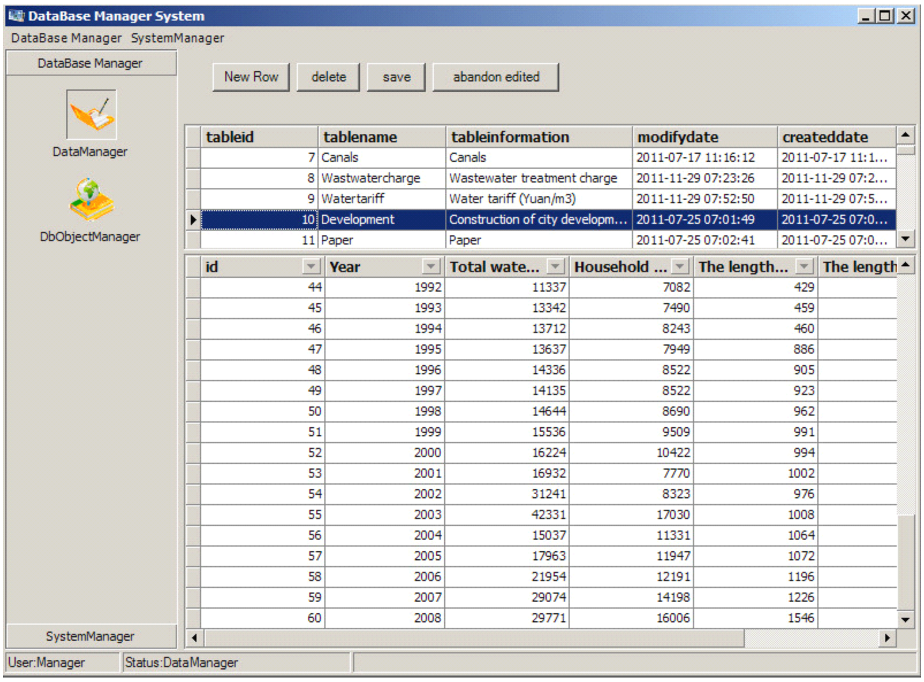
7.2.4.2 Development environment

The development environment of the water resources management and information system for Urumqi includes a hardware development environment and a software development environment. The architecture of the system is a combination of the B/S and C/S structures, with the B/S structure as the main frame of this system. The server system includes the web server, database server and GIS server. These three servers are logical divided, but in reality, one server can support these three servers.

Due to the relatively large amount of system data, the server sends and receives large amounts of data. According to the tests during the development process and in order to achieve the optimal running of the system, the server should have a memory of more than 1GB, CPU clocked at 2.8 MHZ or better, and a hard disk space of 160 GB. There are no special requirements for the client software environment, besides the required browser IE 6.0. A regular operation system can meet the requirements, such as WinXP or Win2000.

7.2.5 Design of the functional modules

The primary functions of this information system are to maintain the database, as well as to manage and query the data. It can be divided logically into three subsystems: a maintenance and authority management subsystem, a database management subsystem, and a data query subsystem. The subsystem for system maintenance and authority management contains the authority management of the system users, function adjustment of the system, and database backup and recovery. The database management subsystem also contains the functions of data editing, data input and output. The main function of the subsystem for data query is to publish data in the basic database, to supply services for data query and to download the data under the permits (see Figure 7-5).



tableid	tablename	tableinformation	modifydate	createddate
7	Canals	Canals	2011-07-17 11:16:12	2011-07-17 11:1...
8	Wastwatercharge	Wastewater treatment charge	2011-11-29 07:23:26	2011-11-29 07:2...
9	Watertariff	Water tariff (Yuan/m3)	2011-11-29 07:52:50	2011-11-29 07:5...
10	Development	Construction of city developm...	2011-07-25 07:01:49	2011-07-25 07:0...
11	Paper	Paper	2011-07-25 07:02:41	2011-07-25 07:0...

id	Year	Total wate...	Household ...	The length...	The length
44	1992	11337	7082	429	
45	1993	13342	7490	459	
46	1994	13712	8243	460	
47	1995	13637	7949	886	
48	1996	14336	8522	905	
49	1997	14135	8522	923	
50	1998	14644	8690	962	
51	1999	15536	9509	991	
52	2000	16224	10422	994	
53	2001	16932	7770	1002	
54	2002	31241	8323	976	
55	2003	42331	17030	1008	
56	2004	15037	11331	1064	
57	2005	17963	11947	1072	
58	2006	21954	12191	1196	
59	2007	29074	14198	1226	
60	2008	29771	16006	1546	

Figure 7-5 Database management subsystem used to manage database and functions (source: own design).

The data processing functions of the Urumqi water resource management and information system can be divided into three basic functional modules, i.e. data input, data output and data editing. The data input module contains two parts: the input of data attributes and the input of spatial information. The data output module allows output in the form of statistical reports and thematic maps. The data edit module contains data management and manipulation. Data management allows the adding, deleting and modifying of data. Data manipulation includes data query, data statistics, data analysis and thematic mapping (see Figure 7-6).

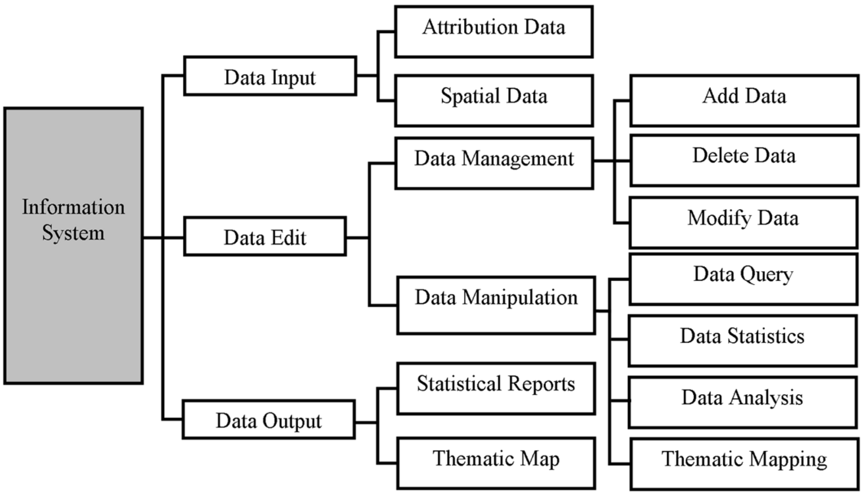


Figure 7-6 The structure of basic functional modules (source: own design).

7.2.6 System user interface design

The user interface is a junction between a user and a computer program. A good user interface can maintain efficient service for users. The users of the Urumqi water resource management and information system allows the option to create high-level decision-make users and general users. When the user interface is designed, the functional requirements of the system must be considered as well as different user demands. Therefore, the characteristics of the user interface are as follows:

1. Workability

   The user interface is simple and the terminology in the user interface is standardized. The system response is fast when the user interface is running.

2. Flexibility

   The user interface can be modified according to the requirement of the users. It can provide a different level of response information.

3. Consistency of style

   In the different levels of interface, the style of the settings is consistent with all other interfaces.

4. Simple inputs

   The operation which requires frequent input is provided with a drop-down menu or selection list.

5. Clear outputs

   The output interface which is used for analysis offers a clear graph.

7.3 Water resources information system for Urumqi

The water resources information system for Urumqi is a comprehensive and updatable database system. Based on the collection and processing of water resources information (section 7.3.1), there the database employs two methods to store and manage data, via relational or spatial connections. According to the design of the relational database, the water resources information system for Urumqi has been developed and the system can provide data to users and receive external data using the data interface of Web Service (section 7.3.2).

7.3.1 Information collection and processing

Data is the core of the water resource information system. The information system's database covers basic data on climate, hydrology, urban water, the regional economy, municipal information, agriculture and picture, and natural geographic information. The database also contains multiple data sources, such as basic geographic data, thematic geographic data, aerial photographs, satellite images, basic hydrological attribute data, water resource management data, statistical data and reports (See Table 7-1). The types of data collected are text data, numerical data, images and videos, raster and vector data.

All the data is used to demonstrate the available opportunities for water resources and socioeconomic development in Urumqi. Part of the collected data can be inputted manually or imported after simple collection. The data can be used directly after processing and analysis. The processing of information mainly requires data format conversion (such as raster data and vector data conversion, text data and other forms of storage data (excel, access) conversion), remote sensing image processing (image stitching, cutting, fusion, enhancement and classification), and thematic map extraction (various thematic maps combining the collected data and the extracted boundary information).

In order to optimise the collection, processing, querying, analysis and presentation of the data, the database of this information system was designed according to the attributes of the water resources in Urumqi. The database contains two parts, the basic database which saves the basic data referred in Table 7-1 (the data on climate, hydrology, urban water, regional economy, municipal information, agriculture and pictures), and the geo-database which saves the basic geographic data, thematic geographic data, aerial photographs and satellite images (CHEN 2006). There are seven functions of the information system. These are system maintenance, system control, function management, data processing, data management, data analysis and geographic information function (see Figure 7-7).

Table 7-1 The information stored and managed by the water resources management and information system for Urumqi (source: own design).

Type	Information classification	Information contents	Sources
Basic database	Climate	Precipitation, temperature, hours of sunshine and humidity	Numerical data, statistical data and reports
	Hydrology	Rivers, canals, power stations and reservoir information	Numerical data, statistical data and reports
	Urban water	Water resource, water supply, water consumption, wastewater, industrial water, water use index, water tariff and wastewater charge.	Numerical data, statistical data and reports water resource management data
	Regional economy	Gross national product, farming, forestry, animal husbandry and fishery gross national product, and the rate of farming, forestry, animal husbandry and fishery in the gross output.	Numerical data, statistical data and reports
	Municipal information	Municipal construction, urban construction, urban facility development and population	Numerical data, statistical data and reports
	Agriculture	Crops	Numerical data, statistical data and reports
	Pictures	Images of water resources in Urumqi	Reports
Geo-database	Natural geographic information	Remote sensing data and color infrared aerial photography data, river basin district map, water system map and reservoir distribution map	Basic geographic data, thematic geographic data, aerial photographs and satellite images.

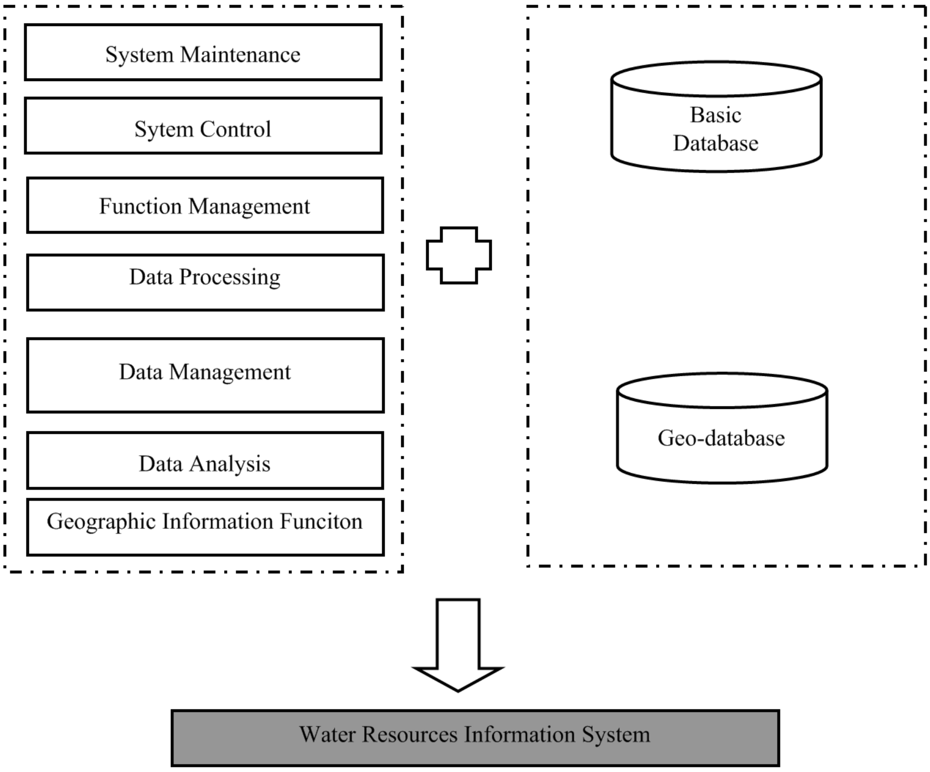
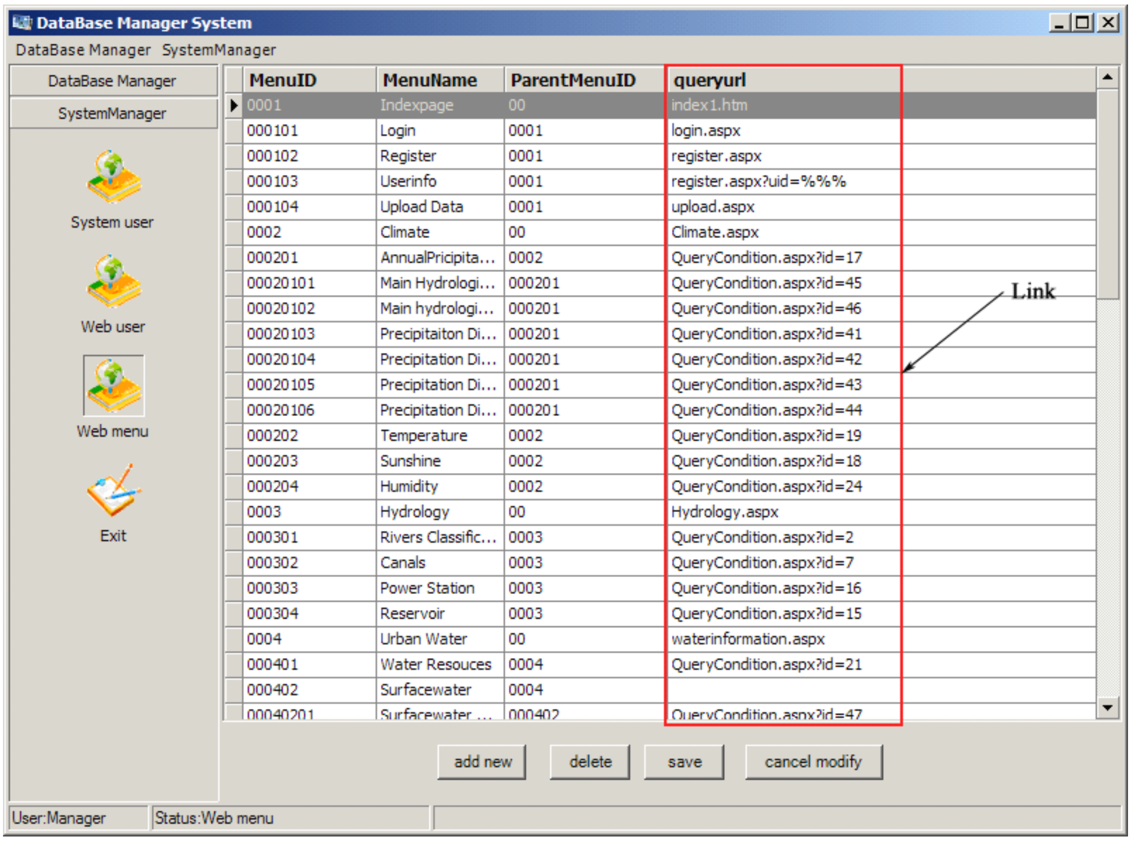


Figure 7-7 The logical structure of the water resources information system (source: own design).

Based on the functional modules mentioned in section 7.2.5, the system maintenance, system control and function management can be realized. Moreover, the various data sets (e.g. water supply and consumption) can be analyzed and managed by data analysis tools according to the user interface (GEORGAKAKOS 2004, 3). In addition, the geographic information function (e.g. map export, visual information query) can be used to visualize and analyze the spatial data via GIS Server.

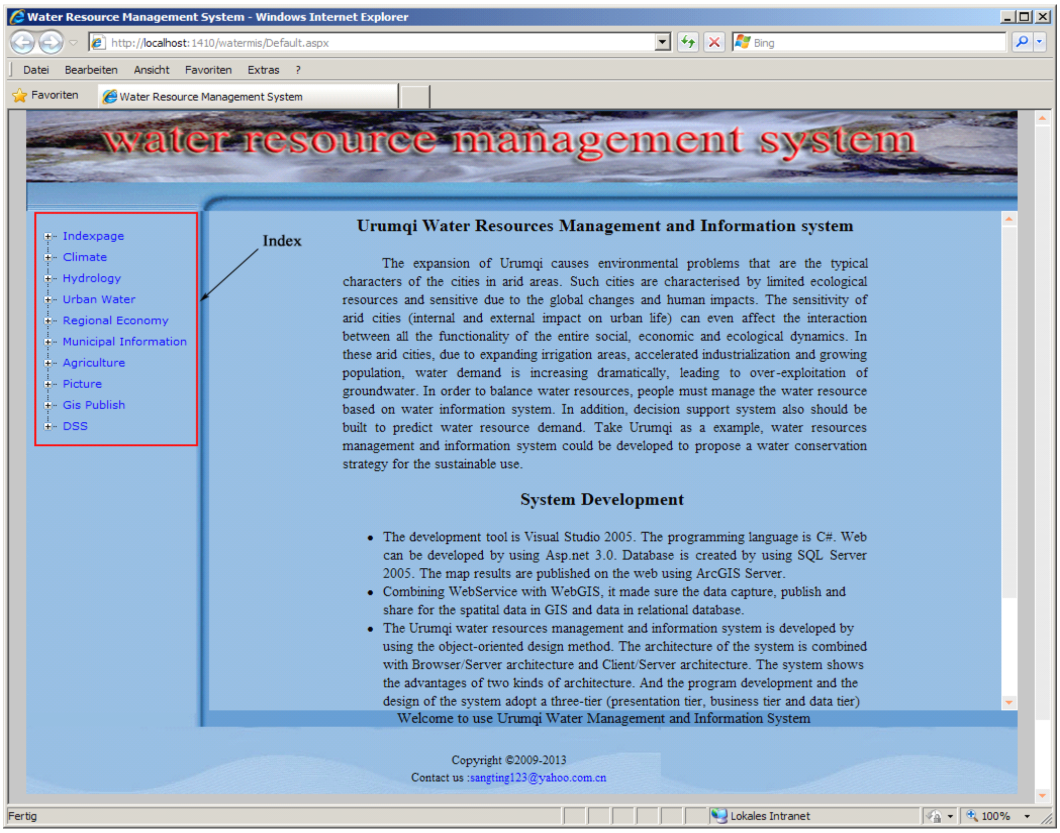
7.3.2 Information system development achievements

As explained in section 7.2.2, the information system is designed according to two kinds of architectures, Client/Server (C/S) architecture and Browser/Server (B/S) architecture. Therefore, this system is easy to maintain and expanded. Development and maintenance of the system are carried out by the server side, thereby reducing development and maintenance workload. Figure 7-8 shows the line of the menu between the system and a specific page in a control class. The system development results of the Browser/Server architecture are shown in a series of web pages. The operation of the user interface is similar to the normal internet operations. Through the interface index, the user can browse and query by allowing a function to call itself (recursive algorithm) (see Figure 7-9).



MenuID	MenuName	ParentMenuID	queryurl
0001	Indexpage	00	index1.htm
000101	Login	0001	login.aspx
000102	Register	0001	register.aspx
000103	Userinfo	0001	register.aspx?uid=%%%
000104	Upload Data	0001	upload.aspx
0002	Climate	00	Climate.aspx
000201	AnnualPricipita…	0002	QueryCondition.aspx?id=17
00020101	Main Hydrologi…	000201	QueryCondition.aspx?id=45
00020102	Main hydrologi…	000201	QueryCondition.aspx?id=46
00020103	Precipitaiton Di…	000201	QueryCondition.aspx?id=41
00020104	Precipitation Di…	000201	QueryCondition.aspx?id=42
00020105	Precipitation Di…	000201	QueryCondition.aspx?id=43
00020106	Precipitation Di…	000201	QueryCondition.aspx?id=44
000202	Temperature	0002	QueryCondition.aspx?id=19
000203	Sunshine	0002	QueryCondition.aspx?id=18
000204	Humidity	0002	QueryCondition.aspx?id=24
0003	Hydrology	00	Hydrology.aspx
000301	Rivers Classific…	0003	QueryCondition.aspx?id=2
000302	Canals	0003	QueryCondition.aspx?id=7
000303	Power Station	0003	QueryCondition.aspx?id=16
000304	Reservoir	0003	QueryCondition.aspx?id=15
0004	Urban Water	00	waterinformation.aspx
000401	Water Resouces	0004	QueryCondition.aspx?id=21
000402	Surfacewater	0004	
00040201	Surfacewater …	000402	QueryCondition.aspx?id=47

Figure 7-8 The management of the link of the user interface and the information system's database (source: own design).



Urumqi Water Resources Management and Information system

The expansion of Urumqi causes environmental problems that are the typical characters of the cities in arid areas. Such cities are characterised by limited ecological resources and sensitive due to the global changes and human impacts. The sensitivity of arid cities (internal and external impact on urban life) can even affect the interaction between all the functionality of the entire social, economic and ecological dynamics. In these arid cities, due to expanding irrigation areas, accelerated industrialization and growing population, water demand is increasing dramatically, leading to over-exploitation of groundwater. In order to balance water resources, people must manage the water resource based on water information system. In addition, decision support system also should be built to predict water resource demand. Take Urumqi as a example, water resources management and information system could be developed to propose a water conservation strategy for the sustainable use.

System Development

- The development tool is Visual Studio 2005. The programming language is C#. Web can be developed by using Asp.net 3.0. Database is created by using SQL Server 2005. The map results are published on the web using ArcGIS Server.
- Combining WebService with WebGIS, it made sure the data capture, publish and share for the spatital data in GIS and data in relational database.
- The Urumqi water resources management and information system is developed by using the object-oriented design method. The architecture of the system is combined with Browser/Server architecture and Client/Server architecture. The system shows the advantages of two kinds of architecture. And the program development and the design of the system adopt a three-tier (presentation tier, business tier and data tier)

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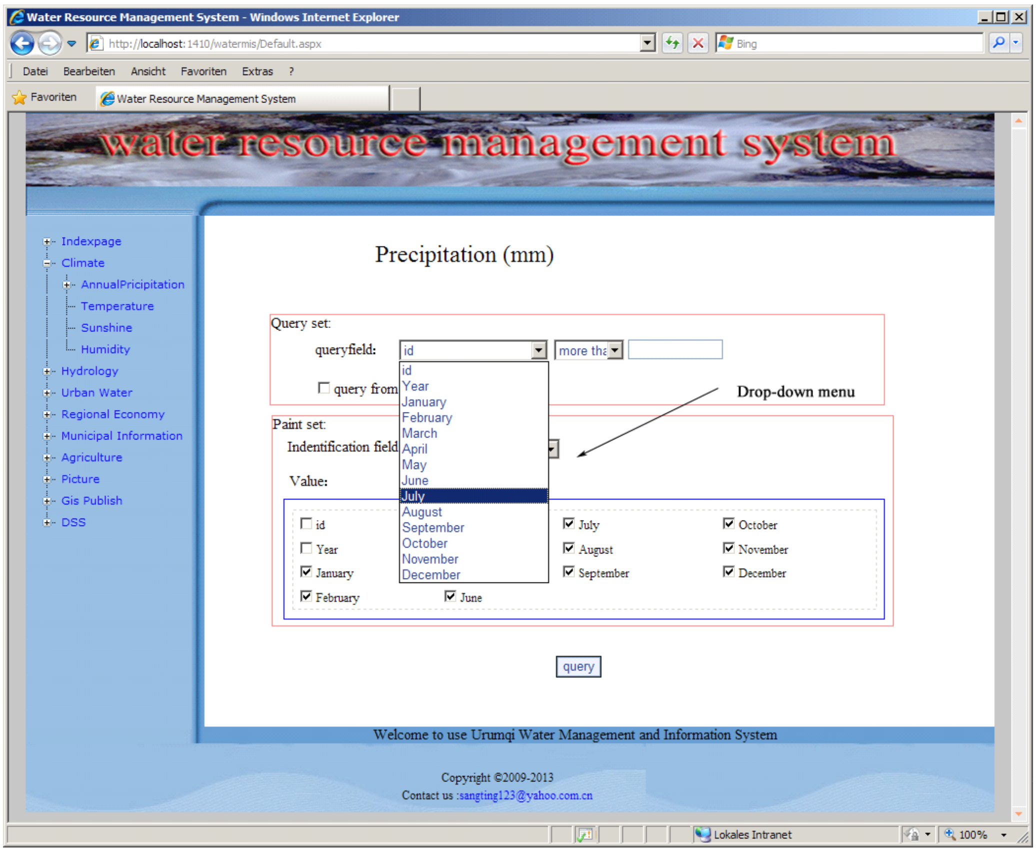
Figure 7-9 The home page and index of the information system (source: own design).



queryfield: id ▾ more tha ▾

☐ query from

Indentification field

☐ id
☐ Year
☑ January
☑ February
☑ June
☑ July
☑ August
☑ September
☑ October
☑ November
☑ December

Drop-down menu

Figure 7-10 The query interface of the information system (source: own design).

As well as the functions of information collection, storage and processing, the information system also has a basic query function and a download function. Users can directly query information according to the query field and the query criteria in the drop-down menu (see Figure 7-10). The query results can be showed in a new interface, which can then also be downloaded in Excel form. In addition, users are only granted access to the information system through their accounts and passwords. This guarantees the security of the system.

7.4 Water resources decision support system for Urumqi

A decision support system (DSS) is a computer application system (GU & TANG 2000, 61) which provides ancillary information for the decision maker. The water resources management and information system for Urumqi contains a knowledge database and a model database to serve as DSS. Some data in the basic database can be used as the inputted data in the models of the decision support system. The knowledge database is managed by the information system which is described in section 7.3 and is used to store, organize, manage, apply and share knowledge (section 7.4.1). On the other hand, the expert knowledge in the knowledge database can be used as an a priori knowledge model library for decision-making.

From the two models described in chapter 6, the quota method and the grey model were used to predict water demand in Urumqi. The water scarcity decision model includes an Analytic Hierarchy Process (AHP) model, which is used to measure the ability of the decisions for solving water scarcity (section 7.4.2). According to the evaluation of predicted results and decisions, the recommended solutions for the sustainable development of Urumqi's water resources can be provided (see Figure 7-11).

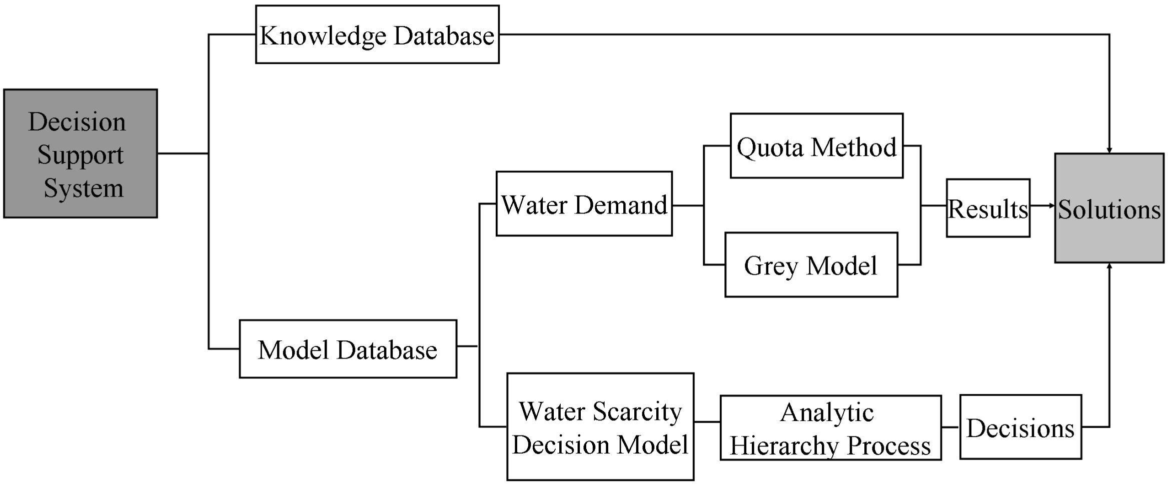
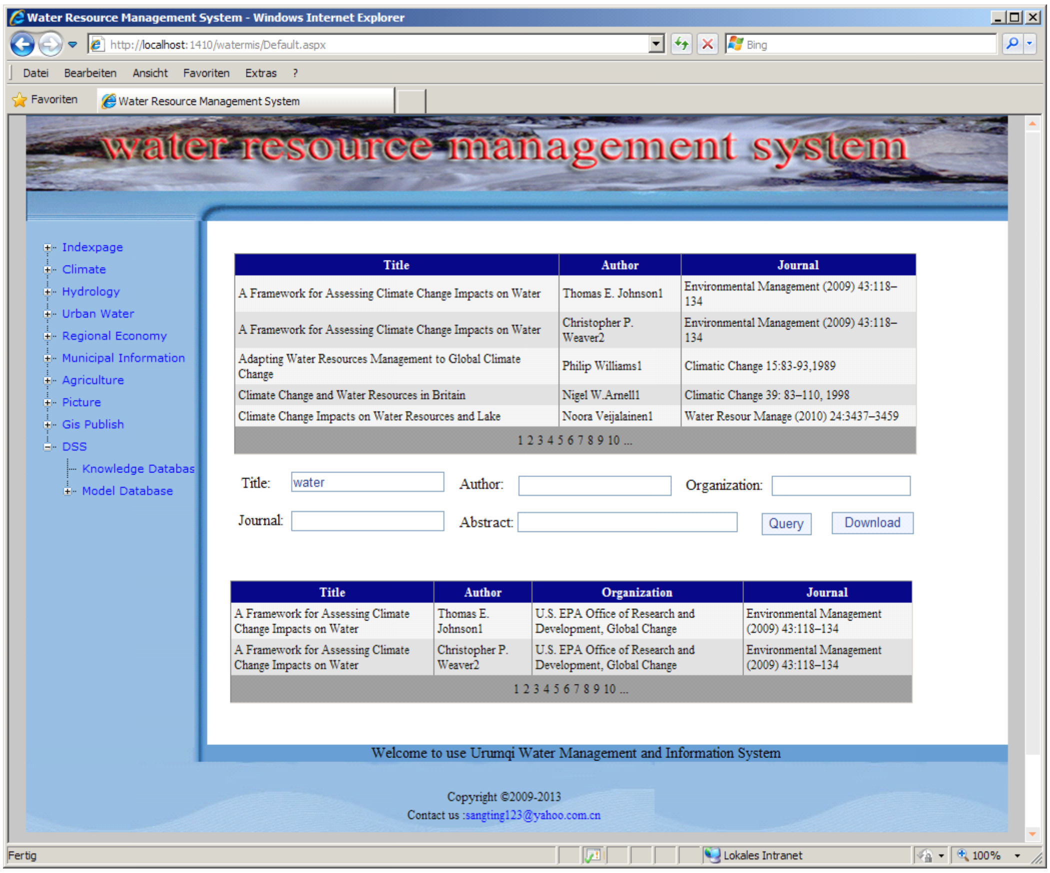


Figure 7-11 The structure of the decision support system in the water resources management and information system (source: own design).

7.4.1 Knowledge database

The knowledge database is a special kind of database which is used to manage knowledge. It can store expert knowledge and expertise, both of which are used to support planning and decisions in climatology, meteorology, hydrology, ecology, environmental science and water resources (GEORGAKAKOS 2004, 1). The modules of the knowledge database allow the loading, updating, browsing and saving of information. Through interaction with experts, the knowledge can be updated to improve the accuracy of information in the database.

The acquisition and organization of the information within the knowledge database is difficult, since expert skills in brain and unorganized documents need to be transformed into reusable and searchable explicit knowledge (ERFANI et al. 2010, 39). Therefore, reasoning technologies have to be used, such as knowledge mining, and classification searches. All the knowledge in the knowledge base is relevant to water resource issues. Users can query and download the knowledge by using the keywords title, author, organization, journal and abstract (see Figure 7-12).



Title	Author	Journal
A Framework for Assessing Climate Change Impacts on Water	Thomas E. Johnson1	Environmental Management (2009) 43:118–134
A Framework for Assessing Climate Change Impacts on Water	Christopher P. Weaver2	Environmental Management (2009) 43:118–134
Adapting Water Resources Management to Global Climate Change	Philip Williams1	Climatic Change 15:83-93,1989
Climate Change and Water Resources in Britain	Nigel W.Arnell1	Climatic Change 39: 83–110, 1998
Climate Change Impacts on Water Resources and Lake	Noora Veijalainen1	Water Resour Manage (2010) 24:3437–3459
1 2 3 4 5 6 7 8 9 10 ...		

Title: water
Author:
Organization:
Journal:
Abstract:

Title	Author	Organization	Journal
A Framework for Assessing Climate Change Impacts on Water	Thomas E. Johnson1	U.S. EPA Office of Research and Development, Global Change	Environmental Management (2009) 43:118–134
A Framework for Assessing Climate Change Impacts on Water	Christopher P. Weaver2	U.S. EPA Office of Research and Development, Global Change	Environmental Management (2009) 43:118–134
1 2 3 4 5 6 7 8 9 10 ...			

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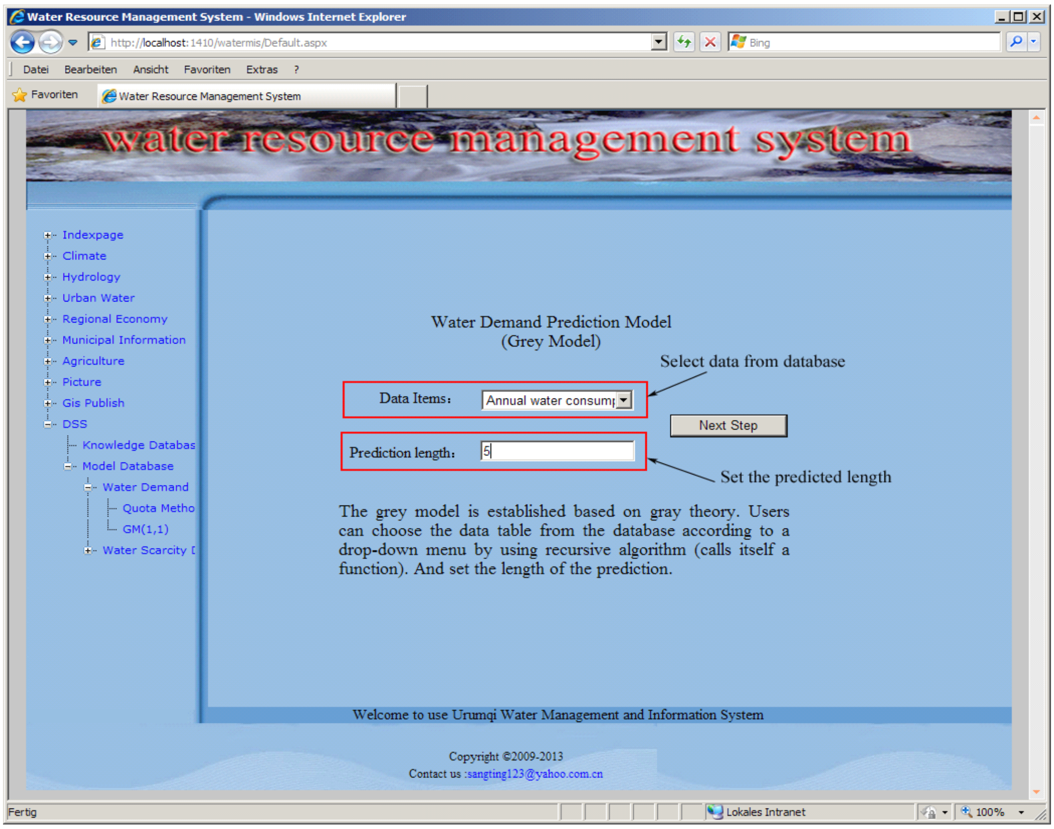
Figure 7-12 The user interface for conditional query via the knowledge database (source: own design).

7.4.2 Model database

By using the decision support system, the user can make decisions based on the model in the model database. The model database is the core of the decision support system. It is a collection of various statistical models, all of which are created according to the analysis model by analyzing the mature models (ZHANG 1995, 61; ZUO & CHEN 2007, 85). In a particular field of research, researchers will study different areas, but when they use the same research methods, the use of the model database can significantly shorten study time, improve work efficiency and quality.

The model database is constructed independent of the data, and it could be easily transplanted. By using object-oriented approaches and deeming all the resources in the system as objects, designers can create objects which are in accordance with their own needs. In this thesis, the model database includes a water demand prediction model which can predict future water demand in Urumqi according to the water information in the database, and a water scarcity decision model which is used to make decisions to solve water scarcity in Urumqi.

In the water demand prediction model, a quota method and a grey model are included. The quota method is a concise mathematical algorithm of the calculation which has been mentioned in section 6.2. The operating methodology of the quota method is that users can autonomously determine the water quota of various sections (agriculture, industry, domestic, and livestock) by querying and browsing the knowledge database and information system database. In addition, by considering water resources planning and the Urumqi master planning in the knowledge database, users can also determine other parameters (farmland area, value added by industry, the total number of livestock , the total population and urbanization). Then water demand can be predicted through the user interface. The grey model is established based on the grey theory. The modeling process has been mentioned in section 6.3. The operating methodology of the grey model is that users can choose the data table from the database according to a drop-down menu (see Figure 7-13) by using a recursive algorithm (called a function). Then according to the selected column in the data table and order field, the water demand can be predicted (see Figure 7-14).



Water Demand Prediction Model
(Grey Model)

Select data from database

Data Items: Annual water consum

Prediction length: 5

Set the predicted length

The grey model is established based on gray theory. Users can choose the data table from the database according to a drop-down menu by using recursive algorithm (calls itself a function). And set the length of the prediction.

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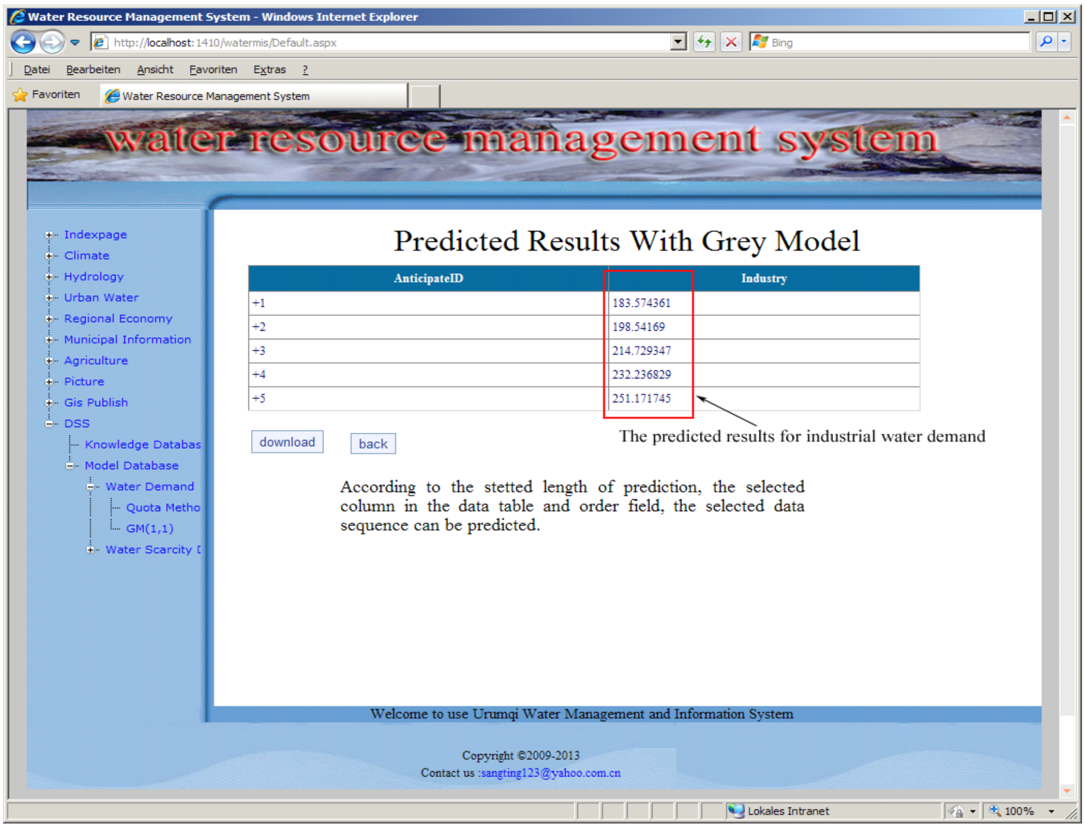
Figure 7-13 The user interface for the water demand prediction model (source: own design).



Predicted Results With Grey Model

AnticipateID	Industry
+1	183.574361
+2	198.54169
+3	214.729347
+4	232.236829
+5	251.171745

The predicted results for industrial water demand

According to the stetted length of prediction, the selected column in the data table and order field, the selected data sequence can be predicted.

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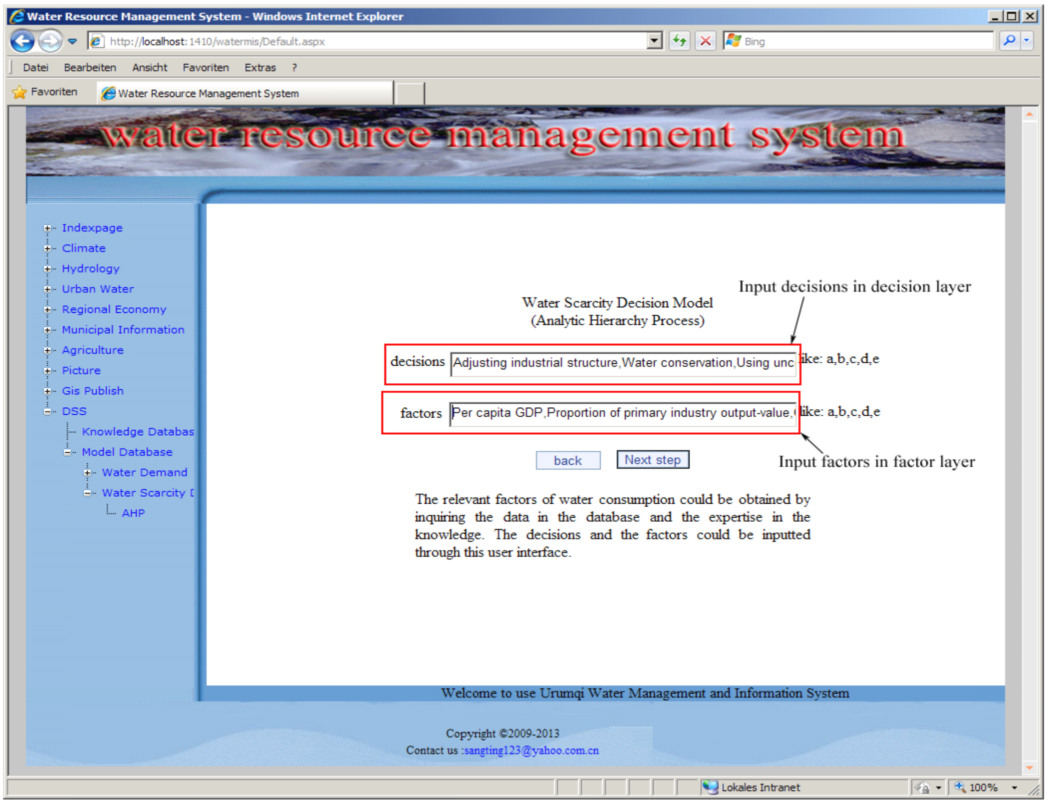
Figure 7-14 The user interface for the results predicted by the grey model (source: own design).

The water scarcity decision model is built by adopting the Analytic Hierarchy Process (AHP) according to the decisions and the factors for solving the water scarcity as presented in chapter four. The decision model contains four steps for analyzing decisions.

1. The relevant factors of water consumption can be obtained by searching the data in the database and the expertise in the knowledge base (mentioned in section 4.5.2). All the strategies for solving water scarcity can be found out according to the water scarcity risk assessment indexes (mentioned in section 4.5.1).The decisions and the factors can be inputted through the user interface (see Figure 7-15).



Input decisions in decision layer

Water Scarcity Decision Model
(Analytic Hierarchy Process)

decisions Adjusting industrial structure,Water conservation,Using unc like: a,b,c,d,e

factors Per capita GDP,Proportion of primary industry output-value,(like: a,b,c,d,e

Input factors in factor layer

The relevant factors of water consumption could be obtained by inquiring the data in the database and the expertise in the knowledge. The decisions and the factors could be inputted through this user interface.

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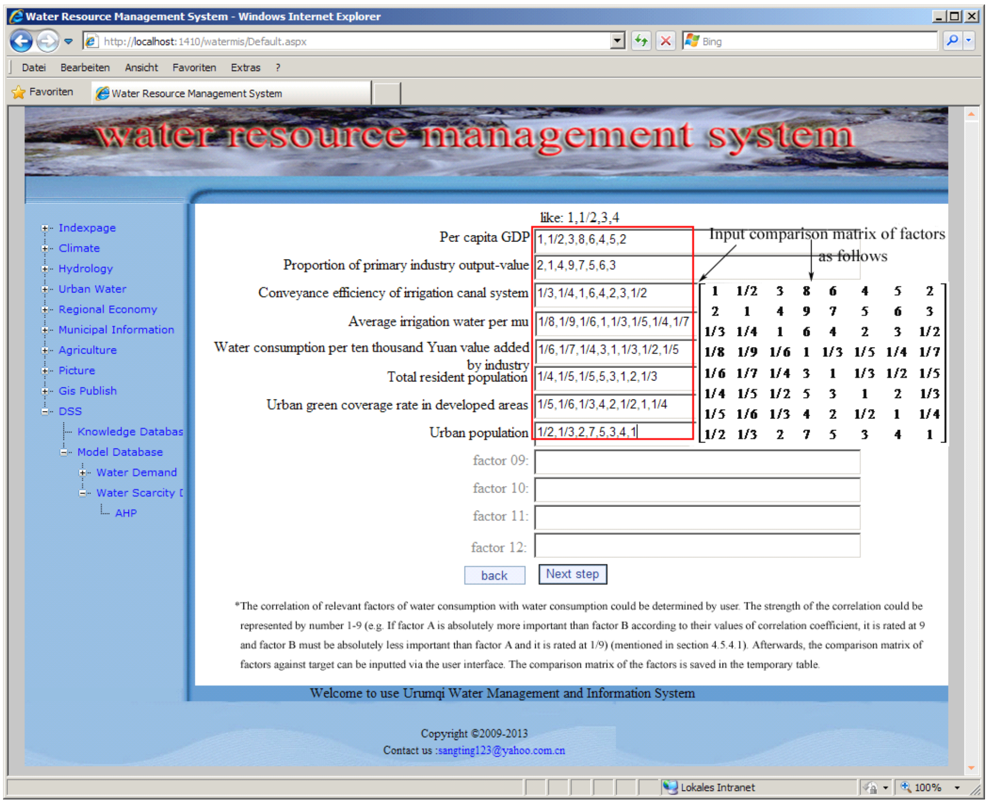
Figure 7-15 The user interface for inputting factors and decisions in the water scarcity decision model (source: own design).



like: 1,1/2,3,4

Per capita GDP 1,1/2,3,8,6,4,5,2
Proportion of primary industry output-value 2,1,4,9,7,5,6,3
Conveyance efficiency of irrigation canal system 1/3,1/4,1,6,4,2,3,1/2
Average irrigation water per mu 1/8,1/9,1/6,1,1/3,1/5,1/4,1/7
Water consumption per ten thousand Yuan value added by industry 1/6,1/7,1/4,3,1,1/3,1/2,1/5
Total resident population 1/4,1/5,1/5,5,3,1,2,1/3
Urban green coverage rate in developed areas 1/5,1/6,1/3,4,2,1/2,1,1/4
Urban population 1/2,1/3,2,7,5,3,4,1
factor 09:
factor 10:
factor 11:
factor 12:

Input comparison matrix of factors as follows

$$\begin{bmatrix} 1 & 1/2 & 3 & 8 & 6 & 4 & 5 & 2 \\ 2 & 1 & 4 & 9 & 7 & 5 & 6 & 3 \\ 1/3 & 1/4 & 1 & 6 & 4 & 2 & 3 & 1/2 \\ 1/8 & 1/9 & 1/6 & 1 & 1/3 & 1/5 & 1/4 & 1/7 \\ 1/6 & 1/7 & 1/4 & 3 & 1 & 1/3 & 1/2 & 1/5 \\ 1/4 & 1/5 & 1/2 & 5 & 3 & 1 & 2 & 1/3 \\ 1/5 & 1/6 & 1/3 & 4 & 2 & 1/2 & 1 & 1/4 \\ 1/2 & 1/3 & 2 & 7 & 5 & 3 & 4 & 1 \end{bmatrix}$$

*The correlation of relevant factors of water consumption with water consumption could be determined by user. The strength of the correlation could be represented by number 1-9 (e.g. If factor A is absolutely more important than factor B according to their values of correlation coefficient, it is rated at 9 and factor B must be absolutely less important than factor A and it is rated at 1/9) (mentioned in section 4.5.4.1). Afterwards, the comparison matrix of factors against target can be inputted via the user interface. The comparison matrix of the factors is saved in the temporary table.

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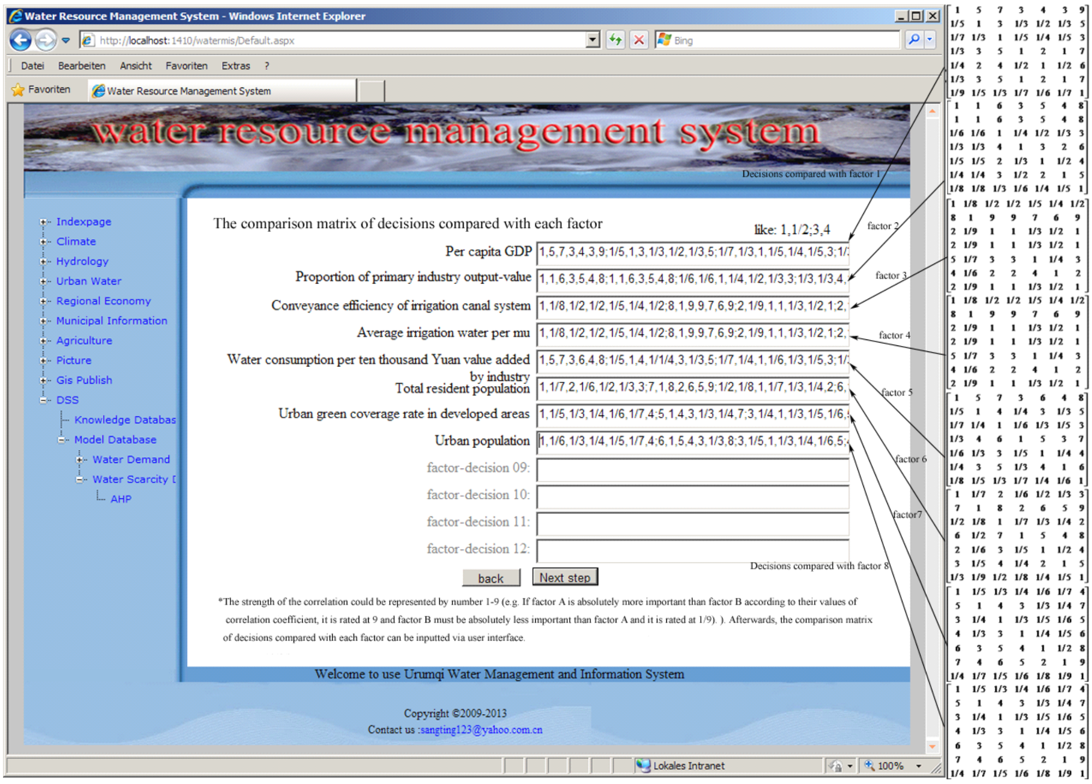
Figure 7-16 The user interface for inputting the comparison matrix of the factors against total water consumption (source: own design).

2. The correlation of relevant factors of water consumption with water consumption can be determined by the user. The strength of the correlation can be represented by the numbers 1-9 (e.g. if factor *A* is absolutely more important than factor *B* according to their values of correlation coefficient, it is rated at 9 and factor *B* must be absolutely less important than factor *A* and it is rated at 1/9) (mentioned in section 4.5.4.1). Afterwards, the comparison matrix of factors can be built (see Figure 7-16). The comparison matrix of the factors is saved in the temporary table.



The comparison matrix of decisions compared with each factor

like: 1,1/2;3,4

Per capita GDP: 1,5,7,3,4,3,9;1/5,1,3,1/3,1/2,1/3,5;1/7,1/3,1,1/5,1/4,1/5,3;1/

Proportion of primary industry output-value: 1,1,6,3,5,4,8;1,1,6,3,5,4,8;1/6,1/6,1,1/4,1/2,1/3,3;1/3,1/3,4,

Conveyance efficiency of irrigation canal system: 1,1/8,1/2,1/2,1/5,1/4,1/2;8,1,9,9,7,6,9;2,1/9,1,1,1/3,1/2,1;2,

Average irrigation water per mu: 1,1/8,1/2,1/2,1/5,1/4,1/2;8,1,9,9,7,6,9;2,1/9,1,1,1/3,1/2,1;2,

Water consumption per ten thousand Yuan value added by industry: 1,5,7,3,6,4,8;1/5,1,4,1/1/4,3,1/3,5;1/7,1/4,1,1/6,1/3,1/5,3;1/

Total resident population: 1,1/7,2,1/6,1/2,1/3,3;7,1,8,2,6,5,9;1/2,1/8,1,1/7,1/3,1/4,2;6,

Urban green coverage rate in developed areas: 1,1/5,1/3,1/4,1/6,1/7,4;5,1,4,3,1/3,1/4,7;3,1/4,1,1/3,1/5,1/6,

Urban population: 1,1/6,1/3,1/4,1/5,1/7,4;6,1,5,4,3,1/3,8;3,1/5,1,1/3,1/4,1/6,5;

factor-decision 09:

factor-decision 10:

factor-decision 11:

factor-decision 12:

*The strength of the correlation could be represented by number 1-9 (e.g. If factor A is absolutely more important than factor B according to their values of correlation coefficient, it is rated at 9 and factor B must be absolutely less important than factor A and it is rated at 1/9).). Afterwards, the comparison matrix of decisions compared with each factor can be inputted via user interface.

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$$\begin{bmatrix} 1 & 5 & 7 & 3 & 4 & 3 & 9 \\ 1/5 & 1 & 3 & 1/3 & 1/2 & 1/3 & 5 \\ 1/7 & 1/3 & 1 & 1/5 & 1/4 & 1/5 & 3 \\ 1/3 & 3 & 5 & 1 & 2 & 1 & 7 \\ 1/4 & 2 & 4 & 1/2 & 1 & 1/2 & 6 \\ 1/3 & 3 & 5 & 1 & 2 & 1 & 7 \\ 1/9 & 1/5 & 1/3 & 1/7 & 1/6 & 1/7 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1 & 6 & 3 & 5 & 4 & 8 \\ 1 & 1 & 6 & 3 & 5 & 4 & 8 \\ 1/6 & 1/6 & 1 & 1/4 & 1/2 & 1/3 & 3 \\ 1/3 & 1/3 & 4 & 1 & 3 & 2 & 6 \\ 1/5 & 1/5 & 2 & 1/3 & 1 & 1/2 & 4 \\ 1/4 & 1/4 & 3 & 1/2 & 2 & 1 & 5 \\ 1/8 & 1/8 & 1/3 & 1/6 & 1/4 & 1/5 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1/8 & 1/2 & 1/2 & 1/5 & 1/4 & 1/2 \\ 8 & 1 & 9 & 9 & 7 & 6 & 9 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 5 & 1/7 & 3 & 3 & 1 & 1/4 & 3 \\ 4 & 1/6 & 2 & 2 & 4 & 1 & 2 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1/8 & 1/2 & 1/2 & 1/5 & 1/4 & 1/2 \\ 8 & 1 & 9 & 9 & 7 & 6 & 9 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 5 & 1/7 & 3 & 3 & 1 & 1/4 & 3 \\ 4 & 1/6 & 2 & 2 & 4 & 1 & 2 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 5 & 7 & 3 & 6 & 4 & 8 \\ 1/5 & 1 & 4 & 1/4 & 3 & 1/3 & 5 \\ 1/7 & 1/4 & 1 & 1/6 & 1/3 & 1/5 & 3 \\ 1/3 & 4 & 6 & 1 & 5 & 3 & 7 \\ 1/6 & 1/3 & 3 & 1/5 & 1 & 1/4 & 4 \\ 1/4 & 3 & 5 & 1/3 & 4 & 1 & 6 \\ 1/8 & 1/5 & 1/3 & 1/7 & 1/4 & 1/6 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1/7 & 2 & 1/6 & 1/2 & 1/3 & 3 \\ 7 & 1 & 8 & 2 & 6 & 5 & 9 \\ 1/2 & 1/8 & 1 & 1/7 & 1/3 & 1/4 & 2 \\ 6 & 1/2 & 7 & 1 & 5 & 4 & 8 \\ 2 & 1/6 & 3 & 1/5 & 1 & 1/2 & 4 \\ 3 & 1/5 & 4 & 1/4 & 2 & 1 & 5 \\ 1/3 & 1/9 & 1/2 & 1/8 & 1/4 & 1/5 & 1 \end{bmatrix}$$

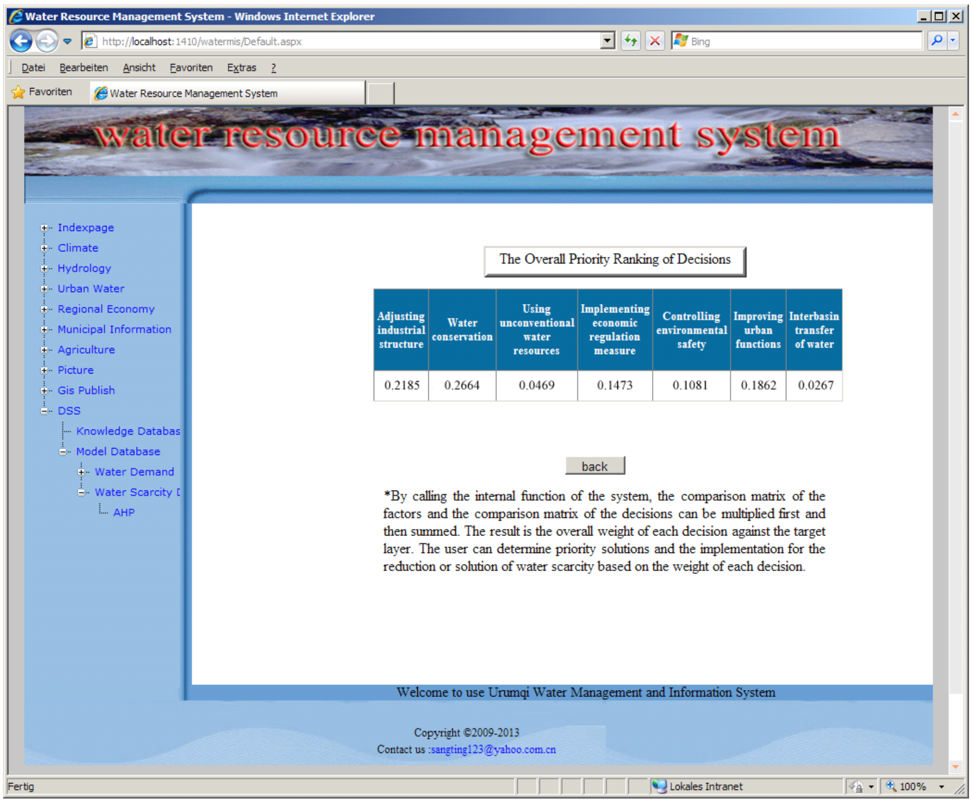
$$\begin{bmatrix} 1 & 1/5 & 1/3 & 1/4 & 1/6 & 1/7 & 4 \\ 5 & 1 & 4 & 3 & 1/3 & 1/4 & 7 \\ 3 & 1/4 & 1 & 1/3 & 1/5 & 1/6 & 5 \\ 4 & 1/3 & 3 & 1 & 1/4 & 1/5 & 6 \\ 6 & 3 & 5 & 4 & 1 & 1/2 & 8 \\ 7 & 4 & 6 & 5 & 2 & 1 & 9 \\ 1/4 & 1/7 & 1/5 & 1/6 & 1/8 & 1/9 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1/5 & 1/3 & 1/4 & 1/6 & 1/7 & 4 \\ 5 & 1 & 4 & 3 & 1/3 & 1/4 & 7 \\ 3 & 1/4 & 1 & 1/3 & 1/5 & 1/6 & 5 \\ 4 & 1/3 & 3 & 1 & 1/4 & 1/5 & 6 \\ 6 & 3 & 5 & 4 & 1 & 1/2 & 8 \\ 7 & 4 & 6 & 5 & 2 & 1 & 9 \\ 1/4 & 1/7 & 1/5 & 1/6 & 1/8 & 1/9 & 1 \end{bmatrix}$$

Figure 7-17 The user interface for inputting the comparison matrix of decisions, comparing with each factor (source: own design).

3. Then the correlation of decisions against each factor is determined. The comparison matrix of the decisions is built (mentioned in section 4.5.4.1) (see Figure 7-17). The method for building this comparison matrix is the same as above.

4. Using the internal function of the system, the comparison matrix of the factors (above 2) and the comparison matrix of the decisions (above 3) can be multiplied first and then summed (mentioned in section 4.5.4.2). The result is the overall weight of each decision against the target layer (see Figure 7-18). The user can determine priority solutions and the implementation for the reduction or solution of water scarcity in Urumqi based on the weight of each decision.



The Overall Priority Ranking of Decisions

Adjusting industrial structure	Water conservation	Using unconventional water resources	Implementing economic regulation measure	Controlling environmental safety	Improving urban functions	Interbasin transfer of water
0.2185	0.2664	0.0469	0.1473	0.1081	0.1862	0.0267

*By calling the internal function of the system, the comparison matrix of the factors and the comparison matrix of the decisions can be multiplied first and then summed. The result is the overall weight of each decision against the target layer. The user can determine priority solutions and the implementation for the reduction or solution of water scarcity based on the weight of each decision.

Figure 7-18 The user interface for the overall priority ranking of decisions (source: own design).

7.5 Summary

The water resources management and information system is a kind of program that can manage information and generate decisions for users. The purpose of building such a system is to provide a platform for strategy and decision-making for the sustainable use of water resources of the Urumqi Region.

If the spatial data and the basic geographic information of water resources could be fully considered, then the water resources could be effectively utilized. Thus, the water resource management and information system could provide accurate information services and advanced technical support for local water resources planning, management and decision-making.

Based on the requirements and the functions of the water resources management and information system, the construction of this system in Urumqi includes two core modules (see Figure 7-19):

1. Water resource information system

   The water resource information system is used to manage basic data about water resource information. It can be set up using the installation program with the guidance of the administrator. The water resource information system can manage various types of data that are collected from different areas. Users can browse and query the data in this system through the user interface. The water resource information system also provides information as a basis for the decision support system.

2. Decision support system

The decision support system can analyze the information from the water resource information system and help users to predict water demand and make decisions. The decision support system contains two parts, the knowledge database and the model database. The model database includes a water demand prediction model.

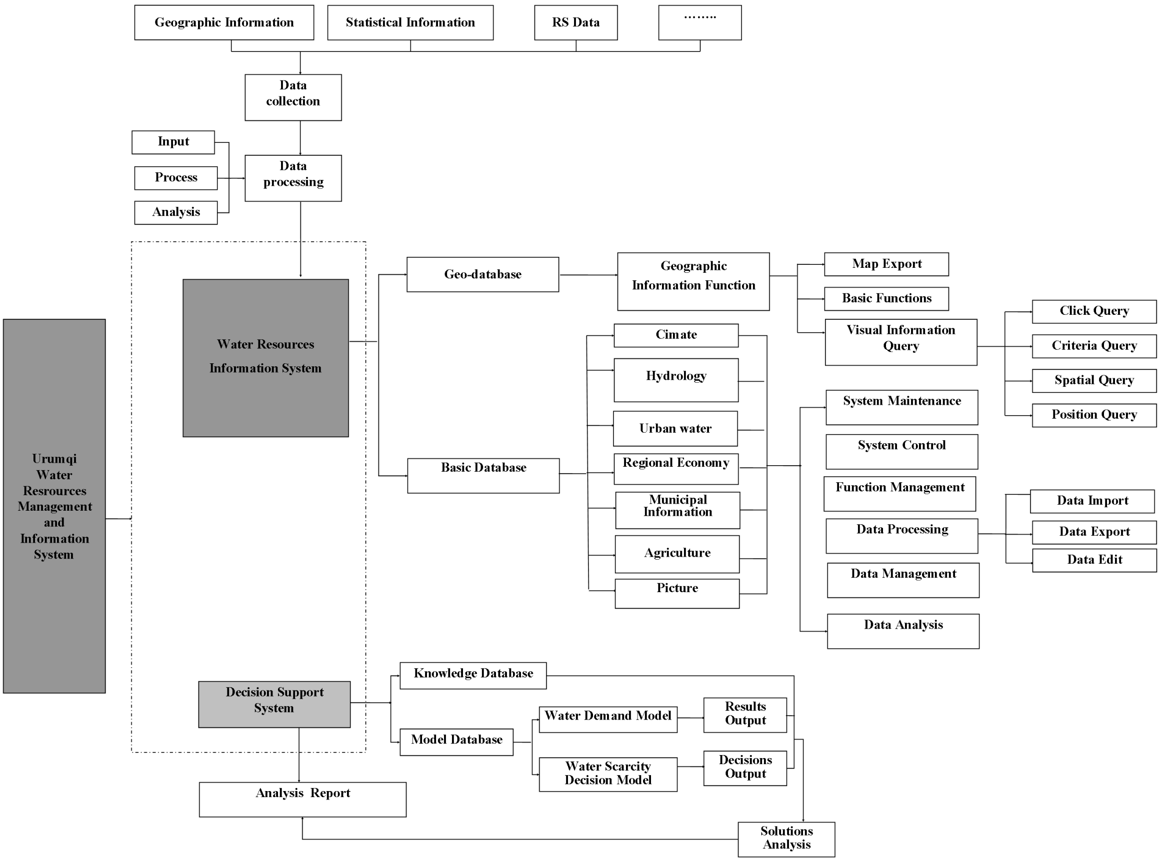


Figure 7-19 Overall structure of the water resources management and information system for Urumqi (source: own design according to YAO 2010).

The expert knowledge, the predicted results and decisions in the decision support system can be used to guide the improvements of the functions of the information system. Therefore, the water resource information system and the decision support system are interdependent.

Through the unified management of water resources information in the water resources information system, it can rapidly supply reliable data for users. Authorized users can access these data through the interface. The decision support system can be connected with the information system and users via model-data access- the man-machine interface. The advantages of this approach are that the use and the maintenance of this system are more convenient and users can work in a more comfortable environment. In addition, by uniformly managing data, predicting water demand and analyzing water scarcity decisions, this water resources management and information system could supply strategies for the rational allocation of water resources and sustainable water use.

8 Conclusion and outlook

In Urumqi, some problems with regard to water resources management, water resources allocation, and water resources security, which intensify the gap between water supply and water demand, lead to water scarcity. Meanwhile, with the developments of population, urbanization, agriculture, and industry, municipal sewage in Urumqi increases year by year and water resources pollution only further aggravates water scarcity. Water scarcity has affected all social and economic sectors and will threaten the sustainable development of the socio-economy and the environment. Therefore, the aim of this thesis is to help Urumqi address water resources problems and to achieve the sustainable management and development of water resources in Urumqi. The research in this thesis covers water reuse, water scarcity risk assessment and decision systems, water conservation, water demand predication, and a water resources management and information system.

Urumqi is severely lacking in available water resources. Water reuse is an effective measure to reduce water scarcity. By analyzing the status of water reuse in Urumqi, some suggestions of advancing the wastewater system to improve the ratio of water reuse are put forward: 1) Establish a reasonable price system of water. 2) Increase the use of reclaimed water. 3) Heighten the enterprises' awareness of environmental protection and strengthen supervision and administration. 4) Adopt a managerial responsibility system of contracting. 5) Closely monitor the directly discharged sewage for persons or businesses and carry out a prize and punish system. 6) Improve the sewer pipe systems. 7) Popularize small decentralized wastewater treatment plants. 8) Design wastewater reservoirs to store the treated wastewater. 9) Optimize the position of water reuse facilities. All these suggestions could help Urumqi reduce the amount of wastewater and protect the water environment. Based on the current treatment technology of the wastewater treatment plants in Urumqi, being able to increase wastewater treatment rates and water reuse rates is realistic. That means the available water resources for Urumqi can be increased and water scarcity can be reduced in the future.

Meanwhile, by considering the status of society, the economy, the environment, technology and management involved in the allocation of water resources, a water scarcity decision model was built by adopting the advanced Analytic Hierarchy Process (AHP) methodology. According to the analysis of the water scarcity decision model, the priorities for solving water scarcity in Urumqi are water conservation, adjusting industrial structures, improving urban functions, implementing economic regulation measures, controlling environmental safety, using unconventional water resources (precipitation, treated wastewater reuse) and the interbasin transfer of water. Furthermore, water conservation is the most important step for reducing water scarcity in Urumqi. There is a great potential to reduce agricultural and industrial water consumption. The measurements for agricultural water conservation that can be taken are reducing the agricultural irrigation quota, adjusting agricultural reform and structure, transforming the large-sized irrigation areas, expanding water–saving irrigation areas and improving the conveyance efficiency of the irrigation canal system. Industrial water conservation can be achieved through adjusting industrial structures by developing high standards of environmental protection requirements, developing high-tech industries and advanced technology to improve traditional industries, raising the price of fresh water withdrawals and the costs of wastewater discharges and improving industrial facilities and implementing advanced measures.

In order to implement the sustainable use of water resources, water demand was predicted by using a quota method and a grey model. Since the water demand for forestry, animal husbandry and fishery is not considered in the quota method and the water demand predicted by the grey model is under the premise of the current water conservation facilities, without considering the water conservation measures adopted in the future, the actual total water demand in Urumqi should fall between the predicted results of the quota method and the grey model. If all the predictions prove to be right, the gap between the total water resources and the water demand will be reduced from 474.07 million m^3 to 156.72 million m^3 million m^3 in 2015, only by adopting water conservation measures. Agriculture remains the major water user. The results of the two water demand prediction models showed the measures to reduce water scarcity in different aspects (e.g. agricultural water conservation, population control and industrial structure adjustment). In order to reflect the relationship of restriction and simulation between many variables (e.g. economy, population, standard of living and climate change) which can affect water demand, a grey model (1, n) will be built.

In addition, an intersectoral and multidisciplinary approach to uniformly and effectively managing Urumqi's water resources and integrating the water demand prediction models (the quota method and the grey model) and the water scarcity decision model mentioned above is required. Therefore, a water resources management and information system for Urumqi was built up. It included two parts: a water resources information system and a decision support system. The water resources information system can manage water resources information in Urumqi and can ensure the standardization and codification of the raw data through the scientific management method and the normalized management system. By using the friendly interface, users can query, browse and analyze the data. The decision support system can analyze the information from the water resource information system and help users to predict water demand and make decisions. The research method (models loosely connected to GIS) of the water resources management and information system for Urumqi did not need many technological workers, and when it is put into use, it can ensure the sustainable utilization of water resource and water conservation. This system was developed using a hybrid architecture of a Browse/Sever (B/S) and a Client/Server (C/S). Compared with traditional management information systems (using only Browse/Sever (B/S) architecture or Client/Server (C/S) architecture), this system reduces the number of direct links to the application server and data server, and effectively reduces the burden on the server (TONG et al. 2003, 126; JIA et al. 2008, 8). It also greatly ensures the security of the data, as only authorized users can change, query, and browse the data. This system can also be expanded according to users' requirements. More functions can be added to it without the need to make procedural changes. In addition, since this water resources management and information system does not require a hardware and running system, it can be installed on any normal computer. The water resources management information system uses a unified method (ADO technology) to access different databases, which greatly simplifies the programming and increases the portability of the program (ZHANG et al. 2000a, 1; YU et al. 2004, 74; YUAN et al. 2011, 3). It means this system not only can be applied in Urumqi, but also in other regions.

The water resource system is a complex system which is related to many disciplines. Due to limited access to data, analysis and research carried out on some of the problems could is not perfect. The future management of water resources will be moving in the direction of the development of integrated water resources management. The simulation model of the conjunctive management of surface water and groundwater will be built up by combining GIS with water demand prediction model (MASSMANN & FREEZE 1987, 368; MARINO 2001, 165; MENG et al. 2004, 234; GAO et al. 2011, 542). This simulation model will supply further suggestions and advice for the sustainable use of water resources in Urumqi.

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Abbreviations

A	Access
A_1	The proportion of agricultural water consumption to the total water consumption [%] (% of water demand by agriculture)
a	System developing parameter of grey model
a_i	The average conveyance efficiency of irrigation canal system [%]
AGO	Accumulated generating operation
AHP	Analytic Hierarchy Process
ANN	Artificial neural networks
AQSIQ	General Administration of Quality Supervision, Inspection and Quarantine of PR China
β	The industrial water recycle rate [%]
B/S	Browser/Server
C	Capacity
CEH	Center for Ecology and Hydrology
CESIA	China Environment Service Industry Association
CI	Consistency index
Cl_2	Chlorine
COD	Chemical oxygen demand
CR	Consistency ration
CR'	The overall consistency of hierarchy
C/S	Client/Server
C_v	Coefficient of variation
$\Delta^{(0)}(i)$	The absolute error sequence
$\delta(k-i)$	Correction parameter
DOI	United States Department of the Interior
DSS	Decision Support System
ε	The error variable
E	Environment

EPA	Environmental Protection Agency
η_t	The state variable of water resource system
$E(X)$	The average of the state variable of water resource system for several years
F	The fatal accident (water supply cannot meet water demand)
FAO	Food and Agriculture Organization of the United Nations
f_a	Farmland area [mu]
φ	Growth rate
$\text{Ø}(avg)$	The average relative error [%]
$\text{Ø}(i)$	The relative error sequence
$\text{Ø}(prob)$	Error probability [%]
γ	The normal state of water resource system
GDP	Gross domestic product
GIS	Geographic information system
GM	Grey model
IAGO	Inverse accumulated operation
ι	The risk rate of water system [%]
I_O	The industrial output [billion Yuan]
I_{va}	Value added by industry [billion Yuan]
IWISA	International Workshop on Information Security and Application
IWMI	International Water Management Institute
κ	Correlation coefficient
χ_l	The leakage rate of the city pipe network [%]
$\lambda_{\max}$	The maximum eigenvalue
LAWA	Länderarbeitsgemeinschaft Wasser
l/person and day	Liter per person per day
l/head and day	Liter per head per day
m a.s.l.	Meters above sea level
MCC	Ministry of Construction of PR China
MHURDC	Ministry of Housing and Urban-Rural Development of PR China
mu	Chinese unit of land measurement (1 mu=666.67 m^2)
MWRC	Ministry of Water Resources of PR China

NAS	National Academy of Sciences
NDRCC	National Development and Reform Commission of PR China
NH_3-N	Nitrogen from ammonia
N_{rr}	Population in rural areas [person]
N_{ru}	Population in urban areas [person]
ω	The priority vector
$\bar{\omega}$	The proportion of the agricultural economy (agriculture, forestry, animal husbandry and fishery) [%]
P	The annual precipitation [mm]
$\bar{P}$	The average annual precipitation during several years [mm]
P_a	Anomaly rate of precipitation [%]
π_i	The i-th probability of occurrence of loss [%]
P_i	The precipitation for the i-th year [mm]
ψ_i	The i-th severity of loss of the system
Q_A	The average irrigation water quota [m^3/mu]
Q_L	The quota of water demand for livestock [l/head and day]
ρ	The distinguished coefficient
R	Resource
R_1	The total water resources [million m^3]
R_2	The total population [million people]
RI	Random consistency index
r_u	Urbanization rate [%]
$RWUI$	The rate of water resources utilization index [%]
SAC	Standardization Administration of PR China
σ	The standard deviation
θ	The recoverability of water system
SCC	State Council of PR China
SEPA	State Environmental Protection Administration of PR China
SRTM	Shuttle Radar Topography Mission
STSA	State Technology Supervision Administration of PR China
SVM	Support vector machine
S_r	Surface runoff [million m^3]
τ	The relational degree [%]
TCP/IP	Transmission Control Protocol / Internet Protocol
TNF	The total number of fatal accident

T_{nl}	Total number of livestock [head]
TWS	The total water supply [million m^3]
Total P	Total phosphorus
Total N	Total nitrogen
U	Use
u	Grey action quantity
U_a	The average water usage
UEPB	Urumqi Environment Protection Bureau
UNESCO	United Nations Educational, Scientific and Cultural Organization
USUG	United States Geological Survey
UW	Unconventional water resources [million m^3]
U_1	Per capita urban domestic water consumption (including public water use, such as water used for construction and greening) [l/person and day]
U_2	Per capita rural domestic water consumption (including water used for the rural greening) [l/person and day]
V_r	Variance ratio [%]
W_A	Water used for agriculture [million m^3]
WAI	Water availability index
WC_{DP}	The proportion of domestic water consumption to the total water consumption [%]
WC_{IP}	The proportion of industrial water consumption to the total water consumption [%]
WC_{Iva}	Water consumption per value added by industry [$m^3/10^4$Yuan]
WC_T	Total water consumption by all sectors [million m^3]
WC_{pc}	The per capita comprehensive water consumption [m^3]
W_D	Water used for domestic purposes [million m^3]
WD_T	Total water demand [million m^3]
W_g	Groundwater resources [million m^3]
W_I	Water used for industry [million m^3]
WMO	World Meteorological Organization
WPI	Water poverty index
WRU	Water resources utilization rate
$WRVI$	Water resources vulnerability index

WSI	Water stress index
$WSPI$	Water supporting index
WUE	Water-use efficiency [%]
WWO	World Water Organization
WWWT	Wastewater treatment plant
X	Multi-dimensional random variable of a probability distribution
Yuan	Unit of currency of PR China, Renminbi
ζ	The vulnerability of water system

Appendix

A.1 Overview of the input data

Table A-1 The input data for factors in water scarcity decision model in Urumqi (B_1: Per capita GDP [Yuan]; B_2: Proportion of primary industry output-value [%]; B_3: Average conveyance efficiency of irrigation canal systems [%]; B_4: The average irrigation water per mu (m³/mu); B_5: Cultivation index [%]; B_6: Industrial water recycle rate [%]; B_7: Water consumption per ten thousand Yuan of value added by industry [$m^3/10^4$Yuan]; B_8: Per capita daily domestic water use [l/person and day]; B_9: Total resident population [person]; B_{10}: Treated wastewater reuse rate [%]; B_{11}: Annual average precipitation [mm]; B_{12}: Wastewater treatment rate [%]; B_{13}: Ratio of wastewater to total water resources [%]; B_{14}: Annual average temperature [°C]; B_{15}: Rate of Industrial wastewater up to the discharge standards [%]; B_{16}: Urban green coverage rate in built-up area [%]; B_{17}: Urban population [person]) (source: STATISTICS BUREAU OF URUMQI 2004-2011; WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010).

Year	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}	B_{17}
2003	19085	2.39	38	821	4.23	94.38	105	250.2	1998144	17	369.4	46.2	23.87	6.7	87.77	23.84	1732947
2004	21990	2.35	40	720	4.18	95.78	82	160.1	2045955	20	314.2	44	17.21	7.9	91.69	25.13	1775614
2005	24444	2.24	45	671	4.98	95.45	73	161.89	2129503	39	276.3	50	16.33	7.5	92.39	25.31	1856052
2006	27357	2.08	46	649	4.79	96.48	40	162.99	2210302	20	235.9	69.3	15.73	8.6	85.14	21.47	1931114
2007	30771	2.01	48	685	4.58	96.79	36	176.41	2312964	24	419.5	66	16.05	8.5	99.3	24.22	2223036
2008	35953	1.54	50	677	4.76	95.61	47	186.18	2360527	13	171.8	59.5	20.9	8.7	79.16	24.22	2269418
2009	38249	1.53	54.9	613	4.88	96.89	43	142.45	2411938	23	353.1	54	17.48	8	87.98	34.25	2318846
2010	44917	1.49	62	639	4.81	95	30	142.45	2430315	24.5	282.4	60.7	22.9	7.4	91.95	34.8	2335780

Table A-2 The input data for the quota method used to predict water demand prediction in Urumqi (Q_A: the average irrigation water quota [m^3/mu]; f_a: the farmland area [mu]; T_{nl}: the total number of livestock [head]; Q_L: the quota of water demand for livestock [l/head and day]; I_{va}: the value added by industry [billion Yuan]; WC_{Iva}: the water consumption per value added by industry [m^3/10^{4}Yuan]; U_1: the per capita urban domestic water consumption (including public water use, such as water used for construction and landscaping) [l/person and day]; U_2: the per capita rural domestic water consumption (including water used for the rural environment) [l/person and day]; R_2: the total population [million people]; r_u: the urbanization rate [%]) (source: STATISTICS BUREAU OF URUMQI 2005, 2006, 2008,2009,2010 and 2011; WATER AFFAIRS BUREAU OF URUMQI 2003, 2004, 2005, 2007, 2008, 2009 and 2010).

Year	Q_A [m^3/mu]	f_a [mu]	T_{nl} [head]	Q_L [l/head and day]	I_{va} [billion Yuan]	WC_{Iva} [m^3/10^4 Yuan]	U_1 [l/person and day]	R_2 [million people]	r_u [%]	U_2 [l/person and day]
2004	720	734400	860300	13	12.4	82	326	2.045955	86.79	91
2005	671	687600	888000	14	16.553	73	298	2.129503	87.16	108
2007	685	865650	802300	15	26.1	36	311	2.312964	96.11	129
2008	574	1014300	799100	8	35.5	47	234	2.360527	96.14	117
2009	613	1008450	794900	10	38.6	43	198	2.411938	96.14	124
2010	639	994500	802600	10	52.488	30	267	2.430315	96.11	140
2015	550	975000	893618	10	122	22.5	270	2.940431	94.5	120

A.2 The results of calculations

Table A-3 The anomaly rate of precipitation from 1988 to 2010 (source: own calculations; Total annual precipitation: STATISTICS BUREAU OF URUMQI 1989-2011)

Year	Total annual precipitation [mm]	Average annual precipitation [mm]	Anomaly rate of precipitation
1988	373.5	304	0.23
1989	262.2	304	-0.14
1990	291.6	304	-0.04
1991	177.8	304	-0.42
1992	348.4	304	0.15
1993	300	304	-0.01
1994	311.4	304	0.02
1995	240.7	304	-0.21
1996	390.9	304	0.29
1997	159.8	304	-0.47
1998	419.2	304	0.38
1999	336.3	304	0.11
2000	332.3	304	0.09
2001	277.7	304	-0.09
2002	342.2	304	0.13
2003	369.4	304	0.22
2004	314.2	304	0.03
2005	276.3	304	-0.09
2006	235.9	304	-0.22
2007	419.5	304	0.38
2008	171.8	304	-0.43
2009	353.1	304	0.16
2010	282.4	304	-0.07

Table A-4 The monthly precipitation anomaly percentage (unit: %) (source: own calculations).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1988	8	28	-85	-26	87	89	-9	91	75	30	-47	-51
1989	-7	-6	-66	-25	-100	96	-74	-20	181	58	-56	-53
1990	102	-38	120	29	-77	-27	34	-86	-41	-23	121	-61
1991	-60	-51	-10	-96	-79	-3	-48	89	-60	-56	-78	-9
1992	-25	-41	-8	-13	67	5	81	-75	70	-22	23	32
1993	-75	72	75	-56	-11	81	-27	28	15	-52	-42	-1
1994	-29	-33	-55	119	-41	-35	-4	-88	-12	130	-7	98
1995	-72	22	3	-57	19	-70	-19	-27	-88	92	-33	-12
1996	65	-54	44	97	6	-62	109	18	-11	62	32	-48
1997	-24	-73	-34	-99	9	-60	-50	-33	-97	-99	40	-60
1998	-47	-18	-9	58	206	-69	82	78	-16	-57	-25	13
1999	57	-83	53	-23	-59	67	-32	94	51	10	-30	84
2000	138	56	-30	-42	-38	100	-53	34	-26	138	41	-52
2001	103	-47	-79	33	-85	-25	52	-59	62	97	-56	-69
2002	-25	25	69	156	-53	113	-6	-85	-28	-62	-18	57
2003	4	-38	-40	6	43	21	69	54	136	-100	38	-55
2004	-25	185	23	-35	-12	-78	47	-15	-35	-29	-12	147
2005	-56	-70	-67	-1	-39	-2	-59	176	-91	-57	70	34
2006	36	227	-48	-46	23	-44	-70	-77	-66	-26	59	-69
2007	35	-17	-61	-6	161	-42	165	70	23	-27	-72	-5
2008	-76	-12	-10	-39	-62	-69	-48	-46	-24	-39	-34	-29
2009	-51	-10	78	83	72	35	-73	-61	60	-26	41	30
2010	22	-28	138	-16	-36	7	-67	-60	-77	55	45	77

Table A-5 The frequencies of monthly drought (source: own calculations).

Month	Drought frequency [%]			
	Light	Moderate	High	Extremely high
Jan	17.39	13.04	0	0
Feb	17.39	8.7	4.35	0
Mar	13.04	17.39	4.35	0
Apr	17.39	0	0	8.7
May	13.04	13.04	4.35	4.35
Jun	8.7	26.09	0	0
Jul	21.74	17.39	0	0
Aug	8.7	17.39	13.04	0
Sep	4.35	13.04	8.7	4.35
Oct	17.39	4.35	0	8.7
Nov	17.39	8.7	0	0
Dec	26.09	13.04	0	0

Table A-6 The values for the total population predicted by the polynomial regression, the malthusian growth model and the logistic model (unit: million people) (source: Investigated values: STATISTICS BUREAU OF URUMQI 2011; own calculations).

Year	Investigated values	Polynomial regression	Malthusian growth model	Logistic model
1949	0.10771	0.0674779	0.404446	0.393883
1950	0.121746	0.102032	0.416788	0.407911
1951	0.125275	0.137364	0.429505	0.422393
1952	0.137533	0.173372	0.442611	0.437340
1953	0.150658	0.209956	0.456117	0.452763
1954	0.20236	0.247021	0.470035	0.468675
1955	0.220296	0.284473	0.484377	0.485086
1956	0.275752	0.322221	0.499157	0.502008
1957	0.394431	0.360179	0.514389	0.519453
1958	0.408566	0.398262	0.530085	0.537431
1959	0.589337	0.436393	0.546259	0.555955
1960	0.703968	0.474494	0.562928	0.575034
1961	0.598746	0.512494	0.580105	0.594681
1962	0.514719	0.550327	0.597806	0.614906
1963	0.518996	0.587929	0.616047	0.635719
1964	0.578645	0.625244	0.634845	0.657131
1965	0.626242	0.662217	0.654217	0.679152
1966	0.640836	0.698803	0.674179	0.701792
1967	0.680541	0.734959	0.694751	0.725060
1968	0.721428	0.770648	0.715951	0.748965
1969	0.769472	0.805841	0.737797	0.773516
1970	0.763979	0.840514	0.760310	0.798720
1971	0.779667	0.874648	0.783510	0.824585
1972	0.967543	0.908232	0.807418	0.851118
1973	1.014345	0.941261	0.832055	0.878325
1974	0.987454	0.973738	0.857444	0.906212
1975	1.048828	1.00567	0.883608	0.934783
1976	1.098866	1.03708	0.910570	0.964043
1977	0.95133	1.06798	0.938355	0.993995
1978	1.14844	1.09842	0.966988	1.024642
1979	1.160109	1.12843	0.996494	1.055984
1980	1.190511	1.15805	1.026901	1.088022
1981	1.206337	1.18736	1.058235	1.120757
1982	1.242716	1.2164	1.090526	1.154185
1983	1.239603	1.24526	1.123802	1.188306
1984	1.28277	1.27402	1.158093	1.223114
1985	1.310609	1.30277	1.193431	1.258605
1986	1.344845	1.33162	1.229847	1.294773
1987	1.362899	1.36067	1.267374	1.331610
1988	1.378097	1.39005	1.306047	1.369108
1989	1.414874	1.41989	1.345899	1.407257
1990	1.462561	1.45034	1.386968	1.446046
1991	1.488794	1.48154	1.429289	1.485461
1992	1.522376	1.51365	1.472902	1.525490
1993	1.512427	1.54687	1.517846	1.566117
1994	1.53872	1.58136	1.564161	1.607326
1995	1.606502	1.61733	1.611889	1.649098
1996	1.646063	1.65499	1.661074	1.691414

1997	1.687328	1.69455	1.711760	1.734254
1998	1.716648	1.73625	1.763992	1.777596
1999	1.75958	1.78034	1.817818	1.821418
2000	1.816918	1.82707	1.873286	1.865694
2001	1.865712	1.87671	1.930447	1.910399
2002	1.936091	1.92955	1.989353	1.955508
2003	1.998144	1.98588	2.050055	2.000992
2004	2.045955	2.04602	2.112610	2.046822
2005	2.129503	2.11027	2.177074	2.092970
2006	2.210302	2.17899	2.243504	2.139404
2007	2.312964	2.25252	2.311962	2.186094
2008	2.360527	2.33123	2.382509	2.233007
2009	2.411938	2.41549	2.455208	2.280111
2010	2.430315	2.5057	2.530125	2.327373
2011		2.60228	2.607329	2.374760
2012		2.70563	2.686888	2.422236
2013		2.81621	2.768875	2.469770
2014		2.93446	2.853364	2.517324
2015		3.06087	2.940431	2.564867

Table A-7 The results of agricultural water demand, industrial water demand, domestic water demand and total water demand in Urumqi predicted by the grey model (unit: million m³) (source: own calculations).

Year	Agriculture		Industry	Domestic sector	Total	
	Grey model	Advanced grey model			Grey model	Advanced grey model
2003	500.10	500.10	103.67	201.25	805.02	805.02
2004	456.55	448.92	106.06	185.44	746.45	738.76
2005	493.21	492.89	114.70	189.93	797.35	797.84
2006	532.81	537.25	124.05	194.53	851.73	857.36
2007	575.59	582.00	134.17	199.24	909.81	917.32
2008	621.80	627.13	145.11	204.06	971.85	977.73
2009	671.73	672.66	156.94	209.00	1038.13	1038.58
2010	725.66	718.60	169.74	214.06	1108.92	1099.89
2011	783.92	764.93	183.57	219.24	1184.54	1161.65
2012	846.87	811.66	198.54	224.54	1265.32	1223.86
2013	914.86	858.81	214.73	229.98	1351.61	1286.54
2014	988.32	906.37	232.24	235.54	1443.78	1349.68
2015	1067.67	954.34	251.17	241.25	1542.23	1413.29

A.3 Matlab Program

A.3.1 The priority vector and consistency for water scarcity decisions

Main Program

```
clear %clears all variables
```

```
clc %clears screen
A=[ ]; % input data
M1=A(1,1)*A(1,2)*A(1,3)*A(1,4)*A(1,5)*A(1,6)*A(1,7)*A(1,8);%eqation (4.21)
M2=A(2,1)*A(2,2)*A(2,3)*A(2,4)*A(2,5)*A(2,6)*A(2,7)*A(2,8); %eqation (4.21)
M3=A(3,1)*A(3,2)*A(3,3)*A(3,4)*A(3,5)*A(3,6)*A(3,7)*A(3,8); %eqation (4.21)
M4=A(4,1)*A(4,2)*A(4,3)*A(4,4)*A(4,5)*A(4,6)*A(4,7)*A(4,8); %eqation (4.21)
M5=A(5,1)*A(5,2)*A(5,3)*A(5,4)*A(5,5)*A(5,6)*A(5,7)*A(5,8); %eqation (4.21)
M6=A(6,1)*A(6,2)*A(6,3)*A(6,4)*A(6,5)*A(6,6)*A(6,7)*A(6,8); %eqation (4.21)
M7=A(7,1)*A(7,2)*A(7,3)*A(7,4)*A(7,5)*A(7,6)*A(7,7)*A(7,8); %eqation (4.21)
M8=A(8,1)*A(8,2)*A(8,3)*A(8,4)*A(8,5)*A(8,6)*A(8,7)*A(8,8); %eqation (4.21)
n=8;
N1=M1^(1/n); %eqation (4.22)
N2=M2^(1/n); %eqation (4.22)
N3=M3^(1/n); %eqation (4.22)
N4=M4^(1/n); %eqation (4.22)
N5=M5^(1/n); %eqation (4.22)
N6=M6^(1/n); %eqation (4.22)
N7=M7^(1/n) %eqation (4.22)
N8=M8^(1/n) %eqation (4.22)
N=N1+N2+N3+N4+N5+N6+N7+N8;
Omigar=[N1/N   N2/N   N3/N   N4/N   N5/N   N6/N   N7/N   N8/N]'
Bu=A* Omigar;
LamarMax=Bu(1)/(r*Omigar(1))+Bu(2)/(r*Omigar(2))+Bu(3)/(r*Omigar(3))+Bu(4)/(r*Omigar(4))+Bu(5)/(r*Omigar(5))+Bu(6)/(r*Omigar(6))+Bu(7)/(r*Omigar(7))+Bu(8)/(r*Omigar(8)); % The maximum eigenvalue λmax of the comparison matrix %equation (4.25)
CI=(LamarMax-r)/(r-1); %equation (4.26)
RI=1.41;% Table 4-12, when n = 8, RI = 1.41
CR=CI/RI % Consistency index (CI) and consistency ration (CR)%equation (4.27)
```

A.3.2 Matlab program for population projection

A.3.2.1 Malthusian growth model

```
<fun.m>
function f=fun(P, t)
```

```
f=exp(P(1)+P(2)*t)
end

Main Program
clear %clears all variables
clc %clears screen
t=1949:1:2010
population=[] %input data (investigated values)
P0=[0, 0]
[P,resnorm]=lsqcurvefit(@fun,P0,t,population) %call the fun.m
a=P(1)
b=P(2)
u=1949:1:2015
s=exp(a+b*u)
```

A.3.2.2 Logistic model

```
<fun1.m>
function f=fun1(P,t)
f=1./(1/5+exp(-P(1)-P(2)*t));
end

Main Program
clear %clears all variables
clc %clears screen
t=1949:1:2010
population=[] % input data (investigated values)
P0=[0,0]
[P,resnorm]=lsqcurvefit(@fun1,P0,t,population) %call the fun1.m
a=P(1)
b=P(2)
u=1949:1:2015
s=1./(1/5+exp(-a-b*u))
```

A.3.3 Matlab program for prediction of water demand

A.3.3.1 Agricultural water demand predicted by the grey model

```
Main Program
clear %clears all variables
clc %clears screen
format long
A0=[500.1 464.27 505.11 484 590.15 628.87 706.18 701.11] % input data (original
sequence)
[m,n]=size(A0);
A1=cumsum(A0);%AGO
A2=[];
for i=1:n-1;
  A2(i, :)=A1(i)+A1(i+1)
end
M=-0.5.*A2;
t=ones(n-1,1);
M=[M,t]; % the accumulated matrix M %equation (6.25)
YN=A0(2:end);
P_t=YN./A1(1:(length(A0)-1));
N=inv(M.'*M)*M.'*YN.';
a=N(1);
u=N(2);
c=u/a;
b=A0(1)-c;
 A=[num2str(b),'exp','(',num2str(-a),'k',')',num2str(c)];
 strcat('A(k+1)=',A);
for t=1:length(A0)+5
    k(1,t)=t-1
 end
 k
Y_k_1=b*exp(-a*k)+c;
for j=1:length(k)-1
  Y(1,j)=Y_k_1(j+1)-Y_k_1(j)
end %IAGO
```

```
AY=[Y_k_1(1),Y]; %predicted value
AYY=AY(1:length(A0));
CA=abs(AYY-A0); % Error
Theta=CA; % Absolute error sequence % equation (6.29)
qq= CA./A0; % equation (6.30)
q=sum (abs(qq))/(length (A0)); % Average relative error
AV=mean(CA); % the mean of the absolute error
R_k=(min(Theta)+0.5*max(Theta))./(Theta+0.5*max(Theta));% Relational coefficient test
ρ=0.5 % equation (6.32)
R=sum(R_k)/length(R_k); % The relational degree (τ)
Temp0=(CA-AV).^2;
Temp1=sum(Temp0)/length(CA);
S2=sqrt(Temp1); % The standard deviation of the absolute error sequence % equation
(6.35)
AV_0=mean(A0);
Temp_0=(A0-AV_0).^2; % The mean of the original sequence
Temp_1=sum(Temp_0)/length(CA);
S1=sqrt(Temp_1); % The standard deviation of the original sequence % equation (6.34)
TempC=S2/S1*100; % The variance ratio (Vr) % equation (6.36)
C=strcat(num2str(TempC), '%'); % Posteriori error test
SS=0.6745*S1; %Posteriori error test
Delta=abs(CA-AV); % Posteriori error test
TempN=find(Delta<=SS); % Posteriori error test
N1=length(TempN);
N2=length(CA);
TempP=N1/N2*100;
P=strcat(num2str(TempP),'%') % the error probability (Ø(prob))
```

A.3.3.2 Agricultural water demand predicted by the advanced grey model

Main Program

```
clear %clears all variables
clc %clears screen
format long
T=[500.1 464.27 505.11 484 590.15 628.87 706.18 701.11];
```

```
% input data (original sequence)
n=length(T);% the size of the original sequence
lamda=T(1:n-1)./T(2:n); % equation (6.50)
range=minmax(lamda);
ran=[exp(-2/(n+1)),exp(2/(n+2))];
A0=T+sum(T);% T is the sum of the variables in the original sequence % equation (6.51)
[m,n]=size(A0);
A1=cumsum(A0);%AGO
A2=[];
for i=1:n-1
   A2(i,:)=A1(i)+A1(i+1)
end
M=-0.5.*A2;
t=ones(n-1,1);
M=[M,t];
YN=A0(2:end);
P_t=YN./A1(1:(length(A0)-1));
N=inv(M.'*M)*M.'*YN.';
a=N(1);
u=N(2);
c=u/a;
b=A0(1)-c;
 A=[num2str(b),'exp','(',num2str(-a),'k',')',num2str(c)];
 strcat('A(k+1)=',A);
for t=1:length(A0)+10
     k(1,t)=t-1
 end
 k
Y_k_1=b*exp(-a*k)+c;
for j=1:length(k)-1
   Y(1,j)=Y_k_1(j+1)-Y_k_1(j)
end %IAGO
AY=[Y_k_1(1),Y];
AYY=AY(1:length(A0));
CA=abs(AYY-A0); % Error
```

```
Theta=CA; % Absolute error equation (6.29)
qq= CA ./ A0; % equation (6.30)
q=sum (abs(qq))/(length (A0)); % Average relative error
AV=mean(CA);
R_k=(min(Theta)+0.5*max(Theta))./(Theta+0.5*max(Theta));% Relational coefficient test
ρ=0.5 % equation (6.32)
R=sum(R_k)/length(R_k)  % The relational degree (τ)
Temp0=(CA-AV).^2; % The mean of the original sequence
Temp1=sum(Temp0)/length(CA);
S2=sqrt(Temp1); % The standard deviation of the absolute error sequence % equation
(6.35)
AV_0=mean(A0);
Temp_0=(A0-AV_0).^2;
Temp_1=sum(Temp_0)/length(CA);
S1=sqrt(Temp_1); % The standard deviation of the original sequence % equation (6.34)
TempC=S2/S1*100; % The variance ratio (Vr) % equation (6.36)
C=strcat(num2str(TempC), '%'); % Posteriori error test
SS=0.6745*S1; % Posteriori error test
Delta=abs(CA-AV); ); % Posteriori error test
TempN=find(Delta<=SS); % Posteriori error test
N1=length(TempN);
N2=length(CA);
TempP=N1/N2*100;
P=strcat(num2str(TempP),'%'); % the error probability (Ø(prob))
TT=AY-sum(T) %predicted value
```

A.4 The comparison matrix for decisions against each factor

The pairwise comparison matrix for decisions against factor 1 (the per capita GDP):

$$C_1 = \begin{bmatrix} 1 & 5 & 7 & 3 & 4 & 3 & 9 \\ 1/5 & 1 & 3 & 1/3 & 1/2 & 1/3 & 5 \\ 1/7 & 1/3 & 1 & 1/5 & 1/4 & 1/5 & 3 \\ 1/3 & 3 & 5 & 1 & 2 & 1 & 7 \\ 1/4 & 2 & 4 & 1/2 & 1 & 1/2 & 6 \\ 1/3 & 3 & 5 & 1 & 2 & 1 & 7 \\ 1/9 & 1/5 & 1/3 & 1/7 & 1/6 & 1/7 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 2 (the proportion of primary industry output-value):

$$C_2 = \begin{bmatrix} 1 & 1 & 6 & 3 & 5 & 4 & 8 \\ 1 & 1 & 6 & 3 & 5 & 4 & 8 \\ 1/6 & 1/6 & 1 & 1/4 & 1/2 & 1/3 & 3 \\ 1/3 & 1/3 & 4 & 1 & 3 & 2 & 6 \\ 1/5 & 1/5 & 2 & 1/3 & 1 & 1/2 & 4 \\ 1/4 & 1/4 & 3 & 1/2 & 2 & 1 & 5 \\ 1/8 & 1/8 & 1/3 & 1/6 & 1/4 & 1/5 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 3 (the average conveyance efficiency of irrigation canal systems):

$$C_3 = \begin{bmatrix} 1 & 1/8 & 1/2 & 1/2 & 1/5 & 1/4 & 1/2 \\ 8 & 1 & 9 & 9 & 7 & 6 & 9 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 5 & 1/7 & 3 & 3 & 1 & 1/4 & 3 \\ 4 & 1/6 & 2 & 2 & 4 & 1 & 2 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 4 (the average irrigation per mu):

$$C_4 = \begin{bmatrix} 1 & 1/8 & 1/2 & 1/2 & 1/5 & 1/4 & 1/2 \\ 8 & 1 & 9 & 9 & 7 & 6 & 9 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \\ 5 & 1/7 & 3 & 3 & 1 & 1/4 & 3 \\ 4 & 1/6 & 2 & 2 & 4 & 1 & 2 \\ 2 & 1/9 & 1 & 1 & 1/3 & 1/2 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 7 (the water consumption per value added by industry):

$$C_7 = \begin{bmatrix} 1 & 5 & 7 & 3 & 6 & 4 & 8 \\ 1/5 & 1 & 4 & 1/4 & 3 & 1/3 & 5 \\ 1/7 & 1/4 & 1 & 1/6 & 1/3 & 1/5 & 3 \\ 1/3 & 4 & 6 & 1 & 5 & 3 & 7 \\ 1/6 & 1/3 & 3 & 1/5 & 1 & 1/4 & 4 \\ 1/4 & 3 & 5 & 1/3 & 4 & 1 & 6 \\ 1/8 & 1/5 & 1/3 & 1/7 & 1/4 & 1/6 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 9 (the total resident population):

$$C_9 = \begin{bmatrix} 1 & 1/7 & 2 & 1/6 & 1/2 & 1/3 & 3 \\ 7 & 1 & 8 & 2 & 6 & 5 & 9 \\ 1/2 & 1/8 & 1 & 1/7 & 1/3 & 1/4 & 2 \\ 6 & 1/2 & 7 & 1 & 5 & 4 & 8 \\ 2 & 1/6 & 3 & 1/5 & 1 & 1/2 & 4 \\ 3 & 1/5 & 4 & 1/4 & 2 & 1 & 5 \\ 1/3 & 1/9 & 1/2 & 1/8 & 1/4 & 1/5 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 16 (the urban green coverage rate in built-up areas):

$$C_{16} = \begin{bmatrix} 1 & 1/5 & 1/3 & 1/4 & 1/6 & 1/7 & 4 \\ 5 & 1 & 4 & 3 & 1/3 & 1/4 & 7 \\ 3 & 1/4 & 1 & 1/3 & 1/5 & 1/6 & 5 \\ 4 & 1/3 & 3 & 1 & 1/4 & 1/5 & 6 \\ 6 & 3 & 5 & 4 & 1 & 1/2 & 8 \\ 7 & 4 & 6 & 5 & 2 & 1 & 9 \\ 1/4 & 1/7 & 1/5 & 1/6 & 1/8 & 1/9 & 1 \end{bmatrix}$$

The pairwise comparison matrix for decisions against factor 17 (the urban population):

$$C_{17} = \begin{bmatrix} 1 & 1/6 & 1/3 & 1/4 & 1/5 & 1/7 & 4 \\ 6 & 1 & 5 & 4 & 3 & 1/3 & 8 \\ 3 & 1/5 & 1 & 1/3 & 1/4 & 1/6 & 5 \\ 4 & 1/4 & 3 & 1 & 1/3 & 1/5 & 6 \\ 5 & 1/3 & 4 & 3 & 1 & 1/4 & 7 \\ 7 & 3 & 6 & 5 & 4 & 1 & 9 \\ 1/4 & 1/8 & 1/5 & 1/6 & 1/7 & 1/9 & 1 \end{bmatrix}$$

A.5 Software requirements of the water resources management and information system for Urumqi

The software requirements of the water resources management and information system for Urumqi must be configured as follows:

Operation system: Windows XP

Web server: Microsoft Internet Information (IIS) 5.0

Environment for running programs: .Net Framework 2.0

Database server: Microsoft SQL Server 2005

GIS server: ArcGIS Server 9.3

Environment for running GIS: Web ADF.net

Eidesstattliche Erklärung

Ich erkläre hiermit, dass ich die vorgelegte Dissertation selbst verfasst und mich keiner anderen als der von mir ausdrücklich bezeichneten Quellen und Hilfen bedient habe.

Ich erkläre hiermit, dass ich an keiner anderen Stelle ein Prüfungsverfahren beantragt bzw. die Dissertation in dieser oder anderer Form bereits anderweitig als Prüfungsarbeit verwendet oder einer anderen Fakultät als Dissertation vorgelegt habe.

Heidelberg, den 29.01.2013