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A Spatial Model (SWAM) for Water Efficiency and Irrigation Technology Choices

A case study from Northwestern China

Lan Fang

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**A Spatial Model (SWAM) for Water Efficiency and Irrigation
Technology Choices
A case study from Northwestern China**

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Preface

The study is a part of a series of analyses of the farming and rural system economics in China, carried out within the DAAD Program "Agricultural Economics and Related Sciences". This PhD thesis and the underlying empirical and methodological research has been supervised by Prof. Dr. Ernst-August Nuppenau at the University of Giessen / Germany. The research, including a half-year field study, has been done within the period between 1999 and 2003 and led to a PhD-Degree for the author.

In the study a spatial water allocation model, SWAM, was designed to assess the impact of public and private investments on water resource allocation and social welfare in an irrigation area in northwestern China. The author made use a combination of econometrics and mathematical programming approaches for this work. An important feature of the study is to use dynamic optimal control theory to model the movements of canal water and groundwater in an irrigation area. The results of the model suggest that public investments play a very important role in improving water transit efficiency. The private investments in irrigation technology will improve on-farm water efficiency significantly. A high water price will strongly drive farmers to go for modern irrigation technologies. The study also unveils a relationship of combination between public and private investments. They are complementary with respect to improving overall water efficiency in an irrigation area, and they are substitutional with respect to absolute costs within social welfare. Finally, based on the model results, the author recommends a set of policies, which may initiate a more efficient water management.

For the editors: Siegfried Bauer, University of Giessen, Germany

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List of Abbreviations

SWAM: Spatial water allocation model
Mu: Chinese land measurement. One Mu = 1/ 15 Hectare
CWU: Canal water users
GWU: Groundwater users
MTU: Modern irrigation technology users
TTU: Traditional irrigation technology users

List of scenarios

LSEK: Optimal public investment scenario, base run model.
LSDI: Nearly real situation scenario
LSAI: Potential requirement of government intervention scenario
LSFI: Government promoted scenario
LSRK1: A removal of public investment under low soil permeability scenario
HSRK1: A removal of public investment under high soil permeability scenario
LSRK2: A removal of public investment with private investment participation scenario under low soil permeability
HSRK2: A removal of public investment with private investment participation scenario under high soil permeability

1   INTRODUCTION

1.1   Background and problem statement

Water, as a vital resource for human beings, is increasingly becoming scarce on our planet. A United Nation (UN)-sponsored Conference of water experts, held in Geneva in February 1999, stated, that in 50 years time, up to 2 billion people could face severe water shortages. At least one billion people will be living in regions of absolute water scarcity (BBC, 2001).

Agriculture is the biggest consumer of water. Typically, the major consumption of water is irrigated agriculture, which accounts for 73% in both developing and developed countries. Industrial consumption accounts for 21% and domestic uses account for the rest of 6% (SECKLER, DAVID, DAVID MOLDEN et al., 1999). It becomes increasingly important to manage and use water resources more efficiently, especially in developing countries. Developing countries possess 75% of the world's irrigated land area, and moreover twice as much water is used per acre in developing countries than in developed countries, in particular, due to poor management (SECKLER et al., 1999).

China is rich in water resources but its water resources are extremely unevenly distributed over the country. China possesses two of the world's longest rivers, the Yangtze and the Yellow Rivers with water reserves of total 2,800 billion cubic meters (m^3). China's water resources are the fifth richest in the world after Brazil, Russia, Canada and the United States. But the uneven distribution of water resources in China creates severe water shortages in certain areas of the country. In the densely populated areas of southern China, the Yangtze River and the Pearl River basins provide a relatively abundant water supply. But areas north of the Yangtze River which account for 60% of China's land mass and half of its population only receive approximately 20% of the nation's water resources. In particular, the northwest region and the northern China Plain often suffer from great water shortages (WWW.H2O-CHINA.COM, 2001).

Managing and utilizing the water resources efficiently is a challenge to China. Inefficient use of limited water supply worsens the situation of water shortage. China only recycles 20-30% of its industrial water. The water consumption per industrial product is 5 to 10 times higher than that in industrialized countries. Agriculture consumes approximately 80% of China's water supply, but only about 57% of this water is used efficiently. The rest is lost due to under-developed technology and inefficient management (WWW.H2O-CHINA.COM, 2001).

Given limited water resources and inefficient utilization of water, water scarcity and mismanagement will certainly hamper the further growing of the Chinese economy. How to improve the management of water resources, especially in irrigated agriculture, is a great task that Chinese people are facing in the next decades.

1.2   Objectives and hypotheses of the study

The purpose of this study is, on one hand, to provide policy makers with a theoretical and quantitative tool to manage public goods, such as water resources, more efficiently and to improve the allocation of water in irrigation projects. On the other hand, farmers' behaviors are taken into account in terms of adoption of modern irrigation technology. Hence the objectives of this study are:

- To determine the optimum amounts of surface and groundwater consumption at different locations in an irrigation project.

- To investigate the efficiency of water conveyance systems supported by public investment.

- To investigate on-farm water use efficiency by analyzing the necessary private investment to be undertaken.

- To explore the relationship between public investment and private investment.

- To analyze different impacts on the social economy and water resource allocation by considering different amounts of public and private investment.

- To optimize the social welfare of farmers living in an irrigation area.

In line with these objectives of the study, two main hypotheses are tested:

1) The efficiency of using water can be improved by adopting modern irrigation technologies combined with an increase of public investment in a water conveyance system.

2) If the optimization for an entire watershed is considered, it may be justified to allow for significant water losses from the canal and the fields.

1.3   Presentation of the study

In order to achieve the aforementioned objectives, this dissertation is presented in eleven chapters.

- Chapter one gives a general introduction to the research background and a problem statement as well as the objectives, hypotheses and organization of this study.

- Chapter two explains the research design and describes the socio-economic situation, the farming system, and the current status of irrigation in the survey area.

- Chapter three gives a primary analysis of the application of current water saving technologies and revenues from apple production. It shows input shares of apple production in terms of irrigation fees, labor contribution, fertilizer and insecticide expenditures as based on empirical findings of the field survey.

- Chapter four reviews literatures as related to institutional aspects of water allocation, definition of water saving, water conveyance, and water management as well as the intended modeling approaches. Models used for surface water allocation and for groundwater allocation are presented, as well as models for a conjunction of water use of surface and groundwater are reviewed.

- Chapter five describes the methodology and the structural framework of the study. A spatial water allocation model (SWAM), to be applied in the study, is introduced as a spatial mathematic programming model. There are two parts in this model. The first part is an estimated econometric model, and the second part is a non-linear spatial programming model. The estimated econometric model will serve as a component in the programming model through a GAMS approach using the parameters of the econometric model.

- Chapter six presents the results of the econometric model as described in chapter 5. In particular the water demand function, the revenue function and the on-farm water efficiency function as well as the canal water loss function will be documented in this chapter.

- Chapter seven specifies the organization of the programming model. Relevant definitions, variables, and equations are presented there. The objective function and constrain conditions are also presented in this chapter. The maximization of social welfare and some indicators, such as quantity of water consumption, length of canal, revenue, land rent as well as water rent, will be solved through the modeling process.

- Chapter eight starts to present scenarios results. The selected scenarios explore the impacts of changing status of public investment on social welfare and water resource allocation.

- Chapter nine investigates the impacts of different distribution of private investment on social welfare and water resource allocation.

- Chapter ten investigates the impacts of price regime change on social welfare and water resource allocation.

- Chapter eleven summaries the main findings of the study. Policy recommendations and further research are also discussed in this chapter.

2 RESEARCH DESIGN AND GENERAL INFORMATION ABOUT THE STUDY AREA

This chapter presents the research design and offers general information about the study area. The research design includes the selection of the study area, the sample, and the questionnaire design. The general information about the geographical and socio-economic situation as well as a description of different kinds of technologies, applied in the study area, are presented in this chapter.

2.1 Research design

2.1.1 Selection of the case study area

Since the present study has two main goals to achieve through scenario design and optimization, the study area was selected for special purposes. One goal is to provide theoretical and quantitative support to policy makers to better allocate and manage irrigation projects in China. The other goal is to give suggestions to farmers to apply suitable water saving technologies. To achieve these goals, the case study selected, has mainly to fulfill the following criteria (AGRAWAL, EMRICH, FECHTER-ESCAMILLA et al., 1993):

● It should cover a relatively comprehensive irrigation system with advanced irrigation agriculture.

● It should cover all kinds of different irrigation technologies, i.e., from traditional technology to modern technology.

● It should be well documented, in order to facilitate the necessary work in a field survey. For instance, there should be proper records available in the administration of water resource management as well as in the villages.

● It should have a dominant cropping pattern because of requirements for simplification of the model.

According to these mentioned criteria, the Liquan County of Shaanxi province was selected as the study area. The work will show that it has been a right place to carry out the survey.

2.1.2 Sample and questionnaire design and interview conduct

The research started with a farm-family-household survey. In the farm-family-household survey, a simple random technique was applied. There were 149 interviews conducted in the field survey. Farmers in the irrigation area

were questioned according to the designed questionnaire. Two different questionnaires were administered, aiming at two different groups of people. One was designed for a group of farmers, who are located in the irrigation area; the other was designed for a group of employees of water management institutions. By this approach, different aspects of the irrigation system could be covered.

The questionnaire for farmers consists of two parts. The first part is related to farm characteristics, the second part is related to water use information. For instance, in the first part, the demography of the household, family characteristics, labor force, farmland, outlay, on-farm and off-farm income, agricultural inputs, credit and savings are listed. In the second part, irrigation fees, expenditures for purchasing modern irrigation equipment, expenditure of digging a tube well, and distances from the water source to the farm-gate are considered.

The questionnaire, aiming at public institutions, consists of information concerning water resource allocation and management. Problems with the current water management systems and potentials for improvement are also taken into consideration. This questionnaire is less complicated, as compared to that for the farmers. Furthermore, information regarding the existing irrigation systems was collected from published or unpublished materials and documents, all from relevant water institutions. A few interviews were made with government officials and technical staffs at departments of water resource management.
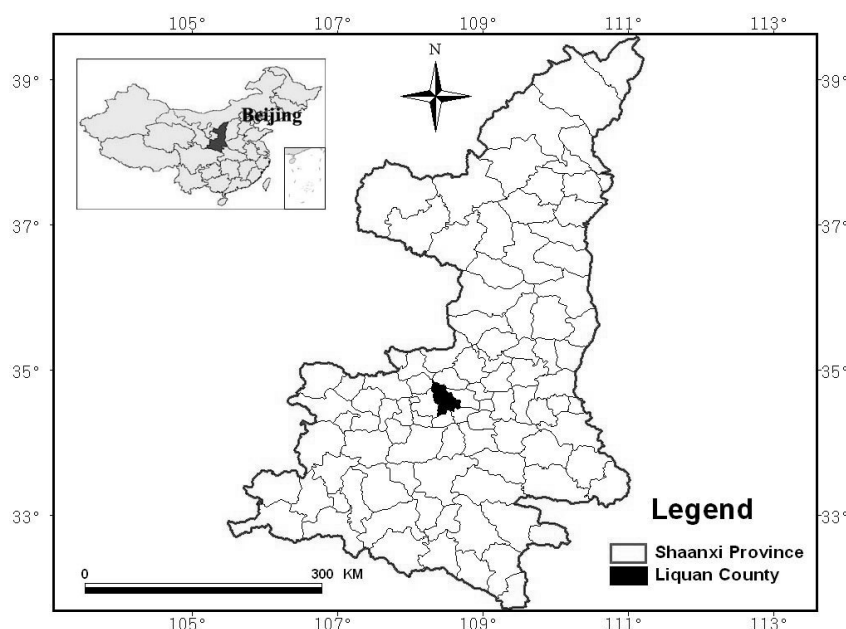
Figure 2.1: Map of Shaanxi Province, China
Source: Map Press, China

2.2   General information about the study area

2.2.1 Geographical and demographic information about the Shaanxi Province

Shaanxi province is situated in the northwest part of China, as shown in Figure 2.1. It extends approximately from 105°29″ to 111°15″ east longitude and from 31°42″ to 39°35″ north latitude. It is 200-500 kilometers (km) wide from east to west, and 870 km long from north to south. It covers an area of 205,600 square kilometer (km^2). It is bordered by Shanxi and Henan provinces in the east, Hubei and Sichuan provinces in the south, Gansu province and Ningxia Hui Autonomous Region in the west, and Inner Mongolia Autonomous Region in the north. The province is divided into two river basins by the Qinling Mountain. The southern area of Qinling Mountain lies in the Yangtze river basin, which covers an area of 72,302 km^2, i. e. 35.2% of the total area of the province; whereas the northern area lies in the Yellow River basin covering an area of 133,301 km^2, i. e 64.8% of the total area. Shaanxi province is divided into 10 districts, 107 counties and 2,135 townships. The total population is about 34 million. The population density is 169 people per km^2. Among the total population, about 27 million are farmers, i. e. 77.5% of the population (SHAANXI PROVINCIAL STATISTIC BUREAU, 2000).

The climate in the Shaanxi province is of a continental monsoon type. It is dry and cold in winter, relatively humid and hot in summer. Rainfall in this area normally concentrates in between July and September. Rainstorm and drought occur very often. According to different characteristics of the climate, the whole province is divided into three different climatic areas: temperate, semi-arid zone in northern Shaanxi, temperate, semi-humid zone in Guanzhong Basin and a sub-tropical humid zone in southern Shaanxi. The average annual rainfall in this province is about 676.4 millimeters (mm). Due to the geographical differences, the precipitation is unevenly distributed in the region. In the north which is located along the Great Wall, the average annual precipitation is 463.4 mm, whereas Guanzhong area receives 670.9 mm per year, and the south i.e., in Qinling–Daba Mountain area can be up to 925.3 mm per year. The evaporation also varies from region to region. It is 1000-1400 mm in the northern region, 900-1200 mm in Guanzhong region, and 800-900 mm in the south. The highest evaporation is observed in the northern desert area, soaring to 1400 mm annually (SHAANXI PROVINCIAL WATER RESOURCES MANAGEMENT OFFICE, 1997).

As a less-developed province, the agricultural sector still plays an important role in Shannxi's economy. By 1999, the provincial GDP reached 18 billion US Dollar,

of which the contributions of agriculture, industry and service sectors were 18%, 43% and 39%, respectively (SHAANXI PROVINCIAL STATISTIC BUREAU, 2000).

2.2.2 Irrigated agriculture in the Shaanxi Province

Shaanxi has a long history of irrigation agriculture. Irrigation agriculture existed already two thousand years ago in the area. Some frameworks of the old canal system still serve today's agricultural activities. There are 13.4 million hectares of irrigated land in this province, which account for 38% of the whole cultivated land of the province (DEPARTMENT OF WATER CONSERVANCY OF SHAANXI PROVINCE, 1997). The province is planning to become one of the main cereal and fruit production areas in China. A well-run irrigation system will be the most important premise to reach this goal.

Water shortage and inefficiency of water use coexist in this region. Most interesting is the Guanzhong Basin. Guanzhong Basin is the most important cereal and fruit production base in Shaanxi province, and it accounts for 75% of effectively irrigated area of the province. It also contributes more than 70% of GDP in the Shaanxi province, but it is severely short of water. The water demand in this region is 7.4 billion cubic meters (m^3) a year (SHAANXI PROVINCIAL WATER RESOURCES MANAGEMENT OFFICE, 1997). The current capacity of water resources basically can only supply 5.5 billion m^3 of water in a year. There exists a gap of 1.9 billion m^3 water annually. Meanwhile, in the three major irrigation areas of Shaanxi province - Jing River, Wei-River and Luo River area, the seepage rates of water transport by canals are normally up to 0.4-0.5% per km. The amount of these annual water losses would be sufficient to irrigate an increased area of 100,000 hectares of land. In addition, compared to water availability, this means that about 50% of water is lost in water conveyance system (WWW.IRIGATE.COM.CN, 2001). Another type of water loss is on-farm water loss. High rate of on-farm water loss indicates that most farmers in the region are accustomed to perform traditional flood and furrow irrigation techniques. This causes a lot of water waste and also crop damages occur. The water resources and the irrigation system in the area, consequently, need an improvement and better management.

2.2.3 Description of the actual area of case study area, Liquan County

It was not possible reasonably well to study the entire region and therefore a county, known as Liquan, was chosen for intensive studies. Liquan County is located in the north of the Guanzhong Basin and has a typical irrigated agricultural area. It was chosen as the case study area.

2.2.3.1 Physical and socio-economic situation in Liquan County

The county lies in the north of the Guanzhong Basin of Shannxi province. It covers 1,010 km^2, of which 56,667 hectares is arable land. The irrigated land is 39,200 hectares, which account for 70% of the total cultivated land. The county extends from 108°17′40″ to 108°41′46″ east longitude, and from 34°20′51″to 34°50′02″ north latitude. Precipitation in Liquan County is 558mm annually. Historically it was a typical rain-fed agricultural area and suffered from frequent drought, almost once every two years. By 1999 the population was 446,800, among them the rural population accounts for 406,200, i. e, 90.9% of the total population. The population density is 442 people per km^2 (BUREAU OF WATER RESOURCES OF LIQUAN COUNTY, 1999).

2.2.3.2 The Farming system in Liquan County

In the last decades, agriculture has developed quickly thanks to a good performance of the irrigation system in this area. Liquan County used to be one of the most important cereal production bases in Shaanxi province up to the 1980s. Still convenient water access secured agricultural production. However, the grain price in China has decreased year by year since the 1990's. Farmers could not get sufficient returns from their cereal products, which they sold to the market or to the government. Due to too high costs and low returns from grain production, some educated farmers converted their conventional grain production to fruit production. At first, this conversion occurred in the northern area, in which the irrigation system is close to end and farmers have relatively poorer access to get cheap water. Other basic inputs, such as fertilizer and insecticides were expensive as compared to those situated in the southern plain. The miracle was that farmers who converted to apple production got quite good returns from selling apples as compared to those still engaged in cereal production. After some years, the apple production became more and more popular in this county. Till now, Liquan County has become the largest apple production area in Shaanxi province. It is now known as a specialization area of apple production. The change in the farming system demonstrates that farmers start to convert production inputs, such as water, fertilizer, labor, etc, from a low-valued conventional grain to a high-valued crop production, such as fruit-trees and vegetables. In terms of water use efficiency, this is exactly what the water management institutions have long been trying to achieve: to persuade farmers to use water more efficiently and convert water into high-valued crops rather than low-value products. Though, a win-win situation occurs, economic and agronomic water efficiency has to be distinguished.

One notable point is, thanks to their early-start of apple production, that farmers located at the northern tail area have been finally better off, and some of them even are more wealthy than those living in the southern plain area of the study area. The major reason for this current situation is that it normally needs 3 to 5 years for a young apple tree to be able to bring an income to the farmers, and farmers situated in the upper southern plain started to grow apple only after they had seen the higher returns achieved by their counterparts in the northern downstream area. This indicates that the farmers located at the northern area benefited from apple production at least three years earlier than those in the southern plain area. And moreover, during that early time period the supply of apples was far less from meeting the demand so that the farmers received very good selling prices. One can also often find that a farmer living in the northern area is better equipped with farming machines than a farmer living in the southern plain. This is a general observation while doing interviews in the survey area. Naturally this kind of phenomenon cannot last long. After apple production becomes popular over the whole survey area, things will change. The average profit of apple production would doubtlessly go down after more farmers entered into the market. On the one side, it is the ever-growing apple supply, whereas the demand for apple cannot grow forever to meet the excessive supply. This certainly brings the price down. It implies that the farmers located at the upper southern plain, who started late to grow apples, might get by and large 2 years good return from that apple production, only. Nowadays the competition becomes even fiercer. However, the market of apples will not be involved in the present study due to limitations in the research scope. Nevertheless, the message delivered should be clear: in the survey area some farmers at the northern tail are already better off than those at the upper southern plain. This provided an opportunity for them, to afford costly modern irrigation technologies.

2.2.3.3 The Public irrigation network and problem statement in Liquan County

Liquan County has a relatively well-managed irrigation network. Public irrigation facilities ensure and promote the agricultural production potential for irrigation. This causes some conflicts between farmers and water management institutions and between farmers themselves. Farmers located close to the water source are used to applying flood irrigation thanks to the relative convenience of cheap access to the irrigation system. Contrary, those who are located distant from the water source cannot get sufficient water to irrigate their crops. In response to this problem, groundwater use has risen considerably. This not only makes the burden of water costs heavier but also potentially increases the probability of decline of the water table. A decline in the water table further increases water costs.

2.2.3.4 Specification of application of irrigation technologies and their application in the study area

In Liquan County, all kinds of irrigation technologies can be found: Traditional flood irrigation, locally produced seepage irrigation (also called locally produced drip irrigation) and modern irrigation technologies, such as drip and sprinkler irrigation technologies. They coexist in the area. Farmers, whose fields are located near the public canal, have convenient water access and get relatively cheap water. They normally apply conventional surface irrigation technologies, such as flood irrigation and border irrigation (also called furrow irrigation). Farmers living far away from the public canal are more likely to apply small-scale surface irrigation, such as basin check irrigation, or they use locally produced low cost seepage irrigation facilities. Modern water saving technologies, such as sprinkler and drip irrigation can also be found mostly, where farmers have heavily invested. Even dry land farming is an option for the poorest farmers. Again as explained before, all farmers use the expected water supply for high value tree-crops, for instance, apples and pears. On a certain area, they irrigate and leave the remaining land either fallow or plant drought resistant crops. Low-value crops are only planted occasionally in the hope there might be unexpected rainfall. In the present study, farmers perceived food security as dependent on high apple yields and apples are sold for food crops. Due to limited land, this means that water and irrigation schemes strongly contribute to survival and are a basis for rural livelihood. Meanwhile most farmers plant only very few conventional food crops, like maize and wheat. Rather, they buy food from local markets.

To get the understanding of technologies prevalent, one hundred and forty-nine interviews were conducted in the area. Among them, 75 farmers applied flood irrigation, 16 farmers applied border irrigation, 11 farmers applied seepage irrigation, 21 farmers applied basin check irrigation, 7 farmers applied sprinkler irrigation, 11 farmers applied drip irrigation, and 8 farmers applied dry land farming. Moreover, the character of different kinds of technologies is specified below:

Flood irrigation is a traditional surface irrigation technique in China. It is characterized by low labor input and simple technical requirements. But, water is wasted to a large extent, and water logging can occur. Increased salinity and alkalization are by-products of flood irrigation. The coefficient of water use is only 40-50%.

Border and basin check irrigation techniques are also a kind of flood irrigation but with smaller scale and more labor intensive. It works like this: a big plot of field is divided into some much smaller sized plots in order to retain water. Normally

this technique requires much more labor and some additional costs as compared to flood irrigation. The coefficient of water use efficiency is around 45-60%.

Seepage irrigation technique, which is also called locally produced drip irrigation, functions like modern drip irrigation, but it doesn't require such expenses as the costly purchase of equipment for drip irrigation. Rather simple tubes with holes are used. The utility coefficient of water is around 70-80%. Its main shortcoming is that tiny sands or soil easily plugs holes where water can seep.

Sprinkler irrigation is one type of modern irrigation technology. It is characterized by a production increase of 20-40% and less salinity. It has a higher efficiency in water use, which reaches approximately 80%. Another advantage is the saving of cultivated land by 15-20% due to the water transport on the field without furrows, ridging, ditches or paths in the fields.

Modern drip irrigation is currently considered the most advanced and effective irrigation technology in the region. It is characterized by a very high production capacity, increasing the efficiency of water use up to approximately 95%. Fertilizer can be at the same time added to the water during irrigation. The effect of fertilizer can increase production by more than 100%. At the same time, salinity is reduced due to low drainage needs.

2.3   Summary

The background and preparing work for the field study have been presented in this chapter. General information about field study area and especially the applied irrigation technologies in the survey area have also been specified. The main findings of field research will be presented in the next chapter.

3   FIELD SURVEY AND EMPIRICAL FINDINGS

The field research was conducted from August 2000 to January 2001 in the Liquan County of Shaanxi province, China. It was done during the harvest time of apples. 149 farmers were interviewed with respect to their production and irrigation activities. Since many farmers do not sell the apples till next year February (the time period of the Chinese New Year, e.g., when they can get a better price than selling the apples right after harvest), it was not possible to enquire the situation of revenue in the same year. The data on prices employed in the present study are from the previous agricultural year (1999), and they depended mainly on farmer's memory because proper paper records were not available. However the necessary information about production, inputs and other elements was collected from the previous (1999) and the current year (2000) and as reference materials recorded. All the information collected from farmers had been verified by local experts before they were incorporated into the database of the study. In order to avoid errors, as much as possible, double checks were carried out.

3.1   Specification of farmer groups by categories

Since the purpose of the study is to value the impacts of private and public investment on social welfare and water resource allocations of farmers by taking the water use efficiency into account, this aspect receives a major focus. In this study the concept of water use efficiency contains two aspects. One is the efficiency of the water conveyance system and the other is on-farm water use efficiency. In most countries, the water conveyance system is constructed and operated by the government, i.e., the public sector, and the improvement of the on-farm water use efficiency is mainly carried out by individual farmers, i.e., the private sector. While the data from field research concerning public investment came mainly from official documents and relevant literature, the main data for the private sector were gathered by interviews with individual farmers.

From the 149 farm interviews, every farm household has its characteristics and diversity. To better describe the situation and analyze farm behavior of individual farmers, clear categorization, in particular on technologies are needed. Since private investment in irrigation technologies is a key factor in this study, and it is represented by monetary costs, e.g., costs in line with various irrigation technologies, investments for technologies can serve as a qualified categorization to fulfill the research requirements of stratified description.

Based on irrigation technologies adopted, the interviewed farmers were divided into eight categories as specified below:

Category A: Farmers who apply flood irrigation.

Category B: Farmers who apply border irrigation (furrow irrigation).

Category C: Farmers who apply basin check irrigation.

Category D: Farmers who apply seepage irrigation.

Category E: Farmers who apply sprinkler irrigation.

Category F: Farmers who apply drip irrigation.

Category G: Farmers who apply dry land farming.

The following empirical analysis of this chapter will be undertaken with these farmer group categories.

3.2   The actual irrigation schemes in the study area

As mentioned before, the Liquan County has a relatively advanced irrigation system and a long history of irrigated agriculture. There are three irrigation categories in Liquan County according to the ownership and execution. They can be classified as the public category, the community category and the private category.

Under the public category, there are two irrigation schemes. One is owned and managed directly by the BUREAU OF WATER RESOURCES MANAGEMENT, Liquan County, named the local scheme. It is characterized by small-scale irrigation networks, such as combinations of several public pumping stations and public tube wells. It normally charges farmers with a very low water rate, in particular due to huge subsidization from the county administration. For instance, this scheme used to charge farmers for water based on how much land they own, instead of how much water they use, i.e., a farmer would be charged the same price if he has the same farm size as compared to his neighbor, no matter how much water he uses. This certainly results in high water use in the covered area. Because of that problem, this method has been basically abandoned due to its encouragement of wasting water. It may be used only in the off-season in order to encourage farmers to use water. Farmers are interested to be covered by this network due to its low costs. Unfortunately it can only supply a certain small area due to the limited infrastructure.

The next irrigation scheme is owned and operated by the BUREAU OF BAO JI XIA IRRIGATION NETWORK MANAGEMENT, which is one of the largest irrigation projects in Shaanxi Province. It covers 4 counties, and is named the provincial scheme. It irrigates 37,333 hectares of land in Liquan County. The amount of water received through this network is equivalent to 160 mm precipitation annually (Office Of Water Resources Management Of Liquan County, 1993). This scheme charges farmers a relatively high though socially acceptable water price based on the quantity of water delivered to them. In comparison the water price charged by BAO JI XIA IRRIGATION NETWORK can roughly be twice the price charged by the local scheme, but it is still on some 50% of the water generation costs (YANG, 1996).

Next with regards to a community scheme, which is the second category, we have an irrigation system that is owned and operated by a village or a small town. It is characterized by three criteria: low pumping capacity, low technical level and low operation costs. Normally a scheme consists of one small scale pumping station and several small sub-watercourses. It can deliver water to one or two villages. There is no permanent staff employed in such a scheme. A few skilled farmers do the routine operation and maintenance with low payment. Consequently it can supply the cheapest water to farmers as compared to the other schemes, though the capacity is limited.

The private category, which contains three different schemes, is completely owned and operated by individual farmers. Specifically in this study, such scheme refers to farmers who apply basin check irrigation, seepage irrigation, and some sprinkler irrigation and drip irrigation.

The first scheme of private category refers to those farmers, who apply basin check irrigation, pump water directly to their fields. Typically such a scheme is characterized by its small scale and it can only irrigate one or two Mu[1]. Electricity or diesel costs are the only irrigation expenses for these farmers besides digging costs and labor costs. As a second scheme, we have farmers without direct access to water. But they can buy water. For many farmers, who apply seepage irrigation, the situation is much different from privileged farmers. Since they have no surface water and no groundwater access, water has to be transported. They need to transport water from the water source outside the village to their fields. Naturally they have to pay the highest price for irrigation as compared to other farmers. And normally their unit water costs (including transportation fee) can be 10 times higher than those for water from the local scheme or the community scheme.

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[1] Chinese land measurement, 1 Mu=1/15 hectare

Finally farmers using modern sprinkler and drip irrigation, are covered by two big private groundwater suppliers. This is the third scheme. The area where they live is a mountainous area, which is too far away to be served by the public canal water schemes. The two farmers are exceptions. Normally it is too costly to afford a deep well for an average farmer. Many farmers without cheap facilities buy water from the private tubewell owners. Farmers are charged a relative high water price as compared to those living in public water schemes. However, basin check irrigation users, who have their own private shallow tubewells, also think that costs for pumping are high.

3.3   Empirical findings and main results

The primary data, which were collected during the field survey, were analyzed by using Microsoft Excel and the statistical software SPSS. Major results are presented in this section.

3.3.1 Demographic and socio-economic characteristics of sample farmers

3.3.1.1 Land holding and family size

China's household responsibility system has increased agricultural productivity in rural China twice and production has redoubled since 1980's. But it also brought some side effects in rural areas, such as declining size of fields' plots. Since the land was divided into small pieces to every farm household from the former collective cultivation system, land is now scarce. Such effects have become more and more obvious and serious in recent years. It hinders the development of agriculture's modernization and specialization. Liquan County is not an exception, it is located in an area with a population density of 442 persons per square kilometer, and the cultivated land is only 2.1 Mu per capita. The features of the interviewed farmers with respect to farm size are given in Table 3.1

Table 3.1 demonstrates that family size and farm size are small in the investigated irrigation scheme. The average family size is 4.0-5.2 persons in the survey area. The age of the head of household is considerably young. The average age of the household head is less than 47 years among all different farmer categories. Land holding per person in farmer Category A and B are lowest among the interviewed farmers due to higher population density. Farmers in these two categories are situated at the area of the upper portion of canals. They are traditionally well-off groups due to better natural and irrigation conditions. Surface irrigation technologies are most prevalent in this area. Farmers in Category G are lower in land holding per person, but the reason is much different from that in Category A

Table 3.1:   Farm and family characteristics of the interviewed farmers based on adoption of technologies

Farmer Category	Average farm Size (Mu)	Average family Size (number)	Land holdings per person (Mu)	Average age of head of household
A	6.50	4.41	1.30	43.00
B	6.77	5.19	1.47	45.00
C	7.17	4.48	1.60	46.00
D	13.18	4.90	2.69	47.00
E	15.43	4.86	3.18	41.00
F	14.68	4.45	3.30	39.00
G	7.50	4.00	1.88	41.00

Notes: 1Mu= 1/15 Hectare

A: Flood irrigation users; B: Border irrigation users; C: Basin check irrigation users;
D: Seepage irrigation users; E: Sprinkler irrigation users; F: Drip irrigation users;
G: Dry-land farming users

and B. Category G is worst in welfare, it is the category with the lowest income among all the interviewed farmers. They are located in the hilly area where there is shortage of land and water. That is the main reason why the farm size is small in category G. Neither public nor community irrigation schemes reach them.

Farmers in Category C are located at the lower portion of the irrigation area. Their landholding per person is equally low due to relatively higher population density and limited land resources. Next farmers in Category E and F have almost double landholding per person compared with the other farmer categories. They are located at the tail portion of the irrigation area, which implies lower land rents. Because of poor access to public canals and high water costs, land is cheap. Some farmers in this area can perform economies of scale in apple production thanks to relatively cheap land. This is the reason why the land holding per person of category E and F is at a higher level, as compared to the other farmer categories. Economy of scale in production lowers the production cost and hence offers farmers a better return. It also makes it possible for them to afford more modern water saving technologies.

3.3.1.2 Levels of education in the study area

To a certain point, farmers' education levels determine their well-being. Education increases the likelihood of adoption of new irrigation technologies in the study area. Figure 3.1 describes the situation as based on different farmer categories. Farmers in category A and B are the biggest groups to apply traditional surface irrigation. Half of them have finished elementary school, and less than half have finished middle school, meaning that still few of them are illiterate. Farmers in
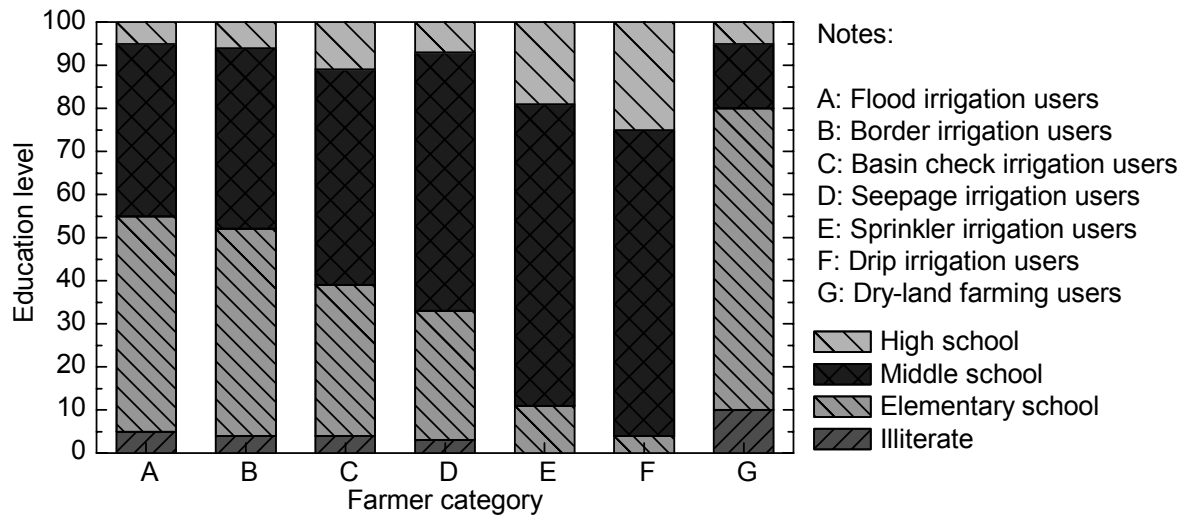
Figure 3.1: Education levels of farmer household heads
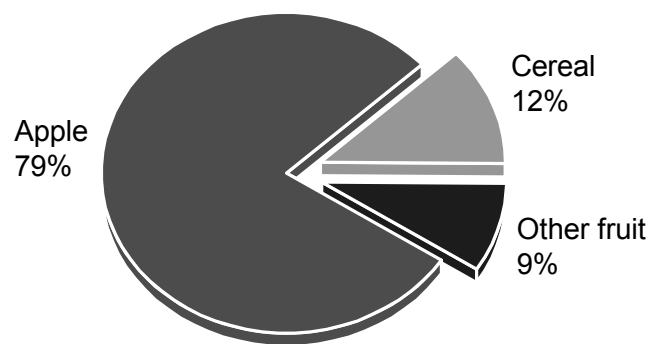
Figure 3.2: Distribution of farmland for different farm activities

category D, E and F are better educated, 60-70% of them have middle school education and some of them received high school education. This can be a reason why they are more likely to adopt new water saving and environmentally more friendly technologies. Farmers in category G have the lowest education level among all categories partially due to their poor economic background. 10% of them are illiterate, 70% of them finished only elementary school and only 5% of them have some high school education.

3.3.2 Production activities in the study area

Apple production is the dominant agricultural activity in the study area. Figure 3.2 describes the distribution of farmland for different farm activities. It is apparent that 79% of the land is used to produce apples, at least, among the interviewed farmers, 12% of land is still used to produce cereals. The remaining 9% is taken

for other fruit production, such as pears, peaches, grapes, etc. The economic background behind this land allocation is quite simple. Fruit production can deliver better returns compared to traditional cereal production. Furthermore, that apple production in the study area is fairly developed. Moreover there is a well-informed network for marketing and transportation to support production. At harvest time, plenty of business individuals and groups gather in market places and purchase fruits from farmers. Some big farmers have had already contracts with them in the previous year. Thanks to reliability and good co-operation between market purchasers and apple growers, those business contacts have developed over years. They are already different kinds of modern "company plus farmer" arrangements and this might be a future way for rural China's modernization with respect to agriculture. Though some farmers kept cereal production to fully utilize their land, it is observed that the land for cereal production is normally small and unfertilized, and it is given less care as compared to fruit production. Cereal output is usually small, and cannot meet the need of farmer household's consumption. Buying food from the local market is very common in the study area. Consequently specialization in apple production boosts the development of local grain markets due to the huge demand from the farm side (rural population accounts for 90.9 % of total population in this county). The suppliers of the local grain market are dominated by neighbor counties, where grain production is still the major production activity. The specialization of apple production, in return, helps to raise the specialization of grain production in neighbor counties. As a general observation, specialization is beneficiary to farmers. Consumption figures show clearly that food security is meanwhile ensured by specialization of commercial agriculture (BUREAU OF STATISTIC, 2000).

3.3.3 The credit market in the study area

Tables 3.2 and 3.3 investigate the credit situation. Small-sized and poor farmers can hardly get loan from formal financial institutions, such as China Agriculture Bank, though it is possible. Most of them cannot meet the security requirements and cannot carry out the complicated procedure to apply for a loan. Additionally, it is difficult for them to raise any asset as a mortgage to the bank. That's why small-sized farmers intend to seek financial support from informal credit sources. Sources are relatives, friends and moneylenders. As mentioned already, a big portion of poor farmers belongs to category A, B, C and G, who are surface irrigation and dry-land farming users. Only less than 5% of them got a loan from formal institutions. More than 80% of the financial needs were borrowed from informal institutions including individuals. Children's education and mainly

Table 3.2: Source of credit and contribution

Farmer category	No credit (%)	Formal institutions (%)	Informal institutions (%)
A	15.50	1.50	83.00
B	16.40	2.00	81.60
C	14.30	3.00	82.70
D	55.10	10.00	34.90
E	78.90	21.10	0.00
F	82.40	17.60	0.00
G	9.20	0.00	90.80

Notes: A: Flood irrigation users; B: Border irrigation users; C: Basin check irrigation users;
D: Seepage irrigation users; E: Sprinkler irrigation users; F: Drip irrigation users;
G: Dry-land farming users

Table 3.3: Distribution of credit use

Farmer category	Children's education (%)	Housing (%)	Farm inputs (%)	Irrigation equipment (%)	Health care (%)
A	40.00	10.00	10.00	0.00	40.00
B	35.00	15.00	15.00	0.00	35.00
C	34.00	10.00	20.00	20.00	16.00
D	30.00	15.00	18.00	27.00	10.00
E	0.00	21.10	0.00	60.00	18.90
F	0.00	17.60	0.00	72.00	10.40
G	50.00	15.00	15.00	0.00	20.00

Notes: A: Flood irrigation users; B: Border irrigation users; C: Basin check irrigation users;
D: Seepage irrigation users; E: Sprinkler irrigation users; F: Drip irrigation users;
G: Dry-land farming users

family health care are the main purposes of credit, and they account for more than 50% of the credit use. It is also observed that credit investment in irrigation technologies is irrelevant among the four farmer categories A, B, C and G. The economic situation of these farmers is vulnerable. They hardly can get a loan from the official credit system, and meanwhile, have to pay a much higher interest rate to informal credit markets. However, credit problems harm the farmer's interests. The situation for farmers in category D, E and F, who are modern irrigation technology users, is different. They have a higher probability to get access to official bank loans since they are relatively better off and can offer mortgage on their own assets. The credit use of farmers in these three categories is more concentrated on irrigation equipment and housing. Children's education fees and family health care play a minor role. Better economic situations lead to more financial resources, and advocate further improvement of the economic situation. Presumably, the income gap between farmers in category E, F, D and farmers in category A, B, C and G is getting bigger. This matter will be investigated more intensively in the coming section.

3.3.4 Distribution of farm income and off-farm income in the study area

In recent years, non-farm incomes have gained additional shares in farmers' total incomes. Non-farm incomes become more crucial for farmers especially, in case they get a bad harvest year. For small-sized and poor farmers, Non-farm income is the main financial resource for them to offset budget deficits. Table 3.4 shows the situation among the farmers interviewed. Farm income still has the biggest share as compared to non-farm incomes. A remarkable phenomenon is observed for farmer category E and F, who are in a better economic situation. Most of their non-farm income is from business, such as performance of transportation. Other business or operation, such as refresh-keeping for local apple growers and marketing is common. However, the sources of non-farm income for small-sized and poor farmers are mostly from cheap labor, offered to urban areas, during off-season of agricultural activities.

Table 3.4:   Distribution of annual farm income and non-farm income

Farmer Category	Off-farm income (Yuan)	Off-farm income (%)	Farm income (Yuan)	Farm income (%)
A	1500.00	30.00	3500.00	70.00
B	2000.00	37.04	3400.00	62.96
C	2400.00	46.15	2800.00	53.85
D	4800.00	48.98	5000.00	51.02
E	30000.00	40.00	45000.00	60.00
F	40000.00	44.44	50000.00	55.56
G	1000.00	31.65	2160.00	68.35

Notes: A: Flood irrigation users; B: Border irrigation users; C: Basin check irrigation users;
         D: Seepage irrigation users; E: Sprinkler irrigation users; F: Drip irrigation users;
         G: Dry-land farming users

3.3.5 Irrigation activities and apple production in the study area

3.3.5.1 Irrigation technologies, quantity and quality analysis of apple production

The output levels for apples are determined by many inputs. They are not only linked to water use. There are also some other important input elements influencing it. However while doing interviews, it has been observed that there were no big differences in the use of fertilizer, pesticides and labor per unit land among different farmer categories. The big differences among them are found with regard to water consumption. Considering this situation, Figure 3.3 investigates the output levels based on different farmer categories. Figure 3.3 surprisingly shows that big differences of apple yields exist among different farmer categories. For instance, farmers in category G, who operate dry land
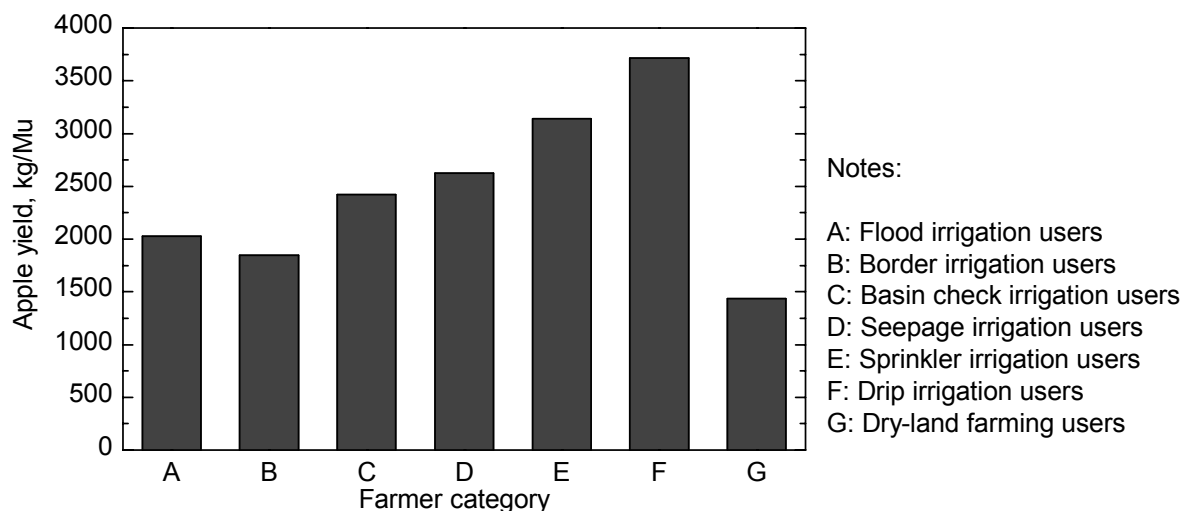
Figure 3.3: Apple yields based on different farmer category
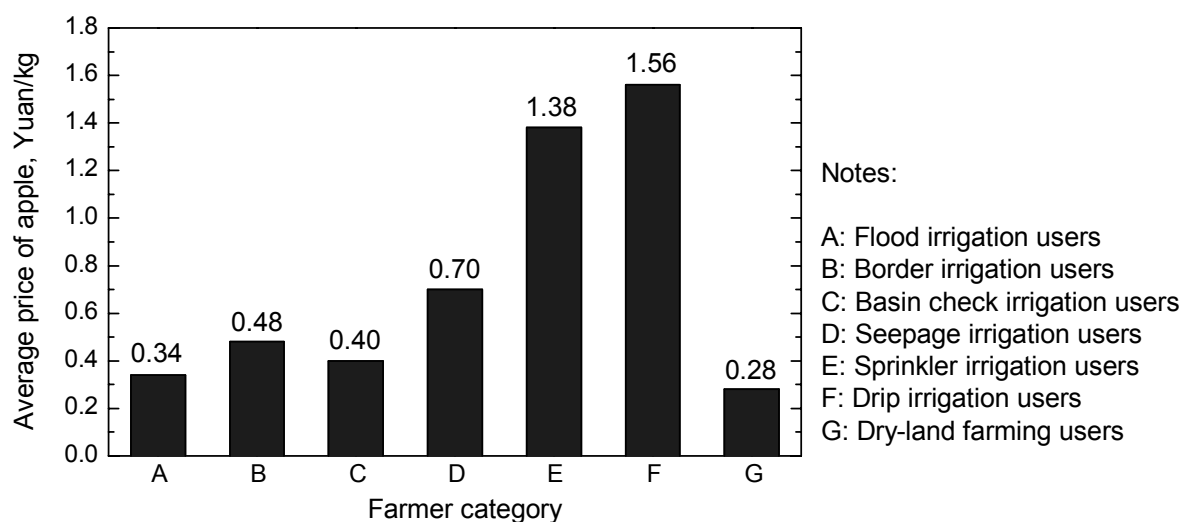
Figure 3.4: Apple prices based on different farmer category

farming, have the lowest apple yields among all the interviewed farmers (nearly three times lower than category F, who operate drip irrigation technique). Also it is merely half of the yields harvested by farmers in the D category, seepage irrigation users. Because the farmers in the G category have not irrigated, their outputs completely rely on limited and irregular rainfall. By contrast, drip irrigation makes it possible that up to 95 % of water can reach the roots of the apple trees. Moreover fertilizer can be fully absorbed by trees by adding it to the water during irrigation. This is the reason why such a huge yield difference between the two farmer categories occurs.

Farmers in A, B, and C are surface irrigation users. No big yield differences are observed among these three categories. Farmers in D, the seepage irrigation users, have also considerably higher yields as compared with surface irrigation users. It has to be mentioned that the quality of apples improves with irrigation. Quality
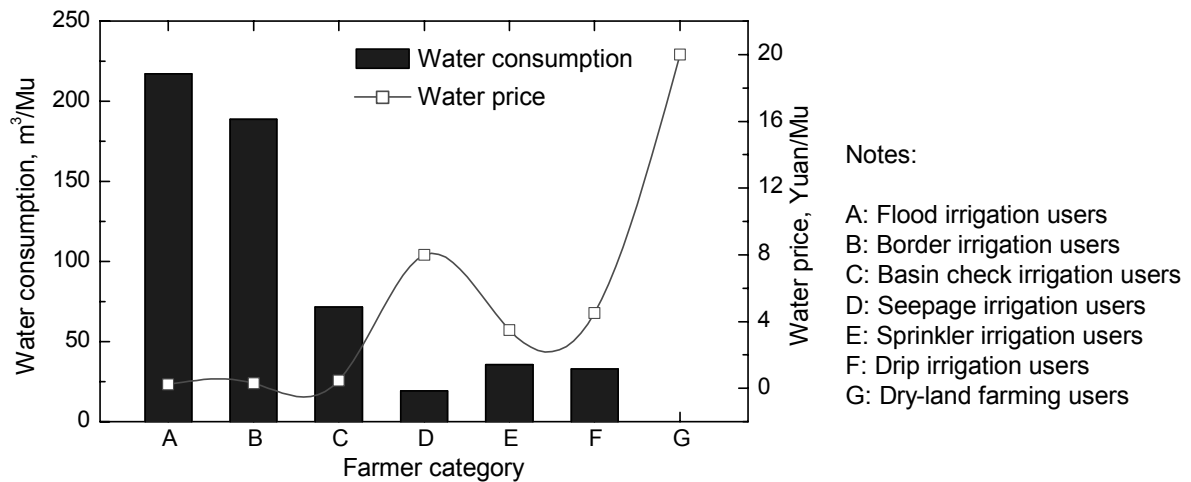
Figure 3.5:   Relationship between water price and quantity of water consumption

differences are mirrored by apple selling prices for different farmer groups. Modern technology users achieve a higher output price due to a better quality of apples. As shown in Figure 3.4, Farmers in category G (Dry land farmers) get the lowest apple price. The apple price for farmer categories E and F (sprinkler and drip irrigation users) can be up to 4.93 and 5.57 folds of that for farmers in the G category. Apart from the extreme case of category G, apple prices for farmer categories E and F are still up to 4.05 and 4.58 folds of that for farmers in the A category, the traditional flood irrigation users.

The big quantity and quality differences of apple production indicate, that the right way to get maximum production and best quality of fruits, with respect to water use, is to use more high-frequency irrigation instead of using traditional irrigation at fairly long intervals (HERVE PLUSQUELLEC, CHARLES BURT, & HANS W.WOLTER, 1992). Schemes, such as drip and sprinkler, seem to increase revenue over proportionally.

3.3.5.2 Water consumption and water price

Water consumption varies while water prices are changing. Figure 3.5 shows the relationship between the water used per Mu and the water price paid. The higher the water price is, the less water will be applied. Farmers in category G are an extreme case. They have to pay a sky-high water price, i.e., more than 20 Yuan (2.44 USD)/m^3 (which is perhaps unaffordable for others due to transportation cost). They want to water their apple trees, but prices are too high. That is why they gave up irrigation and went for dry land farming. Farmers in A and B have better access to cheap water so they consume more water than other categories. The water consumption by categories A and B, on average, can be up to 200 m^3/Mu. Next, since farmers in categories E and F have to pay considerably high
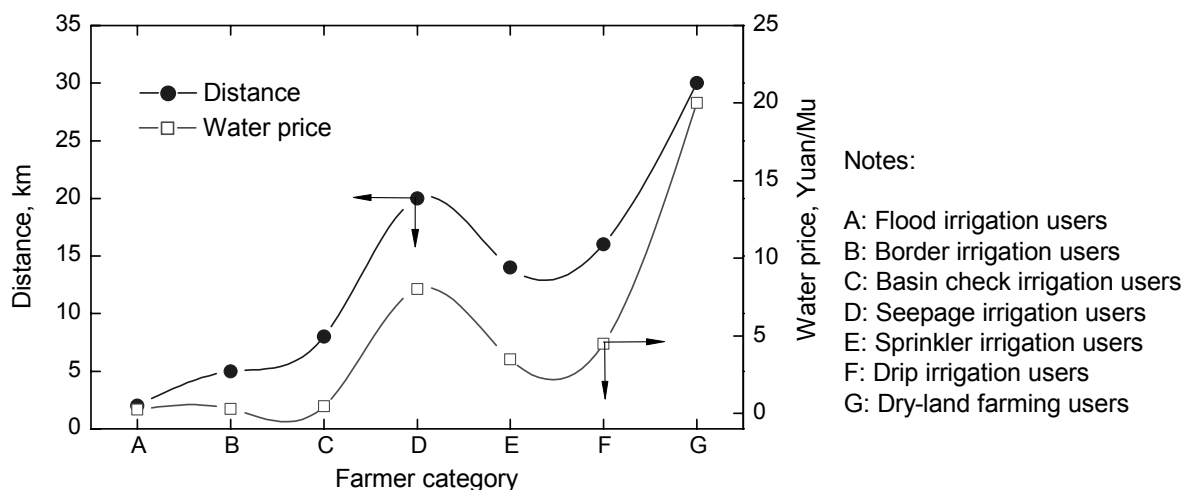
Figure 3.6: Relationship between distance and water price

water prices, modern water saving technologies are alternatives for them, and are attractive. Farmers in D pay the highest water price among all interviewed farmers (except G) since the water price for this group includes transportation costs. It is understandable that they consume the least amount of water among all irrigation farmers. Nevertheless this farmer category still gets considerably good returns compared with categories A, B and C due to the adoption of water saving technologies.

3.3.5.3 Distance and water price

We have seen that the water price and water consumption is significantly connected. The reason is that the water price increases with locations farther away from the water source. Due to increased lining and operation costs, transport costs matter very much. The relationship between the water price and the distance from farm-gate to source based on different farmer categories, is presented in Figure 3.6. It clearly shows, that the two categories (distance and water price) are following a similar path. The water price is fairly low within 10 kilometers from the water source. Importantly, farmers in categories A, B and C are all located in this region. All of them operate surface irrigation. Farmers in categories D, E and F are located in an area more than 10 kilometers away from the water source. Most of them have adopted modern technologies to save water. Then, especially, farmers in the category D need to transport water from the water source to their tanks in the fields. Long distance leads to longer water conveyance, and longer conveyance leads to higher water costs (either by tractor or public canals). The higher water costs encourages farmers to adopt new water saving technologies to minimize the entire costs, to maximize production and to optimize water procurement.

3.3.5.4 Distance, water source type, groundwater, and water consumption

As seen already, water consumption decreases with locations getting farther away from the water source. The longer the distance is, the less water is used. As shown in Table 3.5, farmers close to water source are the heaviest water users. With the distance getting farther, water in the public canal becomes less and less due to a considerable water loss rate. Meanwhile the maintenance and conveyance costs are getting higher. Expensive and insufficient water, provided through the public canal, enforces some farmers to seek alternative solutions, such as groundwater, to satisfy their water requirements.

Groundwater use occurs when transported canal water is getting insufficient and more costly than local groundwater. Farmers in the category C operate surface irrigation. Their water source type is mainly groundwater, instead of surface water. This implies that potential surface water supply in this particular area has become insufficient and costly compared to groundwater supply. For instance, most farmers possess shallow tube wells and pump water by themselves. Farmers in categories E and F live even farther away from the water source than farmers in category C. However they would require more reliable and continuous water flows due to utilization of advanced irrigation technologies. But their small shallow tube wells cannot meet these requirements. Furthermore, two big private tube well owners control the area where the farmer categories E and F are located. Their groundwater procurement is pipe transportation that is ensured by a private operation system. Accordingly, farmers in this area are charged with relatively high water prices. This clearly suggests that groundwater supply replaces the surface water supply when the distance from the surface water source increases. Specifically, in the present study, ground water procurement starts with farmers in the category C and then extends to categories E and F.

Table 3.5:   Distance, water consumption and water source type for each category

Farmer Category	Water source type	Distance (km)	Water consumption (m^3/Mu)
A	Public canal	<2.0	217.23
B	Public canal	2.0-5.0	188.63
C	Private tube well	5.0-8.0	71.67
D	Water tank	16.0-20.0	19.30
E	Private tube well	8.0-20.0	35.71
F	Private tube well	8.0-20.0	32.73
G	No water source	>20.0	0.00

Notes: A: Flood irrigation users; B: Border irrigation users; C: Basin check irrigation users;
         D: Seepage irrigation users; E: Sprinkler irrigation users; F: Drip irrigation users;
         G: Dry-land farming users
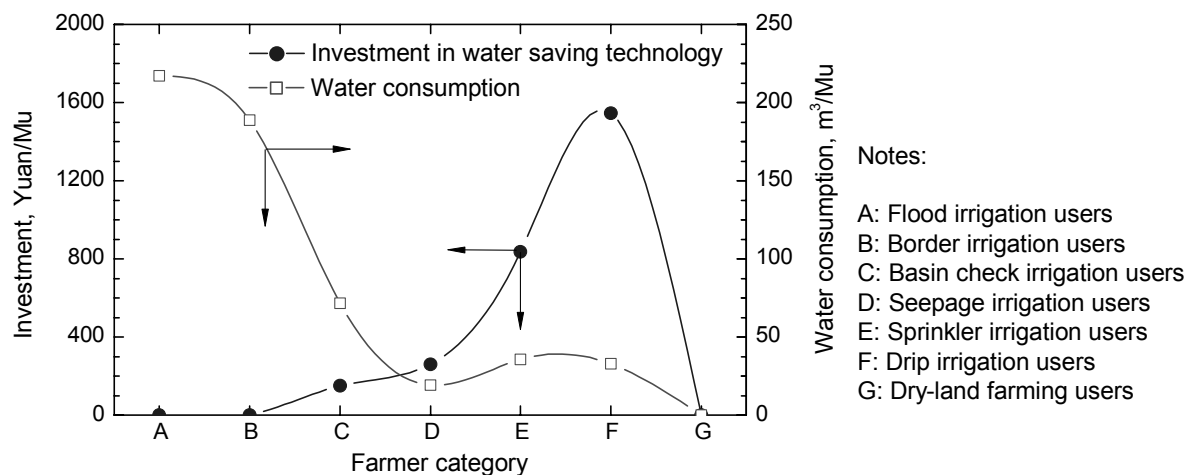
Figure 3.7:   Relationship between investment in irrigation and water consumption

3.3.5.5 Private investment and water consumption

As a major hypothesis we will state that private investment in irrigation technologies improves water use efficiency. The higher the investment is, the less water will be consumed. As shown in Figure 3.7, water consumption is at a fairly high level by farmers in categories A and B, since they operate flood and border irrigation. In the present study, it is assumed that zero investment in water saving technologies is made by these two farmer categories. Farmers in the category C also operate a kind of small-scale surface irrigation, namely, basin check irrigation. They consume much less water than their surface irrigation counterparts in categories A and B. But this scheme requires investment in terms of labor etc. It is observed in the category C that around 150 Yuan/Mu are spent on water saving technologies. The reason behind this is that farmers in category C are groundwater users and their water costs are much higher than with farmers in categories A and B. Specifically, they need to dig a shallow well, to purchase a pump, and to pay electricity costs. Moreover they need to contribute labor to divide their fields into smaller areas. Fields have normally the size of 1.5m x 1.5m per plot. It is a fairly labor-intensive farming system. In this study, such necessary expenditures are taken as irrigation technology costs.

Farmers in the category D operate seepage irrigation. The average cost is 260 Yuan/Mu and the water consumption is 20 m^3/Mu, which is one tenth of the water consumed by farmers in category A. Farmers in categories E and F use modern capital-intensive technology, such as sprinkler and drip irrigation. Their average costs are 835.43/Mu and 1545.35 Yuan/Mu, respectively, 3.5- and 5.9- times of the investment of seepage irrigation. Correspondingly the water consumption of farmers in categories E and F is only one fifth and one sixth of water, which is consumed by farmers in category A. One significant phenomenon is that the

seepage irrigation users even consume a lower amount of water than modern drip irrigation users. This does not suggest that the seepage irrigation technique can use water more efficiently than modern drip irrigation. The hypothesis is that it is because the farmers have bad access to water. As mentioned before, they have to fill their field tanks with costly transported water.

3.3.6 Cost shares in apple production

We investigate the economic situation of farmers as related to water by applying a cost share approach. The cost shares of each farmer category are different. There are four main input elements. They are labor, fertilizer, pesticides and irrigation costs. Among them labor cost has the biggest share. Labor is intensively needed over the whole year in apple production. This includes land ploughing, fertilizing, insecticide spraying, weeding, irrigation, fruit thinning and harvest. According to apple growers, grain production requires labor for three months in a year only, whilst apple production keeps them busy over the whole year. The heaviest work is in the harvest season. Almost every farm household has to hire people to pick and pack apples. As shown in Table 3.6, the share of labor costs varies from 55.18% to 73.02% of the total cost for all interviewed farmer groups. Labor costs were calculated by the amount of man-days used, multiplied by average wages per day. Farmers in the category G (dry land farming operators) have the largest labor cost share due to their bad economic situation. These farmers spent less on other input element besides labor. However, farmers in the category F (modern drip irrigation users) have the smallest share of labor costs in their total cost. Farmers in the category C have higher labor costs as compared with their surface irrigation counterparts A and B. The reason for this is that farmers in category C are required to prepare their field into smaller field plots. This implies that, at a certain point, modern irrigation technologies cannot only save water, but also save labor consumption (For instance, fertilizing and irrigation can be carried out in one procedure by drip irrigation). It is obvious that the shares of irrigation fees are highest in categories D, E and F, since these farmers need to pay high prices for water. Especially farmers in the category D are affected. They need to pay the highest water prices due to additional transportation costs. This is why the irrigation fee as share in this farmer category is the largest among all interviewed farmers. No significant difference is observed on fertilizer and pesticide costs amongst all interviewed farmer categories.

Table 3.6:   Distribution of input share in apple production

Farmer Category	Fertilizer		Pesticide		Irrigation fees		Labor costs	
	Yuan/Mu	%	Yuan/Mu	%	Yuan/Mu	%	Yuan/Mu	%
A	281.31	21.10	164.22	12.32	54.94	4.12	832.82	62.46
B	240.54	19.64	142.34	11.62	51.68	4.22	789.99	64.51
C	165.69	17.81	88.46	9.51	50.00	5.37	626.34	67.31
D	130.00	15.48	60.00	7.14	150.00	17.86	500.00	59.52
E	100.00	19.42	55.00	10.68	60.00	11.65	300.00	58.25
F	110.13	21.16	54.29	10.43	68.82	13.23	287.09	55.18
G	124.11	16.55	78.15	10.42	0.00	0.00	547.43	73.02

Notes: A: Flood irrigation users; B: Border irrigation users; C: Basin check irrigation users;
         D: Seepage irrigation users; E: Sprinkler irrigation users; F: Drip irrigation users;
         G: Dry-land farming users

Notes:

A: Flood irrigation users
B: Border irrigation users
C: Basin check irrigation users
D: Seepage irrigation users
E: Sprinkler irrigation users
F: Drip irrigation users
G: Dry-land farming users
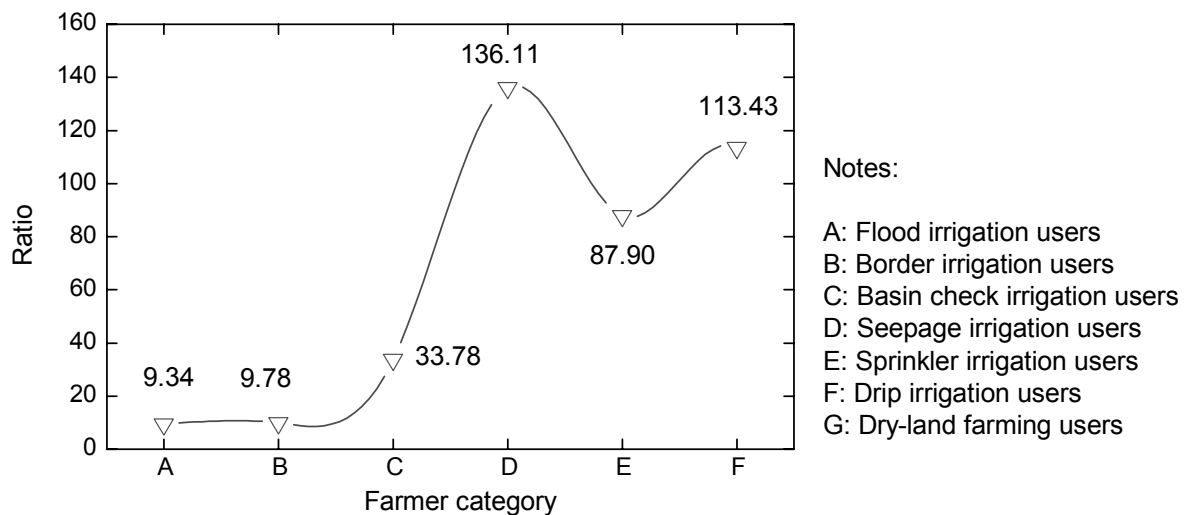
Figure 3.8:   Ratio of apple yields and water consumption

3.3.7 Ratio of apple yields and water consumption

In general one might think, all thing being equal, that the adoption of seepage irrigation technology could be the right solution for water saving of low-income farmers. This is illustrated by a ratio of yields to water applied as shown in Figure 3.8. The ratio is defined as a production coefficient, e.g. apple yield divided by irrigation water consumed, i.e., Ratio = Apple yield (kg/Mu)/Water consumption (m^3/Mu). Naturally apple trees get water not only from irrigation, they also get it from rainfall. Since the survey area is a relatively small area, it is assumed that all the farmers get the same amount of rainfall. Hence the ratio is used to measure the effective costs and benefits in terms of irrigation water use only. As shown in Figure 3.8, farmers in the category A, flood irrigation users, have the lowest ratio

value at 9.34. This suggests that one cubic meter irrigation water can only produce 9.34kg of apple by flood irrigation. It is easy to perceive that much water is wasted by this kind of irrigation method rather than is consumed by apple trees. Farmers in the category B are almost at the same level, with a ratio value at 9.78. The result is different for a farmer of category C, who applies basin check irrigation (small scale surface irrigation). Note that farmers in this category are also groundwater users. They have a relatively high ratio value of 33.78 as compared with the surface irrigation counterparts in the categories A and B. Farmers in categories E and F have an even higher ratio, with a value of 87.9 and 113.43, respectively. The most remarkable result is, that farmers in category D surprisingly get a ratio of 136.11, i.e., $1m^3$ water can produce 136.11 kg apples. This is the highest ratio among all interviewed farmers (This appears if the system functions well. Remember that problems with the holes may occur). As described already, also modern sprinkler and drip irrigation can use water more efficiently than traditional modus and improve productivity. Farmers in categories E and F have a high rank of apple yields and their apple quality is the highest. Though, note that they have the heaviest investment in water saving technologies. Furthermore expenditures on modern irrigation technologies are multi-times that of seepage irrigation. Only few farmers can afford that. Farmers in the category D, i.e., seepage irrigation get already considerable revenue at much lower expenditure on water saving technology as compared with the categories E and F. Based on the above results, the hypothesis can be stated that the adoption of low-cost seepage irrigation technology could be a practical and efficient way to save water for average farmers in the survey area at minimal investment. Despite of problems in maintenance, farmers have a high incentive to adopt this technique as the water price increases.

3.4   Summary

This chapter gave a brief and primary description of the field survey. The preparation, such as the methodology of research design and sample selection, the status of existing irrigation networks as well as the primary data analysis of empirical findings, are also presented here. The collected information provides a basic structure, and we will discuss ideas to establish the econometric and mathematic programming models to optimize the social welfare as well as water resource allocation over the irrigation area.

The following findings are suggested by the empirical analysis:

- Traditional surface irrigation still plays an important role in the surveyed area.

- The water price becomes higher with the location getting farther away from the water source due to an increase of water conveyance costs.

- Increasing and higher water prices motivate farmers to adopt new water saving technologies.

- Locally produced seepage irrigation is under average conditions more economic and practical for low-income farmers to save water than imported modern irrigation techniques in the survey area.

4   LITERATURE REVIEW

Water resource management has become one of the hottest topics in the search for better resource management. A lot of studies have been carried out in this field. Particularly there is a focus on approaches for assessing and improving the performance of water used in agriculture in terms of increasing the water use efficiency (KELLER, KELLER, & SECKLER, 1996; WICHELNS, 1999; CAI, RINGLER, & MARK W.ROSEGRANT, 2001). Furthermore, there is ample literature on increasing competition between water users within river basins (SECKLER, 1996; LEE, 1999; WORLD BANK, 1993). Some authors focus also on the sustainable use of groundwater resources as well as on the contamination problem (HELLERGERS, ZILBERMAN, & VAN IERLAND, 2001; ROSETA-PALMA, 2002; GAYATRI & EDWARD, 2002). Next there are studies that concentrate on water resource institutions and policies. Issues, such as how to utilize the limited water resources efficiently and to protect the environment, have attracted more and more attention, notably from water researchers as well as practioners. Due to limitations and a specific research scope, only a part of these studies will be reviewed here. The literature can be divided into the following three categories based on their focuses: (1) Institutional approaches towards water management, (2) Water markets and irrigation system management, (3) Economic modeling of water resource management.

4.1   Institutional approaches towards water management

We start with institutional approaches and survey historical achievements. Then past policies will be equally reviewed.

4.1.1 History of water management

By institutional approaches, researchers study how communities, governments and societies are dealing with water resource management problems. This involves the investigation of legal aspects, policy approaches, and institutional arrangements. Studies range from national to regional as well as from rural to agricultural levels. Modern scientific water management practices, which have their beginning in the last half of the 19th century, were for many years identified only with centralized approaches issues pertaining to water management. Even during most of 20th century, the centralized top-down system was still the preferred form of water management and these approaches dominated towards water management in most countries. The disadvantage of this system became increasingly obvious in late years showing that many state investments were not well directed. Projects were commonly failing to meet their initial objectives and

the returns of many of investments were very low if not negative (LEE, 1999). Since the 1970s the role of the state in the management of directly productive activities and in the provision of services has been increasingly questioned. Today it is widely accepted that users should be given an important role in water management. Local organizations should be considered the focus of applying scientific approaches to resource management (WORLD BANK, 1993). This user-based approach, i.e., a bottom-up approach of water management, is gaining more attention. As more private participation is involved, water has been considered more and more an economic commodity involving private decision-making. It is also discussed to increase users' responsibilities in water management and to make them coincide with the general adjustment of central governments towards decentralization. An efficient water resource management system can only work successfully, when the top-bottom and bottom-top systems complement each other (LEE, 1999).

Intervention from government is typical for both, heavily centralized bureaucracy and user-dominated systems in particular, when market failures occur. Government intervention can protect the public from abuses of power due to market imperfections and coordinate deficits due to lack of private commitments, but it is dangerous for efficiency. The particular justification for government involvement in water management is based on several characteristics of the water sector. These characteristics can result in a market failure (LEE, 1999). The characteristics have been summarized in a World Bank policy paper on water management (WORLD BANK, 1993) as follows:

- The large and lumpy nature of capital investments and economies of scale tend to create natural monopolies warranting regulation.

- The relatively large size of water investment and the potential for political interference reduce the incentives for private investment.

- Uses of water are interdependent and a government regulation is required to ensure that users abide by the rules of the game for water allocation and the maintenance of water quality.

- Some water-related products, such as flood control and control of waterborne diseases are, at least locally, public goods, which are difficult to charge for on an individual basis. Therefore, public intervention may be necessary to ensure appropriate levels of investment.

- Water resources are often developed for special use purpose because of their assumed importance for overall economic development.

Notably government intervention is often not optimal and even results in failures, albeit it is needed sometimes. There are two broad forms of government failures. One is Rent-Seeking or the pursuit of self-interest by politicians, public sector employees, and other interest groups. The other is regulatory failure or capture, which evenly occur when a public authority falls under the improper influence of some special interest group, either public or private. The recognition of government or regulatory failures challenges the classic public welfare or governance theory that assumes that government is a disinterested pursuer of the public interest. It is nowadays widely accepted that any government intervention will have an economic as well as a political background.

Though there are government failures, it never does mean that government should withdraw from public governance rather the question is how to get a good governance structure. In considering the establishment of water management and regulatory systems, government should be open-minded in judging the various alternatives that are available and be cautious in developing too elaborate systems in environments without traditions of strong public service. Talking on good governance also underlines the need to target intervention on areas where market failures are most pronounced, to pay attention to the costs and benefits, and to design regulatory mechanism to maximize benefits in relation to costs. In the opinion of many researchers, neither privatization nor user-management regimes can, of themselves, release governments from their responsibility to provide their populations with a reasonable and equitable access to basic water-related services. This responsibility has to remain with government in the area of public policy (LEE, 1999).

4.1.2 Water-related policies and concepts

Surface water policies

Traditionally, the existing water laws in many countries have done little to encourage transferring water rights between users to equate values (prices of water). For instance, the prior appropriation system as applied in many states of the USA, allows third parties to block a transfer. Blocks would affect users, regardless of how small the impact is (LESSER, DODDS & ZERBE, 1997).

Market-based surface water policies could enhance water rights transfer and improve economic efficiency (ROSEGRANT & GAZMUI S, 1994). These polices could include the removal of irrigation subsidies. This would make it less likely that development of uneconomic projects would occur and would encourage transfers of water to high-valued uses (RAY & WILLIAMS, 1999).

Groundwater policies

Groundwater allocation policies are complicated by the common-property nature of groundwater as a non-point resource. Several methods have been proposed to privatize groundwater rights or levy "pump taxes" on groundwater. A "pump tax" on groundwater is yet another market-enhancing allocation mechanism. The most difficult issue, emerging with establishing a pump tax, is setting the tax at the right level. With taxes too low, the common-property problem will not be solved. With taxes too high, not enough water will be used, reducing economic efficiency in both cases (LEE, 1999).

Water price policies

Agriculture is not the only area where water is used inefficiently. Few water utilities use marginal cost pricing, because they are either regulated monopolies or branches of local government. In general most water utilities price at average costs, e.g. recovering sufficient revenues to cover their total costs but not reflecting marginal cost. Policies such as increasing block prices, which charge marginal costs for marginal water use while covering average cost on average and allowing people a minimal level of use at a minimal charge, are rare. In such cases, there is little or no incentive to conserve water. However improvements are possible. Some policies attempt to improve the efficiency of their water. For instance, rates for initial blocks of water can be set low, to maintain affordability for an amount of water that is needed for basic survival, and then subsequently blocks can be priced much higher. Then, individuals who wish the luxury will pay more for their water (LESSER et al., 1997).

Irrigation value of water

Irrigation is the single largest use of water in many countries. There have been two alternative valuation methods as suggested by GIBBONS (1986). Methods are crop water production functions and farm crop budget analysis. Crop water production function analysis simply means that a production function for a particular crop is estimated and values are generated by the marginal values of that function. Various combinations of seed, fertilizer, water, labor and capital equipment can be used to produce a particular crop. Specifically, the inputs will be combined in such a way, that the values of their marginal products are precisely equal to their marginal costs. To determine the marginal value of water using this method, controlled experiments are usually carried out. Then, in these experiments, all other crop inputs are held constant besides water. Additional water is applied to a particular crop to determine the change in overall production.

Then this change, times the price of the crop, will be equal to the marginal value of the additional water applied (GIBBONS, 1986).

One of the problems with crop production analysis is that in many areas, no experiments have been performed yet. Thus the actual physical productivity of water is unknown. Nevertheless farm crop budget analysis try to circumvent this problem by developing representative farm budgets that determine the maximum revenue share as deductibles for water. In other words, the total revenue of producing a given amount of crop is estimated, usually by agricultural extension agents. From this total revenue, called a revenue budget, the costs of all of the non-water inputs are subtracted, and the rest is left for water. Then incremental steps are introduced. The incremental residual, will equal the maximum amount a farmer could pay for water and still cover production costs. If the cost of obtaining water is subtracted from the amount of the net value of providing irrigation water, specific values can be compared to other values of obtaining water.

TORRELL et al (1990) used a different approach. He determined the value of water in the Ogallala aquifer by examining the difference in values for irrigated and dry-land sales, thus capturing all of the factors that may contribute to the value of water. This approach has the advantage of being able to determine water values for dry land farming. It can examine price differentials between irrigated and dry land farm sales, though it is rough. In the approach, it is suggested that the difference in sales prices is attributable to the net earnings potential of water. Dividing this value by the average water use at the farm, one can compute the value of water on a per-acre-foot basis.

The "piecemeal" problem

Water is an input to many production processes. The marginal value of water will be determined by its value of marginal product (VMP). However, the VMP may be affected by economic distortions. This is particularly important in determinations of water values for irrigation purposes. A farmer may purchase subsidized electricity and subsidized water, and his participation in government programs creates artificial price support for the crops, which he grows. This will affect his marginal value of water. Because of that the VMP of water maybe significantly distorted. This is sometimes referred to as the "piecemeal" problem and is shown in Figure 4.1, where VMP refers to the "true" value of marginal product of water in the absence of economic distortions (LESSER et al., 1997). The quantity of water will equal Q gallons. Suppose that the only distortion in the market is that farmers receive a subsidized price for their crops. As a result, the VMP for water will shift upward, reflecting the increased value of each additional
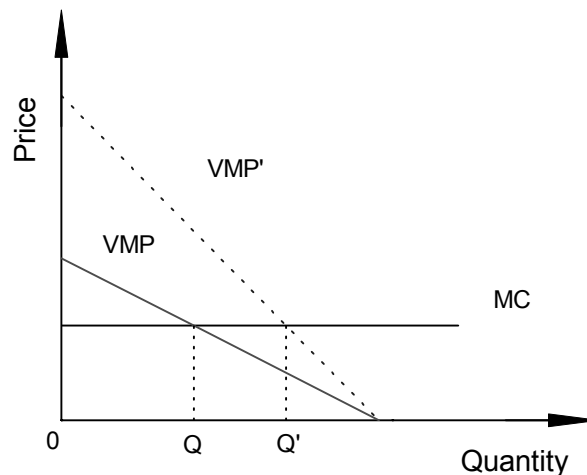
Figure 4.1: Distortion in water use because of subsidized crop prices
Source: Lesser, Jonathan A; Dodds, Daniel E; Zerbe, Jr.,Richard O (1997)

unit of water. As a result, the quantity of water consumed increases to Q' gallons. Marginal values of water will be higher for a given reduction in water supplies.

In addition, irrigation can result in negative externalities on land productivity, such as increased salinity, as well as increases in sedimentation in rivers, silting in navigation channels, and increased use of agricultural chemicals. To the extent that none of these impacts are incorporated into empirical estimates of the value of water, price estimates will be distorted. Even in the presence of fully transferable water rights, efficient transfers will be distorted to the extent that other economic distortions are present.

4.2   Water markets and irrigation system management

4.2.1 Water market management

Let us assume that water is recognized as a tradable economic commodity, then it should be possible to govern its allocation through the market. The initial incentive to establish water markets is due to water scarcity. The increase of private participation in water management is also a boosting for a water market. (Lee, 1999).

A proper system of tradable water rights is the premise of ensuring a water market to function. Firstly, a market requires the prior determination of the total number of water rights to be allocated to the existing water users scheme. Secondly, the rights must be clearly and securely defined and appropriately registered. Once markets are introduced and property rights are established in water, it is expected that transfers of water rights will occur. A market-based system of water

allocation will be therefore, both resilient to shocks and open to take advantage of opportunities.

A water market is actually a water management tool. It is a tool that spreads the burden and difficulties of water management among a larger population, and it permits greater participation in management decisions and can introduce greater flexibility into management systems. Again, so far the theory tells water markets can be distinguished from other processes for water allocation by (LEE, 1999):

● The motivating force is a voluntary perception by both, buyers and sellers, whereas the transaction is in their own best interest given the alternative opportunities available to them.

● No central authority determines the price and other terms of transfer, although it may condition or regulate them administratively.

● The price is generated through voluntary transactions negotiated between willing buyers and sellers.

● The transfer of water is the real purpose of the transaction and the value of water is established independent of the value of other goods and services involved in the transaction.

● A water market only exists where water rights are commodities with an identity, distinct form other real property.

However, a water market has its own limitation, albeit it is powerful. Arguments against proper introduction of water markets are: market power could be exercised in a water market directly through monopolistic behavior, either by a price-setting seller or by a price-setting buyer. There could be a potential for some other economic agents to influence market price levels. Making a water market work well requires a clear understanding of the required institutional and legal framework. It also requires the establishment of clear rules and regulations governing exclusive property rights, the necessity for simple transfer mechanisms, and the corollary of a minimum of bureaucratic interference in the market (HAHN, 1984). It also requires considerable investment by both the public and the private sector in the registration of rights, in a monitoring and measurement system, and in improving water distribution and transportation systems.

4.2.2 Irrigation system management and water saving

The issue of water saving, after a certain point, is that of water saving in irrigation. Thus, irrigated agriculture is increasingly feeling the pressure to demonstrate and

improve its performance (BURT, A.J.CLEMMENS, T.S.STRELKOFF et al., 1997). Irrigation efficiency is a key part of irrigation management. Irrigation management means c.a. water efficiency. There are still arguments about the concept of water use efficiency between water researchers. Some researchers think that there is still considerable room to improve the efficiency and productivity of water utilization in agriculture since the level of average water use efficiency is still pretty low over the world, due to under-developed irrigation techniques and poor management. However, some other researchers have argued that the potential gains from improving agricultural water use efficiencies maybe minimal. They argue that low values for measured water use efficiencies exist. This implies substantial potential efficiency, but losses are often derived from individual system evaluations rather than from basin-wide assessment. Unmeasured downstream recovery of drainage water, recharge and extractions of groundwater can result in actual basin-wide efficiencies. Individual observer may observe the situation. Substantially efficiency can be greater than the nominal values for particular systems compartment.

The concept of real water saving, instead of water saving on paper, was first discussed by SECKLER (1996). He suggested that water saving must take into account the impact of water reuse in a whole water basin. He also argues that in a new era of water management, a "real" not "paper" wise water saving should be achieved. If a water conservation technique simply reduces the amount of drainage water from a particular user and this drainage water is beneficially used downstream, this would be only a "dry "water saving. But, if the drained water flows directly into a salt sink, then "wet" water would be saved. By definition, if all of the usable drainage water, in a closed water basin, is already being used beneficially, water efficiency measures can only be reduced by drainage as measured against "dry" water. In open systems, on the other hand, usable drainage water may be lost to salt sinks. Reducing this loss by reducing drainage water will result in "wet" water saving, a real gain in efficiency! However, whether in close or open water basins, the real efficiency gains can be achieved by increasing the output per unit of evaporated water, reducing water losses to sinks, reducing the pollution water, and reallocating water from lower valued to high valued uses.

A detailed review of the concepts of physical and economic efficiencies of water use is presented by WICHELNS (1999) and CAI et al (2001). There are two types of efficiencies of water use, which are cited in water-related literature. They are physical water use efficiency and economic water use efficiency. The physical water use efficiency compares the volume of water delivered and consumed. It can be increased by decreasing the water used per unit of output. Instead economic water use efficiency relates the value of output minus opportunity costs

of water used in agricultural production to the value of water applied. It can be increased by reallocating water from lower valued to higher valued uses.

Physical irrigation efficiency

Physical irrigation efficiency represents the fraction of water beneficially used compared to the water withdrawn. Classical irrigation efficiency (*IEc*) is defined as the ratio of water volume beneficially used by plants to the volume of water delivered through an irrigation system, adjusted by effective rainfall and changes in the water storage in the root zone (BURT et al., 1997).

$$IEc = \frac{crop\ evaportranspiration -\ effective\ rain\ fall}{volume\ of\ water\ delivered\ -\ change\ of\ root\ zone\ water\ storage} \qquad (4.1)$$

This is mostly applied at project levels. Irrigation efficiency at the project level is typically further divided into distribution efficiency (water distribution in the main canal), conveyance efficiency (water distribution in secondary canals), and field application efficiency (water distribution in the crop fields).

KELLER and KELLER (1995) and KELLER et al (1996) argue that although the classical or local irrigation efficiency concept is appropriate for irrigation system design and management, it could lead to erroneous conclusions and serious mismanagement of scarce water resources, if it is used for water accounting at a larger scale. This is because the classical approach ignores the potential reuses of irrigation return flows (see before). To overcome the limitations of the classical irrigation efficiency, they introduced a new concept, called effective efficiency (*IEe*), which takes into account the quantity of water delivered from and returned to a basin's water supply:

$$IEe = \frac{crop\ evaportranspiration - effective\ rainfall}{volume\ of\ water\ delivered - change\ of\ root\ zone\ water\ storage - volume\ of\ water\ returned}$$

$$(4.2)$$

Economic efficiency

Economic efficiency of irrigation water use refers to the economic benefits and costs of water used in agricultural production. As such, it includes the costs of water delivery, the opportunity costs of irrigation and drainage activities, and potential third-party effects or negative (or positive) externalities (DINAR, 1993). Economic efficiency can be expressed in various forms. For instance, it can be expressed as total net benefit, net benefit per unit of water, or per unit of crop area. It is a broader approach, compared to physical efficiency, and allows an analysis of private and social costs and benefits.

Physical and economic efficiency at the river basin scale

Water use efficiency at a river basin scale basically extends the efficiencies at local sites to the basin level. Irrigation efficiency at the basin level is the ratio of crop water evapotranspiration to total water depletion for irrigation in the basin. The concept takes into account the potential reuse of return flows and potential decline in the water quality of return flows. Thus, it follows the concept of effective water use efficiency suggested by KELLER and KELLER (1995). However, the concepts of basin water use efficiency and effective water use efficiency are based on the following assumptions:

● The amount of return flow is significant relative to the water withdrawal;

● The quality of the return flow should meet water quality requirements for downstream water uses;

● The return flow can be reused through natural and /or engineering process, such as withdrawal from rivers and streams, stored in reservoirs or aquifers and could be delivered or pumped, or used for in-stream committed environment flow, hydropower generation and for ecological preservation.

● The time lag of flow for returning or for reuse is neglected. It should be noted that for some basins, there might be a "time lag" for return flows, and the time lag will affect the reuse of, at least, part of the return flow by downstream users, which depends on specific hydrologic characteristics in a basin.

The relationship between physical and economic efficiency

It is suggested by WALLENCE and BATCHELOR (1997) that in general both, physical and economic efficiencies, can be improved in irrigation systems by the following four ways:

● Agronomic improvements, such as improved crop husbandry and cropping strategies;

● Technical improvements, such as advanced irrigation systems;

● Managerial improvements, such as adoption of a demand-based irrigation scheduling system and improved maintenance of equipment; and

● Institutional management, such as introduction of water pricing and improvement in the legal environment.

The improvement of physical efficiency of water use is related to water conservation by increasing the fraction of water beneficially used compared to the water applied. Enhancing economic efficiency is a broader concept, which seeks

the highest economic value of water use through both, physical measures and allocations of water, to the highest obtainable valued of uses and users.

As an interesting study, LYNNE, ANAMAN and KIKER (1987) showed that the management of soil moisture in the crop root zone differs for the objectives of optimal physical and economic irrigation efficiency. According to Eq. (4.1), the physical efficiency is determined by the selection of the depth of irrigation (related to the water source and supply capacity) and the uniformity of water application (related to the irrigation system and field water management.). Once optimal physical efficiency is achieved, the economic efficiency can be improved, if it is based on the selection of the frequency of water application. The frequency is determined by selecting the optimal management and allowed deficit (MAD), which is expressed as a percentage of the available moisture capacity. MAD is the difference between full water requirements and the amount of water applied that allows for maximum economic efficiency.

Based on an agronomic-economic simulation model for lettuce, SUTTON and JONES (1994) proposed that optimal physical efficiency could differ from optimal economic efficiency under various physical conditions and economic incentives. Physical efficiency is expressed as crop production per unit of water applied, which is identical to classical irrigation efficiency assuming that crop yields are proportional to crop evapotranspiration. Whereas economic efficiency is defined as a net benefit per unit of land area. They think that optimal physical efficiency is achieved at a lower relative water supply than optimal economic efficiency.

Results from above both studies analyzed efficiency concepts at the crop field scale. At basin level, the relationship between physical efficiency and economic efficiency can be even more complex. Due to issues such as water allocation among various water users, and contribution for upstream return flows to downstream water availability, things may change.

Finally, if improvement in physical efficiency leads to environmental or ecological damage, such as reduction in water quality levels, water logging and salinization, or other negative externalities as well as third-party effects, the economic efficiency levels actually will decrease (WICHELNS, 1999).

Furthermore, socio-economic studies have to be mentioned. Based on game theoretical inquires, SAKURAI and PALANISAMI (2001) conducted a theoretical and empirical analysis on the issue of institutional evolution for resource management focusing on irrigation water. Two management types for irrigation schemes, a community management regime (tank irrigation) and an individualized management regime (well irrigation) are compared in terms of rice production

efficiency. They found that the profit of rice production using well water is low because well irrigation management requires a high labor input. Their estimation of profit functions reveals that the profit of farmers using both tank and well water is statistically significantly higher than that of farmers who use either well water, only, or tank water, only. The result, based on game theoretical inquiries, implies that in equilibrium tank and well irrigation can coexist.

4.3   Economic modeling of water use

There is a lot of research contributing to water-related economic modeling. The literature can be roughly divided into the following three aspects according to their research scope. These are surface water use modeling, groundwater use modeling and conjunctive water use modeling.

4.3.1 Surface water use model

CHAKRAVORTY et al (1995) developed a spatial model to determine the optimal conveyance investment, water allocation, and investment in farm-specific conservation technology. This model is a von Thuenen-like spatial model of a water project in which a regulated utility supplies water to individual farms and invests in the distributions systems (canals). Optimal water prices, investment in conveyance, and individual farm's investment in irrigation technology are determined at each location. The model hypothesis and results are:

● The net benefits from a project with optimal conveyance are higher than that from a project with no conveyance. The project area, i. e., the length of the canal is higher in the optimal case than without conveyance.

● The aggregate land rent is much lower in the model with conveyance and it is the highest in the uniform pricing model where farms pay a fixed rate for water that does not vary with location.

● Conveyance improvements reduce water loss. Correspondingly the shadow price of water differentiates slightly across locations. Thus, the variation in head-tail shadow prices is of little importance and the differences in water and technology investment from head to tail are negligible.

CHATTERJEE et al (1998) developed a dynamic model to analyze the inter-temporal allocation of surface water for irrigation and for hydropower production in the western United States. This issue arises because peak irrigation demands may not coincide with periods of peak demand for power. This study focused on the trade-off between water used for agriculture versus water used for

hydroelectric power. The analysis was done under two dimensions. One is to concentrate on the level of the water-irrigation district. The other is to study the implications for agriculture and hydropower production of intra-year variations in the release of water. The dynamic model is to determine the optimal flows of water releases by taking into account the value of water for both irrigation and hydropower production. The key trade-off developed in the model is that water released in spring to satisfy irrigation demands diminishes revenues from hydropower production for two reasons. First, power generated in the spring is less valuable than power generated during the summer period of peak demand. Second, water released in the spring diminishes its power-generating potential. The results of this model show considerable deviations between the actual and the optimal allocations. Such models are important when seasonal demand for water differs.

4.3.2 Groundwater use model

There are two well-developed branches of economic research that focuses on groundwater use. One uses dynamic optimization models, which are similar to those in typical renewable resource problems, for instance, to analyze pumping patterns. These models emphasize the difference between optimal pumping paths and common property outcomes. The other models study aquifers with contamination as an externality imposed by productive activities. They analyze aquifer contamination in a pollution control perspective giving special emphasis to non-point pollution, namely when pollution is caused by irrigated agriculture. It is clear that there is a gap between quantity and quality management in these two branches of studies and studies have seldom been crossed. The study of ROSETA-PALMA (2002) fills this gap. This study suggests that the value of water as a resource depends as much on the quantity available as on its quality, so that both aspects should be considered simultaneously for adequate management. The major contribution of this study is the analysis of the performance of groundwater quantity-quality interactions in a most general setting. In the study, a quality variable was added to a typical resource extraction model using three different hydrological assumptions. Then it is shown, that an optimal groundwater stock, at the steady state, always becomes higher than in quantity-only models. This is an expected result, since water use becomes less profitable. Furthermore, it is shown that private common property solutions can be characterized by small water stock, or low quality, and both. Thus, if there is intervention from a central planner, at least one of the two features of an aquifer will be improved. Though, there is a possibility that such an improvement is achieved at the expense of the other. It is also shown that an efficient steady-state level of polluting actions might be higher

than the one chosen by private agents, as long as the steady-state water quality is higher.

Nevertheless PALMA (2002) brought quality and quantity into the above model. However, his model contains a number of unrealistic simplifications with respect to the hydrological component. Next HELLEGERS et. al (2001) investigated the groundwater extraction problem in the Netherlands. They studied socially optimal agricultural groundwater extraction patterns and showed how desiccation and contamination can be integrated into an optimal control model. In contrast to above approaches, this approach considers temporal changes in both quantity and quality of the stock as mutually interacting. This theoretical model has not been tested yet on the basis of an empirical application but there is scope. HELLEGERS et. al (2001) show the importance of bringing the impact of agricultural shallow groundwater extraction on groundwater quality into resource management models. Their model demonstrates that the current low price of agricultural groundwater use is inefficient and provides few incentives for the adoption of modern irrigation technologies. The system does not consider the cost of desiccation and contamination in the price of water. The model also demonstrates that internalization of the negative as well as the positive externalities from agricultural shallow groundwater extraction on stock quality at the price of groundwater is particularly significant, if the recharge of groundwater is large compared with stock size.

HEANEY et al (2001) developed a model incorporating the relationship between agricultural production and groundwater hydrology. They estimated the benefits of improved irrigation efficiency in the Riverland of South Australia. Benefits from improvement in irrigation efficiency may be derived by two factors. First, internal benefits may accrue to the individuals undertaking the action as a result of more efficient agricultural production. Second, improved irrigation efficiency may decrease the amount of groundwater leakage, thereby decreasing the amount of saline groundwater being transported to the river system. These are external benefits, as they will not be straightly reflected in the returns to irrigators. Farmers make the investment in irrigation efficiency and are, therefore, the source of less potential market failures. The framework is a dynamic representation of the relationship between a hydrological cycle and economic returns to alternative land uses. Within this modeling framework, economic models of land use are joined with a representation of hydrogeological processes in a catchment. (The hydrogeological component incorporates the relationships between rainfall, evaportranspiration and surface water runoff). The effects of land use change on groundwater recharge, discharge rates and the process, governing salt accumulation in streams and soil, are investigated. In the agro-economic

component of the model, land use is allocated to maximize economic return from the use of agricultural land and irrigation water. Incorporated in this component is the relationship between salinity and yield losses for each agricultural activity. The model demonstrates that increased irrigation efficiency can generate external benefits to downstreamers through reduced discharge of saline groundwater. But achieving optimal irrigation efficiency is likely to require institutional arrangements to promote investment and public expenditure in the irrigation system.

4.3.3 Conjunctive water use model

To reiterate, in the surface water model, seepage from the canal has been treated as a negative effect on a water project. However, in many cases, water goes down and replenishes the aquifer, generating positive effects for the groundwater stock. Therefore, recently, the conjunctive water use becomes a more and more researched subject. UMETSU and CHARKRAVORTY (1998) extended the previous spatial surface water use model (CHAKRAVORTY et al., 1995) and developed a new spatial conjunctive water use model. By taking into account the irrigation return flows, they seek system efficiency. The return flow is assumed to recharge the groundwater aquifer. With all other parameters being the same, only variables related to groundwater use are newly introduced. The result suggests that both seepage and the investment in the water distribution systems play a critical role in the spatial organization of irrigation and production. Differences in seepage rates are much more critical in projects with high distribution losses than those with low losses. Unlike previous models where the choice of on-farm technology is guided solely by the shadow price of water, high seepage in this model induces high water losses on the farm, thus replenishing the groundwater aquifer. The model also challenges water polices based on conventional wisdom that encourages the investment in distribution canals and in better on-farm irrigation technologies separately. If the seepage rate is significantly high, attempts to reduce water losses on the farm through improved technology adoption maybe of little benefit. As described above, CHARKRAVORTY et al (1998), (1995) studied the optimal water allocation and impact of irrigation projects by using optimal control theory rather than programming approaches.

RAY and WILLIAMS (1999) used mathematical programming models to evaluate the water price policy in rural India. The presence of water theft was also analyzed in their paper. In their study area, the canal irrigation is critical for the productivity of agriculture. Subsidies to water interact with low domestic prices for wheat and high support prices for water-intensive sugarcane. Around a canal, farmers' locations are never homogeneous. A heterogeneity in location suggests

that a price regime could have significant efficiency and distributive consequences. Location is a key determinant of such thing as water "theft" because it is much easier for upstream farmers to siphon off extra water, impacting on downstream farmers' irrigation returns. Survey data were used to develop a location-centered, mathematical programming model of a canal, with a number of farms in sequence. The model's central features are the spatial flow of the surface water and subsurface water, the seepage, the seasonal interlocking of year-round agriculture and a farm-level optimization. With a realistic range of crops, technical coefficients, and water response functions, the data-driven model determines each farmer's water deliveries, actual water use, and optimal crop choices, and shows how these vary within the price regime. The model also makes the water deliveries to downstream farms endogenous to the choices made by individually optimizing upstream farmers.

4.3.4 Irrigation technology choices

Some researchers have studied the impact on efficiency by the selection of irrigation technologies. Their work tended to take an engineering approach (KNUTSON, ROBERT, CURLY et al., 1978). For a variety of circumstances, these studies computed and compared profits associated with the use of alternative irrigation technologies and determined the set of circumstances under which each technology is the most desirable choice. The engineering approach is more useful for determining when to adopt the new technologies than for predicting adoption patterns. This approach ignores variability in perceptions and information among farmers and does not consider the actual adoption data. CASWELL and ZILBERMAN (1985) took an alternative approach that used econometric tools and actual data on adoption patterns to explain and predict parameters and factors affecting the diffusion of modern irrigation technologies in California. The methodology of the approach has two characteristics. (a) It investigates the adoption of technologies that are non-crop specific and the behavior with respect to these technologies for growers. Several crops in several regions in a given period were included (Most studies have investigated the adoption of crop-specific technologies, and studied the behavior over time of the growers of a specific crop in one or several regions). (b) The model uses aggregate data and applies the discrete-choice econometric framework. A multinomial Logit model was applied using the land shares of each of the technologies for each of the regions as estimated by adoption probabilities (Traditionally, this framework has been used with panel data based on the decisions of individual farmers). The results from this model demonstrate that economic considerations (cost saving) have significant impact on the tendency to adopt new irrigation technologies. It was also shown that the groundwater users

are more likely to adopt modern technologies than surface water users. A further finding was that water-price policies could also help to promote the adoption of modern irrigation technologies and lead to substantial water saving.

4.4   Summary

In this chapter, some previous work in the field of water resource management has been reviewed. It can be observed that little systematic analysis has been done with respect to programming models. By using mathematical programming to investigate the aggregate impacts on water resource allocation and social welfare as well as agricultural activities simultaneously, separate aspects have been brought in dispense analyses to the systems analysis, especially based on first hand empirical data. Moreover, in terms of technology adoption, the previous work was done primarily at discrete technologies, exogenously, instead of a continuous technology level, endogenously to systems. Specifically in conjunctive water use models, production activity problems at farm level are seldom tackled.

In the present study, an attempt will be made to fill this gap. A spatial mathematic programming model is established based on empirical data through field research. It will be discussed in detail in the next chapters.

5   METHODOLOGY AND STRUCTURAL FRAMEWORK OF THE STUDY

In this chapter, the methodology of the study and the framework of the model, as employed in the study are discussed. The methodology of the study is presented by building a comprehensive modeling framework, named a spatial water allocation model (SWAM). The framework contains two packages. One is an econometric model using regression methods (SPSS). The other is a mathematical programming model, employing a General Algebraic Modeling System (GAMS). In the programming model, variables, parameters and equations are expressed in ways in which GAMS requires them. The objective of the SWAM model is to achieve optimal social welfare as rent from water and to provide simultaneously the optimal water allocation in a given irrigation area. The structure shall impact on farmers' choices of irrigation technologies and hence minimize investment to obtain the rents. The data used in the model were collected and processed during the field research. Data as shown is from a specialized apple production area, the Liquan County of Shaanxi Province, China, and covers one agricultural year. As described the employed farming system is fairly typical for current commercial agricultural production in rural China. The natural conditions of agricultural activities, such as soil quality, climate, etc., are assumed constant and excluded. Whereas the heterogeneity of location along the public canal is given priority of optimization. The model's usefulness is therefore, not regionally confined. Quantitative relationships such as agricultural input, output, and water use efficiency are brought in line with investments as applied to different farmer groups. Farmer categories of investment are derived endogenously through the modeling procedure. The solutions suggest that a better and more efficient water allocation and consumption could be achieved by a reduction of canal water losses and farmer's rational adoption of modern water saving technologies.

5.1   Structure of the model

The SWAM model, portrayed in this study is a combination of empirical studies using an econometric and mathematical programming model. In general, a framework, such as applied by SWAM, can be classified by two different approaches. First results from an econometric model are directly introduced into the programming model as part of the functional relationships to be explored. Some variables, though included in the econometric model, are later considered as endogenous variables in a system wide approach. Furthermore, the empirical foundation serves as a starting point. Second, econometric models are considered as sub-models to estimate parameters and then look for the impact of their

endogenous re-calculation. A change of estimated parameters is then part of flexibility in the programming model. In the study, the two approaches are put together. This procedure suggests that the econometric model incorporated into the programming model, can be used either as component or set of parameters. Then a comprehensive programming model will be used to optimize the social welfare of the irrigation area.

Figure 5.1 shows the structural framework of the SWAM model. Field data were collected via interviews with farmers, water resource management officials, and technical staffs. These data were already reported in Chapter 3. The data are from both the private and the public sector. Some of the data are used to estimate relevant functions in the econometric model (see details in Chapter 6). Most importantly the model includes a water demand function, a profit function, an on-farm water efficiency function, a canal water loss function, and a water price function over the locations. Those estimated functions are then used as part of the stated objective function as revealed technology description. Functions serve as constraint conditions as well as parameters in the modeling. It is noticed further, some other technical data, such as the seepage rate in the irrigation area, can be directly used by the programming model. The objective function is designed to maximize social welfare and it is subject to technical constrains on production and investment activities. Furthermore the water availability in the model is specified. For simplicity, the model incorporates only two types of activities of farming. They are apple production and private investment in irrigation technology. Water conservation is undertaken by the public and the private sector. There are also two major constraints for the management of the irrigation system. One is a fixed constrain, such as water resource availability, the other is a variable constrain, such as water efficiency. The last is an equation of motion for water in the canals and includes procurement of the groundwater. Except to the equations of motion, all other variable constrain functions can be achieved through econometric approaches. Finally the matrix of technical coefficients of the model can be obtained directly from field data and other related sources. The mathematical model is developed using the GAMS program (see details in Chapter 7) and the mathematical simulations were carried out using GAMS/CONOPT and GAMS/MINOS in the modeling process. Several different scenarios are also modeled.

Field data

Private sector:

Apple production, Investment in water saving technologies

Public sector:

Water generation and transportation

Database

Technical parameters

Econometric model:

- Water demand function
- Profit function
- On-farm water efficiency function
- Canal water loss function
- Water price function over location

Programming model:

Objective function:
Maximize social welfare

Constrains:

- On-farm water use efficiency
- Canal water loss rate
- Equations of motion for canal water and groundwater

Output of the model:

- Maximum social welfare
- Optimal choices of irrigation technology
- Optimal investment in the water conveyance system
- Water-related revenue,
- Land rent,
- Water rent,
- Water consumption

Scenario analysis:

- Impacts of status of public investment change
- Impacts of different allocation of irrigation technology
- Impacts of price regime change

Figure 5.1: Diagrammatic presentation of the structure of the SWAM model

5.2   Specification of the model

5.2.1 Layout of the irrigation area and adoption of various technologies in the study area

The model is developed from UMETSU's (1998) spatial water use model. The irrigation system of the model is assumed as a relatively closed water cycle system instead of an open river basin, and it contains controlled inflows and outflows. Farmers extract water from the canal, and simultaneously water is assumed to recharge the aquifer below the topsoil due to seepage from the canal and farmer's fields. Every farmer has access to groundwater. Neither a time lag nor a third party impact is considered in the model. The water flow, water loss, and likely choice of irrigation technologies are illustrated in Figure 5.2. A central planner supplies water to the project area. Farmers' fields are all located along the canal. At the head of the canal, upstream water is cheaper than downstream water, so that traditional surface irrigation technologies, such as flood irrigation and border irrigation, might be intensively adopted. Along the canal moving into the irrigation area, water becomes scarce due to extraction by individual farmers and leakage from the canal. Finally, canal water will be used up to a certain point, such as point C, as shown in Figure 5.2. It is assumed that the point C will emerge somewhere along the canal, on which farmers stop using canal water and switch to groundwater. Further, the switch point C is endogenous to the system and it will be determined by the model internally. It implies that, upstream farmers, who are located before point C, extract water from the public canal rather than from the groundwater aquifer. Since the cost of canal water is much lower than that of groundwater, this is reasonable.

In order to simplify the model, it is assumed that pumping is available for each farmer and pumping costs are constant throughout the survey area. However, downstream farmers start pumping water from the aquifer at point C, since there is no longer much water available in the canal. After the point C, groundwater supply gradually becomes the dominant water source in the tail area. Relatively expensive groundwater encourages farmers to adopt modern irrigation technologies in order to save water and lower costs. As shown in Figure 5.2, basin check irrigation, locally produced seepage irrigation, modern sprinkler and drip irrigation are dominant at the tail of the survey area.

It is necessary to stress that the distribution of irrigation technology dotted in Figure 5.2 just describes the situation in the survey area, in general, as a point of references. In a practical model established in the study, we attempt to achieve technology that it is not too regionally confined. The different distribution of the irrigation technology will be discussed in detail under different situations.
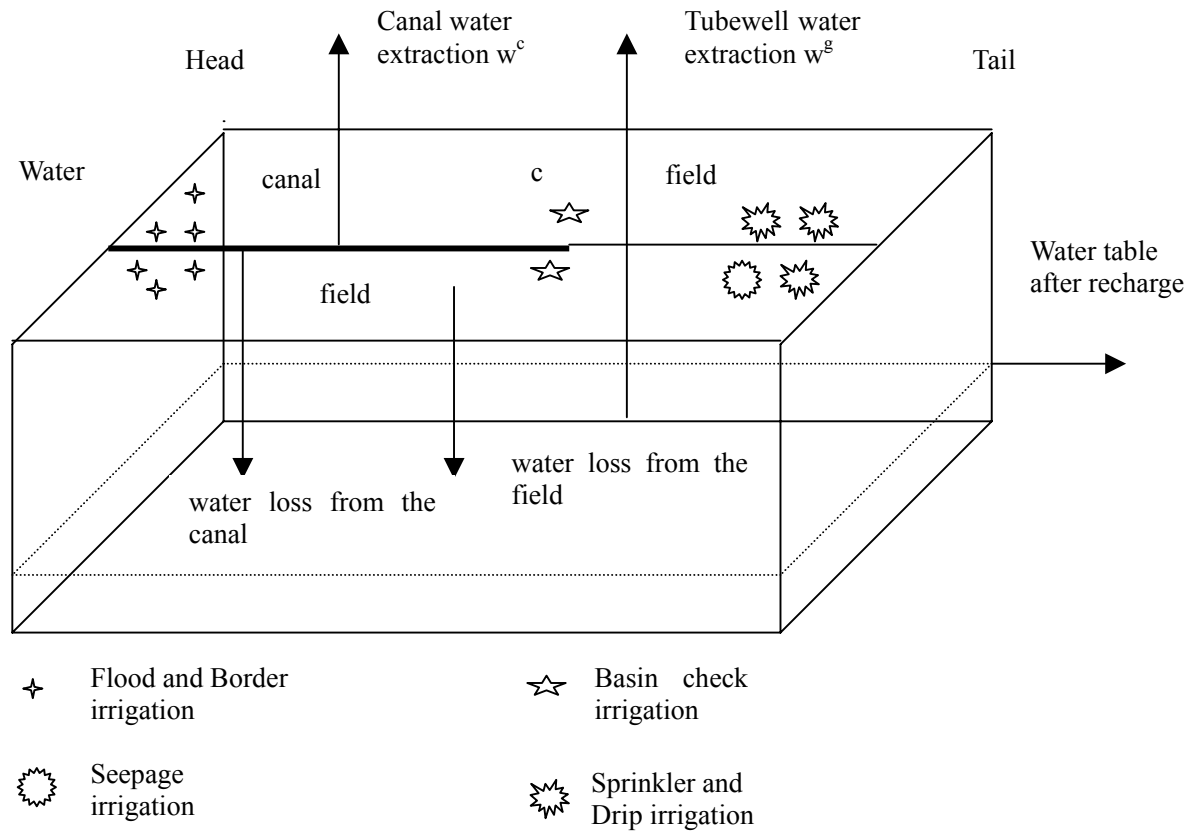
Figure 5.2: Water flow and allocation of irrigation technologies in the survey area
Source: Modified from Umetsu and Chakravorty, 1998

5.2.2 Dual investment activities

In order to understand the model further, we briefly have to touch on functional relationships with respect to investments. The main purpose of this study is to investigate the impact of investment in irrigation technologies on social welfare and water resource allocation. By improving the water use efficiency on farmer's fields and in the water conveyance system, social welfare shall increase. By aiming at improvement, investments are required from both, the side of individual farmers and the public side. Two types of investments for water conservation, namely public investments and private investments are to be considered in the current model simultaneously. As shown in Figure 5.3, in general, public investment is mainly from the central government and a local government is focusing on improvement of irrigation infrastructure. For instance, in the current case, the investment flows into the irrigation project for example, for water generation and canal lining, are part of a Chinese government's investment strategy for agriculture. But public investment has to be supplemented by private participation, i.e. private investment. Private investments are made by individual
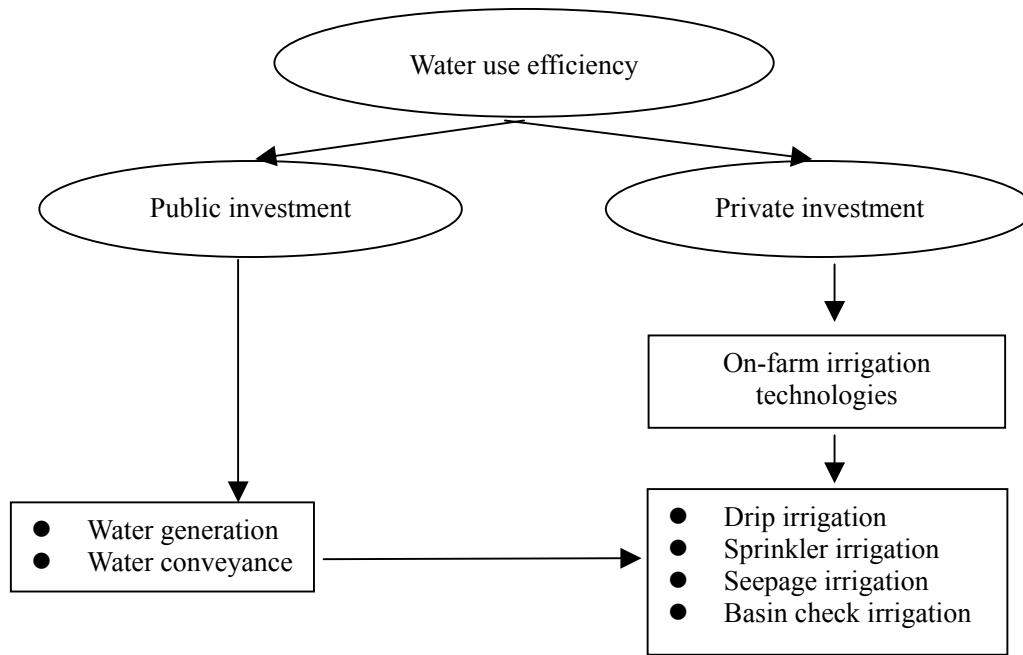
Figure 5.3: Structure of investment in water use efficiency

farmers along their cost-benefit-analysis. In terms of water conservation, this case refers to expenditures on water saving technologies at the farm level, such as procurement of locally produced seepage irrigation, modern sprinkler or drip irrigation. It is to be noted that various investment types reflect and influence all together the adoption of different techniques, and they correspondingly result in different on-farm water use efficiencies.

5.2.3 Adoption of different irrigation technologies as a endogenous continuous cost variable

As the adoption of different types of irrigation techniques is an important factor to be re-considered in this study, we go for a continuous presentation. In lots of previous studies, they were mostly taken as a discrete and exogenous variable (CASWELL & ZILBERMAN, 1985), (CHAKRAVORTY et al., 1995), (UMETSU & CHAKRAVORTY, 1998). The key argument of this study is to assume that all kinds of techniques are in a continuous set and it depends on monetary costs rather than on a kind of fixed technical coefficient to invest. By this approach the model can optimize technologies endogenously instead of exogenously fixing it. As illustrated in Figure 5.4, water use efficiencies for different irrigation techniques are roughly graphed together in a quadratic function. It is perceived that, the higher the water use efficiency shall be, the more investment is required. This on-farm water use efficiency function will be discussed more in the coming section.
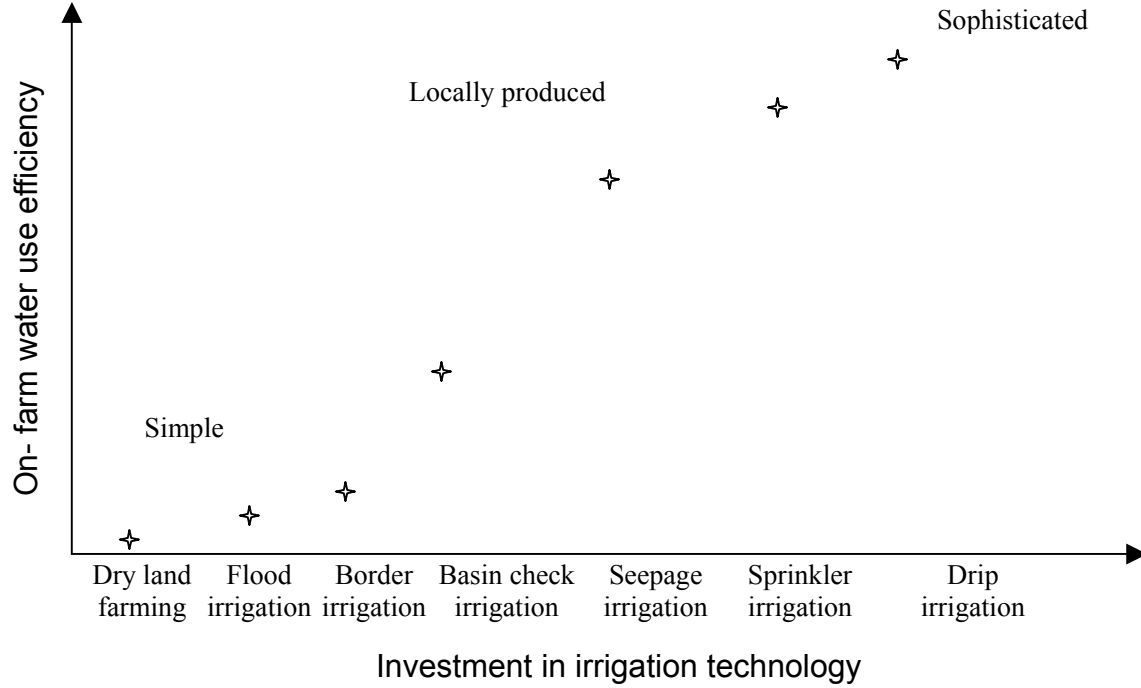
Figure 5.4: Water use efficiency and private investment

5.2.4 Introduction of coefficient of on-farm water use efficiency

Since on-farm effective water consumption is one of the key measurements of optimal water resource allocation, it is very essential to introduce a coefficient to reflect the on-farm water use efficiency. In general, the effective water use is defined as actual water consumption by plants, i.e., the amount of water that is consumed for plant's transpiration rather than that of water run-off, evaporation as well as leakage into the ground. Hence the amount of effective water consumption actually needs a coefficient to measure how much water is actually consumed by plants. Due to research scope, we will not calculate the plant's water requirement of transpiration, which is assumed constant to all the plants in the present study. The key issue of the study is to investigate how much irrigation water can be effectively consumed by plants. A coefficient of on-farm water use efficiency h will be introduced into the modeling process. The coefficient h is closely tied to irrigation technology, as different techniques will lead to different on-farm water use efficiency. The coefficient h is assumed a quadratic function of private investment in irrigation technology, which varies from 0.48 to 0.95 as obtained from field research. For instance, if no private investment is made, i.e., farmer operate traditional flood irrigation, then the on-farm water efficiency will be at the base level, i.e., 0.48. If farmers adopt the modern drip irrigation, then the water efficiency can be up to 0.95. This coefficient will be estimated later in the next chapter based on empirical data and will serve as an important component in the modeling process.

5.2.5 Introduction of coefficient of water loss rate in the water conveyance system

Water use efficiency incorporates not only on-farm water use efficiency, but also the efficiency of the water conveyance system. A coefficient to reflect the water conveyance efficiency is also required in the study. Based on field survey and relevant literatures, we establish a canal water loss function a to reflect the water efficiency during water transportation. The water loss function is assumed a quadratic function, which ranges from 0 to 1. If public investment is made maximally, for instance, a pipe canal is constructed, this indicates that a is equal to zero. It indicates that a zero water loss rate is achieved in this case. If public investment is removed from the water conveyance system, the water loss rate will be high. Different types of canals suggest different water loss rates. For instance, the highest water loss rate is found in a muddy canal, which reported of a loss rate of around 0.74 according to relevant literatures (GUO, 1980). The canal water loss function will be estimated in the coming chapter.

5.3　Summary

In this chapter, the methodology of the study, the framework and specification of the model have been discussed. A combined econometric and a spatial mathematical programming model has been suggested. They can be used to systematically analyze activities of a farming system to minimize cost of production, to increase spatial water use efficiency and to guarantee the effectiveness of investment in water conservation, and consequently to optimize the social welfare and water resource allocation over the irrigated area. The idea is to have a closed water supply system as much as possible. The irrigation technology is introduced as a continuous variable, which is more dependent on monetary cost. It is endogenously decided in the programming modeling instead of using fixed technical coefficients exogenously. The background and main features of functions of on-farm water efficiency and canal water loss rate have been briefly discussed, which will be further worked in the coming chapter. Furthermore, the mathematical programming model is adopted in the current study instead of a solely optimal control theory model. More details of the econometric model and the spatial programming model will be given in the next two chapters.

6   THE ECONOMETRIC MODEL

The SWAM model structure and methodology as well as the general specifications of the model have been discussed in the previous chapter. An econometric sub-model will be estimated in this chapter. An econometric model plays a key role in estimating the relevant functions of the approach, as employed in this study, such as the water demand function, the profit function, the on-farm water use efficiency function of private investment and the canal water loss function of public investment. All the estimated functions will then be employed as components in the spatial mathematical programming model. Especially we design the objective function by our functional approach. For this, we need a brief introduction into production theory, i.e., essentially the duality principle. This principle will be reviewed in the first section. The main empirical results for estimation will then be presented in a sub-chapter.

6.1   The Duality approach: Shephard's Lemma and Hotelling's Lemma

The concept of the profit function provides an alternative approach to the analysis of the production function and technology revelation (LAU & YOTOPOULOS, 1972). For a given technology and a given endowment of fixed factors of production, the profit function expresses the maximized profit of a firm as a function of the prices of output and of variable inputs. Moreover it measures coefficients for the quantities of fixed factors of production. The assumptions employed in the formulation of the profit function are: (a) firms are profit maximizing, (b) firms are price takers in both output and variable inputs markets, and (c) the production function is concave with regard to variable inputs. This implies, among other facts, that there are decreasing returns to scale with regard to all variable inputs taken, all together.

The profit function possesses many desirable properties for immediate empirical analyses. There exists a one-to-one correspondence between a set of concave production functions and a set of convex profit functions. Every concave production function has a dual property, which is a convex profit function, and vice versa. Hence, without loss of generality, we can consider only profit functions as a dual approach for the empirical analysis of the behavior of profit-maximizing and price-taking firms, instead of using a primal approach.

For further analysis, consider a firm with a production function with the usual neoclassical properties in equation (6.1a).

$$V = F(X_1, \cdots, X_m; Z_1, \cdots, Z_n) \tag{6.1a}$$

Where V is output, X_i represents variable inputs, and Z_i represents fixed inputs. The profit (defined as current revenues less current total variable costs) can be written

$$\pi = pF(X_1, \cdots, X_m; Z_1, \cdots, Z_n) - \sum_{i=1}^{m} c_i' X_i \tag{6.1b}$$

Where π is profit, p is the unit price of output, and c_i' is the unit price of the *i*th variable input.

By re-arranging, (6.1b) can be rewritten as (6.1c) to obtain a "Unit-Output-Price" function. The "Unit-Output-Price" (UOP) profit function is introduced to simplify the mathematical process.

$$\pi' = \frac{\pi}{p} = F(X_1, \cdots, X_m; Z_1, \cdots, Z_n) - \sum_{i=1}^{m} c_i X_i \tag{6.1c}$$

Where π' is "Unit-Output-Price" profit, or UOP profit.

The UOP profit function is decreasing and convex in the normalized prices of variable inputs and increasing in quantities of fixed inputs. It follows also that the UOP profit function is increasing in the money price of the output (LAU, 1978).

Through mathematical proofs, it can be shown, that there is a set of dual transformations connecting the production function and the profit function (MCFADDEN, 1971). One of the important relations is referred to as the Shephard's Lemma (SHEPHARD, 1953), namely,

$$X_i^* = -\frac{\partial \pi^*(c, Z)}{\partial c_i}, \quad i = 1, \cdots, m, \tag{6.1d}$$

$$V^* = \pi^*(c, Z) - \sum_{i=1}^{m} \frac{\partial \pi^*(c, Z)}{\partial c_i} c_i \tag{6.1e}$$

Where X_i^* is the factor demand function, V^* is the supply function.

There are many advantages to work with the UOP profit function instead of the traditional production function. Firstly, through equations (6.1c) and (6.1e), Shephard's Lemma makes it possible to derive the supply function, V^*, and the factor demand functions, X_i^*'s, directly from an arbitrary UOP profit function. The UOP profit function is decreasing and convex in the normalized prices of variable inputs and increasing in the fixed inputs (LAU & YOTOPOULOS, 1972). No explicit specification of the corresponding production function is required, rather

a specification at the profit function is enough. Secondly, by starting from a profit function, it is assured, by duality, that the resulting system of supply and factor demand functions are obtainable from profit maximization. A firm with a concave production function in the variable inputs, subject to given fixed inputs and under competitive markets is sufficiently described by maximizing a concave profit function. Thirdly, the profit function, the supply function, and the derived demand functions obtained, may be explicitly expressed as functions of variables normally determined independently of the firm's behavior. Econometrically, this implies that these variables are exogenous variables (LAU & YOTOPOULOS, 1972).

However, Hotelling's Lemma (HOTELLING, 1932) reveals a relationship between the profit function and the factor demand function as well as the supply function. Hotelling's Lemma introduces two kinds of prices for the profit function, output and input prices. In other words, the profit function, as defined in Hotelling's Lemma, is a function of the output price and the input factor price rather than that of the variable costs and it specifies a quantity of fixed inputs of production. As in the case of Shephard' s Lemma, Hotelling 's Lemma is presented below:

Let y (p, w) be the firm's supply function and let x_i be the firm's demand function for factor i. Then

$$y(p,w) = \frac{\partial \pi(p,w)}{\partial p} \tag{6.2a}$$

$$x_i(p,w) = -\frac{\partial \pi(p,w)}{\partial w_i} \quad i = 1,\cdots,n \tag{6.2b}$$

This requires that the derivatives exist for $w \gg 0$, $p > 0$. Where p is defined (a scalar) price of output and w is the vector of factor prices. The mathematical proof is given below (VARIAN, 1984):

Proof: Suppose (y^*, x^*) is a profit-maximizing supply-demand plan at prices (p^*, w^*). Then we define a function:

$$g(p,w) = \pi(p,w) - (p \cdot y^* - w \cdot x^*) \tag{6.2c}$$

Obviously, the profit maximizing production plan at prices (p, w) will always be at least as profitable as the production plan (y^*, x^*). However, the plan (y^*, x^*) will be a best plan at prices (p^*, w^*), so that the function g reaches a minimum value of 0 at (p^*, w^*). The assumptions on prices imply this is an interior minimum. The first-order conditions for a minimum then imply that

$$0 = \frac{\partial g(p^*,w^*)}{\partial p} = \frac{\partial \pi(p,w)}{\partial p} - y^* \tag{6.2d}$$

$$0 = \frac{\partial g(p^*, w^*)}{\partial w_i} = \frac{\partial \pi(p, w)}{\partial p} + x_i^* \quad \text{for} \quad i = 1, \cdots, n \qquad (6.2e)$$

Since this is true for all w^* and p^*, Hotelling's Lemma is obtained by re-arranging above equations (6.2d) and (6.2e).

It is further noticed that the concept of "profit" can be more broadly interpreted as function instead of being limited to the word of "profit". It can be a net profit, a gross margin, or a net revenue and so on. This depends on how input variables are specified. The "profit" in the present study is defined as water related net revenue achieved by individual farmers. This will be explained soon in the following section.

6.2   The econometric model of the study

A relevant econometric model in this study is estimated by using regression methodologies. It consists of several equations. All the relevant data are from the field survey database. The statistical program, SPSS, was employed to carry out the calculations. Two statistical indicators (*t*-test and *F*-test) and the adjusted R^2 are used for testing the significance of the estimated functions. The *t*-test can be used to test the individual partial regression coefficient and the *F*-test can be used to test the overall significance of the regression model (PINDYCK & RUBINFELD, 1998). The R^2 explains what percentage of output can be explained by the selected variables.

6.2.1 The inverse water demand function and the net revenue (profit) function

By estimating the profit function, we adopted Hotelling's Lemma. Specifically, what is needed in the model is equation (6.2b), which is a relevant parametric specification of the profit function, i.e., the relationship between profit function and input factor demand function needs a functional form. The approach is to get the inverse of water demand function first. Then, the estimated inverse water demand function will be used to obtain the profit function by integrating the demand function back. This kind of relationship can be more clearly illustrated in Figure 6.1. The Y-axis represents the water price, the X-axis represents the water consumption. A linear inverse water demand function shows a downward trend. The higher the water price is, the less water will be consumed. The small triangle below the inverse water demand function, which intersects with Y-axis and the shadowed rectangle, is the profit area that farmers got from water consumption. Specifically in the current study, the shadowed rectangular area represents a water
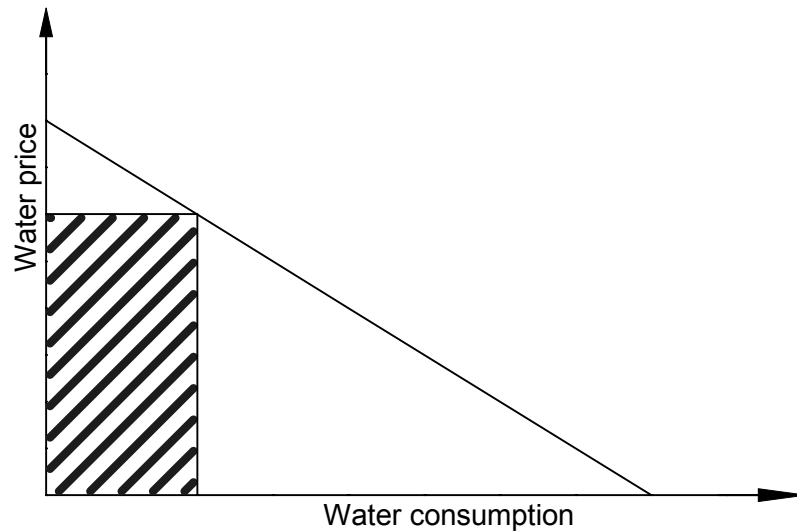
Figure 6.1:   Illustration of relationship between profit function and inverse water demand function

rent for water supplier, or a water expenditure for farmers. The concept of "profit" also needs to be clarified. Note that, the Hotelling's Lemma is still valid, which is independent of the "profit" defined. The profit function, in the model, is actually a water related net revenue function. Hence it is assumed that, in the present model, the variable costs, such as costs of fertilizer, are already deducted. Our concept of profit in the model therefore concerns only the net revenue, which concerns profits to pay for water consumption.

To simplify the water demand, the function of the model is considered to be a linear function of the water price and the annually on-farm irrigation technology investment *I*. The price of water and investment in irrigation technology, for individual farmers are available from the field survey database (see Chapter 3). To estimate the water demand function, it is essential in the model to directly link investment to obtained objectives. As we assumed before, our objective function is a function of effective water use, annual private investment in irrigation technology, as well as annually public investment in canal construction, maintenance and operation. The concept of effective water use, which is defined as actual water consumption by plants, has already been mentioned in the previous chapter 5. In this study, our variable of effective water consumption can be achieved by investigating what kind of irrigation technology farmers operate. In terms of traditional technologies, such as flood irrigation, border irrigation, basin check irrigation, the variable water consumption was obtained by citing the results from several irrigation water filtrate experiments carried out by a research team in the survey area (WANG, 1999). In terms of modern technologies, the variable was obtained by citing international studies (CASWELL & ZILBERMAN,

1985; CHAKRAVORTY et al., 1995). By doing this the variable of effective water consumption for the empirical analysis has been calculated.

Then, after the water demand function is estimated, the profit function of the water project area can be achieved by integrating this function back over the water demand.

For the presentation of results, we start with the effective irrigation water demand function. It is specified as below:

$$EW = 84.643 - 7.4 \times 10^{-2} \times I - 7.152 \times WP \tag{6.3}$$

$$t = 26.502 \quad t = -3.305 \quad t = -4.767 \quad n = 141$$

$$R^2 = 0.347, \quad F = 36.634, sign.F. = 0.0000$$

Where *EW* is the effective water consumption, measured in cubic meter per Mu (Mu is the Chinese land unit measure. 1Mu=1/15 hectare or 666.67 m^2.). *I* is the private investment in irrigation technology per Mu made annually during the life expectancy, and it is measured in Chinese currency Yuan per Mu. *WP* is the water price and it is measured in Yuan per cubic meter.

Since cross-section instead of time series data were used in the model, it is not surprising that the R^2 is only 0.347. Compared to other studies, it is already a relatively high value of R^2 for cross-section data analysis. Both the *F* and the *t* significance are within expectations. The *t* value for the constant term, variable *I* and *WP* also show a strong significance. The estimated water demand function is therefore acceptable for the model. The numbers of observations are n=141 instead of 149, because 8 farmers operate dry-land farming, therefore no irrigation water for them is demanded.

To get profit function, we need firstly to obtain the inverse water demand function from equation (6.3). The inverse water demand function is presented as:

$$WP = 11.83 - 0.01 \times I - 0.14 \times EW \tag{6.4}$$

By having the inverse water demand function, we integrate the function. By integrating this function over quantities (a linear function becomes quadratic), we get the net revenue function (profit function) with respect to the effective water consumption:

$$\pi = 11.83EW - 0.01EW \times I - 0.07EW^2 \tag{6.5}$$

Where π is net revenue of one Mu in the project area, *EW* is effective water consumption per Mu and *I* is annual investment per Mu in water saving technology.

This profit function will be directly used as key component of the objective function.

6.2.2 The on–farm water use efficiency function

Since this study focuses on water use efficiency, the water efficiencies at on-farm level are very crucial in the modeling process. In this section we estimate the function of on-farm water use efficiency. It will serve as a component for the objective function and be a constraint in the programming model. As suggested in the previous empirical analysis, higher investment will result in high water use efficiency. Based on application of different irrigation technologies by farmers at different locations, the corresponding data of the coefficient of water use efficiency and the required private investment can be obtained. Linear and non-linear functional forms have been tested. Comparing the different fitness of the estimated functions, a quadratic functional form is considered being most applicable to reflect most closely the relationship between on-farm water efficiency and private investment. The on–farm water use efficiency function is calculated as follows:

$$h = 0.48 + 0.0025 \times I - 2.94 \times 10^{-6} \times I^2 \qquad\qquad (6.6)$$

$$t = 66.12 \quad t = -11.98 \quad t = 18.76 \quad n = 141$$

$$R^2 = 0.840, \quad F = 361.13, \, sign.F. = 0.0000$$

Where h is the on-farm water use efficiency (in %) and I is the annual unit private investment, measured in Yuan per Mu.

The values of R^2, t and F suggest strong significance, so the equation (6.6) is accepted as the most relevant on-farm water use efficiency function.

6.2.3 The canal water loss rate function

The function of canal water loss rate is another important component of the model. It is related to the public spending on water efficiency in terms of water conveyance in the spatial model. The more investment in the canal is undertaken, the less water will be lost from the canal. This relationship can be modeled by measuring different types of water conveyance systems, i.e., to set different levels of canal construction costs. For example, a closed pipe canal system may cost 10,000 Yuan per km, and it can deliver water 100% to the farm gate without any loss. However, a kind of cement-constructed canal may cost only 3000 Yuan per km, but it may allow 3.3% water loss (GUO, 1980), while water is flowing in the canal, and so forth. This kind of relationship in our model, is reflected by a

quadratic canal water loss function, and by doing this, the unit-costs by the length of the canal as public investment can be measured. The public investment is responsive to distance. The longer the canal is, the more investment in construction, maintenances, and operation is needed. In this study we tried to keep the public investment simple. It is suggested that we can just multiply the unit-length cost by the canal length to get the total public investment. The data of public investment have been collected as well from literature as from the local water resource department. The life expectancy of different types of canals differs in correspondence to their construction level. Some can serve well up to 35 years, such as pipe-canals. Some can operate only 3-5 years, such as muddy canals (Guo, 1980). After some financial mathematics, however, one can make comparison among investments. Since the activities incorporated in the model are surveyed within one agricultural year, the data of investment in the public canal are also taken as annual value.

Finally the estimated quadratic function of canal water loss rate is specified as below:

$$a = -0.000405K + 5.25 \times 10^{-7} K^2 + 0.74 \tag{6.7}$$

$$t = -5.019 \qquad t = 3.534 \qquad t = 6.903 \qquad n = 30$$

$$R^2 = 0.745 \quad F = 19.02 \quad sig.F = 0.0001$$

Where a is the canal water loss rate (%) per km and K is the annual public investment per km in the canal.

The equation (6.7) will serve as component and constraint in the programming model.

6.2.4 Parameter estimation of the canal water price and the groundwater price

Based on field research, it is evident, that the water price varies with the distance getting farther away from the water source (see chapter 3). By analyzing the field data, the empirical analysis indicates, that groundwater and canal water have quite different starting values and tendencies. The canal water price is cheap at the water source, and becomes more expensive when the distance gets farther. However, the groundwater price is higher than the canal water price, at the water source, due to its pumping costs. So farmers have no incentive to use groundwater in the upstream area. The groundwater price also increases with the distance getting farther, but it varies less as compared to the canal water price. The differences of pumping costs mainly depend on the actual depth of a tubewell.

With distance getting farther, it is assumed that the depth of the tube well increases.

However, since no groundwater was used at the water source in the study area, no field data for the groundwater price at the water source area was available. By getting help from local technical experts, the groundwater price and the electricity costs for pumping based on well depth nearby are considered and calculated. By doing this, potential groundwater prices at the head area (upstream) are obtained. The data suggest that the canal water price and the groundwater price are given as being parallel over different locations. Quadratic functional forms are chosen to model the relationship between both price and location. The function of canal water price is expressed as:

$$CWP = 0.13 + 0.0071 \times d + (-4.5 \times 10^{-6}) \times d^2 \tag{6.8}$$

$$t = 16.938 \quad t = 61.709 \quad t = -15.004 \quad n = 141$$

$$R^2 = 0.99 \quad F = 14759.53 \quad sig.F = 0.0000$$

Where *CWP* is the public canal water price, and *d* is the distance from the canal water source to farmer's field.

Next the function of the groundwater price is specified below as:

$$GWP = 0.475 + 0.006 \times d + (-8.698 \times 10^{-6}) \times d^2 \tag{6.9}$$

$$t = 42.935 \quad t = 35.918 \quad t = -20.104 \quad n = 141$$

$$R^2 = 0.98 \quad F = 2006.17 \quad sign.F = 0.0000$$

Where *GWP* is the private groundwater price, and *d* is the distance from the canal water source to farmer's field.

These two functions will serve as parameters in the programming model.

6.3 Summary

The net revenue function, the on-farm water use efficiency function, the canal water loss function, and the functions for the canal water price and the groundwater price have been obtained by using regression methods. These functions will serve as key components in the spatial mathematical model. A detailed discussion of the mathematical programming modeling is presented in the next chapter.

7 THE SPATIAL MATHEMATICAL PROGRAMMING MODEL

An econometric model, which serves the programming model, was presented in the previous chapter 6. In this chapter, the spatial mathematical programming model will be introduced. It is a GAMS model. In the way of GAMS requirements, we present the objective function and the constraints of the approach. Functions estimated in the previous chapter will serve as empirical components of the objective function and outlined constraints in the modeling process. As generally well known, a programming model consists of four basic elements, the objective function, several optional activities, constraints, and a matrix of technical coefficients. In this chapter the four elements will be presented in line with the GAMS code, instead of a pure mathematical presentation.

7.1 Overview of relevant variables, parameters and data

All relevant variables, parameters and scalars are given as basic components of a mathematical programming model. Before we start to discuss the modeling process, it is necessary to clarify all of them in relation to the present study. Variables are listed in Table 7.1 and expressed in the GAMS code. These variables can be divided into endogenous and exogenous ones, which mainly depend on the role they play in the model internally or externally. Specifically in the SWAM model, the endogenous variables include canal water demand, groundwater demand, private investment in on-farm water saving technologies and public investment in the water conveyance system. Furthermore, the canal length, the on-farm water use efficiency, the canal water loss rate as well as the quantity of canal water remaining and the groundwater remaining at any location along the canal are considered. All of them will be determined by the programming model endogenously.

The spatial programming model is initially a static model within one time period. From the aspect of space change, it can be treated as a dynamic process in the present study. An important common character is that an index "j" is appended to all the endogenous and exogenous variables as well as parameters, specifying a location. "j" represents a stretch of 50 meters along the canal. In j, the movement of water at any location along the canal as well as the investment in water conversation can be described and tracked homogenously. It suggests that all the variables and parameters concerned in the model are location wise (spatially) varying while the locations being connected. However, the model is discrete.

Table 7.1:   List of variables, parameters and scalars of the model

GAMS code	Interpretation	Measure unit	Status in the model
Variables			
SW	Social welfare	Yuan	Endogenous
NR (j)	Net revenue at location j	Yuan per Mu	Endogenous
LA (j)	Land rent at location j	Yuan per Mu	Endogenous
WA (j)	Water rent at location j	Yuan per Mu	Endogenous
CW (j)	Canal water consumption at j	m^3 per Mu	Endogenous
GW (j)	Groundwater consumption at location j	m^3 per Mu	Endogenous
CREM (j)	Canal water remains at location j	m^3	Endogenous
GREM (j)	Groundwater remains at location j	m^3	Endogenous
I (j)	Private investment in irrigation technology at location j	Yuan per Mu	Endogenous
K (j)	Public investment in canal at location j	Yuan per km	Endogenous
a(j)	Canal water loss rate at location j	%	Endogenous
h (j)	On-farm water efficiency at location j	%	Endogenous
Parameters			
C0 (j)	Coefficient of net revenue function		Exogenous
C1 (j)	Coefficient of net revenue function		Exogenous
C2 (j)	Coefficient of net revenue function		Exogenous
C3 (j)	Coefficient of private investment		Exogenous
E0 (j)	Coefficient of on-farm water efficiency function		Exogenous
E1 (j)	Coefficient of on-farm water efficiency function		Exogenous
E2 (j)	Coefficient of on-farm water efficiency function		Exogenous
R0 (j)	Coefficient of canal water loss rate function		Exogenous
R1 (j)	Coefficient of canal water loss rate function		Exogenous
R2 (j)	Coefficient of canal water loss rate function		Exogenous
CWP (j)	Price of canal water	Yuan per m^3	Exogenous
GWP (j)	Price of groundwater	Yuan per m^3	Exogenous
Scalars			
CW0	Canal water stock at source	m^3	Exogenous
GW0	Initial groundwater stock	m^3	Exogenous
Beta	Water recharge rate to groundwater	%	Exogenous

Parameters, matrixes, or scalars are exogenous elements. They were obtained either from the econometric model or directly from the database of the model. The parameters of the presented model are all from the estimated functions. They include several coefficients for the revenue function, the on-farm water efficiency function, the canal water loss rate function and the prices of groundwater and canal water. Some of them can vary with location depending on the conditions. Scalars are also exogenous to the model, and they were obtained via interviews with technical staff from the local water resource department and individual farmers as well as from the relevant literature. Also the model contains two different water recharge rates for groundwater, an initial water stock at the source and an initial groundwater stock. These starting conditions are given in the modeling process.

7.2   The objective function of the spatial programming model

7.2.1   General presentation of the objective function

The objective function of the spatial programming model is used to maximize the social welfare in the survey area by focusing on efficient uses of water. It is calibrated with the estimated profit function. The optimization of social welfare is investigated by considering the water related net revenue of the survey area minus the expenditure on water conservation technologies. The net revenue is usually expressed as gross margin or as revenue minus the main variable input costs, such as seeds, fertilizer, pesticides, labor, and land preparing costs. Since the special emphasis of the study is on water use efficiency, all main variable input costs, such as fertilizer, pesticides and labor costs are kept constant and being deducted already. They do not vary with locations. The programming model hence considers only water-related costs. The water-related costs of the model incorporate public expenditure on water transportation in the conveyance system and individual farmers' investment in on-farm irrigation technologies. A detailed discussion about the objective function will be given in a later chapter due to technical needs. A more general description of the objective function is expressed as below:

Social welfare = net revenue − private investment in irrigation technology − public investment in the water conveyance system − canal water costs − groundwater costs

$$\tag{7.1}$$

In line with a mathematical formulation the objective function can be presented as below:

$$Max\ SW = 15\left(\sum_j \pi_j - \sum_j I_j - \sum_j CWP_j \times CW_j - \sum_j GWP_j \times CW_j\right) - 0.05\sum_j K_j \tag{7.2}$$

Where j = location, it ranges from 1 to 200, and it represents a stretch every 50m along the canal, i.e., the length of irrigation system is 10km.

sw= social welfare over the irrigation area

π_j = net revenue in Yuan/ Mu at location j

I_j = annual private investment in technology in Yuan/Mu at location j

K_j = annual public investment in water conveyance in Yuan/km at location j

CWP_j = price of canal water at location j

GWP_j = price of groundwater at location j

CW_j = canal water consumption at location j

GW_j = groundwater consumption at location j

Employment of coefficient "15" is Mu related. It converts to Chinese land measurement in hectare.

The first argument of the right hand side (RHS) $15\sum_j \pi_j$ represents the sum of net revenue of every unit at location j. As defined in previous chapter, a stretch of j is 50 meters long; the length of the whole project area is assumed 10,000 m long and 200 m wide. It suggests that one unit area what j represents is $50\times200 = 10,000\text{m}^2$, which is either equal to 1 hectare or 15 Mu. Since π represents the net revenue per Mu, $15\sum_j \pi_j$ is therefore a representation of the sum of net revenues over all locations. The second argument $15\sum_j I_j$ of the RHS represents the sum of private investment in irrigation technology at every location j. The third and fourth two arguments in the bracket are total canal water costs and groundwater costs respectively. The last argument $0.05\sum_j K_j$ of the RHS represents the sum of public investment in the canal system at every location j. Since K is measured in Yuan/km, one unit of j (50m) is equivalent of 0.05 length of one kilometer.

7.2.2 Components of the objective function and constraints of the model

The net revenue function and the on-farm water use efficiency function are the key components of the objective function of the programming model. They were already estimated in the previous chapter 6 and are presented in this chapter again in way of the GAMS code:

The net revenue function is:

$$\pi_j = 11.83 EW_j - 0.01 EW_j \times I_j - 0.07 EW_j^2 \tag{7.3}$$

Where EW_j is the effective water use, which will be replaced by $TW_j \times h_j$ in the programming model, I_j is the investment. So the net revenue function is newly specified as:

$$\pi_j = 11.83 \times (TW_j \times h_j) - 0.01 \times (TW_j \times h_j) \times I_j - 0.07 \times (TW_j \times h_j)^2 \tag{7.4}$$

Where TW_j is the total water demand in the area of 1Mu and h_j is the on-farm water use efficiency at location j

Our on-farm water use efficiency function: is

$$h_j = 0.48 + 0.0025 \times I_j - 2.94 \times 10^{-6} \times I_j^2 \tag{7.5}$$

The water use efficiency function is directly used in the objective function as one component of the net revenue function. It contributes to the measurement of the effective water consumption, but also serves as one constraint.

The canal water loss function is:

$$a_j = 0.74 - 0.000405 \times K_j + 5.25 \times 10^{-7} \times K_j^2 \tag{7.6}$$

Where a_j is the water loss rate at location j, K_j is annual public investment per km at location j. This canal water loss function will serve as a component of the equations of motion for canal water and groundwater and as one constraint of the optimization process as well.

7.3   Key constraint conditions of the model

7.3.1   The equations of motion of water movement

Equations of motion are the most important constraints in a dynamic model. In this model they are transferred as location wise function. Technically one speaks of differential equations. For us, they are the central elements to solve a location problem. Since canal water is moving between locations and the groundwater stock also changes at locations, differential equations can be expressed as equation of spatial motion respectively.

The equation of (spatial) motion is a classical concept of dynamic optimization procedures (CHIANG, 1992). The simplest problem is an optimal control problem. It can be expressed as below:

Maximize $\qquad V = \int_0^T F(t,y,u)dt \qquad\qquad\qquad\qquad\qquad$ (7.7a)

Subject to $\qquad \dot{y} = f(t,y,u) \qquad\qquad\qquad\qquad\qquad\qquad$ (7.7b)

$\qquad\qquad\qquad y(0) = A$, $\ y(T)$ free, $\quad$ (A,T are given)

and $\qquad\qquad u(t) \in U$, for all $\ t \in [0,T]$

Three types of variables are presented in the problem statement (7.7a): t (time-location), y (state) and u (control). The presence of the control variable u necessitates a linkage between u and y, to reflect how u will specifically affect the course taken by the state variable y. This linkage is provided by the equation $\dot{y} = f(t,y,u)$ where the dotted symbol $\dot{y}$, denotes the time (change in location) derivative dy/dt. At the initial time (location), the first two arguments in the function must take the given value $t = 0$ and $y(0) = A$. Only the third argument is open for us to choose. What this setting does, therefore is to provide the mechanism whereby our choice of the control variable u can be translated into a specific pattern of movement of the state variable y over time (location). For this reason, the equation is referred to as the equation of motion for the state variable (or the state equation for short) (CHIANG, 1992).

For the general interpretation, normally, equations of motion for the stated variables are expressed as dynamic functional forms, i.e., differential equations with respect to time t. However they can also serve as a differential equation with respect to location. This is exactly what is employed in the present study. For the optimal control theory presented above, the equation of motion is always connected to three different stages of the state variable, the initial condition, a terminal condition and a state in between of them. In this study, it is assumed that a relatively closed spatial water supply system exists in the project area, and the area has a stretch "j". "j" substitutes "t". The framework was given in Figure 5.2. It implies that surface water and groundwater are jointly used along "j". It also implies that at a certain point farmers will use groundwater rather than canal water due to the fact that canal water is running out. Therefore, to optimize the model, the equations of motion for canal water and for groundwater must be taken into account simultaneously.

The equation of motion for canal water flows is an application of equation (7.7a) and (7.7b) under special terminal condition, i.e., $y(j) = 0$. $y(j)$ is the canal water consumption at location j (j can be a location where canal water is used up in this case). The equation suggests that the state variable $y(j)$ is no longer free of restrictions as presented in the equations (7.7a) and (7.7b) before. In GAMS modeling, we do not need and cannot pre-determine the terminal condition, since the end point of canal water will be decided by the model internally. The equation of motion for canal water flow in this model is thus expressed as a way of model

requirements (MCKINNEY & SAVITSKY, 2003; DELLINK, SZONYI, & BARTELINGS, 2001). It can be specified as below:

Initial condition:

$$crem_1 = cw_0 - 15 \times cw_1 \qquad (7.8a)$$

Discrete flow motion:

$$crem_j = (1 - a_{j-1}) \times crem_{j-1} - 15 \times cw_j \qquad (7.8b)$$

The equation (7.8a) is the initial condition for canal water flow, where cw_0 represents the canal water supply at the water source. "cw_1" is the quantity of canal water consumed by the first farmer within first 50 meters, $crem_1$ is therefore the canal water that remains after the first farmer and then passes down to the next farmer, i.e., the next location.

Then equation (7.8b) describes the amount of canal water that remains at location j, which starts from the second farmer and is going to be delivered to the next farmer. It is the general function of motions. It is expressed as a value of water that remains from the previous location j-1 minus water consumption at the present location j. Where $crem_j$ represents the canal water that remains, i.e., the canal water stock at location j. In the equations, $crem_{j-1}$ represents the canal water that remained from the previous farmer's location j-1. Additionally we introduce the canal water loss rate a_{j-1} defined as before, it represents the canal water loss rate at location j-1.

This was the canal water movement. In principle, the equation of motion is the same for groundwater motion. The initial point starts from the head of the survey area. It implies that there is an initial condition $y(0) = A$. Specifically "$grem_1$" is the groundwater remaining at the first location of the survey area. In terms of terminal condition, however, groundwater is free of restrictions and gives a lower bound of zero in the optimization process. The only difference is, that the groundwater extraction starts at point C (as shown in Figure 5.2) instead from the first location as for canal water.

It is important to recognize that the groundwater aquifer can be recharged by water leaking from the canal and seepage from farmer's fields. It is therefore, suggested that the groundwater stock will increase all the time due to the recharge from both sources and without any extraction before point C. It is further noticed that, the canal water is so cheap that farmers have no incentive and no need to pump underground water until C. After point C, there is minor water flowing in the canal, and groundwater extraction starts from this point. This implies that the

fraction recharged from canal water becomes zero. The groundwater stock can only be recharged by seepage from farmer's fields. These stages will be also specified in the equation of motion. The mathematical formulation of the equation of motion for groundwater change is presented as below:

Initial condition:

$$grem_1 = gw_0 + \beta \times (1 - h_1) \times 15 \times tw_1 - 15 \times gw_1 \qquad (7.9a)$$

Discrete flow motion:

$$grem_j = grem_{j-1} + \beta \times a_{j-1} \times crem_{j-1} - 15 \times gw_j + \beta \times (1 - h_j) \times 15 \times tw_j \qquad (7.9b)$$

Equation (7.9a) describes the initial condition for groundwater change. Where $grem_1$ represents the groundwater remaining at location 1 which will be available for the second location, gw_0 represents the groundwater base stock at the head location, i.e., the groundwater stock at the first farmer's field. The second part is the fraction of groundwater recharged from the first farmer's field, since no water recharged from canal is observed at the first location due to zero distance from the water source. In this part, tw_1 is the joint conjunctive water used at the first location, β is defined as the recharge rate for groundwater, and h is the water efficiency in farmers' field. gw_1 is the groundwater consumption at the first location. Equation (7.9b) is the change of groundwater stock at any location except the first location. The $grem_j$ represents the groundwater remaining from the previous farmer to the next farmer at location j, here j starts from farmer 2. β is recharge rate for groundwater, so $\beta \times a_{j-1} \times crem_{j-1}$ represents the water loss fraction at the location j-1 from the canal and can be recharged to the aquifer. gw_j is the groundwater quantity extracted by an individual farmer at location j. As defined before, h is the effective water use function, therefore $\beta \times (1 - h_j) \times 15 \times tw_j$ represents the fraction of pumped groundwater and surface water loss from a farmers' field which recharges the groundwater aquifer at location j. It can be used by farmers at the next location.

These equations of motion for canal water flow and groundwater change for each location will serve as the most important constraint conditions in this spatial model.

7.4   Technical coefficients

Quite fortunately, we are getting most of the coefficients from the econometric model, we do not have many technical coefficients directly to incorporate into the programming process. As an important starting point for the model, we have

initial canal water and groundwater capacity at the first location, measured in m^3. They are specified:

$cw_0 = 300,000$; $gw_0 = 1000$

And we also have two different recharge rates of groundwater stock, which are $\beta = 0.3$ and $\beta = 0.8$ respectively.

These coefficients will serve as scalars in the programming model directly.

7.5   Review of employed modeling approaches of the study

From chapter 5 to the present chapter, the structure and methodology of SWAM model have been discussed. By using econometric model and duality approach of profit function, the net revenue function of water was obtained. This procedure provided an important premise for formulating the objective function of the programming model. The latter achieved on-farm water use efficiency function and canal water loss function also simultaneously serve to the objective function and constraints conditions.

As mentioned already, the equation of motion is the most important character of a dynamic model. Normally a dynamic model is related to time. In the present study, the model we built can be considered as a static approximation of a dynamic problem, which is merely related to space change. For the time being, the model is run within one time period, in line with the public and private investment to the water conservation being fixed at one time period too. This is a limitation of the model. In future, it is necessary to consider a more complicated situation, for instance, to run the model with time and space change simultaneously, so that the model's usefulness can be extended while time changing.

7.6   Summary

This chapter has given a presentation of the spatial programming model in a way of GAMS requirements. The relevant variables and parameters were presented. The objective functions and constraints as well as technical coefficients were also discussed and translated into the GAMS language. The most important features of the spatial model, the employment of equations of motion for canal water and groundwater were stressed in this chapter. The applied modeling approaches of the study and the limitation of the spatial model have been briefly reviewed. Based on the establishment of the programming model, some different policies oriented scenarios will be discussed in the coming three chapters.

8. IMPACTS OF PUBLIC INVESTMENT STATUS CHANGE ON SOCIAL WELFARE AND WATER RESOURCE ALLOCATION

The core of this study is to investigate the impacts of improving water use efficiency through public and private investment on social welfare and allocation of water resources. The model structure and the optimization process were introduced in previous chapters. Based on those outlines, different polices oriented scenarios will be discussed in the current and the next two chapters. The selected scenarios are supposed to value the impacts of water efficiency on social welfare and allocation of water resources. Indicators, such as:

- Land rent,

- Revenue,

- Water rent,

- Canal water demand,

- Groundwater demand,

- Private investment,

- Public investment,

- Water use efficiency at on-farm level, and

- Water use efficiency in conveyance system,

will be modeled within these chapters. Among them, private investment and public investment are two critical variables in the study. To investigate the role they play in water saving and the relationship between them, we focus on these variables. They are the main concerns of the study.

8.1. Specification of elements concerning the modeling process

8.1.1 Specification of objective function and related concepts

The general form of the objective function has already been introduced in the previous chapter 7. To explore the movement of private and public investment and their consequent impacts in more detail, the general objective function will be specified as three different forms to model the impacts of different policies orientations. In the present chapter, the impacts of public investment status change on social welfare and water resource allocation will be assessed. Again, this study

solely focuses on water related social welfare. It is therefore suggested that merely the revenue associated with water use and water project spending is incorporated into the objective function. Actually, social welfare would be an economic surplus, i.e. the sum of consumer surplus and producer surplus. Since we investigate production of a small area, we think that this does not impact on prices. Hence, it makes sense to focus on producer surplus only.

The objective function is expressed in such a form in GAMS modeling:

$$Social\ welfare = \sum_{j} 15 \times \left[c0_j \times (tw_j \times h_j) + c1_j \times (tw_j \times h_j)^2 + c2_j \times I_j \times (tw_j \times h_j) \right]$$
$$- \sum_{j} \left(0.05 \times k_j + 15 \times I_j + 15 \times cwp_j \times cw_j + 15 \times gwp_j \times gw_j \right) \qquad (8.1)$$

Where

$c0_j$, $c1_j$ and $c2_j$ are coefficients of the revenue function. They were obtained by integrating the inverse water demand function.

tw_j is water demand per Mu at location j.

h_j is a function of on-farm water use efficiency at location.

I_j is private investment in irrigation technology at location j. measured in Chinese currency RMB Yuan/Mu annually.

k_j is public investment at location j. measured in Chinese currency RMB Yuan per km annually.

cwp_j is a parameter of canal water price at location j.

cw_j is canal water demand per Mu at location j.

gwp_j is a parameter of groundwater price at location j.

gw_j is groundwater demand per Mu at location j.

All definitions of economic welfare are narrowed within water related issues. By doing so, the model can better clarify relationships among different variables. Such questions as how much a variable react to another when any relevant element changes. For instance, the following definitions of revenue, land rent and water rent are narrowly defined within water related domain (UMETSU, 1995). They are specified as below:

Revenue: The revenue computed in the current study is part of total revenue of the apple production. It is related and derived from water consumption in the current study. Revenue from rainfed apple production is considered fixed and will not be concerned in the study. Only irrigation water is investigated. In a certain

acceptable limit, the more water is consumed, the higher the revenue will be. Its mathematical value is:

$$
\begin{aligned}
&Revenue\ (associated\ with\ irrigation\ water) \\
&\quad = computation\ of\ integration\ from\ inverse\ water\ demand\ function
\end{aligned}
\tag{8.2}
$$

Land rent: This is a concept that is related to land productivity and capacity as well as to the expected return from the production activity per Mu. The land rent increases with higher productivity due to irrigation. In this study rents are calculated by subtracting water costs and private investment in on-farm activities from revenue. Note, the private investment in this study is only limited to investment in irrigation technology. The land rent is hence specified as:

$$
\begin{aligned}
&Land\ rent = revenue - canal\ water\ costs - groundwater\ costs \\
&\quad - private\ investment\ in\ irrigation\ technology
\end{aligned}
\tag{8.3}
$$

Water rent: In this study, this term is related to the public sector. It is considered a sum of collected water fee from farmers less the public expenditure on water conveyance system. It is specified as below:

$$
\begin{aligned}
&Water\ rent = canal\ water\ \cos ts + groundwater\ \cos ts \\
&\quad - public\ investment\ in\ water\ conveyance
\end{aligned}
\tag{8.4}
$$

8.1.2   Specification of variables and programming

Before going to programming, it is necessary to clarify some more variables and some more modeling aspects. Please note: A model is to reflect the reality, but it cannot precisely duplicate the complex situation of reality due to its technical limitations. On the other hand, we need a model to show the implications from changing conditions that bring about reality.

To make the model neat and simplified, we assume that the canal length in the model is 10 km and, correspondingly the initial canal water capacity is given as 300,000 m^3, i.e., cw_0=300,000 m^3.

On groundwater, in reality groundwater stock can never be 0. Hence we assume that the initial groundwater stock is 1000 m^3 before any recharge emerges, i.e., gw_0= 1000 m^3. So the total water capacity defined by the model is 301,000m^3. We also assume there are 200 ha land, i.e., 3000 Mu in the modeling process. One Mu can therefore get 100.3 m^3 irrigation water on average (rainfall is not considered in the study) according to the total water capacity. For apple growing in the survey area, within an average year, about 104 m^3/Mu irrigation water is required; within a dry year, about 170 m^3/Mu irrigation water is required (BUREAU OF

WATER RESOURCES OF LIQUAN COUNTY, 1999). Taken them all into account, we assume that unit water consumption under 170 m³/Mu is within a reasonable water requirement for apples. This assumption further indicates, within this limit, the more water is consumed, the higher revenue will be.

In this study, a positive lower bound of total water consumption at any location j is used in the modeling process to ensure that farmers at any location can get a minimum amount of water, either from canal or underground. In the current model, it is set at $tw_j = 20$ indicating that the minimum amount of water a farmer can get at any location, is 20 m³ water.

Soil permeability is an important element in the model. Different soil conditions will cause considerable difference in model results. The survey area is situated at the edge of the Guanzhong Basin, where soils are most loess. The permeability of loess is moderate, ranging from 0.25-0.4 in the survey area (BUREAU OF WATER RESOURCES OF LIQUAN COUNTY, 1999). In the present study, a seepage rate of water (or recharge rate of groundwater) is considered which is identical to soil permeability in the area. We take 0.3 as low soil permeability and 0.8 as high soil permeability, for such soil as loess and sand soil, to model the different impacts on water resource allocation.

The modeling process used to be very difficult to get through. Since the objective function and constraints are highly non-linear, it is difficult to solve the model by only using the Conopt solver (GAMS solver). In order to achieve the optimal solution, a second solve option of Minos (GAMS solver) was added after the first solve.

8.2   Public investment policy scenarios analysis

This chapter will focus on investigating the impacts of public investment status change. As mentioned already, the role, which private and public investments are playing in water saving activities, is one of the main concerns of this study. After investigating a base run model, which keeps public and private investment endogenous in the optimization procedure, further two scenarios are chosen to model the impacts of public investment rather than private investment due to internal properties of private investment (it will be discussed later in this section). Furthermore in order to make the model's application more broadly and close to reality, two types of soil permeability, which are represented by the recharge rate of groundwater, are introduced into the scenario analysis. One of them works with endogenous public investment and the other works with exogenous public investment. The selected scenarios are specified in Table 8.1 respectively:

Table 8.1:   Scenario groupings, names, abbreviations, and descriptions for assessing impacts of public investment status change

Group/Name	Abbreviation	Description
Scenarios of public investment policy:		
Optimal public investment scenario Base run model	LSEK	To maximize the optimal social welfare and water resource allocation under endogenous public and private investment. It is used as the benchmark against which other scenarios are compared so as to quantify the likely effects of the status of public investment changes being models.
A removal of public investment under low soil permeability scenario	LSRK1	To model the overall impacts of a removal of public investment from the water conveyance system under low soil permeability without private investment being made in irrigation technology
A removal of public investment under high soil permeability scenario	HSRK1	To model the overall impacts of a removal of public investment from the water conveyance system under high soil permeability without private investment being made in irrigation technology

All the scenarios analyzed in this study include three parts:

1) To measure the impacts of variations on aggregate indicators, such as social welfare, total water consumption (canal water and groundwater), total private and public investment as well as gains from conjunctive water use.

2) To further investigate the impacts of scenarios on indicators at individual farm level by doing mean value analysis and figure illustration at different locations.

3) To give brief concluding remarks concerning the current scenario and raise further research questions.

8.2.1 Optimal public investment scenario (Base run model)

The optimal public investment scenario (LSEK) is run without restrictions on any endogenous variable. The public investment K and private investment I are endogenous variables in the model. The recharge rate for groundwater is at 0.3. It therefore can be considered a base run model to compare variations with the further scenarios.

8.2.1.1 Impacts on aggregate indicators in the optimal public investment scenario

The aggregate indicators, such as social welfare, total water consumption, total public expenditure on water conveyance as well as irrigated area, are presented in

Table 8.2:   Impacts on social economy and water resource allocation at aggregate level in the optimal public investment scenario (LSEK)

Items	LSEK
Social welfare (Yuan)	1,065,334.88
Total canal water consumption (m^3)	300,000.00
Total groundwater consumption (m^3)	56,635.07
Total water consumption (m^3)	356,635.07
Capacity of water supply (m^3)	301,000.00
Gain from conjunctive water use (m^3)	55,635.07
Total public investment (Yuan)	2,431.55
Switch point (location)	164.00
Canal water length (meter)	8,200.00
Area irrigated by canal water (Mu)	2,460.00
Area irrigated by groundwater (Mu)	540.00
Total private investment (Yuan)	0.00

Notes: The switch point is at location 164, at which canal water ends and groundwater use starts. They are cw_{164}=104.7m^3, gw_{164}= 1.87m^3, respectively.

LSEK: It indicates optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment.

Table 8.2. These indicators represent the optimal level of the aggregate social welfare and water resource allocation in the irrigation area suggested in the optimal public investment scenario (LSEK). The social welfare is reported 1.065 million Yuan over the irrigation area. It means that a sum of producer surplus over the entire irrigation area reaches some 1 million Yuan after deducting basic inputs elements and expenditure on irrigation farming. The total canal water consumption is 300,000m^3, meeting exactly the canal water capacity of the model. The canal water being used up indicates that using cheaper canal water is the first choice for farmers, as compared to using groundwater. Due to seepage from canal and farmers' fields, the groundwater stock has been actually recharged. After canal water is used up, farmers start to take groundwater. The total groundwater consumption is observed at 56,635m^3. Hence, the conjunctive water (canal water and groundwater) consumption over the entire area is 356,635m^3 in total. This is 18.5% more than the initially provided capacity of water supply[2] of 301,000m^3. There is therefore a gain of 55,635m^3 water due to conjunctive water usage. The model also optimizes the social welfare by undertaking the heavy public investment in the canal system, with an average annual costs of 298 Yuan/km and 2431Yuan in total in the irrigation area. Consequently the canal water reaches location 164 (switch point), which covers 82% of the canal length over the

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[2] It is assumed in the model, the total water capacity is 301,000 m^3, of which the initial canal water capacity is 300,000 m^3, and the initial groundwater stock is 1,000 m^3.

irrigation area with a zero-loss-rate being reported. Thanks to water flowing long in the canal, 82% of farmers' lands are irrigated by canal water, while only the remaining 18% are irrigated by groundwater. Total private investment is, however, chosen to be 0 over the entire area. Zero private investment shows that there is no farmer applying modern water saving technology in the irrigation area.

The reasons for high public investment and zero private investment chosen by the model are discussed as follows:

Since social welfare of the irrigation area is to be optimized, any investment in farming, i.e. expenditure, either private investment in irrigation technology or public investment in canal construction, would reduce the entire social welfare. The model internally determines that the public investment is heavily made till location 163 in order to ensure the canal water can be delivered further with low loss rates. It is observed notably, that the public investment is kept 298 Yuan/km on average within the 163 locations annually. According to related technical data from field survey and model results, this type of investment implies that a quasi-pipe canal system is chosen to reduce the canal water loss rate to zero. Also heavy public investment suggests a well-managed canal system. The public investment, on the one hand, lowers the water costs for all farmers and the entire revenue will consequently increase. On the other hand, the public investment is calculated in the objective function based on average annual investment instead of the huge total project costs[3], and moreover, the modeled irrigation area is very small and works with merely a 10km-long canal. At last, it is deducted from a revenue function directly rather than influenced by the investment. So the model result of public investment is relatively small and acceptable for the revenue function as compared to the benefit it can bring. That is why public investment was accorded the highest value in the model.

Contrary to the public investment being high, the model has determined the private investment to be zero over all locations. It suggests that farmers would keep using traditional flood or furrow irrigation rather than adopting any modern water-saving technology in this scenario. The reason for zero private investment can be justified by considering the component of revenue function and its high costs. On the one hand, the revenue function, which is employed in the objective function, is defined as merely part of total revenue. It was obtained by integrating the inverse water demand function (see Chapter 6). Recalling the water demand function, it is a function of water price and private investment in irrigation technology, and any positive private investment would reduce the revenue

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[3] Public lining investment can be very high. Some literatures show a pipe canal system costs 10000 Yuan per kilometer, but it can serve 25-30 years or so. This study just roughly takes an average annual cost into account.

according to the mathematical formula. Moreover, the year when the data were collected was a bad year for most of the farmers. This also results in low revenues and low capability to afford the expensive irrigation technology. Lastly, the irrigation technology costs are quite high compared to the value of the partial revenue[4].

On the other hand, the partial revenue mainly is contributed and measured by apple trees' water consumption according to its component of the mathematical form. In the current study, we assume that apple trees are watered within a reasonable limit. The more water is given, the higher yields will be. The private investment of zero represents that farmers adopt traditional flood and furrow irrigation technologies in the study. It is to be noted further traditional irrigation technique application consumes more water than modern irrigation technologies. The employed mathematical model endogenously determines to consume as much water as possible in order to maximize the social welfare. Taking both views into account, it is understandable why the model in the base run (optimal public investment scenario LSEK) keeps private investment to be zero over all locations. Based on this background, all further scenarios of public investment policy will not force any private investment to influence the optimization procedure. The impact of positive private investment will be further investigated in the coming two chapters. Considering the relationship between private and public investment in the model, the model results suggest a kind of combination between both. In this case, however, private investment is kept zero over all locations, it therefore requires public investment to make more efforts to ensure the water use efficiency for the irrigation area. The model results are also consistent with the actual situation in the survey area, where farmers are poor, and they seldom adopt modern irrigation technologies. However the local government has to support the whole irrigation system.

8.2.1.2 Impacts on social economy and water resource allocation at farm level

The overall impacts on the social economy and allocation of water resources in the irrigation area have been discussed. How are the situations of economy and water distribution for individual farmers? These questions will be investigated in the current section.

Mean figures of some relevant variables under different farmer categories are analyzed and compared. The reason for this is, that the model is a location

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[4] Investment in modern irrigation technology can be very costly for individual farmers. According to the field survey, the costs range from 150-500 Yuan/Mu annually.

specific one and contains 200 locations. It suggests that every variable would get 200 different figures. Due to limitation of space, it is not wise to list and investigate all 200 values of each variable in the study. But it is reasonable to list the most relevant variables employed in the model and compare their mean figures under different scenarios. Variables, such as land rent and revenue, are considered the relevant variables associated with farmers' economic situation, while other variables, such as water rent, water consumption as well as public and private investment in line with efficiency of water conveyance system and on-farm level, are taken into account to analyze water resource allocation at individual farmers' level. According to the characteristics of the model results, three different categories of water users are established. They are specified as categories of all users (AU), canal water users (CWU) and groundwater users (GWU). The number of AU is the sum of CWU and GWU, and equals to 200 in this study (in the following analysis, it is assumed that one location represents one farmer. In reality, one location could situate more than one farmer). However the numbers of CWU and GWU are varying, which depends on where the canal water end point is. Beside tables, some diagrams may also be required in order to investigate more clearly the change of tendency of one variable or the relationship among different variables. The comparison of the impacts on the individual farmers' economic situation and water resource allocation is listed in Table 8.3. Except the public investment, which is measured by Yuan/km, all the other variables are calculated based on the Chinese land unit Mu.

Table 8.3: **Mean values of indicators at farm level in optimal public investment scenario (LSEK)**

| Items | LSEK | | | |
	AU	CWU	GWU	%(CWU&GWU)
Revenue (Yuan)	445.26	451.24	418.02	7.95
Land rent (Yuan)	355.92	371.73	283.93	30.92
Aggregate water demand (m^3)	118.88	121.95	104.88	16.28
Water rent (Yuan)	88.53	78.53	134.09	-41.43
Private investment (Yuan/Mu)	0.00	0.00	0.00	
On-farm water use efficiency	0.48	0.48	0.48	0.00
Public investment (Yuan/km)	243.16	298.35	0	
Water conveyance loss rate		0.00	0.07	

Notes: AU=All users; CWU = Canal water users; GWU = Groundwater users.
    As shown already in Table 8.2, the switch point is at location 164, on which canal water ends and groundwater use starts. They are cw_{164}=104.7m^3, gw_{164}= 1.87m^3, respectively. The groundwater use is so little at switch point that it is ignored when mean analysis is made. The number of CWU and GWU are therefore 164 and 36 respectively.
LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment.

We start from the farmers' economic situation. The average unit revenues are 445.26 Yuan/Mu and 451.24Yuan/Mu for all water users (AU) and canal water users (CWU), respectively. Only a tiny difference in revenue of 5.98 Yuan/Mu is observed between farmer category AU and CWU. The reason for this is CWU account for 82% users of AU. The unit revenue made by CWU, therefore, at a large extent, can represent the performance made by AU. A decline of 7.95% of revenue is reported by GWU as compared to CWU due to less water consumption and high water costs. It indicates that farmers using canal water can make higher revenue than those using groundwater.

A considerable decrease of 30.92% of land rents for GWU is observed compared to that for CWU. This is mainly due to higher groundwater costs. Since no private investment is made under this scenario, the reduction of land rent has merely contributed to increasing water costs. But these water costs do not stimulate purchase of technology due to high costs. The model results clearly suggest, that the land rent will decrease over distance. At the first location, it ranks in the top position of 458.25 Yuan/Mu. This is 1.65 times higher than the lowest land rent of 277.44 Yuan/Mu found at the last location. The average land rent for CWU is 371.73 Yuan/Mu, which is 30.92% higher compared to 283.93 Yuan/Mu for GWU.

The average aggregate water consumption per Mu for AU over the irrigation area is 118.88m^3. This amount of water consumption is less than that for CWU and more for GWU. CWU on average consume the biggest volume of water at unit level, i.e., 121.95 m^3/Mu, due to the relatively low costs of water. Used water is 16.28% more than that consumed by GWU. As shown later in Figure 8.1, the tendency of aggregate water demand from water source to tail declines gradually due to increasing water price over distance. The high public investment ensures that the canal water is with a zero-loss-rate before it is used up so that more farmers can benefit from the canal water with relative low costs.

A water rent as defined before, is a concept associated with a water supplier, who collects a water fee from water users. It is closely tied to public investment, since the collected water fee will be used to build and operate a water conveyance system. Water rent is therefore expressed as a form of water charges less the public investment. Specifically, in the model, the average unit water rent for AU is 88.53 Yuan/Mu, which is slightly higher than that for CWU, and much lower than that for GWU. The unit average water rent for GWU is up to 134.09 Yuan/Mu, with an increase of 41.43% compared to that for CWU. Comparing a decrease of 41.43% of water rent and an increase of 16.28% of water consumption, the two figures indicate that the price difference between canal water and groundwater is the major determining factor for the volume of water consumption.

A base water use efficiency rate of 0.48 at on-farm level is reported over all locations due to zero private investment. The base on-farm water efficiency indicates that farmers will apply traditional surface irrigation technology instead of adopting any modern water saving techniques. Again it is noted that, public investment is suggested to be 243.16 Yuan/km on average over the whole area. For CWU, it is observed to be 298.45 Yuan/km; in line with a zero-loss rate until location 163. After location 164, there is no more water available in the canal. Naturally the conveyance costs become zero, and in line with a base loss rate 0.07 for GWU.

There are only two figures on water consumption and revenue changing presented in this section. We will give more figure illustration in the later scenarios, so that the same variables can be compared among different scenarios. Figure 8.1 describes in more detail the unit water consumption along the canal. The curve of water demand indicates, that the unit water consumption declines gradually with the distance getting farther from the water source. As further found in model results, the canal water consumption at the first location is $138.64m^3$, the highest water demand over the whole area. Contrary, the farmer at the last location takes the least consumption of $103.35m^3$ water. The water remaining in the canal is getting less and less due to farmers' extraction and finally becoming zero at location 165. Location 164 is the last location where canal water is still available. It is also at this location, that a tiny complementary part, solely $1.81 \ m^3$ of groundwater is taken due to insufficient canal water supply. After location 164, there is no longer water available in the canal. Farmers switch to groundwater completely.

Normally there are two factors that drive farmers to switch to groundwater. One is, when the canal water is used up. In this case, the price of canal water is lower than that of groundwater at all time. The other factor is, when the price of canal water is getting higher than that of groundwater somewhere. No matter what kind of situation, the outcome is always the same, i.e., farmers will use up all the canal water before its price gets higher than that of groundwater.

The shape of the revenue is illustrated in Figure 8.2. It is clearly shown that the unit revenue decreases with distance getting farther from the water source due to increasing costs. Farmers at the water source will get the highest revenue among all the farmers. The model results show that the unit revenue at the water source can be up to 477.26 Yuan/Mu. However, it is only 414.6 Yuan/Mu at the last location, which is 13% lower than that at the water source. The average revenues for CWU and GWU are 451.25 Yuan/Mu and 418.02 Yuan/Mu respectively.
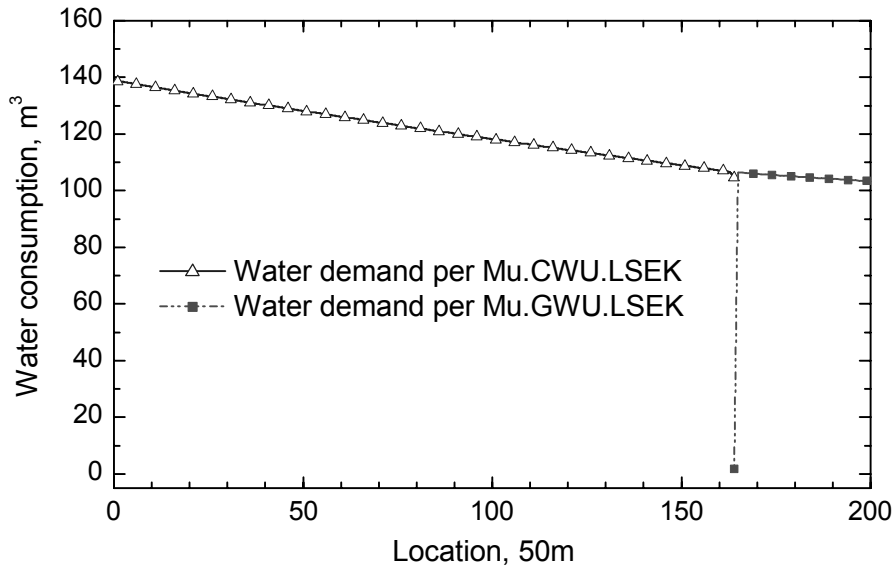
Figure 8.1: Conjunctive water uses over distance for CWU and GWU in optimal public investment scenario (LSEK)
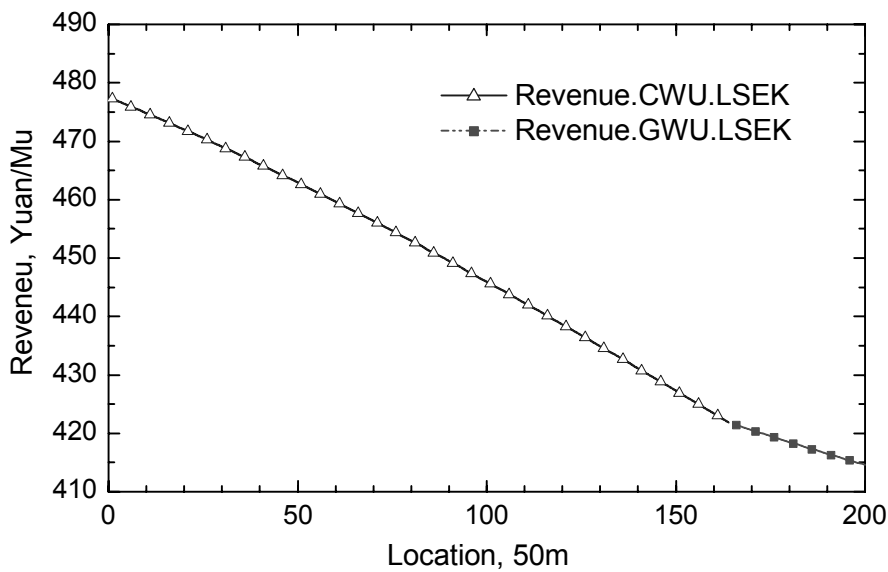
Figure 8.2: Changing in unit of revenue for CWU and GWU over distance in optimal public investment scenario (LSEK)

8.2.2.3 Concluding remarks of optimal public investment scenario (LSEK)

The optimal public investment scenario investigates the impacts on social welfare and water resource allocation by keeping the private and public investment endogenous to the model. As regards to the aggregate social economy and water resource allocation, the model results suggest that, social welfare reaches some 1 million Yuan over the whole irrigation area. A gain from conjunctive water use is up to 55,635 m^3. As regards the average level of individual farmers, it is suggested by the model that revenue, land rent and water consumption decline

with distance from the water source. Thanks to the increasingly higher water price over the distance, the water rent however increases with distance from the water source. The model results also reveal that the public investment is determined internally by the model, being at a high level, and it suggests that a quasi-piped canal system with zero-loss-rate is chosen by the model. However the private investment is chosen to be zero over all locations in the model due to its high costs. The outcomes of public and private investment indicated, for a poor area, such as the survey area, government has to take all the responsibility for water saving activity, since ordinary farmers cannot afford the costly modern irrigation technologies. Based on this characteristic, the further scenario will focus on the impacts of public investment policy change under two different soil conditions.

Further research questions are: Is it possible to model the performance of private investment that was unable to do in the present scenario? This will be discussed in the next two chapters.

8.2.2 A removal of public investment under low soil permeability scenario

The impacts on social welfare and water resource allocation have been discussed in the optimal public investment scenario (LSEK) with private and public investment remaining endogenous. Due to the characteristics of the variable of private investment, which was discussed in previous scenario, we will explore the impacts on social welfare and water resource allocation by changing the status of public investment. The question is: What will happen to social welfare and water resource allocation after the public investment is removed from the irrigation system? In the current scenario, the variable of public investment is no longer endogenous. It is exogenously fixed at 0 over all locations. Zero public investment indicates that government will do nothing to improve the water conveyance efficiency in the irrigation system. The recharge rate for groundwater is still at 0.3 in the current scenario.

8.2.2.1 Impacts on aggregate indicators

The indicators of social welfare and allocation of water resources are shown in Table 8.4. It is observed that in current scenario of a removal of public investment under low soil permeability, namely LSRK1, merely 0.6 million Yuan of social welfare is achieved, a decrease of 43.4% compared to a social welfare of 1.06 million under scenario LSEK. Total canal water consumption declines sharply due to less water availability in the canal. It shows that the total canal water consumption falls to 66,027 m^3 compared to a consumption of 300,000 m^3 in

Table 8.4:   Comparison of indicators at aggregate level between optimal public investment scenario (LSEK) and a removal of public investment under low soil permeability scenario (LSRK1)

Items	LSRK1	LSEK	%
Social welfare (Yuan)	612,782.89	1,065,334.88	-42.48
Total canal water consumption (m³)	66,027.23	300,000.00	-77.99
Total groundwater consumption (m³)	96,554.60	56,635.07	70.49
Total water consumption (m³)	162,581.82	356,635.07	-54.41
Capacity of water supply (m³)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m³)	-138,418.18	55,635.07	-348.80
Total public investment (Yuan)	0.00	2,431.55	
Switch point (Location)	37.00	164.00	-77.44
Canal water length (m)	1850.00	8200.00	-77.44
Area irrigated by canal water (Mu)	555.00	2460.00	-77.44
Area irrigated by groundwater (Mu)	2445.00	540.00	352.78
Total private investment (Yuan)	0.00	0.00	0.00

Notes: Farmers take last chance to get canal at location 37, then switch to groundwater completely from location 38.

LSRK1: It indicates a removal of public investment under low soil permeability scenario, which is run under low soil permeability, exogenous public investment and endogenous private investment.

LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment.

scenario LSEK. It further implies that 77.99% of canal water is lost due to the poorly operated conveyance system. It is not surprising to note that groundwater consumption increases significantly by 70.49%. A large amount of canal water leaks from the canal due to a poorly operated water conveyance system and recharges the groundwater stock. However, the use of groundwater is very expensive compared to that of canal water. That is why an increase of groundwater use deteriorates the entire social welfare so much. Total water consumption also declines sharply, with a decrease of 54% compared to scenario LSEK. Only a total of 162,581.82 m³ water is consumed over the whole area, in comparison to a total water supply capacity of 301,000 m³. It demonstrates, that 138,418,18 m³ water, almost half of the water capacity, is lost due to huge water losses in the water conveyance system and seepage from farmers' field. A net water loss of 138,418 m³ is reported in the scenario LSRK1. As a most general result: A poor managed canal system results in a huge water loss. The canal water is used up already at location 37, and it consequently decreases the canal irrigation area by 77.44%, while the area irrigated by groundwater triples.

All the above indicators strongly suggest that a removal of public support for the water conveyance system under low soil permeability will largely hamper the social economy as well as worsen the allocation of water resources.

8.2.2.2 Impacts on social economy and water resource allocation at farm level

Does a removal of public support for the water conveyance system also deteriorate much individual farmers' economic situation and water resource allocation? Table 8.5 gives more detailed information to analyze these questions. Due to significant water seepage from the canal, the canal water can be used up only over a very short distance. Insufficient water supply can result in decreasing output and hence worsen the farmers' economic situation. It is shown, that the average unit revenue for all the farmers falls by 45.5% to 242.52 Yuan/Mu, as compared to scenario LSEK. Revenue made by CWU decreases slightly. It drops to 436.17 Yuan/Mu compared to that of 451.24 Yuan/Mu in scenario LSEK. This result suggests that CWU can still get considerable revenue compared to their counterpart GWU, since they still have access to cheaper canal water. However the unit revenue for GWU decreases sharply by 52.5% to 198.56 Yuan/Mu, compared with scenario LSEK. GWU averagely make unit revenue only of 198.56 Yuan/Mu, which is less than half of revenue made by CWU within the same scenario and 52.2% less than that in scenario LSEK. The tendency of unit revenue changing in the current scenario LSRK1 demonstrates that under a poorly operated water conveyance system, most farmers' interests would get damaged due to lack of access to cheaper canal water. However few of them, who have access to canal water, can still assure their income. At a certain point, a removal of public investment could be harmful to social efficiency and equity. It worsens not only the overall social economy but also individual farmers' economic situation. It also enlarges the income gap between upstream farmers and downstream farmers.

The same situation happens with regard to land rent. The average unit land rent for the AU is 204.26 Yuan/Mu, which is 42.61% lower than that in scenario LSEK. Exceptionally for CWU, the land rent is 406.75 Yuan, 9.4% higher than that in scenario LSEK of 371.73 Yuan. The reason is that the number of CWU contains merely 37 upstream water users in the current scenario, while it contains 164 users in scenario LSEK. The closer a farmer is located to the water source, the cheaper the water price and hence the higher the land rent will be. The mean value of unit land rent with respect to the 37 farmers, is naturally higher than that for 164 farmers. That is why the average unit land rent can be higher in the current scenario for CWU. However for GWU, the situation is opposite. Average unit land rent is only 158.30 Yuan/Mu, with a decrease of 44.25% as compared to that in scenario LSEK. It also shows a decrease of 61.08% compared with their counterparts CWU in the current scenario LSRK1.

Table 8.5: Comparison of mean values of indicators at farm level between a removal of public investment under low soil permeability scenario (LSRK1) and optimal public investment scenario (LSEK)

Item	AU			CWU			GWU		
	LSRK1	LSEK	%	LSRK1	LSEK	%	LSRK1	LSEK	%
Revenue (Yuan)	242.52	445.26	-45.53	436.17	451.24	-3.34	198.56	418.02	-52.50
Land rent (Yuan)	204.26	355.92	-42.61	406.75	371.73	9.42	158.30	283.93	-44.25
Aggregate water demand (m^3)	54.19	118.88	-54.41	118.97	121.95	-2.45	39.49	104.88	-62.35
Water rent (Yuan)	38.25	88.53	-56.79	29.42	78.53	-62.54	40.26	134.09	-69.98
Private investment (Yuan)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
On-farm water use efficiency	0.48	0.48	0.00	0.48	0.48	0.00	0.48	0.48	0.00
Public investment (Yuan)	0.00	243.16		0.00	298.35		0.00	0.00	0.00
Conveyance water loss rate	0.07	0.07		0.07	0.00		0.07	0.07	0.00

Notes: In scenario LSRK1, farmers take the last chance to get canal water at location 37, then switch to groundwater completely from location 38. So the number of CWU is 37, while GWU is 163.

In scenario LSEK, the switch point is at location 164, at which canal water ended and groundwater use starts. They are cw_{164}=104.7m^3, gw_{164}=1.87m^3, respectively. The groundwater use is so little at the switch point that it is ignored when mean analysis is made. The number of CWU is 164, while GWU is 36.

LSRK1:It indicates a removal of public investment under low soil permeability scenario, which is run under low soil permeability, exogenous public investment and endogenous private investment

LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment.

The water resources are mismanaged and largely lost from the water conveyance system. The average joint water consumption per Mu over the whole area is merely 54.19 m^3, reduced by 54.5% compared with that in scenario LSEK. For CWU, the unit canal water consumption shows a slight decline in scenario LSRK1. It is 118.97 m^3/Mu, compared to 121.95 m^3/Mu in scenario LSEK. It seems, that there is only a slight drop for CWU in scenario LSRK1. It is noticed again that, in scenario LSEK water can be delivered till location 164. In other words, farmers within the 164 locations can benefit from the cheaper public canal water. But in scenario LSRK1, canal water will be used up till location 37. It implies that only 37 farmers can benefit from the public canal water system, and the entire canal irrigation area decreases by 77.43%. Groundwater use starts earlier at location 38 in scenario LSRK1, because canal water is no longer available. The average consumption of groundwater is reported at 39.49 m^3/Mu, reduced by 62.35% as compared to that in scenario LSEK.

The water rent also shows a decreasing trend. This trend is opposite to that in scenario LSEK, in which the water rent increases with distance. A decreasing water rent implies that the farmers consume less water, therefore less water fee can be charged. Considering the definition of water rents, public investment would be deducted from the water rent. The public investment is kept at 0 in the current scenario LSRK1, even though it doesn't help to prevent the water rent from falling. It is reported by the model that the average water rent for AU is down by 56.85% to 38.25 Yuan/Mu, as compared to that in scenario LSEK. For CWU, the water price is still low, but water consumption decreases sharply. So the collected water rent becomes lower too. It accounts for merely 37.46% of the water rent collected in scenario LSEK. The same situation happens to GWU. The water rent for GWU in scenario LSRK1 is reported to be 40.26 Yuan/Mu, compared to that of 134.09 Yuan/Mu in scenario LSEK, a decrease by 70%. Falling water rents result in decreasing income of the water supplier. In particular for the public water supplier, it gets worse off and could not accumulate enough capital to maintain or construct a new irrigation project. Such a performance can be illustrated in Figure 8.3.

Since the removal of public investment from the water conveyance system is the key feature of the current scenario, it is supposed to focus on analyzing its impact on the movement of canal water and groundwater remaining over distance. Two diagrams (Figures 8.4 and 8.5) describe water movement in canal and underground. Figure 8.4 compares the different movements of groundwater remaining under different situations. Remember, in scenario LSEK, there is no canal water lost before it reaches location 164 thanks to heavy public investment. Before this point, it is shown in the Figure 8.4, that the groundwater stock is
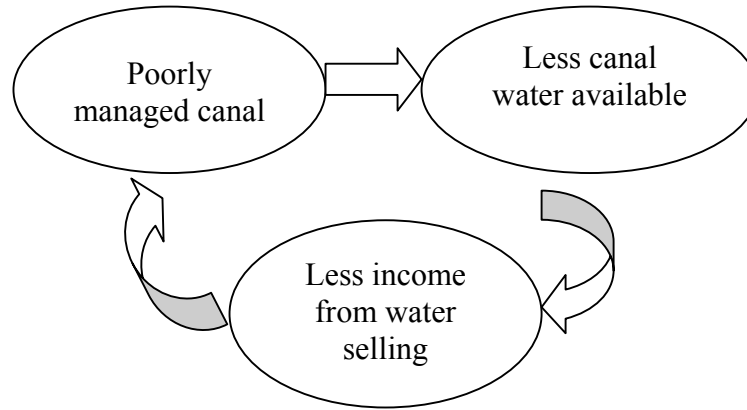
Figure 8.3: Vicious circle of a removal of public investment under low soil permeability
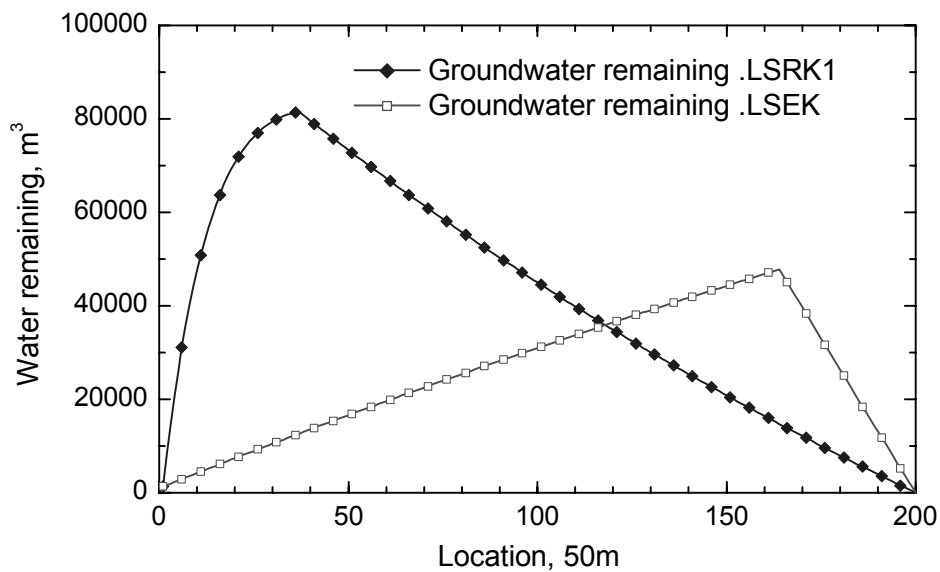
Figure 8.4: **Comparison of groundwater remaining between optimal public investment scenario (LSEK) and a removal of public investment under low soil permeability scenario (LSRK1)**

recharged only by water lost from farmer's field, and moreover no groundwater extraction occurs. So the groundwater stock gradually increases till location 164, and then starts to fall from location 165, where farmers start to take groundwater. However, in scenario LSRK1, it is obviously suggested that the slope of groundwater remaining curve is much deeper than in scenario LSEK. It demonstrates that the groundwater stock is recharged very quickly due to double loss of water from the irrigation system, i.e., conveyance loss and on-farm loss. It also implicates that the peak of groundwater remaining in scenario LSRK1 is much higher than that in scenario LSEK due to more canal water going down to recharge the groundwater stock. Farmers start to consume groundwater very early, as there is no canal water available.
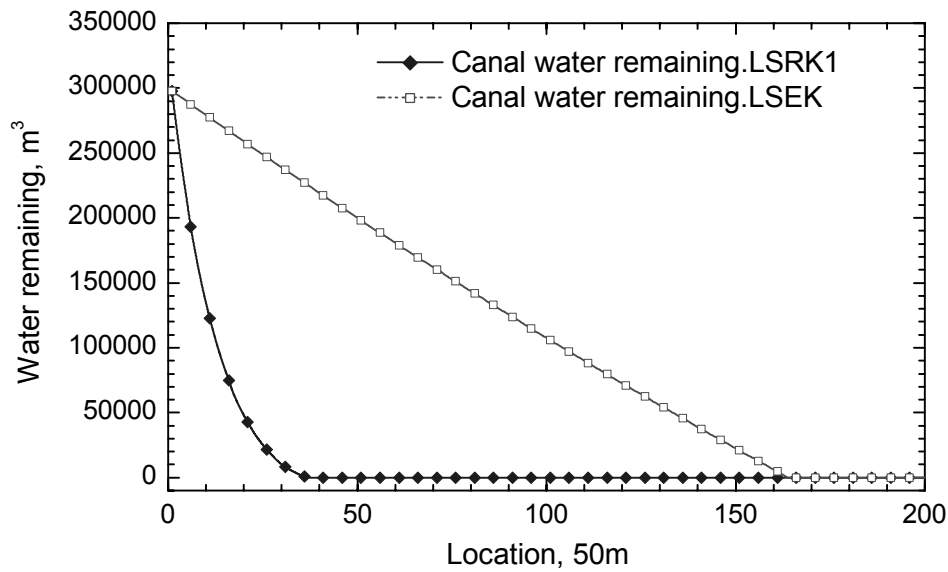
Figure 8.5: Comparison of canal water remaining between optimal public investment scenario (LSEK) and a removal of public investment under low soil permeability scenario (LSRK1)

Figure 8.5 indicates the same phenomenon as described above, here the water movements are analyzed from the aspect of canal water remaining instead of groundwater remaining. We find the canal water remaining in scenario LSEK is able to travel a longer distance gradually. However in scenario LSRK1 it is exhausted very fast, due to huge water losses from the canal system and farmer's extraction.

Some further figures related to revenue, land rent and water rent will be provided later in this chapter, while comparing will be made with the other scenarios.

8.2.2.3 Concluding remarks of a removal of public investment under low soil permeability scenario (LSRK1) and further research questions

This scenario investigates the impacts on social welfare and water resource allocation by removing public investment from the water conveyance system under low soil permeability. The model results suggest that both social welfare and water resource allocation get worse. Specifically the social welfare decreased by almost half, and the water consumption also declines sharply. The area irrigated by canal water largely shrank to one-third of the area in the optimal public investment scenario LSEK. Overall water rents decreased too, and it further results in a scarce public budget for water projects. All these indicators strongly suggest that public investment plays a very important role in optimal water resource allocation and improvement of social welfare.

Further research questions: Different soil permeability can retain different levels of water. The scenario LSRK1 only discussed the situation under a low soil condition. Low soil permeability indicates that only small portions of surface water can go down to recharge the groundwater aquifer. That is why a well-managed water conveyance system can be so crucial for such an irrigation scheme. The further question is: How the situation will be if the irrigation scheme is operated under high soil permeability? This will be investigated in the next scenario.

8.2.3 A removal of public investment under high soil permeability scenario

In the previous two scenarios, the impacts on social welfare and water resource allocation are investigated by changing the status of public investment. Both were undertaken under low soil permeability, with a recharge rate of 0.3. As observed in the scenario of a removal of public investment under low soil permeability (LSRK1), the entire welfare and water consumption are much worse off in the project area, if public investment in the canal is removed. The current scenario will discuss the impacts of high soil permeability on social welfare and water resource allocation. The aim of doing so is to enable the model to be broadly applicable under different geographical conditions.

As higher soil permeability, i.e., higher recharge rate, we assume a recharge rate of 0.8, which indicates that 80% of the lost water, either from the canal system or from the farmers' field, will go underground to recharge the aquifer. The public investment will remain zero exogenously in the current scenario of a removal of public investment under high soil permeability (HSRK1).

8.2.3.1 Impacts on aggregate indicators

Model results of scenario HSRK1 are presented in Table 8.6. It is surprisingly observed that the aggregate social welfare achieved in scenario HSRK1 is 1,062,254 Yuan, which is only 0.29% lower than in the optimal public investment scenario LSEK, and 73.35% higher than in the scenario under low soil permeability (LSRK1). It indicates, because of higher soil permeability and recharge rate, that groundwater use becomes more available and profitable. Due to the considerable canal water loss rate (without lining investment) and high recharge rate, the total canal water consumption slightly increases by 15.93% compared to scenario LSRK1, but dramatically decreases by 74.49% compared to scenario LSEK.

Remarkable change appears in groundwater consumption. Total groundwater consumption reaches 362,341.81m^3, 2.75 times higher than in scenario LSRK1, and 5.4 times higher than that in scenario LSEK. Consequently the total water consumption over the entire irrigation area is 4,388,824.47m^3, which is 1.7 times higher than in scenario LSRK1 and 23.06% more than it in scenario LSEK. In the current scenario, the gain from conjunctive water use is quite significant. It achieves 137,884.47 m^3, almost half of the capacity of water supply. It is correspondingly 1.48 times of the gain in scenario LSEK. These results seem not correct intuitively. The reason for these results is, that the higher recharge rate results in groundwater being able to be pumped more conveniently and abundantly. Due to high soil permeability, farmers have to pump more frequently to meet their water requirement. The model calculates these volumes of accumulated pumping and re-pumping, it hence results in such a bigger total water consumption, even much more than its actual capacity. In other words, water is re-used in the current scenario, and it is calculated as long as this takes place.

It is noticed that the area irrigated by canal water decreases sharply due to huge water losses from the canal system and farmer's fields. The canal water is almost used up already at location 31, i.e., after 1550 meters, the shortest distance within the three scenarios. On the one hand, the irrigated area by canal water is down to 465 Mu, a decrease by 16.22% and 81.1% respectively compared to scenario LSRK1 and scenario LSEK. On the other hand, the area irrigated by groundwater grows dramatically, with a considerable increase by 3.68% and 369.44% respectively compared to scenario LSRK1 and scenario LSEK.

Model results of scenario of a removal of public investment under high soil permeability imply that the overall social economy and water resource allocation does not get much worse, as compared to the scenario of optimal public investment (LSEK), moreover it gets much better than the scenario of removal of public investment under low soil permeability (LSRK1). Probably, it could be reasonable and economic to abandon public investment in the canal system, if the soil permeability is very high. We will further analyze the other indicators at the farm level and see how it is going on with individual farmers.

Table 8.6: Comparison of indicators at aggregate level among optimal public investment scenario (LSEK), scenarios of removal of public investment under low soil permeability (LSRK1) and high soil permeability (HSRK1)

Items	HSRK1	LSRK1	LSEK	%(LSRK1 & LSEK)	%(HSRK1 & LSRK1)	%(HSRK1& LSEK)
Social welfare (Yuan)	1062253.93	612782.89	1065334.88	-42.48	73.35	-0.29
Total canal water consumption (m³)	76542.66	66027.23	300000.00	-77.99	15.93	-74.49
Total groundwater consumption (m³)	362341.81	96554.60	56635.07	70.49	275.27	539.78
Total water consumption (m³)	438884.47	162581.82	356635.07	-54.41	169.95	23.06
Capacity of water supply (m³)	301000.00	301000.00	301000.00	0.00	0.00	0.00
Gain from conjunctive water use (m³)	137884.47	-138418.18	55635.07	-348.80	199.61	147.84
Total public investment (Yuan/km)	0.00	0.00	2431.55		0.00	
Switch point (Location)	31.00	37.00	164.00	-77.44	-16.22	-81.10
Canal water length (m)	1550.00	1850.00	8200.00	-77.44	-16.22	-81.10
Area irrigated by canal water (Mu)	465.00	555.00	2460.00	-77.44	-16.22	-81.10
Area irrigated by groundwater (Mu)	2535.00	2445.00	540.00	352.78	3.68	369.44
Total private investment (Yuan)	0.00	0.00	0.00	0.00	0.00	0.00

Notes: the switch point of scenario HSRK1 is actually observed at location 32, on which canal water ends and groundwater starts. Complementary water is used at this point. $cw32=10.36m^3$, $gw32= 144.27m^3$. The consumption of canal water at location 32 is neglected while calculating compared to that of groundwater at location 32, so that the canal water consumption at location 32 is very small the canal water length and area irrigated by canal water. It therefore suggests a switch point at location 31 instead of 32.

HSRK1: It indicates a removal of public investment under high soil permeability scenario, which is run under high soil permeability, exogenous public investment and endogenous private investment

LSRK1:It indicates a removal of public investment under low soil permeability scenario, which is run under low soil permeability, exogenous public investment and endogenous private investment

LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment.

8.2.4.2 Impacts on social economy and water resource allocation at farm level

Table 8.7 gives more detailed information about the impacts on individual variables at farm level in the irrigation area. The average unit water consumption is reaching up to 146.3m^3/Mu for AU in scenario HSRK1, which is the highest water consumption level among the three scenarios, mainly due to re-pumping water from underground. It is 2.7 times higher than that in scenario LSRK1, and 23.06% higher than that in scenario LSEK. In terms of canal water use, the model result suggests the same up-tendency. But the consumption volume increases not so significantly as compared to that for AU. On average the unit canal water consumption is 164.61m^3, ranking in the top place among the three scenarios. In terms of groundwater consumption, a considerable difference between the current scenarios HSRK1 and the previous two is observed. Unit groundwater consumption in scenario HSRK1 also ranks in the highest position among the three scenarios. It reaches a volume of 142.94 m^3, 3.7 times of that in scenario LSRK1 and 36.29% more than in scenario LSEK. High seepage rates result in less water availability in the canal and huge groundwater recharge, and hence enforce farmers to pump groundwater. Variables, such as revenue, land rent, and water rent are following the tracks of movement of joint water consumption. They show a strong signal of overall better off in scenario HSRK1.

8.2.3.3 Concluding remarks of scenario of a removal of public investment under high soil permeability and research limitation

The scenario of a removal of public investment under high soil permeability (HSRK1) demonstrates, that the social welfare and the water resource allocation are only slightly worse off compared to the optimal public investment scenario, which is a scenario with high public investment. Farmers are much better off as compared to scenario LSRK1, which is a removal of public investment with a low recharge rate. This indicates clearly, that a suitable policy or public expenditure with respect to a canal system is needed. It has to take the local natural conditions, such as climate, soil condition etc, into account. As discussed already, the status of soil permeability is so important that it can have totally different impacts on the same project. In an area with low soil permeability, it is necessary to invest more in the water conveyance system, as shown in the optimal public investment scenario as compared in an area of high permeability. However, if an area has very high soil permeability, and, if the local community is facing budget shortage, it might be wise not to invest much into the canal system as demonstrated in the current scenario HSRK1. The model results of scenario HSRK1 actually suggest a basin wide optimal rather than a point optimal solution.

Table 8.7: Comparison of mean value of indicators among optimal public investment scenario (LSEK), scenarios of removal of public investment under low soil permeability (LSRK1) and high soil permeability (HSRK1) at farm level

Items	AU			CWU			GWU		
	HSRK1	LSRK1	LSEK	HSRK1	LSRK1	LSEK	HSRK1	LSRK1	LSEK
Aggregate water demand (m³)	146.30	54.19	118.88	164.61	118.97	121.95	142.94	39.49	104.88
Revenue (Yuan)	484.08	242.52	445.26	497.30	436.17	451.24	481.62	198.56	418.02
Land rent (Yuan)	354.05	204.26	355.92	457.78	406.75	371.73	335.05	158.30	283.93
Water rent (Yuan)	129.96	38.25	88.53	39.51	29.42	78.53	146.55	40.26	134.09
Private investment (Yuan)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
On-farm water use efficiency	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Public investment (Yuan)	0.00	0.00	243.16	0.00	0.00	298.35	0.00	0.00	0.00
Conveyance water loss rate	0.07	0.07	0.07	0.07	0.07	0.00	0.07	0.07	0.07

Notes: Mean analysis is made based on the number of CWU being 31 and GWU being 169.

HSRK1:It indicates a removal of public investment under high soil permeability scenario, which is run under high soil permeability, exogenous public investment and endogenous private investment.

LSRK1:It indicates a removal of public investment under low soil permeability scenario, which is run under low soil permeability, exogenous public investment and endogenous private investment.

LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment.

Research limitation of the current scenario: It is suggested by the model that more water consumption will bring higher output. Though the model simulates the groundwater price over distance, it does not consider the pumping costs. In the current study, the groundwater price is reflected only by electricity costs. It is far from enough to reflect the real pumping costs. That is a main reason why a large amount of re-pumping still does not influence social welfare much in current scenarios. In future work, pumping costs are needed to be modeled more precisely.

8.2.4 Comparison of indicators among scenarios at spatial level

In previous sections, three scenarios were made to evaluate the different impacts on social welfare and water resource allocation. A comparison of some crucial variables will be reviewed in this section. Since most of the relevant variables already have been presented by using tables, we will employ more diagrams (Figure 8.6-8.13) to describe different performances of these crucial variables.

A comparison of canal water consumption over distance among scenarios of removal of public investment under high (HSRK1) and low soil permeability (LSRK1) as well as optimal public investment scenario (LSEK) is illustrated in Figure 8.6. In scenario HSRK1, the canal water starts from the top level but ends quickly over a short distance. In scenario LSRK1 it also starts from a relatively high level and is used up quickly too. The common reason for quick ending of
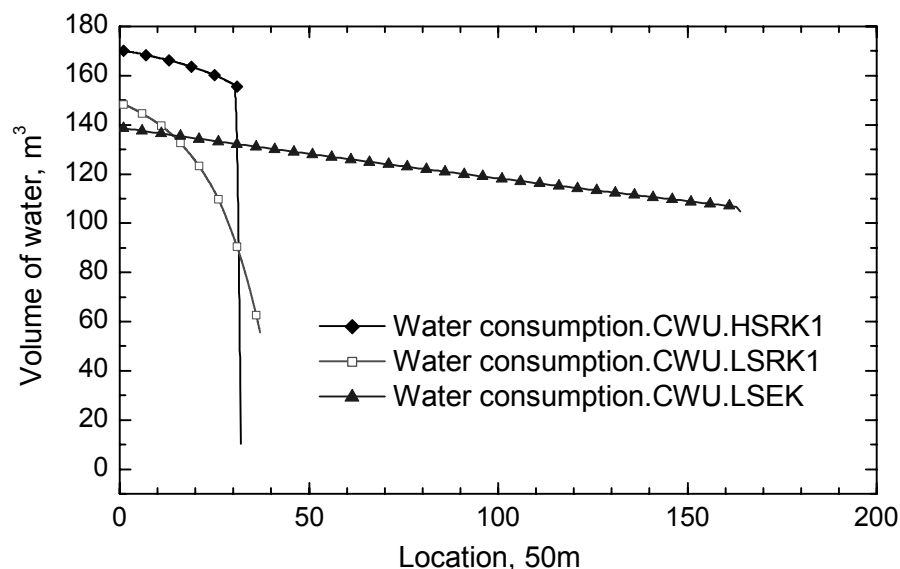
Figure 8.6: **Comparison of canal water consumption at different locations among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)**

Figure 8.7: **Comparison of groundwater consumption at different locations among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)**

canal water use is the removal of public investment in both scenarios, so that the water in the canal suffers a high base water conveyance loss rate of 0.07. In scenario LSEK the canal water has traveled the longest distance, due to its improved water conveyance system.

In the following Figure 8.7, we can compare the groundwater consumption at different locations under the three scenarios. It is easy to understand that the track of groundwater movement is exactly opposite to that of canal water. For instance, as shown in Figure 8.6, canal water in scenario HSRK1 travels the shortest distance; hence in Figure 8.7, groundwater use, in scenario HSRK1, appears early at location 32 and travels the longest distance.

Both figures indicate, that the tendency of canal water movement changes more dramatically than that of groundwater movement. The reason for this is, that canal water movement is influenced by a double loss of water, i.e., conveyance water loss and on-farm water loss, and moreover the farmers' extraction. Canal water therefore, is reduced faster than groundwater. Groundwater movement can be influenced by the on-farm water loss rate and less extraction by groundwater users. Consequently they perform in such a tendency.
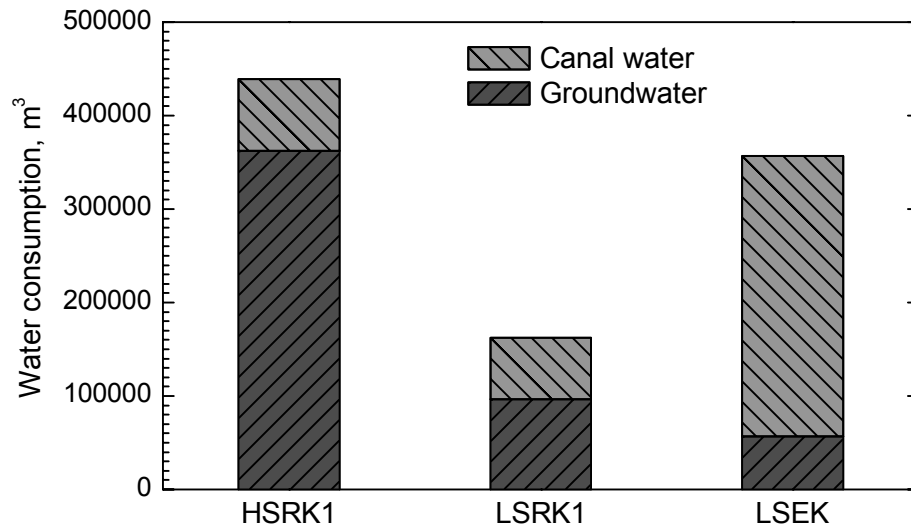
Figure 8.8: **Comparison of total water consumption among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)**
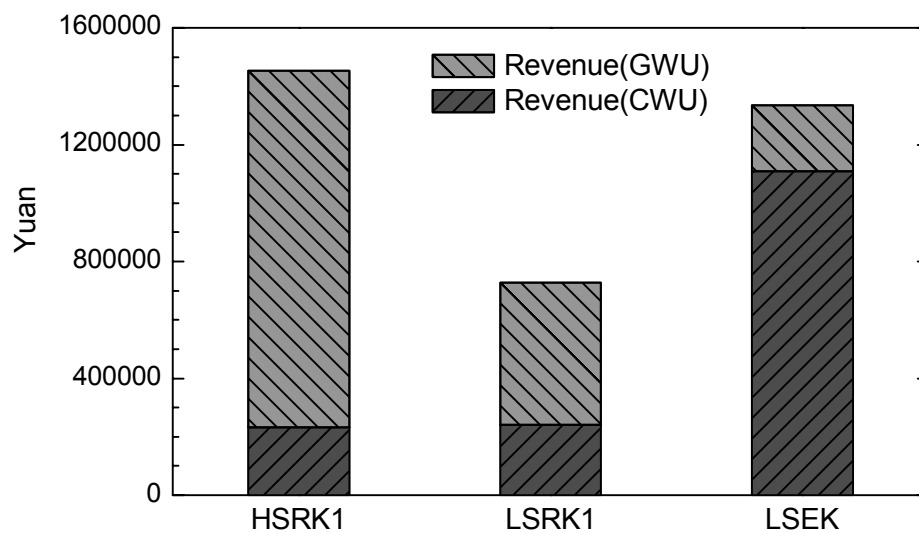
Figure 8.9: **Comparison of total revenue among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)**

Figure 8.8 describes the total canal water and groundwater consumption in different scenarios. It shows clearly that the biggest groundwater consumption appears in scenario HSRK1, mainly thanks to its huge conveyance water loss rate and a higher recharge rate to the groundwater aquifer. The smallest one is found in scenario LSEK, due to zero-loss rate in the canal and low recharge rate to the groundwater aquifer. However, the biggest canal water consumption is found in scenario LSEK thanks to its dominant canal system. The chart also suggests that the aggregated water consumption (sum of canal water and groundwater consumption) in scenario HSRK1 ranks in the top place among the three

scenarios, since re-pumping is very popular in this scenario. Due to seepage and recharge, there also exists a gain from the use of return flows. As stated already, the total water capacity in the model is 301,000 m^3. Total water consumption in scenario HSRK1 is almost 1.5 times the initial water capacity in the irrigation area. In scenario LSEK, a gain of 55635.07m^3 water consumption is also observed. But contrary to scenario HSRK1 and scenario LSEK, a net water loss is reported in scenario LSRK1, mainly due to its huge water loss from the conveyance system and low recharge rate of groundwater.

Next Figures 8.9-8.10 compare different performances of revenue under the three scenarios presented. We start firstly to analyze the total revenue. As shown in Figure 8.9, total revenue of scenario HSRK1 ranks in the top, but it is mainly from groundwater use. Contrary to scenario HSRK1, the total revenue of scenario LSEK, which ranks in the second position, are mainly contributed by canal water uses. This is plausible given the model assumption. Scenario HSRK1 is under high seepage rate and a poorly operated canal system, so farmers use more groundwater. However, scenario LSEK is under low seepage rate and a well-operated canal system, so farmers go for canal water. Lastly, the total revenue of scenario LSRK1 is the worst, due to insufficient water availability.

The movements in unit of revenue over distance, under the three scenarios, give the same results. The unit revenue, in scenario HSRK1, starts from the canal source at its highest level, and then declines gradually, though slowly. It can be observed that the curve of revenue change in scenario HSRK1 keeps staying above all the other ones for all locations. The second highest revenue starts from the canal source in scenario LSRK1, but it drops sharply and eventually falls down to a very low level in comparison with the other two scenarios. Further, the revenue in scenario LSEK starts from a relatively low level and then too declines slowly. This curve is positioned below the revenue curve of scenario HSRK1 and above that of scenario LSRK1. The revenue in scenario LSRK1 undoubtedly is the lowest one among the three. The curve of revenue in scenario LSEK looks similar to that in scenario HSRK1, though they are modeled with much different background. Scenario HSRK1 is optimized under a very high recharge rate of 0.8, while scenario LSEK is optimized under a moderate recharge rate of 0.3. And moreover, in scenario HSRK1 the public investment is removed from the irrigation system, while in scenario LSEK government makes high public investment in canals. From the performance of unit revenue in the different scenarios, a conclusion can be drawn: The revenue is closely tied with water consumption. The more water is consumed, the higher revenue will be.
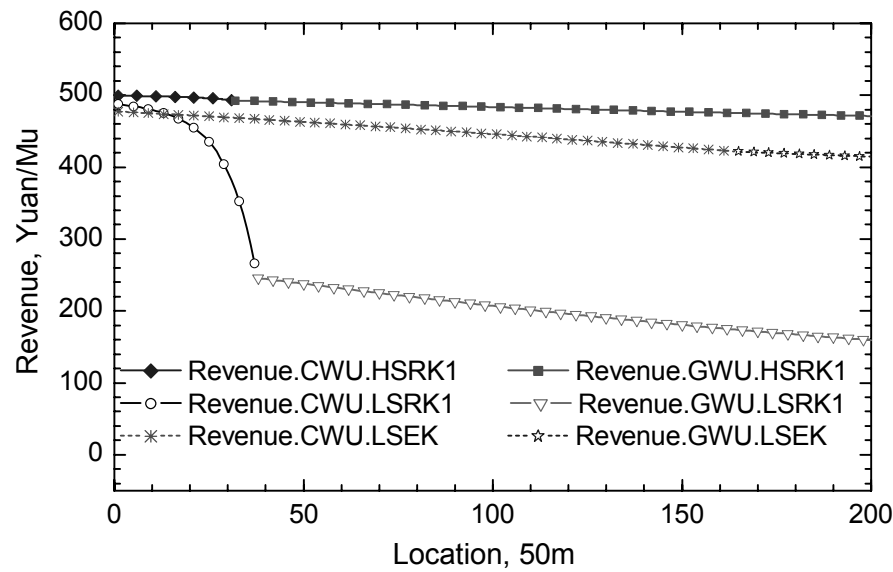
Figure 8.10: Comparison of unit revenue for CWU and GWU among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)
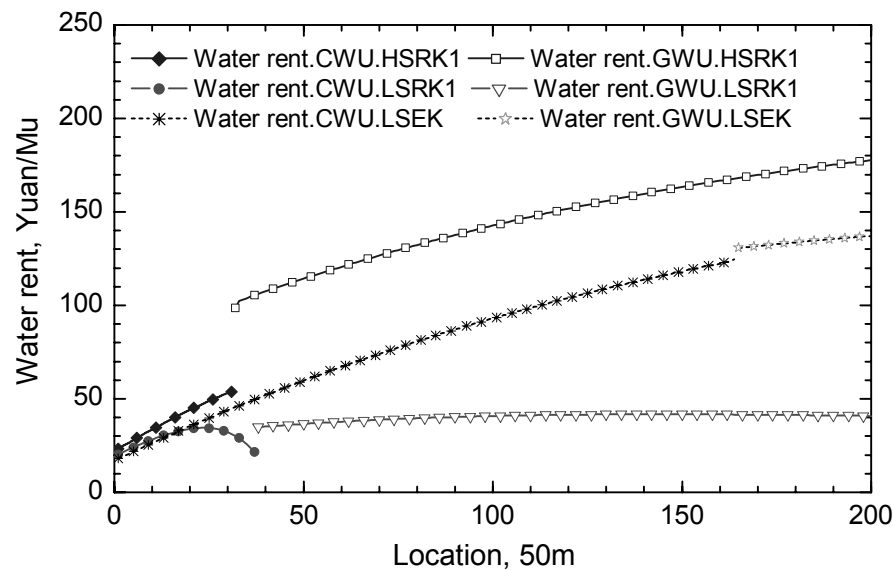
Figure 8.11: Comparison of unit water rent for CWU and GWU among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)

Figure 8.11 shows the situation of the unit water rents in different scenarios. The highest unit water rent, at water source, emerges in scenario HSRK1. Farmers in this case get the largest amount of water as compared to the other scenarios. After farmers switch to groundwater use in scenario HSRK1, a jump between unit canal water rent and groundwater rent can be observed. Further note that water rents decrease wages. The main reason for this development is, that the price of groundwater is considerably higher than that of canal water; it therefore causes a big jump in residual wages from canal water to groundwater rent.

The second highest unit water rent also occurs at the water source in scenario LSEK, and then it moves up gradually with the water price getting higher. Due to a better managed canal system, canal water dominates the most part of the irrigation area in scenario LSEK. Unit water rent of groundwater in LSEK shows no big difference compared to canal water when water flows close to the tail of the canal. Here the price of canal water becomes closer or even higher than that of groundwater. That is why the curve moves relatively smoothly without any sudden jump as happened in scenario HSRK1.

The lowest unit water rent is again observed in scenario LSRK1. An interesting phenomenon appears in the curve of canal water rent in scenario LSRK1. The movement of canal water rent first goes up, then goes down before it switches to the groundwater. By checking the model result, the point of water rent going down is reported at location 25. The reason is, that water leaks so fast in the canal, that farmers get much less water as compared to their upper stream counterparts (those situated before location 25). The rent collected within these locations is therefore even lower than in previous locations, despite they are charged a higher water price than previous users. After location 38, the groundwater rent starts picking up, and it moves rather strait and stays at the lowest level due to decreasing water availability.

Figure 8.12 further compares the accumulated water rents in the irrigation area among the three scenarios. As defined already, the water rent is closely tied with the public sector. More precisely, it is the canal water rent that influences the public sector much more rather than the groundwater rent. Since the public water supplier collects canal water rents, rents are directly portrayed. However the groundwater rents cannot directly go to the water related authority. For instance, in the survey area, the groundwater rents are used to cover expenses of the electricity by authority. Finally after a second time distribution, part of money could go to water related projects. The model results are consistent with the real situation. With relatively high water rents in scenarios like LSEK, the public water supplier can maintain its conveyance system and therefore can create more sources to support the system. Contrary to scenario LSEK, a removal of public investment from the irrigation system in scenario LSRK1 can result in less canal water supply, and finally the system might collapse. This ends the whole public water irrigation system. Scenario HSRK1 is a special case, since it optimizes under high soil permeability. In this situation, a public expenditure is not strongly suggested. A removal of public investment might be more economic.
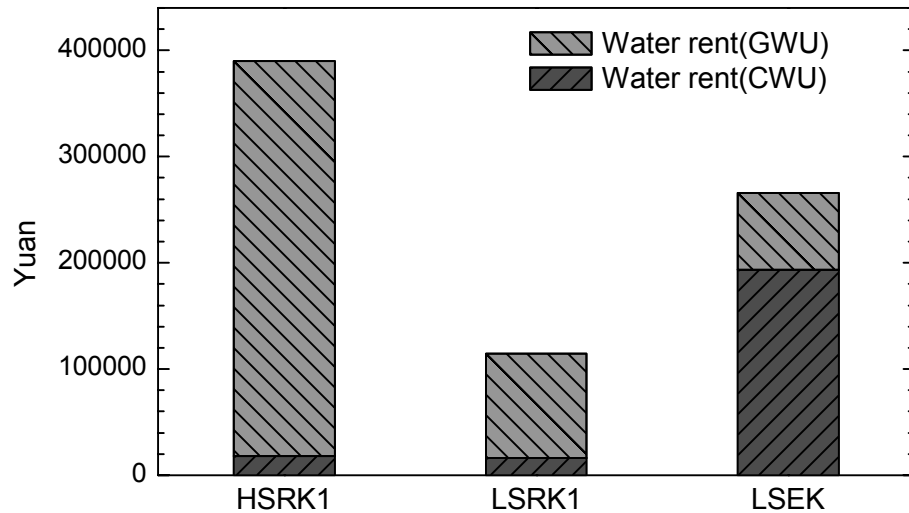
Figure 8.12: Comparison of accumulated water rents for CWU and GWU among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)
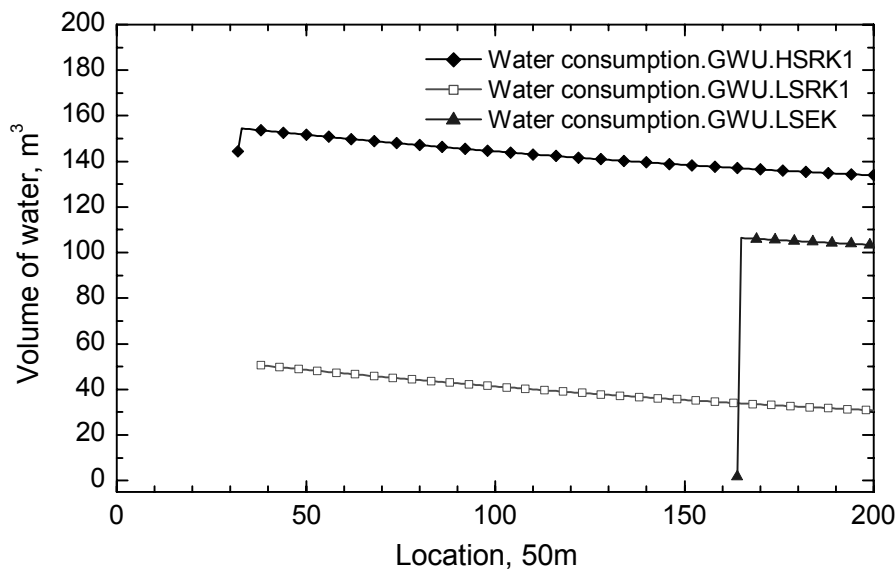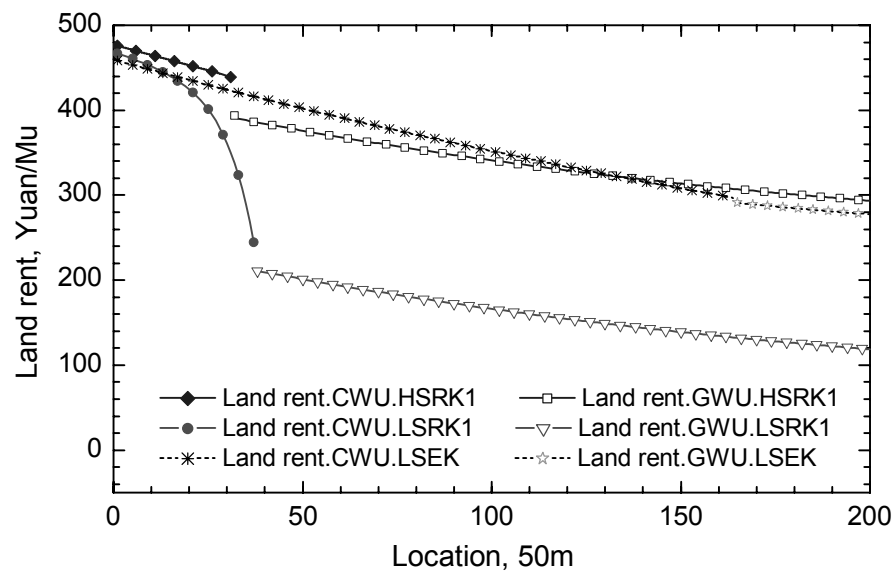

Figure 8.13: Comparison of unit land rent for CWU and GWU among optimal public investment scenario (LSEK) and scenarios of removal of public investment under low (LSRK1) and high soil permeability (HSRK1)

Figure 8.13 describes the change of the unit land rent in different scenarios. The land rent, in scenario HSRK1, still starts at the highest level from the first location. It declines gradually with distance getting farther. After the 31st location, farmers switch to groundwater. The land rent therefore goes down and we notice a down-jump from canal water area to groundwater area, thanks to the high groundwater price. That is exactly the opposite of the previous description of the water rent, when it turns out to up-jump. A slight difference with respect to the land rent exists between scenario HSRK1 and scenario LSEK. The development

suggests, that sufficient groundwater, at a certain point offsets a negative impact due to higher water charges. It didn't reduce the land rent much as seen in scenario HSRK1. Scenario LSEK shows a smoothly declining curve of land rent for the whole area. The curve is lying between scenario HSRK1 and scenario LSRK1. The starting point of the unit land rent in scenario LSRK1still ranks the lowest. And it declines sharply, as compared to scenario HSRK1 and scenario LSEK. Groundwater is not sufficiently recharged in this scenario due to a relatively low seepage rate. Consequently the entire irrigation area suffers water shortage. Eventually the canal water irrigated area shrinks, output declines and the land rent goes down inevitably.

The outputs of the models may be a surprise for people. Due to unexpectedly better outcome from scenario HSRK1, as opposed to expectations from scenario LSEK, a request for explanation appears. Between the two different recharge rates, in the irrigation systems, scenario LSEK is with a quasi-piped canal system investment. Whereas scenario HSRK1 is without any public investment at all. Surprisingly no big gap of social welfare and other important economic indicators exists between both scenarios. Especially, in the one without public investment, a bad canal system even makes revenue higher than the one that was better managed. This reminds policy makers to collect as much information as possible and compare their impact before they take any decision.

8.3   Summary and further research questions

Three scenarios have been made by focusing on investigating the impact of changing public investment status. The model results suggest optimal solutions for an irrigation system with low and high soil permeability, respectively.

Since the private investment in irrigation technology is a very heavy expenditure for farmers, the base run optimal public investment scenario (LSEK) internally determined a zero investment in irrigation technology over all locations in the model. Based on this result, the further selected scenarios hence valued the impacts on social welfare and water resource allocation merely by focusing on the role the public investment plays. They have been undertaken with public investment being made or removed under two different soil conditions. If the soil permeability is low, public investment will largely improve the aggregate social welfare and water resource allocation. However if the soil permeability is very high, an irrigation system without public investment shows that the social welfare and water resource allocation are only slightly worse off. This indicates that public investment will do especially well in improving water resource allocation and social welfare in a system under low soil permeability. But its effects to social

welfare and water resource allocation are much smaller under high soil permeability.

Further research work is needed on questions such as how to avoid limitation in explored scenarios, which failed to model the impacts of private investment participation. This limitation will be improved in the next two chapters.

9   IMPACTS OF DIFFERENT DISTRIBUTIONS OF IRRIGATION TECHNOLOGY ON SOCIAL WELFARE AND WATER RESOURCE ALLOCATION

So far the impacts of the status of public investment change on social welfare and water resource allocation have been modelled in the previous chapter. To solve the remaining problem in the previous public investment policy scenarios, where private investment was chosen being zero endogenously over all locations, an extended optimization model is introduced into the present chapter. The way the extended optimization model works is to optimize the social welfare in the project area by introducing a coefficient for private investment in the objective function, so that the model can distinguish a positive solution for private investment from public investment.

9.1   Specification of an additional coefficient on private investment and the extended optimization model

9.1.1   Specification of the coefficient on private investment

The employment of an additional coefficient on private investment is a key feature of the extended optimization model. The purposes of employing such a coefficient are: One is to investigate the effects of different policy orientations, the other is to enable positive private investment (adoption of modern irrigation technology) in the modeling process. The additional coefficient is actually derived from a scaled function of private investments over various locations. The way the function of scaled private is derived is given as follows: As observed from the field survey, the likelihood of the adoption of modern irrigation technologies increases with the distance from farm-gate to water source that gets longer. The reason is that, water is becoming more expensive with the distance getting longer due to increasing costs of canal construction, lining up and operation costs. Based on this background, a compound function of a scaled private investment over location is estimated, by using regression methodology. The estimated function is specified as below:

$$SPRI_j = 0.045 \times 1.028^{ord(j)} \tag{9.1}$$

$t = 558.06 \quad t = 3.336 \quad n = 141$

$R^2 = 0.63 \quad F = 238.74, \quad sign.F = 0.0000$

Where $SPRI_j$ is the scaled private investment at location j, which is different from the previous definition of the actual private investment. The empirical observations of actual private investment are scaled by 50 before regression analysis is made. It means that, if farmers invest 500 Yuan in irrigation technology, then the 500 Yuan will be scaled down to 10 in the estimated function.

ord(j) is the ordinal number along all the locations. It depicted 200 locations in the current model. So we have *ord(j) =1,2,3,...,200*, respectively. As known already, we have a canal of 20 km in the survey area. A unit j represents 50m in the model. So we would have 400 locations in total if the entire survey area were involved. For speeding up the model's running, we scale the 400 locations to half, i.e., 200 locations.

By doing so, the private investment becomes much smaller than the initial value, which now ranges from 0.046 to 11.468. *SPRI* is a more artificial argument compared to the real term of private investment, but it mirrors the relationship between private investment and distance. It is understood reasonably to consider *SPRI* as an additional coefficient to the real term of private investment in the modelling process. As presented in the objective function (see equation 8.1), we had already coefficient *c1* and *c2* for net revenue function. To keep the model neat and consistent, we use *c*3 to replace *SPRI*.

This approach indicates that, in the extended optimization model, the variable of private investment will be multiplied by a coefficient *c*3 at every location, i.e., with every index *j*. By computing the equation (9.1), 200 figures of *c*3 can be obtained and will serve as parameter for private investment at every location in the modelling process.

9.1.2 Specification of the extended optimization model

Most components of the extended optimization model are the same as those of the initial model, except the introduction of a coefficient *c*3. The presentation of objective function with *c*3 can be further specified as below:

Social welfare = net revenue (*with c*3) − *private investment* (*with c*3)

$\qquad$ − *public investment* − *canal water costs* − *groundwater costs* $\qquad$ (9.2)

Its mathematical formulation is expressed in the following form:

$$Social\ welfare = \sum_j 15 \times \left[c0_j \times (tw_j \times h_j) + c1_j \times (tw_j \times h_j)^2 + c2_j \times c3_j \times I_j \times (tw_j \times h_j) \right]$$
$$- \sum_j \left(0.05 \times k_j + 15 \times c3_j \times I_j + 15 \times cwp_j \times cw_j + 15 \times gwp_j \times gw_j \right) \qquad (9.3)$$

Where $c0_j$, $c1_j$ and $c2_j$ are coefficients taken directly from the net revenue function, respectively. They are obtained by integrating an inverse water demand function. The parameter $c3_j$ serves as an additional coefficient for private investment. The definitions of rest variables and parameters have been already given in the previous chapter.

For further discussions: A critical point of the extended optimization model is the employment of $c3$. The entry of $c3$ to the extended model has two advantages. From a technical point of view, it helps in making the model flexible to handle the options of private investment. From a policy point of view, it helps government to predict effects of different distributions of irrigation technology, so that governments can choose where and when to support individual farmers to adopt modern water saving technologies. It is necessary to clarify that $c3$ works only within the framework of objective function of the extended model, i.e., within which the arguments are associated with private investment I. The constraints, which are also associated with private investment I, are kept the same so that the initial relationships among different variables are still valid. Based on these facts, it becomes clear, that social welfare in the extended optimization model is not comparable with that of the initial model, but the other individual indicators are still comparable between the two models.

9.2 Simultaneous private and public investment undertaken scenarios analysis

9.2.1 Specification of the selected scenarios

As mentioned already, the main concerns of this study are to explore the role, which both investments - public and private-, are playing and the relationships between them. The role public investment is playing in water saving activities, has been investigated already in the previous chapter of public investment policy scenarios analysis. The studying of private investment was hampered in previous scenarios due to the internal definition of objective function and perhaps high costs as associated with the case study. The extended optimization model is to focus on the role of both investments. In particular, the impacts of private investment are emphasized.

As mentioned already, the coefficient $c3$ has been obtained by estimating a function of the scaled private investment based on empirical data. But one thing is needed to mention is that, the empirical data were obtained from the field survey, in which wealthier farmers situated at the tail end area of canal. This kind of geographical allocation is less common in reality. Normally richer farmers gather

at the head area instead of the tail end area of a canal thanks to good access to water. To make the model more broadly applicable, we can model the adoption of irrigation technology by altering the order of c3. By doing so, a nearly real situation and a potential requirement of government intervention could be modeled.

The nearly real situation indicates that, wealthier farmers situated at the upstream area would adopt modern irrigation technology. This situation is modeled by giving a normal order, i.e., an ascending order of coefficient c3. Since c3 will multiply the variable of private investment in the model, an ascending order of c3 will lead to a decreasing private investment along the canal. This decreasing private investment indicates that upper stream farmers will more likely adopt modern irrigation technology than downstream farmers. This possibility of adoption will decrease with location getting farther, as farmers' economic situation gets worse with distance, and they cannot afford the costs of modern irrigation technology.

The potential requirement of government intervention assumes, that downstream farmers would apply modern irrigation technology. This situation is modeled under a reverse order, i.e., a descending order of c3. A descending order of *c*3 will result in an increasing private investment along the canal. The increasing investment indicates that downstream farmers will adopt modern irrigation technology rather than upstream farmers. Since farmers in downstream area are poor, they can hardly afford the costly irrigation technology. For a potential requirement of government intervention, this scenario is to test how much farmers can afford, and how much the government shall support.

Five scenarios focusing on different distributions of irrigation technologies are to test in this chapter. They are listed in Table 9.1. The first two scenarios (LSDI and LSAI) will be done under two different orders of c*3*. The third scenario LSFI is modelled under a choice of fixed technology promoted by government. The last two scenarios (LSRK2 and HSRK2) are to investigate the impacts of removal of public investment under the extended optimization model.

Table 9.1: **Scenario groupings, names, abbreviations, and descriptions for assessing the impacts of different distribution of irrigation technology**

Group/Name	Abbreviation	Description
Scenarios of different allocation of irrigation technology under the extended optimization model:		
Nearly real situation scenario	LSDI	To model the impacts of allocation of modern irrigation technology gathering at the upstream area.
Potential requirement of government intervention scenario	LSAI	To model the impacts of allocation of modern irrigation technology gathering at the downstream area.
Government promotion of a fixed type technology scenario	LSFI	To model the impacts of adoption of one fixed type modern irrigation technology over the whole area.
A removal of public investment under low soil permeability scenario in the extended model	LSRK2	To model the overall impacts of a removal of public investment with private investment participation under low soil permeability
A removal of public investment under high soil permeability scenario in the extended model	HSRK2	To model the overall impacts of a removal of public investment with private investment participation under high soil permeability

9.2.2 Nearly real situation scenario

The recharge rate is set at 0.3. Public investment K and private investment I are endogenous variables to the model. Coefficient $c3$ enters in a normal order, i.e. ascending order. The purpose of this scenario is to analyze the impact of a decreasing private investment on aggregate social welfare and water allocation in the irrigation area.

9.2.2.1 Impacts on aggregate indicators

The aggregate economic and water-related indicators are presented in Table 9.2. The social welfare is reported at 1,096,337 Yuan over the whole area. The total canal water consumption is 299,998.47m^3. Groundwater consumption is reported at 46,635m^3. Thus the total water consumption over the whole area achieves 346,634 m^3. Compared to the total water supply capacity, a gain of 45,634 m^3 water is reported thanks to conjunctive water use. As happened in the previous scenarios of public investment policy, the model chooses public investment at the highest level to ensure a zero loss rate of water conveyance. In the current scenario, the total public investment is observed at 2,579.31 Yuan, which covers 174 locations along the canal, i.e., 8700m within a 10,000-meter-long canal. The area irrigated by canal water achieves a high of 2,602.2 Mu, 6.54 times more than that by groundwater. The whole area is dominated by canal water irrigation.

Table 9.2: **Impacts on social welfare and water resource allocation at aggregate level in nearly real situation scenario (LSDI)**

Items	LSDI
Social welfare (Yuan)	1,096,337.38
Total canal water consumption (m^3)	299,998.47
Total groundwater consumption (m^3)	46,635.30
Total water consumption (m^3)	346,633.77
Capacity of water supply (m^3)	301,000.00
Gain from conjunctive water use (m^3)	45,633.77
Total public investment (Yuan)	2,579.31
Switch point (Location)	174.00
Canal water length (m)	8,700.00
Area irrigated by canal water (Mu)	2,602.20
Area irrigated by groundwater (Mu)	397.80
Total private investment (Yuan)	138,470.08

Notes: In scenario LSDI, the switch point is observed at location 174, at which canal water becomes insufficient. It is reported an extraction volume of 56.62 m^3 canal water and 61.76 m^3 groundwater taking place at location 174. So the item of area irrigated at this location is calculated by considering the ratio of their contribution at this point. They are 0.48 and 0.52 for canal and groundwater respectively.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

But as a difference, total private investment in irrigation technology is now found at 138,470 Yuan. It is in line with 89 positive observations of irrigation technology users, over the irrigation area.

9.2.2.2 Impacts on social welfare and water resource allocation at farm level

Our new mean analysis of unit economic and water-related items, based on different categories, is documented in Table 9.3. Two new categories are added from now on, they are specified as modern irrigation technology users (MTU) and traditional technology users (TTU). The modern technologies in the study refer to actively pro-water saving technologies, such as drip irrigation, sprinkler irrigation and seepage irrigation, etc. The traditional technologies refer to water-consuming techniques, such as flood irrigation and furrow irrigation.

The unit aggregate water demand for AU is observed at 115.54m^3/Mu, which slightly differentiates it from 115.29 m^3/Mu of CWU and 117.23 m^3/Mu of GWU. However it is higher than 105.13 m^3 of MTU. It becomes very obvious as shown in Table 9.3, that the water consumption of MTU is 15.15% lower than that of TTU, thanks mainly to the adoption of modern water saving technologies. This change suggests, that no big differences from most items are observed among the

Table 9.3:   Mean values of indicators at farm level in nearly real situation scenario (LSDI)

Items	AU	CWU	GWU	MTU	TTU	%(M&T)
Aggregate water demand (m^3)	115.54	115.29	117.23	105.13	123.90	-15.15
Revenue (Yuan)	435.53	434.23	444.02	410.63	455.49	-9.85
Land rent (Yuan)	295.67	296.15	292.49	258.63	325.36	-20.51
Water rent (Yuan)	92.85	83.88	151.53	47.28	129.38	-63.45
Private investment (Yuan)	46.16	53.21	0.00	103.72	0.00	
On-farm water use efficiency	0.58	0.59	0.48	0.70	0.48	44.96
Public investment (Yuan/km)	257.93	298.19	0.00	298.19	0.00	
Water conveyance loss rate		0.00	0.07	0.00	0.07	

Notes: All items are measured based on Chinese land unit Mu except public investment, which is based on kilometre. 1Mu=1/15 hectare.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

category of AU, CWU and GWU. But it shows that the double water saving system narrows the gap between CWU and GWU. However, significant differences are mostly found between MTU and TTU. The average unit revenue for MTU is reported at 9.85% less than that for TTU, due to the costly modern irrigation technologies and less water demand. A significant decline of 20.51% of land rent on average is also reported for MTU compared to that for TTU. As a consequence of the expensive investment in irrigation technologies, land becomes less scarce. The average level of water rent drops by 63.45% due to less water being taken by MTU. The private investment is on average suggested to be 103.72 Yuan/Mu and results in average on-farm water use efficiency achieving a high of 0.7 for MTU, improved by 45% compared to base water use efficiency of 0.48 for TTU.

9.2.2.3 Illustration of movement and relationships between some key indicators at spatial level

As already said the aim of the study is to investigate the impacts on economic, social and natural resources in an irrigation area, connected with the adoption of modern irrigation technology and improvement of the water conveyance system. In terms of the public expenditure, there exist little controversies, since it plays a positive role in the optimization process all the time, as proved already in previous chapter 8. In terms of private investment, this is somewhat different. The aim of the study is also to demonstrate or model different situations (scenarios). For example, we want to find at which location farmers will adopt modern technology and where it will be optimal for the whole irrigation area? Which technology could be adopted? What happens, if upstream farmers adopt modern

technology contrary to their downstream counterparts? The big advantage of such a modeling exercise is, that it can simulate different kinds of assumptions and then compare the results. In other words, the advantage of a model is that of its simulations rather than showing the real world only.

Based on this background, the movement of selected indicators will be illustrated in detail, in order to answer the above-mentioned questions and provide designers of irrigation project or policy makers accurate and clear information on individual farmers at different locations. Moreover, it will be very helpful for evaluating the entire impacts of an irrigation project from the aspect of individual farmer's economic situations.

Since private investment is the focus of this section, this requires investigating its performance. Figure 9.1 illustrates the relationship between private investment in irrigation technology and on-farm water use efficiency. The more investment is undertaken, the higher the water use efficiency will be. As shown in Figure 9.1, the distribution of irrigation technology gathers together at the upper area of the canal, and decreases with the canal. The highest water use efficiency rate of 0.88 is observed at the water source, in line with an investment of 214 Yuan/Mu at this place. With the distance becoming longer, the investment declines. When farmers stop to invest in irrigation technology at location 90, consequently the on-farm water use efficiency falls down to its lowest level, at a base on-farm water use rate of 0.48.
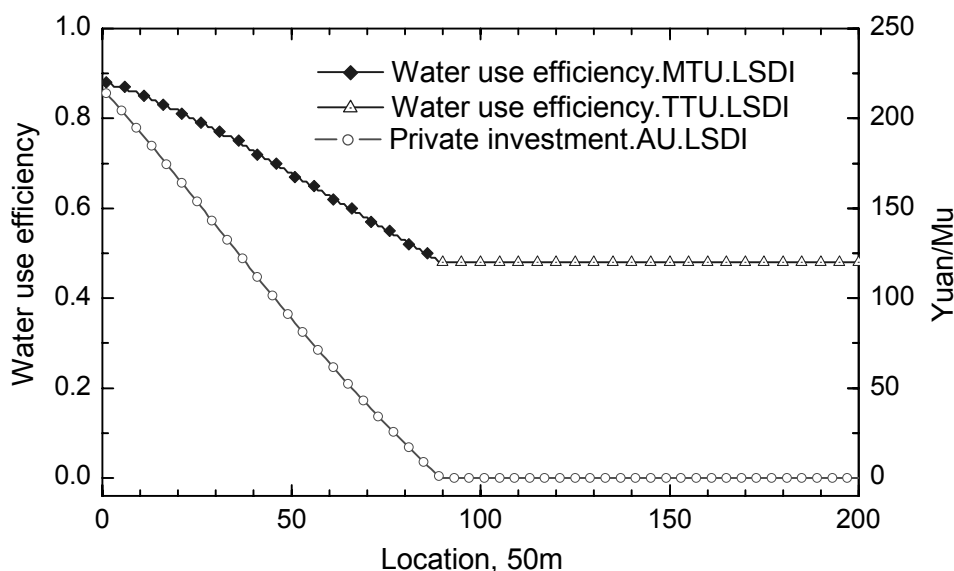
Figure 9.1: Illustration of private investment and water use efficiency in nearly real situation scenario (LSDI)
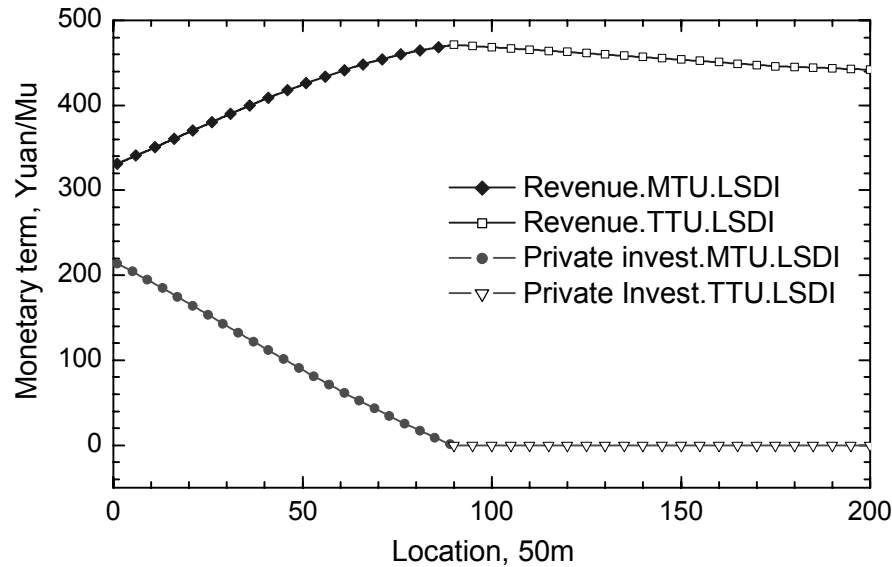
Figure 9.2: Movement of unit revenue and private investment in nearly real situation scenario (LSDI)

In order to better explore relationships among different variables after private investment being undertaken, several diagrams will be provided to fulfill this task. Figure 9.2 graphs the movement of unit private investment and revenue over distances together. On one side, it is clearly shown, that the lowest level of revenue 331.23 Yuan/Mu is found at the first location, afterwards it goes up steadily, and then reaches a peak of 471.05 Yuan at location 90. After this point until to the final farmer, no penny is invested in modern irrigation technology. On the other side, the highest private investment is made at the first location, and it declines gradually till 0 at location 90. Location 90 is such a point, where revenue reaches a peak and private investment falls to bottom. This movement suggests that private investment in irrigation technology means a considerable expenditure for farmers. This can be large enough to consume all their revenue in certain situations. Model results tell us that the private investment ranges from 214.01 Yuan at the first location to 1.03 Yuan at location 89. This implicates, that the choice of irrigation technologies varies and downgrades over space. For instance, the private investment at first location is reported 214.01 Yuan per Mu annually, which ranks in the top over the area. According to the investment requirements of different technologies, it indicates, that farmers at this location apply kinds of mixed technologies, such as primary sprinkler and seepage irrigation (locally produced drip irrigation). With the distance getting farther and the water price getting higher, farmers reduce the investment in irrigation technology rapidly.
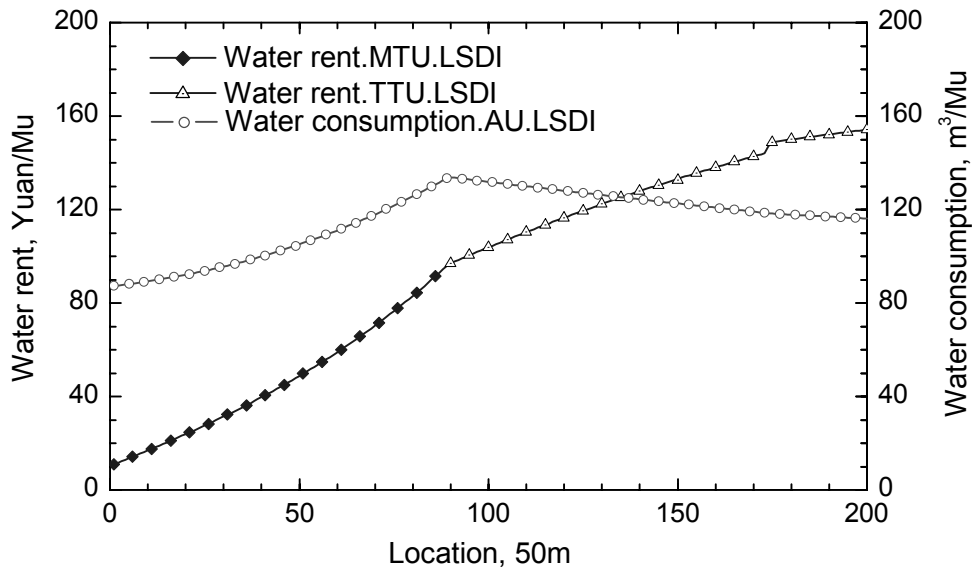
Figure 9.3: Illustration of relationship between water rent and water consumption in nearly real situation scenario (LSDI)

Such a distribution of private investment suggests that upstream farmers rather than downstream farmers would apply modern irrigation technologies. This result seems to be paradoxical and unrealistic compared to the field survey results. As we explained already, it could be an exception that richer farmers gathered at downstream instead of upstream area in the survey area, as compared to the reality. Normally farmers situated at upstream area are better off than that at downstream area. To make the model be broadly applicable in general irrigation project, the solution should not be regionally confined within the field survey findings. It is understandable that farmers situated at upstream area are the mostly likely group to adopt the modern irrigation technology.

Figure 9.3 investigates the relationship between water rent and water consumption. One of the premises of the study is, that the water price increases with the distance getting longer. This must be kept in mind all the time. It is observed that the lowest level of water consumption is at the water source due to the highest investment in irrigation technology at this point, and then it increases gradually, while the grading of irrigation technology goes down. The highest water consumption is at location 90, at which no water saving technology is employed, and the water price there is lower than afterwards, so a peak of water consumption occurs. The water consumption eventually goes down due to an increasing water price. This too can be observed in the curve of the water rent. Normally the water rent goes up with distance, mainly due to the increasing water price if no big differences are reported in water consumption among different water users. It is suggested in Figure 9.3 that the curve of water rent goes up sharply compared to that of water consumption before it reaches location 90
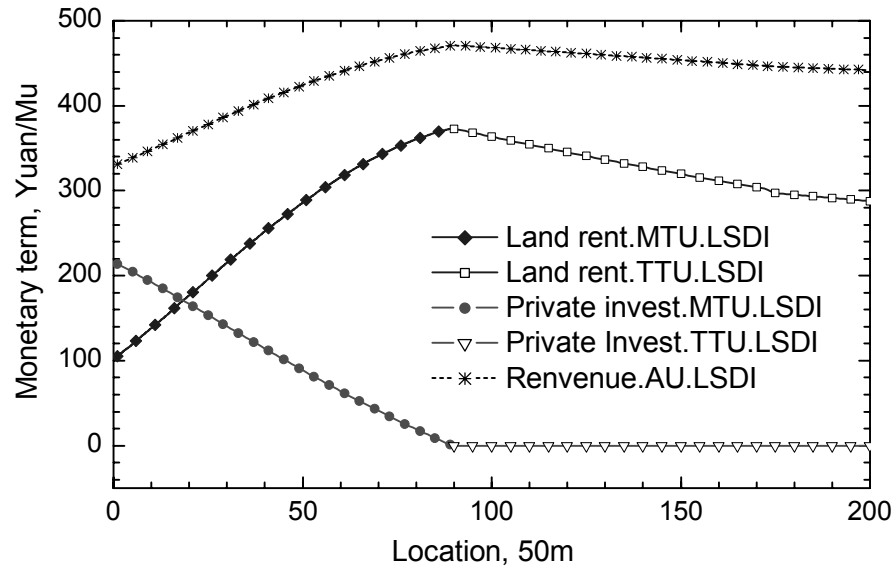
Figure 9.4: Illustration of relationship among revenue, land rent and private investment in nearly real situation scenario (LSDI)

(within MTU).The reason for this is that, the water rent is not only influenced by the water price, but also by the largely reduced water consumption at upper stream. Due to expensive investment in water saving technology and the public expenditure on the conveyance system, water values more. After location 90, the water rent still keeps going up, thanks to a dramatic increase of the water price and gradual reduction of public expenditure on the canal, though the water consumption shows a decline after location 90.

Figure 9.4 unveils the relationship among revenue, land rent and private investment. It is understood that the curve of revenue stays above the other two all the time. Location 90 still remains the crucial point while comparing the model results. Recalling the definition of land rent, it was defined as an equation of revenue less private investment in the present study. Figure 9.4 exactly describes this kind of relationship. The lowest land rent occurs at the water source due to its highest expenditure on irrigation technology. With investment decreasing, land rent therefore is increasing. The land rent reaches its peak exactly at the point, where the private investment touches its bottom, i.e., no private investment is undertaken any longer. It too suggests that adoption of modern technology is indeed a big investment for farmers. That also explains why the zero-private investment is kept all the time in the initial optimal model.

9.2.2.4 Concluding remarks of the nearly real situation scenario

The nearly real situation scenario investigates the impacts of distribution of irrigation technologies on social welfare and water resource allocation with the

help of an additional coefficient $c3$ for private investment. The modern irrigation technologies are adopted by upstream farmers in this scenario. And moreover, the grade of irrigation technologies varies in the current scenario instead of being held zero under the public private investment scenarios. With the variation of irrigation technology, water resource allocation is changing too:

1. Considering the switch point in this scenario, it is somewhat different from previous scenarios of public investment policy, which are run under an initial optimization model. The switch point in this scenario is the point where MTU switches to TTU. However the switch point in the initial optimization model was the point where CWU switches to GWU, since no any irrigation technology was adopted by farmers. It is very important to note that, in the current nearly real situation scenario, the appearance of modern technologies at a certain point changes the allocation of water resources and farmers' behavior over space. For instance, without using modern technology, farmers have consumed the biggest amount of water at the water source as suggested in the previous public investment policy scenarios. In contrast, now they consume the smallest amount of water after the modern technology has been adopted. Affording modern technologies needs a change in the revenues, perhaps due to changes in the cropping pattern. Moreover, farmers located at the tail of the project area normally get insufficient water due to an overuse of water by their upper stream counterparts. After modern technology is applied on the upper stream, more water in the canal can be left for downstream farmers. As suggested in the previous optimal public investment scenario (LSEK), the longest canal water length can be till location 164, but it now can be extended until location 174 in the current scenario. By applying modern irrigation technologies at upper stream areas, we see large benefits for those living downstream.

2. One might be skeptical that upstream instead of downstream farmers would apply the modern water saving irrigation technology. Normally upstream farmers are better off, and they are the most likely group to afford the expensive equipment compared to their downstream counterparts. So they might have incentive to do that. As they can get sufficient and cheaper water from the water source, finance is available. For a country like China, with 80% rural population and an increasing threat of water shortage, it could happen one day, that the irrigation water is no longer cheap, as it happens already today in western US, let alone in Israel. For the government, the critical point is to save water so as to let the water flows longer to benefit more people. This will improve social welfare and water allocation for the whole area. Intuitively imagine, if more water could be saved at the upstream,

then the more water would be left in the canal to serve additional people downstream. Moreover, modern irrigation technologies can not only save water, but also improve the quality and quantities of the crops considerably as presented in the field survey. Based on these arguments, it is, however, still plausible and closer to reality that upstream farmers would adopt modern irrigation technologies. The nearly real situation scenario will therefore also serve as a benchmark for a comparison with the coming scenarios.

9.2.3 Potential requirement of government intervention scenario

9.2.3.1 Specification of the additional coefficient on private investment in a reverse order

The intention of the potential requirement of government intervention scenario (LSAI) is to model the impacts of private investment increasing with distance as based on government concern for social welfare and water resource allocation. By employing the coefficient $c3$ for private investment in a reverse order, this can be matched. In the previous nearly real situation scenario (LSDI), the coefficient $c3$ has been employed in a normal order. It was suggested in scenario LSDI that farmers would adopt modern water saving technologies at the upper canal area; especially those situated at the water source would undertake the highest investment under market conditions.

In the current scenario, we will investigate a situation of government intervention by applying $c3$ in a reverse order, i.e., descending order. Note that, the change in coefficient $c3$ is associated with government supports based on ground of equity. For poor farmers situated in the downstream area, will it be possible for them to apply modern irrigation technology? How much can they afford? And how much shall the government support them? How is the situation of social welfare and water resource allocation if distribution of irrigation technology changes from upstream to downstream area?

9.2.3.2 Impacts on aggregate indicators

It is assumed that all the other conditions, except coefficient $c3$, are kept the same as in the nearly real situation (LSDI), i.e., the recharge rate is still at 0.3, and private and public investments are endogenous in the model. But $c3$ is in descending order contrary to the ascending order in scenario LSDI.

Table 9.4 shows the aggregate impacts on social welfare and water resource allocation with a distribution of technology at downstream area. Social welfare is

Table 9.4: **Comparison of indicators at aggregate level between nearly real situation scenario (LSDI) and potential requirement of government intervention scenario (LSAI)**

Items	LSDI	LSAI	%
Social welfare (Yuan)	1,096,337.38	1,136,078.96	3.62
Total canal water consumption (m^3)	299,998.47	300,000.00	0.00
Total groundwater consumption (m^3)	46,635.30	45,088.61	-3.32
Total water consumption (m^3)	346,633.77	345,088.61	-0.45
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	45,633.77	44,088.61	-3.39
Total public investment (Yuan)	2,579.31	2,357.24	-8.61
Switch point (Location)	174.00	160.00	-8.05
Canal water length (m)	8,700.00	7,900.00	-9.20
Area irrigated by canal water (Mu)	2,602.20	2,370.00	-8.92
Area irrigated by groundwater (Mu)	397.80	630.00	58.37
Total private investment (Yuan)	138,470.08	219,114.08	58.24

Notes: The switch point in scenario LSAI is suggested at location 160, at which farmers start to take groundwater completely. The number of MTU in scenario LSAI is 93, against 89 in scenario LSDI.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c_3 in an ascending order.

LSAI: It indicates the potential requirement of government intervention scenario, which is run under low soil permeability, endogenous public and private investment, c_3 in a descending order.

observed at 1,136,079 Yuan over the entire irrigation area, which is a slight growth of 3.62%, as compared to that in scenario LSDI. The total canal water consumption shows little change, with merely a volume of 1.53 m^3 more than in scenario LSDI. Total groundwater consumption is reported slightly declining compared to scenario LSDI, with a decreasing rate of 3.32%. This is mainly due to the water saving technologies being largely adopted at downstream areas. Total consumption of canal water and groundwater shows a small decline, with a tiny rate of 0.45% compared to scenario LSDI. So a gain from conjunctive water use is reported of 44,089 m^3, and it is 3.39% lower than in scenario LSDI. Due to more water consumed at the upper canal area, canal water length gets shorter than that in scenario LSDI, shortened by 9.2%. Consequently the public investment is reduced by 8.61% in the current scenario. Contrary to a decrease of the area irrigated by canal water by 8.92%, the area irrigated by groundwater increases by 58.37%. Significant increase takes place in total private investment, with a growth of 58.24% compared with scenario LSDI. The model results also suggest, that the number of farmers adopting modern technology rises to 93 against 89 in scenario LSDI. More advanced technology, say modern sprinkler irrigation, is adopted

broadly at the tail of the irrigation area. The significant increase of private investment suggests that a high water price will drive more farmers to go for modern irrigation technology.

9.2.3.3 Impacts on social economy and water resource allocation at farm level

Table 9.5 investigates the impacts on different indicators at farm level. In the current scenario LSAI, modern water saving technology is largely adopted by the GWU. The average water demand in unit for all farmers shows negligible differences between scenario LSAI and scenario LSDI, with a tiny drop of 0.45%. For CWU, it increases to 125.79 m^3/Mu, with a growth of 9.11% compared to that in scenario LSDI. It is however significantly reduced for GWU by 37.46% compared to scenario LSDI, mainly due to GWU adopting modern water saving technology. Due to different location, the average water consumption by MTU in scenario LSAI is 16.54% lower than that in scenario LSDI. The area, where MTU situates in the current scenario LSAI, is from location 108 till the end of the irrigation area. Groundwater use starts from location 160 in this scenario. This information indicates that more than half MTU are using groundwater in the current scenario LSAI. However all the modern technology users in scenario LSDI use canal water. Therefore MTU in scenario LSAI consumes less water than in scenario LSDI. The same reason can explain why TTU in scenario LSAI consumes more water than in scenario LSDI.

Let's come to unit revenue now. For AU, the average unit revenue does not change much, while comparing both scenarios. The biggest decline is observed in farmer category GWU, with a drop of 30.12% compared to scenario LSDI. This is due to the higher investment in irrigation technology being made in scenario LSAI as compared to scenario LSDI.

It is observed evidently, that land rent falls down sharply for GWU in scenario LSAI, with an average negative value of 33.47 Yuan/Mu being reported, compared to a positive one of 292.49 Yuan/Mu in scenario LSDI. The reason for this is that more advanced irrigation technology is applied at the tail area, and hence the biggest expenditure is also made at this area.

The biggest change of water rent is found in MTU. It reports a growth of 101.04% against a decline of the other categories compared to scenario LSDI. Obviously this takes place, because the MTU in scenario LSAI are mostly located downstream and have to pay higher water prices. Though the water consumption by MTU is reduced due to adopting the water saving technology, the higher water prices still push the water rent up.

Table 9.5: **Comparison of mean values of indicators at farm level between nearly real situation scenario (LSDI) and potential requirement of government intervention scenario (LSAI)**

Items	AU			CWU			GWU			MTU			TTU		
	LSDI	LSAI	%	LSDI	LSAI	%	LSDI	LSAI	%	LSDI	LSAI	%	LSDI	LSAI	%
Aggregate water demand(m^3)	115.54	115.03	-0.45	115.29	125.79	9.11	117.23	73.31	-37.46	105.13	87.73	-16.54	123.90	138.75	11.99
Revenue(Yuan)	435.53	426.82	-2.00	434.23	456.87	5.21	444.02	310.28	-30.12	410.63	369.38	-10.05	455.49	476.75	4.67
Land rent (Yuan)	295.67	273.20	-7.60	296.15	352.27	18.95		292.49	-33.47	258.63	116.70	-54.88	325.36	409.22	25.77
Water rent (Yuan)	92.85	79.80	-14.05	83.88	76.35	-8.97	151.53	93.18	-38.50	47.28	95.06	101.04	129.38	66.54	-48.57
Private investment (Yuan)	46.16	73.04	58.24	53.21	27.26	-48.77	250.57	103.72		157.07	51.43				0.00
On-farm water use efficiency	0.58	0.62	7.06	0.59	0.54	-9.02	0.48	0.92	91.47	0.70	0.77	11.24	0.48	0.48	0.00
Public investment (Yuan/km)	257.93	235.72		298.19	298.39	0.07	298.19	164.92	-44.69	298.19	164.92	0.00		297.27	0.00
Water conveyance loss rate	0.00	0.00		0.00	0.00	0.00	0.07	0.07	0.00	0.00	0.07	0.03	0.07	0.00	0.00

Notes: LSDI:It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

LSAI: It indicates the potential requirement of government intervention scenario, which is run under low soil permeability, endogenous public and private investment, c3 in a descending order.

Private investment increased by 58.24% for all farmers on average in scenario LSAI. The highest investment of 250.57 Yuan/Mu is observed in GWU compared with a zero-investment in scenario LSDI, in line with on-farm water use efficiency reaching 0.92, improved by 91.47%. Comparing the investment for MTU between the both scenarios, an increase of 51.43% in scenario LSAI is found. This indicates, that farmers in scenario LSAI on average apply more advanced technology than in scenario LSDI. For instance, the highest investment for MTU in scenario LSAI and scenario LSDI are 280.21 and 214.01 Yuan/Mu respectively, in line with an average on-farm water efficiency of 0.77 being reported in scenario LSAI against one of 0.70 in scenario LSDI.

9.2.3.4 Illustration of movement and relationships between some key indicators at spatial level

Several figures are given below to describe relationships between some crucial variables under different scenarios. Figures 9.5 and 9.6 compare the movement of revenue in scenario LSAI and scenario LSDI, and they further investigate the relationship between revenue and private investment. It is clearly shown in Figure 9.5, that the highest revenue is reported at the water source in scenario LSAI. However it is suggested at location 90 in scenario LSDI. Though the scenarios indicate different peaks of revenue, the common reason for this is the private investment.

At the water source area, as shown in Figure 9.6 for scenario LSAI, farmers undertake zero investment in modern irrigation technology. So they get the highest revenue mainly due to zero expenditure in irrigation technology and the best geographical position as well as the cheapest water available. However in the scenario LSDI, farmers invest most in modern irrigation technology at the water source (see Figure 9.2). The lowest revenue hence is observed at the water source area despite of the lowest water price charged here too. Figure 9.6 explores more about the relationship between revenue and private investment in scenario LSAI. As shown in this figure, before private investment is made, the curve of revenue goes down quite smoothly and flat due to the influence of only one indicator, the price of water. The area, where TTU situates, is covered completely by the public canal water system in the current scenario. This indicates, that the water price is relatively low and changes little. From location 108 farmers start to invest in water saving technology, the revenue falls quickly. Figure 9.6 shows an exact opposite direction of the two movements. Where the revenue hits a peak, the private investment falls at its bottom.
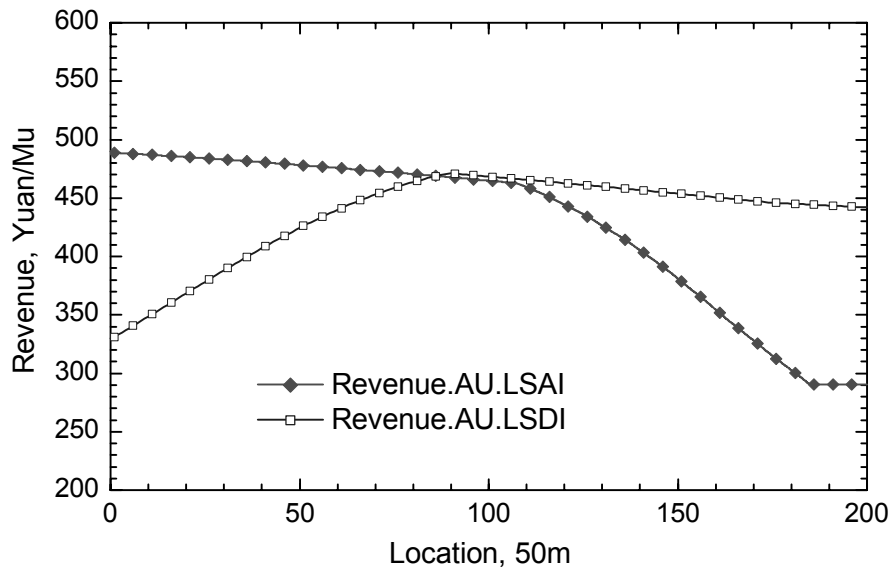
Figure 9.5: Comparison of revenue between potential requirement of government intervention scenario (LSAI) and nearly real situation scenario (LSDI)
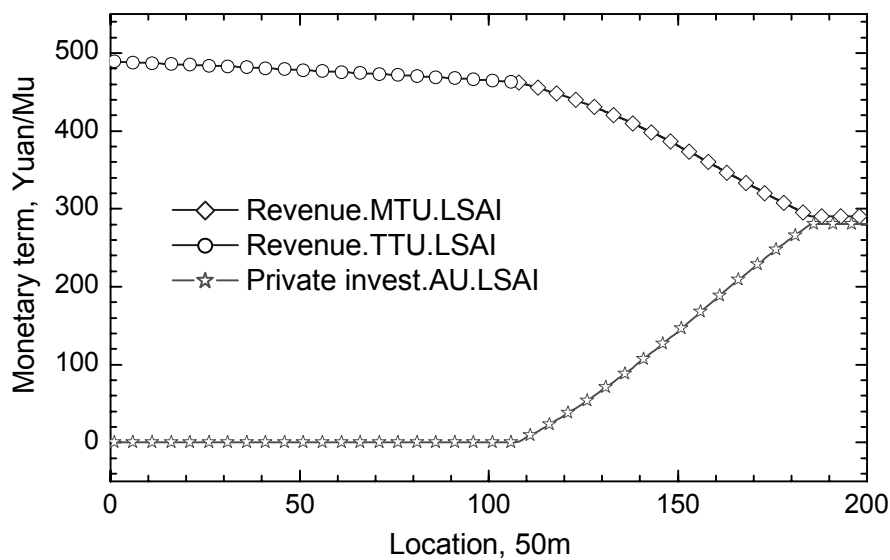
Figure 9.6: Illustration of relationship between revenue and private investment in potential requirement of government intervention scenario (LSAI)

Figure 9.7 compares the movement of the water rent in the current scenario LSAI and scenario LSDI. Due to the adoption of modern technology at the tail of the area, the water consumption is largely reduced in this area. As shown in Figure 9.7, the water rent in scenario LSAI at the beginning slightly goes up. With the distance becoming longer, it reaches a peak at location 108, where the farmers switch from TTU to MTU. After location 108 it suddenly goes down due to the adoption of modern water saving technology. The longer the distance is, the more private investment occurs. This is also shown in Figure 9.7. An up-jump of the water rent is observed at location 160 within TTU, at which groundwater
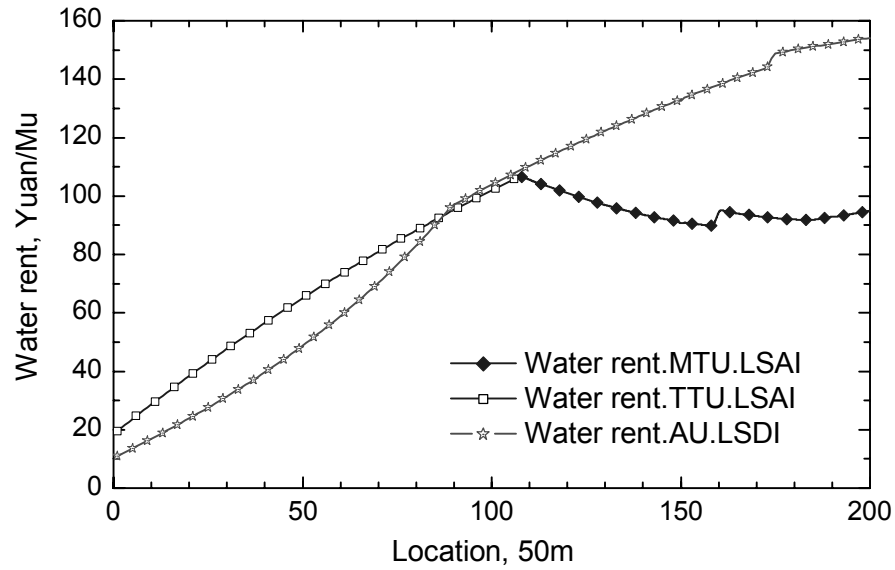
Figure 9.7: **Comparison of water rent between potential requirement of government intervention scenario (LSAI) and nearly real situation scenario (LSDI)**
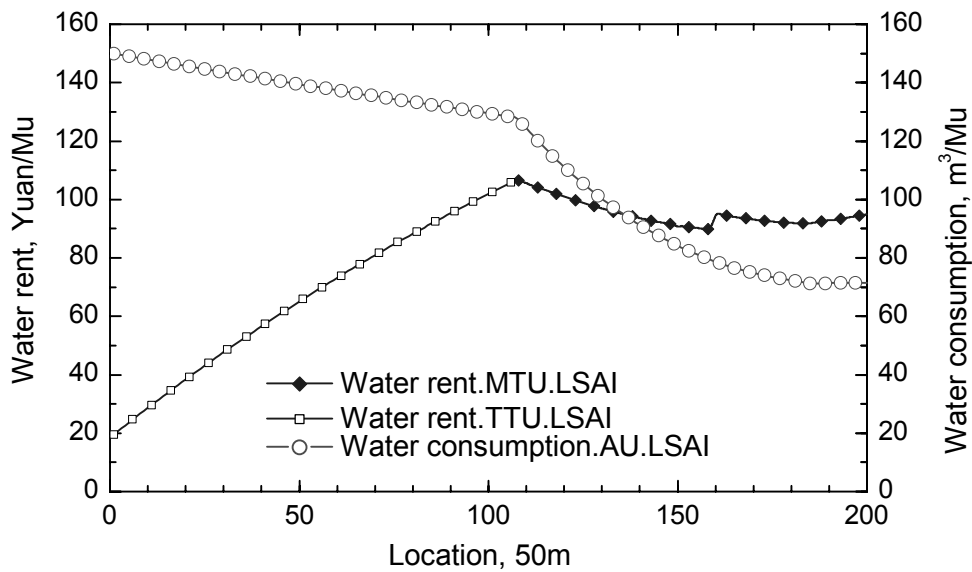
Figure 9.8: **Illustration of relationship between water rent and water consumption in potential requirement of government intervention scenario (LSAI)**

taking starts. This causes a small up-jump of the water rent. Differently from scenario LSAI, the water rent in scenario LSDI moves up more smoothly. It hits the lowest water rent at the water source, due to the lowest water price and the highest water saving technology being used.

Figure 9.8 describes in more detail the relationship between water rent and water consumption in scenario LSAI. As shown in the figure, the lowest water rent appears at the water source due to a low price. At this point the biggest water consumption is reported. With distance getting longer, the water rent increases
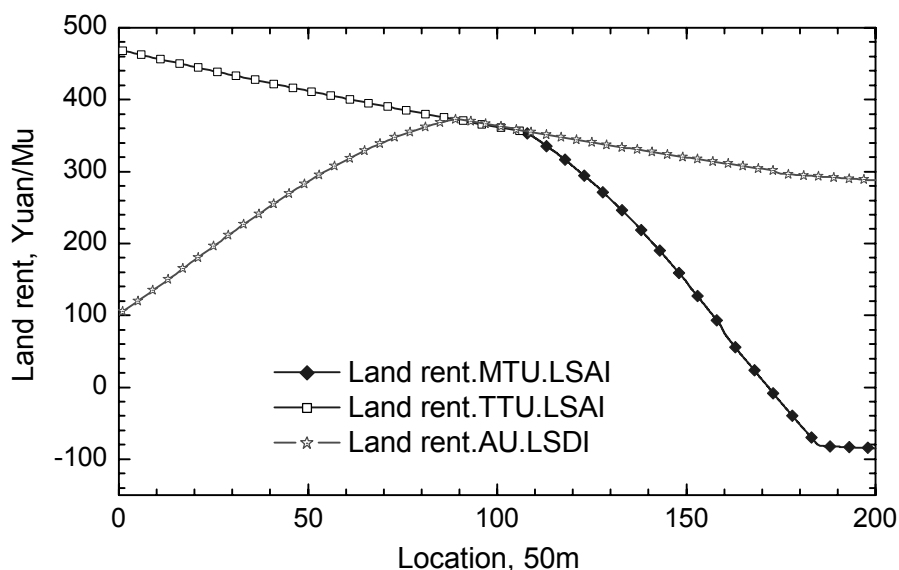
Figure 9.9: Comparison of land rent between potential requirement of government intervention scenario (LSAI) and nearly real situation scenario (LSDI)

quickly due to a continuously rising water price. For TTU despite of a decline of water consumption, prices continue to rise. After farmers start to apply water saving technologies, water consumption has been reduced considerably. Next shown in the figure, the curve of water consumption goes down sharply after the switch point of technology is being taken. However the curve of the water rent moves downward relatively smoothly due to the effect of an increasing water price.

It is clearly shown in Figure 9.9 that the land rent in scenario LSAI moves towards an opposite direction as compared with that in scenario LSDI. Due to a different distribution of water saving technology, this move occurs. In scenario LSAI, farmers adopt modern water saving technology at the downstream area. In this area, the land rent decreases quickly with the private investment getting higher. Especially from location 172 to 200, negative land rents are observed within these locations. This indicates, that the high private investment is a heavy burden for farmers, in particular those, situated at the tail of the irrigation area. So an intervention of subsidy from government to support poor farmers to adopt modern irrigation technology is required.

Moreover, the application of water saving technology narrows the difference between CWU and GWU. And it enlarges the difference between TTU and MTU. As shown all the time under the extended model, only in which private investment becomes endogenously, the switch point for all individual variables is between TTU and MTU rather than CWU and GWU. As further shown in Figure 9.10, the land rent is closely tied with private investment and water costs. The land rent decreases naturally and smoothly with distances getting further away. From
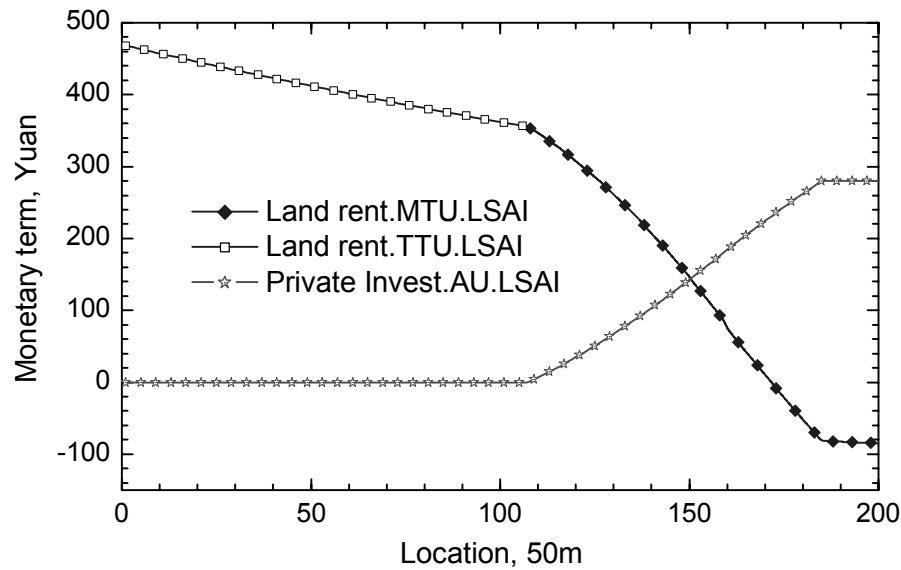
Figure 9.10: Illustration of relationship between land rent and private investment in potential requirement of government intervention scenario (LSAI)
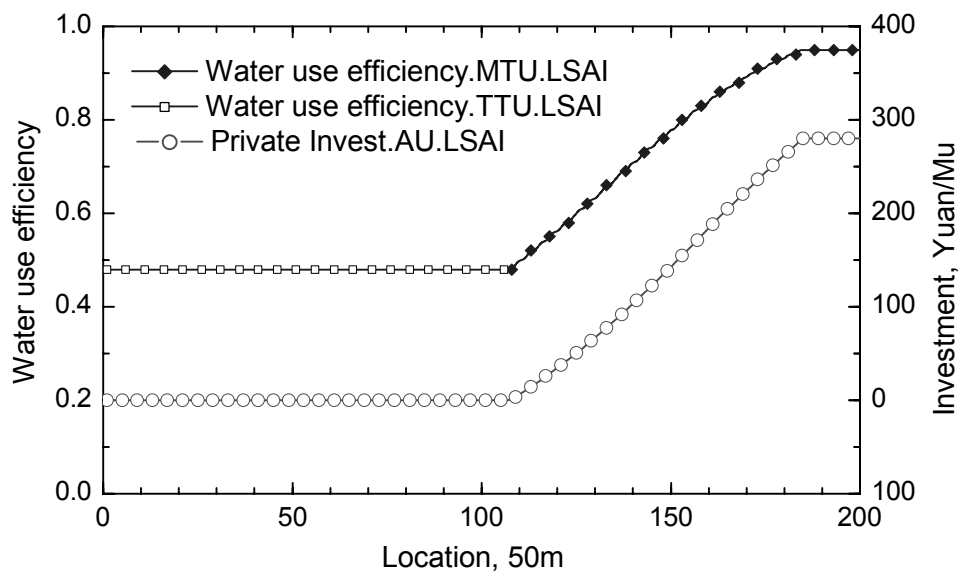
Figure 9.11: Illustration of relationship between water use efficiency and private investment in potential requirement of government intervention scenario (LSAI)

location 108, from which farmers start to invest in modern irrigation technology, the land rent goes down dramatically. By investments getting densely and heavily, the land rent falls deeply and eventually becomes negative. At the end of the irrigation area the investment hits its peak, while the land rent falls to the bottom.

Apparently, on-farm water use efficiency varies with the private investment in water saving technology. As shown in Figure 9.11, when investment keeps zero, the on-farm water use efficiency can only achieve the baseline on-farm water use efficiency at 0.48. After private investment increases in the irrigation area, the

on-farm water efficiency improves. At the tail area, with the highest investment of 280.21 Yuan/Mu, an ever-high rate of on-farm water use efficiency of 0.95 is reported.

9.2.3.5 Concluding remarks of potential requirement of government intervention scenario

The above scenario analysis has been done with an increasing private investment over distance, i.e., a distribution of technology gathering in the downstream area. The model results suggest that the social welfare in the current potential requirement of government intervention scenario (LSAI) is slightly increased with a growth of 3.6% in comparison to the nearly real situation scenario (LSDI). The on-farm water use efficiency is considerably improved due to heavy private investment in water saving technology. Different distributions of irrigation technology change the water resource allocation. The tail end area becomes the area, where the modern technology concentrates and the lowest amount of water is consumed there. Contrary to the current scenario LSAI, the modern water saving technology concentrates at the head area in scenario LSDI, at which the lowest water consumption is reported. In the case of scenario LSAI, the opposite occurs. The comparison shows how important structural conditions are.

In total the average on-farm water use efficiency is increased and the total water consumption over the project area is more reduced in scenario LSAI as compared to scenario LSDI. From the point of view of water saving, scenario LSAI is more optimal than scenario LSDI. But considering the required private investment, it becomes tricky to judge. The average on-farm water use efficiency is improved from 0.58 in scenario LSDI to 0.62 in scenario LSAI, however the total private investment over the irrigation area is required to reach 219,114 Yuan, an increase by 58.24%. Moreover, excluding social welfare and on-farm water use efficiency, the other indicators of social economy and water resource allocation are worse off. This refers to additional revenue, land rent and water rent. Especially the land rents observed become negative within the last 29 locations, due to the heavy investment needed. Such model results strongly call for government subsidy to support poor farmers to adopt modern irrigation technology.

As regards public investment in the conveyance system, model results suggest a decrease in scenario LSAI as compared to scenario LSDI due to the much heavier private investment. But the relationship between public and private investment is still a combination of a complementary rather than substitution. They are primarily complementary. In the current case, the increasing private investment results in a reduction of public investment. This can be explained as a partial

substitution with respect to absolute costs. An improvement of water efficiency needs participations from both sectors. The relationship between public and private investment still needs to be further investigated in the coming scenarios.

The model results of current scenario LSAI actually suggest a potential possibility and requirement for government intervention to help farmers, who lack self-finance, to adopt modern water saving technology. Comparing the model results, as unveiled by scenario LSDI and scenario LSAI, it looks reasonable, to keep the coefficient $c3$ in a normal instead of a reverse order in the programming process. Since the public investment only focuses on the water conveyance system rather than on-farm water efficiency in the current study, c3 in a normal order reflects private incentives and is more close to reality. Therefore, the following scenarios will be modeled only under $c3$ in a normal order.

9.2.4 Government promoted scenario

In the previous two scenarios, the impacts of private investment on the social economy and water resource allocation, as caused by a different distribution of irrigation technology, i.e., a concentration at the head area in nearly real situation scenario (LSDI) and at the tail end area in the potential requirement of government intervention scenario (LSAI), were discussed. Now we seek to know how government promotes farmers to adopt modern irrigation technology. For instance, we will investigate what happens if the government promotes that all the farmers adopt one type of modern irrigation technology in the whole irrigation area. Will this be associated with an improvement or a worsening of the social welfare and water resource allocation and how does it affect the water use efficiency? These questions are investigated in the current government promoted scenario (LSFI). To be explicit, the current scenario LSFI investigates the impacts on social welfare and water resource allocation if the private investment is exogenous over all locations. The recharge rate is still at 0.3, public investment is still endogenous, and importantly private investment is assumed to hold constant at 100 Yuan/Mu exogenously. This implies that the type of locally produced water saving technology is applied over all locations. Will this turn out to be more optimal than in the nearly real situation scenario (LSDI)? The model no longer internally determines the different private investments, i.e., no varied irrigation technologies.

9.2.4.1 Impacts on aggregate indicators

Table 9.6 compares the aggregate impacts on social welfare and water resource allocation between scenario LSFI and scenario LSDI. The only difference

Table 9.6:   **Comparison of indicators at aggregate level between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)**

Items	LSFI	LSDI	%
Social welfare (Yuan)	288,074.95	1,096,337.38	-73.72
Total canal water consumption (m^3)	257,879.17	299,998.47	-14.04
Total groundwater consumption (m^3)	9,801.02	46,635.30	-78.98
Total water consumption (m^3)	267,680.19	346,633.77	-22.78
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	-33,319.81	45,633.77	-173.02
Total public investment (Yuan)	2,163.23	2,579.31	-16.13
Switch point (Location)	176.00	174.00	1.15
Canal water length (m)	8,750.00	8,700.00	0.57
Area irrigated by canal water (Mu)	2,625.00	2,602.20	0.88
Area irrigated by groundwater (Mu)	375.00	397.80	-5.73
Total private investment (Yuan)	300,000.00	138,470.08	116.65

Notes: The switch point in scenario LSFI is found at location 176, at which farmers start to take groundwater.

LSFI: It indicates government promoted scenario, which is run under low soil permeability, exogenous fixed private investment, c3 in an ascending order.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

between the two scenarios is the status of private investment, which is endogenous in scenario LSDI and however exogenously fixed at 100 Yuan/Mu in scenario LSFI. The social welfare drops to an ever-lowest level of 288,074.95 Yuan over the whole area, a decrease by 73.72% compared to scenario LSDI due to the heavy expenditure of fixed private investment over all locations. The total canal water consumption reaches 257,879 m^3, which is a decrease of 14.04% compared to that in scenario LSDI. Additionally, the total groundwater consumption falls dramatically by 78.98% in comparison to scenario LSDI, mainly due to lower water losses from the canal and the fields, imposed by the heavy public and private investment in water saving. This is for the first time a model results, where still 28,004 m^3 of water are left in the groundwater stock at the last location. In comparison to all the previous cases, which have been reported, always a zero groundwater remains at the last location. High investment saves much water. For the first time the aquifer is protected. The result indicates a huge positive effect of water saving, which is connected with the scenario; though it of course creates a huge expenditure. The private investment is observed to reach as high as 300,000 Yuan in total, with a growth of 116.5% compared to the investment in scenario LSDI. The public investment, however, reaches only 2163 Yuan in total, which means a drop of 16.13% as compared to scenario LSDI. Due to the substitution relationship between the two investment activities, the

government saves money. The area irrigated by canal water and the canal water length is extended slightly, though public investment is reduced significantly. The benefits from broadly adopted modern irrigation technology, save water in farmers' field and hence leave it more available in the canal. Consequently the switch point of the area is at location 176, on which farmers start to take groundwater. The canal water length is reported to reach 8750 m, which is 50m more than that in scenario LSDI, in line with a slight increase of 0.88% of the area irrigated by the canal. Table 9.5 demonstrates that if private investment is heavily undertaken, the public investment could be reduced correspondingly without affecting much the aggregated water use efficiency over the project area. This result suggests, as regards the effects of water saving, the public and private investment are complementary to each other. Both will do good to improve water efficiency. As regards absolute costs, they show a substitutional relationship. That is, one increasing will result in another one's decreasing.

9.2.4.2 Impacts on social economy and water resource allocation at farm level

Table 9.7 further explores the impacts on different variables undertaking a mean analysis. The average water demand is 89.23 m^3/Mu for AU in the current scenario, as compared to a consumption of 115.54m^3/Mu water in scenario LSDI, which is a decrease by 22.78%. For CWU, the water demand is reduced, with a drop of 14.79% as compared to scenario LSDI. The most significant change of unit water consumption is observed in GWU, with a decrease of 77.71% as compared to scenario LSDI. Since it is now supposed that all farmers over locations will invest 100 Yuan for a certain type of technology, the number of MTU is actually the same as that of AU in the current scenario. Thanks to the heavy flat private investment in irrigation technology over all locations, the unit water consumption for MTU in the current scenario is 15.12% lower than that in scenario LSDI, in which the varied technologies are distributed at different locations.

Note further, the revenue of all water user categories decreases sharply as compared to that in scenario LSDI. In particular for GWU, unit revenue shows the biggest drop of 63.53% compared to scenario LSDI, due to huge decreases in water consumption. The slightest decrease of revenue is observed in CWU with a fall of 7.44%, only. The land rent too goes down, with a decrease of 28.45% for AU as compared to scenario LSDI. The deepest fall of land rent is reported for GWU, with a drop of 90.34% as compared to scenario LSDI. There are even negative values of land rent at the last 5 locations. The unit water rent for AU falls

Table 9.7: Comparison of mean values of indicators at farm level between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)

Items	AU			CWU			GWU			MTU		
	LSDI	LSFI	%	LSDI	LSFI	%	LSDI	LSFI	%	LSDI	LSFI	%
Aggregate water demand(m³)	115.54	89.23	-22.78	115.29	98.24	-14.79	117.23	26.14	-77.71	105.13	89.23	-15.12
Revenue (Yuan)	435.53	371.92	-14.60	434.23	401.92	-7.44	444.02	161.95	-63.53	410.63	371.92	-9.43
Land rent (Yuan)	295.67	211.54	-28.45	296.15	237.72	-19.73	292.49	28.24	-90.34	258.63	211.54	-18.21
Water rent (Yuan)	92.85	59.67	-35.74	83.88	63.37	-24.44	151.53	33.71	-77.75	47.28	59.67	26.19
Private investment (Yuan)	46.16	100.00	116.65	53.21	100.00	87.93	0.00	100.00	100.00	103.72	100.00	-3.59
On-farm water use efficiency	0.58	0.70	21.52	0.59	0.70	18.21	0.48	0.70	45.83	0.70	0.70	0.60
Public investment (Yuan/km)				298.19	265.43	-10.99	0.00	0.00	0.00	298.19	265.43	-10.99
Water conveyance loss rate				0.00	0.02		0.07	0.07	0.00	0.00	0.02	

Notes: LSFI: It indicates government promoted scenario, which is run under low soil permeability, exogenous fixed private investment, c3 in an ascending order.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

with a drop of 35.74%. The biggest drop of 77.75% of water rent is observed for groundwater users due to lower water consumption. A positive growth of water rent on average is observed for MTU, with a rate of 26.19% more than in scenario LSDI. The reason is that in the current scenario MTU and AU are overlapping each other, so that it covers 200 users. However the MTU, in scenario LSDI, cover only 89 users and all of them have access to cheap canal water. Strongly influenced by the high groundwater price, the water rent for MTU in the current scenario turns out to be higher than that in scenario LSDI.

The private investment in unit is observed to be increasing over all categories except a tiny decrease of 3.59% for MTU, as compared to scenario LSDI. The reason is that farmers have chosen the various technologies internally in scenario LSDI, and some of them went for a more advanced technology. That did not fix their choice at the level of 100 Yuan. In line with the heavy investment in irrigation technology, on-farm water use efficiency is improved from 0.58 to 0.70 over the whole irrigation area. A significant improvement from 0.48 to 0.71 is shown for GWU, with a considerable increase of 45.83%. Public investment for CWU shows a decrease of 10.99 %, in line with a slight water loss rate of 0.02 reported in CWU and MTU as compared to a zero loss rate in scenario LSDI.

9.2.4.3 Illustration of movement and relationships between some key indicators at spatial level

After the relevant variables have been discussed by doing mean analysis, we will next employ some diagrams to investigate them spatially. The first question is how unit revenue is affected. Figure 9.12 compares the move of unit revenue between the current scenario LSFI and scenario LSDI. The diagram clearly shows that the curve of revenue for AU in scenario LSFI is pretty plain before it reaches the downstream area due to the slow change of canal water consumption and a constant expenditure on irrigation techniques. It goes downward sharply after farmers switch to groundwater. Particularly at the upper area of the canal the revenue is higher than in scenario LSDI. Later, it keeps staying below the curve in scenario LSDI till the end of area. More precisely, it is at location 47, that the revenue in scenario LSDI exceeds that in the current scenario. At location 47, where the revenue in scenario LSDI reaches 419.36 Yuan/Mu compared to 418.77Yuan/Mu in the current scenario. The reason is that farmers have undertaken the heaviest investment at the upper area in scenario LSDI as compared to a moderate fixed investment of 100 Yuan in scenario LSFI. The high investment made in scenario LSDI lowers revenue deeply at the upper area of canal (before location 47). Due to a continuously rising water price, however, the revenue in scenario LSFI falls gradually. Close to the switch point (location 176),
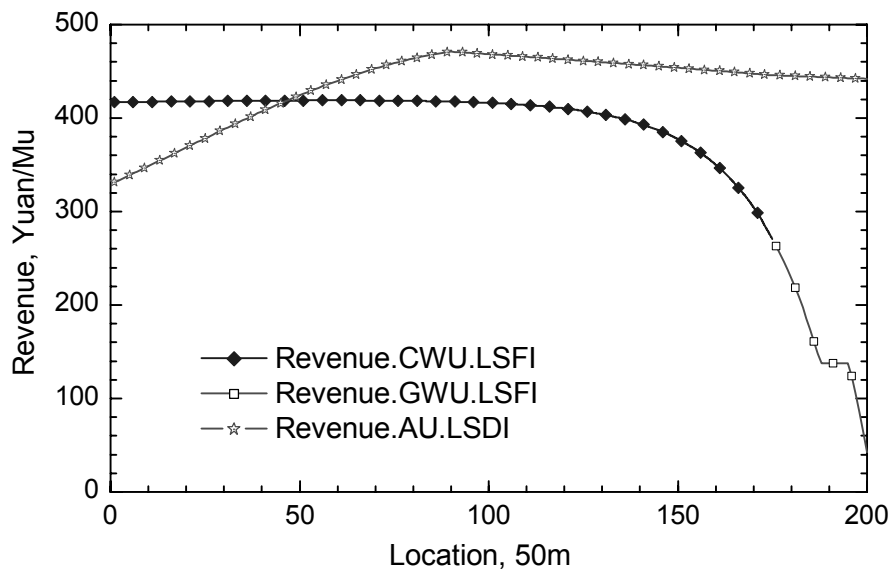
Figure 9.12: Comparison of revenue between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)
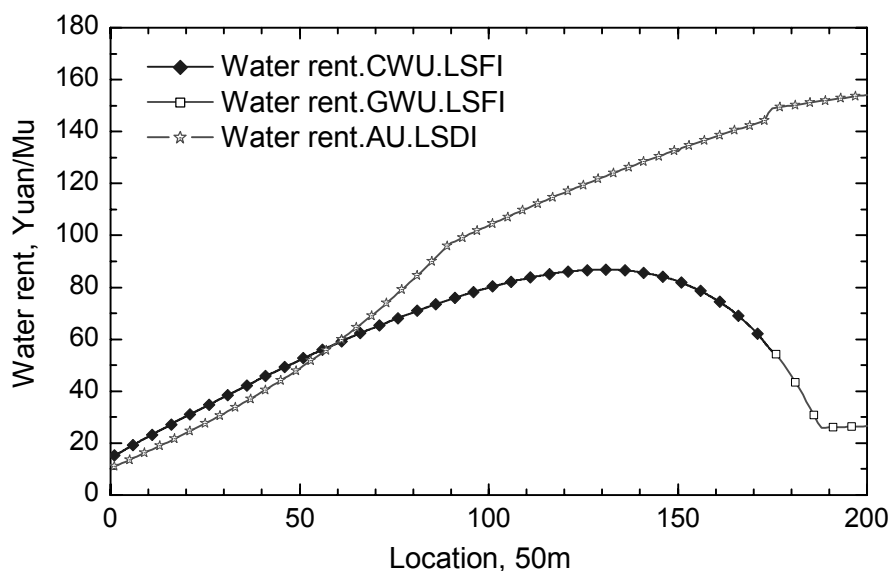
Figure 9.13: Comparison of water rent between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)

where farmers switch to groundwater, the revenue falls very quickly. Farmers situated at the tail area suffer not only from a high groundwater price, but also from the expensive fixed investment in irrigation technology. Consequently an almost vertical drop of revenue after groundwater extraction is observed.

Figure 9.13 describes the tendency of water rent in the two different scenarios. It shows, in scenario LSFI, that the water rent slowly goes up with the distance getting farther. It also implies that the water price is increasing with the distance. Thanks to the adoption of the same irrigation technology on each location, the

water consumption within CWU shows only a slight difference. The tendency of the water rent, hence, follows the track of a continuously rising water price within CWU. It increases firstly due to the rising price and negligible change of water consumption volume, and then falls dramatically due to a largely reduced groundwater consumption, which is contributed by application of water saving technology. This happens, though a higher groundwater price is suggested in this area. The water rent, however, in scenario LSDI shows an ever-up tendency compared to the downward trend in scenario LSFI, since merely 89 farmers at the upper area apply water saving technology. The rest of farmers still applies traditional irrigation techniques. That is why considerable groundwater consumption can be observed at the tail of the irrigation area in scenario LSDI.

Let us turn now to land rents. Figure 9.14 describes the situation of land rents in the current scenario LSFI and scenario LSDI. The curve of land rents in scenario LSFI moves similar as that of revenue in this scenario. Based on the same expenditure on irrigation technology, the decisive indicators for the land rent at different locations are actually the revenue and the water costs. The upper canal area has access to cheap and to abundant water, so it possesses the lowest water costs and highest revenue. Consequently the highest land rent is observed in this area. With the water price increasing, the land rent decreases with the distance. Due to the heavy burden of the adoption of modern irrigation technology, the land rent becomes negative at the last 5 locations. This suggests, that it would be no longer profitable to do any production at the tail area of the canal in this case, except that investments are subsidized.

For comparison, the land rent in scenario LSDI developed somewhat differently. In scenario LSDI, the lowest land rent is reported at the water source due to the high investment in irrigation technology there. The peak of the land rent is reached at location 90, where the private investment becomes 0. Finally, on average, thanks to the heavy expenditure in irrigation technology, the average land rent in scenario LSFI is 28.45% lower than that in scenario LSDI.

Now we come to public investment that is endogenous in the current scenario LSFI. Figure 9.15 compares the public investment undertaken in scenario LSFI and scenario LSDI. It shows that public investment in scenario LSDI keeps a constant level of 297.27 Yuan/km with the exception of one single sky-high observation of 474.16 Yuan/km reported at location 150. This kind of level of investment indicates a quasi-piped canal, which is suggested until location 173. As described already, the water can flow in the canal till location 174. However, in scenario LSFI, the model proposes a constant public investment level of 297.27 Yuan/km, but this is only undertaken till location 92. After location 92, the public
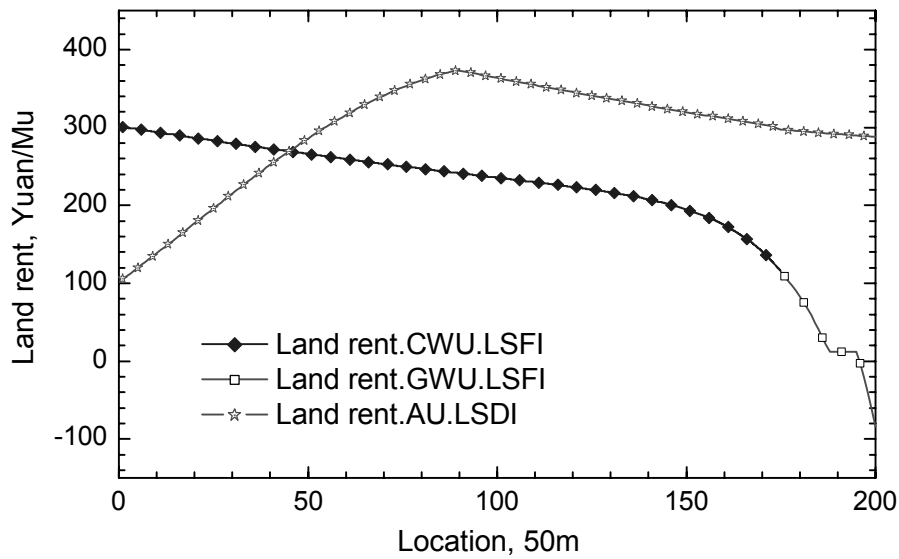
Figure 9.14: Comparison of land rent between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)
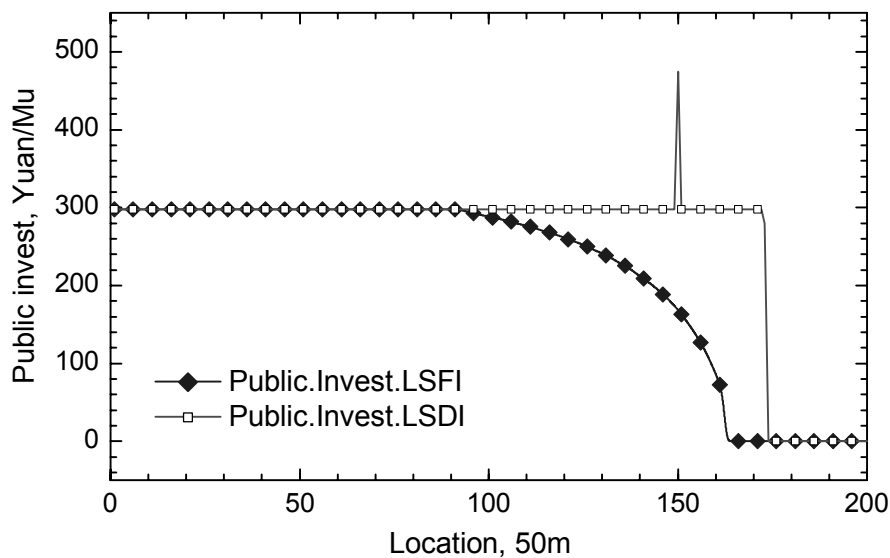
Figure 9.15: Comparison of public investment between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)

investment reduces gradually and finally it stops completely after location 163. Even in this case, the water can still flow in the canal till location 175. The main reason for this is that a relatively heavy private investment in water saving technology is made over all locations and offtakes public investment. So more water is left in the canal despite the fact that the loss rate of the water conveyance system increases slightly due to a decrease of public investment.

As happens in previous scenarios, the canal water is normally used up at the location next to the end point of public investment. For instance, in scenario LSDI, the canal water ends at location 174, and the public investment ends at
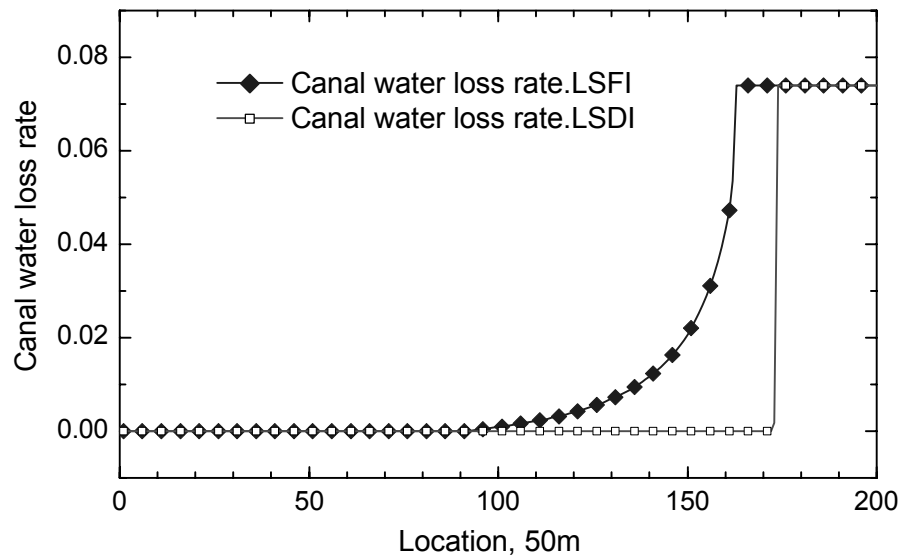
Figure 9.16: **Comparison of water conveyance efficiency between government promoted scenario (LSFI) and nearly real situation scenario (LSDI)**

location 173. But in the current scenario LSFI, this is different. The public investment ends at location 163, and the canal water still flows till location 175. These tendencies can be assigned to the combined relationship between private and public investments. Both investments are substitutes in this case, since the increase of one can balance the decrease of the other. As indicated in scenario LSFI, private investment is undertaken heavily, with an average of 100-Yuan/Mu over all locations, and consequently the pubic investment is reduced as compared to scenario LSDI. Finally this does not affect the water supply system too much. Thanks to the considerable adoption of water saving technologies, farmers get sufficient water. Canal water flows till location 175, even one location more than in scenario LSDI. But we see a drop of public investment by 10.99% as compared to scenario LSDI. This indicates, that heavy private investment can, at a certain level, offset the effects of falling public expenditures.

Further more, a constant public investment results in constant water use efficiency in the conveyance system. As shown in Figure 9.16, in scenario LSDI, the water loss rate is kept at 0 before it reaches location 174, and is kept at 0.07 of the base loss rate after location 174. This indicates that a quasi-piped canal with the same quality is required before location 174 in this scenario. However in the current scenario LSFI, the canal water loss rate at the beginning is kept at 0 before it reaches location 92. It then increases after location 92 due to a gradual decrease of public investment, and is kept at 0.07 of the base water loss rate after location 163. This varied water loss rate suggests that a well-managed canal exists at the upper canal area, and then it deteriorates due to poor lining and maintenance at the downstream area. Notice finally it is abandoned to operate at all.

Such a performance of public investment in scenario LSFI suggests that: If private investment is kept heavy and constant over all locations exogenously, public investment will vary and decrease gradually rather than keeping at a constant level, as happened in scenario LSFI. Moreover the decreased public investment will not reduce the social welfare much, thanks to the substitutional function of private investment. As proved already in previous scenarios, public investment always plays a positive role in the water saving activity and improves the social welfare. Private investment is also a very important factor to influence the social welfare and water resource allocation. The participations of private investment not only can ease the burden of public expenditure, but also improve the water use efficiency considerably due to incentives from individual farmers. Such a complementary relationship between private and public investment is very essential for managing an irrigation project.

9.2.4.4 Concluding remarks of government promoted scenario

After analyzing and comparing the government promoted scenario (LSFI) and the nearly real situation scenario (LSDI), the following conclusion can be drawn: For the whole irrigation area the impacts on social welfare are negative if a relative strong and fixed water saving irrigation technology is adopted over all locations. Revenue, land rent and water rent will decrease in comparison to a system with a varied irrigation technology. However, the effect of water saving in the irrigation area is significant due to the considerable contribution of water saving technology and well-managed canal system. But the investment requirements are heavy and might be shouldered by the poor. The model results indicate that the optimal solution still might be to adopt different technologies at different locations rather than going for one kind of technology. This would not only reduce total costs, but also ensure social welfare and water use efficiency.

9.2.5 A removal of public investment with private investment participation scenario under low soil permeability

The previous three scenarios focused on investigating the different impacts on the social economy and water resource allocation caused by altering the distribution of irrigation technology over the irrigation area. In other words, the analysis has stressed the role of private investment in water saving activities. As discussed already in those public investment policy scenarios (see chapter 8), public investment always plays a positive role in maximizing social welfare. But the limitation of the previous public investment policy scenarios is that no private investment is undertaken while public investment was being made. Now the

questions could be: How much will such a removal influence social welfare and water resource allocation? Further, how much will it influence the private investment? The removal of public investment with private investment participation scenario under low soil permeability (LSRK2) will analyze the above-mentioned questions. The groundwater recharge rate is still held at 0.3, and public investment is fixed at 0 exogenously.

9.2.5.1 Impacts on aggregate indicators

Table 9.8 investigates the impacts of a removal of public investment on social welfare and water resource allocation with private investment participation under low soil permeability, and it compares the results with scenario LSDI, which is with endogenous public investment. It clearly shows that the overall social welfare is decreasing with a drop of 39.43% compared to that in scenario LSDI. The total canal water consumption declines sharply by 83.36% due to a large amount of water lost from the canal system. This occurs in line with a rapid increase of groundwater consumption by 92.5% as compared to that in scenario LSDI. The total water consumption reaches 139,684.85 m^3, which is 59.7% lower than in scenario LSDI. This means a net water waste of 161,315.15 m^3 in scenario LSRK2, as compared to a net gain of 45,633.77m^3 water in scenario LSDI. As a consequence of public investment, if this is removed, the canal water end point emerges as early as at location 42, compared to location 174 in scenario LSDI. It too shows that the length of canal water shortens by 75.86%, and the area irrigated by canal water shrinks sharply by 75.92%. Indicators, such as the groundwater consumption, the area irrigated by groundwater and the private investment, increase significantly as compared to those in scenario LSDI. Due to huge water losses from the water conveyance system, canal water is used up very quickly. Farmers have to start to pump groundwater from location 42. Therefore the area irrigated by groundwater increases by 496%, however the groundwater consumption shows only a moderate increase of 92.51% compared to the increase of area irrigated. This indicates that the entire system is short of water; as there is only 30% of water that goes down to recharge the aquifer. As a major consequence, the removal of public investment results in huge water losses and water shortage over the entire irrigation system. This drives farmers to adopt modern irrigation technologies to use the water available more efficiently. The total private investment in irrigation technology shows an increase of 54.88% as compared to that in scenario LSDI. This indicates, that very high efforts in private investment are required, if no public investment is undertaken in water saving activities.

Table 9.8:   Comparison of indicators at aggregate level between scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2) and nearly real situation scenario (LSDI)

Items	LSRK2	LSDI	%
Social welfare (Yuan)	664,009.66	1,096,337.38	-39.43
Total canal water consumption (m^3)	49,907.62	299,998.47	-83.36
Total groundwater consumption (m^3)	89,777.24	46,635.30	92.51
Total water consumption (m^3)	139,684.85	346,633.77	-59.70
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	-161,315.15	45,633.77	-453.50
Total public investment (Yuan)	0.00	2,579.31	
Switch point (Location)	42.00	174.00	-75.86
Canal water length (m)	2,100.00	8,700.00	-75.86
Area irrigated by canal water (Mu)	626.70	2,602.20	-75.92
Area irrigated by groundwater (Mu)	2,373.30	397.80	496.61
Total private investment (Yuan)	214,455.86	138,470.08	54.88

Notes: The switch point in scenario LSRK2 is at location 42, on which cw_{42}=38.34, gw_{42}=11.02. Area irrigated by canal water is therefore calculated based on the ratio of canal water of 0.78, however, of groundwater of 0.22.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

LSRK2: It indicates the scenario of a removal of public investment with private investment participation under low soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

9.2.5.2 Impacts on social economy and water resource allocation at farm level

Table 9.9 studies further the impacts on the level of individual variables given average unit level and compares them with scenario LSDI. The average unit water demand for all farmers reaches 45.56 m^3/Mu, which is a decrease by 59.7% as compared to scenario LSDI. This shows additionally that water consumption decreases by 30.92% and 67.73% for CWU and GWU, 40.92% and 74% for MTU and TTU, respectively, again as compared to those in scenario LSDI. A comparison between different farmer categories within the current scenario LSRK2 also shows, CWU still consume the highest amount of water, with a volume of 79.64 m^3, and TTU consume the least amount of water, with a volume of 32.21 m^3. The reason is that TTU are all located distant from the water source; they suffer water shortage instead of saving water.

The biggest revenue decrease is observed in TTU, with a drop of 63.55 % as compared to scenario LSDI. The second largest drop is reported in GWU, with a decrease of 53.63%, since TTU and GWU overlap each other. Both suffer water shortage; moreover both have to afford the high groundwater price due to their

Table 9.9: **Comparison of mean values of indicators at farm level between scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2) and nearly real situation scenario (LSDI)**

Items	AU			CWU			GWU			MTU			TTU		
	LSDI	LSRK2	%	LSDI	LSRK2	%	LSDI	LSRK2	%	LSDI	LSRK2	%	LSDI	LSRK2	%
Aggregate water demand(m^3)	115.54	46.56	-59.70	115.29	79.64	-30.92	117.23	37.83	-67.73	105.13	62.11	-40.92	123.90	32.21	-74.00
Revenue(Yuan)	435.53	237.94	-45.37	434.23	359.25	-17.27	444.02	205.91	-53.63	410.63	315.86	-23.08	455.49	166.02	-63.55
Land rent (Yuan)	295.67	131.57	-55.50	296.15	165.56	-44.10	292.49	122.60	-58.08	258.63	134.61	-47.95	325.36	128.77	-60.42
Water rent (Yuan)	92.85	34.88	-62.43	83.88	21.02	-74.94	151.53	38.54	-74.56	47.28	32.33	-31.64	129.38	37.24	-71.21
Private investment (Yuan)	46.16	71.49	54.88	53.21	172.67	224.49	0.00	44.77		103.72	148.93	43.58	0.00	0.00	0.00
On-farm water use efficiency	0.58	0.62	8.00	0.59	0.82	38.18	0.48	0.57	18.81	0.70	0.78	11.53	0.48	0.48	0.00
Public investment (Yuan/km)	298.19	0.00	-100.00	298.19	0.00	-100.00	0.00	0.00	0.00	298.19	0.00	-100.00	298.19	0.00	-100.00
Water conveyance loss rate	0.00	0.07	0.07	0.07	0.07	0.00	0.00	0.07	0.07	0.00	0.07	0.07	0.07	0.07	0.00

Notes: The number of MTU is observed 96 in scenario LSRK2, and that of TTU is 104; in previous scenario LSDI, it is reported that the number of MTU is 89, and of TTU is 111.

LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

LSRK2: It indicates the scenario of a removal of public investment with private investment participation under low soil permeability, endogenous private investment, c3 in an ascending order.

less-favored geographical position. That is why they loose much in revenue. The smallest revenue loss is shown in CWU, with a decrease of 17.37% compared to scenario LSDI. The CWU in the current scenario LSRK2 contains only 42 farmers. These farmers still benefit from their location, i.e., where there is access to convenient canal water.

Land rents follow the same story, and decline in all user categories. Especially the land rent of TTU shows the biggest decrease of all categories, i.e., 60.42%, as compared to scenario LSDI. The water rent of CWU shows a decrease of 74.94%. This is the biggest decrease among all the categories. There are two main reasons for this: One is, that not enough water is available in the canal. The other is that all CWU are also MTU in this case, so they actively save water by using modern irrigation technology. These two reasons together reduce canal water consumption and hence lower the water rent so much for CWU in scenario LSRK2. Private investment shows significant increases, i.e., 54.88% for AU, 224.49% for CWU and 43.58% for MTU, as compared to scenario LSDI. Especially an average unit investment of 44.77 Yuan/Mu is undertaken for GWU as compared to zero investment in scenario LSDI. This indicates that water shortage is the main incentive for farmers to adopt water saving technology. Note that public investment is removed in current scenario, so that a base loss rate of 0.07 is observed over the whole area.

9.2.5.3 Illustration of movement and relationships between some key indicators at spatial level

Finally several figures will be given to describe the relationship among different indicators spatially. Figure 9.17 investigates the relationship between revenue and investment based on farmer category CWU and GWU. As shown in Figure 9.17, the highest revenue occurs at the water source due to the relative sufficient water availability. Farmers start to adopt modern irrigation technology from the water source, but the highest level of irrigation technology appears not at the water source. With the distance getting bigger (water price getting higher), we observe an increase of private investment. Hence, the revenue goes down gradually till location 42. This location can be called a first switch point in the current scenario LSRK2. Here exactly the private investment reaches its peak and the canal water is used up. After location 42, the water price becomes higher than at previous locations, due to the start of groundwater use. Farmers gradually reduce their costly investment in irrigation technology; and this results in an up-going curve of revenue for a certain area. Later revenue drops again due to the high groundwater price, and farmers eventually give up applying any water saving technology after location 96. This can be considered as a second switch point after which

Figure 9.17: Illustration of relationship between revenue and private investment for CWU and GWU in scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2)
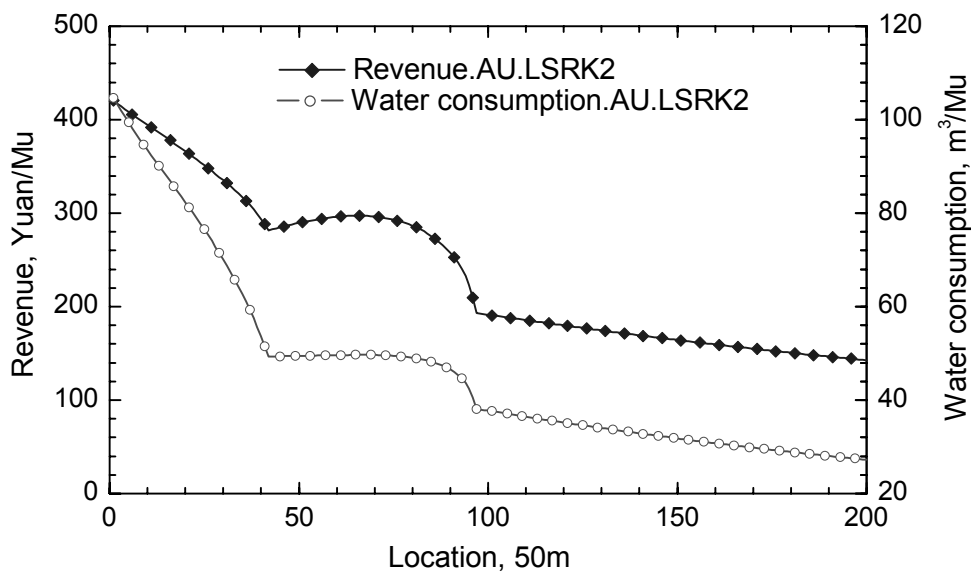
Figure 9.18: Illustration of relationship between water consumption and revenue in scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2)

farmers stop to invest in irrigation technology and the curve of revenue becomes pretty plain.

What the diagram is telling us is, that private investment performs well and efficient when water is becoming scarce. In such a situation farmers will adopt modern technology, in particular more likely as compared to a situation of abundant water. Moreover by adopting modern technology MTU farmers can
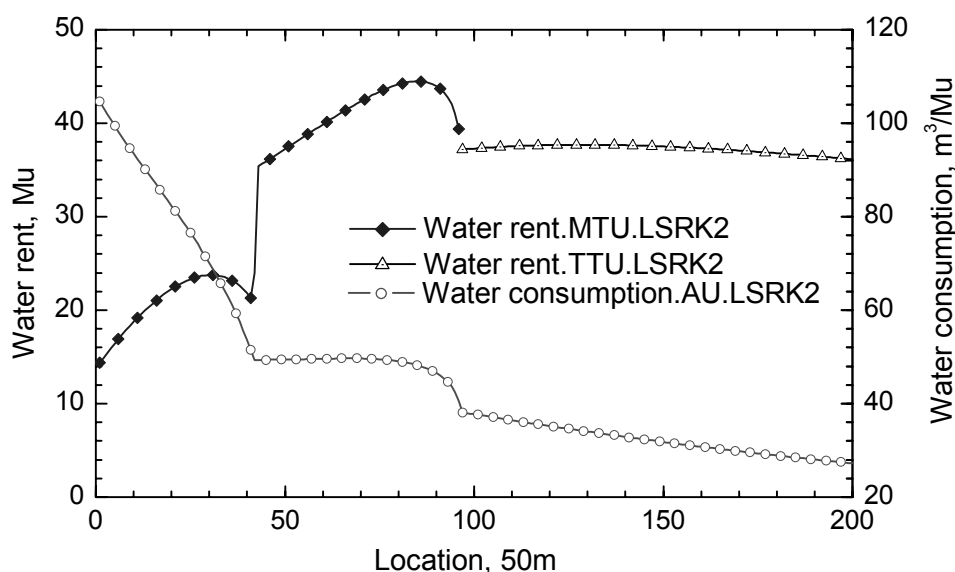
Figure 9.19: Illustration of relationship between water rent and water consumption for MTU and TTU in scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2)

make a better return as compared to TTU farmers, if they can afford the high costs for the technology.

For further discussion, two factors strongly influence the revenue in the present study. One is private investment in irrigation technology, which has been investigated so far, and the other is water consumption. Figure 9.18 describes the relationship between revenue and water consumption. It shows that the highest revenue occurs at the place of highest water abundance, where exactly the water consumption takes place. Figure 9.18 demonstrates that the development of revenue is closely tied to water consumption, especially in such a situation of severity of water shortage. The more water is available, the higher the revenue will be.

Figures 9.19 illustrate the relationship between water rent and water consumption (based on categories MTU and TTU). In Figure 9.19, it comes out clearly again that the water rent increases with the distance becoming larger. The highest water consumption occurs at the first location, but the lowest water rent is also found at the same position. This indicates that the water price at the water source area is very low. Before location 42, which is the area dominated by canal water in scenario LSRK2, the water rent increases slowly thanks to the low canal water price. After location 42, where the groundwater use starts, a sharp up-jump of the water rent is observed. This demonstrates that a higher groundwater price results in a big gap of water rent between CWU and GWU farmers. Water rent keeps increasing further after farmers switch to groundwater. At location 85, the highest water rent of 44.49 Yuan/Mu is reported. Afterwards, the water rent goes down
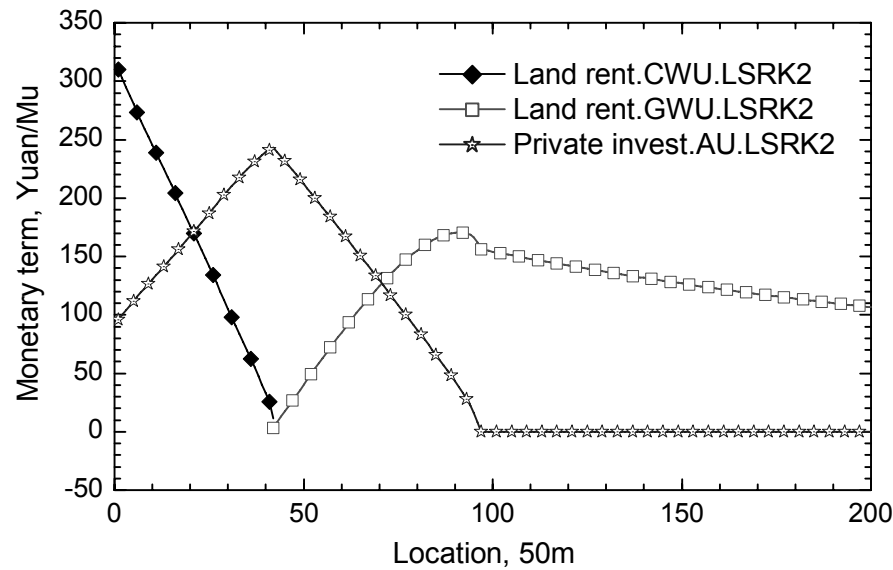
Figure 9.20: Illustration of relationship between land rent and private investment for CWU and GWU in scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2)

until to the end of the project area. Note, normally the groundwater price changes slowly and smoothly over space compared to the canal water price. It therefore creates a relatively flat groundwater consumption and water rent, as shown in both curves of water rent after location 96. Before reaching the location 96, the water consumption and the water rent, are fluctuating dramatically due to the varied irrigation technologies being applied.

The land rent is also an important concept to be investigated. Figure 9.20 illustrates the relationship between the land rent and private investments. As mentioned already, the land rent is related mainly to water costs and private investment in the current study. Since water costs are relatively small compared to the expensive investments in irrigation technology, the figure investigates how the land rent is influenced by private investment. As shown in Figure 9.20, the highest land rent naturally is observed at the water source, where private investment starts from a relatively low level. The land rent decreases gradually with private investment increasing over space. At location 42, the private investment reaches its peak of 242.91 Yuan/Mu. This suggests that kinds of sprinkler or drip irrigation techniques are adopted at this point, which is an important result. Model results also show that the location 42 is a switch point of CWU and GWU, where the canal water is used up, and small parts of groundwater are taken as a complement (a share of 22% of total water consumption at this location). However, at the next location 43, the lowest land rent of 8.17 Yuan is observed, since the farmers have to switch to expensive groundwater completely while expenditure on irrigation
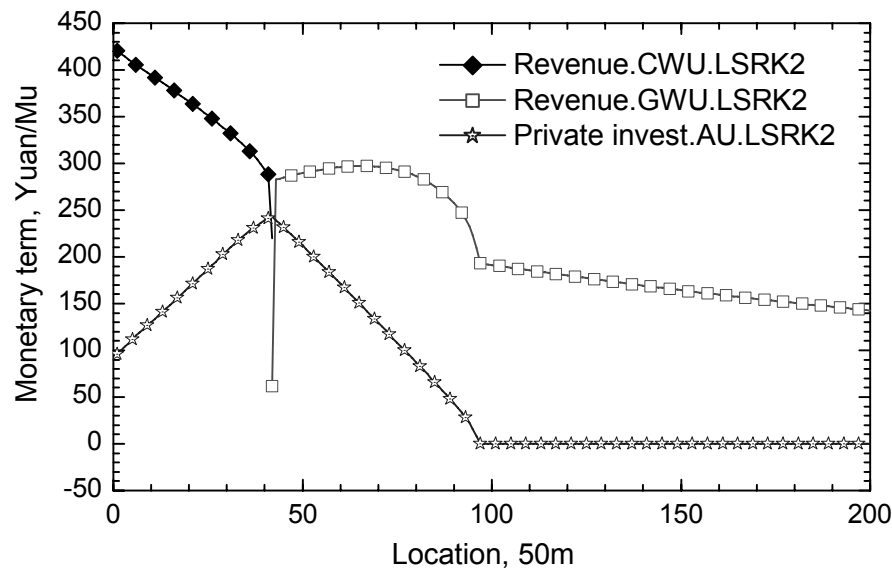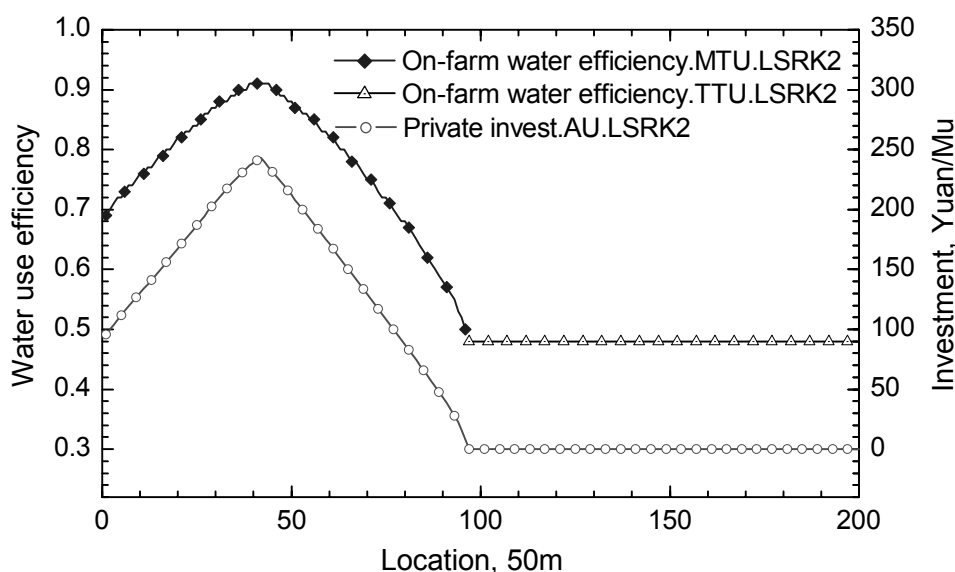
Figure 9.21: Illustration of relationship between private investment and water use efficiency in scenario of a removal of public investment with private investment participation under low soil permeability (LSRK2)

technology remains very high. After location 42, farmers reduce private investment gradually, and the land rent starts to rise again within GWU. It reaches the second biggest amount of 170.63 Yuan/Mu at location 91, where probably the water price is not very high as compared to the latter locations and private investment is also almost close to zero. After the peak of location 91, private investment stops soon at location 96. Afterwards land rent decreases smoothly over distance.

Since water use efficiency is a prime concern, we document it in Figure 9.21. The diagram shows that on-farm water use efficiency increases with investment getting higher. It reaches its peak rate of 0.91 at location 39 to 44, in line with the investment ranging from 236.61 to 235.39 Yuan/Mu. This indicates that farmers situated within these 6 locations adopt kinds of modern irrigation technologies i.e., sprinkler and seepage irrigation (the type of locally produced drip irrigation technique). After the peak area, investment decreases, and hence the water use efficiency drops until 0.50 at location 96, after which no farmer will invest in irrigation technology. A flat base rate of 0.48 of water use efficiency is reported for TTU from location 97 till the end of area.

9.2.5.4 Concluding remarks of scenario of a removal of public investment with private investment participation under low soil permeability

One decisive conclusion can be drawn from the above analysis: The overall social welfare and water allocation decreases if public investment is removed. The whole irrigation area suffers from water shortage. Consequently the revenue, the

land rent, and the water rent decreases sharply due to insufficient water supply in the system as compared to the nearly real situation scenario (LSDI). A notable change is that private investment increases significantly compared to that in scenario LSDI. This indicates that more farmers adopt modern water saving technologies than in scenario LSDI due to water scarcity. The average on-farm water use efficiency is hence improved in the current scenario. However this scenario demonstrates again that water shortage will create the highest incentive for farmers to adopt modern irrigation technologies. It also indicates that, if public investment falls short, private investment has to bridge the gap.

9.2.6 A removal of public investment with private investment participation scenario under high soil permeability

All the previous scenarios were analyzed under a soil condition of moderate permeability, i.e., the recharge rate was fixed at 0.3. To make the model broadly applicable, as it was exercised in the public investment policy scenarios, a higher recharge rate for groundwater will be tested in the following scenarios. The previous scenario LSRK2 has discussed the comprehensive negative impacts on social welfare and water resource allocation when public investment is removed from the irrigation system under a recharge rate at 0.3. What will happen if soil conditions change? Will the social welfare decline and water resource allocation worsen under higher soil permeability? How does it affect allocation of private investment? These research questions will be discussed in the current scenario.

The current scenario of a removal of public investment with private investment participation under high soil permeability (HSRK2) assumes that other conditions remain equal in comparison to scenario LSRK2, i.e., the private investment is endogenous in the model and public investment is removed from the system. Public investment is held constant at 0 in the modeling process. Importantly the recharge rate is increased to 0.8.

9.2.6.1 Impacts on aggregate indicators

The overall impacts on social welfare and water resource allocation is investigated in Table 9.10. The social welfare is surprisingly preserved at 1,068,977.80 Yuan over the whole area, which is now 60.99% higher than in scenario LSRK2. The total canal water consumption also increases, with a growth of 29.82% as compared to scenario LSRK2. Considering groundwater, the growth of total groundwater consumption is significantly doubled, with an increase of 279.22% due to a higher recharge rate to groundwater as compared to scenario LSRK2. To sum up, the total water consumption over the irrigation area reaches

Table 9.10: **Comparison of indicators at aggregate level between scenarios of a removal of public investment with private investment participation under high soil permeability (HSRK2) and low soil permeability (LSRK2)**

Items	HSRK2	LSRK2	%
Social welfare (Yuan)	1,068,977.80	664,009.66	60.99
Total canal water consumption (m^3)	64,789.70	49,907.62	29.82
Total groundwater consumption (m^3)	340,457.07	89,777.24	279.22
Total water consumption (m^3)	405,246.76	139,684.85	190.12
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	104,246.76	-161,315.15	
Total public investment (Yuan)	0.00	0.00	0.00
Switch point (Location)	35.00	42.00	-16.67
Canal water length (m)	1,750.00	2,100.00	-16.67
Area irrigated by canal water (Mu)	520.61	626.70	-16.93
Area irrigated by groundwater (Mu)	2,479.39	2,373.30	4.47
Total private investment (Yuan)	68,257.55	214,455.86	-68.17

Notes: The switch point of scenario HSRK2 is observed at location 35, where the canal water and groundwater are co-used, and cw_{35}=78.39, gw_{35}= 32.42, respectively. All the related items of scenario HSRK2 are calculated based on the ratio of canal water and groundwater use, and they are 0.71 and 0.29 respectively.

HSRK2: It indicates the scenario of a removal of public investment with private investment participation under high soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

LSRK2: It indicates the scenario of a removal of public investment with private investment participation under low soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

405,246.76 m^3, which is an increase of 190.22% and almost the double water consumption shown in scenario LSRK2. This consequently produces a net gain of water use of 104,246.76 m^3, compared with a net loss of 161,315.15 in scenario LSRK2. The switch point is now at location 35, at which the canal water ends and the groundwater use starts. Already after location 35, canal water is no longer available. Farmers switch to groundwater completely. The canal length is suggested at 1750m, which is 350m shorter than that in scenario LSRK2. In line with canal water shortage, the area irrigated by canal water is reduced by 16.93%, and however the area irrigated by groundwater increased slightly by 4.47% respectively, as compared to scenario LSRK2. The total private investment is suggested to decline compared with scenario LSRK2, with a significant drop of 68.17%. Overall, the Table 9.9 indicates that, except private investment and canal water length, all the other indicators show a strongly positive impact compared to scenario LSRK2.

9.2.6.2 Impacts on social economy and water resource allocation at farm level

Table 9.11 investigates the impact of scenario HSRK2 on social economy and water allocation at the farm level, as based on different farmer categories and compares it with scenario LSRK2. All the indicators suggest that the water supply becomes sufficient thanks to a much higher recharge rate of groundwater in scenario HSRK2. As shown in the table, the average unit water demand for AU is suggested at 135.0 m^3/Mu, which is 1.9 times water demand in the previous scenario LSRK2. The biggest increase of unit water consumption is observed in TTU and GWU, with growths of 337.37% and 263% respectively compared to those in scenario LSRK2. In the current scenario HSRK2, the TTU are completely covered by GWU. That is why the two groups possess the highest increase among all the other categories.

The revenue increases over all as compared to scenario LSRK2, with a growth of 96.66%. The highest increase is observed in TTU and GWU, with rises of 188.92% and 130.09%, respectively, compared to those in scenario LSRK2. The reason is not only because farmers have access to abundant groundwater, but also that there is no need for them to invest in irrigation technology compared to their counterparts CWU and MTU. In scenario HSRK2, the number of CWU is 35, and that of MTU is 79, therefore the CWU overlaps with MTU completely since the water saving irrigation users are centered in the upper area in this case. As explained already, the revenue made by CWU farmers and MTU farmers increases, but with only limited growth of 22.54% and 42.48% respectively compared to their counterparts GWU and TTU.

The land rent increases largely, with an average growth of 143.96% over the whole area for AU, as compared to that in scenario LSRK2. The biggest increase of 159.22% is still reported in GWU, while the land rent in TTU ranks second. Surprisingly the land rent for MTU increases by 139.15%, ranking third. The average private investment in scenario HSRK2 is much lower than that in scenario LSRK2. This is mirrored by the land rent, which is calculated by deducting private investment and water costs from the revenue. That is why the land rent for MTU is suggested to increase significantly compared with that in scenario LSRK2.

The water rent, based on all categories, is reported to increase considerably. The average water rent for AU shows a growth of 256.08% compared to that in scenario LSRK2. The highest increase of water rent is observed for TTU, which increase by 327.65% compared to that of scenario LSRK2. GWU ranks second, with a growth of 272.85%. CWU shows the lowest increase of 49.24% compared

Table 9.11: Comparison of mean values of indicators at farm level between scenarios of a removal of public investment with private investment participation under high soil permeability (HSRK2) and low soil permeability (LSRK2)

Items	AU			CWU			GWU			MTU			TTU		
	HSRK2	LSRK2	%	HSRK2	LSRK2	%	HSRK2	LSRK2	%	HSRK2	LSRK2	%	HSRK2	LSRK2	%
Aggregate water demand(m³)	135.08	46.56	190.12	124.44	79.64	56.26	137.32	263.00	126.19	62.11	103.18	140.89	32.21	337.37	
Revenue(Yuan)	467.95	237.94	96.66	440.23	359.25	22.54	473.77	205.91	130.09	450.03	315.86	42.48	479.65	166.02	188.92
Land rent (Yuan)	320.98	131.57	143.96	336.12	165.56	103.03	317.81	122.60	159.22	321.92	134.61	139.15	320.37	128.77	148.79
Water rent (Yuan)	124.21	34.88	256.08	31.37	49.24	143.71	21.02	38.54	272.85	70.51	118.12	159.27	37.24	327.65	
Private investment (Yuan)	22.75	71.49	-68.17	72.73	172.67	-57.88	12.26	44.77	-72.62	57.60	148.93	-61.32	0.00	0.00	0.00
On-farm water use efficiency	0.53	0.62	-14.45	0.65	0.82	-21.08	0.51	0.57	-10.85	0.61	0.78	-21.11	0.48	0.48	0.00
Public investment (Yuan/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water conveyance loss rate	0.07	0.07	0.00	0.07	0.07	0.00	0.07	0.07	0.00	0.07	0.07	0.00	0.07	0.07	0.00

Notes: HSRK2: It indicates the scenario of a removal of public investment with private investment participation under high soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

LSRK2: It indicates the scenario of a removal of public investment with private investment participation under low soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

to the other categories, because they apply water saving technologies and therefore consume relatively less water.

A notable fact is that the average private investment decreases based on all categories. For AU, it is reduced by 68.17%. For CWU and GWU, it is reduced by 57.88% and 72.62%, respectively. Comparing the private investment for MTU in the two scenarios, there is a drop of 61.32% in the current scenario HSRK2. The falling of private investment suggests that farmers reduce to invest in water saving technology and downgrade the level of technologies employed thanks to the sufficient water supply. In line with the reduction of private investment, the on-farm water use efficiency decreases to 0.53, compared with an efficiency rate of 0.62 in scenario LSRK2. The deepest reduction of water use efficiency is reported for CWU: 0.65 against that of 0.82 in scenario HSRK2, a drop of 21.08%.

9.2.6.3 Illustration of movement and relationships between some key indicators at spatial level

Further, with the help of diagrams (Figure 9.22-9.27), the movement over distance and relationships between different indicators become visible. A comparison between different scenarios can be now more clearly presented. Figure 9.22 describes the relationships between revenue and private investment based on canal water users and groundwater users. It suggests that the connecting point between CWU and GWU becomes the key switch point for revenue in scenario HSRK2. As shown in Figure 9.22, before the switch point, i.e., until location 35, the average unit revenue declines gradually mainly due to an increase of private investment. After location 35, the revenue goes up while investment is going down, regardless whether farmers start to take the expensive groundwater. Figure 9.22 indicates, that private investment is the most important factor being able to influence farmer's revenue. The price gap between canal water and groundwater affects the revenue, too. As shown in Figure 9.22, as farmers still have access to cheap canal water, they can afford to increase investment in irrigation technology. After they switch to use groundwater, they have to go for the expensive groundwater and hence reduce their investment quickly. Till location 80 the investment in irrigation technologies drops to zero, and the revenue hits a peak of 487.28 Yuan/Mu. Finally after location 80, the revenue declines smoothly due to the relatively straight groundwater price and only tiny differences in groundwater consumption occur.

Figure 9.23 explores the relationship between revenue and water consumption in scenario HSRK2. It shows a similar track of both curves. Again, water
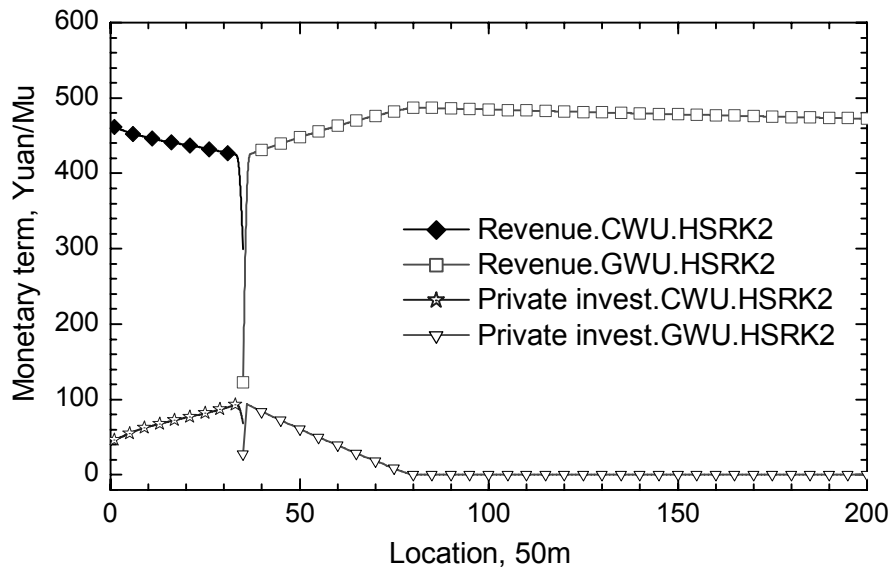
Figure 9.22: Illustration of relationship between revenue and private investment for CWU and GWU in scenario of a removal of public investment with private investment participation under high soil permeability (HSRK2)
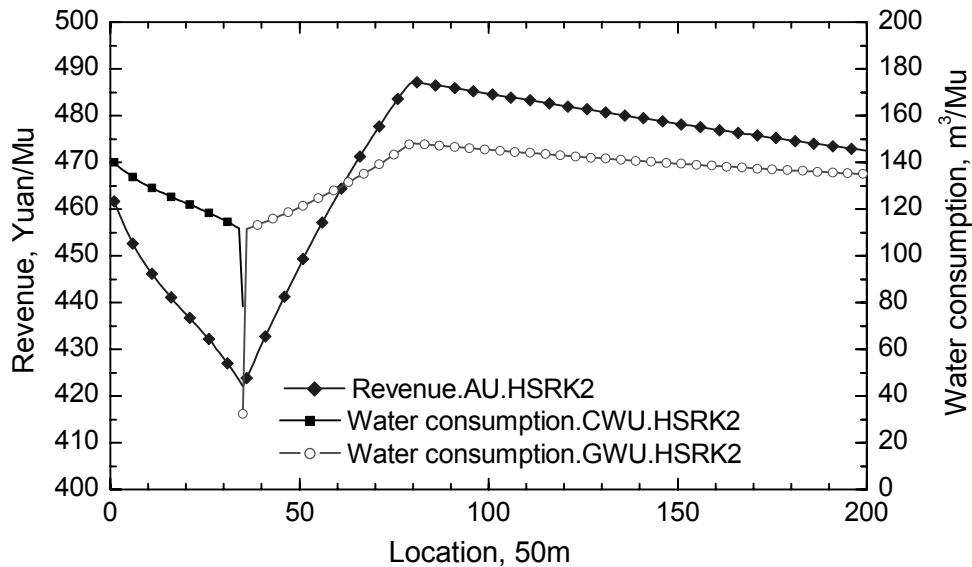
Figure 9.23: Illustration of relationship between revenue and water consumption in scenario of a removal of public investment with private investment participation under high soil permeability (HSRK2)

consumption is a very important indicator to measure revenue in an irrigation project. The more water is consumed, the higher the revenue will be. There exists a strong positive relationship between both as shown in Figure 9.23. The highest revenue of 487.28 Yuan /Mu is observed at location 80, from which the biggest volume of water consumption is reported. This corresponds with the definition of the revenue function, which was obtained by integrating an inverse water demand function.
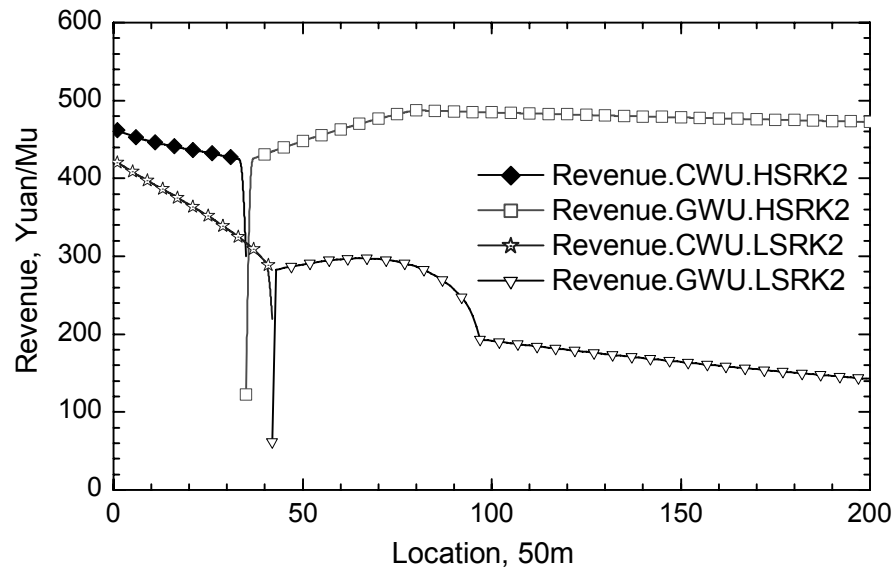
Figure 9.24: Comparison of revenue for CWU and GWU between scenarios of a removal of public investment with private investment participation under high soil permeability (HSRK2) and low soil permeability (LSRK2)

Figure 9.24 compares the revenue achieved by farmers in scenario HSRK2 and LSRK2. It obviously suggests that the revenue in scenario HSRK2 is higher than that in scenario LSRK2. Public investments are removed in both scenarios; the only difference is a recharge rate of groundwater. The different recharge rates result in different water supply capacities. In scenario LSRK2, the model results show that the whole irrigation area suffers from water shortage due to the huge water loss from the canal. And moreover, the low soil permeability prevents the underground aquifer from recharging. This explains, why the peak of revenue occurs at the water source instead of elsewhere in scenario LSRK2, as the biggest volume of water consumption is also observed there. However in scenario HSRK2 there is no water shortage at all. With a higher recharge rate, more canal water is lost than in scenario LSRK2, but the groundwater gets sufficiently recharged. Since canal water ends at location 35 in the current scenario HSRK2, more than 3/4 of the irrigation area is being controlled by groundwater. It is surprising to see that the consumption of groundwater in the current scenario HSRK2 is even higher than that of canal water. Moreover the CWU apply modern irrigation technologies and most GWU do not. That is why the peak of revenue in the current scenario HSRK2 occurs at location 80, at which water consumption hits its highest level and farmers also stop investing in irrigation technologies.
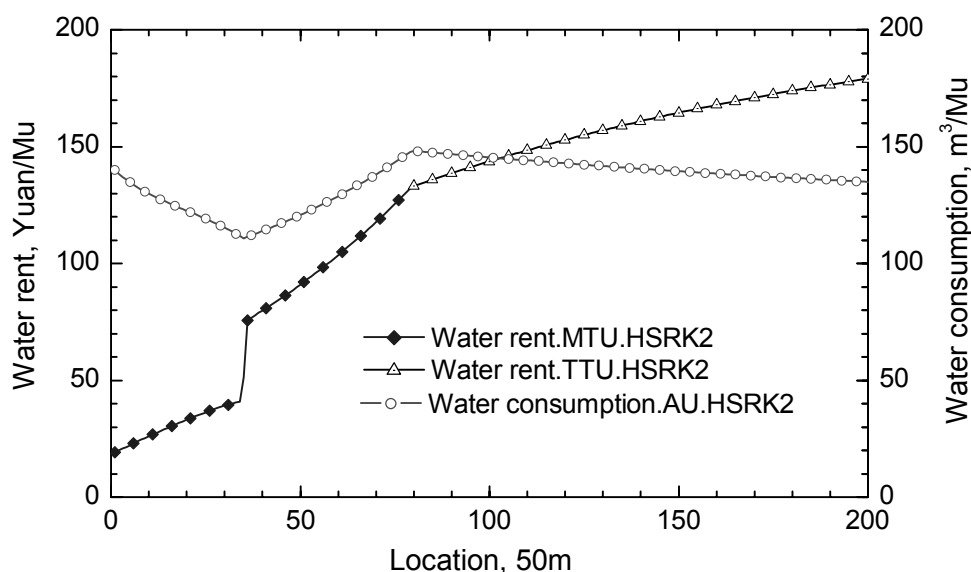
Figure 9.25: Illustration of relationship between water rent and water consumption for MTU and TTU in scenario of a removal of public investment with private investment participation under high soil permeability (HSRK2)

Figure 9.25 studies the relationship between water rent and water consumption based on categories MTU and TTU at different locations. Over all the water rent goes up with the distance. In the current scenario it is mainly influenced by water costs, as the public investment is zero. Figure 9.25 clearly suggests an up-jump of water rent at location 36, at which farmers switch to expensive groundwater completely. As suggested in the model, the highest investment is made at location 35, so the lowest water consumption among all locations is observed at this point. As shown in Figure 9.25, the highest water consumption is observed at location 80, at which farmers stop to invest in water saving technology completely. The up-going curve of water rent is relatively plainer compared with that before location 80, mainly due to the small difference of groundwater consumption after farmers stop investing in irrigation technologies. Naturally the increasing groundwater price still pushes the water rent going up till the end of the irrigation area.

It is noticed again that the difference between scenario LSRK2 and HSRK2 is soil permeability. Different soil permeability results in different groundwater capacity. Figure 9.26 compares water rent between the two scenarios. As already presented, the total water consumption increases considerably in scenario HSRK2, and therefore it leads to a significant high level of water rent. The price gap between canal water and groundwater is responsible for the up-jumps of the water rent in both scenarios when farmers switch from canal water to groundwater.
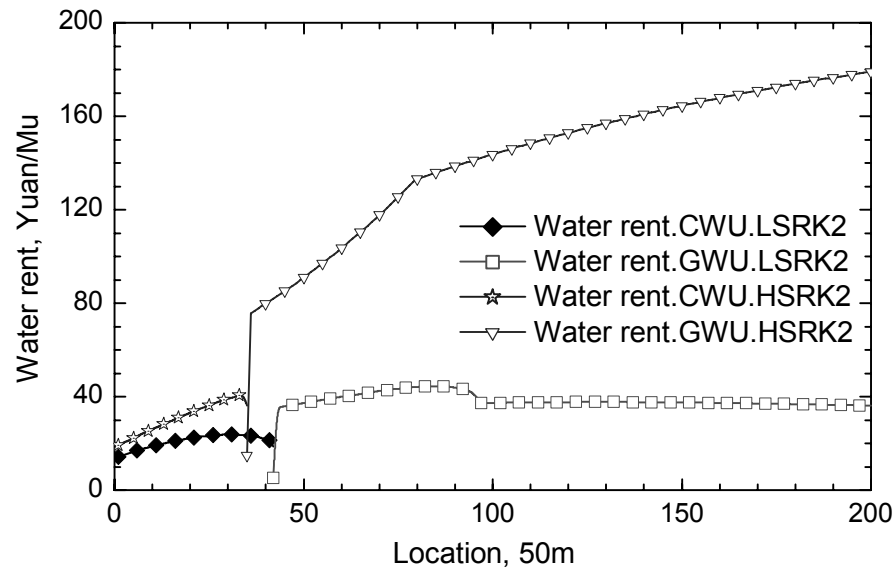
Figure 9.26: Comparison of water rent for CWU and GWU between scenarios of a removal of public investment with private investment participation under high soil permeability (HSRK2) and low soil permeability (LSRK2)
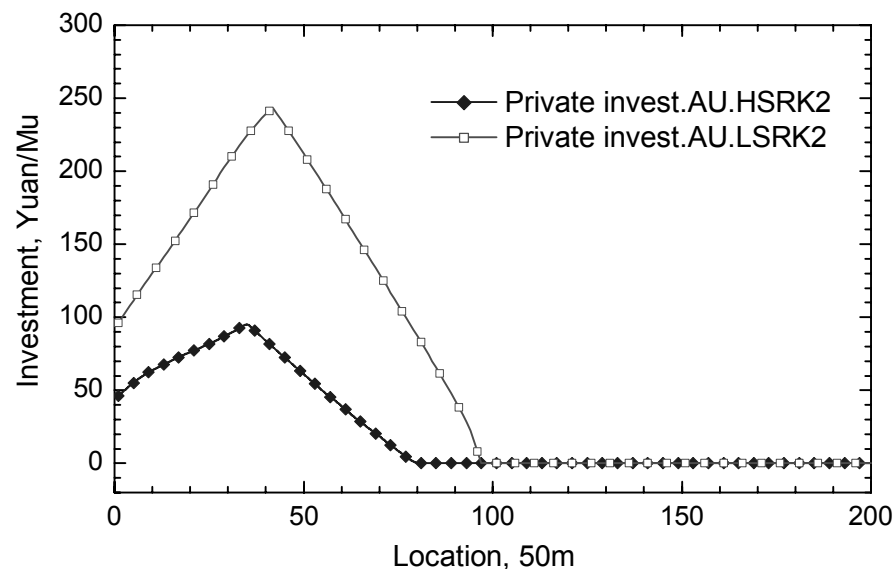
Figure 9.27: Comparison of private investment between scenarios of a removal of public investment with private investment participation under high soil permeability (HSRK2) and low soil permeability (LSRK2)

Figure 9.27 compares the different level of private investment between the two scenarios. Due to water scarcity in scenario LSRK2, farmers make more efforts to save water than they do in scenario HSRK2. The average private investment undertaken by farmers in scenario LSRK2 is 68.17% higher than that in scenario HSRK2. The highest level of irrigation technology adopted by farmers with an investment of 242.91 Yuan/Mu in scenario LSRK2 is undertaken, which is a kind of modern sprinklers and advanced locally produced drip irrigation technology. They can improve the water use efficiency up to 0.91. However, in scenario

HSRK2, farmers reduce the private investment sharply mainly due to the relatively sufficient water supply (mostly from groundwater) and expensive groundwater costs. The highest technology level of scenario LSRK2 is achieved with an investment of 95.78 Yuan/Mu, which is kind of low level instead of advanced locally produced drip irrigation; in line with a reported water use efficiency rate of 0.69. Moreover, only 79 farmers have adopted water saving technologies in scenario HSRK2 against a number of 96 in scenario LSRK2. All the above-mentioned results suggest that an environment of abundant water supply will certainly hamper the adoption of modern water saving technologies.

9.2.6.4 Concluding remarks of scenario of a removal of public investment with private investment participation under high soil permeability

The scenario of a removal of public investment with private investment participation under high soil permeability (HSRK2) showed big differences compared with the previous one under low soil permeability (LSRK2). Contrary to indicators of social economy and water resources worsening in scenario LSRK2, indicators are largely improved in scenario HSRK2. The reason is that the high soil permeability results in considerable recharge to groundwater. The social welfare is improved by 60.99% and the total water consumption almost doubles. A further notable change is that the private investment is reduced considerably by 68.17% compared to that in scenario LSRK2. The reasons for this development are: with high soil permeability, on one hand, farmers loose the incentive to invest more in their fields to save water. On the other, the water supply is so abundant that there is no need to apply modern advanced water saving technologies, especially for groundwater users.

9.2.7 Comparison of indicators among scenarios in the extended optimization model

After analyzing the different scenarios one by one, a review of model results among scenarios and indicators is given in Table 9.12. All the relevant indicators at aggregate and at farm level are listed in the table, which can be a reference for comparison among different scenarios in the extended optimization model.

Table 9.12: Comparison of indicators among scenarios in the extended model

Items at aggregate level	LSDI	LSAI	LSFI	LSRK2	HSRK2
Social welfare (Yuan)	1,096,337.38	1,136,078.96	288,074.95	664,009.66	1,068,977.80
Total canal water consumption (m^3)	299,998.47	300,000.00	257,879.17	49,907.62	64,789.70
Total groundwater consumption (m^3)	46,635.30	45,088.61	9,801.02	89,777.24	340,457.07
Total water consumption (m^3)	346,633.77	345,088.61	267,680.19	139,684.85	405,246.76
Capacity of water supply (m^3)	301,000.00	301,000.00	301,000.00	301,000.00	301,000.00
Gain from conjunctive water use (m^3)	45,633.77	44,088.61	-33,319.81	-161,315.15	104,246.76
Total public investment (Yuan)	2579,31	2,357.24	2,163.23	0.00	0.00
Switch point (location)	174.00	160.00	176.00	42.00	35.00
Canal water length (m)	8,700.00	7,900.00	8,750.00	2,100.00	1,750.00
Area irrigated by canal water (Mu)	2,602.20	2,370.00	2,625.00	626.70	520.61
Area irrigated by groundwater (Mu)	397.80	630.00	375.00	2,373.30	2,479.39
Total private investment (Yuan)	138,470.08	219,114.08	300,000.00	214,455.86	68,257.55
Items in unit at farm level					
Water demand (m^3/Mu)	115.54	115.03	89.23	46.56	135.08
Revenue (Yuan/Mu)	435.53	426.82	371.92	237.94	467.95
Land rent (Yuan/Mu)	295.67	273.20	211.54	131.57	320.98
Water rent (Yuan/Mu)	92.85	79.80	59.67	34.88	124.21
Private investment (Yuan/Mu)	46.16	73.04	100.00	71.49	22.75
On-farm water use efficiency	0.58	0.62	0.70	0.62	0.53
Public investment (Yuan/km)	257.93	235.72	216.32	0.00	0.00

Notes: LSDI: It indicates the nearly real situation scenario, which is run under low soil permeability, endogenous public and private investment, c3 in an ascending order.

LSAI: It indicates the potential requirement of government intervention scenario, which is run under low soil permeability, endogenous public and private investment, c3 in a descending order.

LSFI: It indicates government promoted scenario, which is run under low soil permeability, exogenous fixed private investment, c3 in an ascending order.

LSRK2: It indicates the scenario of a removal of public investment with private investment participation under low soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

HSRK2: It indicates the scenario of a removal of public investment with private investment participation under high soil permeability, which is run under exogenous public investment, endogenous private investment, c3 in an ascending order.

9.3   Summary and research questions

In chapter 9, we extended the initial optimization model by introducing an additional coefficient $c3$, so as to value the impacts on social welfare and water resource allocation by modeling private and public investment simultaneously. Five scenarios were tested under the extended model.

Three different distributions of irrigation technologies were modeled by altering the order of coefficient $c3$. The first distribution is the nearly real situation, in which farmers adopt modern irrigation technology at the upper area. The second is a prediction for a potential of government intervention, in which farmers adopt modern irrigation technologies at the downstream area. And the third is also associated with government promotion of the same type irrigation technology over all location. The model results of the three scenarios suggest clearly that it is more reasonable and economic to adopt various irrigation technology rather than fixed type at different locations.

The normal order, i.e., ascending order of coefficient $c3$, based on the real situation was selected as the default order of $c3$ in the following modeling process. According to this distribution of irrigation technologies, the impacts caused by public investment were analyzed under two different soil conditions. The two scenarios of removal of public investment with private investment participation under different soil condition showed similar results as compared to those of without private investment participation in the initial model. The differences are that the social welfare and the water resource allocation are not only influenced by public investment but also by private investment. This feature is given more emphasis under the extended optimization model. If the irrigation system is under low soil permeability, the model results suggest that public investment will improve social welfare and water resource allocation a lot. However less improvement of social welfare and water resource allocation will be achieved comparably with high soil permeability. Under high soil permeability, a removal of public investment will do less damage. It moreover indicates that the relationship between public and private investment shows a kind of substitution rather than complementarity in terms of absolute costs under these two scenarios. If public investment is removed from the system, farmers will likely increase their private investment to ensure water availability. However, if public investment is undertaken heavily, the private investment will considerably decline. Another feature is that, in a system with low soil permeability, farmers would invest more in modern irrigation technologies than in a system with higher soil permeability.

Based on the results of the five scenarios, the relationship between public and private investment can be judged from two aspects: One is the effect of water use

efficiency. From this aspect, the relationship between private and public investment is complementary. A well managed water conveyance system will lower farmers water costs and hence might give them the opportunity to adopt modern irrigation technology. However, broadly adopted modern irrigation technology by farmers will consume less water, therefore the public canal can benefit more farmers. Consequently the overall water efficiency will get improved. From another aspect of absolute costs, the relationship between both investments is more substitutional, one increasing will lead to the other one decreasing.

Finally as research questions, we state:

The impacts of different distribution of private investment are investigated in this chapter, but it is with the help of an additional coefficient $c3$. Will it be possible for farmers to afford the costly irrigation technology if we increase the output level? And what happens if we let the model endogenously determine the distribution of technology? These questions will be further discussed in the next chapter.

10   IMPACTS OF PRICE REGIME CHANGE ON SOCIAL WELFARE AND WATER RESOURCE ALLOCATION

Let us have a review here. In chapter 8, the impacts on social welfare and water resource allocation have been investigated by changing the status of public investment. All the scenarios in chapter 8 suggest that public investment plays a very important role in water saving and improving social welfare. However, individual farmers do not invest in irrigation technology, due to its high costs. Then in chapter 9, with the help of introducing a coefficient $c3$ for private investment, we enforced the model to simulate the impacts of different distributions of irrigation technologies and performance of public investment in the irrigation area simultaneously. In the present chapter, we will model the impacts by changing the output (apple) price and input (water) price.

Two scenarios are designed to value the impacts of price regime change on social welfare and water resource allocation by investigating farmers' active adoption of irrigation technology. As presented in Table 10.1, one is focusing on effects of apple price change; the other is dealing with apple price and canal water price change simultaneously.

Table 10.1: Scenario groupings, names, abbreviations, and descriptions for assessing the impacts of price regime change

Group/Name	Abbreviation	Description
Scenarios of price regime change:		
High output (apple) price scenario	HA	To model the likelihood of farmer's adoption of modern irrigation technology if their financial situation is improved
Simultaneous high output price and input (canal water) price scenario	HCW	To model the likelihood of farmer's adoption of modern irrigation technology if their financial situation is improved, but simultaneously the water price gets higher than that in HA

10.1   High output price scenario

10.1.1 Specifications of a high output price scenario

The background of a high apple price is that, a higher return from apple production can provide farmers more opportunities to adopt modern water saving technology. As explained already in chapter 3, the year, when the field data were collected, was a bad harvest year for apple growers in the study area combined

with low prices. That could be one of the reasons why the models in chapter 8 choose private investment to be 0 for all locations.

In this chapter we assume that the apple price is 3 times the current price, which is not unrealistic, since the apple price at 1999 was only 35% of the average. Reflected in the modelling process, this assumption is undertaken by multiplying the net revenue function by 3. By doing so, a new revenue function of higher return is hence obtained. The other conditions are kept the same as given in scenario optimal public investment scenario (LSEK) in chapter 8: Public and private investment are endogenous variables, and the recharge rate is set at 0.3.

The objective function is specified below:

$$Social\ welfare\ = \sum_j 15 \times 3 \times \left[c0_j \times \left(tw_j \times h_j \right) + c1_j \times \left(tw_j \times h_j \right)^2 + c2_j \times I_j \times \left(tw_j \times h_j \right) \right]$$
$$- \sum_j \left(0.05 \times k_j + 15 \times I_j + 15 \times cwp_j \times cw_j + 15 \times gwp_j \times gw_j \right) \qquad (10.1)$$

The equation (10.1) will serve in the optimization process in the current chapter.

10.1.2 Impacts on aggregate indicators

As mentioned already, the only condition change made in the current high output scenario (HA) is that, the output price is increased by 3 times, as compared to the base run optimal public investment scenario (LSEK) in the initial model. It is therefore reasonable to compare the model results of the two scenarios.

Indicators at aggregate level of the two scenarios are presented in Table 10.2. It is evident that, except indicators of social welfare and private investment, only negligible differences to the other indicators are found between scenario LSEK and scenario HA. Social welfare increases significantly, which is 251.69% more than in scenario LSEK, thanks to high selling price of apples. Water resource-related indicators do not change much as compared to scenario LSEK. As shown in Table 10.2, total canal water consumption remains unchanged. Total groundwater consumption decreases slightly. There is still a gain from conjunctive water use, which is 2.47% lower than in scenario LSEK. Total public investment changes little. The area irrigated by canal water increases by 1.22%, and the area irrigated by groundwater decreases by 5.56% correspondingly. A remarkable change is given for the total private investment, which is found at 13911.23Yuan as compared to a zero-investment in scenario LSEK. As the model results further show, from location 66, farmers start to invest in water saving technologies until the end of the project area. It means that there are 134 farmers, which accounts for 67% of all the farmers, they go for water saving technologies. The amount of the private investment is still small, but it shows a very clear and positive signal:

Table 10.2: Comparison of indicators at aggregate level between high output price scenario (HA) and optimal public investment scenario (LSEK)

Items	HA	LSEK	%
Social welfare (Yuan)	3,746,690.30	1,065,334.88	251.69
Total canal water consumption (m^3)	300,000.00	300,000.00	0.00
Total groundwater consumption (m^3)	55,263.21	56,635.07	-2.42
Total water consumption (m^3)	355,263.21	356,635.07	-0.38
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	54,263.21	55,635.07	-2.47
Total public investment (Yuan)	2,437.67	2,431.55	0.25
Switch point (Location)	166.00	164.00	1.22
Canal water length (m)	8,300.00	8,200.00	1.22
Area irrigated by canal water (Mu)	2,490.00	2,460.00	1.22
Area irrigated by groundwater (Mu)	510.00	540.00	-5.56
Total private investment (Yuan)	13,911.23	0.00	

Notes: HA: It indicates the high output price scenario, which is run under low soil permeability, endogenous public and private investment and 3 times high output price;

LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment, low output price.

Farmers will adopt modern water saving technology actively if they are wealthy enough. Note that, the adoption of technology in scenario HA is modelled endogenously without help of an additional coefficient, such as $c3$ in chapter 9. The model results strongly support the idea that we have an emphasis on water scarcity and high water price. This is a central incentive for farmers to adopt water saving technology. But financial availability is the premise to fulfil it.

10.1.3 Impacts on social economy and water resource allocation at farm level

The indicators of social economy at farm level are presented in Table 10.3. All indicators show overall better results as compared to scenario LSEK. The average unit revenue doubles for all farmer categories. Land rent also increases by 251.12%, 241.74% and 304.67% for AU, CWU, and GWU, respectively and significantly. Water resource-related indicators change slightly for all categories as compared to scenario LSEK. Private investment is undertaken endogenously in the current scenario, though it is still at a very low level. For AU farmers, it is on average at 4.64 Yuan/Mu. For CWU and GWU farmers, it is 2.95 Yuan/Mu and 12.89 Yuan/Mu respectively. GWU farmers invest more in irrigation technology, since they need to pay high groundwater prices. On-farm water use efficiency increases by 2.39%, 1.52% and 6.61% for AU, CWU and GWU respectively, as compared to scenario LSEK. It is clear that farmers, who use canal water, have less incentive to invest in water saving technology, rather than those using

Table 10.3: Comparison of mean values of indicators at farm level between high output price scenario (HA) and optimal public investment scenario (LSEK)

Items	AU			CWU			GWU		
	HA	LSEK	%	HA	LSEK	%	HA	LSEK	%
Aggregate water demand(m³)	118.42	118.88	-0.38	120.48	121.95	-1.20	108.36	104.88	3.32
Revenue(Yuan)	1344.92	445.26	202.05	1353.96	451.24	200.05	1300.80	418.02	211.18
Land rent (Yuan)	1249.71	355.92	251.12	1270.35	371.73	241.74	1148.98	283.93	304.67
Water rent (Yuan)	89.75	88.53	1.38	79.68	78.53	1.46	138.94	134.09	3.61
Private investment (Yuan)	4.64	0.00		2.95	0.00		12.89	0.00	
On-farm water use efficiency	0.49	0.48	2.39	0.49	0.48	1.52	0.51	0.48	6.61
Public investment (Yuan/km)	245.24	243.16	0.86	295.48	298.35	-0.96	0.00	0.00	0.00
Water conveyance loss rate	0.01	0.01	-5.41	0.00	0.00	0.00	0.08	0.07	8.82

Notes: HA: It indicates the high output price scenario, which is run under low soil permeability, endogenous public and private investment and 3 times high output price;

LSEK: It indicates the optimal public investment scenario, which is run under low soil permeability, endogenous public and private investment, low output price.

groundwater. The amount of unit private investment, which is made by GWU farmers, represents a relatively low level water saving technique. It means farmers go for such technologies for instance, basin check irrigation technology, according to the field research investigations. Public investment changes little, with tiny decreases being observed.

10.1.4 Comparison of private investment at different locations between high output price scenario and optimal public investment scenario

Since private investments are the main feature of the current high output price scenario (HA), we will compare its performance with the optimal public investment scenario (LSEK) by using a diagram. Figure 10.1 clearly shows, that private investment in scenario HA starts from location 66, by which farmers are still covered by the canal water system. This suggests that CWU farmers actively apply water saving technology due to the increasing water price over distance. An up-jump is observed in Figure 10.1 at location 166, which is at a switch point where farmers start to take groundwater. This again suggests that groundwater users adopt relatively more advanced technologies than canal water users, as they are charged a higher water price. However, the private investment is kept at 0 over all locations in scenario LSEK, in which farmers' income stays at a low level (3 times lower than in HA), and they do not invest in any modern irrigation technology.
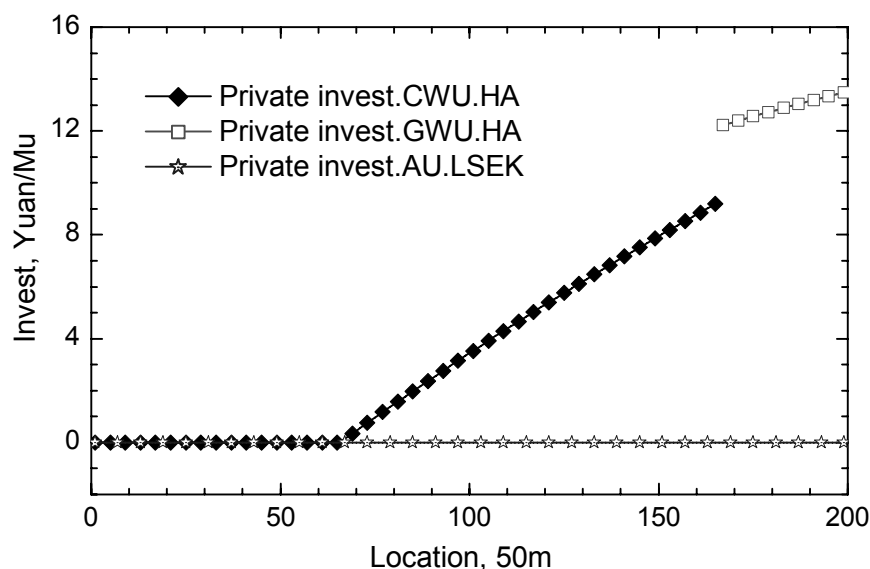
Figure 10.1: Comparison of private investment for CWU and GWU between high output price scenario (HA) and optimal public investment scenario (LSEK)

10.2   Simultaneous high output and input price scenario

10.2.1 Specifications of simultaneous high output and input price scenario

In the previous scenario HA, impacts of a high output price have been modelled. High agricultural returns provide opportunities for farmers to adopt modern irrigation technology. This possibility has been proved in the previous scenario HA. But the level of adopted technology is very low in scenario HA. The questions now are: What happens if the canal water price is raised by 10 times? Will the high canal water price enforce more farmers adopt water saving technologies? These questions will be discussed in the current simultaneous high output and input price scenario (HCW).

Other things being equal to scenario HA, the canal water price is assumed to increase by 10 times in the current scenario HCW, and the groundwater price is kept at the same as in the previous scenarios.

10.2.2 Impacts on aggregate indicators

The indicators of social economy and water resource allocation at aggregate level are listed in Table 10.4. It shows clearly that high costs of water worsen the social economy and water resource allocation. Social welfare decreases by 38.58% as compared to scenario HA. Total canal water consumption also decreases sharply by 40.41%. Since canal water becomes expensive, more farmers go for groundwater. Total groundwater consumption increases significantly by 30.98%. In total a net water loss of 49,850 m^3 is reported in the current scenario HCW, as compared to a net gain of 54,263 m^3 in scenario LSEK. The reason for this is, that expensive canal water reduces farmers' canal water consumption. Consequently more canal water is wasted by seepage during transportation in the canal. Total public investment decreases significantly by 74.49% as compared to scenario LSEK, since the canal becomes shorter. Consequently canal water is used up only until location 119. Public investment has already stopped at location 107. This result indicates again that, less canal water is taken by farmers, due to its high costs and adoption of water saving technology.

The area irrigated by canal water declines and, that by groundwater increases. Total private investment shows tremendous increase, with a growth rate of 547.5% as compared to scenario LSEK. This development strongly suggests that high water prices drive farmers to adopt modern water saving technology.

Table 10.4: Comparison of indicators at aggregate level between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

Items	HCW	HA	%
Social welfare (Yuan)	2,301,280.02	3,746,690.30	-38.58
Total canal water consumption (m^3)	178,767.10	300,000.00	-40.41
Total groundwater consumption (m^3)	72,382.54	55,263.21	30.98
Total water consumption (m^3)	251,149.64	355,263.21	-29.31
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	-49,850.36	54,263.21	-191.87
Total public investment (Yuan)	621.95	2,437.67	-74.49
Switch point (location)	119.00	166.00	-28.31
Canal water length(m)	5,950.00	8,300.00	-28.31
Area irrigated by canal water (Mu)	1,785.00	2,490.00	-28.31
Area irrigated by groundwater (Mu)	1,215.00	510.00	138.24
Total private investment (Yuan)	90,075.76	13,911.23	547.50

Notes: HCW: It indicates the simultaneous high output and input price scenario, which is run under low soil permeability, endogenous public and private investment, 3 times high output price and 10 times high canal water price;

HA: It indicates the high output price scenario, which is run under low soil permeability, endogenous public and private investment and 3 times high output price.

10.2.3 Impacts on social economy and water resource allocation at farm level

Table 10.5 investigates the impacts on individual indicators of social economy and water resource allocation at farm level. Similar to the overall impacts in the previous table, most indicators of individual variables show negative performances as compared to scenario HA. The unit water demand on average decreases by 29.31% for AU, 16.88% for CWU, and 45.02% for GWU respectively. Average unit revenue and land rent also decline over all farmer categories. The water rents show considerable increase for AU and CWU, mainly thanks to a high canal water price, though canal water demand falls largely. However, the water rent for GWU decreases, since demand for groundwater decreases sharply and the price remains unchanged. High water costs drive more farmers to adopt more advanced water saving technology. Farmers start to invest earlier and invest more in the current scenario than in scenario HA. It is also shown, in the Table 10.4, that the unit private investment increases tremendously for all farmer categories. The significant increase of unit private investment suggests that more advanced irrigation technologies are adopted by farmers, as compared to scenario HA. With more private participation in water saving activity, public investment decreases. This result suggests again, in terms of absolute costs, the relationship between public and private investment is more substitutional rather than complementary.

Table 10.5: Comparison of mean values of indicators at farm level between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

Items	AU			CWU			GWU		
	HCW	HA	%	HCW	HA	%	HCW	HA	%
Aggregate water demand(m³)	83.72	118.42	-29.31	100.15	120.48	-16.88	59.57	108.36	-45.02
Revenue(Yuan)	1110.57	1344.92	-17.42	1225.06	1353.96	-9.52	942.36	1300.80	-27.56
Land rent (Yuan)	767.48	1249.71	-38.59	730.66	1270.35	-42.48	821.58	1148.98	-28.49
Water rent (Yuan)	312.68	89.75	248.38	476.57	79.68	498.11	71.90	138.94	-48.25
Private investment (Yuan)	30.03	4.64	547.50	17.19	2.95	483.29	48.89	12.89	279.22
On-farm water use efficiency	0.55	0.49	12.15	0.52	0.49	6.96	0.60	0.51	16.31
Public investment (Yuan/km)	116.25	245.24	-52.60	195.38	295.48	-33.88	0.00	0.00	0.00
Water conveyance loss rate	0.04	0.01	219.16	0.02	0.00	0.00	0.07	0.08	-2.86

Notes: There are 154 farmers who adopt irrigation technology in scenario HCW, and 134 farmers in scenario HA.

HCW: It indicates the simultaneous high output and input price scenario, which is run under low soil permeability, endogenous public and private investment, 3 times high output price and 10 times high canal water price.

HA: It indicates the high output price scenario, which is run under low soil permeability, endogenous public and private investment and 3 times high output price.
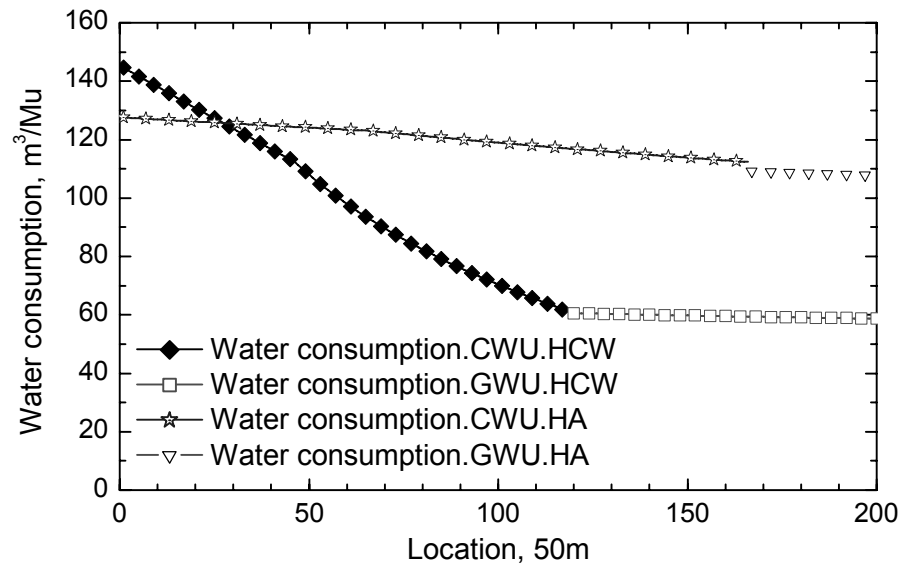
Figure 10.2: Comparison of water consumption for CWU and GWU between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

10.2.4   Comparison of some key indicators between simultaneous high output and input price scenario and high output price scenario

The previous discussion of impacts of the price regime is based on static mean figures. Now we will compare some key indicators at different locations between the two scenarios spatially. Figure 10.2 compares water consumption between scenario HCW and HA. The diagram clearly shows that, at most parts the curve of water consumption in scenario HCW stays below that of scenario HA. In particular within CWU farmers, water consumption declines dramatically due to the high water price. After farmers switch to groundwater, water consumption becomes stable for GWU in scenario HCW, but the consumption volume is still much lower than that in scenario HA. This diagram demonstrates, that a high canal water price prevents farmers from taking much water. Compared to the previous scenario HA, farmers save more water in scenario HCW. Such performance can be a good quantitative example for government to design a water price-related policy. The price level should be set at a reasonable level, at which social welfare should not be damaged, and water resource can be better allocated.

Figure 10.3 compares the different performances of private investment between the two scenarios. Thanks to high canal water costs, farmers in scenario HCW start very early, at location 46, to invest in water saving technology. However in scenario HA, farmers start to invest at location 66. Moreover, it is clearly shown in Figure 10.3, that the level of private investment in scenario HCW is much higher than that in scenario HA. As explained already, scenario HA is modeled
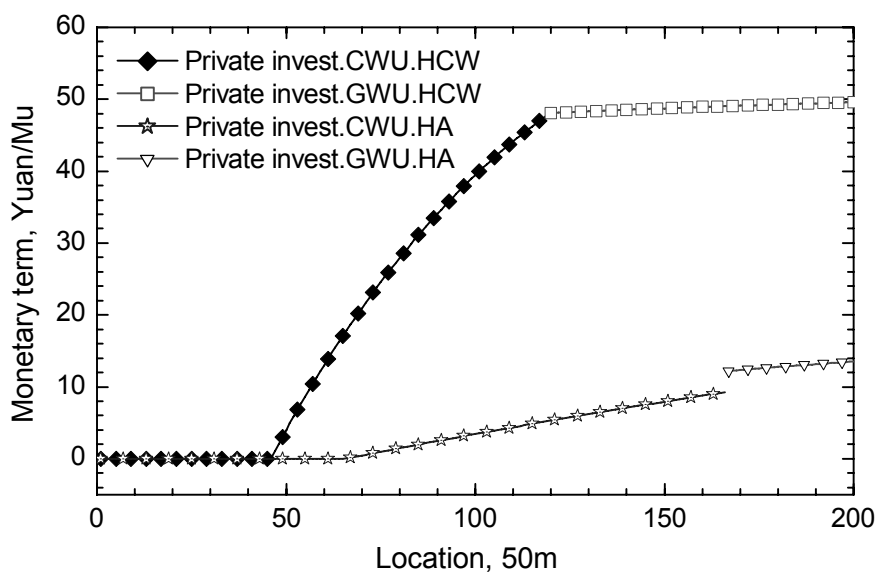
Figure 10.3: Comparison of private investment for CWU and GWU between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)
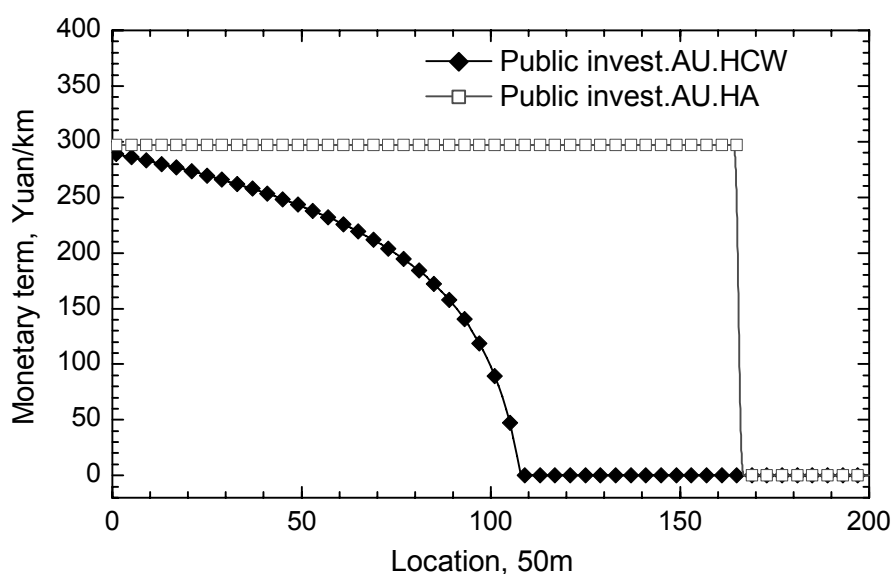
Figure 10.4: Comparison of public investment for CWU and GWU between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

under a high output price. Farmers in scenario HA undertake investment in water saving technology already, but with very low level, since they still can get cheap canal water and do not want to invest much in water saving. However the situation is changed in scenario HCW. Scenario HCW is modeled under the same high output price but also under a high water price. Farmers in this scenario have to invest more in water saving technology, since they need to lower their water costs. Moreover due to the high output price, it is possible for them to invest more in water saving technology. The model results strongly suggest: a high water price

is the most important incentive for farmers to invest in water saving technology, but only financial availability ensures such investment.

Figure 10.4 further demonstrates the performance of public investment at different locations. In scenario HA, public investment is kept constant and a maximal level until location 166 occurs. This kind of level of public investment suggests a 8300-meter-long canal with zero loss rate. Moreover in scenario HA, from water source on, high output prices bring high returns. Since the water price is still low at the upper area of the canal, farmers invest little money in water saving technology. However in scenario HCW, the canal water price sharply increases, and hence canal water irrigation becomes expensive and unprofitable. Such situation enforces farmers to go for groundwater earlier and adopt modern water saving technology. By doing so, they can lower their high costs of water. With more farmers going for groundwater and more private investment being made in water saving technology, public investment declines gradually over the irrigation area. Such a performance suggests again a kind of substituional relationship between the absolute costs of public and private investment.

10.3   Summary

This chapter discussed the changes in the social economy and water resource allocation by a price regime change. The output price was increased 3 times in both scenarios. Further in the high output and input price scenario (HCW), the input price of canal water was increased simultaneously by 10 times. Model results from both scenarios showed significant differences as compared to the previous work done in chapter 8 and 9. Private investment is now chosen by both scenarios, internally, without the help of an additional coefficient. Especially the high output and input price scenario (HCW) showed a significant improvement of water use efficiency as compared to the scenario with only output price increasing. The highest level of private investment in scenario HCW reaches a type of primary locally produced drip irrigation. These performances strongly suggest, that a high water price drives farmers to go for water saving technology, and moreover, sufficient financial credibility can promote such adoption.

11   CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

This chapter summarizes the main findings of the study, draws the policy recommendations and raises questions for future research.

11.1   Summary of the main results

In order to deal with the water scarcity problem, public and private sectors have made tremendous efforts worldwide. The aim of this study is to provide policy makers with a theoretical and quantitative tool to manage public water supply and conveyance systems more efficiently and to support the optimal allocation of water for irrigation projects. Furthermore, the current situation and potential likelihood of adopting modern irrigation technology are taken into account for private individuals.

To achieve the objectives of this study, a spatial mathematic model, SWAM, was designed to assess the impacts of public and private investment on social welfare and water resource allocation. By analyzing the different status of public and private investment in an irrigation project area, this study seeks specifically (1) To determine the optimum amounts of surface and groundwater consumption at different locations in an irrigation project. (2) To investigate the efficiency of water conveyance systems supported by public investment. (3) To investigate on-farm water use efficiency by analyzing the private investment undertaken. (4) To explore the relationship between public and private investment. (5) To analyze different impacts on social economy and water resource allocation by considering different amounts of public and private investment.

11.1.1   Major findings of the field survey

To fulfill the research target, a field survey was conducted in the cropping season of 2000/2001 in Liquan County, Shaanxi, China. A total of 149 farmers were interviewed about their agricultural production, socio-economic situation and participation in irrigation activities. Besides the interview with farmers, contact with key persons and technical staffs in water-related government organizations and institutions was also made.

The results of the field survey described the major socio-economic situations of farm households in terms of demographic, resource endowments, education, production activities, credit markets, and sources of income, as well as participation in irrigation activities. All the interviewed farmers were divided into

eight categories based on irrigation technologies adopted. The eight categories were specified as Category A for farmers who apply flood irrigation, Category B for farmers who apply border irrigation, Category C for farmers who apply basin-check irrigation, Category D for farmers who apply seepage irrigation, Category E for farmers who apply sprinkler irrigation, Category F for farmers who apply drip irrigation, and Category G for farmers who apply dry land farming. All the field data were analyzed based on these farmer categories.

The average family size ranges from 4.0 to 5.2 persons in the survey area. The average farm size varies from 6.5 Mu to 14.7 Mu per farm household. Farmers situated at the upper area of the canal have smaller farm sizes than those situated at downstream area, due to dense population at the upstream area. Landholding per person differs from different locations. Farmers at upstream own only 1.3 Mu per person on average. However, those located at the downstream can be up to 3.3 Mu per person. The level of education, at a certain point, can influence the adoption of modern irrigation technology. The better-educated farmers are more likely to adopt modern irrigation technologies.

The farming system in the survey area is dominated by apple production, which accounts for 79% of the farmland. The credit market in the survey area is not well developed. Small farm households have big barriers to access formal financial institutions. The main source of income for ordinary farmers is still agricultural production, and their main financial expenses are children's education and health caring. Only few wealthy farm households go for irrigation equipment.

The field survey also reveals that, modern irrigation technology can not only improve water use efficiency, but also improve crop quality. Farmers who apply modern sprinkler and drip irrigation techniques get the highest output level and selling price among all farmer categories. Those farmers who do dryland farming get the lowest returns. Modern irrigation technology users consume much less irrigation water than those using traditional techniques. The empirical data analysis unveiled the following findings: (1) Traditional surface irrigation still plays an important role in the survey area. (2) The water price becomes higher with the distance to the water source due to an increase of water conveyance costs. (3) Increasing water prices motivate farmers to adopt new water saving technologies. (4) Compared with imported irrigation technology, locally produced seepage irrigation technique under average conditions is more economic and practical for low-income farmers to save water, as compared to expensive imported technologies, in the survey area.

11.1.2 Model and simulation results

The methodological objective of the study was to build a comprehensive modeling framework. A spatial water allocation model (SWAM) was designed. The framework contains two packages. One is an econometric model using regression methods (SPSS). The other is a mathematical programming model employing the General Algebraic Modeling System (GAMS). The employed farming system in the survey area is fairly typical for current commercial agricultural production in rural China. The natural conditions of agricultural activities, such as soil quality, climate, etc., are assumed constant and excluded, whereas the heterogeneity of location along the public canal was given priority in the optimization. The model's usefulness is, therefore, not regionally confined.

To deal with the econometric model, Hotelling's Lemma is applied to obtain a net revenue function by integrating an inverse water demand function. Furthermore, the on-farm water use efficiency function, the water loss function, and the functions for the canal water price and the groundwater price have been estimated by using regression methods. These functions served as key components in the programming model.

To deal with the programming model, an objective function and several constraints were incorporated. The objective function was formulated in a way to maximize the social welfare (related to producer surplus) in the survey area by focusing on efficient use of water. The optimization of social welfare was investigated by considering the water related net revenue of the survey area minus the expenditure on water conservation and other water related costs. The constraints include the on-farm water use efficiency function, the canal water loss function and equations of motion on water movement. In particular, the equations of motion are the most important constraints in the spatial model. Due to the high non-linear characteristics of the objective function and constraints, the model was solved by using Conopt (GAMS solver) and Minos (GAMS solver), together.

Three sets of scenarios were designed to test impacts of different policy orientations. Firstly we focus on impacts of public investment status change. Secondly we focus on impacts of distribution of private investment. At last, we explore the impacts of a price regime change.

To measure the impacts of public investment status change, the model was run based on endogenous and exogenous public investment, respectively. The endogenous private and public investment scenario, namely optimal public investment scenario, suggest an optimal solution for an irrigation area, which also provides a base run model for the further scenario analysis. The model results showed that private investment was chosen to be zero in this scenario due to its

high costs, but public investment was kept at a maximal level to ensure a zero-loss rate in the water conveyance system. The canal water flow can reach location 164, i.e., 8200m without water loss via transport. However, when public investment becomes exogenously in the model, i.e., if public investment is removed from the water conveyance system, the model results showed considerable different consequence according to different soil conditions. If the soil permeability, i.e., recharge rate for groundwater, is low, a removal of public investment will largely damage the social welfare and water resource allocation. The aggregate social welfare decreases by 42.48% as compared to a system with optimal public investment (the base run model). This removal will reduce the total water consumption by 54.41%, since water is largely lost via the poorly operated canal system, simultaneously the groundwater stock cannot get sufficiently recharged. The canal water length can only reach location 37, i.e., 1850m, in line with the area irrigated by canal water shrinking sharply by 77.44% as compared to the system with optimal public investment. If the soil permeability is very high, the model results suggest that a removal of public investment will slightly decline the social welfare and water resource allocation as compared to a well-managed public canal system. Social welfare decreased only by 0.29%. Total water consumption increased by 23.06%, mainly attributed to groundwater consumption, thanks to a high seepage rate. The canal water length becomes even shorter, reaching only location 31, 1550m. Sufficient groundwater compensates the canal water shortage. By analyzing the impacts of status of public investment, our model results indicate that public investment will always function positively in an irrigation system, and will do especially well in a system under low soil permeability. On the other hand, its impacts on social welfare and water resource allocation are smaller under high soil permeability.

The impacts of public investment have been discussed above, but the role private investment plays, is not concerned much (it was chosen to be zero endogenously by the model due to its high costs). To avoid this limitation, we extended the initial model by introducing an additional coefficient for private investment (namely $c3$) to help model the performance of private investment. The coefficient $c3$ is achieved by estimating a function of scaled private investment over distances. There are two advantages to employ the coefficient $c3$. One is that, the model becomes capable to deal with private investment. This indicates, that the private investment in irrigation technology is able to vary over space instead of being held zero as did in the public investment policy scenarios, so that the impacts of public and private investment on social welfare and water resource allocation can be modeled simultaneously The other advantage is a nearly real situation and other different policy orientations can be modelled by changing the

order of $c3$. For instance, a nearly real situation indicates that the distribution of irrigation technology centers at the upper area of the canal, since normally wealthier farmers are situated in this area due to the access to cheap canal water, and they are likely to afford the costly irrigation technology. In this case the coefficient $c3$ enters into the model in a normal order, i.e., an ascending order. As regards a situation of a potential requirement of government intervention, the model distributes irrigation technology at the downstream area where poor farmers gather. In this case, $c3$ is in a reverse order, i.e. a descending order. At last, a situation of government promotion based again on factual condition, i.e. $c3$ enters in a normal order, was modeled. Under this situation, a deliberately fixed irrigation technology was allocated over the whole irrigation area.

The model results of all the three scenarios suggest that, the different distributions of irrigation technology will change water resource allocation. When irrigation technology centres at the upper area, upstream farmers consume the smallest amount of water. Moreover, more water in the canal becomes available for downstream farmers. As suggested in the previous base run model, i.e., the optimal public investment scenario, which is without participation of private investment, the longest canal water length could be up to location 164, but it can be extended up to location 174 in the modeled nearly real situation scenario. These results support the complementary relationship between public and private investment in terms of effects on water efficiency.

When irrigation technology is allocated at the downstream area, which is molded as a potential requirement of government intervention, the social welfare is slightly increased with a growth of 3.6% in comparison to the nearly real situation, in which farmers adopt the irrigation technology at upper stream area. The average on-farm water use efficiency is increased from 0.58 to 0.62. But the required private investment reaches up to 219,114 Yuan, which is an increase by 58.24%, as compared to the nearly real situation. However, with private investment soaring, public investment in the conveyance system is reduced much. Excluding social welfare and on-farm water use efficiency, the indicators of revenue, land rent and water rent are worse off as compared to situation that technology centers at the upstream area. For instance, in the downstream area, land rents for some farmers become negative if they invest in modern irrigation technology. Such kinds of model results strongly suggest that irrigation technology adopted in the downstream area will significantly increase the on-farm water use efficiency, but a government subsidy for supporting poor farmers to adopt modern irrigation technology is potentially required.

When one fixed type irrigation technology is allocated over the entire area, which is an assumption of a government promotion of one fixed type irrigation technology situation. The model results indicate that the impacts on social welfare and water resource allocation are negative. If a relatively strong and fixed water saving irrigation technology (100 Yuan/Mu annually) is adopted over all locations without considering different location's conditions, farmers loose. The social welfare will decrease by 73.72% in comparison to a system with a varied irrigation technology (nearly real situation scenario). Indicators, such as water consumption, revenue, land rent and water rent, decrease strongly too by 22.78%, 14.6%, 28.45% and 35.74%, respectively. However, the effect of water saving in the irrigation area is significant. It is improved due to the considerable contribution of water saving technology and a well-managed canal system. The on-farm water use efficiency increases by 21.52% as compared to the nearly real situation. But the expenditures are too high to afford, either by farmers or by government.

The model results of the three distributions of irrigation technology suggest that an optimal solution can be achieved if different technologies at different locations rather than going for one fixed type technology are adopted. This will not only reduce total costs, but also ensure social welfare and better water use efficiency.

Under the extended optimization model, the impacts of public investment were investigated, too. They are designed by removing the public investment from the water conveyance system under different soil permeability. The models showed similar results as they did under the initial optimal model. That is: Public investment will improve social welfare and ensure water use efficiency a lot under low soil permeability instead of high soil permeability.

At last the model assesses the impacts of price regime change. When the output price is raised by 3 times, the model results suggest a huge increase of social welfare as compared to the lower output price. A remarkable change is that private investments are chosen by the model, internally, without the help of an additional coefficient. This result indicates that farmers will actively adopt modern irrigation technology, if they can afford the costs.

Further, by keeping the high output price, the model additionally increased input (the canal water) price by 10 times. A significant change is that, more farmers adopt modern irrigation technologies, and a more advanced technology level is found in this scenario, as compared to the previous one merely with output price change. These performances strongly suggest that a high water price drives farmers to go for water saving technologies, and moreover, sufficient financial credibility can drive such adoption activity.

11.2   Policy recommendations

Based on the model and simulation results, the following policy recommendations can be made:

(1) Public investment plays a very important role in water saving activities. This result suggests that government should make more efforts to improve water use efficiency, either in water generation or conveyance systems. Public investment in water conveyance system will do better under low soil permeability rather than high soil permeability. Under such a condition, an irrigation project should be rejected if it would be constructed under high soil permeability.

(2) The study unveils a relationship of combination between public and private investment. With regard to effects of water efficiency, they are complementary. On the one side, a well managed canal system will reduce water losses in water conveyance systems. It therefore lowers the water costs for farmers so that they could have more financial possibilities to adopt modern irrigation technology. On the other side, broadly adopted modern irrigation technologies by farmers will leave more water in the canal, so that more farmers can benefit from public water conveyance systems. Consequently the overall water efficiency will get improved. Concerning absolute costs of public and private investment, they show a more substitutional relationship. One investment increasing will lead to the other decreasing. Considering the vulnerable economic situation of Chinese farmers, it may be rational to let the government do more to improve water use efficiency rather than individual farmers. What the government could do is not only to improve the water conveyance system, but also to assist farmers to finance modern irrigation technologies. By doing this, the overall water use efficiency will be improved. However, due to substiutional relationship, in terms of absolute costs, this may not be a big burden for the public budget.

(3) A high water price is the biggest incentive for farmers to adopt modern water saving technology. For government, it is very crucial to set a reasonable water price level. Such a price level should be able to encourage farmers to adopt water saving technology, and not to do damage to farmers interests.

11.3   Research questions for future work

The presented study could not address all of the important issues as related to social welfare and water resource allocation. There is more work for future research.

The SWAM model of the present study is actually a static spatial programming model, in which the dynamic approach was used to model water movement along the canal within one time period. No time lag is considered while recharge to the groundwater aquifer emerging in the present study. Furthermore, the movements of private and public investment were simulated statically too. A meaningful future work can be centered round the movement of water and investments over time and location changing simultaneously.

Another limitation of the study is that labor costs are not concerned in the optimization model. Labor costs are a very important input element in agricultural production. An effort has been made to model a labor response function. But, as mentioned already, the bad harvest year resulted in a low revenue function. The model results suggested zero costs for labor. This problem could be solved either by getting a better revenue function, or employing a coefficient for labor. Due to limitations in the research scope, this work should be done in future investigations.

The current study investigated canal water and groundwater utilizations. For canal water, a cost concept is clear enough. For groundwater it becomes tricky. Though sufficient groundwater can compensate water shortages, it is with high costs (due to limitation of data, groundwater costs have not been fully calculated in the present study, that is why the model suggests less disadvantage from groundwater taken). For example, pumping costs are not concerned in the current study for simplification. It is specified as electricity costs rather than real pumping costs. The electricity costs are merely responsive to volume of water extraction rather than the cost of construction of water wells. The real situation could be further complicated due to different well depths. In reality, this means if more farmers go for groundwater, it could worsen the social welfare very much as compared to what the model suggested currently.

Finally the investigation is made based on a field survey. The modelled area is still relatively small. By enlarging the irrigation area, the model could be more broadly used for some bigger irrigation projects. Further more, this study is carried out by investigating a single crop pattern to simplify the model. Multi-cropping patterns can also be incorporated in future work.

ZUSAMMENFASSUNG (GERMAN SUMMARY)

Auswirkungen einer effizienten Wasserallokation auf Wohlfahrt und die Ressource Wasser in Nord-West China: eine raumbezogene Modellanalyse

Problemstellung und Zielsetzung

Um Probleme der Wasserknappheit lösen zu können, haben sowohl private Unternehmen als auch der öffentliche Sektor weltweit enorme Bemühungen unternommen.

Das Ziel dieser Studie ist es, mit Hilfe eines theoretisch-quantitaiven Instruments, die öffentliche Wasserversorgung und ein Bewässerungssystem effizienter zu gestalten sowohl eine optimale Allokation der Bewässerungsprojekte zu erreichen, um damit politischen Entscheidungsträgern eine Hilfestellung zu geben. Des weiteren werden die aktuelle Situation und die potenzielle Wahrscheinlichkeit für die Einführung von modernen Bewässerungstechnologien bei privaten Bauern berücksichtigt. Um diese Ziele zu erreichen wurde ein dynamisch-mathematisches Modell entwickelt, um die Einflüsse von öffentlichen und privaten Investitionen auf die Wohlfahrt und die Wasserallokation abzuschätzen. Durch eine Analyse der Wirkungen von öffentlichen und privaten Investitionen in einer Beispielregion mit Bewässerungslandwirtschaft soll diese Studie insbesondere 1) den optimalen Verbrauch von Grund- und Oberflächenwasser an verschiedenen Stellen eines Bewässerungsprojektes ermitteln, 2) die Effizienz von Bewässerungssystemen untersuchen, die aus öffentlichen Geldern gefördert werden, 3) die Effizienz des Wasserverbrauchs bei Betrieben untersuchen, indem die privaten Investitionen auf diesem Gebiet analysiert werden, 4) die Beziehung zwischen öffentlichen und privaten Investitionen erforscht werden und 5) die Auswirkungen auf die Sozio-Ökonomie und die Wasserallokation analysieren, werden unter Berücksichtigung der Höhe der öffentlichen und privaten Investitionen.

Modell- und Simulationsergebnissen

Um die Forschungsziele erreichen zu können, wurden Feldforschungen in der Vegetatious Periode in den Jahren 2000 / 2001 in den Gebieten Liquan Country, Shaanxi, China durchgeführt. Insgesamt wurden 149 Landwirte interviewt, die Angaben zu den folgenden Themenbereichen gemacht haben: Eigene Agrarpoduktion, sozial-ökonomische Situation, und Beteiligung der Landwirte an Bewässerungsmaßzahme. Außerdem wurden zusätzliche Kontakte zu den

wichtigsten fachlich ausgebildeten Personen,   die in den staatlichen Institutionen für Wasser zuständig sind, hergestellt.

Die Ergebnisse der Feldforschung beschreiben die Bedeutung der sozioökonomischen Situation der landwirtschaftlichen Haushalte im Hinblick Demographie, Ressourcenausstattung, Bildung, Produktionsaktivität, Kreditmarkt und der Einkommensquelle sowie deren Beteiligung an Bewässerungsaktivitäten. Die empirische Analyse hat zu den folgenden Ergebnissen geführt: (1) Die traditionelle Flächenbewässerung spielt in dem analysierten Gebiet immer noch eine wichtige Rolle. (2) Der Wasserpreis ist um so höher, je weiter man von der Quelle für Wasser entfernt ist, da damit die Wasserförderungskosten steigen. (3) Ein steigender Wasserpreis führt dazu, dass Landwirte eher bereit sind in neue Bewässerungstechnologien zu investieren. (4) Die vor Ort entwickelte Bewässerungstechnologie ist für Farmer mit wenig Einkommen billiger, einfacher und effizienter als importierte Bewässerungstechnologien.

Das Ziel der Arbeit war es sodann, einen umfassenden Modellrahmen für eine Bewässerungsgebiet zu entwickeln, und eine sogenanntes raumbezogenes Wasserallokationsmodell (SWAM) zu etablieren. Der Rahmen besteht aus zwei Bereichen: Der eine Bereich ist ein ökonometrisches Modell, das Regressionsmethoden benutzt (SPSS). Der zweite Bereich ist ein mathematische Programmierungsmodell GAMS (General Algebraic Modeling System).

Das untersuchte   Farmingsystem in der Beispielregion ist typisch für die aktuelle kommerzielle Agrarproduktion im ländlichen China. Die natürlichen Bedingungen für Agraraktivitäten, wie z.B. Bodenqualität, Klimabedingungen usw., sind als konstant und angenommen. Hingegen wurde Heterogenität der Standorte entlang eines öffentlichen Kanals Priorität beigemessen. Die Nutzbarkeit des Modelles ist dadurch   regional nicht begrenzt.

Mit Hilfe der Anwendung eines ökonometrischen Modells (Hotelling´s Lemma), wird eine netto Erlösfunktion in eine inversen Wassernachfrage integriert und ermittelt. Die On-Farm Wassereffizienzfunktion, Wasserverlustfunktion, und die Preisfunktion für das Kanalwasser und der Grundwasser sind mit Regressionsmethoden geschätzt worden.   Diese Funktionen dienen als Schlüsselkomponenten in einem räumlichen,   dynamisch-mathematischen Model.

In diesem Programmierungsmodell sind eine Zielfunktion und   mehrere Beschränkungen enthalten. Mit der Zielfunktion wird die Wohlfahrt (Produzentenrente) im Untersuchungsgebiet maximiert, wobei der Fokus auf der effizienten Wassernutzung lag.

Die Optimierung der Wohlfahrt wurde untersucht, indem von wasserbezogenen Einkünften im Untersuchungsgebiet die Ausgaben für Wasserbeschaffung und andere wasserbezogene Ausgaben abgezogen wurden. Die Restriktion enthält auch die On-Farm Wassernutzungseffizeinzfunktion, die Wasserverlustfunktion und die Funktionen für die „Beförderung" von Wasser. Letztere Funktionen sind die wichtigsten Restriktionen für das räumliche Modell. Aufgrund der hohen Nicht-Liniaritäts-Characteristika der Zielfunktion und der Nebenbedingungen, musste zur Lösung dieses Problems Conopt (GAMS solver) und Minor (GAMS solver) benutzt werden.

Die erste Gruppe von Szenarien fokussiert auf den Einfluss der öffentlichen Investitionen auf die soziale Wohlfahrt. Die zweite Gruppe der Szenarien hat die Verteilung der privaten Investitionen als Gegenstand. Die drite Gruppe der Szenarien untersucht die Auswirkungen eines Preisregimewechsels.

Der Einfluss der öffentlichen Investitionen werden in drei einzelnen Szenarien untersucht. Im ersten Szenario sind die optimalen öffentlichen Investitionen endogen. Die letzten beiden Szenarien werden mit zwei unterschiedlichen Bodeneigenschaften betrachtet, wobei die öffentlichen Investitionen hier exogen sind. Die Modellergebnisse zeigen, dass bei niedriger Bodendurchlässigkeit von Wasser nicht getätigten bei öffentlichen Investitionen die augregierte Wohlfahrt um 42 % sinken würde im Vergleich zu einer optimalen öffentlichen Investition. In Gebieten, die durch einen Kanal bewässert werden, kommt es zu einem starken Rückgang des Wasserverbrauchs in Höhe von 77%. Weiterhin wird deutlich, dass die Wohlfahrt und Wasserallokation kaum sinkt im Vergleich zum öffentlichem Kanalsystem, wenn die Bodendurchlässigkeit hoch ist. Die Wohlfahrt sinkt lediglich um 0,3%. Die Modellergebnisse verdeutlichen, dass die öffentlichen Investitionen in das Bewässerungssystem immer einen positiven Effekt auf die Wasserallokation haben, speziell unter der Annahme, dass eine niedrige Bodendurchlässigkeit angenommen wird.

In der zweite Gruppe von Szenarien werden die Investitionen in das Zentrum der Betrachtungen gestellt. Insbesondere wurden die Verteilungswirkungen der verschiedenen, räumlich angewendeten Bewässerungstechnologien ermittelt. Ein ergänzender Koeffizient c3 ist für die privaten Investitionen in das erweiterte Optimierungsmodell eingeführt worden. Dieser Koeffizient resultiert aus einer geschätzten Funktion der tatsachlichen skalierten, räumlich anfallenden, privaten Investitionen. Bei dieser Methode können die privaten Investitionen in der Zielfunktion im Gegensatz zum Ausgangsmodell, wo die privaten Investitionen Null sind, variieren. Ein weiterer Vorteil aus der Verwendung des Koeffizienten c3 ist, dass sowohl die reale Situation, als auch verschiedene Politikmaßnahmen

durch Veränderungen des Koeffizienten c_3 modelliert werden können. Drei unterschiedliche lokale Anwendungen in Abhängigkeit von der Entfernung zur Wasserquelle der verschiedene Bewässerungstechnologien sind durch die Veränderung des Koeffizienten c_3 erklärbar.

Wenn c_3 einen steigenden Verlauf aufweist, so modellieren wir eine realitätsnahe Situation. Unter diesen Bedingungen werden die Landwirte im oberen Teil des Kanals die moderne Bewässerungstechnologie anwenden.

Wenn dieser Koeffizient absteigend verläuft, so modellieren wir eine Situation, in der eine staatliche Intervention vorgenommen werden sollte bzw. öffentliche Investitionen nicht nur für die Beförderung des Wassers, sondern auch für die moderne Bewässerungstechnologie verwendet werden sollten. Unter diesen Bedingungen werden die Landwirte im unteren Bereich des Kanals die moderne Bewässerungstechnologie anwenden.

Im letzten Fall modellieren wir eine staatliche Förderung für nur eine Bewässerungstechnologie in dem gesamten betrachteten Gebiet.

Die Modellergebnisse suggerieren, dass die unterschiedlichen Bewässerungstechnologien einen Einfluss auf die Wasserallokation haben. Weiterhin wird deutlich, dass eine optimale Lösung erreicht werden kann, wenn unterschiedliche Technologien in unterschiedlicher Entfernung von der Wasserquelle eingesetzt werden. Dies führt nicht nur Senkung der Kosten, sondern sichert auch die Wohlfahrt und steigert die Wassereffizienz.

Mit dem erweitern Modell modellieren wir auch die Effekte der öffentlichen Investitionen. Die Modellergebnisse dieser Szenariengruppe zeigen, dass die Effekte der öffentlichen Investitionen ähnlich wie in der ersten Szenariengruppe ausfallen. D.h. öffentliche Investitionen werden die Wohlfahrt und die Wassereffizienz stärker bei einer niedrigen Bodendurchlässigkeit erhöhen, als bei einer höheren Bodendurchlässigkeit.

In der letzten Szenariengruppe werden die Effekte von Veränderungen des Preisregimes analysiert. Es wird ein drei mal höher Outputpreis angenommen, was natürlich mit einem Wohlfahrtanstieg einhergeht. Dieser Preis wurde gewählt, weil sich die ursprüngliche Analyse auf ein Jahr mit schlechtem Apfelpreis bezog und untersucht wedern sollte, was geschieht, wenn der Apfelpreis höher wäre.

Das erste Szenario dieser Gruppe veranschaulicht, dass die Farmer bereit sind, moderne Bewässerungstechnologien einzusetzen, wenn die Kosten durch hohe Preise gedeckt sind.

In dem zweiten Szenario wird ebenfalls ein verdreifachter Outputpreis angenommen bei einer gleichzeitigen Verzehnfachung der Wasserpreise. Dies führt zu signifikanten Veränderungen, bei dem deutlich mehr Landwirte moderne Bewässerungstechnologien anwenden.

Diese Ausführungen zeigen eindeutig, dass ein hoher Wasserpreis Landwirte zu einem Wechsel zu wassersparenden Technologien veranlasst. Eine ausreichende finanzielle Kreditsicherung kann diese Tendenz weiter unterstützen.

Diskussionspunkte und Empfehlungen

In dieser Arbeit sind mehrere Punkte zu diskutieren.

Diese Studie analysiert die Beziehungen zwischen öffentlichen und privaten Investitionen. In Bezug auf die Wassereffizienz ergänzen sich öffentliche und private Investitionen. D. h. ein gut organisiertes Kanalsystem kann den Wasserverlust reduzieren. Dies führt dazu, dass die Kosten der Farmer für den Wassereinsatz sinken und damit einen größeren Spielraum für die Einführung moderner Bewässerungstechnologien haben. Die Einführung moderner Bewässerungstechnologien führt dazu, dass in den Kanälen mehr Wasser zur Verfügung steht, so dass mehr Landwirte eine Rente aus dem öffentlich bereitgestelltem Wasserangebot (Kanal) realisieren können.

Betrachtet man die absoluten Kosten der privaten und öffentlichen Investitionen, so zeigt die Studie, dass hier eine substitutive Beziehung vorliegt.

Setzt man eine schlechte ökonomische Situation der chinesischen Farmer voraus, so macht es Sinn, dass der chinesische Staat die Landwirte durch öffentliche Investitionen in Bewässerungsanlage unterstützt. Eine Unterstützung seitens des Staates verbessert die Wassereffizienz. Mehr noch, eine Unterstützung in dieser Form führt langfristig zu einer höher sozial Wohlfahrt. Die öffentlichen Investitionen spielen auch bei der Sicherung der Wasservorräte eine wichtige Rolle.

Dieses Ergebnis suggeriert, dass der Staat durch seine Unterstützung die Wassereffizienz verbessern kann: sowohl bei der Wasser-Bereitstellung als auch bei den Durchleitungssystemen. Nur bei sehr durchlässigen Böden sollten keine öffentliche Investitionen in das Kanalsystem vorgenommen werden.

Wichtigster Anreiz für die Landwirte, moderne Bewässerungstechnologien einsetzen, ist ein hoher Wasserpreis. Für den Staat ist es damit besonders wichtig, ein vernünftiges Wasserpreisniveau festzusetzen. Solch ein Preisniveau sollte die Farmer zur Anwendung von moderner Bewässerungstechnologie

ermutigen. Wird der Wasserpreis jedoch zu hoch festgelegt, so werden in erster Linie die Einkünfte der Landwirte sinken.

Forschungsausblick

Die Studie kann nicht alle wichtigen Fragen in diesem Themengebiet beantworten. Im Mittelpunkt dieser Arbeit stehen die Wohlfahrtseffekte und die optimale Wasserressourcenallokation. Darüber hinaus besteht noch ein umfangreicher Forschungsbedarf.

Das hier präsentierte SWAM-Modell ist ein statisches Analyseverfahren, ein dynamischer Ansatz wurde lediglich zur Abbildung des Wasserverlaufs innerhalb einer Zeitperiode angewandt. Statisch simuliert wurden auch private und öffentliche Investitionen. Eine sinnvolle zukünftige Arbeit wäre daher die dynamische Darstellung des Verlaufes von Wasser und Investitionen in Zeit und Raum.

Die Arbeitskosten spielen hier eine wichtige Rolle, da diese als Inputkosten in die landwirtschaftliche Produktionsfunktion eingehen. Die Auswirkungen variierender Arbeitskosten werden in dieser Studie nicht explizit untersucht. Hier wäre die Entwicklung eines Modells zur Abbildung des Arbeitsmarktes bzw. der Arbeitsangebotsfunktion wünschenswert. Eine weitere Verbesserung des Modells könnte erreicht werden, wenn eine bessere Abschätzung der Ertragsfunktion vorliegen würde oder in dem Modell ein Beschäftigungskoeffizient für den Arbeitseinsatz berücksichtigt werden könnte.

Die aktuelle Studie erforscht die Nutzung von Kanal- und Grundwasser. Die Kosten des Kanalwassers sind eindeutig ermittelbar. Die tatsächlichen Grundwasserkosten sind hingegen schwierig zu kalkulieren. Beispielsweise sind die Pumpkosten für Grundwasser in der aktuellen Studie nicht explizit enthalten in Abhängigkeit von der Tiefe der Brunnen. Diese Kosten sind nur als Elektrizitätskosten berücksichtigt worden. Das Modell kann die Realität nur bedingt abbilden. In der Realität werden die Farmer das Grundwasser nutzen und die Wohlfahrt wird schlechter ausfallen, als dies im Modell dargestellt ist.

Letztlich steht diese Studie eine Fallstudie in einem kleinen Gebiet dar. Das Modell ist relativ klein und es wurde zur Vereinfachung eine „ein-Produkt-Region" gewählt. Dennoch ist die Übertragbarkeit des Modells auch für größere Bewässerungsprojekte gegeben.

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APPENDICES:

Appendix 1 **Spatial Water Allocation Model in GAMS format for a small irrigation area in Northwestern China**

<u>Sets</u>

J	location /1*200/
Jfirst(j)	first location
Jlast(j)	last location;
Jfirst(j) =	yes$(ord(j) eq 1);
Jlast(j) =	yes$(ord(j) eq CARD(j));

<u>Scalars</u>

Beta	recharge rate to groundwater stock /0.3/
cw0	stock of canal water at source /300000/
gw0	groundwater stock at water source /1000/

<u>Parameters</u>

c0(j)	constant term from water demand function
c1(j)	coefficient of water demand
c2(j)	coefficient of water demand and investment in irrigation technology
c3(j)	coefficient of private investment over space
e0(j)	coefficient of water base use efficiency
e1(j)	coefficient of investment in irrigation technology
e2(j)	coefficient of investment of square form in irrigation technology
r0(j)	coefficient of public investment in canal
r1(j)	coefficient of public investment of square form in canal
r2(j)	coefficient of water base loss rate
cwp(j)	canal water price at location j
gwp(j)	groundwater price at location j;

c0("1")= 11.83;
c1("1")= -0.07;
c2("1")= -0.01;
e0("1")= 0.48;
e1("1")= 0.0025;
e2("1")= -2.936E-6;
r0("1")= -0.000405;

r1("1")= 5.25E-7;
r2("1")= 0.074;
loop (j,c0(j+1)= c0(j));
loop (j,c1(j+1)= c1(j));
loop (j,c2(j+1)= c2(j));
c3(j)=0.045*1.028**ord(j);
loop (j,e0(j+1)= e0(j));
loop (j,e1(j+1)= e1(j));
loop (j,e2(j+1)= e2(j))
loop (j,r0(j+1)= r0(j));
loop (j,r1(j+1)= r1(j));
loop (j,r2(j+1)= r2(j));
cwp(j)= 0.13+0.0071*ord(j)-4.5E-06*ord(j)**2;
gwp(j)= 0.475+0.006*ord(j)-8.698E-06*ord(j)**2;
display c0, c1, c2, c3, e0, e1, r0, r1, cwp, gwp;

Variables

cw(j)	canal water demand at j
gw(j)	groundwater demand at j
crem(j)	canal water remaining at location j and can be used for next farmer at location j+1
grem(j)	groundwater remaining at location j and can be used for next farmer at location j+1
sw	social welfare of the project area
h(j)	coefficient of water use efficiency at location j
a(j)	canal water loss rate at location j
k(j)	investment in public canal at location j
I(j)	investment in irrigation technology at location j
tcw	canal water demand over the project area
tgw	groundwater demand over the project area
ttw	total water demand over the project area
tw(j)	canal water and groundwater demand at location j
la(j)	land rent at location j
wr(j)	water rent at location j
nr(j)	net revenue from apple production;

Positive variables

h(j), tcw, tgw, k(j), cw(j), gw(j), tw(j), crem(j), grem(j), a(j), nr(j);

Equations

Eobj	objective function
Ecrem1(j)	equation for canal water remains at the first location and can be used for the second location
Ecrem(j)	equation for canal water remains at location j and can be used for next location j+1
Egrem1(j)	equation for groundwater remains at the first location and can be used for the second location
Egrem(j)	equation for groundwater remains at location j and can be used for next location j+1
Etcw	canal water demand over the project area
Etgw	groundwater demand over the project area
Ettw	total water demand over the project area
Etw(j)	canal water and groundwater demand at location j
Eh(j)	equation for water use efficiency in farmer's field at location j
Ea(j)	equation for canal water loss rate reduction at location j
Ela(j)	equation for land rent at location j
Ewr(j)	equation for water rent at location j
Enr(j)	equation for net revenue at location j;

*without c3 to private investment
Eobj..
SW=E=
sum(j,15*(c0(j)*(tw(j)*h(j))+c1(j)*sqr(tw(j)*h(j))+c2(j)*I(j)*(tw(j)*h(j)))-0.05*k(j)-15*I(j)-15*cwp(j)*cw(j)-15*gwp(j)*gw(j));

*with c3 to I
*Eobj..
SW=E=
sum(j,c0(j)*(tw(j)*h(j))+c1(j)*sqr(tw(j)*h(j))+c2(j)*c3(j)*I(j)*(tw(j)*h(j)-0.05*k(j)-c3(j)*I(j)-cwp(j)*cw(j)-gwp(j)*gw(j));
Etcw..
tcw=e= sum (j,15*cw(j));
Etgw..
tgw=e= sum (j,15*gw(j));
Etw(j)..
tw(j)=e= cw(j)+gw(j);
Ettw..
ttw=e=tcw+tgw;

Ecrem1(j)$(ord(j)eq 1)..
crem(j)=l=cw0-15*cw(j);
Ecrem(j)$(ord(j)gt 1)..
crem(j)=e=(1-a(j-1))*crem(j-1)-15*cw(j);
Egrem1(j)$(ord(j)eq 1)..
grem(j)=e=gw0+ beta*(1-h(j))*15*tw(j)-15*gw(j);
Egrem(j)$(ord(j)gt 1)..
grem(j)=e=grem(j-1)+beta*a(j-1)*crem(j-1)-15*gw(j)+ beta*(1-h(j))*15*tw(j);
Eh(j)..
h(j) =l= e0(j)+e1(j)*I(j)+e2(j)*sqr(I(j));
Ea(j)..
a(j)=e= r0(j)*k(j)+r1(j)*sqr(K(j))+r2(j);
Ela(j)..
la(j)=e=c0(j)*(tw(j)*h(j))+c1(j)*sqr(tw(j)*h(j))+c2(j)*I(j)*(tw(j)*h(j))-
cwp(j)*cw(j)-gwp(j)*gw(j)-I(j);
Ewr(j)..
wr(j)=e= cwp(j)*cw(j)+gwp(j)*gw(j)-0.05*1/15*k(j);
Enr(j)..
nr(j)=e= c0(j)*(tw(j)*h(j))+c1(j)*sqr(tw(j)*h(j))+c2(j)*I(j)*(tw(j)*h(j));

*Scaling and bounds
Egrem.scale(j)=1e3;
Ecrem.scale(j)=1e4;
crem.scale(j)=1e5;
Eobj.scale=1e3;
cw.lo(j)=0;
gw.lo(j)=0;
I.lo(j)=0;
tw.lo(j)=20;
h.up(j)=.95;
h.lo(j)=0.01;
a.up(j)= .80;
a.lo(j)=0;
a.l(j) = 0.1;
cw.l(j) = 50;
crem.l(j) = 5000;
gw.l(j) = 50;
tw.l(j) = 100;
h.l(j) = 0.5;
grem.l(j) = 1000;

```
model water /all/;
water.scaleopt=1;
option iterlim=100000;
option nlp=conopt2;
solve water using nlp maximizing sw;
option nlp=minos;
solve water using nlp maximizing sw;
display w.l, gw.l, I.l, crem.l, grem.l, tcw.l, h.l, tcw.l, tgw.l, tw.l, k.l, a.l, la.l, wr.l,
nr.l, sw.l;
```

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