A SPATIAL MODEL (SWAM) FOR WATER EFFICIENCY AND IRRIGATION TECHNOLOGY CHOICES USING GAMS - A CASE STUDY FROM NORTHWESTERN CHINA

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1 INTRODUCTION

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 corresponding 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. The hypothesis is that spatially different water prices will encourage farmers to invest in water saving technologies.

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, the 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 in canals.

(3) To investigate on-farm water use efficiency by analyzing the private investment undertaken in irrigation technologies.

(4) To explore the relationship between public and private investment.

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

2 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 use 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 most efficiently and to protect the environment, have attracted more and more attention, notably from water researchers as well as practioners. This study follows an approach developed by UMETSU and CHARKRAVORTY (1998) to investigate the water efficiency and investment in irrigation technology in an irrigation area by building a spatial water allocation model using GAMS.

3 FIELD SURVEY AND EMPIRICAL FINDINGS

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 was 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 were made.

The results of the field survey described the major socio-economic situations of farm households in terms of demography, resource endowment, education, production activities, credit markets, and sources of income, as well as participation in different types of 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.

Then our field data was 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[1] 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, primarily, due to dense population at the upstream area. Landholding per person differs from locations. Farmers at upstream own only 1.3 Mu per person on average. However, those located at the downstream can have up to 3.3 Mu per person. Notice further, the level of education, at a certain level, 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 food, 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 and selling price among all farmer categories. Those farmers who do dry-land farming get the lowest returns. Modern irrigation technology users consume much less irrigation water than those using traditional techniques.

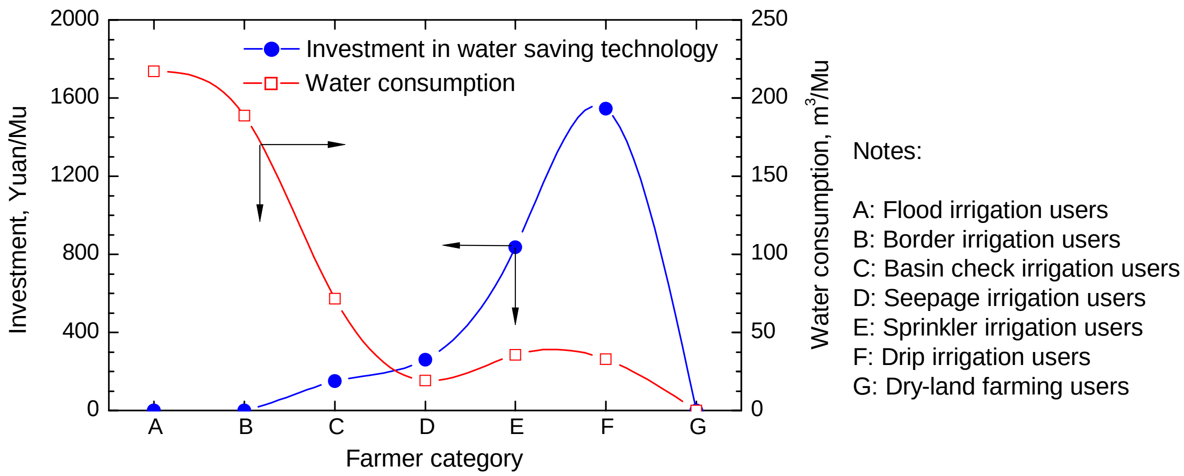

Figure 3.1: Relationship between investment in irrigation and water consumption

A key hypothesis of the study and an important field survey findings is that there exists a relation between 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 3.1, water consumption is at a fairly high level by farmers in categories A and B, since they operate flood and border irrigation. In our present study, it is assumed that zero investment in water saving technologies is made by these two farmer categories. Farmers in the category C operate a kind of small-scale surface irrigation technology, 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. Category C 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. Their 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, i.e. 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.

Based on the empirical data analysis, we further 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.

4 ECONOMETRIC AND PROGRAMMING MODEL OF THE STUDY

The methodological objective of the study was to build a comprehensive modeling framework on data recovering and programming. A spatial water allocation model (SWAM) was designed. The framework contains two packages.

One is an econometric model using regression methods. The other is a mathematical programming model employing the General Algebraic Modeling System (GAMS). Note, 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 for the empirical foundation 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 an efficient use of water. Specifically, the optimization of social welfare was investigated by taking the water related net revenue of the survey an 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 an equation of motion on water movement. In particular, the equation of motion is 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.

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

The model has been developed by UMETSU's (1998) and is applied to our spatial water use problem. The irrigation system of the model assumes 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 flows, water losses, and likely choices of irrigation technologies are illustrated in Figure 4.1. 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

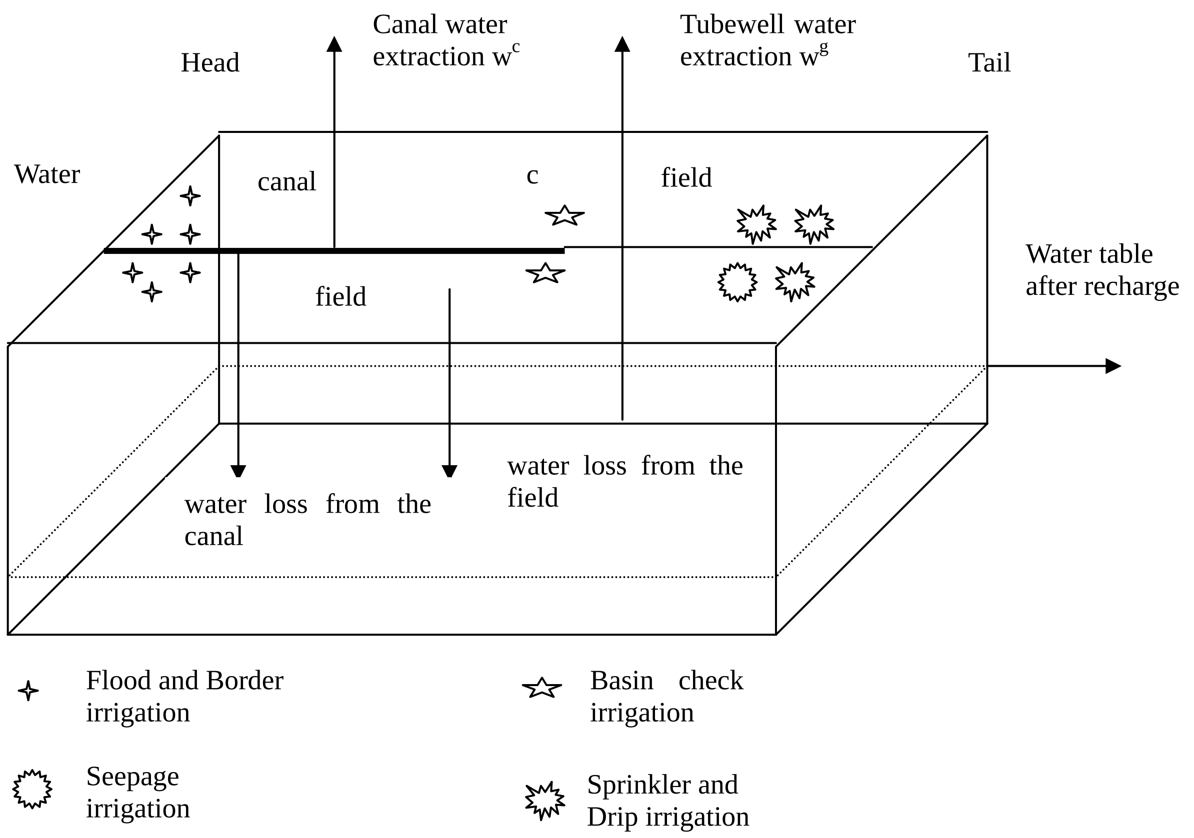

Figure 4.1: Water flow and allocation of irrigation technologies in the survey area
Source: Modified from Umetsu and Chakravorty, 1998

downstream water, so that traditional surface irrigation technologies, such as flood irrigation and border irrigation, should 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 can only be used up to a certain point, such as point C, as shown in Figure 4.1. We assume 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. C depends on the efficient use of water. 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 4.1, basin check irrigation, locally produced seepage irrigation, modern sprinkler and drip irrigation should be dominant at the tail of the survey area.

It is necessary to stress that the distribution of irrigation technology dotted in Figure 4.1 just describes the situation in a survey area, in general, as a point of references. In a practical model, as established in the study, we attempt to achieve technologies that are not too regionally confined. The different distribution of the irrigation technology will be discussed in detail under different situations.

4.2 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 space. 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 and benefits 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. It is perceived that, the higher the water use efficiency shall be, the more investment is required.

4.3 ECONOMETRIC MODEL

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

For estimating the profit function, we adopted Hotelling's Lemma. The approach shows how to get the inverse of the water demand function, first. Then, the estimated inverse water demand function will be used to obtain the profit function by integrating the demand function backwards. The profit function, in the model, is actually a water related net revenue function. Hence it is assumed that, in the present model, other variable costs, such as costs of fertilizer, are already deducted. Our concept of profit in the model, therefore, concerns only net revenues, which means profits to pay for water consumption.

For convenience we integrate a linear inverse water demand function (4.1a) which is specified below:

$$EW = 84.643 - 7.4 \times 10^{-2} \times I - 7.152 \times WP \quad (4.1a)$$

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

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

Where *EW* is the effective water consumption, measured in cubic meter per Mu. *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.

By integrating this function over quantities (a linear function becomes quadratic), we get the net revenue function (profit function) (4.1b) with respect to the effective water consumption “EW”, given “I” as investment:

$$\pi = 11.83EW - 0.01EW \times I - 0.07EW^2 \quad (4.1b)$$

Where π is net revenue of one Mu in the project area, *EW* is effective water consumption per Mu and *I* is an annual investment per Mu in water saving technology. Soon, this profit function will be directly used as key component of the objective function.

4.3.2 The on–farm water use efficiency function

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, an effective water use is defined as the 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 are losses. Hence the amount of effective water consumption is a coefficient to measure how much water is actually consumed by plants. Due to the research scope, we will not calculate the plant’s water requirement for 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. As a coefficient of on-farm water use efficiency, *h* will be introduced into the modeling process. The coefficient *h* is closely tied to irrigation technologies, as different techniques will lead to different on-farm water use efficiency. The coefficient *h* is assumed to be a quadratic function of private investment in irrigation technology; it 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. The coefficient is estimated based on empirical data and will serve as a further important component in the modeling process. The equation is expressed below:

$$h = 0.48 + 0.0025 \times I - 2.94 \times 10^{-6} \times I^2 \qquad (4.2)$$

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

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

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 (4.2) is accepted as the most representative for on-farm water use efficiency function.

4.3.3 The canal water loss rate function

Water use efficiency incorporates not only on-farm water use efficiency, but also the efficiency of a water conveyance system. A coefficient to reflect the water conveyance efficiency is also required in the study. Based on the field survey and relevant literature, we establish a canal water loss function a to reflect the water efficiency during water transportation in a public system. The water loss function is assumed a quadratic function with a coefficient, 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 achievable 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 a loss rate of around 0.74 according to relevant literature (GUO, 1980). Our canal water loss function is estimated below:

$$a = -0.000405K + 5.25 \times 10^{-7} K^2 + 0.74 \qquad (4.3)$$

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

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

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

The equation (4.3) will serve as a constituting component and flexible constraint in the programming model.

4.4 MATHEMATICAL PROGRAMMING MODEL

Our spatial programming model is initially a static model within one time period. From the aspect of space and spatial change, it can be treated as a dynamic process in the presented study. An important common feature 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 are being connected. However, the model is discrete.

4.4.1 The objective function of the spatial programming model

As said, 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 all water related net revenues 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. Also, 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 below:

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

(4.4)

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

$$Max\ SW = 15\left(\sum_j \pi_j - \sum_j I_j - \sum_j CWP_j \times CW_j - \sum_j GWP_j \times CW_j\right) - 0.05\sum_j K_j \quad (4.5)$$

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 a coefficient of "15" it is Mu related. It converts 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 a 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. This framing suggests that one unit area j represents 50×200 = 10,000m^2, which is either equal to 1 hectare or 15 Mu. Since π represents the net revenue r in 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.

4.4.2 Key constraint conditions of the model- the equations of motion of water movement

Equations of motion are the most important constraints in a dynamic model (now to be interpreted as spatial movement). 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 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:

$$crem_1 = cw_0 - 15 \times cw_1 \tag{4.6a}$$

Discrete flow motion:

$$crem_j = (1 - a_{j-1}) \times crem_{j-1} - 15 \times cw_j \tag{4.6b}$$

The equation (4.6a) 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, and $crem_1$ is therefore the canal water that remains after the first farmer has used his water, it then passes down to the next farmer, i.e. the next location.

Then equation (4.6b) 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 volume 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*. 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 is basic concept for the canal water movement. In principle, the equation of motion is the same for groundwater motion (4.7a) and (4.7b). As initial point it starts from the head of the survey area. This 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 4.1) instead from the first location as for canal water.

It is important to recognize that groundwater aquifers can be recharged by water leaking from a 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 has further to be noticed that the canal water is cheaper that farmers have no incentive and no need to pump underground water until C, though they can supplement canal water. 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 are specified in the equation of motion. The mathematical formulation of the equation of motion for groundwater change is presented below:

Initial condition:

$$grem_1 = gw_0 + \beta \times (1 - h_1) \times 15 \times tw_1 - 15 \times gw_1 \quad (4.7a)$$

Discrete flow motion:

$$grem_j = grem_{j-1} + \beta \times a_{j-1} \times crem_{j-1} - 15 \times gw_j + \beta \times (1 - h_j) \times 15 \times tw_j \quad (4.7b)$$

Equation (4.7a) describes the initial condition for groundwater change. Here $grem_1$ represents the groundwater remaining at location 1 which will be available for the second location; i.e. gw_0 represents the groundwater base stock at the head location. 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. In (4.7a) gw_1 is the groundwater consumption at the first location. Equation (4.7b) gives 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 the 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 water can be recharged to the aquifer. Note 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.

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

4.5 Review of employed modeling approaches of the study

Let’s have a brief review of the employed approach of the study. 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 can simultaneously serve to determine the objective function and constraints conditions for the programming approach.

For comparison, 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 spatial problem, which is related to space change. For further clarification and 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, i.e. the annual costs of investment. 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 and to model explicitly the time aspect of investments, so that the model's usefulness can be extended while time is changing.

5 SCENARIOS ANALYSIS AND SIMULATION RESULTS

Four scenarios were designed to test the impacts of different policy orientations on social welfare and water allocation. Firstly we had a base run model, in which public and private investments are endogenous variables. The second one, namely a removal of public investment scenario, follows the base run model and it let public investment become exogenous. The third and forth scenarios are focused on the impacts of price (input and output) regime changes and water resource allocation, both on social welfare and water efficiency.

5.1 The base run model

To maximize the optimal social welfare and water resource allocation, a base run model is built under endogenous public and private investment. It is used as a benchmark against which other scenarios are compared so as to quantify, for instance, the likely effects of the status quo of public investment and price regime changes being modelled in other scenarios. The abbreviation of the base run model is LSEK. The public investment K and private investment I are endogenous variables in the model. The recharge rate for groundwater is 0.3 and we operate 200 potential locations. The model results are presented in Table 5.1.

5.2 A removal of public investment scenario

To analyze the impacts of public investment status change, we secondly modeled a removal of public investment in a separate scenario, which is a revised base run model. The variable of public investment is no longer endogenous as it was in the base run model. It is exogenously fixed at 0 over all locations in the removal of public investment scenario. Zero public investment indicates that government will do nothing to improve the water conveyance efficiency in the irrigation system. It remains at the status quo. The recharge rate for groundwater is still at 0.3. The abbreviation of this scenario where we have a removal of the public investment is LSRK1.

Table 5.1: Comparison of indicators at aggregate level between base run model scenario (LSEK) and a removal of public investment scenario (LSRK1)

Items	LSRK1	LSEK	%
Social welfare (Yuan)	612,782.89	1,065,334.88	-42.48
Total canal water consumption (m^3)	66,027.23	300,000.00	-77.99
Total groundwater consumption (m^3)	96,554.60	56,635.07	70.49
Total water consumption (m^3)	162,581.82	356,635.07	-54.41
Capacity of water supply (m^3)	301,000.00	301,000.00	0.00
Gain from conjunctive water use (m^3)	-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 base run scenario, which is run under low soil permeability, endogenous public and private investment.

The model results of both scenarios are shown in Table 5.1. It is observed that in the scenario of a removal of public investment, namely LSRK1, merely 0.6 million Yuan of social welfare are achieved; this is a decrease of 43.4% compared to a social welfare of 1.06 million in the base run scenario LSEK. Total canal water consumption declines sharply due to less water availability in the canal. The comparison shows that the total canal water consumption falls to 66,027 m^3 compared to a consumption of 300,000 m^3 in scenario LSEK. It further implies that 77.99% of the canal water is lost due to the poorly operating conveyance system. It is not surprising to note that groundwater consumption increases significantly by 70.49% implying high cost for farmers. A large amount of canal water leaks from the canal due to a poorly operating water conveyance system and the recharges to the groundwater stock are high. 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 in LSEK. Only a total of 162,581m^3 water is consumed for plants over the whole area, in comparison to a total water supply capacity of 301,000 m^3. It demonstrates, that 138,418,18 m^3 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 m^3 is reported in the scenario LSRK1. As a most general result it can be drawn: A poor managed canal system results in a huge water loss. The canal water is used up already at location 37 from 200 possible locations, and it consequently decreases the canal irrigation area by 77.44%, while the area irrigated by groundwater triples.

Note the scenario was calculated under low permeability. This can be altered, though the results become only slightly less aggravated under higher permeability. All the above indicators strongly suggest that a removal of public support for the water conveyance system under modest soil permeability will largely hamper the social economy as well as worsen the allocation of water resources. [2]

Since the removal of public investment from the water conveyance system is the key feature of the LSKR1 scenario, we can focus on analyzing its impact on the movement of canal water and groundwater remaining over distance. Two diagrams (Figures 5.1 and 5.2) describe the water movement in the canal and underground. Figure 5.1 compares the different movements of groundwater remaining under different situations. Remember, in the base run model LSEK, there is no canal water lost before it reaches location 164, thanks to heavy public investment. Before this point, as shown in the Figure 5.1, the groundwater stock is recharged 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. In scenario LSRK1 this changes. It is obviously suggested that the slope of groundwater, as remaining curve, is much deeper than that in scenario LSEK. Figure 5.1 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. This scenario implicates that the peak of groundwater, remaining in scenario LSRK1, is much higher than that in scenario LSEK, primarily 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.

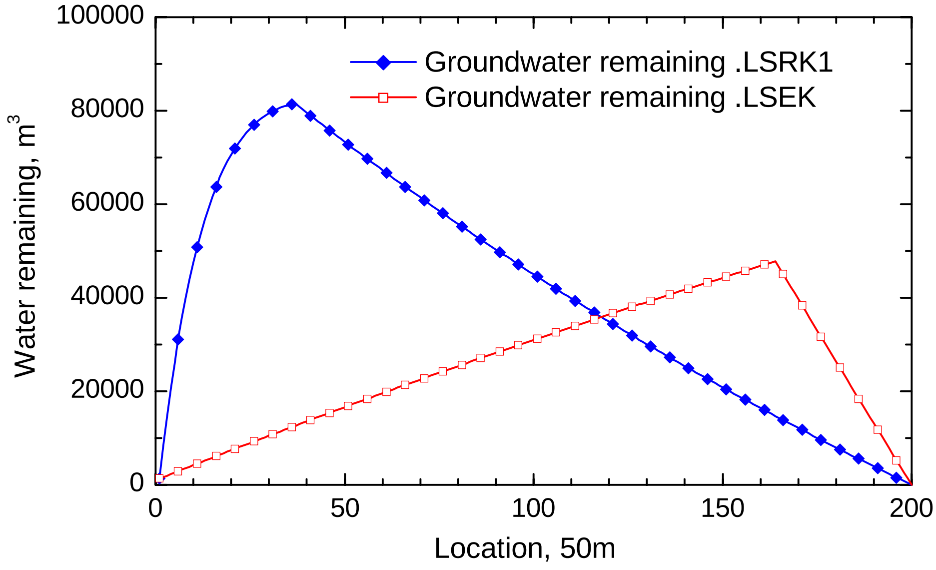

Figure 5.1: Comparison of groundwater remaining between base run model scenario (LSEK) and a removal of public investment scenario (LSRK1)

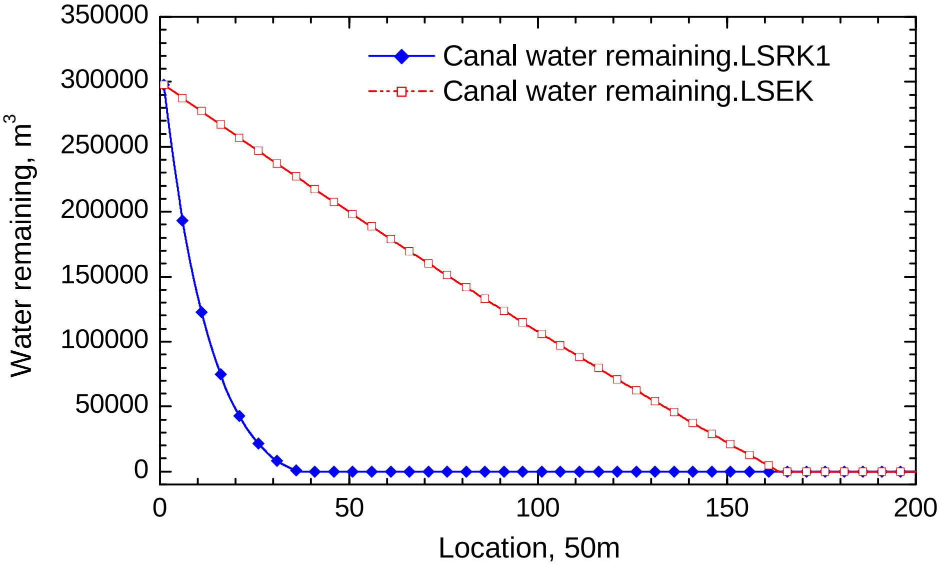

Figure 5.2: Comparison of canal water remaining between base run model scenario (LSEK) and a removal of public investment scenario (LSRK1)

Figure 5.2 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.

The removal of public investment as investigated in the scenario, highlights the importance of public investment for social welfare and water resource allocation.

By removing the water conveyance system under low soil permeability heavy losses occur. 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 shrinks to one-third of the area as compared to the base run model LSEK. Overall water rents decreased too, and this further results in a scarce public budget for water projects. All the indicators strongly suggest that public investment plays a very important role in optimal water resource allocation and improving social welfare.

5.3 High output price scenario

The impact of public investment has been discussed above, but the role which private investment plays, was not of concern so far (it was chosen to be zero endogenously by the model due to its high costs). The base run model and public investment scenario suggests that public investment plays the most important role in water saving and improving social welfare given the base scenario. However, individual farmers do not invest in irrigation technology, due to its high costs. In the present section, we extended the base run model increasing the output price by 3 times. We ask: What happens to social welfare and water resource allocation if farmers have the possibility to afford the costly technology? This high output price scenario is aiming to model situations where a balance exists between investment and profits.

In the scenario we assume that the apple price is 3 times the current price of the base line, which is not unrealistic, since the apple price at 1999 was only 35% of the average. Note for correct replication the base line worked with an actual price of 1995 of a low price year. Hence the high price scenario can be considered more the average. At least the scenario shows the potential of the model to demonstrate price effects. 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 obtained. The other conditions are kept the same as given in scenario of base run model (LSEK). Public and private investment are endogenous variables, and the recharge rate is set at 0.3.

The objective function is specified below:

$$\begin{aligned} Social\ welfare &= \sum_j 15 \times 3 \times \left[c0_j \times (tw_j \times h_j) + c1_j \times (tw_j \times h_j)^2 + c2_j \times I_j \times (tw_j \times h_j)\right] \\ &- \sum_j \left(0.05 \times k_j + 15 \times I_j + 15 \times cwp_j \times cw_j + 15 \times gwp_j \times gw_j\right) \end{aligned} \tag{5.1}$$

The equation (5.1) serves in the optimization process of the current scenario.

5.3.1 Impacts on aggregate indicators

As mentioned already, the only change in conditions, made in the current high output scenario (HA), is that, the output price is increased by 3 times, Indicators at the aggregated level of the two scenarios are presented in Table 5.2. It is evident that, with the exception of indicators of social welfare and private investment, other indicators only show negligible differences to previous indicators as found in 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. But, water resource-related indicators do not change much as compared to scenario LSEK. As shown in Table 5.2, 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, as it already reaches the optimal level in LSEK. 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,

Table 5.2: Comparison of indicators at aggregate level between high output price scenario (HA) and base run model 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 base run model scenario, which is run under low soil permeability, endogenous public and private investment, low output price.

which is found at 13911.23Yuan per MU as compared to a zero-investment in scenario LSEK. The model results further show, that, 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 who invest in saving technologies, which accounts for 67% of all the farmers; they deliberately go for water saving technologies. Though the amount of the private investment is still small, it shows a very clear and positive signal:

Farmers will adopt modern water saving technology actively if they are wealthy enough. The model results strongly support the idea that we have an emphasis on water scarcity and reliable water prices. Prices are a central incentive for farmers to adopt water saving technology.

5.3.2 Private investment at different locations in scenarios of high output prices and the base run

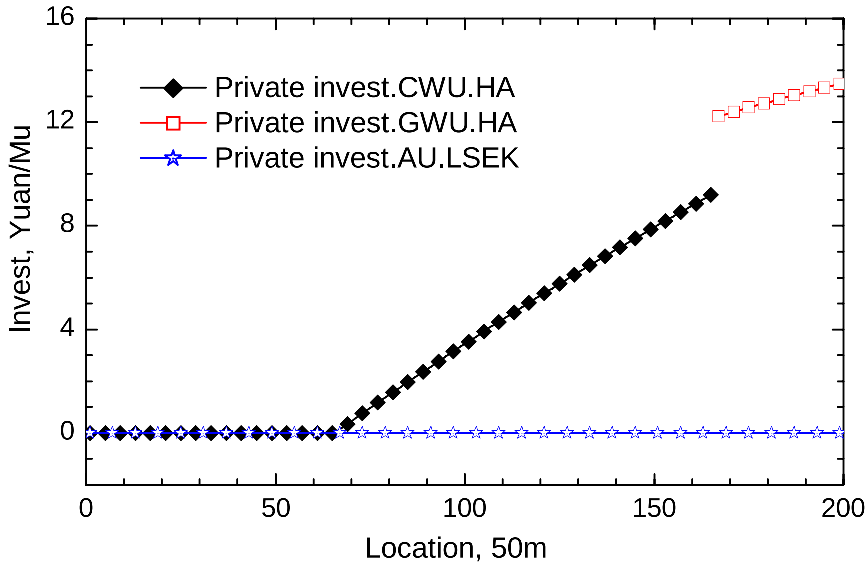

Figure 5.3: Comparison of private investment for CWU and GWU between high output price scenario (HA) and base run model scenario (LSEK)

Notes: CWU: Canal water users; GWU: Groundwater users; AU: All users

Since private investments, undertaken are the key to previous model runs, we compare it's the performance of HA with the base run model using a diagram. Figure 5.3 clearly shows, in scenario HA, that private investment is positive, i.e. farmers adopt modern water saving technology, which starts at location 66. Note, by location 66 farmers are still covered by the public canal water supply system. This suggests that canal water users actively apply water saving technology due to an increasing water price over distance. An up-jump is observed in Figure 5.3 at location 166, which is at a switch point where farmers start to take groundwater. This observation suggests that groundwater users adopt relatively more advanced technologies than canal water users, as they are charged a higher water price. For comparison remember, the private investment was zero over all locations in base run model, in which farmers' income stays at a low level (3 times lower than in HA), and they did not invest in any modern irrigation technology.

5.4 Simultaneous high output and input price scenario

5.4.1 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 still very low in scenario HA. The questions now are: What happens if the input (canal water) price is raised by 10 times? Will a higher canal water price enforce more farmers to adopt water saving technologies? These questions will be discussed in the current simultaneous high output and input price scenario (HCW). Note, other things are 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.

5.4.2 Impacts on aggregate indicators

All relevant indicators of the social economy and water resource allocation at aggregate level are listed in Table 5.3. Table 3 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. But now total canal water consumption 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. Next, 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. This is an important finding. It shows that adoption of technologies is strongly dependent on water pricing.

Furthermore, the area irrigated by canal water declines and, that by groundwater increases. Total private investment shows tremendous increase, with a growth rate

Table 5.3: 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.

of 547.5% as compared to scenario LSEK. Again, this development strongly suggests that high water prices drive farmers to adopt modern water saving technology.

5.4.4 Key indicators in simultaneously high output and input price scenarios

The previous discussion of the impact of the price regime has been based on static figures. Now we will compare some key indicators along different locations between the two scenarios in a spatial framework. Figure 5.4 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 canal water users farmers, water consumption declines dramatically due to the high water price. After canal water use farmers switch to groundwater; water consumption becomes stable for groundwater users in scenario HCW, but the consumption volume is still much lower than that in scenario HA. The diagram demonstrates, that a high canal water price prevents farmers from taking much water. And compared to the previous scenario HA, farmers save more water in scenario HCW. Such demonstration of the system performance can be a good quantitative example for governments to design a

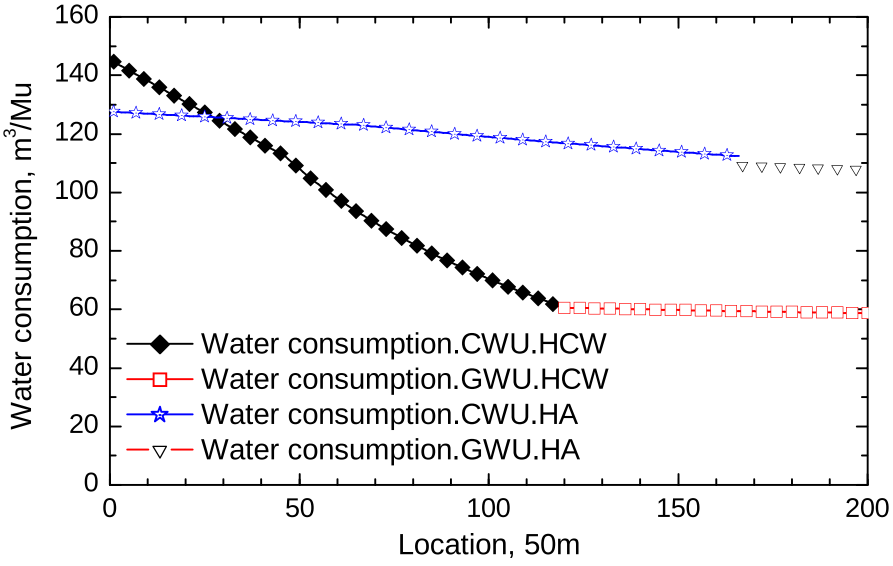

Figure 5.4: Comparison of water consumption for CWU and GWU between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

Notes: CWU: Canal water users; GWU: Groundwater users.

water price-related policy. The price level should be set at a reasonable level, at which welfare should not be damaged, and water resource can be better allocated.

Figure 5.5 compares the different performances of private investment between the two scenarios. Thanks to high canal water costs, farmers in scenario HCW start now very early, at location 46, to invest in water saving technologies. In scenario HA, farmers started to invest only at location 66. Moreover, it is shown in Figure 5.5, that the level of private investment in scenario HCW is much higher than that in scenario HA. As explained already, scenario HA is modeled under a high output price. Farmers in scenario HA undertake investment in water saving technology already, but at very low levels, 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. Note, again, the scenario HCW is modeled under the same high output price but also under a high water price. 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.

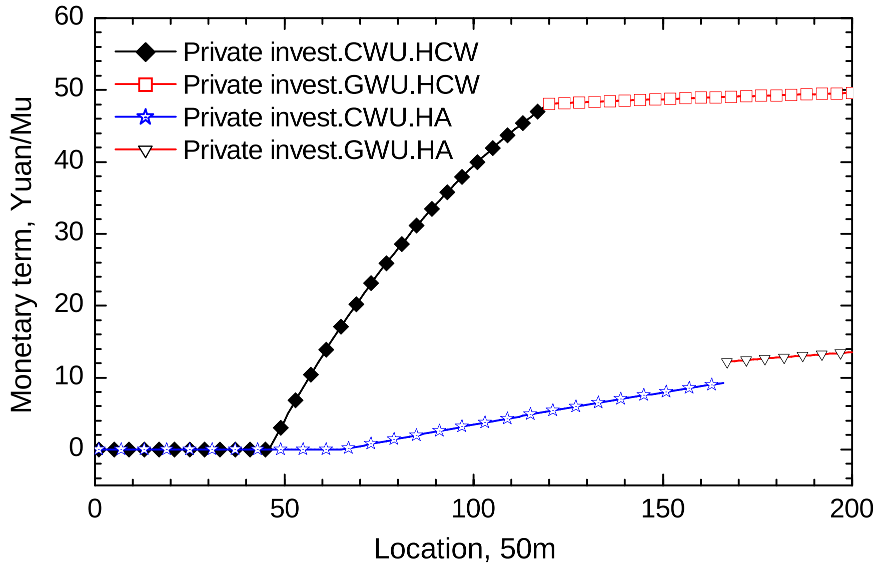

Figure 5.5: Comparison of private investment for CWU and GWU between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

Notes: CWU: Canal water users; GWU: Groundwater users.

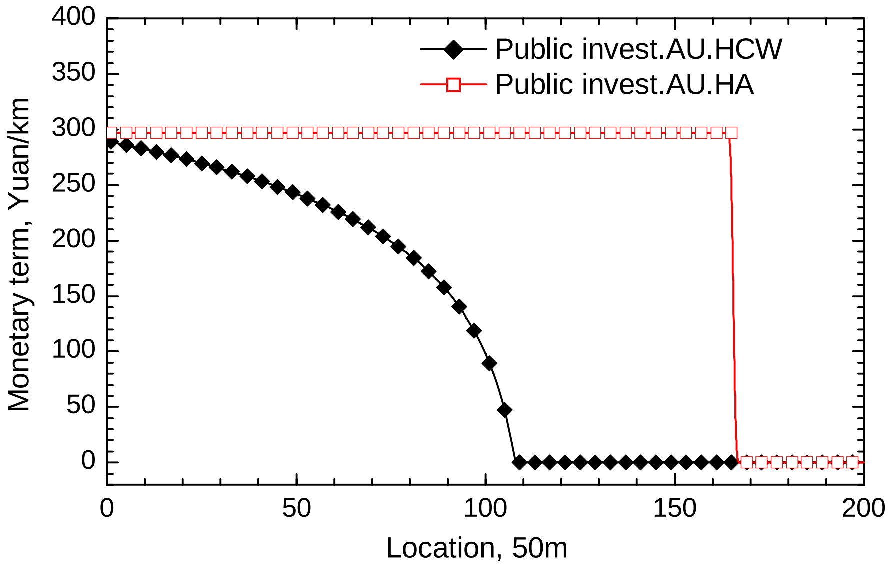

Figure 5.6: Comparison of public investment for CWU and GWU between simultaneous high output and input price scenario (HCW) and high output price scenario (HA)

Notes: AU: All users

Finally, Figure 5.6 further demonstrates the performance of public investment at different locations. In scenario HA, public investment has been kept constant and a maximal level before location 166. 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. 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 substitution between the absolute costs of public and private investment.

To summarize, in this section we 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 the base run model and public investment scenario. Private investment is now chosen by both scenarios, internally, it was no longer staying at 0. 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 technologies, and moreover, sufficient financial credibility can promote such adoption.

6 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Conclusions and Policy recommendations

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

(1) Public investment plays a very important role in water saving activities and securing the social welfare. The results of the modeling suggest that governments should make more efforts to improve water use efficiency, either in water generation or better conveyance systems. Public investment in water conveyance systems will do better under low soil permeability rather than 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 the

water conveyance systems. It therefore lowers the water costs for farmers so 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 improve. Concerning absolute costs of public and private investment, model runs show a substitution effects. Increasing one investment 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 rely on investment from 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 substitution effects, 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 (welfare).

6.2 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, especially in terms of adjusting and extending the model to relevant questions.

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 could 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 treated explicitly 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 and official wages could not be covered. The model results suggested very low returns 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, especially pumping 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 instance, extra 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 the 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 as compared to what the model suggested.

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 to simplify the model. Multi-cropping patterns can also be incorporated in future work.

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Notes:

[1] Chinese land measurement, 1Mu=1/15 ha.
[2] Due to limitation of space, we do not present the situation of high soil permeability, under which public investment only played a minor role.