# Application of a spatial water model in a Chinese watershed

**Lan Fang[1], Ernst-August Nuppenau[2]**

**[1]Shaanxi Provincial Development and Reform Commission, Xi'an 710006, China**

**[2]Institute of Agricultural Policy and Market Research, Justus-Liebig-Universität, Giessen 35390, Germany**

**E -mail:orchidd17@yahoo.com**

**Contributed paper prepared for presentation at the International Association of Agricultural Economists Conference, Gold Coast, Australia, August 12-18, 2006**

# 1 INTRODUCTION

As the whole world is devoted to the water issue in the 21st century, China, as a country with a huge population, faces heavier pressures in the field. The average water resources per capita in China is less than 2,200 cubic meters, only a quarter of the world average (Water in China, 2003), and water is not used rationally. Water logging and soil salinization are common problems in China (Water and Irrigation, 2003). Lack of proper administration over water saving is the main problem. However, many studies have been carried out in the field of responses to water scarcity and contamination. Some of them focus on approaches to assess and improve the performance of water use in agriculture in terms of increasing the water use efficiency (Keller, et al., 1996; Wichelns, 1999; Cai, et al., 2001). Some have focused on the sustainable use of groundwater resources as well as on contamination problems (Hellergers, et al., 2001; Roseta-Palma, 2002; Gayatri and Edward, 2002). Issues, such as how to utilize 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 Chakravorty (1998) to investigate water use efficiency in irrigation activities and to calculate corresponding investment needs from the public and private sectors. The study establishes a spatial water allocation model based on an empirical analysis. The economic and environmental impacts from the adoption of efficient modern irrigation technologies and the construction of high quality canal systems are studied and simulated. Water pricing and institutions are involved. Additionally we consider interactions of private investments in on-farm water saving technologies and public investments in water conveyance systems. The model results suggest that better water allocation increases economic and ecological efficiencies of water use. Public investments play an important role in water saving activities, securing social welfare and reducing the negative externality, and additionally it works complementarily with private investment. The paper also states that high water price is the biggest motivation for farmers to go for water saving technologies.

## 2 FIELD SURVEY AND EMPIRICAL FINDINGS

For the paper a field survey has been conducted in a typically Chinese managed watershed and irrigation project in the county Li Quan of the Shaanxi Province, in 2001. In this county the farming system is dominated by apple production. Farmers ensure their food security by growing apples for food exchange. Knowing that farms are very small in China, water efficiency and increased apple production contribute to food security, and there is a big pressure for farmers to invest in water saving technologies. The socio-economic situation of farm households is described in a field survey overview (Fang, 2004). Here we just present some highlights concerning current water use and technologies. A key hypothesis of the paper and the field survey finding is that there is a positive relation between private investment, water consumption reduction and pricing. Currently (2001), the water use per hectare declines already with escalating water prices. As shown in Figure 1, the higher the water price is, the more investment in irrigation technology one can find, and consequently the less water is consumed. As a further result, the negative effects of high water consumption, water logging and salinization, can be reduced. By taking into account farmers' adoption of modern water saving technologies, improvements of public water transit systems, objective functions are empirically grounded. Based on such empirical data analysis, we then have established a spatial water allocation model which contains an econometric and a mathematic programming model.

## 3 METHODOLOGY OF THE STUDY

### 3.1 Layout of the irrigation area and adoption of various technologies in the study area

The basic outline of the model was developed by Umetsu (1998) and is applied to our spatial water use problem. As an innovation, we include investments for irrigation. The irrigation system of the model assumes a relatively closed water cycle system, instead of an open river basin; and importantly, it contains controlled inflows and outflows. Farmers extract water from a canal, and simultaneously water seeps from the canal. It is assumed that farmers' fields recharge an aquifer which is below a layer of top soil. Each farmer has access to groundwater. For a preliminary description, to reduce complexity, neither time nor a third party impact is considered. Water flows, losses, and potential choices of irrigation technologies are illustrated in Figure 2. A central planner supplies water to farmers who are located along the canal in the project area. In the system we consider construction and maintaining costs of the canal. The end of canal construction is more expensive; upstream water is, therefore, cheaper than downstream water. If the central planner charges costs per meter of canal, as a hypothesis, traditional surface irrigation technologies, such as flood irrigation and border irrigation, should be intensively adopted at the head of the canal, whereas water saving technologies, such as drip irrigation, better pay off at the tail. Along the move of the water in the canal, approaching the tail irrigation area, water becomes scarcer due to extraction by individual farmers and leakage from the canal. Finally, canal water can be used up to a certain point, such as point C, as shown in Figure 2. We assume that the point C will emerge somewhere in a watershed, on which farmers stop using canal water and switch to groundwater. Point C (stretch of canal, see results) depends on the efficient use of water. It is endogenous to the system and it will be determined by the model. It implies that, upstream farmers, 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. After point C, groundwater supply gradually becomes the dominant water source in the tail area. Importantly, relatively expensive groundwater should encourage farmers to adopt modern irrigation technologies in order to save water and lower costs (Fang, 2004). As shown in Figure 1 and 2, basin check irrigation, locally produced seepage irrigation, modern sprinkler and drip irrigation should be dominant at the tail of the survey area.

For methodological reason, as the adoption of different types of irrigation techniques is an important factor to be re-considered in this study, we go for a more continuous presentation in space. In many previous studies, researchers mostly regarded technologies discrete and exogenous, rather than making them choice variables (Caswell and Zilberman, 1985; Chakravorty et al., 1995; Umetsu and Chakravorty, 1998). The key argument of the study is 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. Apparently we have discrete technologies, but look at the varied water efficiency and investment from a functional view point or production function approach, then we can categorize technologies along a track of marginal costs. Note, our water efficiency function is a quadratic one and we consider technology as an occurrence on the line. By this approach the model can optimize technologies endogenously instead of exogenously fixing a technology.

### 3.2 ECONOMETRIC MODEL

The econometric model of the study contains three functions. The Hotelling Lemma is applied to retrieve a restricted profit function (Eq.1) based on empirical observations of the farm budgets in the Liquan county. Hereby a contingent water demand is depicted dependent on gross margins. Also investments in water saving technologies, water prices, etc. are derived. A regression analysis was used to obtain an on-farm water use efficiency function (Eq.2) and a water loss function (Eq.3). Then, functions serve as key components for the empirical foundation in the spatial model (Fang, 2004). Note, our restricted profit function is quadratic. It is expressed below in Eq.1 (t values for coefficients and statistics are attached):

$$\begin{array}{lll} \pi = 11.83EW & - 0.01EW \times I & - 0.07EW^2 \\ t = 26.502 & t = -3.305 & t = -4.76 \end{array} \tag{1}$$

$n = 141$, $R^2 = 0.347$, $F = 3634$, $sign.F. = 0.0001$

Where $\pi$ stands for profits (net income or gross margin are used synonym) per Mu (Chinese land measure) in the project area, $EW$ is the effective water consumption per Mu, and $I$ is annual investment per Mu in water saving technology, measured in Yuan per Mu.

Since on-farm effective water consumption is one of the key measurements of optimal water resource allocation, it is an essential thing to introduce it as a coefficient in the profit function (to reflect the on-farm water use efficiency). Umetsu and Chakravorty (1998) specify this coefficient as a proportional factor (0<h<1). The empirical analysis on a farm water use efficiency function, as dependent on investments, is expressed below in Eq. (2). Our efficiency has been calculated according to IWMI standards. It is quadratic and is derived from individual farm calculations of water balances (Fang, 2004). Note that the efficiency is calculated as a net efficiency without precipitation:

$$h = 0.48 + 0.0025 \times I - 2.94 \times 10^{-6} \times I^2 \quad (2)$$
$$t = 66.12 \quad t = -11.98 \quad t = 1876$$

$$n = 141, \quad R^2 = 0.840, \quad F = 361.13, \quad sign.F. = 0.0001$$

Specifically *h* is depend on investments and can be interpreted as on-farm water use efficiency, which is a percentage of water embodied compared to water applied. *I* is again the annual private investment per Mu. The data, grouped, is from 141 observations along the canal in the watershed.

Equivalently to on farm efficiency, a canal water loss function "*a*", as a coefficient describing the efficiency of public water management (in programming variable), is used to evaluate the efficiency of the water conveyance performance. This canal water loss function depends on public investment and is based on a field survey and relevant literature. The function has been estimated as:

$$a = -0.000405K + 5.25 \times 10^{-7} K^2 + 0.74 \quad (3)$$
$$t = -5.019 \quad t = 3.534 \quad t = 6.903 \quad n = 30$$

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

Again, our own calculation and regressions give "*a"* (the canal water loss rate as percentage) per km, and it is dependent on *K* which is the public investment per km in a canal. Hereby, we follow a strategy of having non-discrete investment types, though building canals is normally discrete with concrete or tubes; as observations and decision make the investment opportunities continuous.

### 3.3 MATHEMATICAL PROGRAMMING MODEL

To deal with the programming model, an objective function and several constraints are to be constructed and incorporated. In our case the objective function is depicted by a restricted profit function approach depending on scarcity in water allocation. More specifically, farmers are specialized in irrigated apple production, other crops are not taken into account. Then, we merely focus on spatial water allocation. Natural conditions of agricultural activities, such as soil quality, climate, etc., are assumed constant and excluded; only the heterogeneity of location along the public canal is given priority in the optimization. The model's usefulness is, therefore, not regionally confined.

The objective function is formulated in a way that it maximizes the social welfare (i.e. net income as value added or producer surplus in a restricted profit function) in the survey area by focusing on efficient use of water. In detail, the optimization of social welfare, in the survey area, was investigated by taking into consideration a water related revenue (as gross margin) minus the expenditure on water conservation and other water related costs. The constraints include the estimated on-farm water use efficiency function, the canal water loss function and two sets of equations of motion on water movement. In particular, the equations of motion are the most important constraints in the spatial model. Then, due to the high non-linear characteristics of the objective function and constraints, the model was solved by using Conopt (GAMS solver) and Minos together.

In addressing space, specifically, our programming model is a static model within one time period framework. Some remarks are to be made on the outlay: The model considers the economic impacts of investments on water efficiency as an annual annuity problem of optimizing returns from investment. From the aspect of space and spatial change, the model should be treated as a quasi- dynamic process (process of motion in space). In the present study the mathematics of motion, normally used in a time framework, are applied now to a spatial framework. All variables and parameters of the model are location-wise (spatially) variables, while the locations are connected through a new dimension: the direction and length of canal. In such case the mathematics of control theory which is found in dynamic optimization could be applied to space, considering space as a continuous dimension. For technical reasons, our model is discrete. It splits a potential distance of 10 km, for a canal, in 200 locations (each of 50 m length along the canal). Then the watershed has a width of 200m. It means each farm has 1 ha (200x50). By this spatial framing the objective function of the spatial programming fits into a set-up that maximizes the social welfare of 200 farmers living in the whole survey area. Mathematically the sum of individual profits gives the social welfare.

By focusing on efficient uses of water on farms and in the watershed as well as reducing negative externalities, the profits of the whole area are maximized summing up over the distance of the canal. Then, in line with a mathematical formulation the objective function can be presented as:

$$Max\,SW = 15\left(\sum_j \pi_j - \sum_j I_j - \sum_j CWP_j \times CW_j - \sum_j GWP_j \times GW_j\right) - 0.05\sum_j K_j \qquad (4)$$

where: $j$ = location, ranging from 1 to 200 in the model, since it represents a stretch every 50m along the canal, i.e., the total length of irrigation system is 10km; $SW$ = social welfare over the irrigation area;

$\pi_j$ = profit 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 $j$ ( K is measured in Yuan/km, one unit of $j$ (50m) is equivalent of 0.05 length of one kilometer, so it gets a coefficient 0.05);

$CWP_j$ = price of canal water at location $j$; $CW_j$ = canal water consumption at location $j$;

$GWP_j$ = price of groundwater at location $j$; $GW_j$ = groundwater consumption at location $j$.

(Note: the objective function becomes Mu related by employing a coefficient of “15”. It converts Chinese land measures “Mu” to 1 ha (15 Mu are equal to 1 ha). Further, farm sizes are not explicitly considered, though as been mentioned, farms are small and 1 hectare is representative. )

Next, following the notation of dynamic optimization, equations of motion are most important constraints in a spatial-dynamic model (now to be interpreted as spatial movement from the head to the tail of the watershed: 10 km). In this model equations of motion are transferred to a location-wise function. Technically one can speak of difference equations. For us, they are central elements to solve a location problem. Since canal water is moving with locations and groundwater stocks are also changing, water flows can be expressed as difference equations of spatial motion, respectively.

Remember, an equation of motion (now spatial) is a classical concept in dynamic optimization procedures (Chiang, 1992). The equation of motion for canal water flows in our modeling framework is expressed in a way of fulfilling GAMS model requirements (McKinney and Savitsky, 2003; Dellink, Szonyi, and Bartelings, 2001). It can be specified, as below, with *initial condition*:

$$crem_1 = cw_0 - 15 \times cw_1 \qquad (5)$$

and *discrete flow motion*:

$$crem_j = (1 - a_{j-1}) \times crem_{j-1} - 15 \times cw_j \qquad (6)$$

To explain the context in which Eq.(5) and (6) depict water use efficiency, please appreciate:

1. The Eq.(5) is the initial condition for canal water flows, 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 the first 50 meters, and $crem_1$ is therefore the canal water that remains after the first farmer has extracted his water. This remaining water then passes down to the next farmer, i.e. the next location. In total we have 200 decision making units for a potential distance of 10 km which are connected through the flows. If enough water is available and water is not merely used at the head area, all farmers might receive water, but this is hypothetical. Overuse in the head will result in no water for those living at the tail. Eq. (6) describes the amount of canal water that remains at location $j$, which starts from the second farmer and goes to the next farmer. The general function of motion, Eq.(6), is expressed as a volume of water that remains from the previous location, $j$-1, minus water consumption at the present location, $j$. But $crem_j$, which represents remaining canal water, i.e. the canal water stock at location $j$, is not only a technical matter. Additionally we introduce a canal water loss rate $a_{j-1}$, defined, as before, as behavioral equation; it represents the canal water loss rate at location $j$-1.

2. As Eq. (6) is a basic concept for canal water movement, in principle, the equation of motion is the same for groundwater motion, i.e., the initial condition Eq. (7), and the flow Eq. (8). At an initial point, in Eq.(7), groundwater stocks start to build up from the head of the survey area. This implies that there is an initial condition $grem(0) = A$. 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; it is given a lower bound of zero in the optimization process.

3. It is important to recognize that groundwater aquifers are recharged by water leaking from the canal and seepage from farmer's fields. The model therefore suggests that groundwater stocks will increase all the time due to the recharge from both sources, canal and field leakage, noticeable without any extraction before point C (in Figure 2). At least in the first section of the watershed, where mostly canal water is used, farmers will probably not extract groundwater. Groundwater ex-

traction starts at point C. The reason is that canal water is cheaper than groundwater. Farmers have no incentive and need to pump groundwater until C, though technically they could supplement canal water through ground water. After point C, there is minor water flowing in the canal, groundwater extraction starts from this point, and supplements canal water. This implies that the fraction recharged from canal water becomes zero. From point C the groundwater stock can only be recharged by seepage from farmers' fields. The stages are specified in the equation of motion (8). The mathematical formulation of the equation of motion for groundwater change is presented below:

*Initial condition:*

$$grem_1 = gw_0 + \beta \times (1 - h_1) \times 15 \times tw_1 - 15 \times gw_1 \tag{7}$$

*Discrete flow motion*:

$$grem_j = grem_{j-1} + \beta \times a_{j-1} \times crem_{j-1} - 15 \times gw_j + \beta \times (1 - h_j) \times 15 \times tw_j \tag{8}$$

Eq. (7) describes the initial condition for groundwater. Here $grem_1$ 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. 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, it is zero). $\beta$ is defined as the recharge rate for groundwater, $tw_1$ is the conjunctive water used at the first location, and $h$ is the water efficiency in fields. At last, $gw_1$ is the groundwater consumption at the first location. Then Eq. (8) 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. Since $\beta$ is the recharge rate for groundwater, $\beta \times a_{j-1} \times crem_{j-1}$ represents the fraction of water loss from the canal and can be recharged to the aquifer at the location $j$-1. At any location water can be recharged to the aquifer. The element $gw_j$ is the groundwater quantity extracted by an individual farmer at location $j$. The last fraction $\beta \times (1 - h_j) \times 15 \times tw_j$ represents the joint water volume, i.e. pumped groundwater and surface water losses from a field, which recharges the groundwater aquifer at location $j$.

4. Finally water balances are given for each location, are dynamically modeled by Eq. (6) and (8), which are valid for each location, and are guaranteed for the whole watershed. The two sets equations serve as the most important constraints in the spatial model. In combination with Eq. (2), Eq.(3), and objective function Eq.(4), we can built a complete model on spatial water allocation.

## 4 SCENARIOS ANALYSIS AND SIMULATION RESULTS

Four scenarios were initially designed to test the impacts of different policy orientations on social welfare and water allocation. The first two scenarios are presented here in detail: In the first scenario we will discuss a base run model, in which public and private investments are endogenous variables, just driven by model optimization. In the second scenario we will analyze the impacts of a removal of public investment. It follows the base run model, but public investment has become exogenous to show the importance of internal optimization. In a third and fourth scenarios we have focused on the impacts of price (water and output) regimes, i.e. changes in price and water resource allocation are investigated as dependent on price policy. Note, for the four scenarios social welfare and water efficiency are crucial indicators. They show the performance of policies. Furthermore, as a side objective, we can show the capability of the model to handle policy relevant issues as related to improving water efficiency and welfare in watersheds and as being dependent, for instance, on price and investment policies. Finally, the scenarios show costs for the public to foster water efficiency and they differ according to priorities set by farmers and a government. Since hydrologic coefficients such as soil permeability affect the optimality of private and public investments as well as policies, scenarios are contingent on the characteristics of natural science and agronomic conditions.

**A: Base run model of Low Soil permeability, Endogenous public and private investment (K) "LSEK"**

As a base run scenario this model is used firstly as a benchmark with which other scenarios can be compared to quantify, for instance, the likely effects of the status quo of public investment and price regimes. Notice carefully, public investments in later presented scenario are fixed or nil. Any changes modelled in other scenarios depend on the same coefficients. The public investment $K$

and private investment $I$ are endogenous variables in the LSEK scenario. The recharge rate for groundwater is 0.3, which is at a low permeability rate, and we operate 200 potential locations. Essential model results are presented in Table 1 which shows drastic changes if other policies occur.

**B: Low Soil permeability, endogenous private but Removed public investment (K1) "LSRK1"**

To analyze the impacts of the public investment status, we have secondly modeled a removal of public investment in a separate scenario, which is a revised base run model (for any other thing it is kept the same). Zero public investment indicates that governments will do nothing to improve the water conveyance efficiency in the irrigation system. Canal quality remains at the status quo; so we see water moving, but no efficiency gains. For interpretation results of both scenarios are in Table 1

In the scenario LSRK1 a removal of public investment leaves only 0.6 million Yuan of social welfare; this is a decrease of 43.4% as compared to a social welfare of 1.06 million in the base run scenario LSEK. This change means that farmers can approximately buy half the food as compared to LSEK. Thus no government investment has a tremendous negative impact on food security. Total canal water consumption declines sharply due to water scarcity in the canal; 77.99% of the canal water is lost due to poorly operating conveyance. Besides a positive aspect of recharging groundwater, it can happen that certain amounts of lost water increase the possibility of water logging in the project, especially close to the canal head. However, that depends on the permeability rate.

As in reality (currently, the government has not invested into canal maintenance and improvement) groundwater becomes a major water source. Canal water is only available until 1.8 km as compared to 8.2 km in LSEK. Because the use of groundwater versus canal water is very expensive, especially at the tail, many farmers incur higher water prices. This is the major reason why an increase of groundwater use deteriorates the entire social welfare so much. As a fairly general result it can be concluded: A poorly managed canal system (nil public investment) results in a huge water loss and water logging. The above indicators strongly suggest that a removal of public support for water conveyance under modest soil permeability will largely hamper the social economy as well as worsen the allocation of water resources, and additionally increase the possibility of water logging.

Figure 3 describes the different movements of groundwater along a canal and its remaining under different scenarios in a spatial framework of the canal. In LSEK, there has been canal water available until the canal reaches location 164, apparently, thanks to heavy public investment. Before location 164, as shown in Figure 3, the groundwater stock is recharged permanently by water which is permeating from farmers' fields instead of public canal, as only minor water leakage happens. Simultaneously no groundwater extraction occurs. Consequently the groundwater stock reaches its peak at location 164, and then it starts to fall from location 165. In other words, at a distance of 8.2 km (from 10 km), farmers start to take groundwater. In scenario LSRK1, the availability of water (canal and ground water) changes and modifies water prices. It is apparent that the curvature of the groundwater stock, as a remaining curve, in LSEK1 is much deeper than that of scenario LSEK. Also Figure 3 demonstrates that the groundwater stock is recharged very quickly due to double losses of water from the canal (conveyance) and farms (irrigation). However, some water can be recovered, apparently, at high costs of pumping groundwater. The net loss depends on the hydrology.

Both, base run model and public investment scenario, suggest that public investment plays an important role in water saving and improving social welfare. By removing public investment from water conveyance heavy losses occur, social welfare and water resource allocation get worse.

However one might notice that the private investments have not been observed in both initial scenarios. A major reason is that high costs of equipments and low returns make private investment unreasonable under given pricing of apples. To show the potential for investment and for further policy analysis, we have extended the base run model. Two scenarios of price regime changes were designed. One was a high output price for apple; one was a high output and high cost of water price. Only some key results are mentioned here due to space limitation; the detailed simulation process and model results can be found in Fang (Fang, 2004). In both latter cases the model showed considerable private investments. As compared to base run model LSEK, the new scenarios give potential changes in the social economy and water resource allocation by price regime changes. Private investments are chosen endogenously above zero. Especially the high output and input price scenario shows a remarkable improvement of water use efficiency. The performance indicators strongly suggest that a high water price is one of the most important incentives for farmers to invest in water saving technology; but only the availability of financial resources ensures such investment.

## 5 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

Based on the model and simulation results, the following conclusions can be obtained:

(1) Public investment plays a very important role in water saving activities, securing social welfare and reduces the negative externality of water loss. The results of the modeling suggest that governments should make big efforts to improve water use efficiency and to avoid negative externalities, stabilize output prices and introduce a cost effective recovering of canal water and assure low water conveyance costs.

(2) The study unveils a complementary relationship between public and private investment. With regards to effects of water efficiency and reducing negative external effects, both investments will reduce water losses if the economic environment is conducive to investments. Good investments systems lower the water costs for farmers, so they can have more financial possibilities to adopt modern irrigation technologies. Broadly speaking, well adopted modern irrigation technologies will result in less water consumption and leave more water for farmers downstream, and water logging can be reduced. More farmers can benefit from public water conveyance systems if investments occur. Consequently the overall water efficiency and environment will improve.

(3) A high water price is a good incentive for farmers to adopt modern water saving technology. However, for a government, it is also crucial to set a reasonable water price. Such a price should encourage farmers to adopt new technology, reduce the threat of water loss and not do damage farmers' interests (welfare).

The presented study could not address all important issues related to social welfare and clean environment. But the model is an essential cornerstone to qualify policies. There is a need for more work and future research, especially in terms of adjusting and extending the model to relevant questions, such as the dynamics of investment, valuing negative externalities, etc.. Some remarks for further investigations are to be made. (1) The spatial water allocation model of the present study is actually a static spatial programming model, i.e. a model in which a “moving-water-flow” approach has been used to model water allocation along a canal given one time period. No time-lags are considered while recharging water to the groundwater aquifer. A more detailed study should consider the above mentioned aspects. Furthermore, the effects of private and public investment were simulated statically, taking annual cost rather than the investment as a dynamic problem. To be concise we have to double the dimension to time and space. A meaningful future work could be centered round the movement of water and investments over time and location, changing both simultaneously. (2) The investigation is based on a field survey. The modelled area is still relatively small. By enlarging the irrigation area, the model could become more suitable and broadly useable for some bigger irrigation projects. Furthermore, this study has been carried out by investigating a single crop to simplify the model approach. However, since it is a programming approach, multi-cropping patterns can also be incorporated in future work. That aspect would bring in the water use efficiency of different crops and show further interaction between water savings due to better spatial allocation, due to technology adoption and due to revising cropping matters. Hence, though water is already at the limit, China may have a big potential to use its water more efficiently.

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**Table 1: Comparison of indicators 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: LSRK1: It indicates a removal of public investment under low soil permeability scenario; the run is under low soil permeability, exogenous public investment and endogenous private investment. LSEK: It indicates the base run, which is run under low soil permeability, endogenous public and private investment.

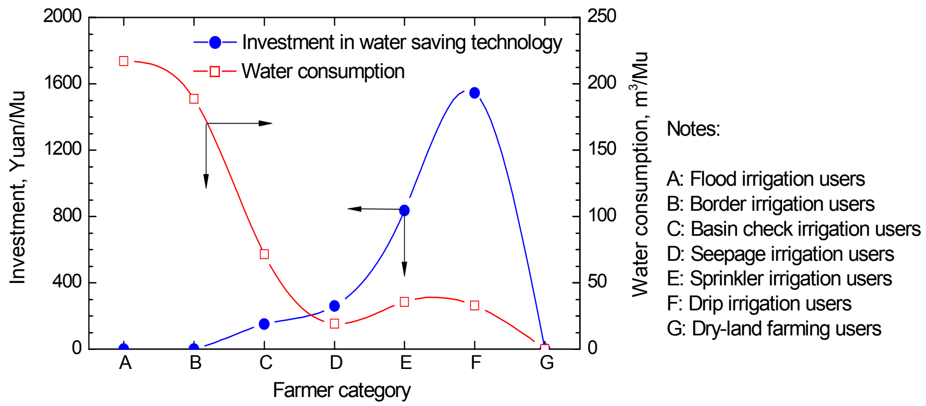


**Figure 1: Relationship between investment in irrigation and water consumption**

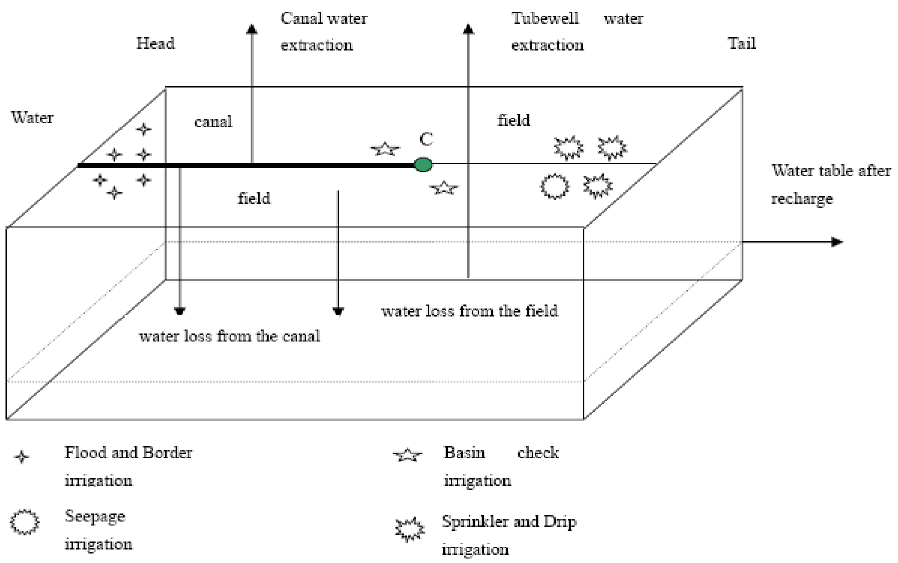


**Figure 2: Water flow and allocation of irrigation technologies in the survey area**

Source: Modified from Umetsu and Chakravorty, 1998

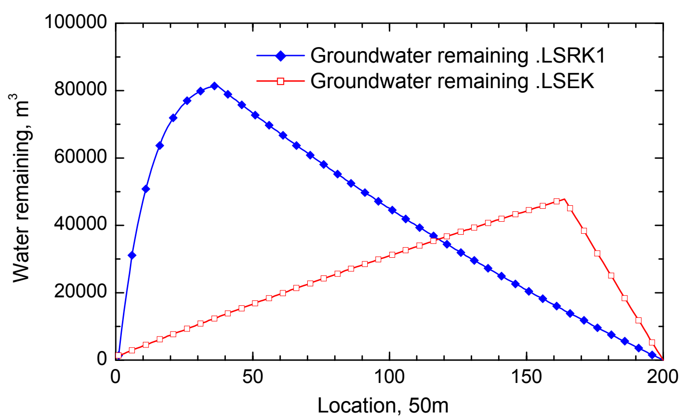


**Figure 3: Comparison of groundwater remaining between base run model scenario (LSEK) and a removed public investment scenario (LSRK1)**