

Bachelor Thesis

# Box model for coordinated application of groundwater and surface water in Guantao China

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## Abstract

Guantao, a small county in the North China Plain, is investing more than half of its area for agriculture. It crops mainly cotton, summer maize and winter wheat, performing double cropping with the latter two. While having an – for single cropping – adequate yearly precipitation of 530 mm, the heavy farming practices demands a bigger water supply, which can only be satisfied with pumping from the shallow and deep aquifer. Hence, the groundwater table in both of their aquifers have been sinking year by year, leaving behind ground fissures, salt water intrusion from the sea, all resulting in the depletion of the last safe water resources near and far.

With the South-North water transfer project and the direct infiltration of the Yellow River into the ground, different solutions for the water shortage in China were looked for. But it becomes apparent that changes in the supply side are hard to realize and not enough, and that therefore the demand side must be worked on to achieve sustainability. This was the motivation for this thesis to create a box model to illustrate the in- and outputs, singling out potential working points that can be modified and setting goals/checkpoints. The first goal is to shut down the deep groundwater pump, which is pumping  $8.7 \text{ mio m}^3$  per year. It can be achieved if the water demand from the crop side is being reduced by this amount. The second goal is to eliminate the yearly deficit in the shallow aquifer storage by trying to get the infiltration rate to be at least as big as the pumping rate.

The program created for this thesis is an interactive user-based software, which allows the simulation of different scenarios to decrease the water demand of agriculture. The user can change the crop combination in Guantao, choose between single and multiple cropping and try out new irrigation systems, all the while seeing what effect those changes will have on the economy and groundwater storages. Additionally, this thesis has examined several parameter alterations and their consequences, beginning with single input changes, to see which are more efficient (minimize groundwater deficit with minimal profit losses). From first examinations it comes apparent that winter wheat reduction is the most efficient and the only single input change to achieve both set goals (13 % reduction to reach 1<sup>st</sup> goal, 52 % reduction to reach 2<sup>nd</sup> goal), but the practicability is arguable. An irrigation system change seems to pay off in the long run even for economy, but contains assumptions, that have to be locally tested first (yield increase through fertilizer).

Currently this program is based on many assumptions, simplifications and also values that are either general or from the Yanqi Basin program. Further development with more accurate and local values will only improve the results from this software and the already derivable strategies will gain more validity.



# Table of Contents

<b>Abstract</b> .....	<b>i</b>
<b>Table of Contents</b> .....	<b>iii</b>
<b>1. Introduction</b> .....	<b>1</b>
1.1 Situation in the North China Plain (NCP) .....	2
1.2 Guantao .....	5
<b>2. Guantao's structure</b> .....	<b>6</b>
2.1 Ground and surface structure .....	6
2.2 Box model Guantao .....	9
2.3 Evapotranspiration and Infiltration .....	12
2.3.1 Calculation of ET and Infiltration rate .....	12
<b>3. Program structure</b> .....	<b>16</b>
3.1 The two main objectives of this program .....	17
3.1.1 The 1 <sup>st</sup> objective: Shut down GW 2 Pump .....	17
3.1.2 The 2 <sup>nd</sup> objective: Deficit of 0 in shallow aquifer .....	19
3.2 Input data .....	20
3.2.1 Parameters of Guantao .....	20
3.2.2 Crop Combination on area 1 (non-saline area) .....	20
3.2.3 Area 2 (saline area) usage .....	21
3.2.4 Multiple cropping .....	21
3.2.5 Irrigation system .....	22
3.3 Program output and Graphical User Interface (GUI) .....	24
<b>4. Results and possible improvement strategies</b> .....	<b>26</b>
4.1 Single input changes .....	26
4.1.1 Winter wheat reduction .....	27
4.1.2 Cotton reduction on saline area 2 .....	28
4.1.3 Subsurface irrigation installation on <i>Maize + Wheat</i> area .....	30
4.2 Multiple Input Changes .....	33
<b>5. Limitations and Outlook</b> .....	<b>37</b>

<b>A. Appendix .....</b>	<b>40</b>
A.1 References.....	40
A.2 Further Literature.....	41
A.3 Acknowledgement .....	41
<b>B. Values used for Software .....</b>	<b>42</b>
<b>C. Matlab script files.....</b>	<b>44</b>
C.1 Entry tables for user .....	44
C.2 Result table.....	48
C.3 Graphical User Interface (GUI) .....	49

# 1. Introduction

Groundwater is a valuable asset, particularly for regions with heavy agriculture practises and not enough surface water supply through rivers and precipitation to complement that. This makes these regions highly dependent on their aquifer and leads to a decreasing of the groundwater level. The challenge in these regions is to achieve sustainability by an effective water management plan, which factors in the low recharge rate of groundwater. In this thesis, Guantao, a southern county in the Hebei province of China, is depicted into a box model and a user-based software is created to illustrate the consequences of possible changes in its agricultural practice. The goal is to find the most effective strategy to decrease the high water demand with minimal profit losses, without changing the status quo significantly.

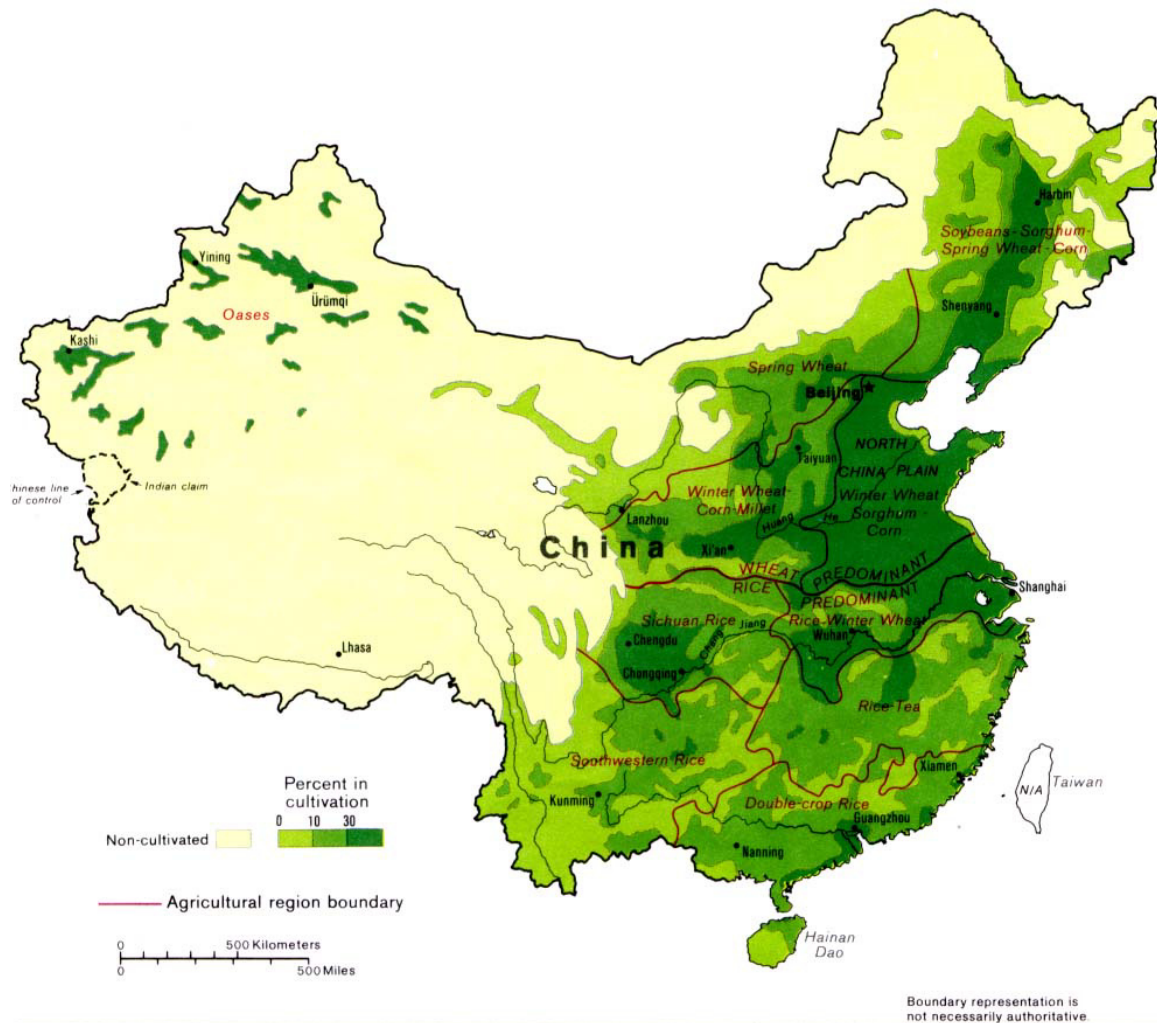
In the first chapter, an introduction on the North China Plain in general is given before focusing on Guantao, one of its counties. After that, the ground and surface structure of this region will be illustrated and the box model including all in- and outputs of water flows will be shown. In the following chapter the software structure with all its components will then be explained and a generated run-through will be shown.

In the next chapter, different strategies to increase the efficiency regarding the water management are analysed, starting with single input changes, to find the parameter with the biggest potential of reducing the high water demand in the most efficient way. Afterwards, several parameters are being changed at the same time to create a realistic strategy on how to solve Guantao's water demand and salinity problem.

In the final chapter, a conclusion about this software is presented, limitations are pointed out and an outlook on how it could be improved with further investigations is given.

## 1.1 Situation in the North China Plain (NCP)

The North China Plain is an area which produces a substantial amount of grain, relative to the area and precipitation in China. A large part of the national wheat production (mostly winter wheat) is being cultivated in this region from October to May. During that period, precipitation is at its lowest, hence additional water supplies like groundwater pumping have to be used, to compensate.



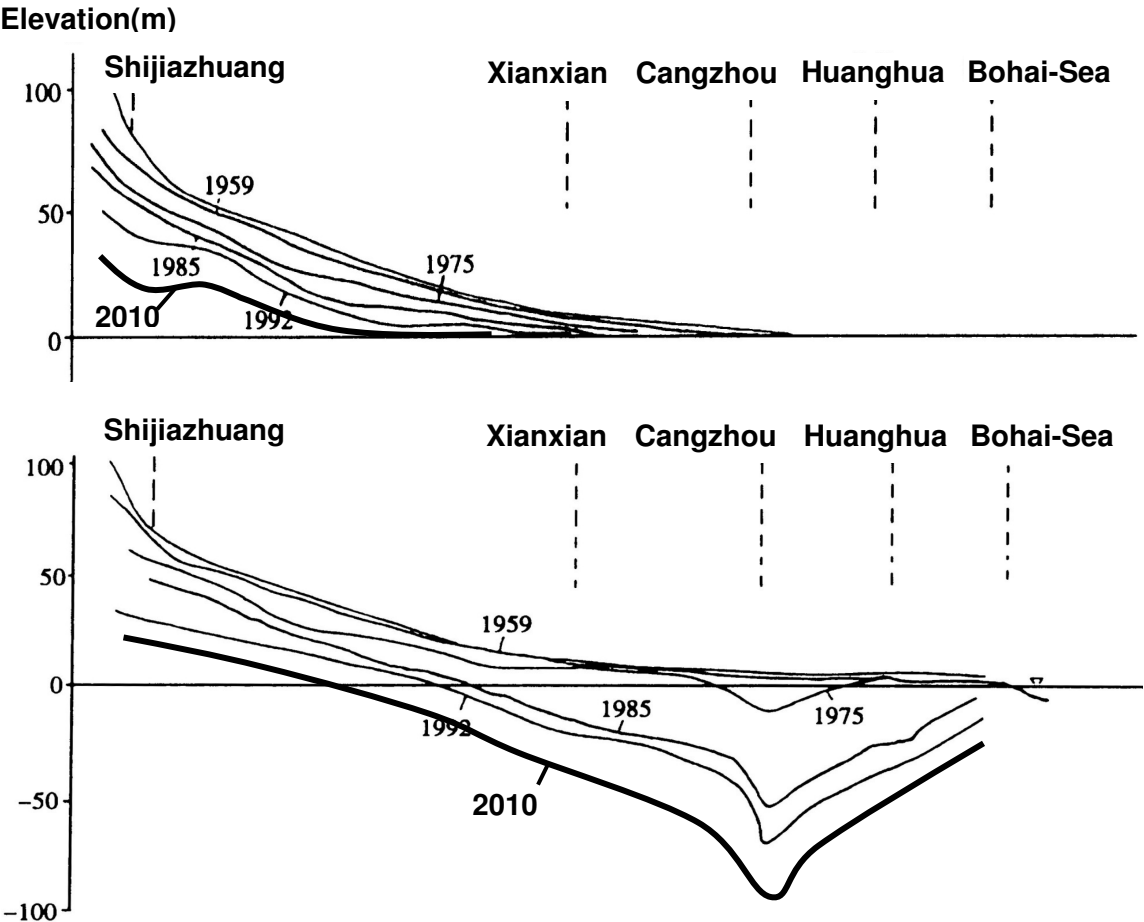
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**Figure 1:** Intensity of Agriculture production in China. The North China Plain mainly produces winter wheat, maize and sorghum [1].



Throughout the years, increasing amounts of water had to be pumped, in order to satisfy the need of agriculture production. This evidently resulted in overpumping and polluting of the shallow aquifer. The well-drillers had to dig deeper into the deep groundwater aquifer which contains fresh water. It is assumed that this water has been supplied from the Taihang mountains, from where it flowed a few 100 meters deep to the Bohai sea, but the recharge rate is negligibly small [2]. The ground structure prevents (mostly through an impenetrable clay layer) a vertical water recharge in the middle of the NCP.

Historically, the groundwater flowed from the mountain regions in the west to the Sea in the east, but through massive overpumping of the deep groundwater aquifer, the entire groundwater flow path changed (see *Figure 2 bottom picture*). Instead of a steady west to east flow, the groundwater now flows from the Taihang mountain range in the west and from the Bohai Sea in the east to the middle of the plain. This leads to salt water intrusion from the Sea, which will increase with time and wander further west, rendering the pumps in its way useless and therefore reducing the water supply for drinking and agriculture.



**Figure 2:** A cross section showing the groundwater level declines in the shallow (top figure) and the deep (bottom figure) aquifers from the mountains in the west to the Bohai Sea in the east [2]. Through heavy pumping, especially in the middle of the NCP, the direction of the deep groundwater has changed.

As China has a very rain-laden south and a relatively dry north, a project was initiated in the middle of the 90s, called the "South-North Water Transfer Project". The goal is to divert around 44.8 billion  $m^3$  per year [3] of (relatively) fresh water to the north. As the quality of this water is fairly high, the cities in the North China Plain could use it as a substitute to some of the pumped deep aquifer groundwater, which, after treatment, could be made suitable for drinking and industrial purposes. The main part of the water though is intended for Beijing. It has already been regulated, how much water will be diverted for each region in the NCP.

Although this project is being criticized for its forceful migration of nearly half a million residents, its potential large amount of water losses through evaporation, in addition to its wasteful handling of water resources, a solution for China's water shortage has to be found. Even with the South-North Water Transfer Project it won't be enough, at least not for Guantao. The groundwater table in North China Plain has been decreasing steadily in the last years, and with it the last water reserve and safety net that this region has. It becomes apparent that when changes in the supply side are insufficient or difficult to execute, they will have to happen on the demand side.

## 1.2 Guantao

Guantao is a county of southern Hebei province, China, in the east of its prefecture-level city Handan. It has a population of 346'000 with 259'000 being farmers, and an area of 456.3  $km^2$  of which two-third (299.48  $km^2$ ) is used for agricultural [4]. The soil in the semi-arid Guantao is very fertile and thus suitable for agriculture.

Guantao is part of the North China Plain, which means that it is growing the same/similar crop, and its only reliable water supply is the already heavily depleted groundwater. With a precipitation of around 530  $mm/a$ , there wouldn't be a big problem with cropping once a year, but because of the big demand for yields – especially for wheat, which is being grown in winter when the precipitation is at its lowest – a large agricultural demand for water exists. Like with most other domains in the North China Plain, that water has to come from groundwater pumping.

In the east of Guantao flows the river Weihe from which it is getting (a small amount of) water through the Weixi Main Channel (4.65  $mio m^3/a$  for irrigation). Compared with the total water demand of the crops, this constitutes a very small part. The river itself is usually not suitable for agriculture as its quality (apart from high seasons) is too low; sewage water from cities and industries are – most likely – being drained into the Weihe River without any or insufficient treatment.

Since 2012, the Yellow River has been diverted to flow into Guantao in winter, when its water is not needed as much for agriculture like in the high season. The main reason for this diversion is to let the water infiltrate directly into the ground and recharge the groundwater, without using it for irrigation. It is not quite clear how much water eventually infiltrates there but it is assumed that from around 10-20  $mio m^3$  water, 7.5  $mio$  is infiltrating each year (efficiency  $\approx 50\%$ ).

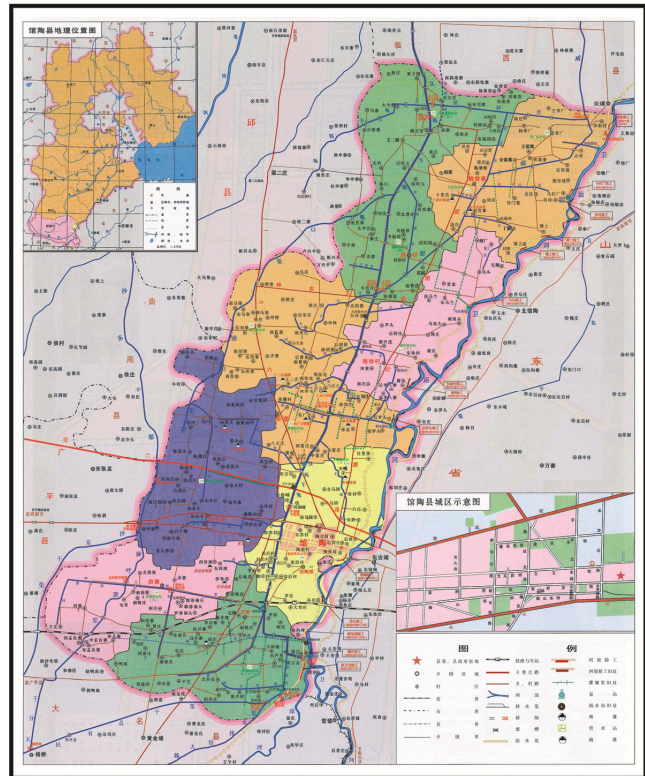


Figure 3: Map of water projects in Guantao [5]. The Weihe River forms the east border.

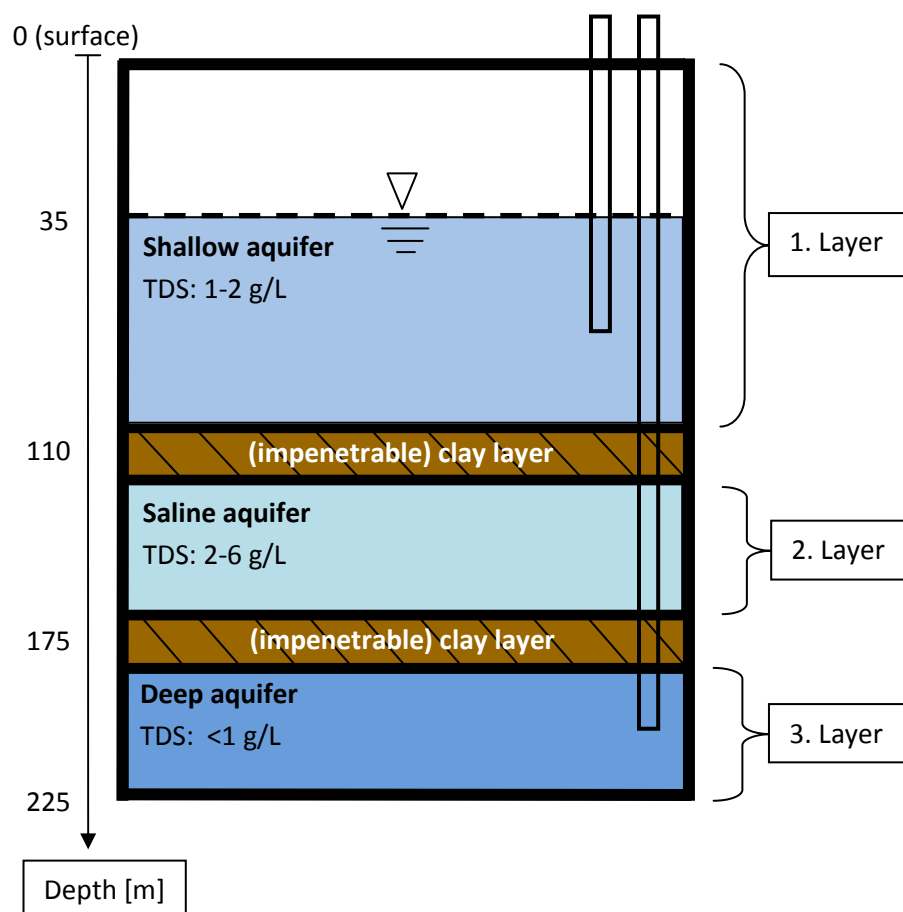
## 2. Guantao's structure

In this chapter, simplified representations for Guantao's ground and surface structure are being illustrated, which help analyze the groundwater and salinity problems. Additionally, the box model with all the water in- and outflows in Guantao is being illustrated. With the information gathered there, it was possible to calculate the evapotranspiration and infiltration rate for each crop.

The following models are not only a good way to get an insight into the high water demand consequences in Guantao, but they are also necessary for the software. The program is based on those models, and with them, goals can be set to reach a more sustainability agriculture practice.

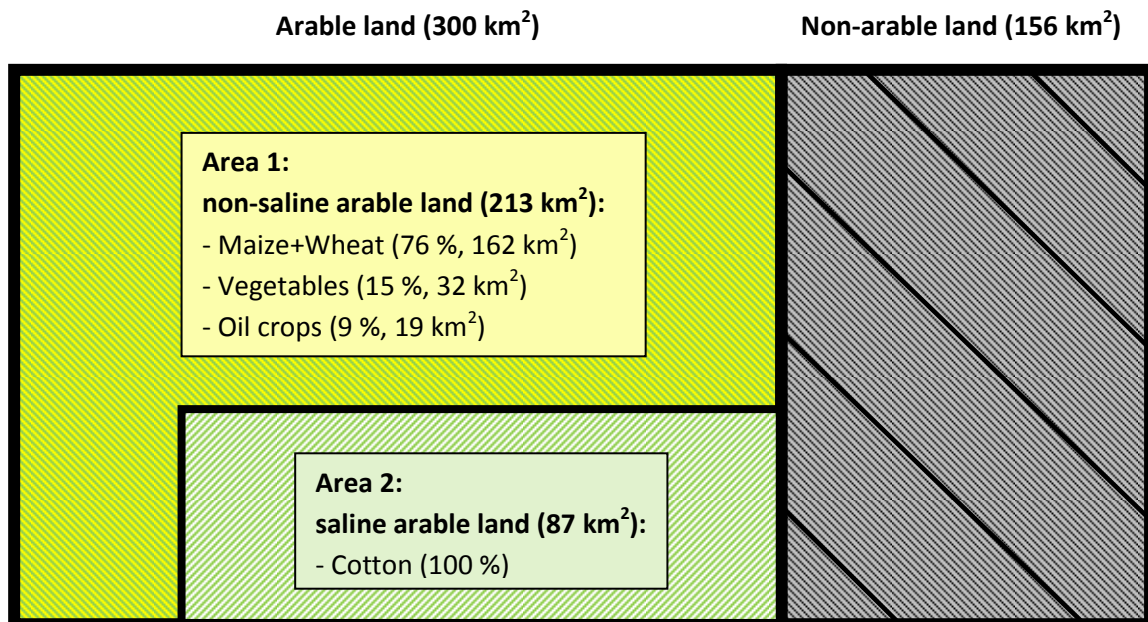
### 2.1 Ground and surface structure

Guantao's geological structure is a complex series of different groundwater layers with regions of different salinity (TDS = Total dissolved solids). It is assumed that there are at least three groundwater aquifers in Guantao with different salinity as shown in the following *Figure 4*.



**Figure 4:** Geological structure in Guantao [4]. Water is being pumped from the deep and shallow aquifer. The average elevation of Guantao is 41 meters above sea level [6].

The farmers are mainly pumping water from the shallow aquifer for agriculture ( $89.3 \text{ mio m}^3/\text{a}$ ). Although crops are – at the moment – "accepting" this water, its slight salinity is gradually causing the soil to concentrate more and more salt. As a result of continuously using this slight saline water from the shallow aquifer, and the fact that the irrigation water is being left on the soil to evaporate and infiltrate without using a discharge to wash out the salt in the soil (there is a small discharge in Guantao, but it is negligible small), increasing amount of yield penalties occurred, especially in areas with more sensible crops. Today the agriculture area in Guantao can be divided into two parts: A slight saline area ( $213 \text{ km}^2$ ) with a TDS lower than  $2 \text{ g/L}$  and a more brackish area ( $87 \text{ km}^2$ ) with a TDS higher than  $2 \text{ g/L}$  [7] (see *Figure 5*). It is evident from the trend of salinity level changes, that Guantao's current agriculture practice is not sustainable; the quantity of salt in the soil is accumulating and thus yield penalties will also increase, eventually even for cotton.



**Figure 5:** Area of Guantao can be divided into two parts: non-arable and arable land. The latter one can again be divided into non-saline arable land (area 1) and saline arable land (area 2) [8].

As a result of the mediocre water quality of the shallow aquifer, farmers are also pumping from the deep aquifer ( $8.7 \text{ mio m}^3/\text{a}$  [4]), which contains high valuable fresh water, and mix it in with the soil, to temporarily reduce the negative effects of a high salinity. This high quality water is also being used for Guantao's drinking water supply and local industry.

As there isn't any significant recharge from the groundwater flow to the deep aquifer, and because of the impenetrable clay layer, which prevents vertical water movements, the outputs surpass the inputs heavily, and the groundwater level is therefore steadily decreasing (see *Figure 6*).

This reduction of the available water supply can also cause local collapses of the clay barrier, which not only leads to ground fissures and land subsidence (see *Figure 7*), but also to salt water intrusion from the above saline aquifer, which pollutes the high quality water.

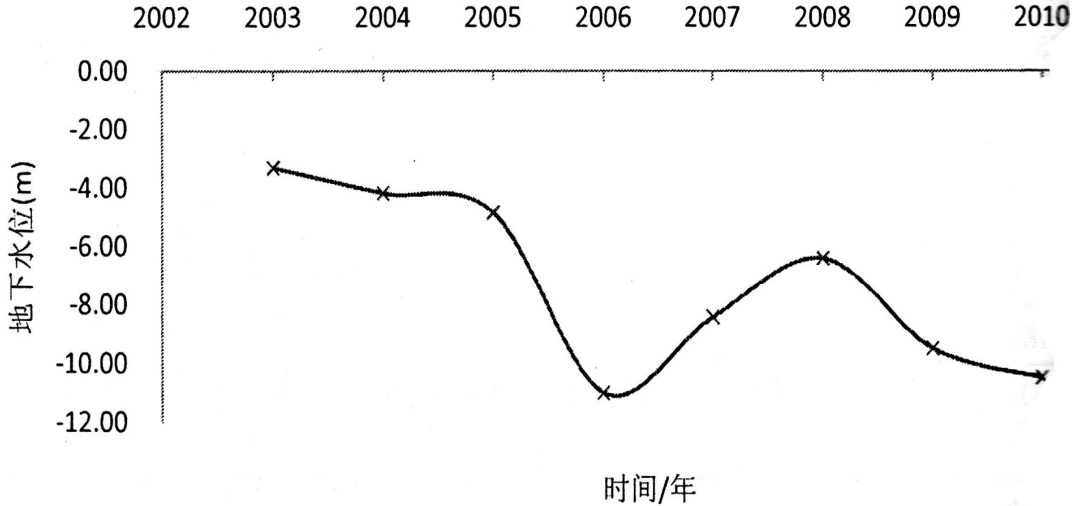


图 3-3 2003-2010 年馆陶县深层地下水平均水位年际变化曲线

Figure 6: Groundwater level decline of the deep aquifer in Guantao for the years 2003-2010 [9].



Figure 7: Overpumping of the deep aquifer destabilizes the ground and eventually leads to a collapse of the clay layer, which causes land subsidence (left picture) and ground fissures (right picture) [2].

## 2.2 Box model Guantao

The Box model of Guantao, as shown in *Figure 8*, is a simplified portrayal of the reality. The in- and outputs are, for the most part, based on data from "*Reports of project achievements in Guantao County*" [4]. Most of them are yearly average values or the mean over several years. In reality, they are not as constant as they seem in the box model. This is especially true for the precipitation, where slight changes in the amount of rainwater have big effects on the available water supply for crops.

In the box model, the surface of Guantao is being split into two parts: The agricultural and the non-agricultural area. It is assumed that those two are for the most part independent from one another, as any possible excess water in cities or industrial places will most likely evaporate or run off with the sewage water in the Weihe River, which would not affect the infiltration or the supply to the irrigation channel in a major way. With the exception of some small individual parts around the city using the runoff water, no water from this non-arable land is either being used for agricultural purposes or is infiltrating into the shallow aquifer. The only (for the program) important water flow of this area is the 14.6 *mio m<sup>3</sup>* yearly deep groundwater pumping. Most of it will be used as drinking water (11 *mio m<sup>3</sup>*) and a smaller part for the local Industry (3.6 *mio m<sup>3</sup>*).

There are several infiltration flows to the shallow aquifer, namely from the Weixi Main Channel, the Weihe River, the Yellow River and infiltration from the agriculture area. As shown in the ground structure of Guantao in *Figure 4*, a water connection between the two usable aquifers doesn't exist, hence no surface recharge in Guantao reaches the deep groundwater, which leads to an input of 0 in this aquifer. The yearly deficit is therefore equal to the output, generated by the deep pumps supplying the agriculture and non-agriculture area. Hence, the only (not too complex) way to reduce the yearly deficit in this aquifer is to minimize the output with either a demand reduction in the agriculture area, and/or a supply increase of fresh water from somewhere else.

All the values in the box model are listed in reports from Guantao [4] with the exception of the infiltration from agriculture and the evapotranspiration. While those values were used to calculate the deficit in the shallow aquifer in the reports, they were not specified there, which is why they had to be derived from the other flows for this model.

$$I_{agri} = P_{GW1} - I_{channel} - I_{Weihe} - I_{YellowRiver} - Def_{GW1} \quad (1)$$

With the infiltration rate from agriculture, the Total Evapotranspiration rate  $ET_T$  has been calculated:

$$ET_T = \frac{Q_{rain} + Q_{channel} + P_{GW1} + P_{GW2} - I_{agri}}{A_T} * [1000 \frac{mm}{m}] \quad (2)$$

$I_{agri}$	Infiltration rate from agriculture to shallow aquifer	$[\frac{m^3}{a}]$
$P_{GW1}$	Pumping rate from shallow groundwater	$[\frac{m^3}{a}]$
$I_{channel}$	Infiltration rate from Weixi Main Channel	$[\frac{m^3}{a}]$
$I_{Weihe}$	Infiltration rate from Weihe River	$[\frac{m^3}{a}]$
$I_{YellowRiver}$	Infiltration rate from Yellow River	$[\frac{m^3}{a}]$
$Def_{GW1}$	Deficit in shallow aquifer	$[\frac{m^3}{a}]$
$ET_T$	Total Evapotranspiration rate	$[mm]$
$Q_{rain}$	Precipitation on Guantao agriculture	$[\frac{m^3}{a}]$
$Q_{channel}$	Irrigation water from Weixi Main Channel	$[\frac{m^3}{a}]$
$P_{GW2}$	Pumping rate from deep groundwater for agriculture	$[\frac{m^3}{a}]$
$A_T$	Total agriculture area of Guantao	$[m^2]$



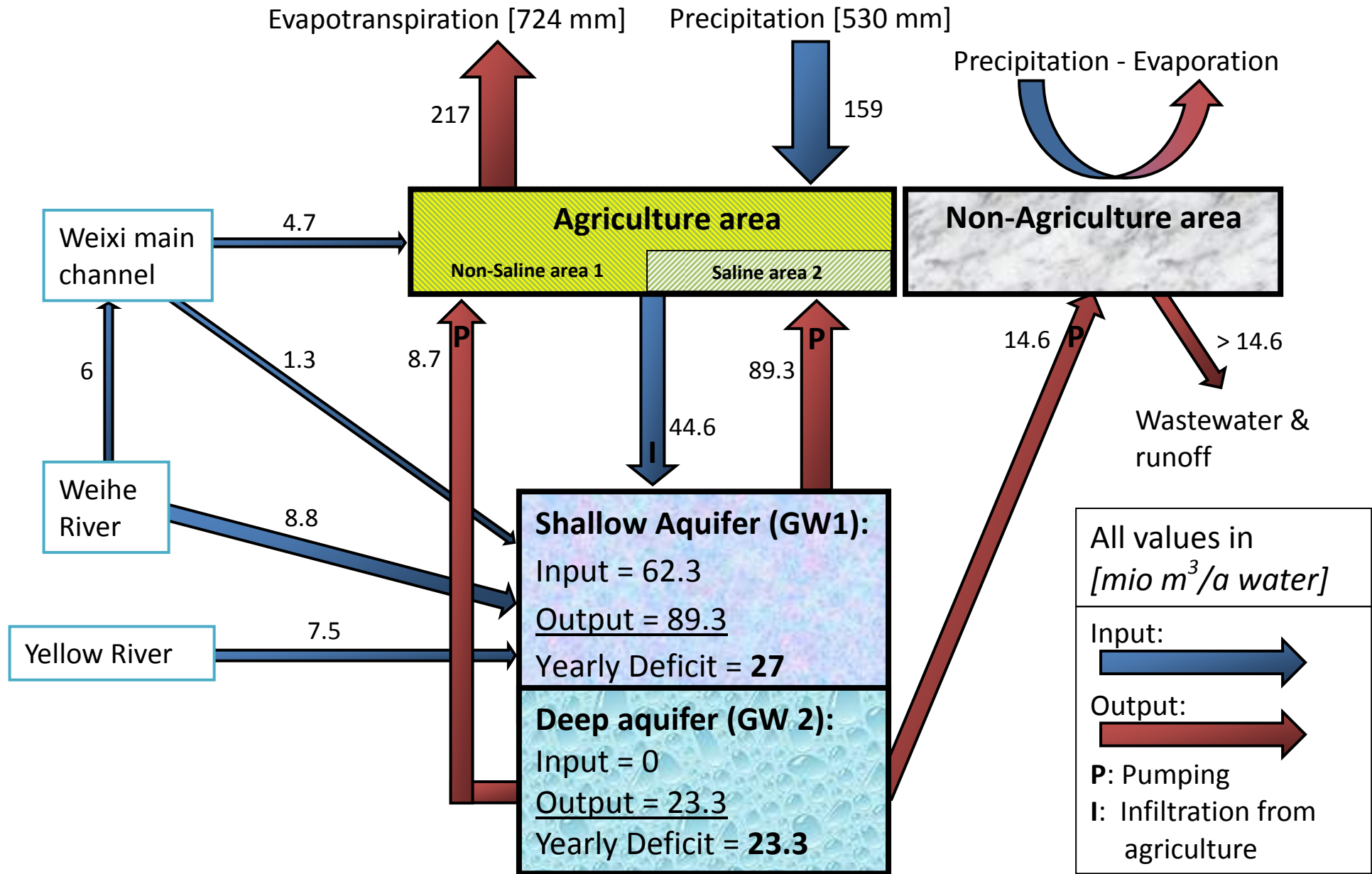


Figure 8: Box model of Guantao. All inputs which result in recharging the aquifer are in blue, while all the outputs are red. Stated values are from the project report of Guantao County, 2014 [4].

## 2.3 Evapotranspiration and Infiltration

Ideally, the evapotranspiration rate for each crop throughout the whole year would be utilized for this model, but as those data and time series, created for example through locally measured long-term lysimeter tests, are not available, assumptions and simplifications were necessary. Another issue is that even with those values known, each farmer still has a similar but not identical agriculture practice and it is not known, if they are giving too much (additional evaporation), too less (deficit irrigation and potential yield decrease) or exactly the right amount of water to each crop.

The main challenge is to get consistent data, which includes all variable parameters, so as to achieve more accurate results. As the examination for evapotranspiration of various crops deserve an entire thesis for itself (see also the bachelor thesis from F. Rufenacht and D. Brülisauer: "Calculating the irrigation water demand for various field crops in Hebei China" ["*Berechnung des Bewässerungsbedarfs für verschiedene Feldfrüchte am Beispiel Hebei China*"]), simplifications for this program have been made, which afterwards can still be easily upgraded with more precise values.

### 2.3.1 Calculation of ET and Infiltration rate

To calculate how much each crop transpires and how much water infiltrates per square meter, two different data sets were joined: Values from the box model (Total Evapotranspiration rate  $ET_T$ ) and values from the Food and Agriculture organization (FAO) (crop coefficient) [10].

With equation 2  $ET_T$  has been calculated. This led to a value of 724 mm, which includes the beneficial and the non-beneficial evapotranspiration (beneficial means, it has been transpired by the plants and used for growth, non-beneficial refers to the "lost" water to the atmosphere). The beneficial evapotranspiration for each crop has been calculated through the following formula:

$$ET_{c,i} = ET_0 * K_{c,i} * K_{s,i} \quad (3)$$

$ET_{c,i}$	Beneficial evapotranspiration rate for crop $i$	[mm]
$ET_0$	Reference evaporation rate in Guantao	[mm]
$K_{c,i}$	Crop coefficient for crop $i$	[-]
$K_{s,i}$	Stress coefficient for crop $i$	[-]

This is the amount that crop  $i$  is using to grow in Guantao. The stress coefficient  $K_s$  was assumed to be 1; no stress or deficit irrigation. The assumption is that through the long history of agriculture in Guantao the farmers know how much water the crop needs. For the crop coefficient  $K_{c,i}$ , data from the FAO has been taken ( $K_{c,mid,i}$ ), but slightly reduced (see Appendix B, Table B. 4). The coefficient  $K_{c,mid,i}$  only applies for the mid-season and the average coefficient over the whole crop lifespan would actually be smaller. The farmers (and especially the precipitation) on the other hand are not following the  $K_c$ -curve strictly (see Figure 9) and most of the time they will actually irrigate more water than what the plants could beneficially use for transpiration. As this program can easily be upgraded later on with more accurate values through precise measurements, rough values are sufficient for now.

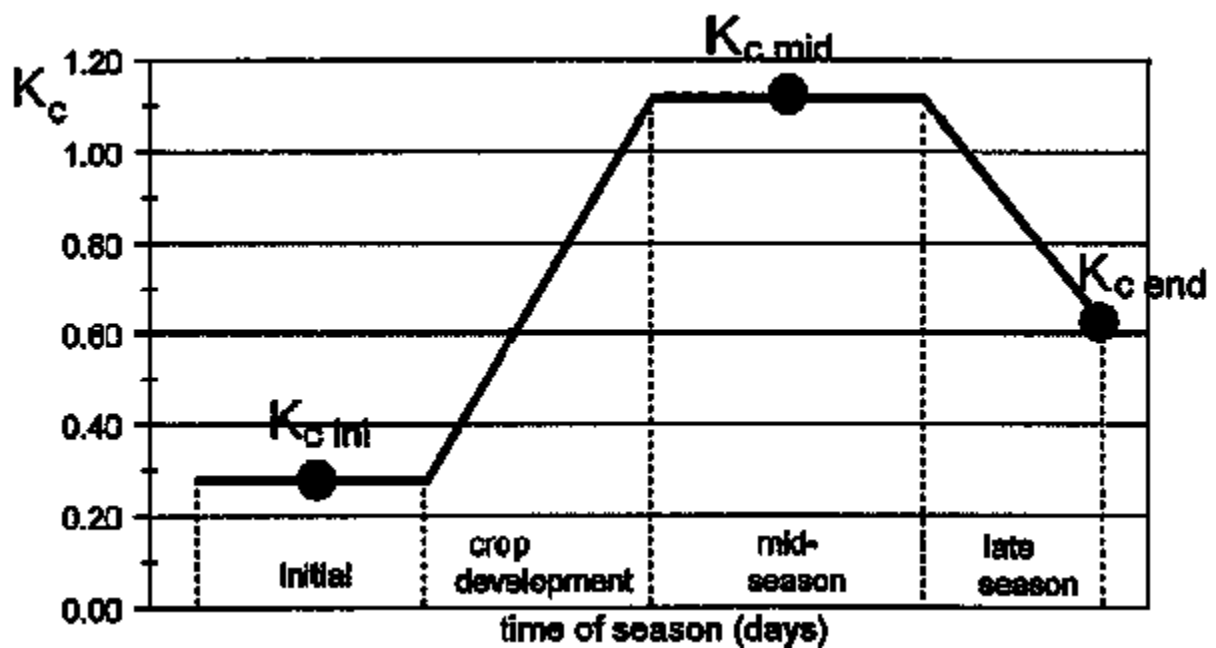


Figure 9: Crop coefficient  $K_c$  in function of its age [10].

With the values for  $ET_T$  and beneficial  $ET_{c,Guantao}$  (based on the crop combination that is being used right now in Guantao), the next parameter to calculate is the non-beneficial evapotranspiration rate  $ET_{nb}$  through a factor  $K_{nb}$  (non-beneficial factor).

$$K_{nb,Guantao} = \frac{ET_T}{ET_{c,Guantao}} \quad (4)$$

$K_{nb,Guantao}$	Non-beneficial ET-factor with Guantao's crop combination	[-]
$ET_{c,Guantao}$	Beneficial ET with Guantao's crop combination	[mm]

This factor is also dependant on the irrigation efficiency with  $K_{nb,Flood} > K_{nb,Subs}$ , though this is a contestable statement. The thought-process is that with the subsurface irrigation, the water is pumped into the soil, leading to a bigger infiltration rate than with flood irrigation, as in the latter, water is on the surface, with higher evaporation rates. With  $K_{nb,Guantao}$  the factor for each irrigation method has been calculated.

$$K_{nb,Guantao} = K_{nb,Subs} * A_{eff,Subs} + K_{nb,Flood} * A_{eff,Flood} \quad (5)$$

With:

$$K_{nb,Flood} = K_{nb,Subs} * \frac{k_{Flood}}{k_{Subs}} \quad (6)$$

$$k_{Flood} = (E_{Flood})^{-1} \quad (7)$$

$$k_{Subs} = (E_{Subs})^{-1} \quad (8)$$

$K_{nb,Subs}$	Non-beneficial ET-factor for subsurface irrigation	[–]
$K_{nb,Flood}$	Non-beneficial ET-factor for flood irrigation	[–]
$A_{eff,Subs}$	Effective area with subsurface irrigation	[m <sup>2</sup> ]
$A_{eff,Flood}$	Effective area with flood irrigation	[m <sup>2</sup> ]
$k_{Flood}$	Water demand factor for flood irrigation	[–]
$k_{Subs}$	Water demand factor for subsurface irrigation	[–]
$E_{Flood}$	Efficiency of flood irrigation	$[\frac{\%}{100}]$
$E_{Subs}$	Efficiency of subsurface irrigation	$[\frac{\%}{100}]$

These non-beneficial factors were necessary to identify how much water will be lost through non-beneficial evapotranspiration ( $ET_{nb}$ ) and how much will infiltrate for each crop  $i$  depending on the irrigation system in Guantao. The non-beneficial evaporation has then been calculated with the following equation:

$$ET_{nb,i} = (K_{nb} - 1) * ET_{c,i} \quad (9)$$

With further development of the program and investigation of the local crops, those used factors will most likely be the first to be modified. They have been implemented to create consistency and to connect two different datasets with one another.

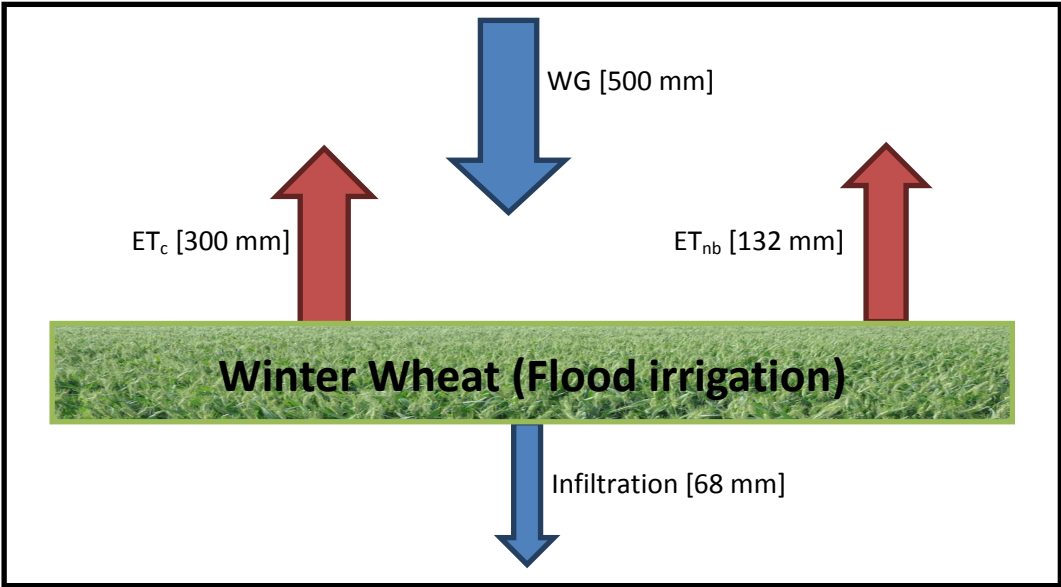
With the amount of water ( $WG$ , irrigation + rain water) that is given to the crop  $i$  the infiltration has been calculated.

$$WG_i = k_{(Flood,Subs)} * ET_{c,i} \tag{10}$$

$$I_{agri,i} = WG_i - ET_{c,i} - ET_{nb,i} \tag{11}$$

$WG_i$	Water that crop will receive through irrigation and precipitation	[mm]
$k_{(Flood,Subs)}$	Water demand factor (either $k_{flood}$ or $k_{Subs}$ )	[-]
$I_{agri,i}$	Infiltration rate of crop $i$ into shallow aquifer	[mm]

To illustrate those calculations, an example has been made with winter wheat, which is being flood irrigated:



**Figure 10:** How much water is given to  $1\text{ m}^2$  of winter wheat with flood irrigation for its whole lifespan and how much of it will evaporate and transpire. The rest (here 68 mm) will infiltrate.

### 3. Program structure

The main objective of this software is to calculate and visualize how different alterations of the present agriculture practices in Guantao would affect the ecology – mainly the groundwater storages – and accordingly the economy from the agriculture side. Furthermore, there are two checkpoints included, to illustrate to the user what effect the water demand decrease would have on the ground water.

The agriculture area is divided into two sectors: The first one ("area 1") takes up 71 % of the total agriculture land [7]. In this area all the listed crops can be planted (wheat, maize, cotton, oil crops, beet, tomato and orchard). Currently in Guantao there are no beets or orchards, and it is not clear if they even can grow there with the local conditions. If this is indeed the case, then they can be seen as temporary place holders for when more suitable plant options are found for Guantao. In the rest of the agriculture land (29 %) only cotton can be planted, as it is the least sensitive to saline soil of those listed ones, hence there aren't any yield losses to be expected (yet). In the program, cotton on the saline area 2 is being named "*Cotton 2*".

The water supplies for agriculture come from precipitation ( $159 \text{ mio m}^3$ ), the Weixi Main Channel ( $4.7 \text{ mio m}^3$ ) and the groundwater pumping ( $89.3 \text{ mio m}^3$  from shallow,  $8.7 \text{ mio m}^3$  from deep aquifer) [4]. If a scenario has been created through putting in more water efficient crops that would decrease the water demand, then this amount will first be subtracted from the groundwater pumping (first deep, than shallow), as this is not only the main goal of this program, but also more cost-efficient, due to the cost of energy for pumping, which is more expensive than the water from the irrigation channel.

Guantao is currently pumping  $89.3 \text{ mio m}^3/a$  water from the shallow aquifer. If through entries in the program, a less ecology-friendly simulation has been found (even more water has to be pumped than currently is), then this would lead to less accurate results. A larger water demand than currently in Guantao, would in reality lead to more pump installations, as soon as the available ones have reached full capacity. This, though, has not been included in this program. Today's Guantao is already residing in the ecological minimum and lowering it goes against the main goal of this thesis.

### **3.1 The two main objectives of this program**

For this program, two main objectives have been created and integrated. The aim is to reduce the yearly groundwater deficit in both aquifers. To achieve that, the water demand has to be reduced and the supply has to be increased. Both of those aspects have been integrated into the program, however, a heavier emphasis lies on the first one, as it is a more realistic and programmable strategy.

The two goals are as follows:

- 1<sup>st</sup>: Shutting down the deep groundwater pump for agriculture (GW 2 pump)
- 2<sup>nd</sup>: Reaching a yearly deficit of 0 in the shallow aquifer

Those two goals can also be seen as checkpoints: If the water demand has been decreased enough, the deep groundwater pump would not be needed anymore. Additionally, with continued downscaling of demand, eventually a shallow aquifer deficit of 0 can be achieved. It is not possible to reach the 2<sup>nd</sup> goal without first reaching the 1<sup>st</sup> one; the deep aquifer is more important than the shallow one, hence water demand reduction affects it first.

It is important to note that not all problems of Guantao's agriculture and aquifers are integrated in those two goals; it is not possible to reach a yearly deficit of 0 in the deep aquifer with agriculture water demand reduction alone, as the drinking and industry fresh water demand is independent of the agriculture. Secondly, the soil salinity problem has no present checkpoint. Nevertheless, the two goals cover the most critical objectives, and reaching them is a vital step towards a sustainable Guantao.

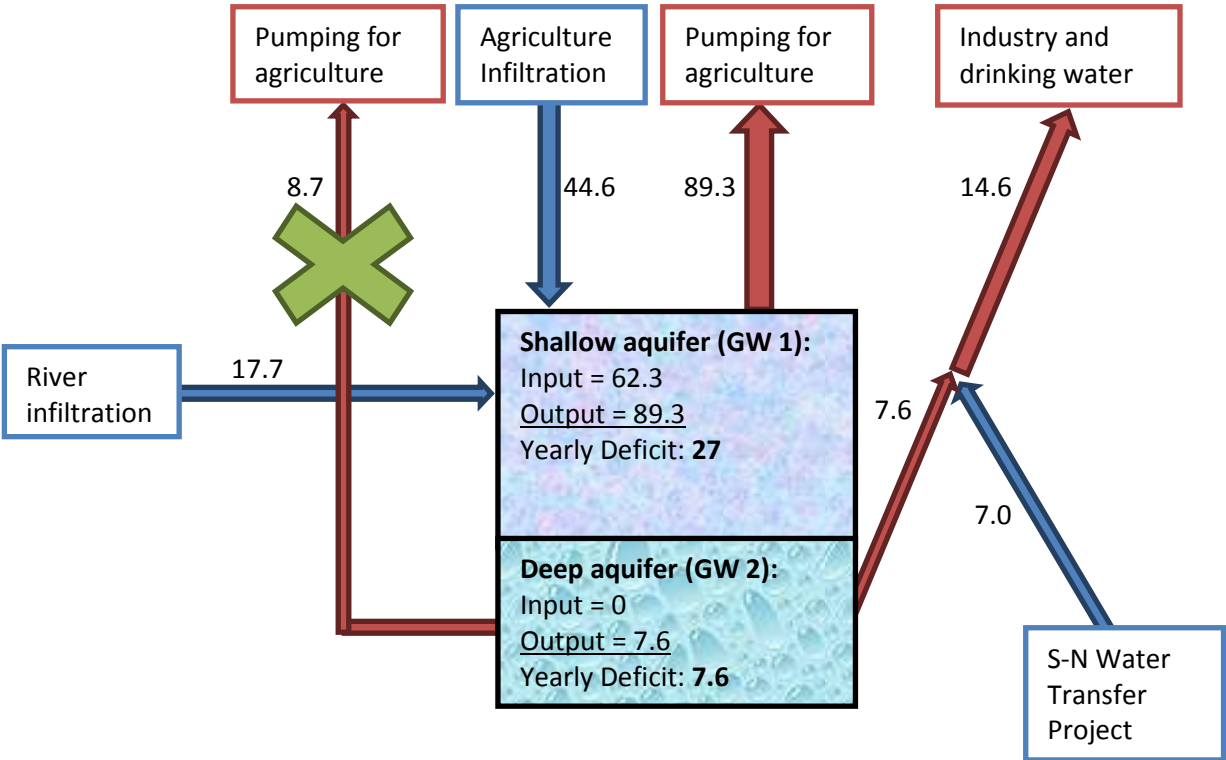
#### **3.1.1 The 1<sup>st</sup> objective: Shut down GW 2 Pump**

The first objective is to reduce the water demand of crops by the same amount as what is being pumped from the deep aquifer for agriculture (see *Figure 11*). The deep aquifer contains fresh valuable water, which is not getting recharged from agriculture infiltration, and is also not being recharged from groundwater flow (not significantly). Therefore the goal is to reduce the output as much as possible.

In today's Guantao 8.7 mio m<sup>3</sup>/a is being pumped from the deep aquifer for agriculture. With entering in different values into the program, a simulation can be created that doesn't need this water. Additionally, in 2014/15 the South-North Water Transfer Project should provide yearly around

7 mio m<sup>3</sup> water. This increase in supply can also be changed in the program, although it probably would not in reality, as this amount has already been predetermined.

Although those two changes from the demand and supply side decrease the deficit, there will still be a yearly output of 7.6 mio m<sup>3</sup> (today's Guantao has a deep aquifer deficit of 23.3 mio m<sup>3</sup>).



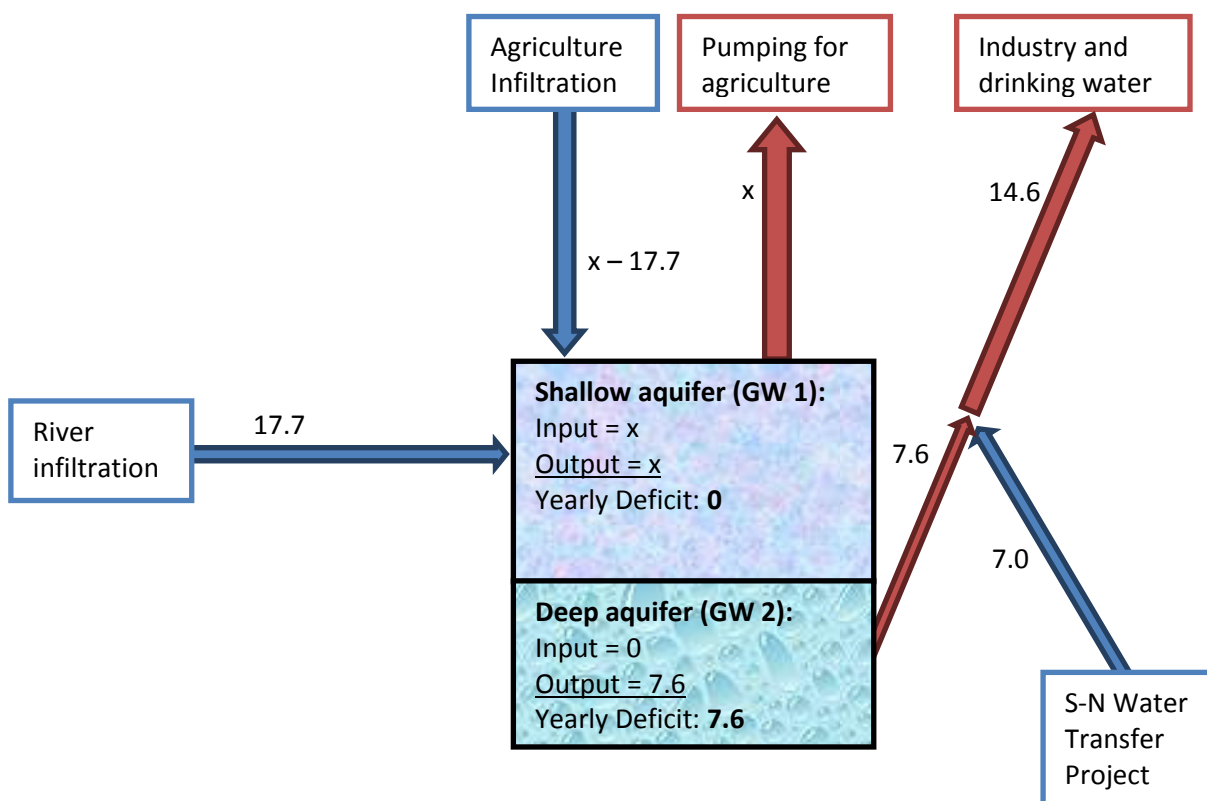
**Figure 11:** Red arrows are outputs/pumping from an aquifer, blue are inputs/infiltration/supply increase. All values are in [mio m<sup>3</sup>/a water]. There is no input into the deep aquifer. The goal is to shut down the GW 2 pump (marked with a green X). After 2014/15 the South-North Water Transfer Project will provide “fresh” water for the non-agriculture area [4].



### 3.1.2 The 2<sup>nd</sup> objective: Deficit of 0 in shallow aquifer

The second objective is to change the agriculture composition, in order to get the yearly input into the shallow aquifer to be equal to the pumping rate from it. The input consists of the infiltration rates of various rivers (Weixi Main Channel, Weihe River and Yellow River) and the one from the agriculture area.

This goal is significantly harder to reach, as the deficit in GW 1 is much higher. Due to the fact that the priority lies on the 1<sup>st</sup> goal (managing the deep aquifer is more vital than the shallow one), the GW 1 pumping rate will only then be reduced, when the GW 2 pump has been shut down. Another factor that makes this goal more difficult to reach is that with a reduction of pumping rates, the effective infiltration from agriculture will also be smaller.



**Figure 12:** Red arrows are outputs/pumping from an aquifer, blue are inputs/infiltration/supply increase. All values are in  $[mio\ m^3/a\ water]$ . The goal is to get the pumping rate  $x$  to be the same as the agriculture infiltration  $x - 17.7$  plus the river infiltration 17.7 to get a yearly deficit of 0 in the shallow aquifer [4].

## 3.2 Input data

### 3.2.1 Parameters of Guantao

The first values that the user can enter are the general parameters of Guantao's agriculture area. The default values represent the current situation. The user can change them, if he/she thinks that they need alterations. Most of the parameters are fairly constant and it is not recommended to alter them too much, but there are also some few exceptions: If the user wants for example to simulate a dry year, he/she can reduce the precipitation rate, or if he/she wants to see the effect of irrigation efficiency changes, he/she can increase or decrease it.

### 3.2.2 Crop Combination on area 1 (non-saline area)

**Requirements:**  $x \leq 100$ ,  $x \geq 0$ ,  $\sum x = 100$

The user can change the combination of crops in area 1 (71% of the total agricultural area, 213 km<sup>2</sup>). The default values represent the current crop combination.

The sum of the entered values should add up to 100, and if it exceeds or falls below that, a warning message will appear. The program is able to work with values being higher or less than that, but the user should know that this would lead to an agricultural area increase/reduction of the current area 1. If less area is used for agriculture, this means that less area needs irrigation and that in the now unused area the rainwater can partially infiltrate and recharge the shallow aquifer. Increasing the area on the other hand, would mean that land has to be given up from the non-agriculture area for area 1.

One of the crops on the list is "*Maize + Wheat*". It refers to the summer maize and winter wheat. Choosing to type in a value here means, that x percentage of area 1 is being used to grow maize in summer and wheat in winter. It is already a double cropping, which is why it won't come up again in the "*Multiple cropping*" entry table.

Simultaneously, with this entry table comes a spreadsheet displaying data of all available crops, including how much profit they will generate with which irrigation technique, how much water they need, and how many times a year they can be cropped.

### 3.2.3 Area 2 (saline area) usage

**Requirements:**  $x \leq 100$ ,  $x \geq 0$

For area 2, the user can decide how much of the saline area he wants to use for cotton production. The rest of the area will stay idle and contribute to the shallow aquifer recharge through rainfall infiltration. While planting cotton is of course economically more reasonable, the user should know that it might not be completely sustainable; the soil there has already accumulated a considerable amount of salt, and by continuous cotton production and irrigation with slight saline water, the salt concentration will only grow, until eventually even cotton can't be grown there anymore. A potential restoration of this land will then be more difficult and expensive.

Values entered here have to meet the requirements listed above. Values above 100 % will lead to an error message, as an area increase is not an option here.

### 3.2.4 Multiple cropping

**Requirements:**  $0 \leq x \leq 1$  (for *Tomato*:  $0 \leq x \leq 2$ )

Only wheat, oil crops, beets and vegetables (represented by tomato) of the listed plants can perform double cropping, with the last one even being able to perform triple cropping. Other crops take either more than half a year to grow, or are not suitable for winter conditions. The user has to enter the following values for his choice:

- Entering a value of  $x = 0 \rightarrow$  Single cropping; crop will be planted once a year
- Entering a value of  $x = 1 \rightarrow$  Double cropping; crop will be planted twice a year
- Entering a value of  $x = 2 \rightarrow$  Triple cropping; crop will be planted three times a year, only for *Tomato*

Entering those values mean that this crop will grow  $x+1$  times a year. *Maize + Wheat* is not an option here, as this specific combination has already been included in the crop combination (see under chapter "3.2.2 Crop Combination").

By choosing to double crop, the "*Designated area*" for this crop (that has been chosen in "*Crop Combination*") is being increased by the factor  $x+1$ . This leads to the "*Effective area*", which is being used to produce crop yield.

$$Effective\ area = Designated\ area * (x + 1) \quad (12)$$

The total yield of the crop  $i$  is a function of the *Effective area*, crop *yield* (data from the Yanqi Basin, see Appendix B, Table B. 3) and the irrigation technique factor  $f_{yield}$  ( $f_{yield}$  for flood irrigation = 1, for subsurface irrigation = 1.2).

$$Yield_{T,i} = Yield_i * Effective\ area * f_{yield} \quad (13)$$

$Yield_{T,i}$	Total yield of crop $i$	[kg]
$Yield_i$	Yield of crop $i$ per $m^2$	$[\frac{kg}{m^2}]$
$f_{yield}$	Yield increase factor through additional fertilizer	[-]

Decimal numbers for  $x$  are also possible. For example  $x = 0.6$  for oil crops means that 60 % of the designated oil crop production will grow twice a year and the rest (40 %) just once.

### 3.2.5 Irrigation system

**Requirements:**  $0 \leq x \leq 1$

The two currently in the program integrated irrigation systems are flood and subsurface irrigation. The user can decide which techniques to use for which crop.

$x = 0$  (→ Flood irrigation)

$x = 1$  (→ Subsurface irrigation)

The benefit of subsurface irrigation is, that it needs less water, resulting in lower overall pumping costs, reduces some planting cost (see Appendix B, Table B. 1), and also leads to a yield increase due to integrated fertilization ( $f_{yield}$ ). The disadvantages are that with less water given to crops, a smaller amount infiltrates to the ground compared to flood irrigation. There is also a tremendous installation cost for the pipes in the first year (included into the program), which have to be replaced each 5 to 10 years (not included).

How much water a farmer needs to give to a specific crop  $i$  is a function of the irrigation efficiency (these equations have also been shown in chapter **2.3.1 Calculation of ET and Infiltration rate**):

$$WG_i = k_{(Flood,Subs)} * ET_{c,i} \quad (10)$$

$$k_{Flood} = (E_{Flood})^{-1} \quad (7)$$

$$k_{Subs} = (E_{Subsurface})^{-1} \quad (8)$$

The lower the efficiency, the larger the amount of water is that has to be given to crops, and therefore the higher the infiltration rate into the shallow aquifer. Thus, the subsurface irrigation doesn't have to be a direct improvement on all fronts compared to the flood irrigation.

Like with double cropping, decimal values are also feasible. A value in between would mean that this amount of the specific crop is being treated with subsurface irrigation and the rest with flood. For example: A value of 0.2 in *Maize* means that subsurface irrigation will be practiced on 20 % of the designated maize area and flood irrigation on 80 %.

### 3.3 Program output and Graphical User Interface (GUI)

All typed in input values will be integrated into the program and their effect on economy (profit, individual costs) and ecology (groundwater deficit in both aquifers, amount of fallow land) will be calculated. Those results will then show up in a table (Figure 13) and simultaneously, the GUI of this program appears (Figure 14).

	mio CNY/a	km <sup>2</sup>	mio m <sup>3</sup> water/a
money won	1.3788e+03	0	0
planting cost	423.3095	0	0
initial S.irrigation cost	0	0	0
cost of pump water	14.7000	0	0
cost for Yellow River water	0.1950	0	0
cost of S-N-project water	49	0	0
profit (money won - cost)	891.6341	0	0
profit in the first year	891.6341	0	0
	0	0	0
unused saline area	0	0	0
unused non-saline area	0	0	0
	0	0	0
yearly deficit in shallow GW	0	0	-27.0324
pumping rate of shallow GW	0	0	89.3350
yearly deficit in deep GW	0	0	-16.2650
pumping rate in deep GW	0	0	8.6650

Figure 13: In this table, the results of the entered values are shown. In this particular table these listed values correspond to the current situation of Guantao (default values).

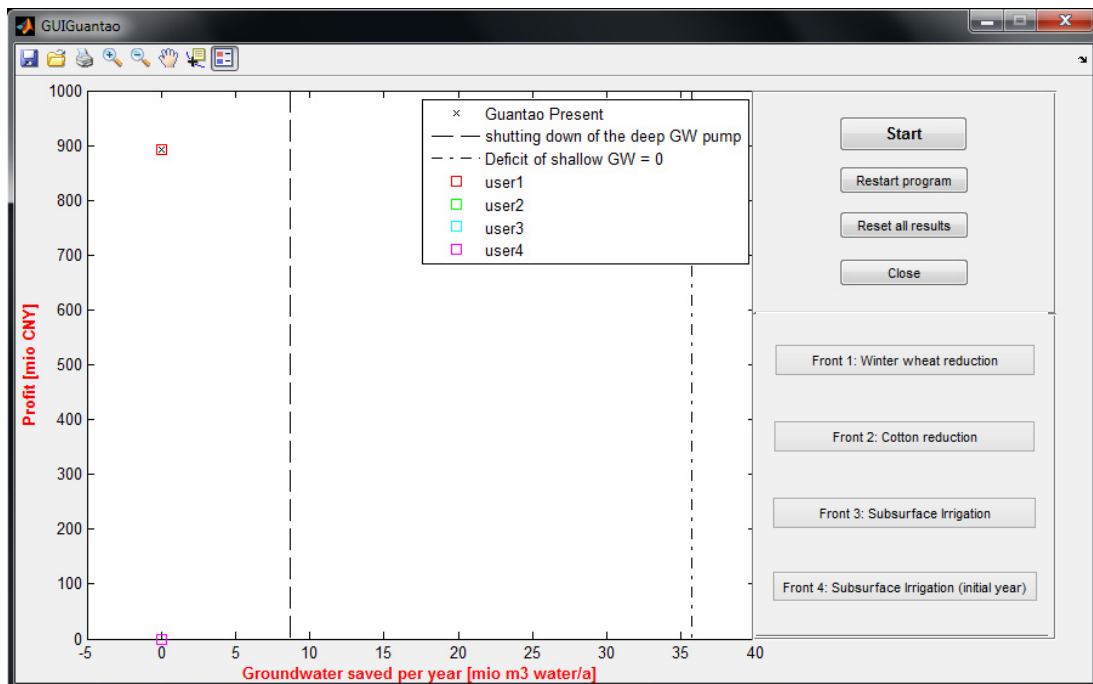


Figure 14: Graphical User Interface of the program. Dashed line on  $x=8.7$  signals the 1<sup>st</sup> goal, dotted line on  $x=35.7$  signals the 2<sup>nd</sup> goal. The x-axis shows the groundwater deficit reduction in both aquifers, while the y-value shows the profit generated through agriculture.

The y-axis shows the profit that will be generated with the crops. The various costs are all included, with the exception of the installation cost of subsurface irrigation.

The x-axis points out how much groundwater the user has saved with his/her entries. The value for x is equal to the amount of deficit reduction in both aquifers. The higher this value, the smaller the yearly deficit will be. At  $x=0$  the situation is exactly the same as it currently is in Guantao. The dashed line at  $x=8.7$  signals the 1<sup>st</sup> goal. After reaching and exceeding this point, the GW 2 pump can be shut down and no more water from the deep aquifer will be used for agriculture. The dashed and dotted line at  $x=35.7$  signals the 2<sup>nd</sup> goal: shallow aquifer deficit is equal to 0. As shown in the figure, the 2<sup>nd</sup> goal is much farther away from the current situation in Guantao than the 1<sup>st</sup> one.

To initiate the GUI, the user has to press **Start**. It will show the user, where his/her entries will lead to (see *Figure 14*). By pressing **Restart program**, the whole program starts itself again and new entries can be typed in, without deleting the mark of the first run-through (user1). A maximum of 4 simulations can be simultaneously shown this way (after that, the first value (user1) will be overwritten). To reset all simulations, the user can press **Reset all results**. By clicking on **Close** the GUI closes.

Additionally, there are several fronts that can be shown in the axis. Those are all single input changes. For example **Front 1: Winter wheat reduction** shows the user how a wheat reduction (or in other words, how much of summer maize and winter wheat has to be transferred into single cropping of just summer maize) will affect the profit and the groundwater. Starting point is the present situation of Guantao and endpoint is when the intensity has reached its maximum, in this case 100 % wheat reduction. There are also single input changes for cotton reduction on the saline area 2 (**Front 2**) and irrigation technique changes on the *Maize + Wheat* field (installation cost in first year excluded (**Front 3**) and included (**Front 4**)). This should give the user an idea, which strategies are more viable and how to reach the set goals more efficiently. Those four fronts will also be examined more closely in this thesis.

## **4. Results and possible improvement strategies**

The user can interact with the software and is able to create different scenarios, regardless of how far-fetched they are in reality. The goal of this thesis though is to find a good strategy to achieve sustainability for Guantao's agriculture with minimal profit losses which does not require a complete overhaul of the current agriculture practices. In this chapter individual parameters have been changed to see their effect on Guantao and to identify a good strategy. This method has first been performed by changing just one single parameter for each run and analyse its effect on profit and groundwater deficit (also shown in the GUI as the four fronts). A test has also been made by changing several parameters at the same time and calculating how large the intensities of the changes are to reach each set goal.

### **4.1 Single input changes**

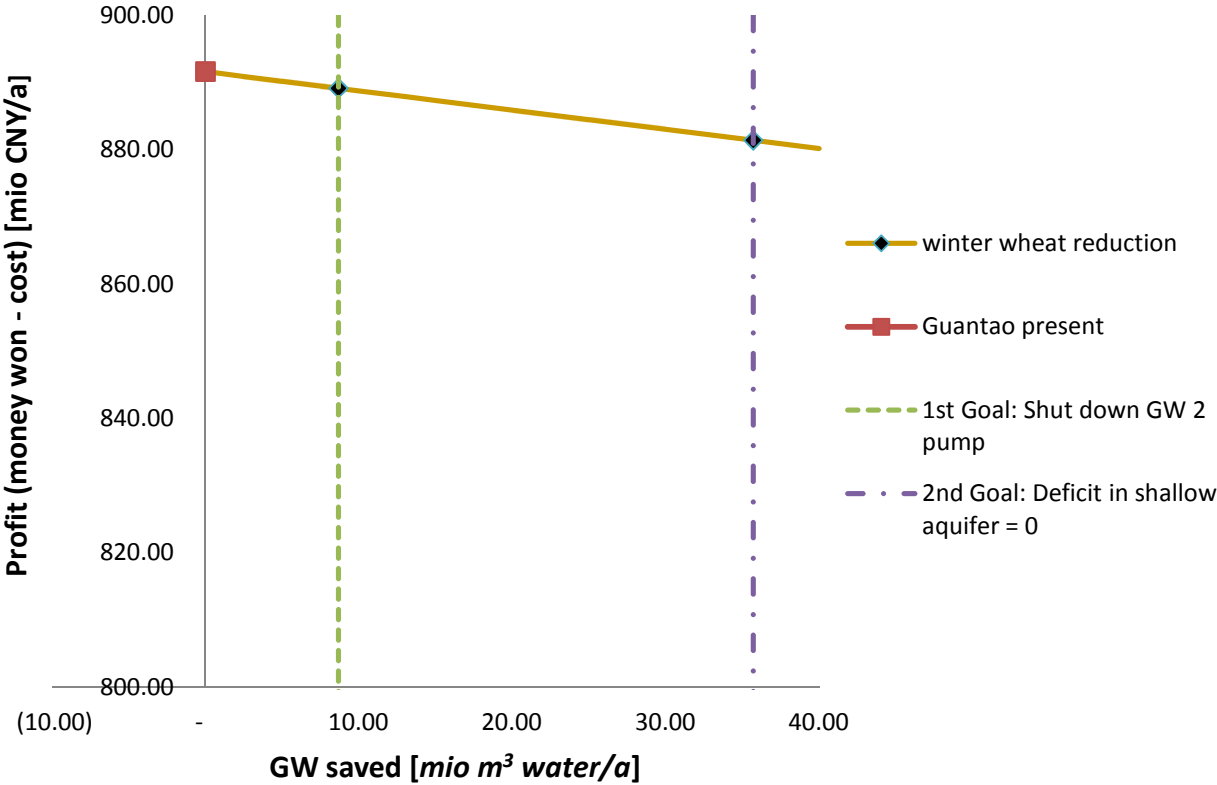
The program has been executed while only changing one single value (all the other ones are default values of today's Guantao and are left unchanged). Through this method the impact of individual changes on groundwater deficit and profit in function of the intensity can be shown. While this single input method is less realistic or efficient to create standalone improvement strategies (multiple input changes can combine with one another to reach a more rewarding result), it is a good way to discover the potential of each possible change for further strategy building.

There are several input changes that can be done with this program. In this thesis the following three will be looked at in detail: Winter wheat reduction, cotton reduction on saline area 2 and irrigation system change on the maize and wheat field.



### 4.1.1 Winter wheat reduction

Farmers in Guantao are using around 76 % of the non-saline area 1 for maize in summer and wheat in winter. This heavy double cropping practice is one of the biggest reasons why so much water has to be pumped in the first place. While those two crops are the main products of Guantao's agriculture area and an important food source for farmers, they are not that profitable relative to the amount of water they need. This is particularly true for wheat, which is – including all associated costs – far less profitable than maize. Hence the idea is to see how much of the winter wheat production has to be given up to achieve a more sustainable situation and what the costs of such a change would be (see *Figure 15* and *Table 1*).



**Figure 15:** Beginning at Guantao present, the amount of winter wheat cropping is steadily being reduced to see its effect on the groundwater deficit and profit.

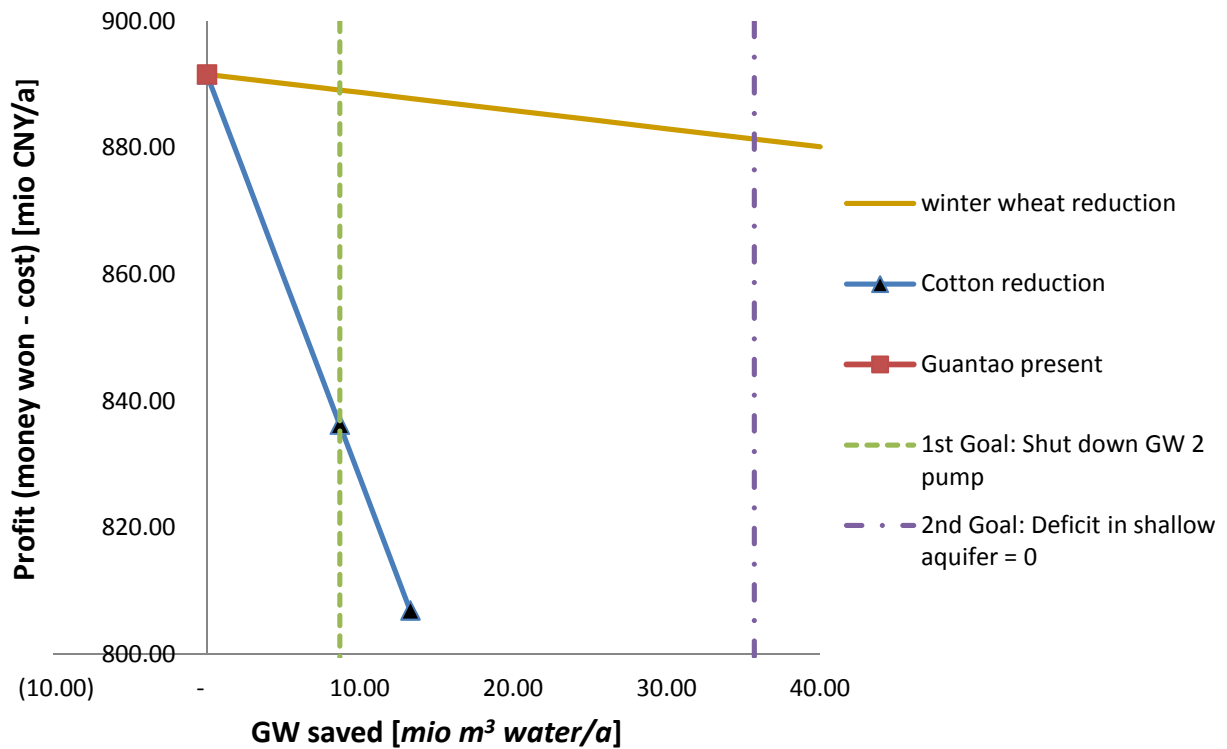
**Table 1:** The effect of winter wheat reduction on yield and profit. Three locations are being looked at: Guantao present ( $x=0$ ), 1<sup>st</sup> goal ( $x=8.7$ ) and 2<sup>nd</sup> goal ( $x=35.7$ ).

Location	Maize field (summer) relative to whole area 1 [%]	Wheat field (winter) relative to whole area 1 [%]	Wheat yield losses [t]	Profit losses [mio CNY/a]
$x=0$	76	76	0	0
$x=8.7$	76	66	11'400	2.5
$x=35.7$	76	35	46'900	10.2

As seen in these illustrations, a reduction of winter wheat can potentially achieve both goals, without suffering a high profit loss. While this method seems very efficient and a good starting point for further improvement strategies, it has to be kept in mind that farmers still need food to eat and maize alone is not enough. They could theoretically just buy wheat from other farmers or import it, as at the moment this would not be much more expensive (if not even a little bit cheaper) than cropping wheat for themselves. But continuing this thought process; the balance of supply (less wheat produced) and demand (more wheat will be bought) would change, rapidly shifting the market price for wheat to the disadvantage of farmers who gave up winter wheat production.

#### 4.1.2 Cotton reduction on saline area 2

The entire saline area 2 is being used for cotton production. The reason why this area has concentrated a considerable amount of salt in the soil is because of the pumping of slight saline groundwater from the shallow aquifer. To stop this soil destruction Guantao either needs to install good discharge channels for agriculture to wash away the salt, use only fresh water from the deep aquifer – which would lead to a massive groundwater level decline and is only a temporary solution for the soil – or give up land, so that rain eventually can wash the salt away (slow process). The third option (reduction of cotton cropping by giving up land) has been examined here to see its effect on groundwater and profit. The results are shown in *Figure 16* and *Table 2*.



**Figure 16:** Beginning at Guantao present, the amount of cotton cropping on the saline area is being steadily reduced to see its effect on the groundwater deficit and profit.

**Table 2:** The effect of cotton planting reduction on saline area on yield and profit. Three locations are being looked at: Guantao present ( $x=0$ ), 1<sup>st</sup> goal ( $x=8.7$ ) and at maximum reduction ( $x=13.3$ ).

Location	Area used for cotton [%]	Unused saline area [km <sup>2</sup> ]	Cotton yield losses [t]	Profit losses [mio CNY/a]
$x=0$	100	0	0	0
$x=8.7$	35	56.7	8'740	55.3
$x=13.3$	0	86.8	13'400	84.7

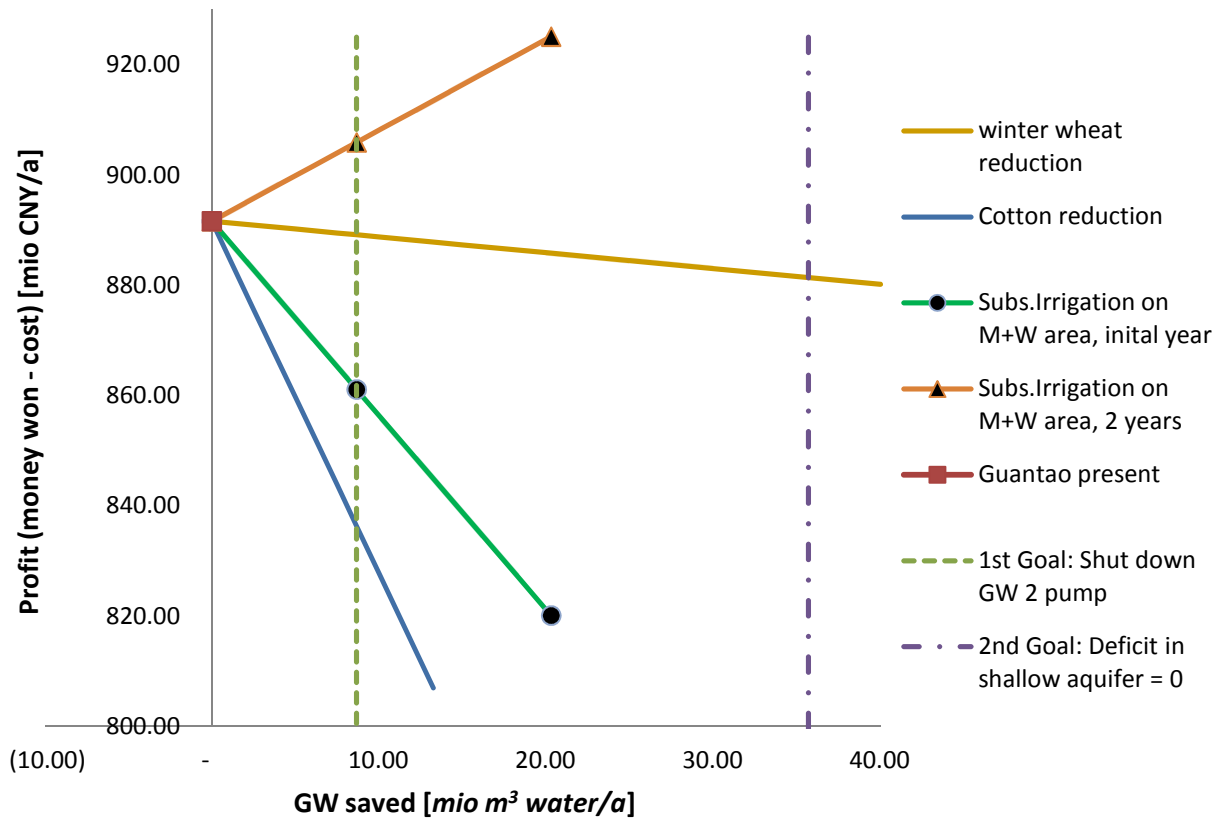
Through sacrificing cotton production the 1<sup>st</sup> goal can be achieved, but the 2<sup>nd</sup> one cannot be reached. At  $x=13.3$  the cotton production on the saline area has completely been shut down. Visible is as well that this method leads to massive profit losses.

Compared to the wheat reduction, it seems like this method is not only far less profitable, but also it does not have the potential to reach all goals. Cotton production is very lucrative, especially compared to wheat. Hence a reduction comes hand in hand with significant profit losses.

While this method seems to be less efficient, it has to be taken into consideration that a cotton reduction is (most likely) an action that eventually has to happen; either through deliberate abandoning of area in favor of water demand reduction or through forced abandoning, as production on it is not worthwhile anymore because of increasing yield penalties through the continued salination of the soil. It is clear that by staying on course with the current cotton practice in Guantao it is only a question of "when" area will be given up and not "if" it will.

#### **4.1.3 Subsurface irrigation installation on *Maize + Wheat* area**

The next single input change examines the effect of irrigation technique swapping from flood to subsurface irrigation. This transition was simulated on the *Maize + Wheat* field as it is Guantao's main production. The benefit of the new system is the more efficient handling of water resources and the yield increase that it brings, due to additional fertilization (this aspect is probably bound to be changed, as it has been taken from the Yanqi Basin and it is not known if additional fertilization will be used in Guantao and how effective this will be). The main disadvantage is the yearly maintenance cost for the pipes and also the high installation cost. Because the latter one has a considerable impact on profit, two versions of this method have been made: One that shows how the irrigation change affects the groundwater and profit in the first year (installation cost included, *green*) and one that takes the average profit of the first two years (year with installation cost + consecutive year without installation cost, *red*). Results can be seen in *Figure 17* and *Table 3*.



**Figure 17:** Beginning at Guantao present, where the *Maize + Wheat* field is 100 % flood irrigated, the system is steadily being replaced with the advanced subsurface irrigation. The green line shows the profit loss on the first year after installation and the red line shows the average profit gain after the first two years (installation year + consecutive year).

**Table 3:** The effect of irrigation system change on yield and profit (first year and average of the first two years). Three locations are being looked at: Guantao present ( $x=0$ ), 1<sup>st</sup> goal ( $x=8.7$ ) and at 100 % subsurface installation (maximum,  $x=20.3$ ).

Location	Percentage of subsurface irrigation [%]	Area with subsurface irrigation [km <sup>2</sup> ]	Maize + Wheat yield gain [t]	Profit losses in installation year [mio CNY/a]	Average profit gain of two years [mio CNY/a]
$x=0$	0	0	0	0	0
$x=8.7$	43	69	29'000	30.5	59.1
$x=20.3$	100	162	68'000	71.5	139

This input change resembles the one for cotton reduction as it also reaches the 1<sup>st</sup> goal while suffering relative high profit losses in the initial year (though not as high) and also never reaches the 2<sup>nd</sup> goal. The difference though is that the high investment pays off, as already in the second year the farmers will make more profit than what they currently make with flood irrigation.

The main reason for never reaching the 2<sup>nd</sup> goal at maximum intensity – although it comes closer to it than cotton reduction – is the fact that although through the higher efficiency of the technique, less water has to be given to the crops (reduction of pumping rate), less will also eventually infiltrate to the shallow aquifer again.

While in the long run it seems to be a good idea to install the newer technique, there are some considerations that have to be made first which are not displayed in this program. An enormous change in the daily routine of a farmer like this requires not only acceptance from his side, but also requires additional know-how. The benefits this system has can quickly be overruled if farmers handle the newly installed subsurface irrigation incorrectly, as they are not used to it (profit and water losses through incorrect application or need of additional repairs). Additional training of farmers will most certainly be required.

Another arguable point is the uncertainty of yield increase generated with the new irrigation system, which has an immense impact on the curve. Relying on the 20 % additional yield increase does not make much sense unless this system has first been successfully tested in Guantao. If this factor is disregarded ( $f_{\text{yield}} = 1$ , no additional yield) the consequences of subsurface irrigation will lessen the profit by a considerable amount, even when the installation costs are excluded.

While the result of this input change is associated with many uncertainties, it has to be said that this is the only single input change, which does not decrease the total yield of Guantao. This means it is the most independent one, as the others are more inclined to require additional changes to make up for their yield losses.

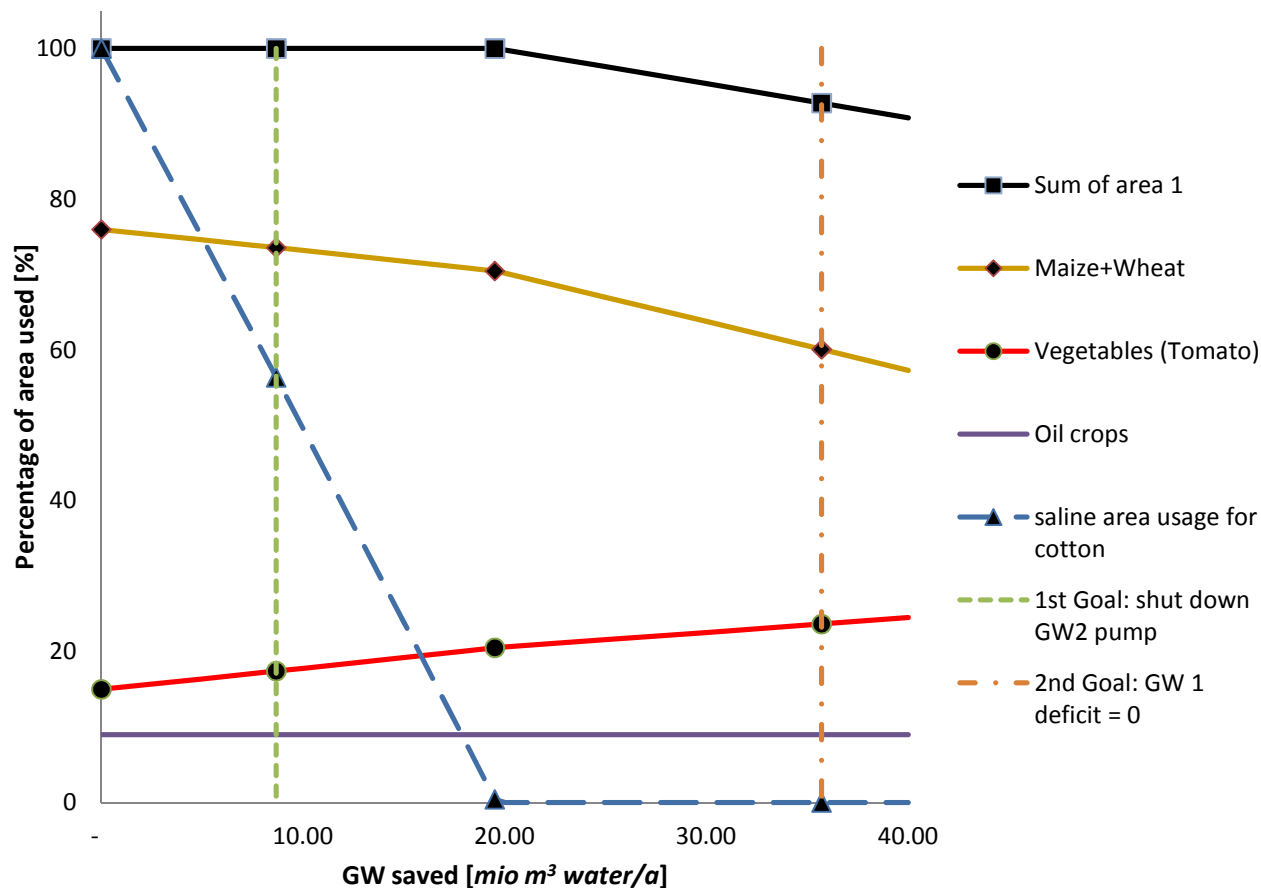
## 4.2 Multiple Input Changes

With single input changes different strategies can be analyzed, but in reality, actions will most likely not concentrate on one single changeable point. Hence with multiple input changes a more realistic design can be created. There is a high number of different scenarios that can be simulated with this program, some more feasible than others. Demonstrated below is a possible scenario and solution that includes – together with the groundwater deficit issue – the problem of the unsustainability of cotton production on saline area.

The changeable parameters are the amount of *Maize + Wheat* and *Vegetables (Tomato)* cropping on area 1 and the *Cotton* production on area 2. In today's Guantao, farmers are also producing a small amount of oil crops, which is not the most cost-efficient crop to grow. Nevertheless, this parameter has been set constant as the amount is relatively small and because it is most likely a product to satisfy the personal need for oil.

The idea for this particular simulation is to see how much vegetable (here represented by tomato) has to replace the maize and wheat production to reach both set goals, without reducing the profit. Though this means that the overall amount of calories will decrease significantly (calories of wheat = 338, maize = 365 and tomato = 18 [kcal] [11]), the idea is to see how much maize and wheat area will have to be replaced by more profitable plants to achieve the two set checkpoints. The most lucrative crop in the program – tomato – has been used, but theoretically for this scenario it does not even have to be a nurturing plant – medical herbs would also be an option. It simply has to be a plant that can be sold at high price so that farmers have enough money to replace the created maize and wheat deficit.

Starting point is again Guantao present at  $x=0$ . The x-axis is the same as before (groundwater deficit reduction compared to today's Guantao). But this time the y-axis shows the percentage of area used by crops and not the profit of agriculture. For this simulation a condition has been set so that the profit cannot decrease and stays exactly the same throughout all severities of changes. This means that at each point on the x-axis, Guantao's agriculture will still generate the exact same amount of money just like it did without any changes.



**Figure 18:** Beginning at Guantao present ( $x=0$ ), the maize and wheat area is gradually being replaced with tomato. To lower the groundwater deficit, first the cotton area has to be reduced and after that, area in the non-saline arable land has to be sacrificed. The sum of *Maize + Wheat*, *Tomato* and *Oil crops* adds up to 100 % at first (black curve), but decreases after a certain point.

**Table 4:** For the multiple input changes several locations are being looked at: Guantao present ( $x=0$ ), 1<sup>st</sup> goal ( $x=8.7$ ), ceasing cotton reduction on saline area 2 ( $x=20$ ) and 2<sup>nd</sup> goal ( $x=35.7$ ).

Location	Area used for	Area used for	Area used for	Usage of area 1	Usage of area 2
	Maize + Wheat	Tomato	Oil crops		
	[%]	[%]	[%]	[%]	for cotton
					[%]
$x=0$	76	15	9	100	100
$x=8.7$	73.6	17.4	9	100	56.4
$x=20$	70.2	20.6	9	100	0
$x=35.7$	60.1	23.1	9	92.2	0



Alterations of the variable parameters follow a specific order: First the least profitable, variable crop will be reduced by a certain amount to achieve higher values on the x-axis. Because this applies to cotton, a steep decline can be observed there. At the same time though, this decline of cotton production would normally lead to a profit loss. To prevent that, a small amount of the maize and wheat field has to be replaced by the more valuable tomato. At first those changes are minimal, but after a certain point all the cotton production will have been given up and now the second least profitable crop is next in line, which is *Maize + Wheat*. Because of this, the grade of its curve gets steeper and the total amount of used area in the non-saline arable land also reduces. Unused agriculture area not only reduces the water demand as it does not need irrigation, but it also contributes to groundwater deficit reduction through rainwater infiltration.

To achieve the 1<sup>st</sup> goal only 2.4 % of area 1 (5.1 km<sup>2</sup>) has to transition from *Maize + Wheat* to *Tomato*. The added benefit is that nearly half of the saline area (38 km<sup>2</sup>) can be laid fallow, without suffering a penalty in profit. The alteration in maize and wheat production though increases after no more saline area can be laid fallow anymore. To achieve the 2<sup>nd</sup> goal, 15.9 % (33.8 km<sup>2</sup>) of the non-saline area used for maize and wheat will have to be given up, with only 8.1 % of those (18.4 km<sup>2</sup>) being replaced by tomato.

The changes necessary to reach the 2<sup>nd</sup> goal are – relative to Guantao's current practice – fairly heavy, which makes a realistic implementation more complicated. The yield decrease of nurturing crops and especially the calorie losses make this strategy not feasible to achieve this goal. The 1<sup>st</sup> goal, on the other hand, seems quite manageable. The alterations to today's Guantao are not that significant (with the exception of the cotton reduction) and not only would this minimize the pumping output from the valuable deep aquifer, but it also would make an important step forward to decrease the salinity problems in area 2. While there still would remain a high deficit in the shallow aquifer, at least the situation in the more important deep aquifer has been improved without suffering a profit loss. This could be used as a breakpoint for further improvements, which after that would probably lead to unavoidable profit losses. Judging from the results of single input changes, the most likely course of action after reaching the first goal with this strategy above would be to reduce the winter wheat and/or to install new irrigation techniques (if they have been proven to be cost and water efficient in Guantao).

A major point of concern though is that the prices for crops depend on the market. An increase of tomato or other special plants production will break the balance of supply and demand in the market. To counteract the increase in supply, the relative demand will decrease and hence also the price of those lucrative plants. For this reason, major alterations in Guantao's production are not recommended, unless the whole market has been integrated.

With the program similar simulations to the above ones can be generated. Another alternative for example is to also make the oil crop production variable. This would lead to an immediate decrease of that crop as it is the least profitable of the four, before the cotton reduction begins. Another possible simulation would be to grow tomato (single cropping) in the winter months, instead of winter wheat, which is the least profitable crop and the easiest to replace (through import). The practicality though makes this simulation questionable (from the crop life span side it could suffice, but constructing a greenhouse after the summer maize has been harvested and deconstructing it to make room for maize again seems too intricate). Another option that has not been utilized in the above simulation is the irrigation technique change. The reason lies in the still fairly unknown impact the subsurface irrigation has on crops in Guantao. With new updated values for this system and other irrigation methods though, the parameter can also be put more reliably into use.

## 5. Limitations and Outlook

The goal of this thesis was to build a box model for the North China Plain county of Guantao on which improvement strategies for the high demand of irrigation water can be based on. The interactive software should then help illustrate, how effective those strategies will be. While the program is very helpful in singling out the more potential input changes and simulate a concrete strategy, it has to be said that these outputs should be looked at with caution. While the results show that winter wheat reduction has the biggest potential to solve the issue with groundwater deficit with minimal profit losses, a further study is necessary to research, how this will affect the available food supply for farmers, import options and possible price alterations.

The software contains many assumptions, simplifications and several values that have been taken from the Yanqi Basin program. The idea is to continuously upgrade those points with better and locally correct values. This will require additional measurements made directly in Guantao or at least in the surrounding area.

A major subject in need of improvement is certainly the calculation of the evapotranspiration and infiltration rate for each crop in Guantao. As these rates are not known, a correction factor had to be implemented ( $K_{nb}$ ) to connect the box model with the values from the FAO. Additionally, the crop coefficient  $K_{c,mid}$  as an average value over the whole crop lifespan has been worked with, instead of including the variability of the crop coefficient throughout the growth (see *Figure 9*).

Another major point in need of improvement is the fact that for precipitation (530 mm) and reference evaporation  $ET_0$  (550 mm [12]) the average value over a year has been used. As seen in *Figure 19*, the rainfall amount is in summer higher than in winter, which also applies to the evaporation rate. The software though has been programmed as if it would rain each day exactly the same amount over the whole year. To justify this assumption, it can be said that all excess water that the crop does not need at the moment of rain fall excess will be stored in the rain-laden summer and used in the dry winter. While it is true that Guantao has in fact storages to collect excess water, the infiltration and evaporation rate of those and their maximum capacity has not been integrated into this program.

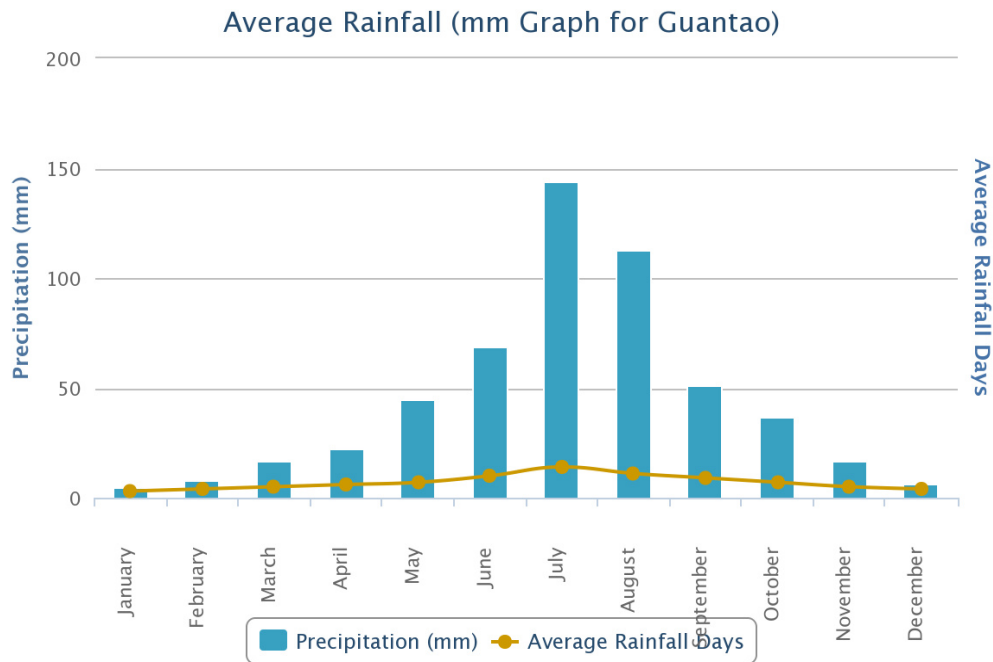


Figure 19: Monthly precipitation and number of rainfall days over one year [11].

The reliability of program outputs and their derivable strategies heavily depend on the accuracy of the input values. For now, data of each crop (yield, cost, price) and cost modifier through installing subsurface irrigation have been taken from the Yanqi Basin (see Appendix B., table B. 1-3). Crop prices are not bound to change much from one Chinese agriculture region to another, but the yield ( $kg/m^2$ ) could very well be different as the soil and especially the climate are not the same in those two locations.

All things considered, this program is – at this stage – not intended to give exact output values to work with, but to demonstrate the effect certain changes on Guantao’s agriculture have on economy and both aquifers. It can show which strategies have a higher potential in solving the immense water demand and groundwater deficit problem. The box model is designed to be the starting point for further investigations as it is constructed to be easily upgradeable with new and more accurate data. Derived strategies will then gain more ground and realistic measures can be attained to help create a more sustainable Guantao.



# A. Appendix

## A.1 References

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- [6] GeoNames geographical database, Guantao Xian;  
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- [8] Crop combination in Guantao: *Study on agricultural cycled-economy in county scale-a case study in Guantao*, 2009; <http://max.book118.com/html/2014/0107/5493813.shtm>
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- [12] H. Zhang, X. Wang, M. You, C. Liu: *Water – yield relations and water-use efficiency of winter wheat in the North China Plain*, May 1998
- [13] World Weather Online, Guantao;  
<http://www.worldweatheronline.com/Guantao-weather-averages/Hebei/CN.aspx>

## **A.2 Further Literature**

The following listed theses have either influenced the making of this one or were an inspiration.

- Dominik Roth, Jan Winkler: *Towards a Consistent Model in the Yanqi Basin*, June 2013
- Stephen Foster: *China: Towards Sustainable Groundwater Resource Use for Irrigated Agriculture on the North China Plain*, Dec. 2004
- Timon Langenegger: *Real-Time Groundwater Model for Guantao (China)*, Feb. 2014
- Gao Fai, Xuan Zijun, Fu Guilu: *The Application of ET Theory in Groundwater Management of The Well Irrigation Area*, March 2009
- Wim Bastiaanssen, Wu Bingfang, Douglas C. Olson, Jiang Liping: *Real water savings and ET reduction; The Hai Basin paradigm*, 2003

## **A.3 Acknowledgement**

First and foremost, I would like to thank Prof. Dr. W. Kinzelbach, who has provided me with crucial firsthand data, insightful literature and was a guiding hand for this thesis.

I would also like to express my sincere gratitude for Dr. N. Li, who has supported me with filling in data gaps, has helped me with the creation of the box model and its structure and who has assisted me with the translation of important data.

My sincere thanks also goes to Florian Ahr, who was responsible for upgrading the Yanqi Basin program with which I have worked with.

## B. Values used for Software

The following values have been taken from the Yanqi Basin program (Table B. 1-3) and FAO (Table B. 4). Data for Table B. 5 has been provided by Prof. Dr. W. Kinzelbach.

**Table B. 1:** Planting cost of each crop with flood irrigation. All values are in  $\frac{\text{CNY}}{\text{m}^2 \cdot \text{a}}$

Crop	Labor	Seed	Fertilizer	Manure	Pesticide	Machine	Plastic	Others
Wheat	0.088	0.063	0.115	0.063	0.005	0.071	0	0.019
Maize	0.208	0.032	0.137	0.031	0.005	0.060	0.015	0.009
Maize + Wheat	0.296	0.095	0.252	0.094	0.010	0.131	0.015	0.029
Cotton	0.204	0.044	0.180	0.035	0.008	0.057	0.054	0.086
Oil Crops	0.085	0.051	0.065	0.021	0	0.026	0	0.007
Beet	0.181	0.035	0.165	0.028	0.010	0.063	0.048	0.017
Tomato	0.663	0.091	0.302	0.273	0.104	0.033	0.207	0.294
Orchard	0.429	0	0.220	0.525	0.265	0.038	0	0.078

**Table B. 2:** Subsurface irrigation changes on cost.

Changes	Neg./Pos. change	Modification [%]	Factor
Yield / Revenues	+	20	1.2
Labour costs	-	20	0.8
Machine costs	-	20	0.8
Fertilizer costs	-	20	0.8
Manure costs	-	20	0.8
Water costs	-	30	0.7

**Table B. 3:** Crop Yield and price. All values are from Yanqi Basin with the exception of *Maize* and *Maize + Wheat*, which has been provided by Prof. Dr. W. Kinzelbach.

Crop	Yield [kg/m <sup>2</sup> ]	Price [CNY/kg]	Price [CNY/m <sup>2</sup> ]
Wheat		0.54	1.23
Maize		1.57	2.3
Maize + Wheat		2.1	2.02
Cotton		0.15	11.2
Oil Crops		0.20	2.85
Beet		5.62	0.18
Tomato		6.14	0.73
Orchard		1.89	2.57



**Table B. 4:** Crop coefficient ( $K_{c,mid}$  value from FAO,  $K_c$  and correction factor self-introduced based on crop lifespan)

<b>Crop</b>	<b><math>K_{c,mid}</math></b>	<b>Estimated correction factor</b>	<b>“corrected” average <math>K_c</math></b>
Wheat	1.15	0.95	1.09
Maize	1.2	0.86	1.03
Maize+Wheat	1.175	0.90	1.06
Cotton	1.15	0.87	1
Oil Crops (Sesame)	1.1	0.92	1.02
Beet	1.05	0.85	0.9
Tomato	1.15	0.88	1.02
Deciduous Orchard	1.1	0.95	1.05

**Table B. 5:** Water prices based on origin. Water from the irrigation channel has been set to 0, as its quantity is fairly low and the real cost is already very close to 0. The average pumping price for both aquifers has been used. Values have been provided by Prof. Dr. Kinzelbach.

<b>Origin of water</b>	<b>Treatment cost [CNY/m<sup>3</sup>]</b>	<b>Water price [CNY/m<sup>3</sup>]</b>	<b>Total Cost [CNY/m<sup>3</sup>]</b>
Pumping price (average)	-	0.15	0.15
S-N Water Transfer project	2	5	7
Yellow River	-	0.026	0.026
Rain water	-	0	0
Weixi Main Channel	-	≈ 0	≈ 0

## C. Matlab script files

### C.1 Entry tables for user

```
function GuantaoV6_1

Excelfile = 'Parameter\Guantao_v1.xlsx';

%% creating Input-Popup: Controlling Parameter

controllparameter = {'Agriculture area 1 (TDS < 2 g/L in soil)
[km^2]:',...
                    'Agriculture area 2 (TDS > 2 g/L)
[km^2]:',...
                    'Precipitation
[mm]:',...
                    'Reference Evaporation
[mm]:',...
                    'Channelflow
[m^3]:',...
                    'Efficiency of Channelflow to Agriculture
[%]:',...
                    'Weiheinfiltration
[m^3]:',...
                    'effective Yellow River Infiltration
[m^3]:',...
                    'Subsurface irrigation efficiency
[%]',...
                    'Flood irrigation efficiency
[%]',...
                    'Industry Fresh water demand
[m^3]',...
                    'Urban settlement Fresh water demand
[m^3]',...
                    'S-N-transfer project
[m^3]'};

dlg_title = 'Guantao Parameter';
num_lines = 1;
def =
{'212.6308', '86.8492', '530.2', '550', '6000000', '77.5', '8800000', '7500000', '7
5', '59', '3600000', '11000000', '7000000'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer_controllparameter =
inputdlg(controllparameter,dlg_title,num_lines,def,options);

%% creating Input-Popup: Plant combination
plantcombi = {'Which plant and how much of it should be planted?
'...
              'The Sum should add up to 100% (but not necessarily).
'...

```

```

    '(Hint: Wheat, Oil crops, Beet and Vegetables (Tomato) can be double
cropped. '...
    'Maize + Wheat is already double cropped.)' '
'...
''...
    'Wheat [%]:',...
    'Maize [%]:', 'Maize + Wheat [%]:', 'Cotton1 [%]:', 'Oilcrops [%]:', 'Beet
[%]:', 'Tomato [%]:', 'Orchard [%]:';

cdata=imread('\TableWithCropValue.bmp');

image(cdata)

dlg_title = 'Plantcombination';
num_lines = 1;
def = {'0', '0', '76', '0', '9', '0', '15', '0'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer_plantcombi = inputdlg(plantcombi,dlg_title,num_lines,def,options);

% Requirement plant_combi:
req1plantcombi=answer_plantcombi;
req2plantcombi=char(req1plantcombi);
req3plantcombi=str2num(req2plantcombi);
req4plantcombi=sum(req3plantcombi);

[cdata]=imread('\warningIcon.png');

if req4plantcombi<100
    choice = questdlg(['You have only used ' num2str(req4plantcombi) ' % of
the total',...
    'agriculture area.'], 'This will lead to an agriculture decrease',
...
    'Continue', 'Cancel', 'Continue');
% Handle response
switch choice
    case 'Cancel'
        return;
end
end

if req4plantcombi>100
    choice = questdlg(['You have used ' num2str(req4plantcombi) ' % of the
total',...
    'agriculture area. This will lead to an agriculture
increase.'], 'Agriculture area increase', ...
    'Continue', 'Cancel', 'Continue');
% Handle response
switch choice
    case 'Cancel'
        return;
end
end

```

```

%% creating Input-Popup: Usage of area 2
area2usage = {'How much [%] of area 2 should be used for cotton? 100% =
86.8492km^2'};

dlg_title = 'Usage of oversalted area 2';
num_lines = 1;
def = {'100'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer_area2usage = inputdlg(area2usage,dlg_title,num_lines,def,options);

%Requirement area 2 usage:

req1area2usage = answer_area2usage;
req2area2usage=char(req1area2usage);
req3area2usage=str2num(req2area2usage);

if req3area2usage > 100
    message1=msgbox('Area 2 usage can not be higher than 100
%', 'Error', 'error');
    return;
else end

if req3area2usage < 0
    message1=msgbox('Area 2 usage can not be negativ', 'Error', 'error');
    return;
else end

%% creating Input-Popup: Double Cropping

doublecropping = {'Which of those plants do you want to plant multiple
times per year?          '...
    'Single cropping -> enter "0"
'...
    'Double cropping -> enter "1"
'...
    'Triple Cropping (works only with Tomato) -> enter "2"
'...
    '(Hint: Values in-between are viable, values above or below will be set
to maximum/minimum)          '...
    '          Wheat:'],...
    'Oilcrops:',...
    'Beet:',...
    'Vegetables (Tomato) (can perform triple cropping (2)):'};

dlg_title = 'Double Cropping?';

num_lines = 1;
def = {'1', '1', '1', '2'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer_doublecropping =
inputdlg(doublecropping,dlg_title,num_lines,def,options);

```

```

%% creating Input-Popup: Flood or Subsurface Irrigation
irrigationstrategy = {'Which Irrigation technique should be used?'
'...
    'For Flood Irrigation -> enter "0"
'...
    'For Subsurface Irrigation -> enter "1"
'...
    'Values between 0 and 1 means that this amount of the crop will be
subsurface irrigated. '...
    'Values lower than 0 or higher than 1 will be set to 0 or 1.
'...
    '
Wheat:'],...
    'Maize:',...
    'Maize + Wheat:',...
    'Cotton in area 1:',...
    'Oilcrops:',...
    'Beet:',...
    'Vegetables (Tomato):',...
    'Orchard:',...
    'Cotton in area 2:'};

dlg_title = 'Flood or Subsurface Irrigation?';

num_lines = 1;
def = {'0','0','0','0','0','0','1','0','0'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer_irrigationstrategy =
inputdlg(irrigationstrategy,dlg_title,num_lines,def,options);

%%
% putting Input into excel file
xlswrite(Excelfile,answer_controllparameter,2,'B4:B16');
xlswrite(Excelfile,answer_plantcombi,3,'B6:B13');
xlswrite(Excelfile,answer_area2usage,3,'G14');
xlswrite(Excelfile,answer_doublecropping,3,'N6:N9');
xlswrite(Excelfile,answer_irrigationstrategy,3,'Q6:Q14');

%%
run ('Table_with_endvalues.m');
%%supertable

run GUIGuantao

%% open Excel-file
%winopen('Parameter\Guantao_v7_uptodate.xlsx');

```

## C.2 Result table

```
Excelfile = 'Parameter\Guantao_v1.xlsx';

Endresults= {'money won'; %1
'planting cost'; %2
'initial S.Irrigation cost'; %3
'Cost of pump water'; %4
'Cost for Yellow River infiltration'; %5
'Cost of S-N-project water'; %6
'Profit (money won - cost)'; %7
'Profit in the first year'; %8
''; %9
'Amount of unused saline area'; %10
'Amount of unused non-saline area'; %11
''; %12
'yearly Deficit in shallow GW'; %13
'Pumping rate in shallow GW'; %14
'yearly Deficit in deep GW'; %15
'Pumping rate in deep GW'};

Mio_CNY_per_year=xlsread(Excelfile,1,'O84:O99');
Ecopoints=xlsread(Excelfile,1,'P84:P99');
Mio_m3_water_per_year = xlsread(Excelfile,1,'Q84:Q99');

supertable=[Mio_CNY_per_year Ecopoints Mio_m3_water_per_year];

%%

f = figure('Position',[500 100 800 450]);
dat = supertable;
cnames = {'mio CNY/a','km^2','mio m^3 water/a'};
rnames = {'money won','planting cost','initial S.irrigation cost','cost of
pump water','cost for Yellow River water',...
'cost of S-N-project water','profit (money won - cost)','profit in the
first year','',...
'unused saline area','unused non-saline area','',...
'yearly deficit in shallow GW','pumping rate of shallow GW','yearly
deficit in deep GW','pumping rate in deep GW'};

t = uitable('Parent',f,'Data',dat,'ColumnName',cnames,...
'RowName',rnames,'Position',[10 100 700 350]);
```

## C.3 Graphical User Interface (GUI)

```
function varargout = GUIGuantao(varargin)
% GUIGUANTAO MATLAB code for GUIGuantao.fig
%     GUIGUANTAO, by itself, creates a new GUIGUANTAO or raises the
existing
%     singleton*.
%
%     H = GUIGUANTAO returns the handle to a new GUIGUANTAO or the handle
to
%     the existing singleton*.
%
%     GUIGUANTAO('CALLBACK', hObject,eventData,handles,...) calls the
local
%     function named CALLBACK in GUIGUANTAO.M with the given input
arguments.
%
%     GUIGUANTAO('Property','Value',...) creates a new GUIGUANTAO or
raises the
%     existing singleton*. Starting from the left, property value pairs
are
%     applied to the GUI before GUIGuantao_OpeningFcn gets called. An
%     unrecognized property name or invalid value makes property
application
%     stop. All inputs are passed to GUIGuantao_OpeningFcn via varargin.
%
%     *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only
one
%     instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help GUIGuantao

% Last Modified by GUIDE v2.5 16-May-2014 16:25:06

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',  gui_Singleton, ...
                  'gui_OpeningFcn', @GUIGuantao_OpeningFcn, ...
                  'gui_OutputFcn',  @GUIGuantao_OutputFcn, ...
                  'gui_LayoutFcn',  [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
```

```

% --- Executes just before GUIGuantao is made visible.
function GUIGuantao_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
% varargin   command line arguments to GUIGuantao (see VARARGIN)

% Choose default command line output for GUIGuantao
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% --- Outputs from this function are returned to the command line.
function varargout = GUIGuantao_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on button press in closepushbutton1.
function closepushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to closepushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
close(GUIGuantao)

% --- Executes on button press in restartpushbutton2.
function restartpushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to restartpushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
close (GUIGuantao)
run ('GuantaoV6_1.m')

% --- Executes on button press in startpushbutton3.
function startpushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to startpushbutton3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
Excelfile = 'Parameter\Guantao_v1.xlsx';

xGuantaopresent= 0;
yGuantaopresent= 891.63413149;

xpumpgw2=[8.665 8.665];
ypumpgw2=[1000 0];
xgw1=[35.69669784 35.69669784];
ygw1=[1000 0];

```



```

%%
usermoney1=xlsread(Excelfile,1,'Q4');           %reading money won value
userwater=xlsread(Excelfile,1,'O58');          %reading Deficit reduction
value

%placing the profit and deficit reduction value in its place (if possible)
mmm1=xlsread(Excelfile,1,'A60');
mmm2=xlsread(Excelfile,1,'A61');
mmm3=xlsread(Excelfile,1,'A62');
mmm4=xlsread(Excelfile,1,'A63');

if mmm1 == 0 & mmm2 == 0 & mmm3 == 0 & mmm4 == 0;           %If field in excel
is already used -> next field
    xlswrite(Excelfile,usermoney1,1,'A60');
    xlswrite(Excelfile,userwater,1,'B60');
elseif mmm1 ~= 0 & mmm2 == 0;
    xlswrite(Excelfile,usermoney1,1,'A61');
    xlswrite(Excelfile,userwater,1,'B61');
elseif mmm2 ~= 0 & mmm3 == 0;
    xlswrite(Excelfile,usermoney1,1,'A62');
    xlswrite(Excelfile,userwater,1,'B62');
elseif mmm3 ~= 0 & mmm4 == 0;
    xlswrite(Excelfile,usermoney1,1,'A63');
    xlswrite(Excelfile,userwater,1,'B63');
else xlswrite(Excelfile,usermoney1,1,'A60');           %If all fields are
used -> overwrite first one
    xlswrite(Excelfile,userwater,1,'B60');
end

%% Reading set values
xu1=xlsread(Excelfile,1,'B60');
yu1=xlsread(Excelfile,1,'A60');

xu2=xlsread(Excelfile,1,'B61');
yu2=xlsread(Excelfile,1,'A61');

xu3=xlsread(Excelfile,1,'B62');
yu3=xlsread(Excelfile,1,'A62');

xu4=xlsread(Excelfile,1,'B63');
yu4=xlsread(Excelfile,1,'A63');

%%
%paretofigure = figure
%set(paretofigure,'name','Pareto Front','numbertitle','off')
paretoplot =
plot(xGuantaopresent,yGuantaopresent,'kx',xpumpgw2,ypumpgw2,'k--
',xgw1,ygw1,'k-.',xu1,yu1,'rs',xu2,yu2,'gs',xu3,yu3,'cs',xu4,yu4,'ms');
%,xu5,yu5,'ys',xu6,yu6,'r+',xu7,yu7,'g+',xu8,yu8,'c+'
paretolegend=legend('Guantao Present','shutting down of the deep GW
pump','Deficit of shallow GW = 0','user1','user2','user3','user4');
%, 'xu5', 'xu6', 'xu7', 'xu8'
xlabel('Groundwater saved per year [mio m3
water/a]','FontSize',10,'FontWeight','bold','Color','r');
ylabel('Profit [mio CNY]','FontSize',10,'FontWeight','bold','Color','r');

```

```

% --- Executes on button press in refreshpushbutton4.
function refreshpushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to refreshpushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
Excelfile = 'Parameter\Guantao_v1.xlsx';
msgbox('Please wait 10 seconds before restarting')
xlswrite(Excelfile,0,1,'A60');
xlswrite(Excelfile,0,1,'A61');
xlswrite(Excelfile,0,1,'A62');
xlswrite(Excelfile,0,1,'A63');

xlswrite(Excelfile,0,1,'B60');
xlswrite(Excelfile,0,1,'B61');
xlswrite(Excelfile,0,1,'B62');
xlswrite(Excelfile,0,1,'B63');

% --- Executes on button press in front1Wmpushbutton5.
function front1Wmpushbutton5_Callback(hObject, eventdata, handles)
% hObject    handle to front1Wmpushbutton5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

Excelfile = 'Parameter\Guantao_v1.xlsx';

y=xlsread(Excelfile,4,'C3:C16'); %reading the Front profit
x=xlsread(Excelfile,4,'D3:D16'); %reading front deficit reduction

xpumpgw2=[8.665 8.665];
ypumpgw2=[1000 0];
xgw1=[35.69669784 35.69669784];
ygw1=[1000 0];

xGuantaopresent= 0;
yGuantaopresent= 891.63413149;

xu1=xlsread(Excelfile,1,'B60');
yu1=xlsread(Excelfile,1,'A60');

xu2=xlsread(Excelfile,1,'B61');
yu2=xlsread(Excelfile,1,'A61');

xu3=xlsread(Excelfile,1,'B62');
yu3=xlsread(Excelfile,1,'A62');

xu4=xlsread(Excelfile,1,'B63');
yu4=xlsread(Excelfile,1,'A63');

```

```

%%
%paretofigure = figure
%set(paretofigure,'name','Pareto Front','numbertitle','off')
paretoplot =
plot(xGuantaopresent,yGuantaopresent,'kx',x,y,'b',xpumpgw2,ypumpgw2,'k--
',xgw1,ygw1,'k-.',xu1,yu1,'rs',xu2,yu2,'gs',xu3,yu3,'cs',xu4,yu4,'ms');
%,xu5,yu5,'ys',xu6,yu6,'r+',xu7,yu7,'g+',xu8,yu8,'c+'
paretolegend=legend('Guantao Present','Front 1','shutting down of the deep
GW pump','Deficit of shallow GW = 0','user1','user2','user3','user4');
%, 'xu5','xu6','xu7','xu8'
xlabel('Groundwater saved per year [mio m3
water/a]','FontSize',10,'FontWeight','bold','Color','r');
ylabel('Profit [mio CNY]','FontSize',10,'FontWeight','bold','Color','r');

% --- Executes on button press in front2cottonpushbutton6.
function front2cottonpushbutton6_Callback(hObject, eventdata, handles)
% hObject    handle to front2cottonpushbutton6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
Excelfile = 'Parameter\Guantao_v1.xlsx';

y=xlsread(Excelfile,5,'B3:B9');    %reading Front Profit
x=xlsread(Excelfile,5,'C3:C9');    %reading Front Deficit reduction

xpumpgw2=[8.665 8.665];
ypumpgw2=[1000 0];
xgw1=[35.69669784 35.69669784];
ygw1=[1000 0];

xGuantaopresent= 0;
yGuantaopresent= 891.63413149;

xu1=xlsread(Excelfile,1,'B60');
yu1=xlsread(Excelfile,1,'A60');

xu2=xlsread(Excelfile,1,'B61');
yu2=xlsread(Excelfile,1,'A61');

xu3=xlsread(Excelfile,1,'B62');
yu3=xlsread(Excelfile,1,'A62');

xu4=xlsread(Excelfile,1,'B63');
yu4=xlsread(Excelfile,1,'A63');

```

```

%%
%paretofigure = figure
%set(paretofigure,'name','Pareto Front','numbertitle','off')
paretoplot =
plot(xGuantaopresent,yGuantaopresent,'kx',x,y,'b',xpumpgw2,ypumpgw2,'k--
',xgw1,ygw1,'k-.',xu1,yu1,'rs',xu2,yu2,'gs',xu3,yu3,'cs',xu4,yu4,'ms');
%,xu5,yu5,'ys',xu6,yu6,'r+',xu7,yu7,'g+',xu8,yu8,'c+'
paretolegend=legend('Guantao Present','Front 2','shutting down of the deep
GW pump','Deficit of shallow GW = 0','user1','user2','user3','user4');
%, 'xu5','xu6','xu7','xu8'
xlabel('Groundwater saved per year [mio m3
water/a]','FontSize',10,'FontWeight','bold','Color','r');
ylabel('Profit [mio CNY]','FontSize',10,'FontWeight','bold','Color','r');

% --- Executes on button press in front3sirripushbutton7.
function front3sirripushbutton7_Callback(hObject, eventdata, handles)
% hObject    handle to front3sirripushbutton7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
Excelfile = 'Parameter\Guantao_v1.xlsx';

y=xlsread(Excelfile,6,'D3:D14'); %reading Front profit (without
installation cost)
x=xlsread(Excelfile,6,'B3:B14'); %reading Front Deficit reduction

xpumpgw2=[8.665 8.665];
ypumpgw2=[1200 0];
xgw1=[35.69669784 35.69669784];
ygw1=[1200 0];

xGuantaopresent= 0;
yGuantaopresent= 891.63413149;

xu1=xlsread(Excelfile,1,'B60');
yu1=xlsread(Excelfile,1,'A60');

xu2=xlsread(Excelfile,1,'B61');
yu2=xlsread(Excelfile,1,'A61');

xu3=xlsread(Excelfile,1,'B62');
yu3=xlsread(Excelfile,1,'A62');

xu4=xlsread(Excelfile,1,'B63');
yu4=xlsread(Excelfile,1,'A63');

```

```

%%
paretofigure = figure
%set(paretofigure,'name','Pareto Front','numbertitle','off')
paretoplot =
plot(xGuantaopresent,yGuantaopresent,'kx',x,y,'b',xpumpgw2,ypumpgw2,'k--
',xgw1,ygw1,'k-.',xu1,yu1,'rs',xu2,yu2,'gs',xu3,yu3,'cs',xu4,yu4,'ms');
%,xu5,yu5,'ys',xu6,yu6,'r+',xu7,yu7,'g+',xu8,yu8,'c+'
paretolegend=legend('Guantao Present','Front 3','shutting down of the deep
GW pump','Deficit of shallow GW = 0','user1','user2','user3','user4');
%, 'xu5','xu6','xu7','xu8'
xlabel('Groundwater saved per year [mio m3
water/a]','FontSize',10,'FontWeight','bold','Color','r');
ylabel('Profit [mio CNY]','FontSize',10,'FontWeight','bold','Color','r');

% --- Executes on button press in fron4sirriinipushbutton8.
function fron4sirriinipushbutton8_Callback(hObject, eventdata, handles)
% hObject    handle to fron4sirriinipushbutton8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
Excelfile = 'Parameter\Guantao_v1.xlsx';

%run ('Table_with_endvalues.m') %i dont need this at all at start

%%Pareto-Front

y=xlsread(Excelfile,6,'C3:C14'); %reading the real Pareto Front
x=xlsread(Excelfile,6,'B3:B14'); %

xpumpgw2=[8.665 8.665];
ypumpgw2=[1000 0];
xgw1=[35.69669784 35.69669784];
ygw1=[1000 0];

xGuantaopresent= 0;
yGuantaopresent= 891.63413149;

xu1=xlsread(Excelfile,1,'B60');
yu1=xlsread(Excelfile,1,'A60');

xu2=xlsread(Excelfile,1,'B61');
yu2=xlsread(Excelfile,1,'A61');

xu3=xlsread(Excelfile,1,'B62');
yu3=xlsread(Excelfile,1,'A62');

xu4=xlsread(Excelfile,1,'B63');
yu4=xlsread(Excelfile,1,'A63');

```

```

%%
%paretofigure = figure
%set(paretofigure,'name','Pareto Front','numbertitle','off')
paretoplot =
plot(xGuantaopresent,yGuantaopresent,'kx',x,y,'b',xpumpgw2,ypumpgw2,'k--
',xgw1,ygw1,'k-.',xu1,yu1,'rs',xu2,yu2,'gs',xu3,yu3,'cs',xu4,yu4,'ms');
%,xu5,yu5,'ys',xu6,yu6,'r+',xu7,yu7,'g+',xu8,yu8,'c+'
paretolegend=legend('Guantao Present','Front 4','shutting down of the deep
GW pump','Deficit of shallow GW = 0','user1','user2','user3','user4');
%, 'xu5', 'xu6', 'xu7', 'xu8'
xlabel('Groundwater saved per year [mio m3
water/a]','FontSize',10,'FontWeight','bold','Color','r');
ylabel('Profit [mio CNY]','FontSize',10,'FontWeight','bold','Color','r');

```