ETH Zürich

Master Thesis

# Conjunctive water management concepts and decision support systems for the Heihe Basin, China.

*Author:*

Jacob Anz

*Supervisor:*

Prof. Dr. Wolfgang Kinzelbach

Department of Civil, Environmental and Geomatic Engineering

Institute of Environmental Engineering

August 2014

## Abstract

The middle reach of the Heihe Basin (China) shows severe depletion of the groundwater level due to intensified agriculture and irrigation supplied by groundwater pumping. With low rainfall volumes ranging between 62-280 mm per year and high evaporation rates the agriculture depends exclusively on groundwater irrigation and surface water irrigation which is abstracted from the Heihe river. As stream depletion increased and downstream regions faced severe ecological problems, the government implemented a yearly minimum outflow constraint for the stream.

Concepts to realize conjunctive use management on a monthly basis were developed and tested by developing a box model and coupling Matlab based algorithms with a groundwater model implemented in Modflow.

The box model helped to visualize the irrigation pattern: In spring and autumn the irrigation depends strongly on groundwater pumping while during summer months the irrigation demand can be satisfied using surface water abstracted from the stream. As the available surface water is always the limiting factor the algorithm focusses on estimating the potential monthly surface water supply rate while still satisfying the downstream outflow constraint.

A second scheme was developed to classify predicted stream flow series and to estimate the required groundwater pumping quota. The results are made available for decision makers by transferring them automatically to a webserver and displaying them using google earth outreach.

Two major depression cones could be identified by comparing a simulated natural steady state scenario without pumping with the actual pumping scenario: Drawdowns of 40 m in the Daman district and of 35 m in the LuoTuoCheng district can be observed.

Applying the first conjunctive use scheme improved the depression cones by 5 meter but left the downstream outflow constraint unsatisfied in some years. The second scheme did not improve the drawdown but performed much better concerning the outflow constraint. The water table varied in a range of ± 2 m at LuoTuoCheng around a steady state level and in/decreased with a rate of 0.8 / 1 m per year for generated best and worst case inflow years.

It could be shown that conjunctive use management shows good results for districts which are located at the model boundary or at greater distance to other districts which irrigate using groundwater pumping. Otherwise neighboring districts need to collaborate to achieve lower drawdown values.

To avoid economic and environmental damages a maximum drawdown level should be defined. If this level is exceeded the groundwater irrigation quota should be decreased or pumping should be discouraged by increasing the subsidized price for electric energy.

Further research should focus on estimating the optimal steady state water level taking social, environmental and economic aspects into account.

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## Thesis goal and foreword

The goal of this thesis was to investigate possibilities for groundwater accounting and conjunctive water use in the Heihe middle reach region by modelling. A *matlab* based program that assesses the partitioning of surface- and groundwater that can be allocated based on the stream inflow coming from the Qilian mountains was developed and the results are made available using a webpage.

This master thesis was developed within the framework of a SDC project with the goal of implementing a real time monitoring and controlling system for pumping rates in the middle reach of the Heihe river basin, north-western China. The project joins IFU (Institut für Umweltingenieurwissenschaften Eidgenössische Technische Hochschule Zürich)researchers, Chinese partners at CAREERI (Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy of Science) and Swiss companies *Hydrosolutions* and *Geopraevent*. The pilot project is carried out in the LuoTuoCheng district, which relies strongly on groundwater pumping and therefore is threatened by excessive groundwater level drawdown.

I had the chance to take part in a two-week field trip in July 2014 to the investigated area, attend meetings and presentations in Lanzhou and Zhangye which improved my understanding of the situation. Some information contained in this thesis stems from personal conversation and is not further referenced.

I would like to thank Gianni Pedrazzini for the many hours we spent together in the office and Wolfgang Kinzelbach for giving me the chance to take part in this project and the field visit.

# 1. Introduction

## 1.1 The study site location and hydrogeology

The Heihe river basin is located in northwestern China. Covering an area of 1.3 • $10^5$ km² and with a total south-east to north-west extension of 821 km, it is the second largest inland river basins in China. This size is comparable to the size of Bangladesh. The investigated area focuses on the middle reach of the Heihe River Basin covering an area of 1.2 • $10^4$ km² (*Fig.1*). With a continental climate and low annual rainfall ranging between 62-280 mm compared to a strong annual evaporation of 1000 -2500 mm it is an arid area (*Zhou et. al, 2010*).

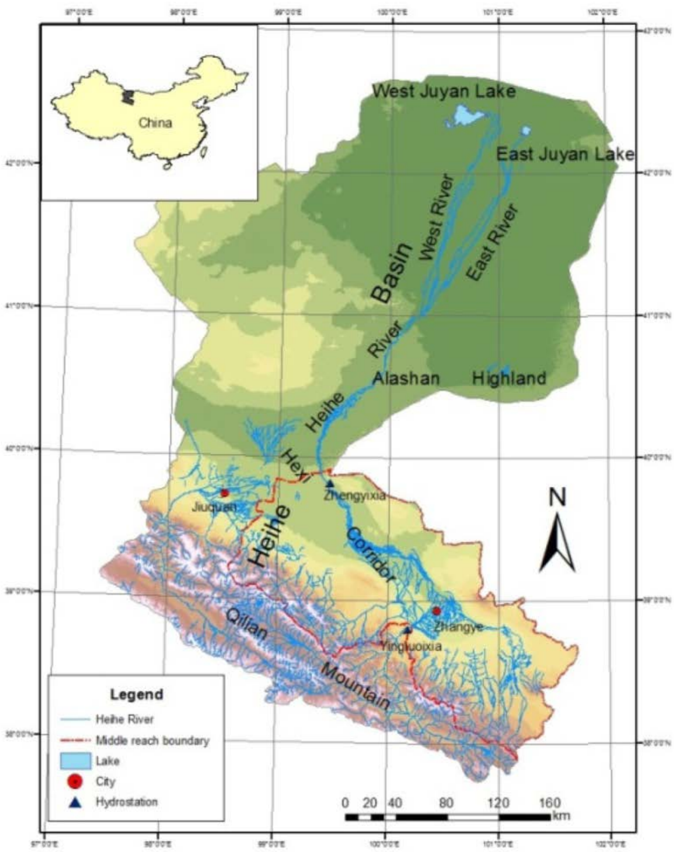


*Fig. 1: Map of the Heihe river system and the middle reach.*

35 streams coming from the Qilian mountains drain into the Heihe river basin but most of them dry up before reaching the Heihe main channel because of surface water abstraction or seepage losses into the ground. Therefore the Heihe river is the only stream flowing through the entire middle reach of the basin.

The river enters the middle reach of the basin through the *Longhsou II Dam*, operating since June 2002 (*ADB, 2007*).

*Fig.2: Aerial view of Longhsou II Dam (left). Alluvial plain at the upstream end of the Heihe middle reach (right).*

The Heihe continues through the alluvial plains in front of the mountains (*Fig.2*) towards the flat fine soil plains further downstream. Here the river is still in a quasi- natural state that allows it to branch and meander. Still it is limited by abstraction channels, bordering fields and roads and by dams (*Fig.3*). Finally it leaves the middle reach at Yanjiaxia through a smaller mountain range. In this downstream regime the river is still meandering broadly in its natural range.


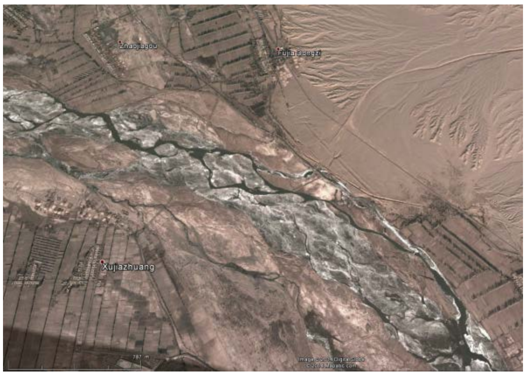


*Fig.3: The Heihe stream in the middle reach (left). The Heihe stream leaving the middle reach (right).*

Finally the stream continues towards the *Gobi desert* and the Mongolian border where it is ending in the Juyan lake (also called *Subozhuoer)* which has no further outflow (*Fig.4*)*.* On its way it is feeding a populus euphratica forest, which is of special touristic importance for the area. It has been reported, that the forest once covered an area of over 280000 km² which decreased to 120000 km² because of the degradation of the Heihe river (*Feng. Q. et al, 2001*).

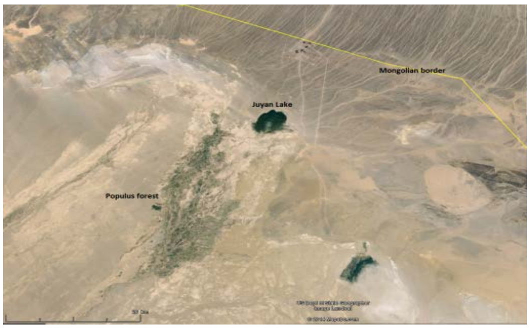


*Fig.4: Terminal lake (left) and populus euphratica forest at the downstream Heihe (right).*

## 1.2 The problem history and agricultural situation

Many names exists for the Heihe River, which is also called Ruo Shui (Chinese: 弱水 ‘weak river’) and further downstream Etsin Gol, Ruo He, Ejina River or black river. It´s history of decreasing stream flow and desertification started around 2000 years ago when Chinese first settled on the upper part of the river. As part of it flows through the Hexi Corridor which was part of the ancient silk road, many outpost were created to protect the silk road traders against Mongolian attacks. (*Hill J.E., 2004*). Since then the banks of the stream were more and more intensely used for cultivation of crops which led to an increase of erosion and a decrease of stream flow.

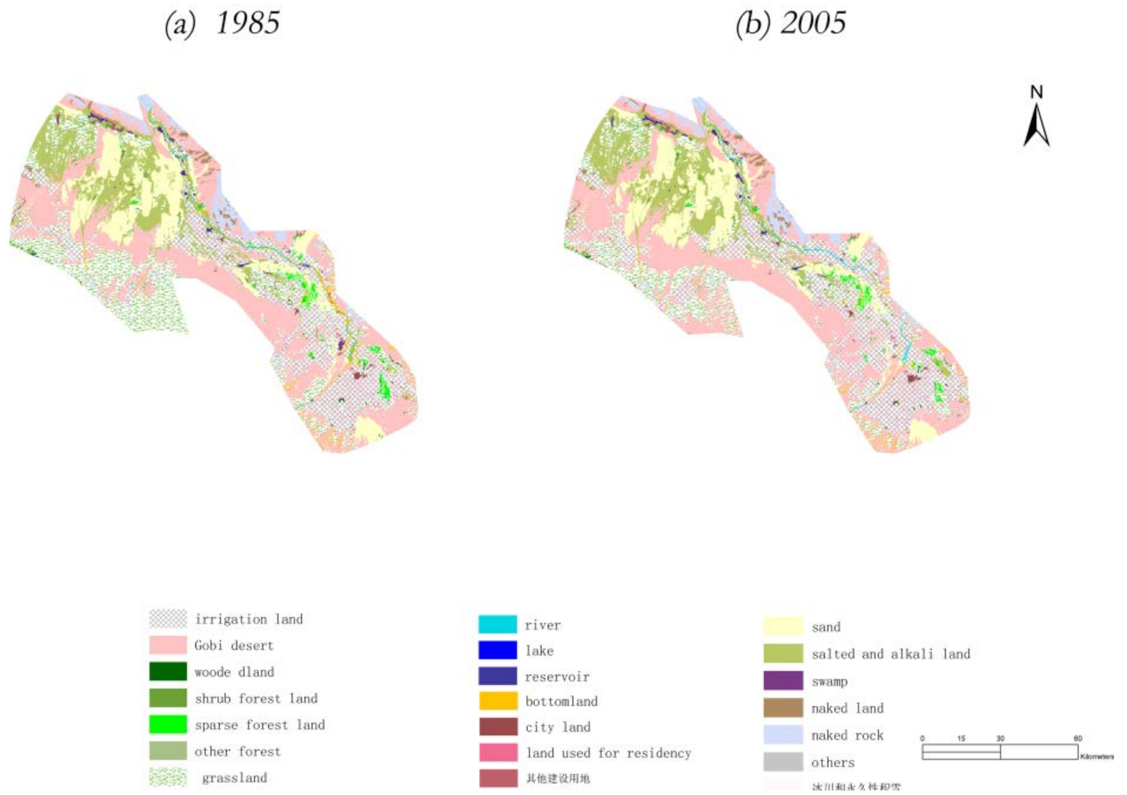


*Fig.5: Land use change in the modelled region between 1985 and 2005.*

As originally only surface water irrigation was applied, the stream flow decreased so much, that the terminal Juyan lakes, earlier divided into East Lake, West Lake and North Lake dried up. Today only the east Juyan lake still exists (*als.gov.cn, 2010*). During droughts in 1961 and 1992 this lake dried out too, which had serious consequences for the ecosystem. The government also related heavy sandstorms that caused strong damages in China to the desertification of this area and as a consequence it introduced the middle reach minimum outflow of $0.95 * 10^9$ $m^3$/ year (*Chen G. et al, 2014*). The farmers, not willing to reduce their cropped area, switched to groundwater irrigation, which in turn led to declining groundwater tables.

Even in the past decade, there has been an increase in agricultural area. Almost the entire agricultural land in the northern middle reach is used for seed maize production, while in the southern part wheat cultivation dominates. In the higher altitudes of the southern part there is still some rice produced but with a decreasing trend (*Fu. L. et al, 2014*).

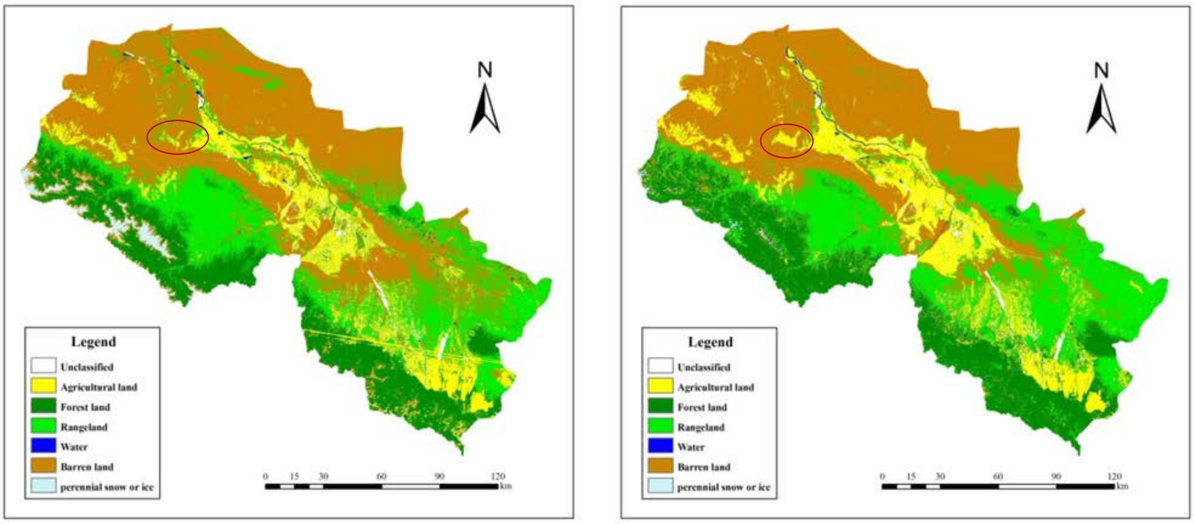


*Fig.6: Remote sensing images for land use classification between 2000 (left) and 2009 (right). The density of agricultural use is intensified and in some areas agricultural use is still expanding (red circle).*

## 1.3 The terminology 'Conjunctive use'

The term '*conjunctive water use*' is often referred to as the simultaneous use of ground water and surface water. The purpose can be the improvement of chemical and biological water quality up to a certain usable level by mixing clean groundwater with degraded surface water (*IWMI Research Report 86, 2004*). Another application of conjunctive use is the meeting of minimum environmental flow (MEF) constraints of streams which are used for surface water irrigation: During low flow seasons, groundwater irrigation compensates for less surface water abstraction to maintain the MEF. During high flow seasons, the groundwater level is allowed to recover again (*Foster S. et al, 2010, P.7*).

In the city of Lima (Peru) conjunctive use enables the recovery of groundwater tables and pumping yields by using external surface water sources to compensate lower pumping rates (*Foster S. et al, 2010, P.4,10-11*). External water sources can for example also be well fields outside of cities from where water is then transported towards pumping zones with high drawdowns. This cycle can be closed by transporting the sewage to wastewater re-use areas where it can infiltrate and recharge the aquifer again.

In general, conjunctive water management (CWM) consists of the two components *recharge* and *recovery.* Different ways of recharge are *natural*, *direct percolation*, *in-lieu*, *fallowing* and *aquifer injection recharge*. Recovery is done by *direct extraction* or by *groundwater substitution*, which aims at leaving more surface water for downstream users in a depleted stream (*Fulton A., Dudley T., 2005*). The operational mode of CWM needs to be categorized into short cycle, annual cycle or long cycle, depending on the usage period and aquifer properties.

The conjunctive water management approach investigated in this thesis aims at drought mitigation and has therefore a rather long (multiannual) cycle. This approach is also referred to as 'water banking'. As the annual rainfall and evaporation account for 200 mm and 2000 mm respectively, one cannot really talk about 'droughts' as the entire agriculture strongly depends on groundwater irrigation all season long. Instead of 'drought years' the correct term would rather be high- and low stream flow years, as the stream flow is the only significant unknown parameter in the system. During years of high stream flow, surface water will be used as major irrigation source while during years of low flow the missing surface water is compensated by groundwater.

A special difficulty is the groundwater management for an aquifer, where administrative power is divided between different districts with individual management departments and officials as it is the case in the Heihe basin. If single districts implement strict irrigation constraints which then lead to the recovery of the water table, neighboring districts will also profit from these effects. To prevent this free-rider problem, a close collaboration between departments within the entire groundwater basin is necessary.

### 1.4 The Irrigation structure

The Irrigation channel structure in the Heihe Basin is very complex. In total there are 20 irrigation districts, which are irrigated by a complex irrigation channel system (Appendix C). The system is divided into a hierarchy of channels, beginning with the category main channel, branching further down into 2$^{nd}$ and 3$^{rd}$ order channels. In addition, there are 5787 pumping- and 119 observation wells listed *(Careeri, 2014).*

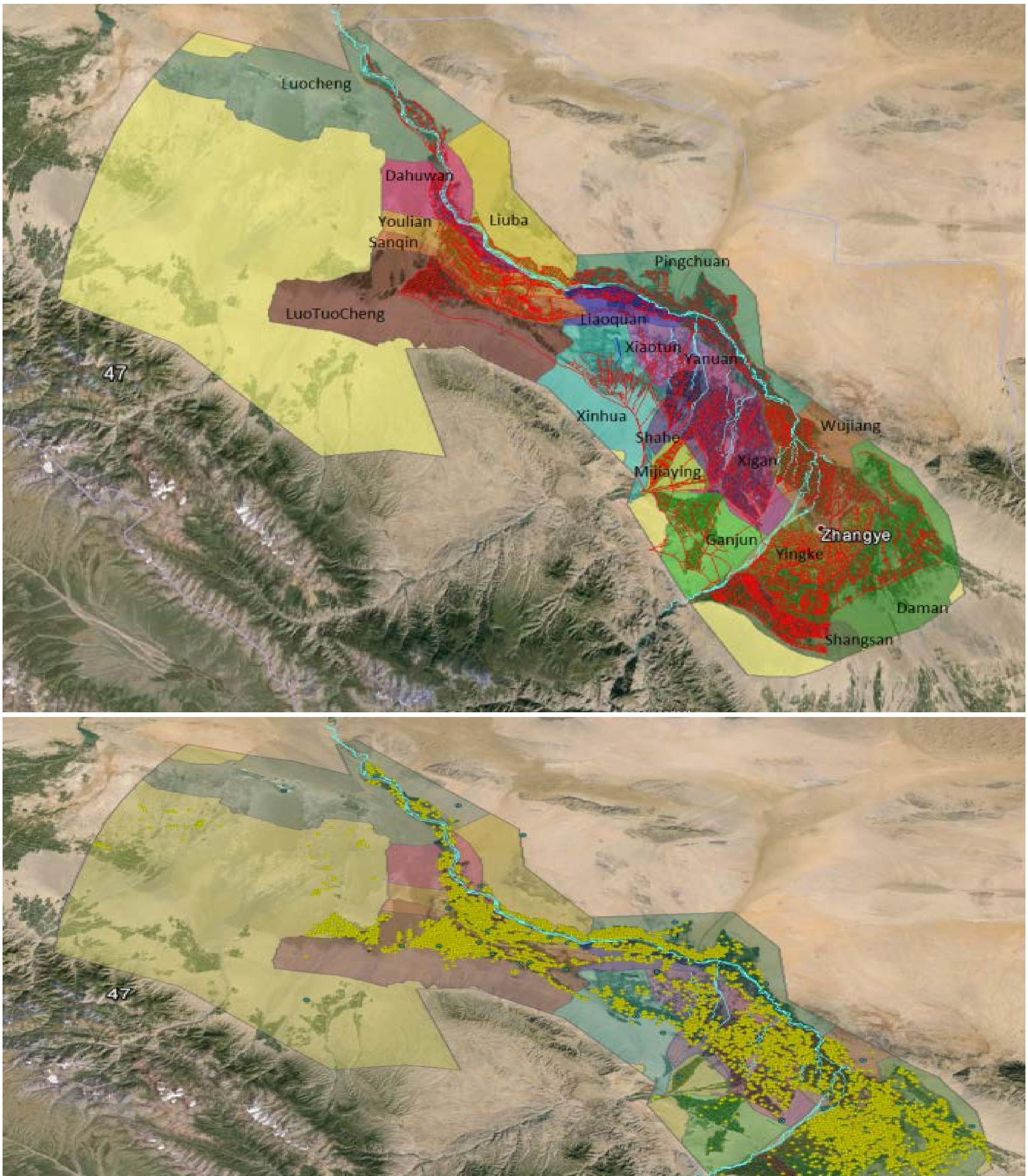


*Fig.10: Districts and irrigation structure in the Heihe basin (top). Pumping wells (yellow),observation wells (blue) and the Heihe stream (bottom).*

# 2. Methodology

## 2.1 The MODFLOW model

A MODFLOW 2000 (*McDonald M.G, 2000*) model was set up using PMWin (*Simcore Software, 2012*) and is constantly updated (*Chen C, 2014*). The finite difference model spans a grid of 236 *236 cells and covers a time span of 276 monthly steps according to 23 years of stream inflow data from the years 1986 -2008. Further model details are listed in *Appendix B*. The model used in this thesis is slightly modified. The stream flow abstractions were changed and the grid size was decreased to 172* 140 cells to shorten computation time. It runs on monthly time steps.

## 2.2 Surface water abstraction and allocation

The surface water abstractions from the stream were modelled according to data from CAREERI from the year 2010. Based on the irrigation scheme (*Appendix C*), the sum of the surface water use rates for the districts which obtain their water from the same main channel is taken. In this way the simulation takes monthly abstractions from the stream at 10 locations into account (*Fig.11*). To implement the stream flow into the Modflow model, the streamflow routing package (*Prudic, 1989*) is used.

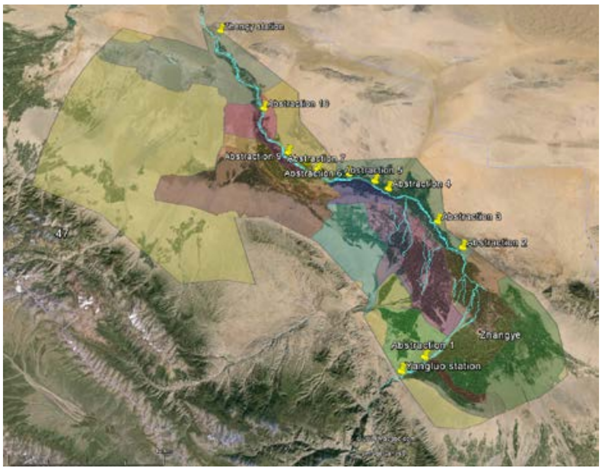


*Fig.11: Location of the simulated surface water abstractions.*

Three districts, defined as the Liyuan river group, are not taken into account in the stream calculation, as they receive their water from the Liyuan river. In a newer version of the Modflow model, this inflow into the Heihe is taken into account. However, as this stream is used heavily for irrigation, none of its water reaches the Heihe stream. Consequently it was neglected in the simulation of the surface water system.

*Fig.12: Liyuan river flowing into the Heihe middle reach and irrigated fields along the stream during July.*

The irrigation seasons generally starts in March and the irrigated amount increases reaching its peak in the high season in either May, June, July and August (*Fig.13*). Another smaller peak can be seen in November. The reason is the flooding of the fields before the winter time with the purpose to moisten the ground before its freezing. This elimimatesinsects which can harm the cultivated plants and guarantees initial soil moisture in spring when the ground starts to thaw. The optimal allocation of the surface water is currently investigated and a web- based program already used by over 60 decision makers is implemented in a test phase in the Heihe area (*Ge Y. et al, 2013*).

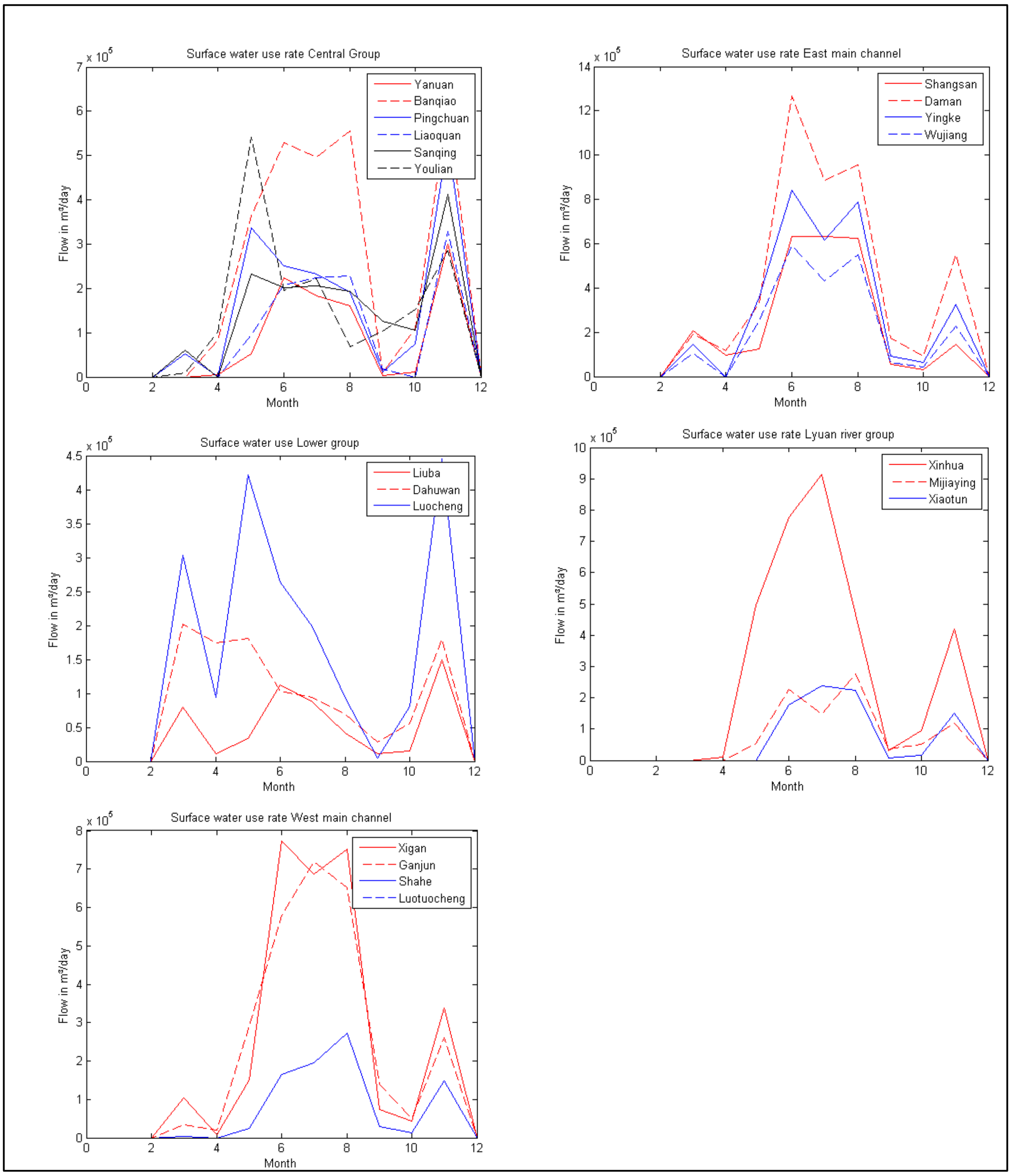


*Fig.13: Monthly surface water use rates in m³/day for the different irrigation districts.*

## 2.3 Groundwater irrigation

The groundwater irrigation data used was extracted from the Modflow model (*Chen C., 2014*). The values stem from the year 2010. As the model grid has a resolution of 1km * 1km, the more than 6000 registered pumping wells were aggregated to 818 wells. Each pump within a district is assumed to have the same pumping rate, which is a disputable assumption.

The groundwater irrigation starts in March, reaching its peak in July and decreases until it stops in October. Groundwater irrigation stations are usually small huts which cover the borehole and the electrical equipment. From there the water is diverted either in underground tubes or more often in open v -shaped channels. The pumping rate is mostly estimated using the electricity meter and a calibration curve which is fitted for the specific pump and borehole. If the calibration curve is not updated regularly, the farmers will be sanctioned automatically for higher drawdowns, as more energy is required to pump the same amount of water.

Groundwater pumping rates are incorporated into the model by writing them into the Modflow well package (WELL) data file.

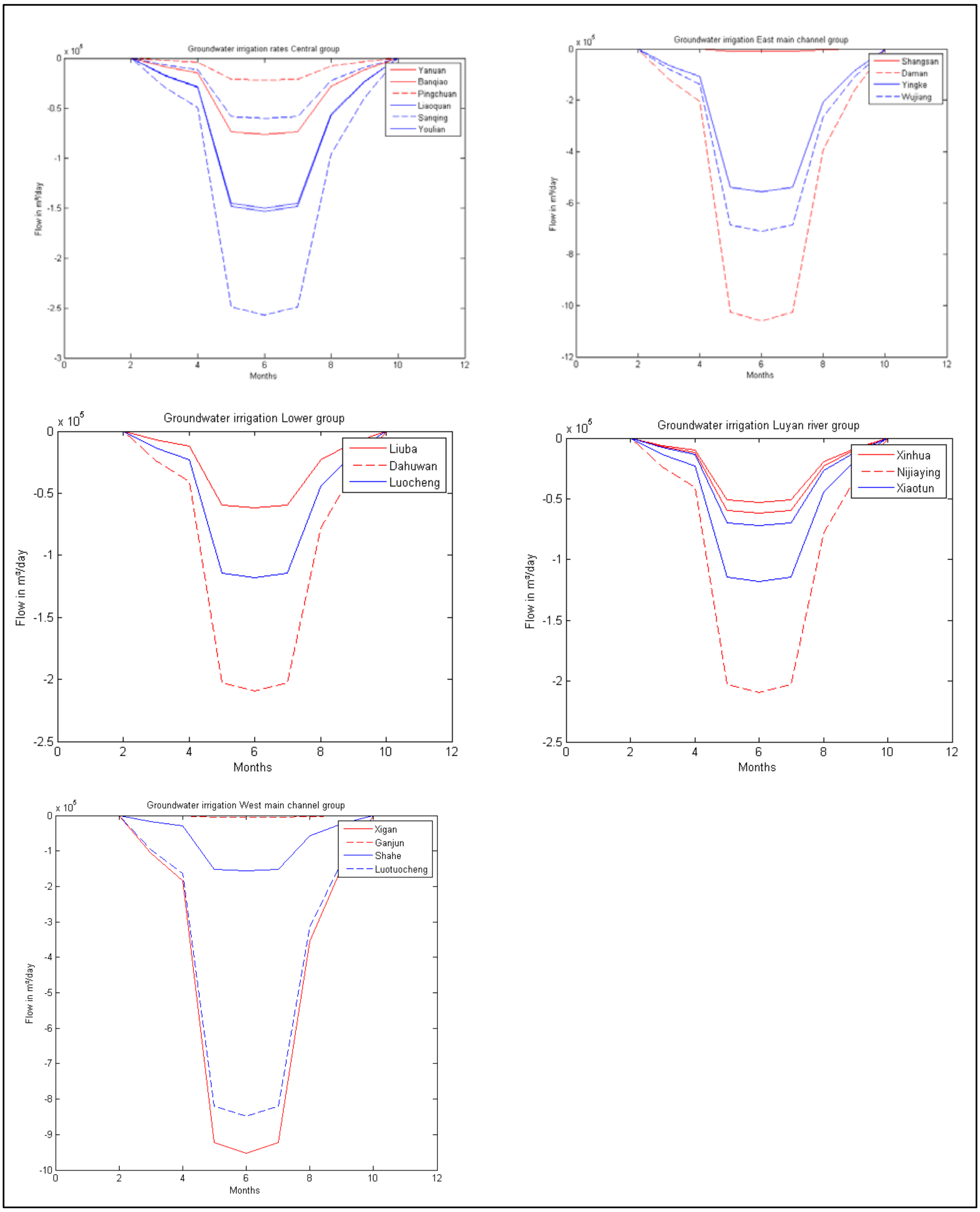


*Fig.14: Monthly groundwater irrigation rates [m³/day] per irrigation district.*

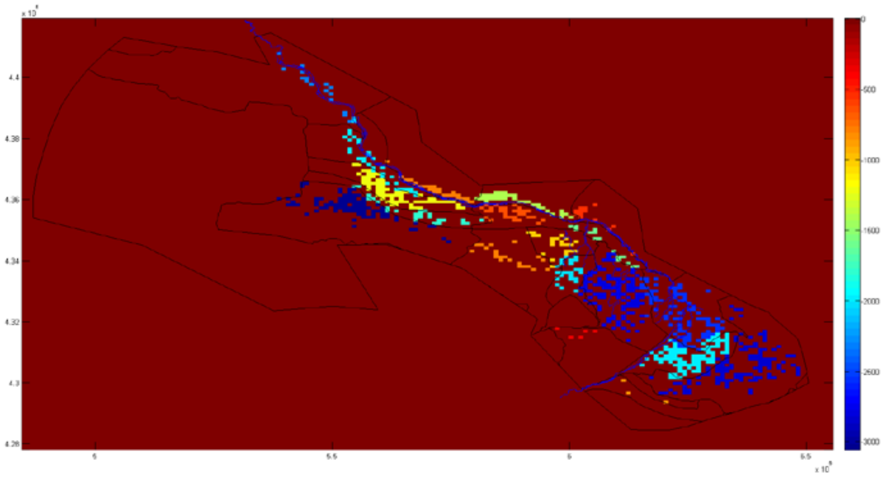

*Fig.15: Distribution and average rate [m³/day] of the pumping wells of the Modflow model.*

## 2.4 Recharge layer

The backflow from irrigation into the aquifer is taken into account using the Modflow recharge package (RCH). The recharge matrix was calculated based on the assumption that whenever there are fields visible in the remote sensing images, there is irrigation backflow. This area was estimated using an automatic image recognition tool originally developed by Prof. K. Schindler (*Institute for geodesy and photogrammetry, ETHZ*). Based on an input picture it distinguishes colors and returns a matrix containing only 1 and 0 values. The marked surface was then assigned to an irrigation district using an overlay image. Only recharge cells within the district boundaries were considered.

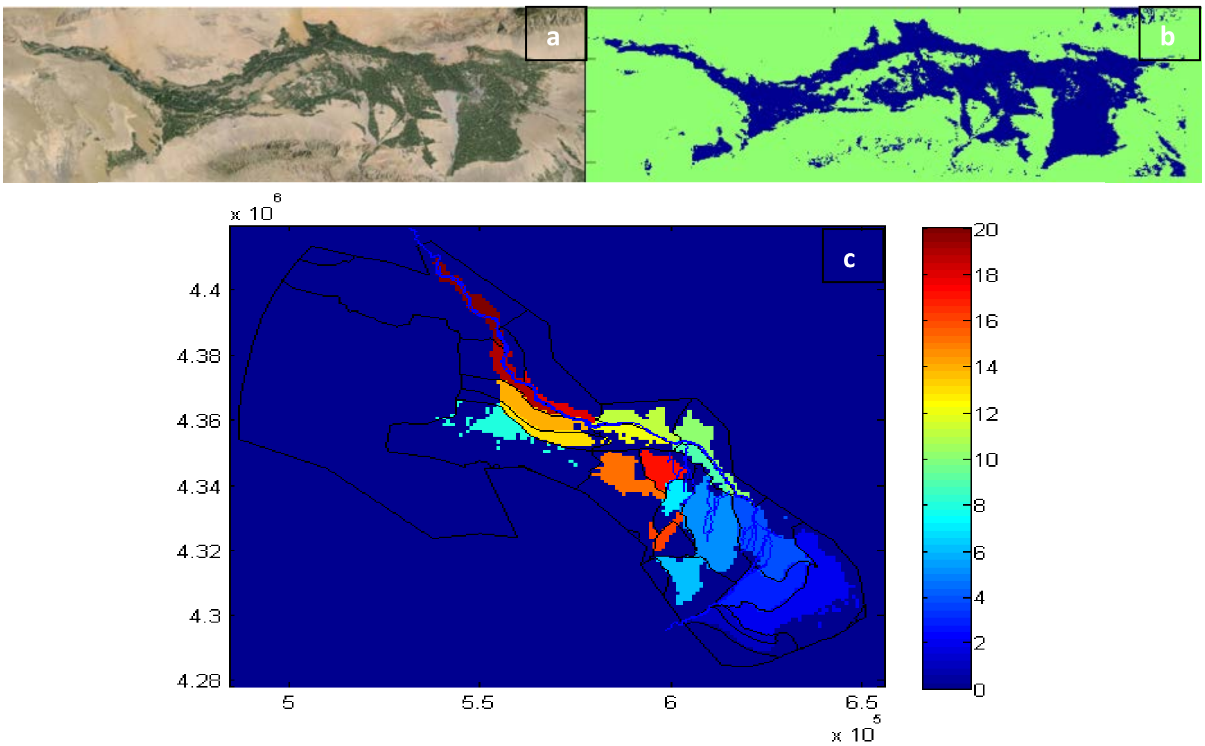


*Fig.16: a-c: The original picture obtained using google earth remote sensing (a), the classification using the image recognition function (b) and the final recharge layer with irrigation districts (c).*

The recharge values per cell in a district were calculated using the sum of surface water ($Q_{irr_{surfacewater,j}}$) and groundwater ($Q_{irr_{groundwater,j}}$) irrigation applied to the district *j* at the time *t* and divided by the number of recharge cells $a_j$ in the district. For simplification it was assumed that 20% of the applied irrigated flow infiltrate independent of time and location in the basin.

$$i_{infiltration,j(t)} = 0.2 * \frac{Q_{irr_{groundwater,j}}(t)+Q_{irr_{surfacewater,j}}(t)}{a_j} \quad (1)$$

This simple assumption could be improved by applying a more sophisticated infiltration model like Hydrus (*HYDRUS 2D/3D, Version 2*). As mostly flood irrigation is applied, the infiltration over time will certainly change once the ground is saturated.

## 2.5 Evaporation

The maximum evaporation depth is set to 3 • $10^{-4}$ m/day, the elevation of the evaporation surface is set to the top layer of the model and the ET extinction depth is 5m uniform for the entire layer. The evaporation is modelled using the Modflow evaporation package (EVT).

## 2.6 The box model

### 2.6.1 Water balance scheme

A box model was developed. It simulates the characteristics of the Modflow model in a simple way, by taking head dependent flows (boundary) and aquifer – stream interaction into account. It was used to develop and test methods for conjunctive water use: As much surface irrigation water as possible should be abstracted from the stream and used for irrigation to save groundwater on a monthly scale without violating the downstream outflow constraint. Groundwater irrigation on the other hand can be applied during months with low stream flow.

The box model is therefore based on a water balance for the model region.

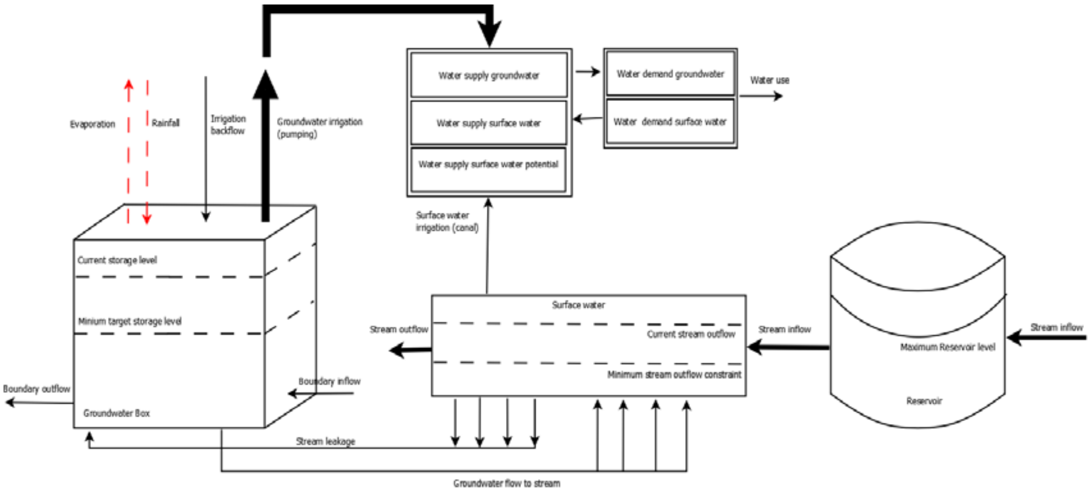

*Fig.17: The water balance scheme for the box model. Evaporation and rainfall are neglected.*

In the following chapter the components of the box model are explained:

### 2.6.2 Surface- and Groundwater demand:

Each district in the Heihe basin has a defined total water demand (Chapter 2.1 and 2.2). To satisfy this demand, the districts can choose either the groundwater reservoir or the surface water reservoir (the stream).

### 2.6.3 The stream (surface water):

It has an inflow from the upper reach and an outflow to the lower reach, the latter being subjected to a minimum outflow constraint of $0.95 \bullet 10^9$ m³. In between, the stream can interact with the aquifer by recharging or by draining it (stream leakage). This rate is dependent on the groundwater level of the aquifer (especially close to the river) and on the water level in the stream. Surface water is abstracted for irrigation at 10 weirs.

### 2.6.4 The groundwater box:

The central part of the model is the groundwater box. To reproduce the Modflow model it has an area of $8.887 \bullet 10^9$ m². The box is recharged via stream leakage from the stream into the groundwater and discharged by groundwater flow to the stream. Then there is in- and outflow via a general head boundary, depending also on the level in the groundwater box. Groundwater is pumped from the box to be used for irrigation, which produces in turn a backflow, composed of backflow both from groundwater pumping and surface water irrigation. Further interactions which are not considered in the box model are recharge via rainfall and losses due to evaporation.

### 2.6.5 Irrigation water supply:

The supply of surface- and groundwater is based on a decision scheme interface. In the ideal case, the supply matches the demand at each time step. In most cases however, demand and supply will not fit as the irrigation season starts before the stream flow increases. To estimate the amount of surface water that can be used a surface water supply potential is defined.

### 2.6.6 Reservoir and infiltration:

The Longshou II Dam (*Fig.2*), located directly upstream of the modeled area, could be used to some degree to store water during times of high stream flow and release it when the surface water demand exceeds the surface water supply potential. As the dam is rather small with a capacity of $8.62*10^7$ m³ (*Asian Development Bank, 2007*), the hydraulic residence time is only about 20 days for a mean stream flow of 4.54 $*10^6$ m³/day and correspondingly less for high flows.

As the Chinese government seems to consider the option of building a bigger upstream dam , this option was also assessed.

Infiltration: In the natural regime, the stream infiltrated largely into the aquifer in the upper part of the mid-reach where still a triangular highly conductive alluvial fan zone can be seen. Today big amounts of water are abstracted before reaching this zone.

### 2.6.7 The decision scheme:

The amount for surface- and groundwater water supply for each time step is estimated using a case sensitive decision scheme. Based on the incoming stream flow, the portion of water that can be used for surface water irrigation (surface water supply potential) is calculated (2). If there is more surface water than demanded, the excess water can be stored in the reservoir or infiltrated into the aquifer, depending on the model option. If there is not enough surface water to satisfy the demand, the lacking portion is defined as unmet demand (3). Now the scheme checks, whether this unmet demand is bigger than a limit (4), which has to be defined in the beginning. If the limit is exceeded, this portion is substituted using groundwater (5), depending on the groundwater level. If the groundwater level is higher than target groundwater level (6), the full amount of groundwater demand and the unmet demand from surface irrigation is supplied (7). If the groundwater level is below the target, the groundwater supply is reduced by a factor, which can be set in advance (8).

*Table 1: Equations used to estimate the monthly partition of surface- and groundwater used for irrigation.*

| | |
|---|---|
| $irr_{sw_{supply_{potential(t)}}} = str_{in(t)} - stream_{out_{constr(t)}} + rech_{out(t)} - rech_{in(t)}$ | (2) |
| $unmet_{demand_{sw(t)}} = irr_{sw_{demand\ (t)}} - irr_{sw_{supply(t)}}$ | (3) |
| $unmet_{demand_{sw(t)}} > unmet_{demand_{sw_{limit(t)}}}$ | (4) |
| $unmet_{demand_{sw_{diff(t)}}} = unmet_{demand_{sw(t)}} - unmet_{demand_{sw_{limit(t)}}}$ | (5) |
| $gw(t) > gw_{target\ level(t)}$ | (6) |

$$irr_{gw_{supply(t)}} = irr_{gw_{demand(t)}} + unmet_{demand_{sw_{diff(t)}}} \quad (7)$$

$$irr_{gw_{supply(t)}} = irr_{gw_{demand(t)}} + unmet_{demand_{sw_{diff(t)}}} * sust_{factor} + unmet_{demand_{sw_{diff(t)}}} \quad (8)$$

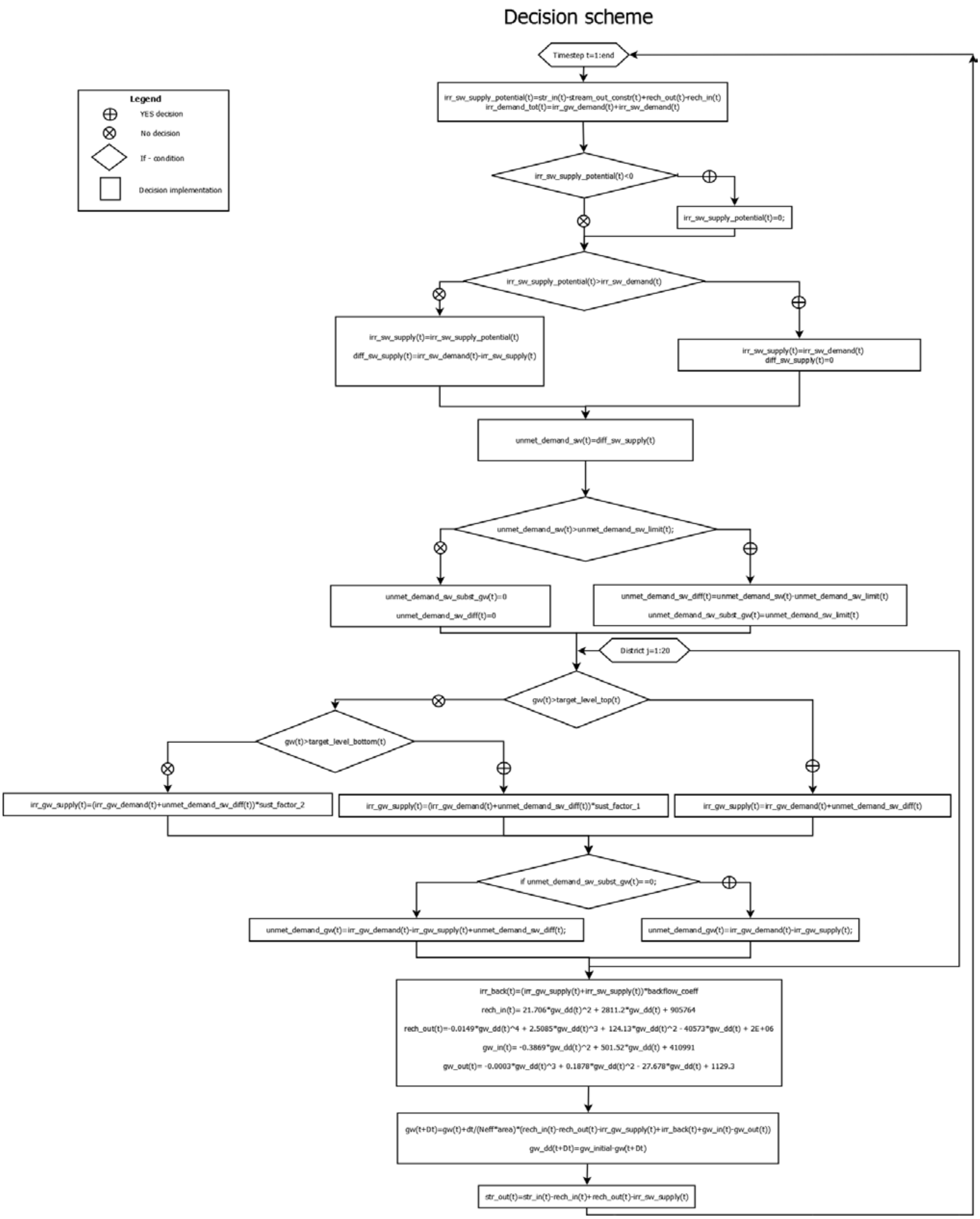


*Fig. 18: The decision scheme for the box model. The decision tree is repeated for each time step.*

## 2.6.8 Non linearity:

Modelling components like the river re- and discharge or the in- and outflow through the boundaries of the model are non-linear. To estimate these flows, a scenario analysis using the water budget of the Modflow model at different groundwater levels at steady state was performed. To arrive at different groundwater levels in steady state, the pumping rate of the wells was changed by a factor. The pumping- and recharge rates as well as the stream flow were taken at a yearly average for simulation. For higher pumping rates than scenario VIII the model is not converging anymore.

*Table 2: Estimation of the water balance for different groundwater levels.*

| Scenario | Pumping [m³/day] | | Stream leakage [m³/day] | | Head dependent boundary [m³/day] | | Lowest drawdown point [m] |
|---|---|---|---|---|---|---|---|
| | factor | rate | in | out | in | out | |
| I | 0.00 | 0 | 9.10E+05 | 1.96E+06 | 4.11E+05 | 1.10E+03 | 0.002 |
| II | 0.25 | 3.11E+05 | 9.19E+05 | 1.66E+06 | 4.14E+05 | 9.36E+02 | 7.326 |
| III | 0.50 | 6.22E+05 | 9.43E+05 | 1.38E+06 | 4.18E+05 | 7.92E+02 | 15.139 |
| IIV | 0.75 | 9.32E+05 | 9.99E+05 | 1.13E+06 | 4.22E+05 | 6.37E+02 | 22.259 |
| IV | 1.00 | 1.24E+06 | 1.04E+06 | 8.65E+05 | 4.27E+05 | 4.24E+02 | 31.937 |
| V | 1.25 | 1.55E+06 | 1.05E+06 | 5.74E+05 | 4.33E+05 | 1.88E+02 | 44.299 |
| VI | 1.50 | 1.86E+06 | 1.10E+06 | 3.21E+05 | 4.39E+05 | 8.20E+01 | 58.202 |
| VII | 1.75 | 2.17E+06 | 1.28E+06 | 2.00E+05 | 4.45E+05 | 3.01E+01 | 75.996 |
| VIII | 2.00 | 2.48E+06 | 1.51E+06 | 1.35E+05 | 4.64E+05 | 0.00E+00 | 115.158 |

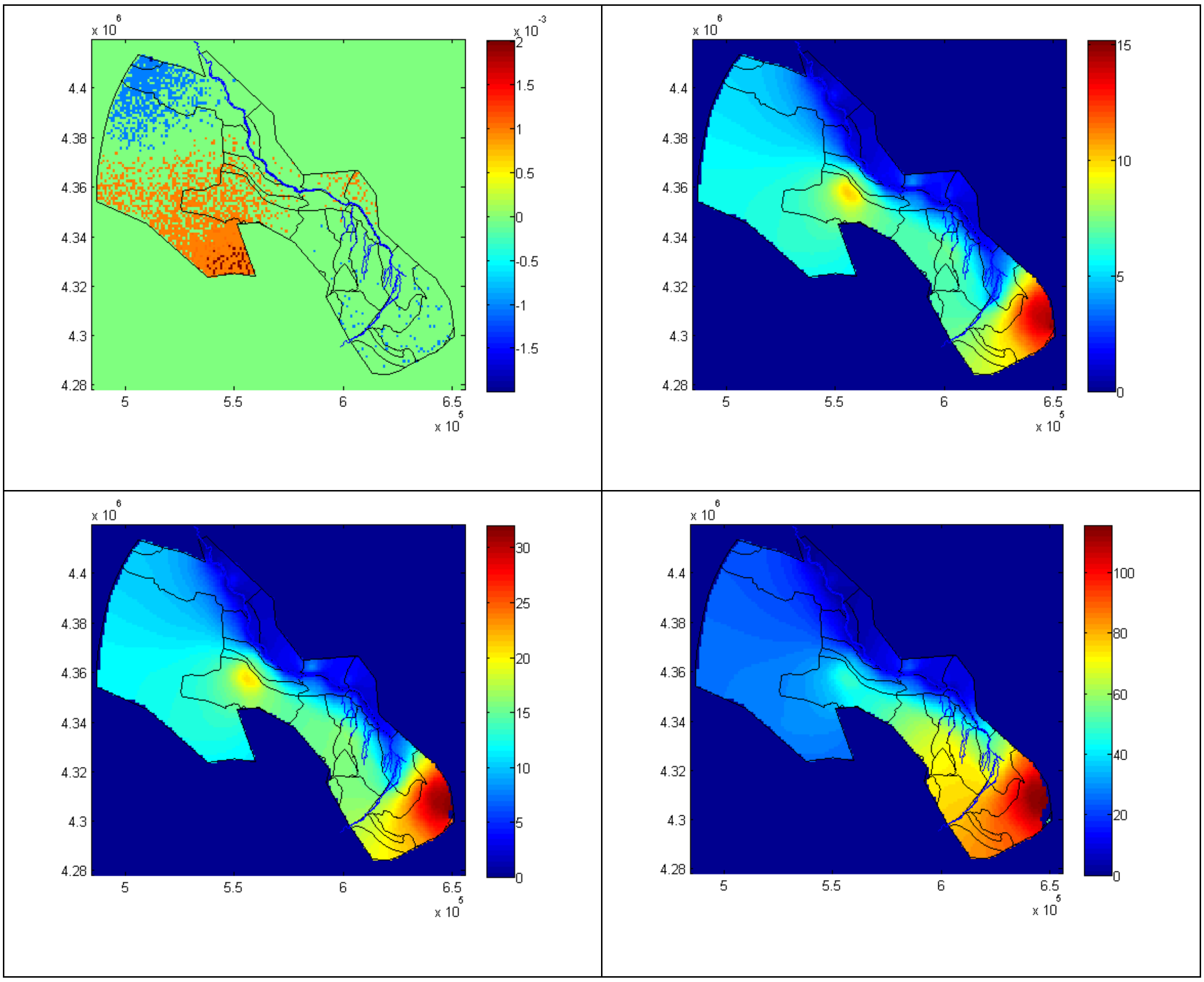

*Fig.19: The drawdown [m] at steady state for selected scenarios (Full selection in Appendix D).*

As the box model water table is uniform unlike the true water table, the problem arises now which points should be taken as reference to reflect the heads. The lowest drawdown point was chosen, other possibilities would be to take an average of all observation wells or to define a function to represent the head level.

The lowest drawdown point of each scenario was then related to the corresponding leakage and the corresponding boundary values. Binominal curves were fitted to the data. The obtained relations were used to calculate the flows in the box model.

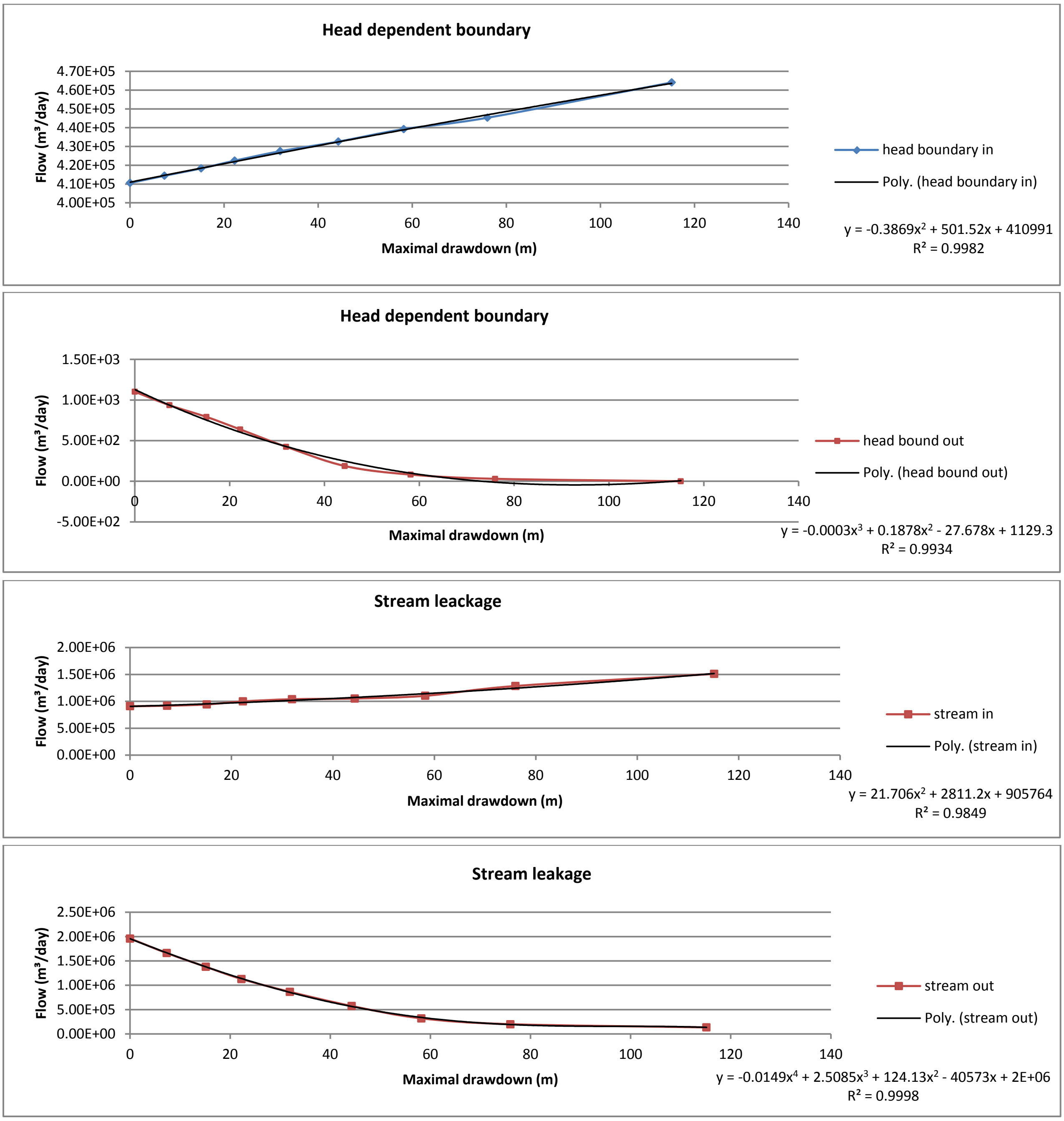


*Fig. 20: Polynomial curves fitted to the head dependent aquifer interaction.*

## 2.6.9 Synthetic time series generation:

The stream inflow data is limited to 276 months (23 years) between 1986 and 2008. To arrive at a steady state situation, this time series is not long enough. To simulate the system behavior under different conditions and to extend the series, an Autoregressive first order model (AR1) to generate synthetic yearly- and a Thomas Fering model (*Burlando, P., 2013*) to generate monthly time series was programmed (Parameters and equations in Appendix E).

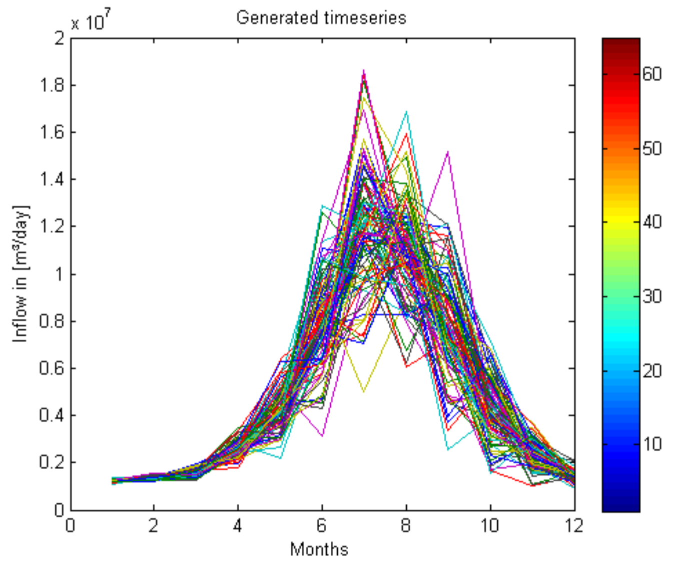


*Fig.21: Envelope of 100 realizations (100 years) of generated monthly inflow time series.*

## 2.6.10 The graphical user interface

The box model settings can be changed using a graphical user interface (GUI). The GUI offers the option, to steer the box model by setting an *Area amplification factor* $\alpha$. This factor reduces the surface $A$ of the box and therefore the contained water volume $V(t)$ in the box at a level $D(t)$. The higher $\alpha$ is set, the faster the box reacts. For $\alpha = 1$, steady state is reached at 1800 monthly time steps (150 years), while for $\alpha = 50$, steady state is already reached after 50 time steps (4 years).

$$V(t) = \frac{A \cdot D(t)}{\alpha} \qquad (9)$$

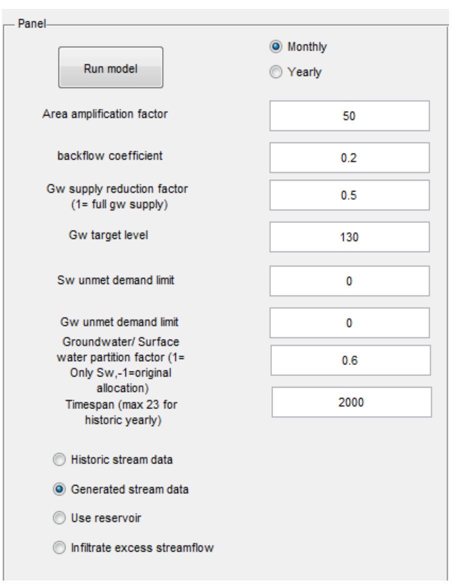


*Fig.22: The graphical user interface for the box model.*

*The GUI enables the user to set the irrigation backflow coefficient (Chapter 2.4), a groundwater target level and a groundwater irrigation reduction factor which is activated if the level drops below the target level.*

*The partition of surface water and groundwater use can be set. A factor of 1 means preferred surface water use and completing the rest of the demand by groundwater irrigation, a factor of 0.4 means the minimum use of 40% groundwater.*

*The simulation time horizon can be selected. It can be chosen between monthly and yearly simulation and between using an   historical or generated inflow time series.*

## 2.7 The coupled model

After setting up the box model with the decision scheme, the algorithm was coupled to the *Modflow* model (*Appendix F*).
The basic assumption of the model is stationary. In the following chapter it is explained where and why this assumption is important.

### 2.7.1 Steady state

To be able to use the aquifer as a reservoir, it is necessary to operate the groundwater surface around a defined level. This level should be steady state, so that the system is in a steady state. If the groundwater heads are constantly dropping, a sustainable operation will not be possible.

As the simulation runs on monthly time steps, it is not possible to calculate this level using steady state simulation on the basis of the monthly input values, for this will return a different level for each month. Performing a transient simulation it takes about 4000 monthly time steps to arrive at this level.

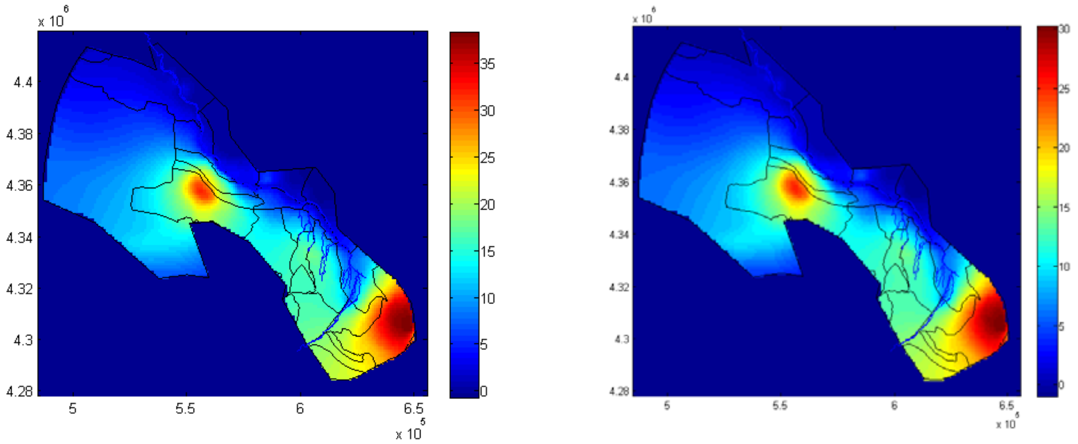

*Fig.23: Steady state drawdown [m] caculated using the transient model with full irigation (left) and with 20% reduced groundwater irrigation (right).*

For example in the district LuoTuoCheng for which the simulation shows some of the largest drawdowns in the entire basin, the steady state drawdown is around 30 meters.

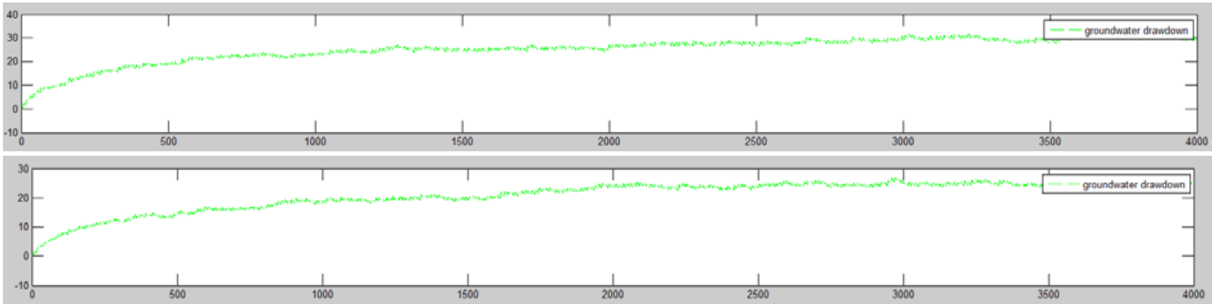


*Fig.24: Drawdown [m] for a transient simulation with 4000 monthly time steps on full groundwater irrigation (top) and 20% reduced groundwater irrigation (bottom).*

The question arises, which maximal drawdown for the operation level should be chosen. The drawdown is a direct consequence of the pumping rates, but the level estimation is a tradeoff between supplying enough groundwater irrigation to meet the farmers demand to a sufficient degree without lowering the water level too much. Finally, this long term decision must be taken by decision makers that define the groundwater pumping rates for a season.  Apart from the ecological effects that a very low water table will have on the vegetation and the ecosystem, it is important to mention that it will be hard to meet the downstream outflow constraint if the water table drops very low as the leakage from the stream into the aquifer will increase (*Fig.25*).

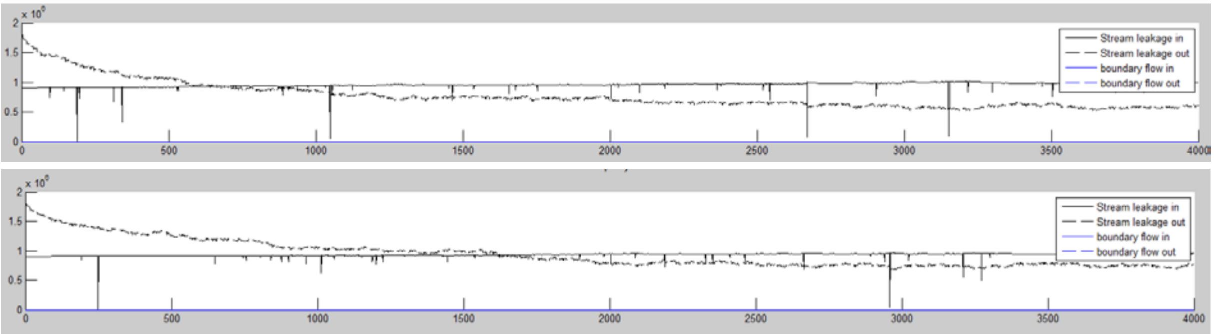


*Fig.25: Stream leakage [m³/day] into the groundwater and out of the groundwater for a transient simulation with 4000 monthly time steps with full groundwater irrigation (top) and 20% reduced groundwater irrigation (bottom).*

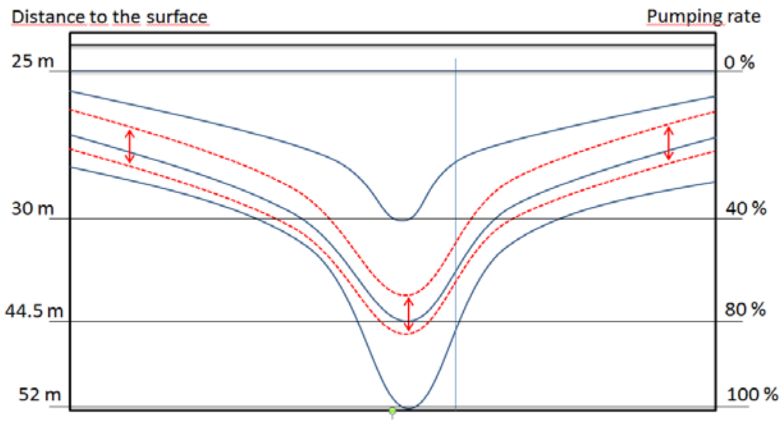


*Fig.26: Schematic visualization of the maximal drawdown in the LuoTuoCheng district for different pumping rates. The red lines mark a possible zone for conjunctive use operation of the groundwater level.*

## 2.7.2 The Irrigation demand

The same data was used for the irrigation groundwater- and surface water demand (pumping rates and irrigation surface water abstraction) as for the box model (Chapter 2.6). Constant rates for each month were assumed. As there is still an increase in agricultural area and on the other hand an improvement in irrigation efficiency, this data should be updated for future research.

## 2.7.3 The irrigation supply

It was assumed, that given a certain irrigation demand, the supply can be delivered either using groundwater or surface water and these are perfectly interchangeable. In reality there is a temporal delay using surface water and not all fields provide the opportunity to interchange these two resources.

### 2.7.4 Prediction models

A prediction model will be used to estimate the Heihe inflow at Yangluo station up to six months in advance. The generic regression model  was generated using *WEKA* software (*WEKA, 2014*) and uses the historic monthly stream data and global atmospheric indices like the Indian Summer Monsoon index, the Asian Monsoon index (*NOAA, CPC 2014*) as input data. Another model using remote sensing snow cover data in the upper catchment zone of the Heihe to predict the runoff is also available, but its performance is still under discussion (*Henze J., 2014)*. As these models are still in development state, generated data was used to simulate the inflow and check the performance of the simulation.

### 2.7.5 Irrigation potential

The irrigation season starts in March. By this time, decision makers should have the information how much surface water is available in this season and how high they have to set the quota for groundwater irrigation use. Generally in years with less predicted stream flow, farmers will have to reduce their area and rely more on irrigation water from groundwater.

### 2.7.6 Temporal availability

It is possible, that in a year of high flow (2003) not much of this stream water can be used because the water comes at a time when no irrigation is going on. On the other hand there could be a year with low inflow but at the right time (1987). It's not only a problem of spatial distribution but also of temporal applicability (*Fig.27*).

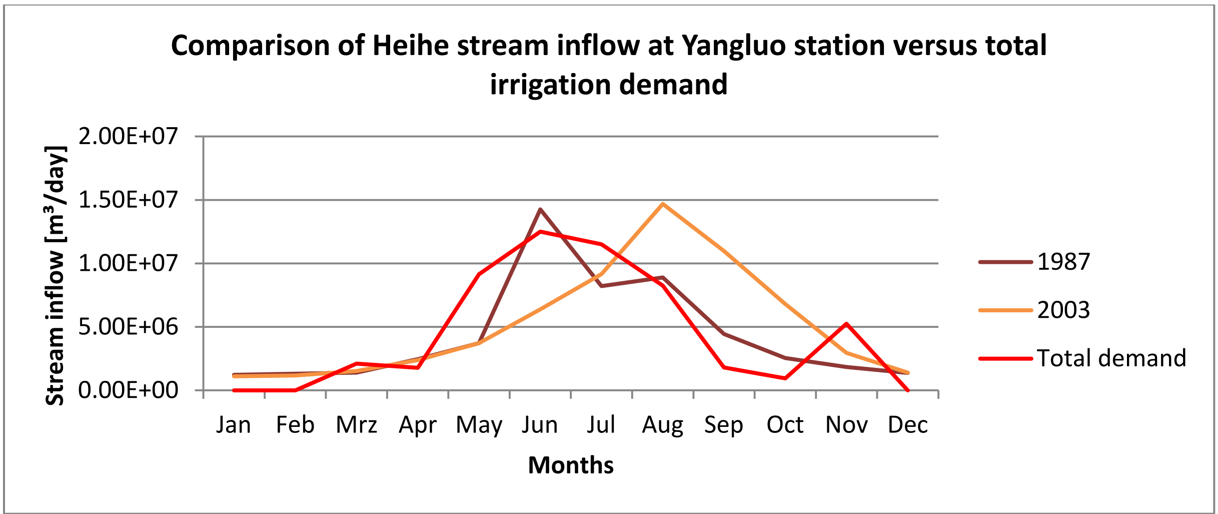


*Fig.27: Comparison of Heihe stream inflow at Yangluo station and total irrigation demand.*

In some months (April, September and October) the inflow is always higher than the demand. This inflow can´t be used and is left for downstream users.

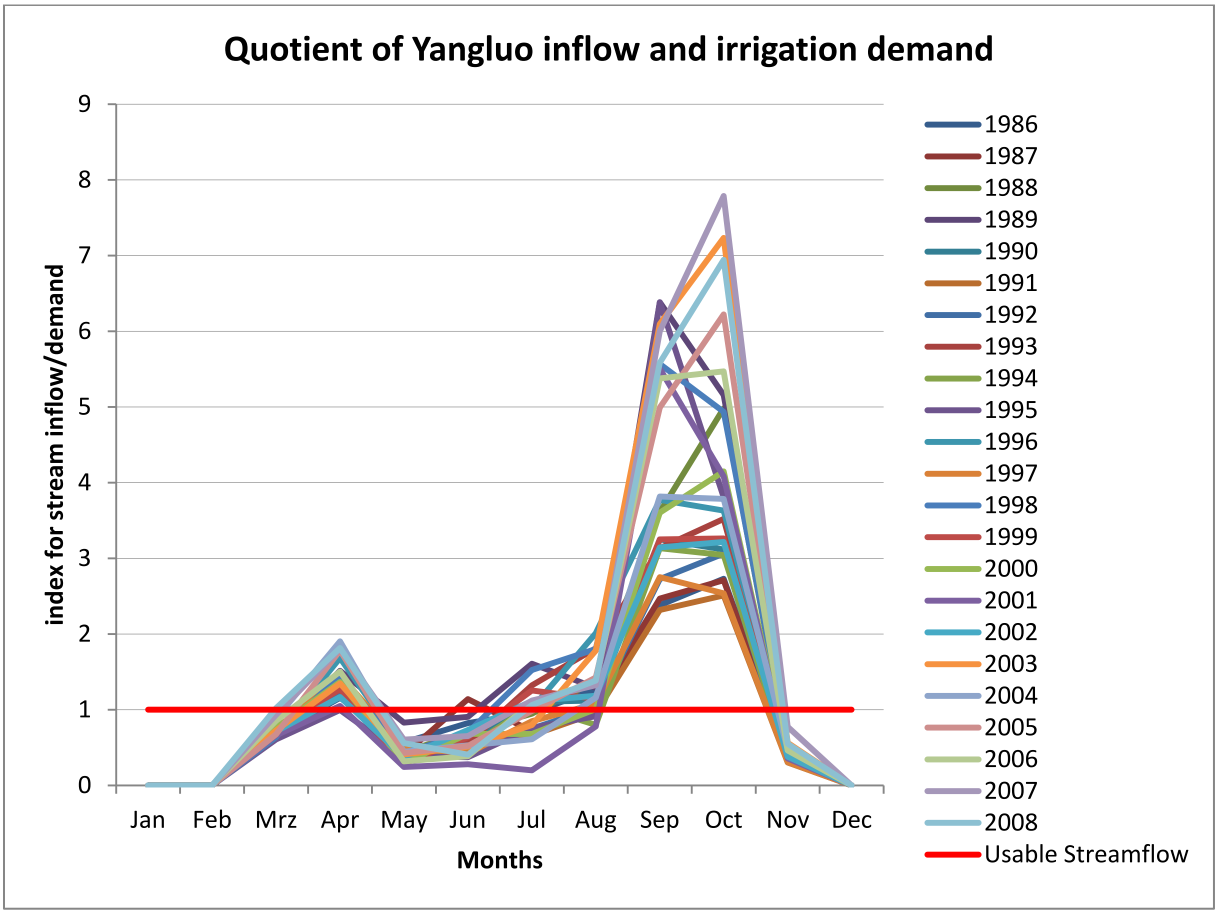


*Fig.28: Quotient of monthly Inflow and demand. An index higher than 1 indicates that not all of the inflow can be used for irrigation.*

### 2.7.7 Estimation of the irrigation potential

Based on the predicted time series, the surface irrigation potential *sip(t)* for each month is estimated by subtracting the monthly river leakage and the monthly outflow constraint from the inflow value.

$$sip(t) = inflow_{pred}(t) - \Delta\ stream_{leakage}(t-1) - outflow_{constraint}(t) \quad (10)$$

The term $\Delta\ stream_{leakage}$ refers to sum of the stream leakage into the aquifer and the leakage from the aquifer into the stream, which depends on the groundwater level. As this is not yet known for the current time step, the level in the previous month *(t-1)* is taken. In months of low flow the inflow is already less than the monthly outflow constraint. As this constraint only needs to be met over the entire year, the months with high flow need to compensate for the months with low flow. A deficit (11) is calculated, which is then abstracted from the months with high inflow (14) depending on their total value (13) to correct the *sip.*
By adding up the monthly surface water supply and comparing to the total yearly demand, the yearly quota for surface- and groundwater irrigation are obtained.

$$constr_{deficit} = \sum_{k=0}^{n} constr_{deficit}(k) \quad if \quad sip(k) < 0 \quad (11)$$

$$sip_{tot} = \sum_{k=0}^{n} sip(k) \quad if \quad sip(k) > 0 \quad (12)$$

$$sip_{percentage}(t) = \frac{sip(t)}{sip_{tot}} \quad if \quad sip(t) > 0 \qquad (13)$$

$$sip_{corrected}(t) \begin{cases} = sip(t) - sip_{percentage}(t) * constr_{deficit} & if \quad sip(t) > 0 \\ = 0 & \text{if} \quad \text{sip(t)} < 0 \end{cases} \qquad (14)$$

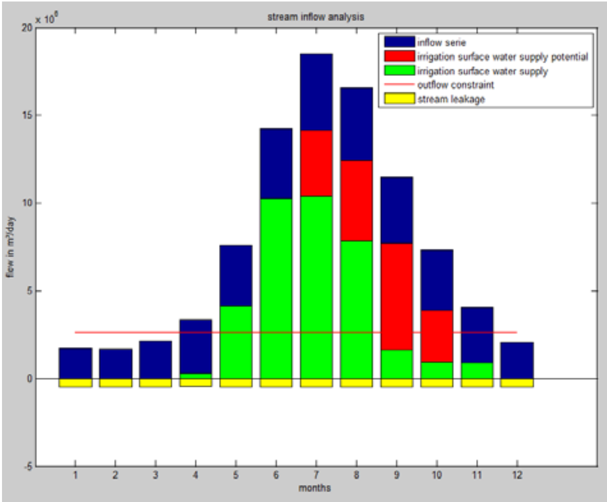


*Fig.29: Estimation of the surface water supply potential for a high flow year. From July to October there is unused potential (marked in red). For better visualization the stream leakage is shown with negative values.*

### 2.7.8 Moving stream classification

The estimation of irrigation potential was applied to the 23 years of inflow data and based on the results a stream classification scheme with seven classes was designed. The classification uses the part of irrigation demand in a year (*y)* that can be satisfied using surface water (*sip*). This part is calculated dividing the total available surface water per year (m³) by the total yearly irrigation demand (m³). To get this figure, the monthly *sip* and irrigation demand is multiplied by the number of days in the month *k* $\left(length_{month}(k)\right)$. The inflow series is then rated using a *stage index*. As the *sip* depends on the stream leakage, the classification system needs to be adapted to a new situation. For every year, the system is automatically recalibrated using the current groundwater level and the resulting stream leakage values. The classification was programmed to be a learning system, which uses new inflow years to make the calibration system now based on 23 years of time series more accurate by adding future inflow time series.

$$Stage\ index(y) = \frac{\sum_{k=1}^{12} sip_{corrected,y}(k) * length_{month}(k)}{\sum_{k=1}^{12} irrigation_{demand}(k) * length_{month}(k)}, k: month, y: year \qquad (15)$$

*Stage 7: > Stage index 6*
*Stage 6: mean stage index +2/3* (max-min) stage index(1986:2008)-> max stage index(1986:2008)*
*Stage 5: mean stage index +1/3* (max-min) stage index(1986:2008) -> mean stage index +2/3* (max-min) stage index(1986:2008)*
*Stage 4: mean stage index -> mean stage index +1/3* (max-min) stage index(1986:2008)*
*Stage 3: min stage index(1986:2008)+2/3*(mean-min) stage index-> mean stage index*
*Stage 2: min stage index(1986:2008)+1/3*(mean-min) stage index -> min stage index(1986:2008)+2/3*(mean-min)*
*Stage 1: min stage index(1986:2008) -> min stage index(1986:2008)+1/3*(mean-min)*

*Fig.30: Stages for the stream flow classification.*

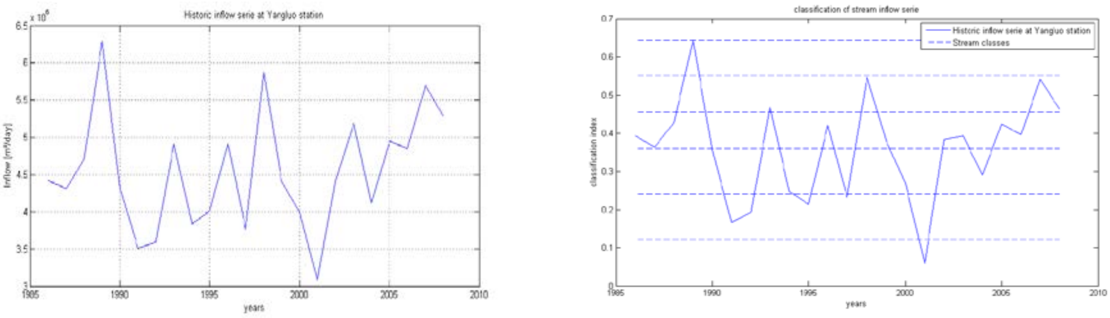


*Fig.31: Original inflow series at Yangluo (left). Classification of the inflow series (right).*

*Table 3: List of ranges for the stream inflow rating.*

| Stream stage availability | Stream stage index | Amount of SW usable yearly [m³] | Part of SW usable yearly [%] | Quota of GW needed yearly [m³] | Quota of GW assigned at stream stage index [m³] |
|---|---|---|---|---|---|
| Very high availability | 7 | > $9.651*10^8$ | > 64.36 | < $5.344*10^8$ | $5.344*10^8$ |
| High availability | 6 | $8.236*10^8$ – $9.651*10^8$ | 54.92 - 64.36 | $5.344*10^8$- $6.759*10^8$ | $6.759*10^8$ |
| Good availability | 5 | $6.821*10^8$ – $8.236*10^8$ | 45.49 - 54.92 | $6.759*10^8$ – 8.174 $*10^8$ | 8.174 $*10^8$ |
| Average availability | 4 | $5.406*10^8$ – $6.821*10^8$ | 36.05 - 45.49 | 8.174 $*10^8$- $9.589*10^8$ | $9.589*10^8$ |
| Moderate availability | 3 | $3.604*10^8$ – $5.406*10^8$ | 24.03 - 36.05 | $9.589*10^8$ – $1.1391*10^9$ | $1.1391*10^9$ |
| Low availability | 2 | $1.802*10^8$ – 3.604 $*10^8$ | 12.02 -24.03 | $1.1391*10^9$ – $1.319*10^9$ | $1.319*10^9$ |
| Very low availability (pumping only) | 1 | 0 – 1.802 $*10^8$ | 0 - 12.02 | $1.319*10^9$ – $1.5*10^9$ | $1.5*10^9$ |

As a stream stage provides a range of possible groundwater quota, the maximum quota within a range is allocated as recommended quantity. This ensures that demand is satisfied and it also provides a bufferif the stream inflow was forecasted too low. On the other hand this way more groundwater than actually needed is allowed to be withdrawn which leads to higher drawdowns.

## 2.7.9 High and low inflow series

To test the system for its behaviour during high and low flow seasons, a high- and a low flow series of 7 years was generated from the 23 years of inflow data using the highest respectively lowest values for each month *(k)* that occurred in the time series.

$$High\ flow(k) = \max\,(timeserie(k,y))\ ; y = \{1:23\} \qquad (16)$$

$$Low\ flow(k) = \min\,(timeserie(k,y))\ ; y = \{1:23\} \qquad (17)$$

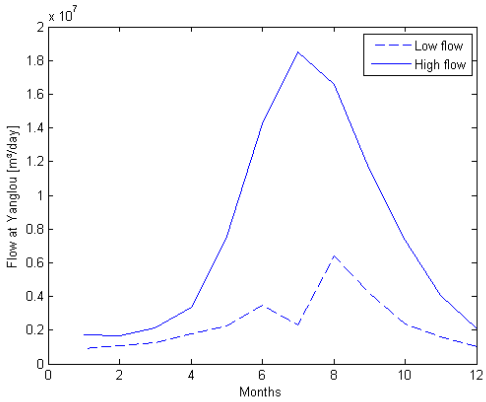


*Fig.32: High and low inflow series generated based on the highest respectively lowest monthly inflow values.*

## 2.8 Visualization

During the project meetings in Lanzhou and Zhangye (China) it became clear that a tool for visualizing the current state of the system and the simulation results is necessary. It should be accessible for decision makers by browsing a secure website and it should be easy to understand. In the pre-studies for this project *google earth* proved to be a useful tool for visualizing results. By implementing google outreach into an ETH hosted webpage, an example for such a tool was realized. It is based on KML layer files integrated into the google earth environment. The tool is updated directly from the Matlab simulation program.

It can be accessed via ''*http://n.ethz.ch/~anzj/Heihe_project/index.html*''.

User: heihe

Password: lanzhou

Hint: The first time the page is accessed it can occur that the password must be entered three times.

### 2.8.1 Setting up of the Web Page.

The webpage uses high resolution DEM and aerial images provided by google earth as background for an overlay image to show the drawdown. The database is a KML file which combines multiple layers and KML files and can easily be updated. It enables the user to visualize:

- Irrigation districts
- The model boundary
- Pumping and observation wells with name, Id and description. Added to each well is a graph showing the pumping rates and the water level in the case of observation wells.
- The past and predicted stream inflow series and the rating with the recommended surface and groundwater allocation rates
- The past and predicted time series of the stream outflow.

For demonstration purpose 4 observation wells are displayed.

### 2.8.2 Matlab interaction

The KML file places symbols and points on specific locations of the map and shows a table or a picture linked to that point. The model results are therefore either written in tables or shown as pictures. The matlab file 'kml_builder.m' saves the model results onto a webserver from where the KML database can access them to show them on the website. After initialization the website calls this database and shows the results. The KML file incorporates the results of the simulation which need to be saved as pictures by creating html tags to them. Therefore the 'kml_builder.m' needs to save the simulation results to a folder on the webserver.

### 2.8.3 Plugins and Security

Depending on the version of web browser (Chrome, Firefox, Internet Explorer, Safari) the g*oogle earth plugin* must be installed. If this is the case, a message will show up instead of the visualization window after logging onto the webpage.

The website must be accessed using a standard http or a VPN connection, using SSL encryption (https) is does not yet work.

The access to the website was set up to be password restricted. With the ETH server being located in Switzerland and secured by the ETH infrastructure, the data should be in a save place. The user accounts are set up by the system administrator.

As the webpage accesses three different server ports, the login question is sometimes posed 3 times when the page is loaded first. The user account and password are the samefor all ports.

### 2.8.4 Database

The static data containing the location of the district boundaries, the channel shape, the irrigation network and the location of pumping- and observation wells are stored in a KML Database on the ETH webserver. The temporal dataset containing the model results as well as a backup copy are stored in the folder '*model_results*' on the ETH webserver.

### 2.8.5 User interaction

The user interface allows the user to zoom into the visualization. By clicking on a district layer, the actual and recommended pumping rate as well as total groundwater and surface water release quotas are shown. By clicking on an observation well, the modelled versus the observed drawdown is plotted.

Under the section *Stream prediction*, the predicted versus the observed in- and outflow curves and the stream rating is shown. A surface- and groundwater release table can be shown as well.

The section *Data Management* is password restricted and can be used to store confidential data for the decision maker. The login and password is: *"mrliu".*

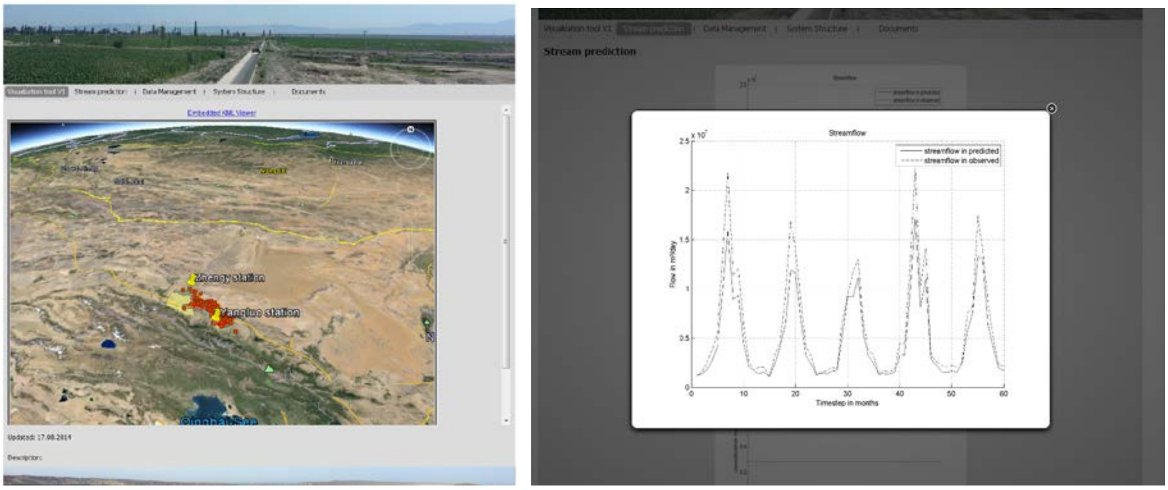


*Fig.33: Examples for the user interface of the webpage.*

# 3. Results and discussion

Before the conjunctive use concept was tested, different scenarios were simulated to gain an understanding of the box model system dynamics. Each scenario was simulated with a time span of 100 years (1200 monthly time steps).

## 3.1 The box model

*Table 4: Scenarios for testing the box model behavior.*

| Scenario | Surface water partition | Supply reduction factor | Draw-down [m] | Stream outflow index | Demand index | Demand index Ground water | Demand index Surface water | Drawdo wn target [m] |
|---|---|---|---|---|---|---|---|---|
| S1 – Natural State | 0 | 0 | <1 | 1.25 | - | - | - | - |
| S2 – Original allocation | -1 | 1 | 110 | -0.20 | 1 | 0.73 | 0.27 | - |
| S3 – Only Surface water use | 1 | 0 | -12 | 0.33 | 0.66 | 0 | 0.64 | - |
| S4 – Only Ground water use | 0 | 1 | 150 | -0.25 | 1 | 1 | 0 | - |
| S5 – Priority Sw use with reduction | 1 | 0.7 | 20-40 | 0.02 | 0.84 | 0.39 | 0.45 | - |
| S6 – Drawdown target level | 1 | 0.7/0.5 | 15-30 | 0.01 | 0.82 | 0.37 | 0.45 | 30 |

*<u>Scenario S1</u>*: The natural state without pumping or surface water abstractions. This scenario defines the zero-drawdown situation. The stream outflow was 1.25 times higher than the constraint requires.

*<u>Scenario S2</u>*: At the present (2010) allocation, the drawdown went down to 110 m and the stream outflow was in average 20% less than required. The reason why the drawdown is so large is that much less surface water can be abstracted from the stream than required. This is compensated by higher groundwater pumping rates, which in turn leads to even lower surface abstractions as the stream already infiltrates more and more water into the aquifer when the water table falls. This goes on until there is a balance between pumping rates and aquifer recharge. Finally only 27% of the irrigation demand can be supplied from the stream.

*<u>Scenario S3</u>*: If only available surface water is used to satisfy the demand and the rest is left unsatisfied, the drawdown is locally even inverted compared to the natural state. This happens due to the irrigation backflow which recharges the aquifer, as the stream outflow index shows. At this state there is 33% more stream outflow to downstream users than required by the constrained. The scenario shows also, that on average 64% of the total irrigation demand can be satisfied using surface water only. In this scenario the time shift in total demand and total supply for the entire basin can be seen (*Fig 34*). In spring there is a surface water deficit while in autumn there is unused surface water potential.

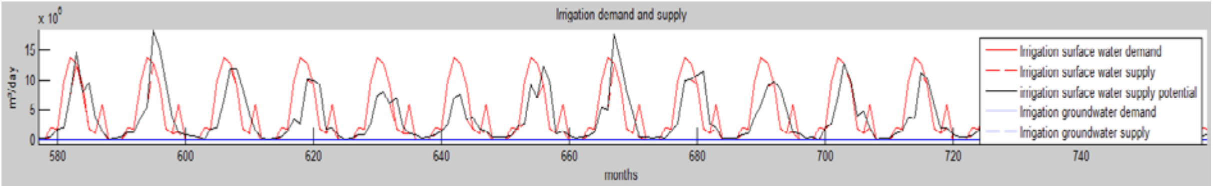


*Fig.34: The total irrigation demand (red curve, defined as irrigation surface demand) and the potential surface water supply (black curve).*

<u>*Scenario S4*:</u> When only groundwater is used, the demand is always satisfied. As a consequence the drawdown drops down to 150 m and the stream leakage out of the aquifer becomes negative, i.e. stream water always infiltrates to the aquifer. This scenario is not realistic as it would also imply that the wetlands along the river would fall dry. The low groundwater head affects the stream so much, that the yearly downstream outflow is 25% below the constraint.

<u>*Scenario S5*:</u> In scenario 5 the use of surface water is given the first priority. The water that can´t be taken from the stream flow is taken from the groundwater reservoir, but with a reduction factor of 0.7 (30% less pumping). This way, 84% of the total demand is met with 39% coming from groundwater and a groundwater level at 25 m +-10 m (*Fig.35, top*).
The fluctuations of the groundwater level within a range of 20 meter show that the conjunctive use concept works: For a consecutive period of low stream flow years the groundwater box is exploited and the water table drops and vice versa. As the reaction time of the system was speeded up by using the *factor* $\alpha$ *(Chapter 2.6.10)* this concept works for very long time scales (>10 years) according to the box model.

The stream outflow constraint is scarcely violated in the long term by 2 %. Another measure of sustainability is the lowest outflow value which occurs in the time series. In this case, the lowest outflow was 20% below the constraint. In this scenario the drawdown shows strong fluctuations in a range of 20 m. Such fluctuations are not necessarily triggered only by low stream flow values but also by the timing of the stream peak. If the timing of the stream peak changes due to external influences like human interaction upstream or climate change and the agriculture is not adapting the irrigation timing, this can also lead to surface water shortages and decreasing water tables. Another important consideration is that meeting the outflow constraint in the long run but in some years staying below it can also bring benefits and a better usage of the streamflow (*Fig.35, bottom*).

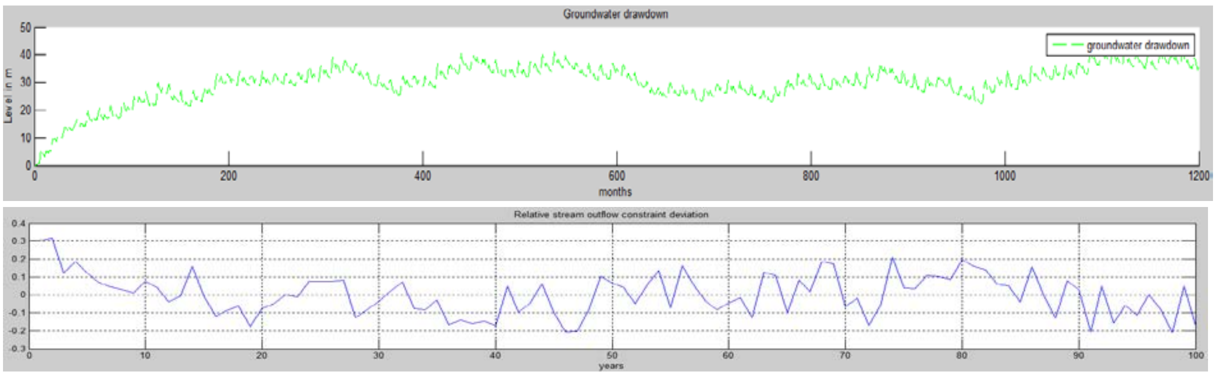


*Fig.35: Fluctuations in the drawdown level (top) and the stream outflow index (bottom). The outflow constraint is met in the long run by fluctuating around it.*

<u>*Scenario S6:* </u> Like in *Scenario S5* a pumping rate reduction of 30% was introduced. Further, a second reduction of 50% was introduced when the drawdown exceeded 30 m (groundwater level of 140m). In Figure 36 (bottom) it can be seen that during the sommer months there is still full supply from surface water, but in spring and autumn the demand relies on groundwater and is therefore not sattisfied anymore. The target level can be met and during good years the drawdown recovers.
Even if the total demand satisfaction is still 80% (*Table 4*), there is a cutoff in irrigation supply of up to 50 -60% in spring.

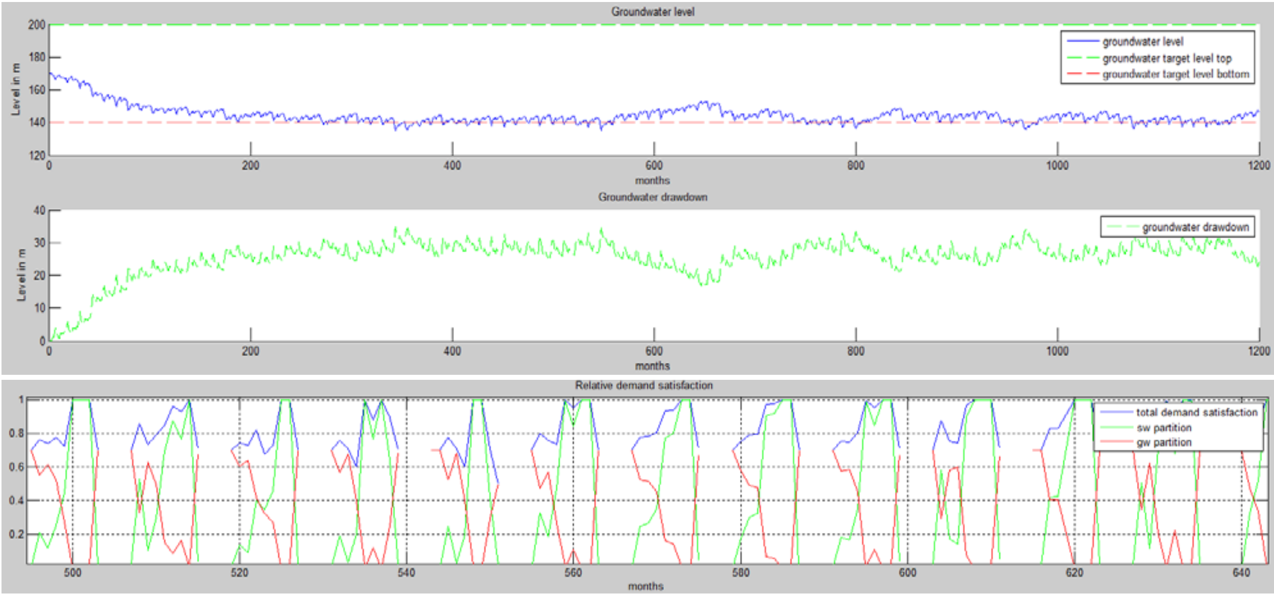


*Fig.36:* Groundwater level (m) and target level (top), drawdown (middle) and demand satisfaction index (bottom).

## 3.2 The coupled model

### 3.2.1 Steady state simulation with and without conjunctive use optimization.

Three different optimization schemes were developed and tested using the coupled model during the work process of this thesis: A version using the conjunctive use optimizer, a version using the optimizer with stream classification and a last version with stream classification and redistributed allocation.

*Table 5: The different optimization schemes.*

| Model version | Model characteristics |
|---|---|
| M1<br>Conjunctive use optimizer | Uses the approach to estimate the surface irrigation potential for every time step of a predicted inflow series and uses it for irrigation. The missing supply is provided by surface irrigation.<br>Advantage: Low irrigation supply, low drawdown.<br>Disadvantage: Stream outflow can be below the constraint. No stream classes. |
| M2<br>Conjunctive use optimizer with stream classes | Taking one year of predicted inflow series and estimating the monthly surface irrigation potential based on the outflow constraint. Classifies the year according to this potential and recommends a yearly and monthly groundwater release quota.<br>Advantage: High downstream outflow, discretized classification.<br>Disadvantage: Higher groundwater quota due to discretization, forgiven surface supply potential. |
| M3<br>Conjunctive use optimizer with redistribution | Redistributes the surface- and groundwater partitions for each district based on the total percentage of each basin of the total demand in the basin. |

M1, *Fig 37b*: Two major drawdown spots can be located in the districts Daman and LuoTuoCheng. At these locations, the approach of using optimized conjunctive water management leads to lower drawdown values than using the current allocation (*Fig 37a)*. Even if the M1 model version delivers the best results, as it is still a rather intuitive approach: The algorithm only evaluates single months without taking the entire year into account. This leads to the problem, that for a low stream flow year with few months of high flow in summer, surface water is still abstracted even if the downstream outflow constraint is not met during this year.

M2, *Fig 37c:* The second version of the algorithm takes the entire year into account to satisfy the downstream outflow constraint. This criterion is therefore met better than in version M1 (Table 5). The algorithm recommends a predefined groundwater supply quota for each year depending on the stream inflow. As the quotas are discretized in seven levels and it takes the higher level to avoid supply deficits, more groundwater than actually needed is allocated to the quota. This results in higher drawdown, similar to the current allocation (*Fig 37a).*

M3, *Fig 37d:* The redistributed allocation provides surface water according to the percentage of each district of total water needed in the entire basin, but does not change the total irrigation demand for each district. This results in allocating surface water from the upstream districts towards districts with low surface water use (especially LuoTuoCheng). It can be seen that the drawdown in the entire area around LuoTuoCheng improves but at the cost of higher drawdowns in the upstream districts

(*Fig 37c &d)*. For having a high drawdown in LuoTuoCheng, the boundary inflow from the north-eastern side can be used better. This situation shows, that it might be good to use groundwater irrigation in the downstream districts and especially LuoTuoCheng, but it should be more evenly distributed to avoid deep drawdown cones.

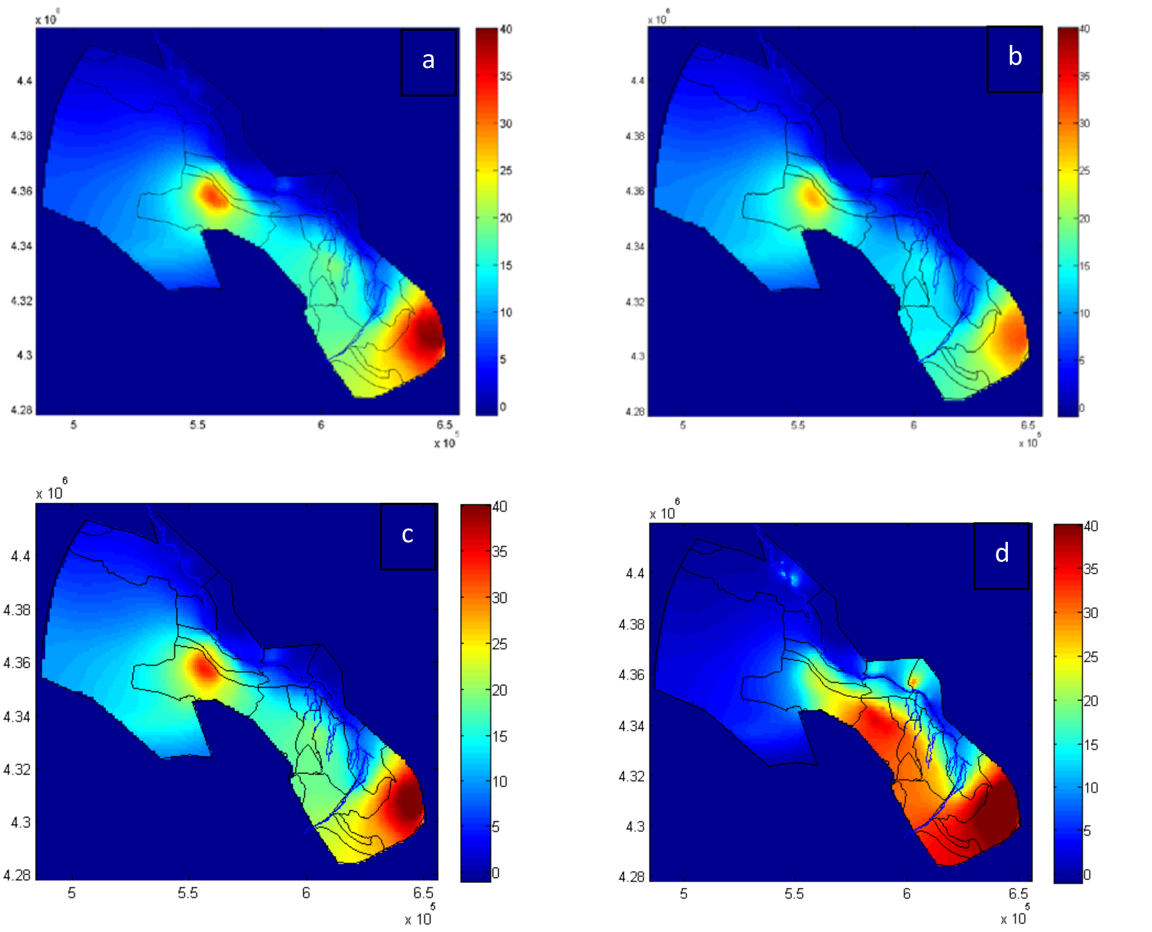


*Fig.37: Steady state drawdown using the current allocation (a), the conjunctive use optimizer (b), the optimizer with stream classifier (c) and redistributed allocation (d).*

*Table 6: Simulation parameters for the different versions at steady state. The maximal drawdown location is at LuoTuoCheng district.*

| | Original allocation | Conjunctive use | Conjunctive use with classifier | Redistributed allocation |
|---|---|---|---|---|
| Maximal drawdown [m] | 40 | 28 | 41 | 47 |
| Outflow index [%] | 8.6 | 5.9 | 23.37 | 20.35 |
| Demand satisfaction [%] | 100 | 100 | 99.64 | 1.04 |

### 3.2.2 Holding a defined target level

By setting the two groundwater supply reduction factors to different groundwater target levels a defined maximal drawdown level can be met. Starting from a steady state situation with a minimum groundwater level of 1325 m at LuoTuoCheng, the target of 1330 m can be met by reducing the groundwater pumping rate in the entire basin by 20%. The water table is rising in the 20 % reduction zone but stays at the target level when it reaches the 10 % reduction zone, indicating that 10% reduction is not enough to hold the 1330 m level.

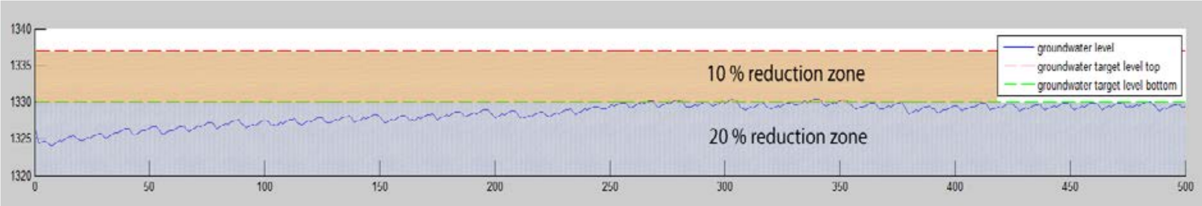


*Fig.38: Rising water table at reduced irrigation. Observation point indicated by the cross in figure 39.*

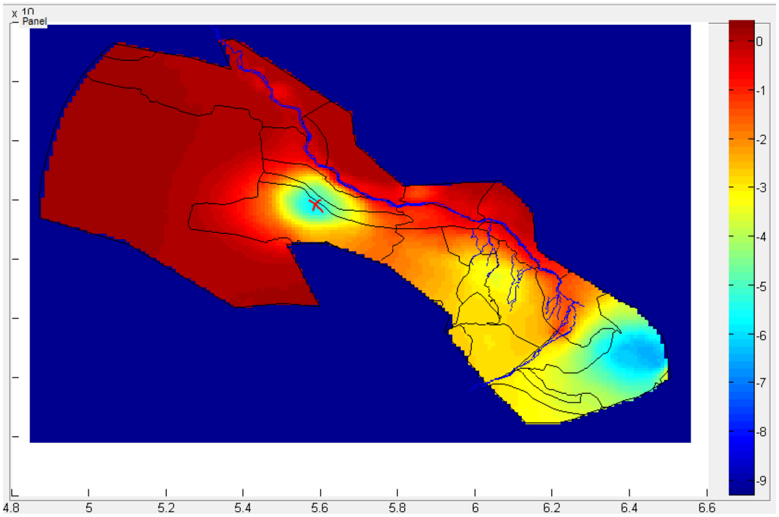

*Fig.39: The level difference [m] after 500 time steps (40 years) referenced to steady state.*

When groundwater use is reduced in the range of 10 -20 % in the entire basin, the water level rises by > 0.1 m per year at the spots with high drawdown. The lower part of the basin is almost not influenced (red color).

### 3.2.3 High and low inflow series with constraint

#### *3.2.3.1 Low flow series*

A time series using 3 normal years and 7 low flow years followed again by 3 normal years was generated. It was simulated how far the level would drop using the stream classifier. The stream class rating according to *table 3* was [4,3,4,1,1,1,1,1,1,1,3,3,4].

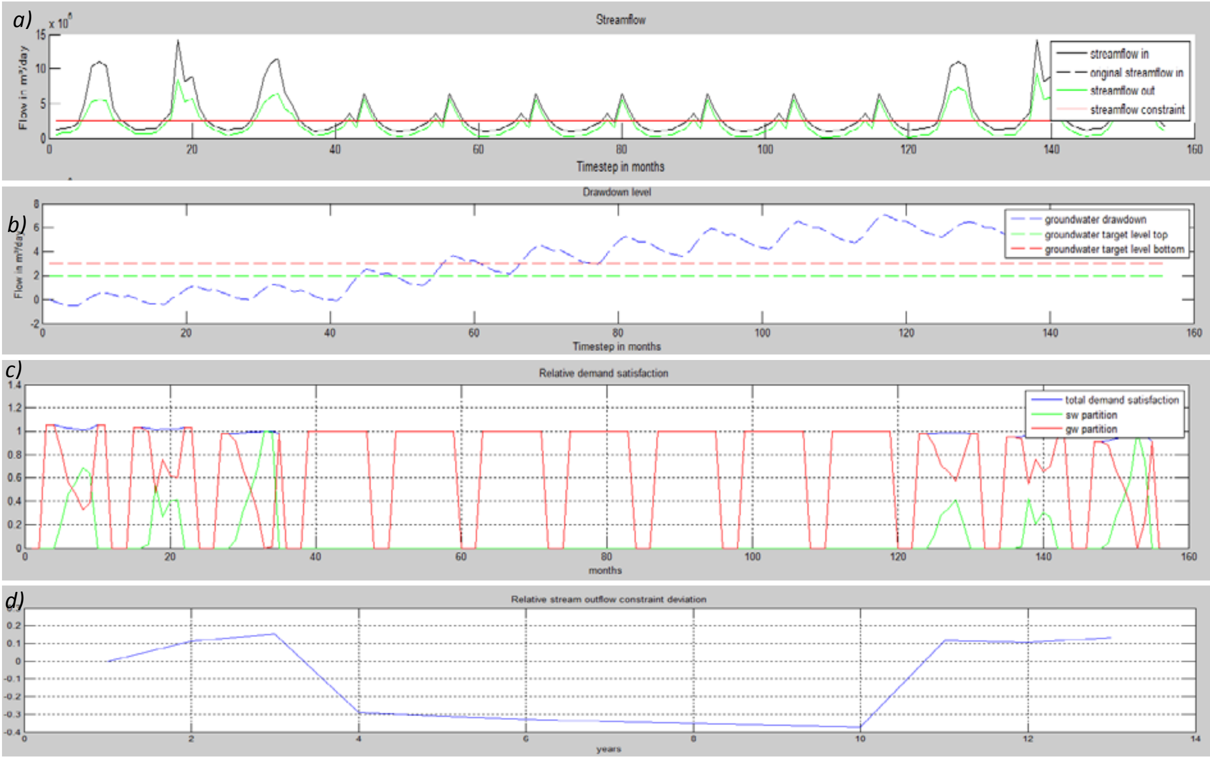


*Fig. 40: Results of the low flow scenario.*

The inflow series during the low flow years (Fig.29 a) are so low, that no surface water at all can be used for irrigation (Fig. 29 c). With the entire agriculture in the basin relying only on groundwater irrigation water during the seven years, the drawdown difference to steady state has a maximum at LuoTuoCheng with 6 meters and two other peaks in the Daman (4.5m) and Shahe (3.5 m) districts. The upstream part of the Heihe middle reach is more affected (around 2m) than the downstream part where almost no effect is seen (Fig.41 left). The outflow during the low flow years is at around 30% below the constraint. During a very bad year the water level drops at a rate of 1m/year at the high drawdown spots.

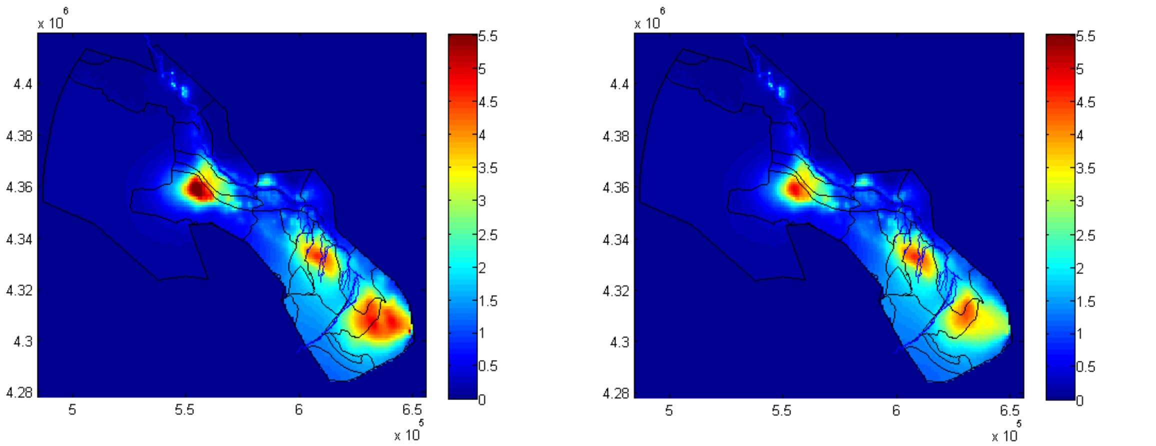


*Fig.41: Drawdown [m] referenced to steady state after 7 years of groundwater irrigation only (left). Drawdown [m] with target drawdown level for the districts LuoTuoCheng and Daman (right).*

### *3.2.3.2 Low flow series with constraints*

With this simulation the question is addressed, if it is possible for a district to realize conjunctive use concepts without cooperation of the other districts. Some districts may apply a maximal drawdown that should not be exceeded even in a period of low flow years. Using the same low flow series as in chapter 3.2.3, the reduction rate to not exceed this defined drawdown was estimated for the two districts with major drawdowns (*Fig.43*). The concept was tested to define the target level in two steps: A first step with a reduction of 20% and a second step with a reduction of 40% (*Table 7*).

*Table 7: Maximal allowed drawdown level and pump reduction for selected districts.*

| District | LuoTuoCheng (Observation well: 6-1) | Daman (Observation well: ZhangYen) | Shahe/ Xigan (Observation well: XiaoHe) | PingChuan (Observation well: Pingchuan) | Pump reduction [%] |
|---|---|---|---|---|---|
| Max. drawdown level I [m] | 2 | 2 | >10 | 10 | 20 |
| Max. drawdown level II [m] | 3 | 2.5 | >10 | >10 | 40 |
| Drawdown without reduction [m] | 3.5 | 3.5 | | | |
| Max. drawdown achieved[m] | 3 | 2.5 | - | - | - |

Applying a reduction of 20% on groundwater pumping was not enough to meet the target level, but with a 40% reduction the level could be met. So with drastic reduction a defined level could be met even during a strong ‘drought’ period.

Maximum drawdown constraints produce different effects depending on their location. Pumping reduction in LuoTuoCheng affects its neighbouring districts Youlian and Sanqing but no effect is seen in the upstream basins, and no effect on constraints in the Daman district is seen on downstream basins (*App. H*). These two districts are large and lie close to model boundaries. A reduction of districts like Shahe or Xigan which lie more in the center of the model and have a lot of neighboring districts show much more effects on other districts. It is therefore less effective to reduce pumping rates and to establish water accounting concepts without the cooperation of neighboring districts.

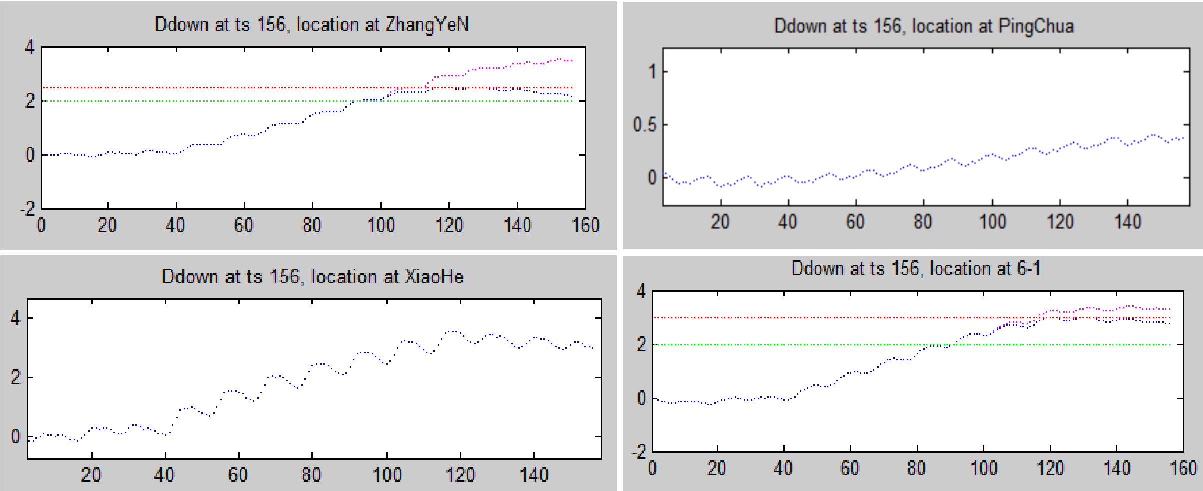


*Fig.42: Modelled drawdown [m] for the low flow time series without constraint (red) and with constraint (blue).*

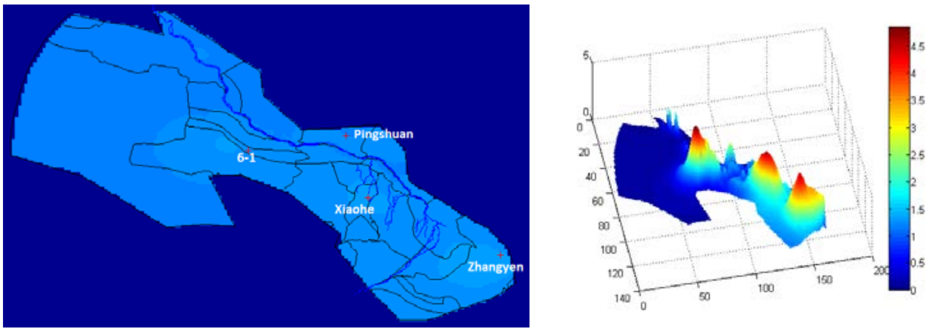


*Fig.43: Location of the observation wells (left) and 3D plot for the high drawdown spots [m] with constraint (right).*

### *3.2.3.3 High flow series*

A time series using 3 normal years and 7 high flow years followed by 3 normal years was generated. The stream class rating according to Table 3 was [4,3,4,7,7,7,7,7,7,7,3,3,4].

During the high flow years irrigation supply in the summer months can be exclusively taken from the stream (*Fig.44 c*). However in spring and autumn groundwater is necessary. During these seven years the aquifer recharges enough water for the water table to increase about 5 meters at the location of observation well 6-1 (LuoTuoCheng) (*Fig.44 b*). This gives a recharge rate of about 0.8 m per year. The stream outflow during this period is around 80% higher than the required constraint (*Fig.44 d*).

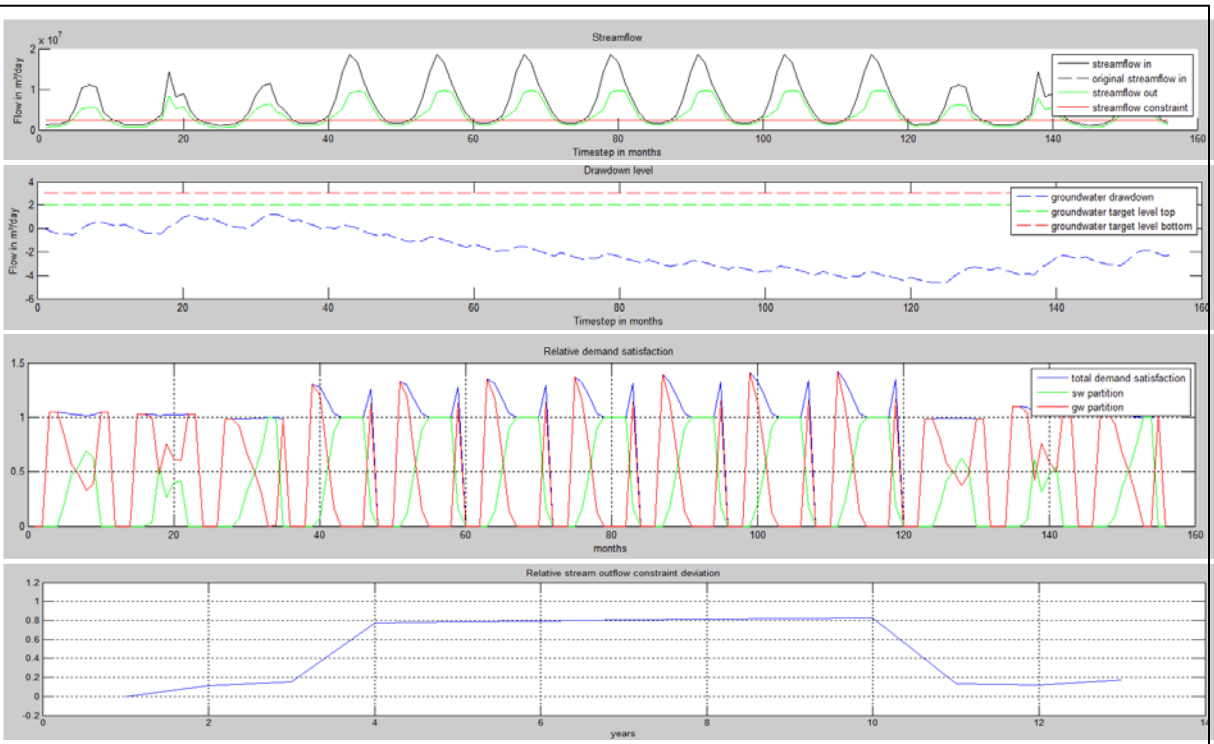


*Fig.44: Simulation results for 7 years of high inflow series.*

During spring and autumn there is too much irrigation water allocated to the supply. The reason is that the classification scheme distributes the minimum quota of groundwater (*Table 3*) to the few months were it is needed. This could be improved by further discretizing the classification scheme (Chapter 2.7.8).

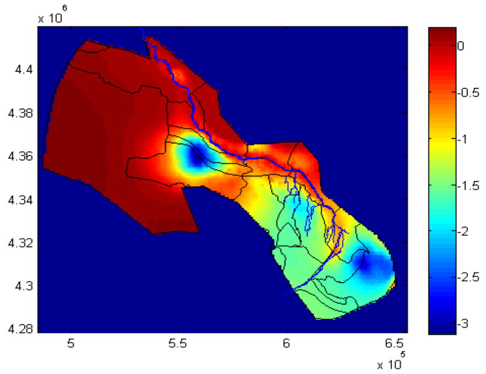


*Fig.45: The increase of the water table [m] from a steady state situation.*

### 3.2.4 Simulation time horizon and variability

How fast does the aquifer react to pumping? In 3.2 and 3.1 it can be seen that within 7 years of high inflow the water table increases by 4 meters, while during seven low flow years it drops 6 meters.

It was simulated that if all pumping stopped, it would take about 150 years for the water table to recover to a new equilibrium with a rate of about 1 m per year at the beginning. As the balance changes from stream leakage into the aquifer to more leakage from the aquifer into the stream (*Fig.46 middle*), there is slightly more stream outflow than inflow, which makes sense as without pumping, the only way out for water is the stream outflow downstream and the evaporation.

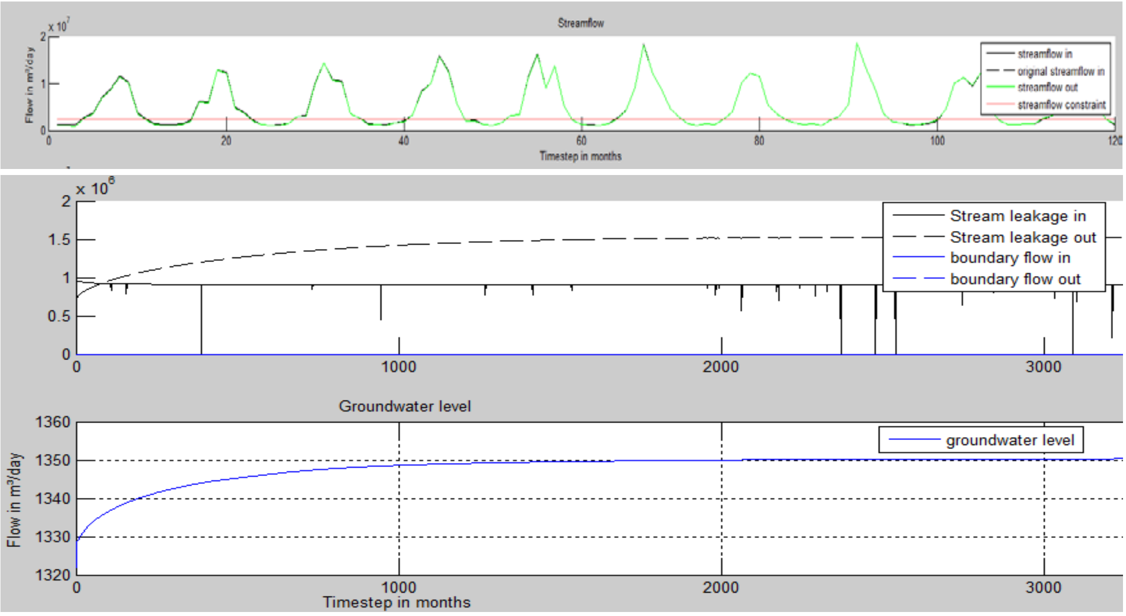


*Fig.46: The recharge curve towards a natural steady state: It takes around 150 years for the water table to recover.*

The simulated water level at steady state shows that there is a variability of the water table (simulation point at observation well 6-1, *Fig.43 left*) of about 4 meters in 10 years. The system is performing automatic conjunctive use: If there are some consecutive years with low inflow, the water table drops while it rises in consecutive years of high inflows. Attention should be paid that this could lead to problems with the pump yield and the pump irrigation counters, which estimate the pumped irrigation amount (and fees) via a calibration curve from electricity use. Additionally there is a seasonal cycle of about 1 m level difference close to the major drawdown spots (LuoTuoCheng, Daman and Shahe/Xigan district).

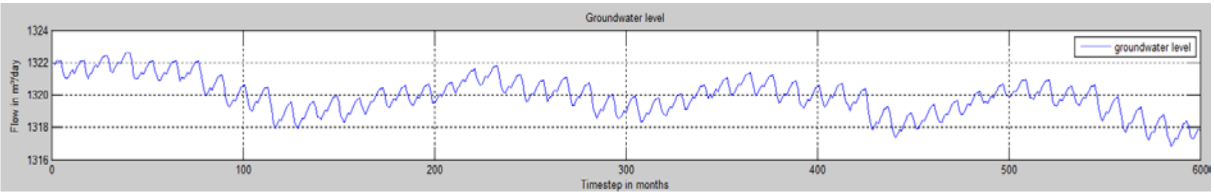


*Fig. 47: The natural variability of the water table at steady state (observation well 6-1).*

### 3.2.5 Prediction example and uncertainty

How does a wrong prediction influence the system behavior?

In a year where the stream flow was predicted to be higher than the actual value, more surface water is allocated for irrigation than can be taken from the stream. If the recommended amount of surface water is anyway diverted from the stream, the stream outflow will be too low and it will not be possible to fulfill the outflow constraint.

If the surface water diverted from the stream is reduced, the quota for groundwater pumping that compensates the missing surface water has to be adjusted.

A random time series of 10 years was created and simulated, then the inflow was reduced by 10%, 15% and 20% in every year. It could be seen that a wrong prediction of 10% already resulted in classifying the stream one stage lower. This leads to a recommendation of usable surface water which is too high and a recommended groundwater pumping quota which is too low. Table 8 shows the deficit of the allocated groundwater quota. The possibility that wrong monthly predictions even each other out were not taken into account.

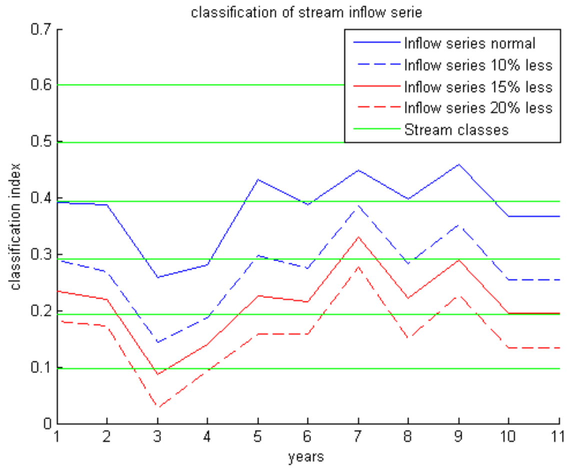


*Fig.48: Predicted (inflow series normal) and reduced inflow series in the stream classification scheme.*

*Table 8: The classification of the stream series and the missing groundwater supply quota.*

| **Year** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | Stream out [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Normal | 4 | 4 | 3 | 4 | 5 | 4 | 5 | 5 | 5 | 4 | + 21.59 |
| 10% | 3 | 3 | 2 | 3 | 4 | 3 | 4 | 4 | 4 | 3 | + 0.4 |
| Supply deficit average (m³/day) | 3.45E+06 | 7.91E+06 | 1.26E+07 | 2.11E+07 | 2.88E+07 | 3.31E+07 | 3.51E+07 | 4.28E+07 | 4.64E+07 | 5.12 E+07 | - |
| % of total | 7.0% | 8.1% | 8.6% | 10.9% | 11.9% | 11.7% | 11.0% | 11.9% | 11.6% | 11.5 % | - |
| 15% | 2 | 3 | 1 | 2 | 3 | 3 | 4 | 3 | 4 | 3 | -10.75 |
| Supply deficit average (m³/day) | 6.12E+06 | 1.30E+07 | 2.05E+07 | 3.13E+07 | 4.26E+07 | 4.97E+07 | 5.36E+07 | 6.38E+07 | 6.97E+07 | 7.72 E+07 | - |
| % of total | 12.5% | 13.3% | 13.9% | 16.1% | 17.6% | 17.6% | 16.8% | 17.8% | 17.4% | 17.3 % | - |
| 20% | 2 | 2 | 1 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | -21.56 |
| Supply deficit average (m³/day) | 8.80E+06 | 1.80E+07 | 2.83E+07 | 4.14E+07 | 5.60E+07 | 6.57E+07 | 7.14E+07 | 8.45E+07 | 9.27E+07 | 1.03 E+08 | - |
| % of total | 17.9% | 18.4% | 19.2% | 21.4% | 23.2% | 23.3% | 22.3% | 23.6% | 23.2% | 23.0 % | - |

There are mainly two ways to address the problem of groundwater quota which are too low because of wrong predictions:

1) Either by making a precise prediction, especially for the summer month when the irrigation uses surface water
2) Assigning a safety margin to the groundwater quota which can be used if the forecasted release schedule can´t be met.

### 3.2.6 Fit of demand and supply

An important difference between a monthly and a yearly analysis of the situation is the fact that demand and available supply don´t fit perfectly in the monthly analysis.  In spring (March, April) irrigation is mostly realized from groundwater pumping as the stream has still little flow. In autumn on the other hand there is enough stream flow but little demand. This situation occurs mainly in September and October (*Fig. 29*). The excess water from these months could be stored in surface reservoirs to be used in November when there is again irrigation demand for winter preparation of the fields.

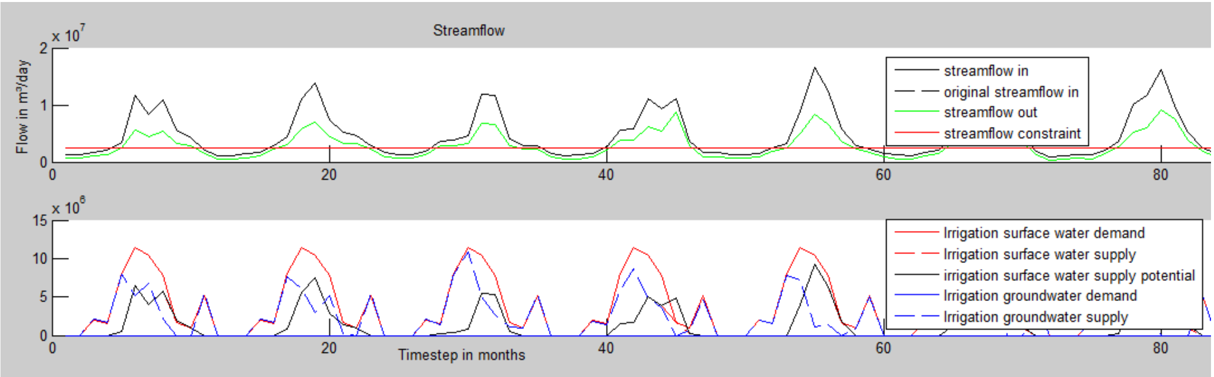


*Fig.49 : Stream in- and outflow, demand- and supply curves for 5 random years.*

### 3.2.7 Reservoir

According to internal information (*Prof. Kinzelbach, ETH Zürich)* the Chinese government is evaluating the option to build a large reservoir in the Qilian mountains to dam the Heihe. While such a dam will certainly have a vast impact on the environment it could relieve the water resource situation in the basin if the dam operation and agricultural water irrigation officials collaborate. It was simulated how the water allocation could be improved if such a reservoir would be used exclusively for irrigation improvement.

The programming scheme (*App.G*) works that way, that it uses the stream water that can´t be used (because there is no irrigation demand at that time) to fill up the reservoir. It is taken into account, that the stream outflow constraint is met. Water from the reservoir is released when the (natural) surface water from the stream is not sufficient to satisfy the demand anymore.

Before entering the Heihe middle reach the river presently already passes a reservoir, the Longshou II Dam. The dimensions of this rather small reservoir (Length: 3080 m, Width: 191 m, Height: 146.5 m, hydraulic residence time about 20 days) were taken and only the level of this dam was used as reference to evaluate the necessary size.

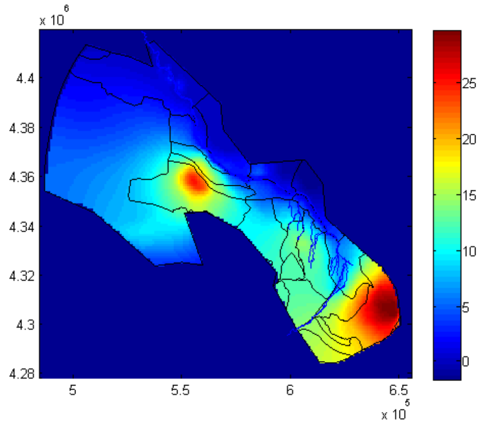


*Fig.50: Steady state drawdown (m) with reference to the natural state including reservoir usage.*

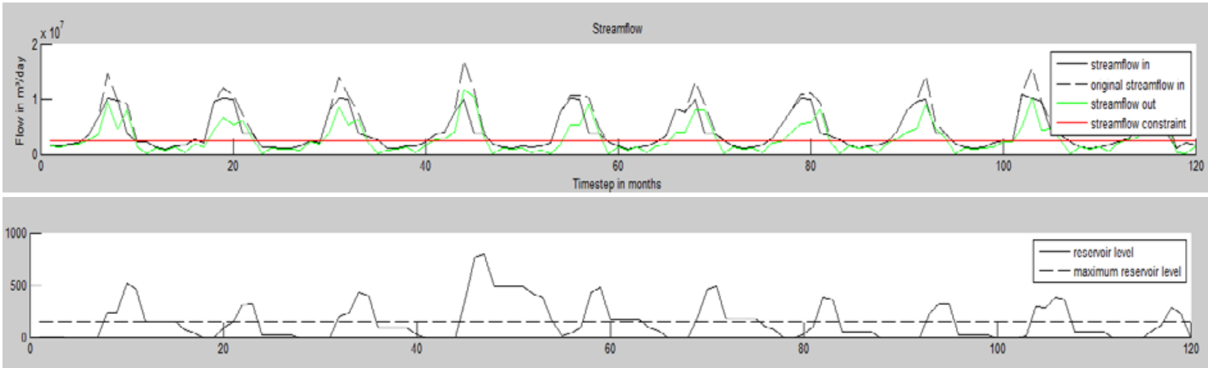


*Fig.51: The inflow series (original streamflow in), the inflow series at Yangluo after filling up the reservoir (streamflow in) and the outflow series (top). The reservoir level (m) and the maximum reservoir level of the Longshou II Dam (bottom).*

The reservoir level fills up at the end of every growth season and is emptied by the last winter irrigation or finally by early spring irrigation the following year. This allows further improving conjunctive use and improving the drawdowns remarkably.  However, a much larger reservoir (3-4 times the size of *Longshou II Dam)* would be necessary.

# 4. Conclusion

Boxmodel

Using a box model programmed in Matlab to simulate the behavior of a basin proved to be a useful tool: The implementation of the decision scheme concepts is rather easy and computation time is short.

Box model simulation showed a change from a natural state where the stream is leaking into the aquifer towards a state where the aquifer is increasingly recharged by the stream with increasing drawdowns. This change in the water balance could also be verified using the coupled model. The box model indicated also the problem of the time shift between irrigation demand and surface water supply: Even during high flow years groundwater is needed for early spring irrigation (March, April) and the irrigation in November for winter preparation. The system does not come to a steady state if the entire basin uses groundwater only.

To simulate drawdowns applying conjunctive use concepts the system must be in a steady state. The drawdown at this steady state was very large >100m. Such a low water table has the consequence that the river leakage into the aquifer increases so much that the downstream outflow constraint can´t be met anymore. The problem of low stream flow therefore has to take into account not only the surface water abstraction, but also the increasing river leakage by lowering the water table.

To simulate the system behavior at steady state, the groundwater irrigation rate was reduced by 30%. At this state, the system showed a maximum drawdown at LuoTuoCheng of 30m with a variability of ± 10m induced by periods of high and low flow years. These level fluctuations occur over very long time horizons (>10 years).

By reducing the groundwater irrigation when exceeding a defined level, the maximum drawdown of 30m at LuoTuoCheng could be maintained. The total irrigation demand could still be satisfied to 82%, but in spring the reduction could be up to 50%. The challenge for sustainable aquifer management is therefore especially to reduce the irrigation demand in spring.

Despite its fast computation time the box model has the major disadvantage that it can´t simulate a spatially distributed water table and the separate water allocation to different districts.

Coupled model

The coupling of a Matlab interface with Modflow is a very challenging and time consuming process. The advantage is that Matlab provides an extensive environment for implementing algorithms, visualizing results and coupling the program code to other applications.

The coupled model showed also that if the current groundwater irrigation practice is continued, the system comes to a steady state in which the groundwater is so low, that it is hard to meet the outflow boundary constraint. The pumping rates must therefore be reduced by 20%.

As reference scenario for the initial heads a natural steady state without surface- or groundwater abstractions was taken

Two major drawdown centers were identified in the districts Daman and LuoTuoCheng when simulating the steady state with irrigation compared to the natural initial heads.

The steady state using the present water allocation resulted in drawdowns of 35 m at LuoTuoCheng and 40m at Daman. Using the conjunctive use approach, the drawdowns could be reduced to 28m respectively 33m. However, the stream outflow could not be met during all years.

As decision makers need to define a groundwater irrigation quota each year, a classification scheme was developed that rates the stream inflow series and recommends a yearly groundwater irrigation quota based on this rating. Using this scheme, the steady state drawdown increased again but the stream outflow constraint was met to a sufficient degree.

Using a simulation which allocates the available surface water according to the percentage of the demand of each district on the entire basin, the drawdown in the entire area around LuoTuoCheng decreased at the cost of increase in the upstream districts. This leads to the conclusion that groundwater pumping in the downstream districts and especially LuoTuoCheng has the advantage that the inflow from the north-western boundary can be utilized better.

The variability in the water table at LuoTuoCheng is around 4 meter on the time scale of 10 years: The water table increases by 2 m during a series of good flow years and decreases by 2 meter during a series of bad flow years applying conjunctive use simulation to a generated time series.

When simulating a generated series of best – and worst case stream flow years, the water table increased at a rate of 0.8m per year when groundwater could be saved respectively dropped at a rate of 1m/year when the entire irrigation had to rely on groundwater only. If all irrigation stopped, it would take about 150 years until the water table recovers from a steady state under present irrigation practice back to the natural state.

The visualization using google earth as background overlay and a KML database integrated into a website proves to be fast accessible, secure and good for keeping the overview.

Even if farmers realize that is important to use irrigation water efficiently, they probably don´t act so until they are forced to (by defined pumping quotas) or when it comes to a financial loss because the irrigation is too expensive. The concept of conjunctive water use is based on the primary use of surface water in years of high flow and high availability to let the aquifer recharge during this time. The pumping quota should be kept small in this time to force the farmers to use the surface water efficiently. During low flow years when there is only little surface water available, they are allowed to pump a higher quota of groundwater. To emphasize the use of surface water, its price should be lower than the groundwater price, in contrast to the current pricing situation.

For an agriculture which relies exclusively on irrigation as the natural precipitation is very low good management practice is crucial. So it is recommended to manage the aquifer using a conjunctive use concept like described in this thesis. To avoid economic and environmental damages a maximum drawdown level should be defined. If this level is exceeded the groundwater irrigation quota should be cut back or the price for pumping should be increased.

Further research should focus on an assessment taking environmental, social and economic aspects into account to find the optimal operation level for the water table.

# Glossary

CWM: Conjunctive water management

*DEM:* Digital Elevation Model.

*Drawdown:* Always referred to as the decline of the water table level at a certain point from an initial value defined in positive direction (Water table level decline of 1m = +1m drawdown).

*GUI*: Graphical User Interface

*Ground water reservoir:* Using the aquifer as a reservoir.

*IFU:* Institute für Umweltingenieurwissenschaften ETHZ

*KML*: Keyhole Markup Language. XML notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers.

*MEF:* Minimum environmental flow

*Natural state:* Reference state for the initial heads representing the system state under natural conditions without stream abstractions, irrigation pumping and irrigation backflow.

*sip:* Surface Irrigation potential

*Surface water reservoir*: Refers to the stream as source for irrigation water

*Yangluo:* Stream measurement station at the upstream boundary of the model.

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# Appendix A - Insurance policy concepts

To reach a sustainable balance between stream flow use, a sustainable groundwater table and a healthy ecology, the farmers will need to reduce their water use and thus their agricultural area. The groundwater use can be controlled by an IC card system, which allows only a predefined amount of water to be abstracted for each pumping station. An insurance concept to improve income security of the farmers and reduce groundwater irrigation is developed:

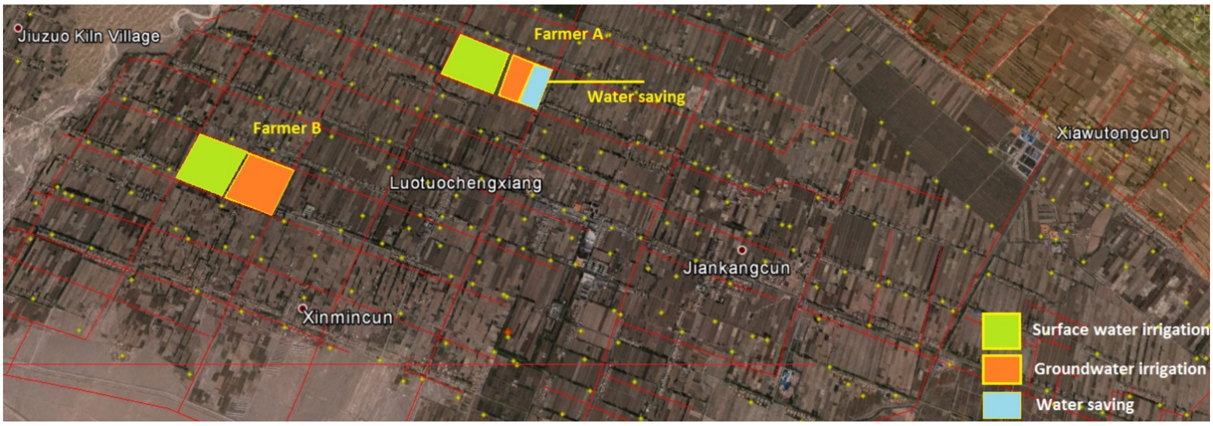
**Situation 1: High flow, sufficient surface water for irrigation, quota on groundwater irrigation.**

Farmer A: The farmer chooses to save groundwater, doesn't cultivate all his fields and does not use the full irrigation quota he could obtain. He earns less than Farmer B but as an incentive, he gets certificates to buy additional groundwater at a preferential price up to a certain quota.

Income = 800

Famer B: The farmer uses his full quota of groundwater all the time and cultivates all of his fields.

Income = 1000




*A.Fig.1:* Situation high flow, enough surface water for irrigation, quota on groundwater irrigation.

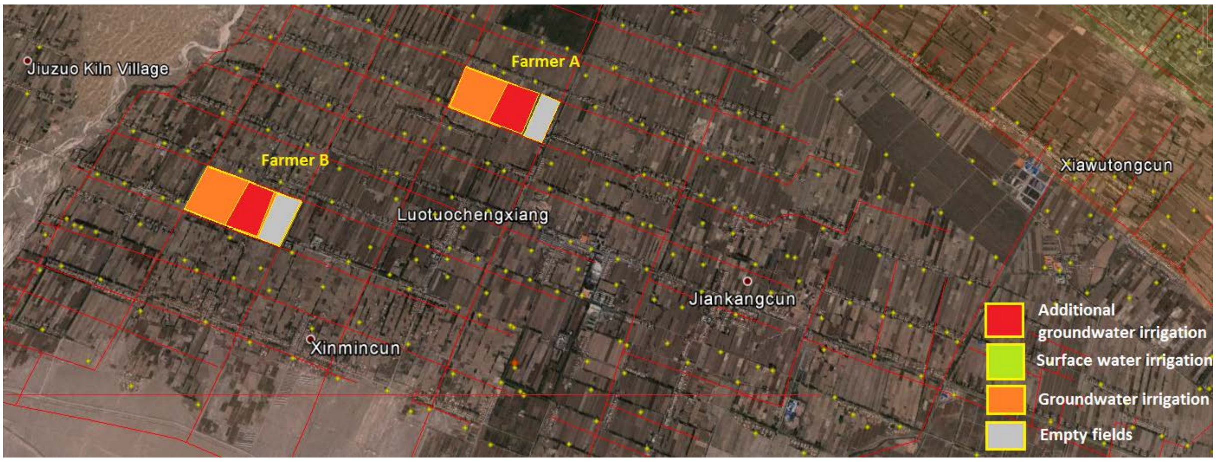
**Situation 2: Situation low flow, no surface water for irrigation, quota on groundwater irrigation.**

Farmer A: The farmer uses only groundwater irrigation and keeps his cultivated area constant. The additional groundwater irrigation exceeding his quota is covered by his certificates; he obtains it for a reduced price of 100.

Income= 800- 100= 700

Famer B: The farmer faces the same situation like Farmer A. He needs to cut back on his irrigated area and has to buy additional groundwater at a higher standard rate of 300.

Income= 800- 300= 500




*A.Fig.2: Situation low flow, no surface water for irrigation, quota on groundwater irrigation.*

In this case the cumulative earnings for both farmers are equal, 1500. But farmer A has the advantage that his income is much more stable (between 700 -800) while farmer B faces a big variability in income (between 500 -1000). Income security is regarded as an essential need for development, as it enables long term planning and investment.

Other insurance policy options are classical Crop-yield insurances, which guarantee farmers an income even during severe droughts (*CCC, 2009. Crop Insurance as a Risk Management Strategy in Bangladesh. Climate Change Cell, DoE, MoEF; Component 4b, CDMP, MoFDM. Month 2009, Dhaka*).

As most of the farmers use groundwater irrigation, this risk is not that severe, because there is always the possibility of groundwater pumping during low stream flow regimes. However with dropping groundwater tables, this risk gets more severe as farmers might not be able to irrigate enough due to decreasing pumping yields. Insurance concepts for the Heihe Basin should therefore rather aim at providing a guaranteed pumping quota to farmers during bad years or a series of bad years.

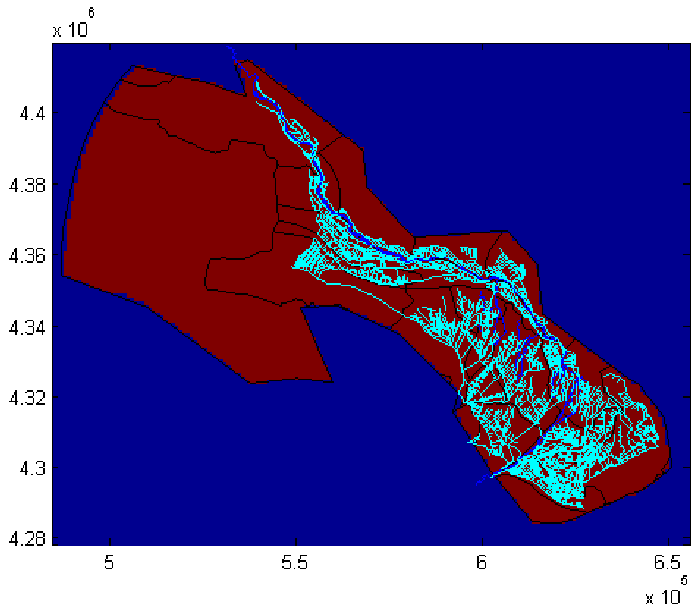
**Institutional framework**

At present the price for surface water is much higher than the price for groundwater, which leads naturally to an overexploitation of the aquifer.

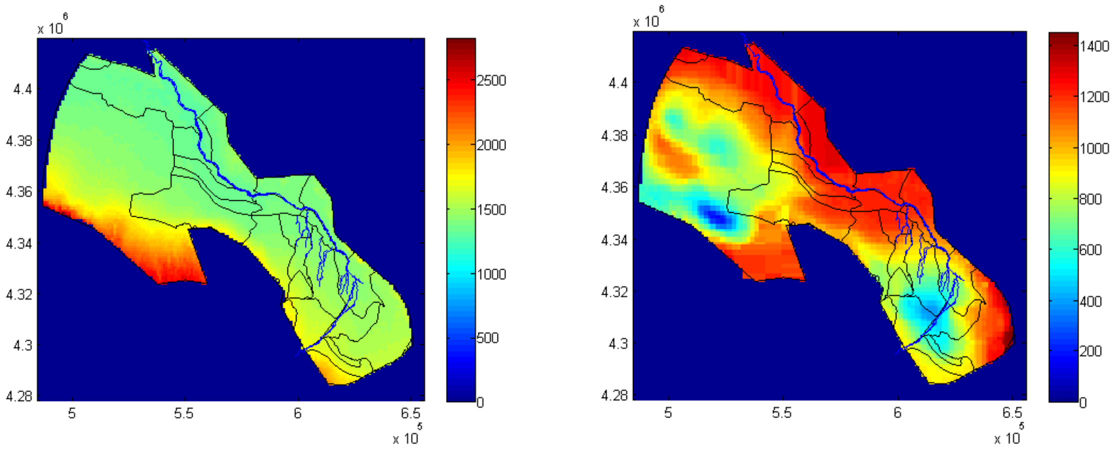
The surface water is sold to the farmers by contractors which work on a provision basis, meaning they earn more when selling more water quotas. Of course such a pattern can´t lead to a water saving philosophy. As reported by officials during the field trip, there is still a severe management problem with the timing of the arrival of surface water. In LuoTuoCheng for example, large amounts of surface water couldn't be used and were infiltrated in nearby forests, as the timing was not suitable. This is a reason, why groundwater irrigation is in any case more convenient for farmers, as they can decide on their own when and how much they want to irrigate.

# Appendix B - Modflow model description

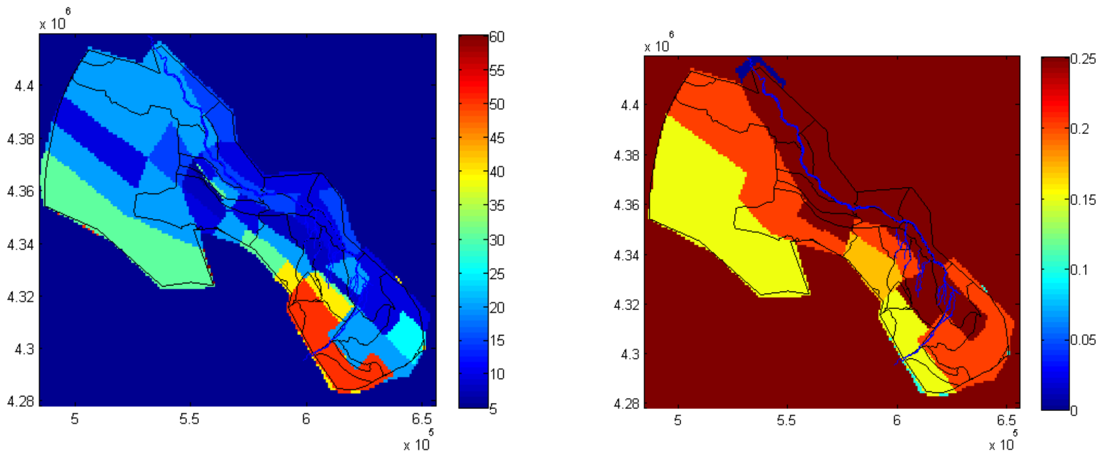
## Basic Layers




*A.Fig.1. The model boundary with stream and channel network. The grid covers an area of 24080 cells, respectively $2.4*10^{10}$ m² with 8887 active cells ($8.887*10^{9}$ m²).*



*A.Fig.2 Top layer (left) and bottom layer (right) elevation (m).*

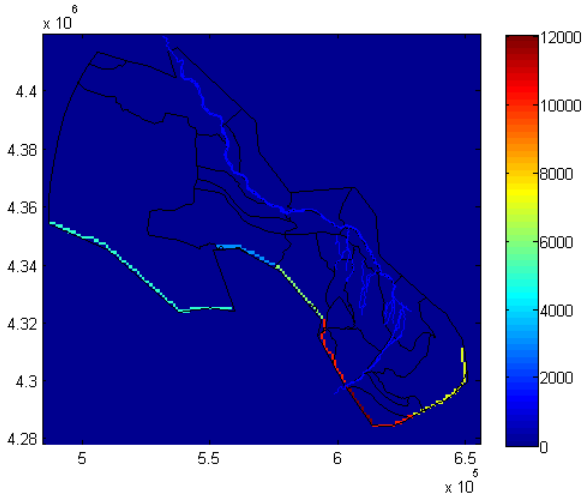



*A.Fig.3 Horizontal hydraulic conductivity (left, m/day) and specific yield (right, dimensionless).*

Porosity: The porosity in the whole model domain in set to 0.25.

## Time variant layers

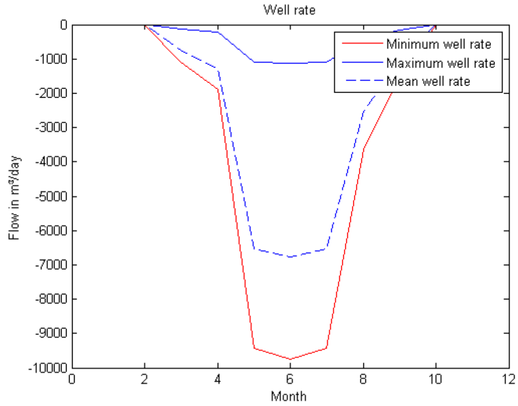
### *Flux boundary*




*A. Fig.4: Flux boundary (included in the well matrix, $m^3$/day).*

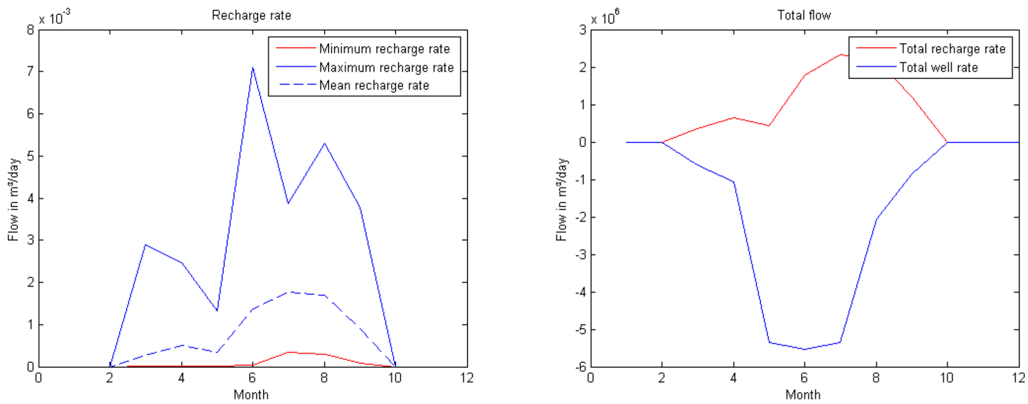
The Flux boundary is divided in 4 different parts with the values 5000, 3000, 6000, 10000, 12000, 10000, 7000 (consecutively from left to right side) units.

## Pumping wells




*A.Fig.5: Aggregated minimum, maximum and mean pumping rate for the entire model.*

## Recharge

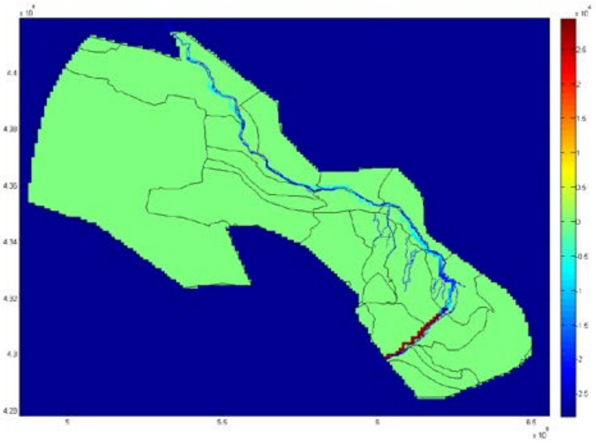



*A.Fig.6: Minimum, maximum and mean recharge rate (left). Total recharge and pumping rates (right)*

## Evaporation

The maximum evaporation rate is set to $3*10^{-4}$ m/d for the entire layer, the elevation of the ET surface is set to the top layer and the ET extinction depth is 5 m.

## Stream

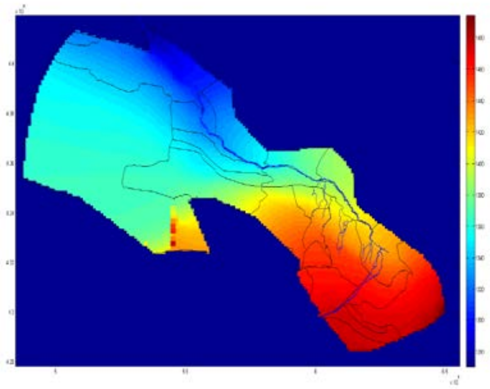


Stream width: 50- 800m
Stream depth: 2m
Stream slope: 0.007
Streambed hydraulic conductance: 13000 upper part, 2000 lower part
Manning roughness coefficient: $3*10^{-7}$

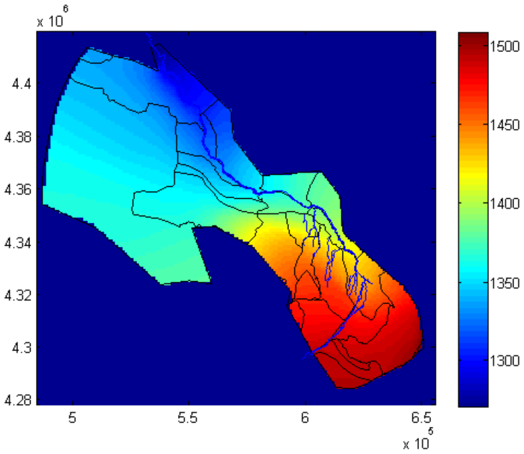
*A. Fig.7: The recharge/ discharge values in steady state and stream location.*

## Initial and steady state conditions

### *Initial heads*



*A.Fig.8: Initial heads 2010 (m).*




*A.Fig.9: Natural state head: Steady state without surface water abstraction, groundwater irrigation and without recharge (m).*

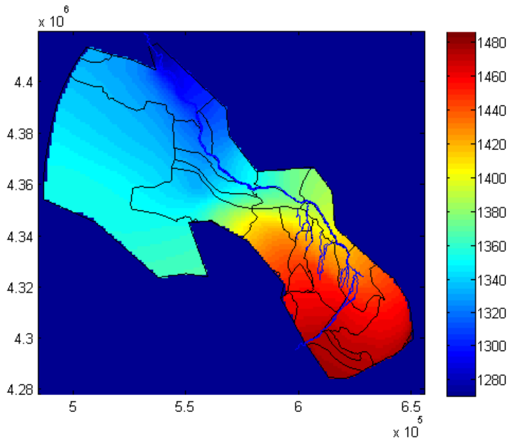



*Fig.10: Steady state head with current pumping and surface water abstraction rates (m).*

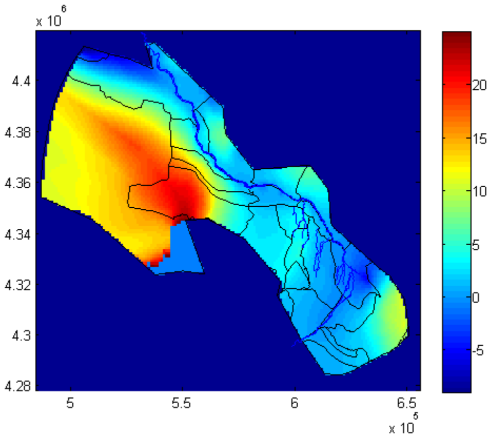



*Fig. 11:Drawdown (in relation to 2010 initial heads) with current pumping and surface water abstraction rates (m).*

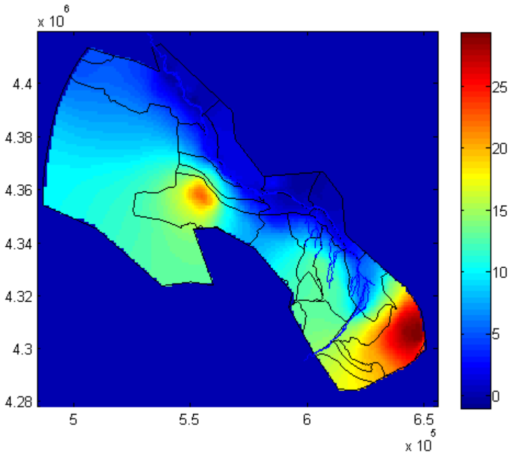
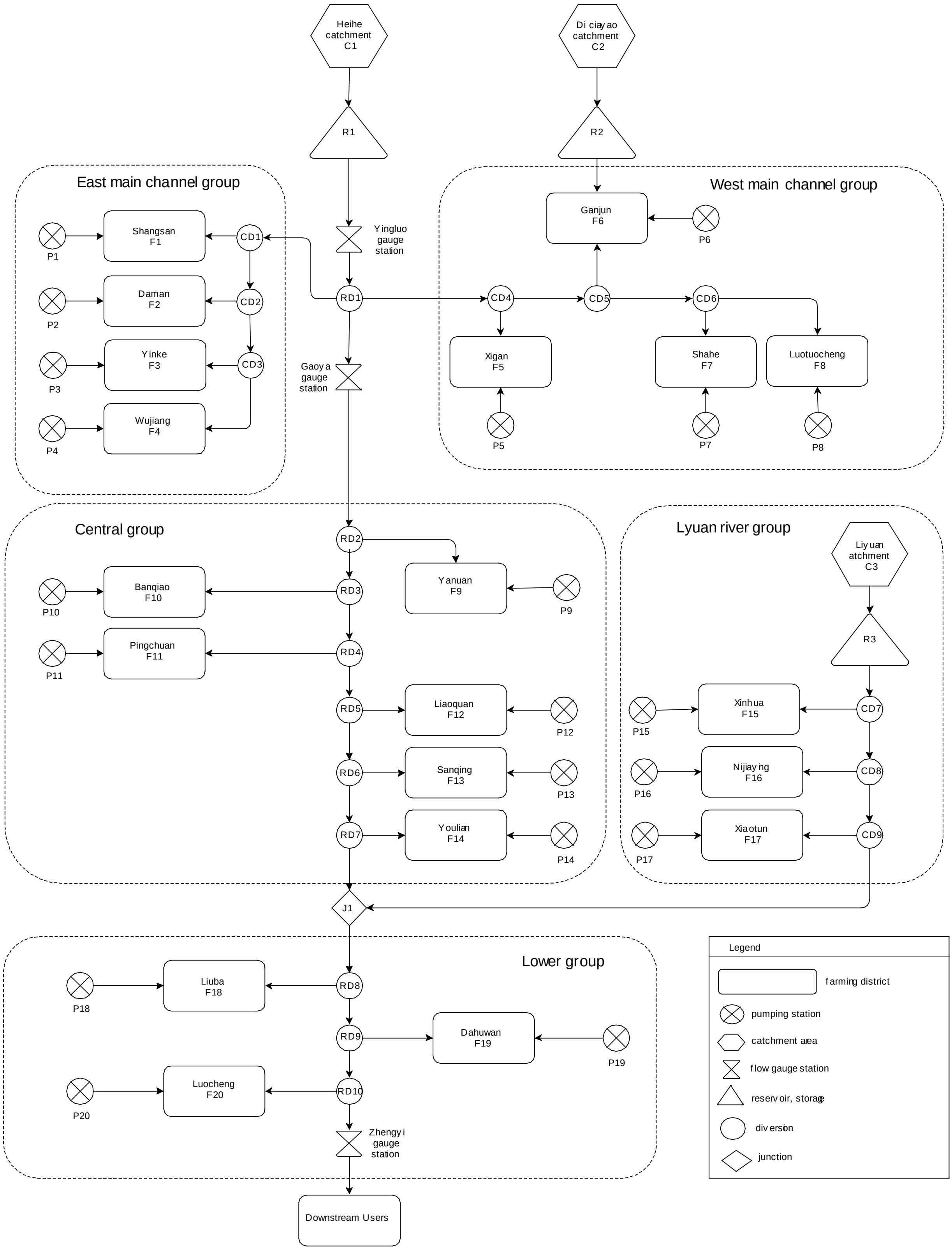


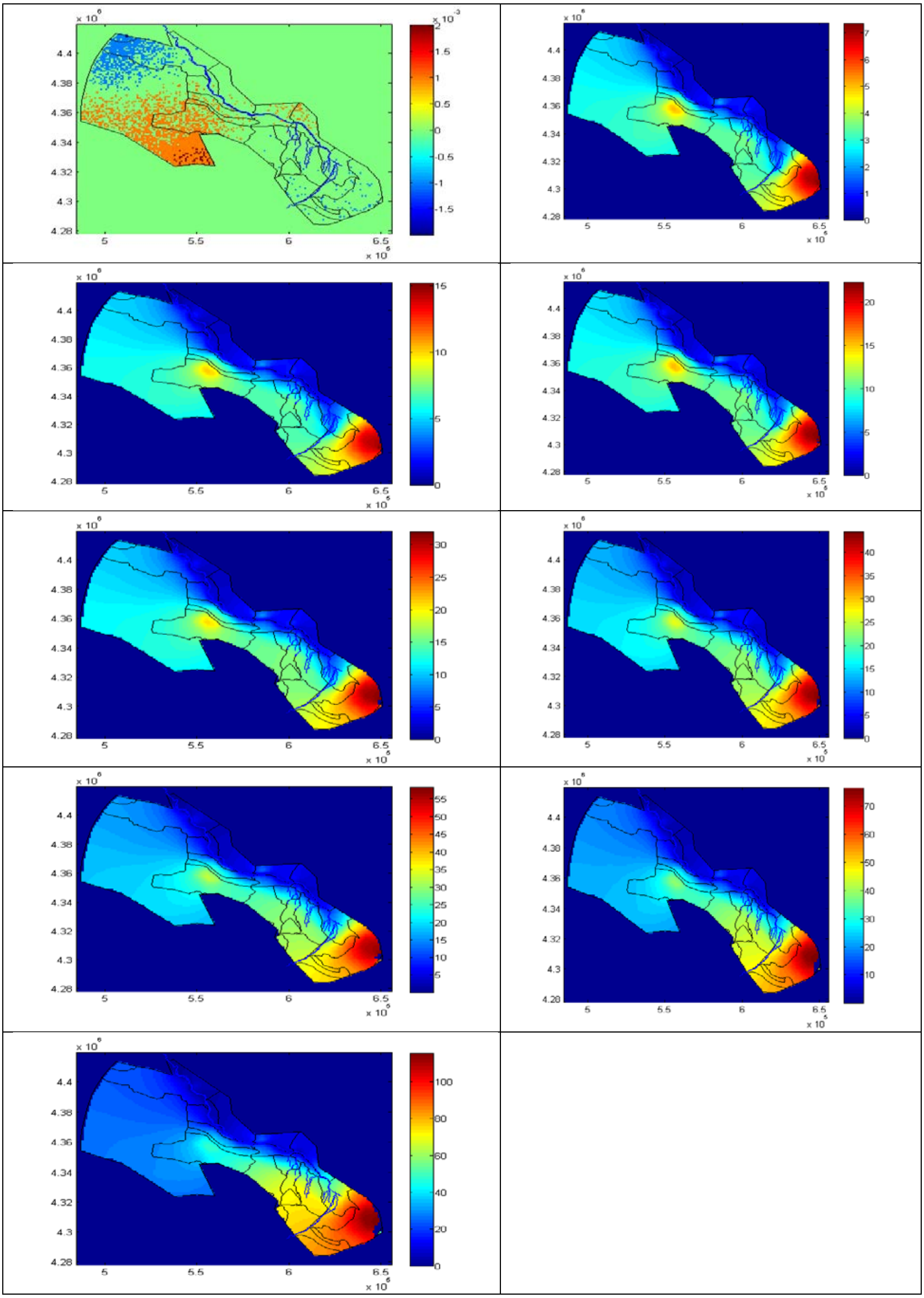

*Fig. 12:Drawdown steady state: natural state – steady state with current irrigation use. (m).*

# Appendix C - The irrigation network




*A.Fig. 13: The irrigation network. Designed by Pedrazzini G., 2014.*

# Appendix D - Steady state drawdown for different pumping rates




*D.Fig. 1: Steady state drawdown [m] for different pumping rates.*

# Appendix E - Synthetic time series generation

*E.Table 1: Equations for the Thomas Fiering model.*

$$Q_t = \bar{Q} + r_1 \cdot (Q_{t-1} - \bar{Q}) + s_x \cdot \sqrt{1 - r_1^2} \cdot \varepsilon_t$$

$$\varepsilon_t = Standard\ Gaussian\ white\ noise$$

$$\bar{Q} = Mean\ inflow$$

$$r_1 = Autocorrelation\ coefficient\ (lag\ 1)$$

$$s_x = Standard\ deviation\ of\ inflow$$

$$Q_{t,\tau} = \overline{Q_\tau} + r_{1,\tau} \cdot \frac{s_{x,\tau}}{s_{x,\tau-1}} (Q_{\tau-1} - \bar{Q}_{\tau-1}) + s_{x,\tau} \cdot \sqrt{1 - r_{1,\tau}^2} \cdot \varepsilon_t$$

$$\overline{Q_\tau} = Mean\ inflow\ for\ month\ \tau$$

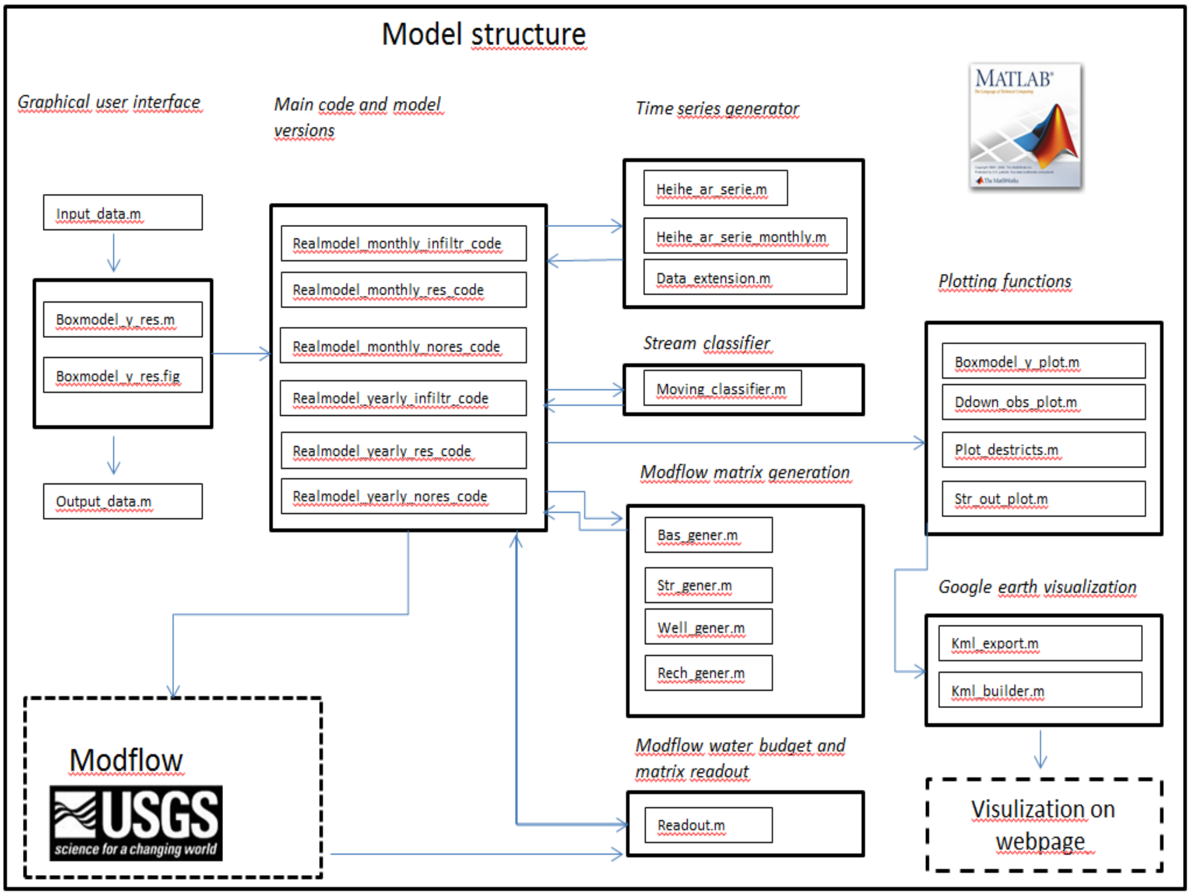
$$r_{1,\tau} = Autocorrelation\ coefficient\ (lag\ 1)\ at\ month\ \tau$$

$$s_{x,\tau} = Standart\ deviation\ of\ inflow\ at\ month\ \tau$$

*E.Table 2: Statistical parameters for the Thomas Fiering model of monthly flow.*

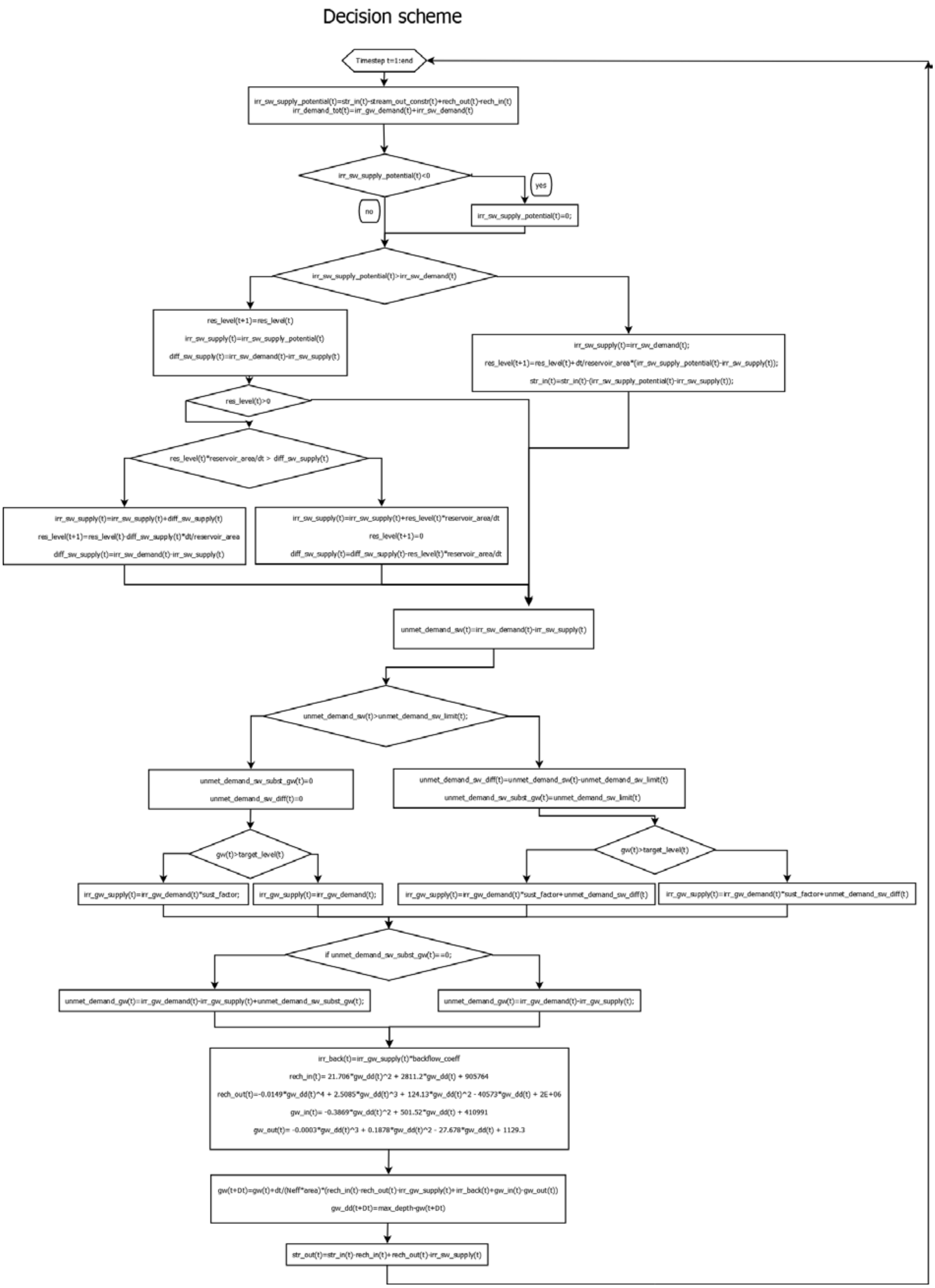
| Parameter | Jan | Feb | Mar | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 1.17E+06 | 1.30E+06 | 1.56E+06 | 2.49E+06 | 3.98E+06 | 7.31E+06 | 1.11E+07 | 1.04E+07 | 7.45E+06 | 4.00E+06 | 2.28E+06 | 1.43E+06 |
| Var | 3.15E+10 | 1.90E+10 | 5.70E+10 | 1.99E+11 | 1.32E+12 | 5.84E+12 | 1.28E+13 | 7.41E+12 | 6.50E+12 | 2.17E+12 | 3.23E+11 | 7.26E+10 |
| St. dev | 1.77E+05 | 1.38E+05 | 2.39E+05 | 4.46E+05 | 1.15E+06 | 2.42E+06 | 3.57E+06 | 2.72E+06 | 2.55E+06 | 1.47E+06 | 5.68E+05 | 2.69E+05 |
| CC Lag(1) | 9.38E-01 | 9.20E-01 | 8.55E-01 | 9.20E-01 | 9.62E-01 | 9.52E-01 | 9.86E-01 | 9.63E-01 | 9.15E-01 | 8.02E-01 | 7.62E-01 | 9.46E-01 |
| PAR 1 | 3.77E+09 | 2.92E+09 | 1.54E+10 | 3.04E+10 | 9.95E+10 | 5.50E+11 | 3.47E+11 | 5.41E+11 | 1.06E+12 | 7.75E+11 | 1.35E+11 | 7.59E+09 |

# Appendix F - The Matlab model structure



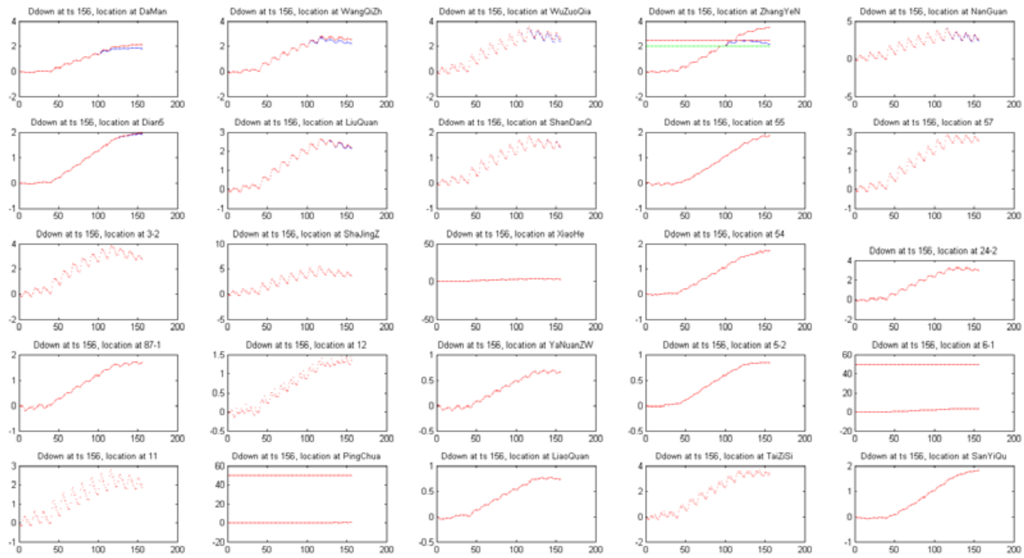

*F.Fig.1: The model architecture and interface to the Modflow model.*

# Appendix G - The Model scheme with reservoir

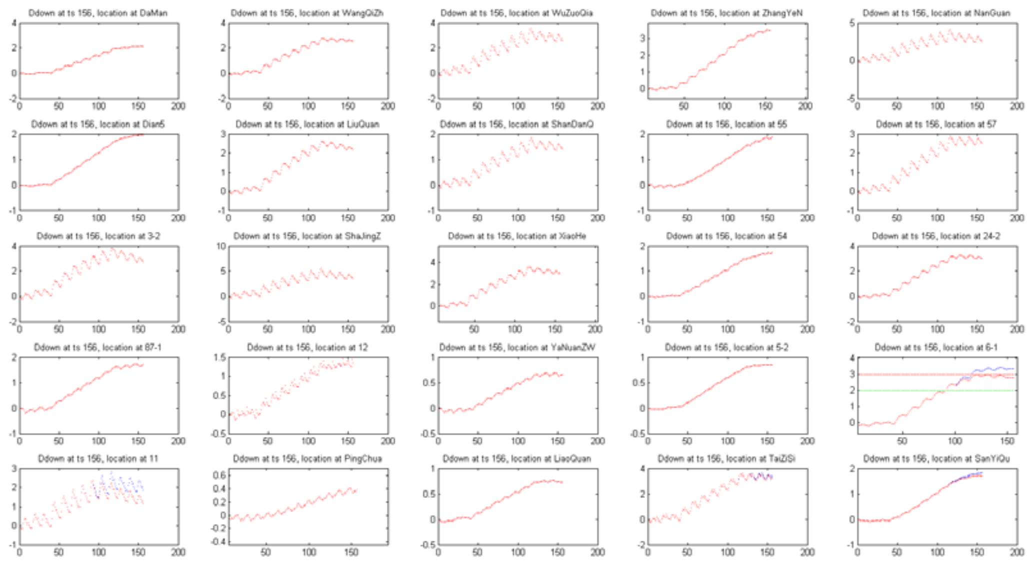



*G.Fig.1: The decision scheme with reservoir.*

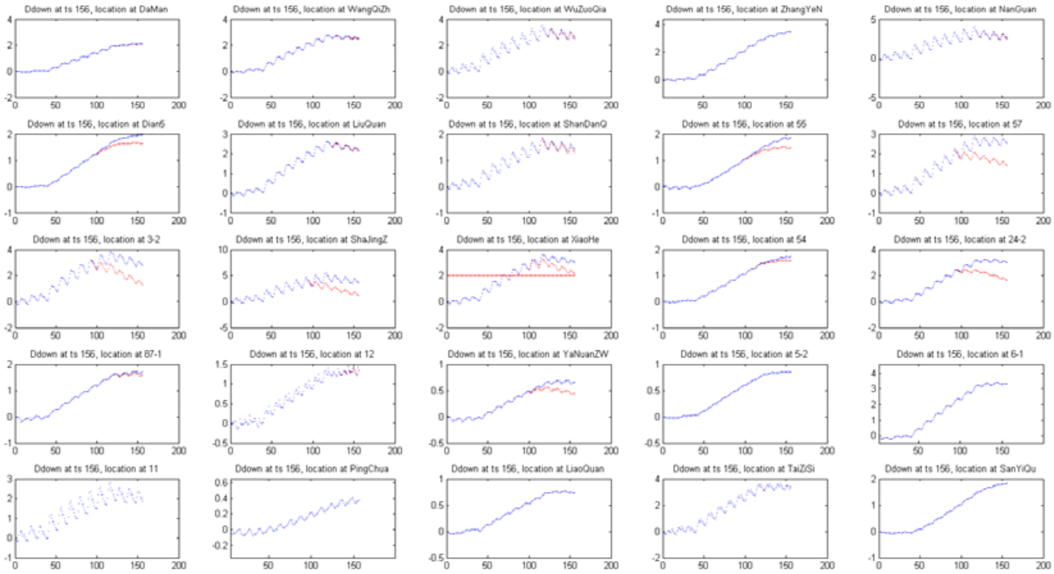
# Appendix H - Interaction of effects on selected districts



*H.Fig.1: The effects of the low flow scenario with-(blue curve) and without constraint of 2.5 m on the observation well Zhangye (District Daman). No effect on downstream district can be seen.*

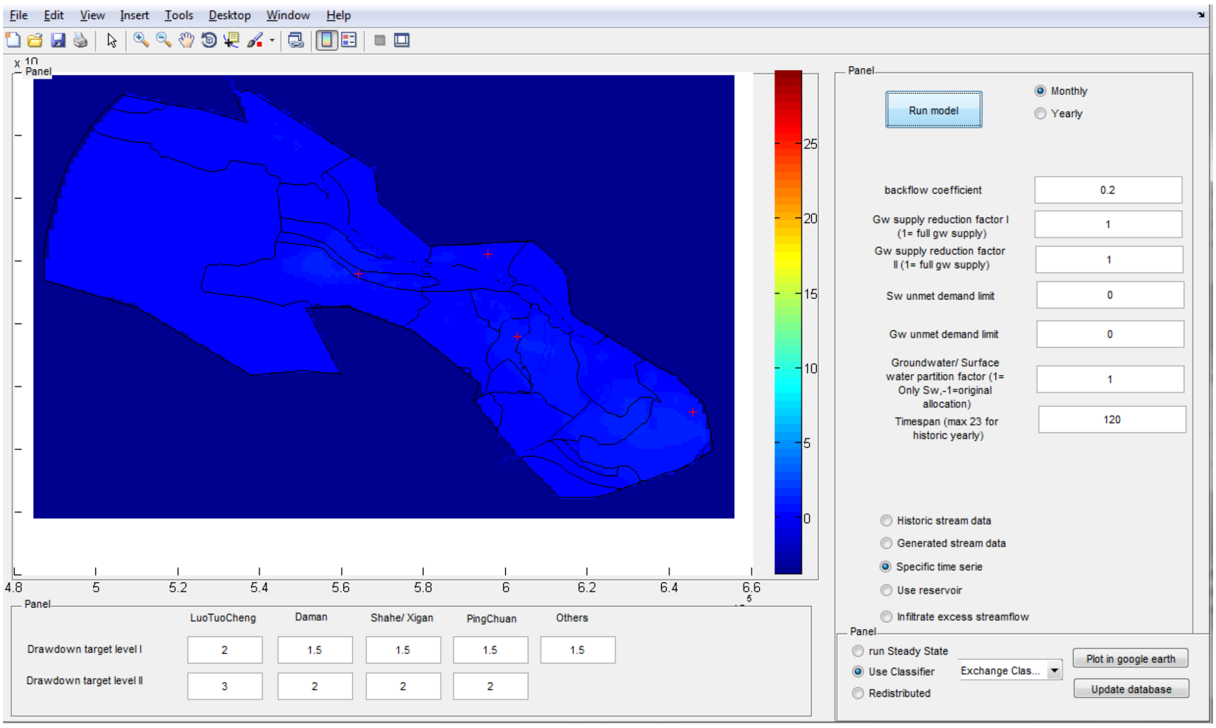


*H.Fig.2: The effects of the low flow scenario with-(blue curve) and without constraint of 2.5 m on the observation well 6-1 (LuoTuoCheng). No effect on upstream district can be seen.*



*H.Fig.3: The effects of the low flow scenario with-(blue curve) and without constraint of 2.5 m on the observation well Xiaohe (Shahe/ Xigan). The effects of the pumping reduction in Xigan can be observed in many other districts too.*

# Appendix I - The graphical user interface




I. Fig.1: The graphical user interface.

The model can also run as a stand-alone exe version, so that it can be used as freeware. In general the model is applicable to every Modflow model, but some individual changes have to be made.

# Appendix J – The Water balance

| | Modflow model (2010 steady state) | Modflow model modified | Chiu et.al 2010 (for 2005 non steady state) |
|---|---|---|---|
| Boundary inflow | $1.32*10^{6}$ | | $7.4*10^{6}$ |
| Boundary outflow | 0 | | $2.68 *10^{6}$ |
| Groundwater recharge from irrigation and pumping | $7.49*10^{5}$ | | $4.96*10^{6}$ |
| Stream inflow average | $4.54*10^{6}$ | | |
| Stream outflow average | $3.16*10^{6}$ | | $2.68*10^{6}$ |
| Evaporation (only surface) | $3.86*10^{5}$ | | $8.49*10^{6}$ (overall) |
| Pumping | $1.74*10^{6}$ | | $2.18*10^{6}$ |
| Surface water abstraction | $1.33*10^{6}$ | $2.69*10^{6}$ | |
| Stream leakage in gw | $9.87*10^{5}$ | | $4.96 *10^{6}$ |
| Stream leakage out | $9.31*10^{5}$ | | |
| Stream leakage groundwater to stream net | $- 5.6*10^{4}$ | | |

*J.Table 1: Water balance for the model, compared to values used by Chiu et. al (2010). All values in $m^3$/day.*

# Appendix K – CD Rom with matlab code and Modflow model

The matlab files, the input data, the modflow model and matrices are contained on the CD Rom. For users who do not have a Matlab license, the compiled (.exe) version is also stored on the CD.

**ETH**

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

# Eigenständigkeitserklärung

Die unterzeichnete Eigenständigkeitserklärung ist Bestandteil jeder während des Studiums verfassten Semester-, Bachelor- und Master-Arbeit oder anderen Abschlussarbeit (auch der jeweils elektronischen Version).

Die Dozentinnen und Dozenten können auch für andere bei ihnen verfasste schriftliche Arbeiten eine Eigenständigkeitserklärung verlangen.

---

Ich bestätige, die vorliegende Arbeit selbständig und in eigenen Worten verfasst zu haben. Davon ausgenommen sind sprachliche und inhaltliche Korrekturvorschläge durch die Betreuer und Betreuerinnen der Arbeit.

**Titel der Arbeit** (in Druckschrift):

Conjunctive water management concepts and decision support systems
for the Heihe Basin, China.

**Verfasst von** (in Druckschrift):

*Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich.*

| Name(n): | Vorname(n): |
|---|---|
| Anz | Jacob |
| | |
| | |
| | |
| | |

Ich bestätige mit meiner Unterschrift:

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- Ich habe alle Methoden, Daten und Arbeitsabläufe wahrheitsgetreu dokumentiert.
- Ich habe keine Daten manipuliert.
- Ich habe alle Personen erwähnt, welche die Arbeit wesentlich unterstützt haben.

Ich nehme zur Kenntnis, dass die Arbeit mit elektronischen Hilfsmitteln auf Plagiate überprüft werden kann.

| Ort, Datum | Unterschrift(en) |
|---|---|
| 7.10.2014, Zürich | |