Heihe middle reach agricultural fields during dry season (March 2014)

Optimizing allocation and sourcing of irrigation water under socio-environmental constraints in the mid-reach of the Heihe River Basin, China

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Abstract

This study develops a modelling based approach to arrive at a more sustainable water use in the Heihe Basin (China) under a set of dynamic socio-environmental constraints through an improved spatial and temporal allocation (conjunctive use) of groundwater and surface water.

Expansion of irrigated perimeters in the middle reach oasis of the basin and new regulations for releases to the downstream led to overexploitation of the aquifer resulting in substantial decline in groundwater table. The drought mitigation potential of the aquifer as buffer in times of surface water scarcity is at risk, wetland ecosystems and water users will eventually suffer from the attenuated residual stream flow water.

Though groundwater model based optimization procedures have been developed for general purposes, none of these has been applied in the Heihe Basin up to now. A tailor-made coupled model which allows optimizing conjunctive use of surface and groundwater on a regional scale is developed in this thesis. A distributed structured-grid groundwater model is used on discrete yearly time intervals to compute groundwater heads, the interaction of surface water with groundwater including percolation from irrigation water as well as exchange and abstraction of river water. A decision model based on a gradient ascent algorithm is designed to optimally allocate quantity and sourcing of irrigation water (groundwater or stream water) to each of the 20 irrigation districts. Three indicators are used to assess the performance of a certain allocation scheme with respect to economic, environmental and social aspects. A number of scenarios are simulated to investigate the performance of the decision model using different index weightings and input data accounting for situations of high and low surface water availability. The outcomes are compared to the ones using the current water allocation of 2010.

The results show that improvements on all three indices can be made. The strategy proposed by the controller shifts to more surface water oriented irrigation in the Luotuocheng district, where steep drawdowns are encountered. Through cuts on irrigation water in the upstream districts more water can be allocated in the downstream districts, which results in an increase in residual stream flow without significant loss in profit. The allocation seems to be less sensitive to the inflow from the upstream catchment but highly sensitive to the weighting of the indexes in the aggregated objective function. A time series simulation showed that the application of the controller over a period of 10 years leads to remarkably smaller drawdowns than when using the current water allocation of 2010 (extremes at 6m instead of 14m). The controller is able to react to surface water availability and residual stream flow can be substantially increased particularly in times of surface water scarcity by up to 150%. These findings should encourage the consideration of new alternatives regarding expansion and reduction of irrigated agriculture on a regional scale within the sub-basin.

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1 Introduction and background

1.1 Current situation

The dry and arid climate in the middle reaches of the Heihe River Basin (Northwest China, Gansu Province) forces farmers to adopt full irrigation in order to produce wheat, maize and vegetable crops. As irrigated agriculture is the main economic activity in the region, this imposes great stress on the already scarce water resources. Traditionally stream water from the Heihe River was used for irrigation. As excessive use led to depletion of the residual stream flow left for the downstream leading to the drying up of the terminal lake, in the year 2000 the Chinese Ministry of Water Resources imposed a 'Program for the Recent Comprehensive Management of the Heihe River Basin' stating that a yearly minimum quota of 0.95 billion m^3 of residual stream water should be released to the downstream for ecological purposes (Chen, et al. 2014).

Continuous expansion of irrigation perimeters in a water scarce environment depleted the available surface water resources. This has lead farmers to resort increasingly to groundwater as irrigation water supply. The situation was aggravated by the commitment to ecological releases of river water to the downstream since 2000. Additional factors enhance the attractiveness of groundwater: the low cost margin for wells close to the river (the overall pumping cost of groundwater lying at only about 2/3 of the cost of surface irrigation water), the fact of its being locally available and not needing large distribution networks, its perennial availability and the low particulate content which allows to use groundwater directly in water saving irrigation such as drip irrigation. Groundwater has been historically perceived as an infinitely large storage of water, supplying farms with water on demand. The overexploitation of this precious resource by currently over 10'000 pumping wells has however lead to a drastic drop in groundwater level in certain areas, particularly in the irrigation districts lying at the far end of the irrigation canal system. Drawdowns of up to 20m could be observed for instance in Luotuocheng District over the last 20 years, which means groundwater table declining rates of up to one meter per year (Zhou, Wang, et al. 2014).

1.2 Stating the problem

The decrease of stream flow and the declining groundwater level imply a number of severe social and environmental risks. The decrease in stream flow is the cause for a number of serious problems in the downstream section of the Heihe River Basin, such as drying up of the terminal lakes East and West Juyuanhai (see Figure 1), deterioration of the ecological environment around the stream, acceleration of desertification and aggravation of sand storms (Zhou, Hu, et al. 2010). The dropping groundwater level for its part increases the vulnerability of society and environment to droughts. If the saturated aquifer thickness is substantially reduced, borehole yields may diminish to the point where wells fall dry and no water can be pumped anymore. This means that no more groundwater could be used in times of surface water scarcity and the capability of groundwater to mitigate the impact of droughts would no longer be ensured. Farmers would have to move away from areas such as Luotuocheng. Secondly the higher pumping costs resulting from extraction at greater depth increase the financial burden for the farmers. Though cost of irrigation water currently makes up only a small fraction in the range of less than 10% of the revenue from crops, this would possibly impose heavier financial stress on the already economically weak small scale farming communities residing on the margins of the middle reach oasis.

1.3 Global implications

As many arid regions worldwide are currently facing imminent threats from water resources overexploitation, the necessity for sustainable ground- and surface water management has gained significance. As groundwater and surface water are often strongly connected to each other, they should be perceived as components of one system and managed in a comprehensive and cohesive way. Recent management approaches focus more and more on the concept of conjunctive use: groundwater storage is used to buffer water-supply against the large variability of surface water supply (Foster, et al. 2010). The idea is to perceive the aquifer as a natural large scale reservoir of water and make use of it in times of surface water scarcity thus decreasing vulnerability to droughts. There is now common understanding that despite the large extent of some aquifers, their water availability is not unlimited and that a balance between abstraction and recharge has to be sought in order to prevent further decline and foster recovery of the water table. There are various technical, non-technical, operational and management measures used to tackle different aspects of irrigation water management and efficiency at different levels. At the farm-scale, efficiency can for instance be improved by technical measures such as adopting water-saving irrigation techniques, management measures such as selecting less water intensive crops or operational measures such as deficit irrigation.

1.4 Brief literature review about optimization and modelling in the field of irrigation water resources management

The principles of decision support systems have been applied in the field of water resources management since the early 1970s (Ge, et al. 2013). As an answer to the demand for integrated water resources management in the last decade modelling tools have evolved "...from biophysical to bio-decisional models, from laboratory research to participatory research, from single to integrated models" (Bergez, et al. 2012). A vast number of different controlling and optimization approaches have been investigated in the context of optimal irrigation water allocation. Among these are methods derived from characteristics of the farmer's decision-making process in the form of decision rules: if<indicator> <operator> <value>, <action 1>, else <action 2> (Bergez, et al. 2012). Other models such as the one described by Harald (1985) adopt tailor-made controlling algorithms in the form of closed-loop controllers to shape the allocation problem. The optimization then often deals with the determination of the optimal control parameters as a once-for-ever decision. Adaptability of such schemes may be limited to a certain extent, as the control parameters are bound to a certain system state and changing the system would require to recalibrate those parameters. Recent approaches have investigated application of more complex theoretical approaches, for example multi-dimensional-critical regulation control theory MCRC (Li, et al. 2014) or stochastic branching methods such as P2m (Crespo, Bergez und Garcia 2010). The GWM (Groundwater Management Process for MODFLOW) software developed by the USGS partly uses similar optimization techniques as described in this work.

1.5 Site setting

The Heihe River Basin is the second largest inland river basin of China (Zhou, Cheng, et al. 2012). An overview map of the entire basin is shown on Figure 1. It is situated in the arid Northwest of China, extending over the provinces of Qinghai, Gansu and Inner Mongolia. This study focuses on the middle reach of the Heihe River Basin, an artificial irrigation oasis located in the prefecture of Zhangye shown on Figure 2. The elongated plain of the middle reach lies in the Hexi Corridor and is surrounded by the Qilian Mountains in the South and the Longshuanshan Mountains in the North (followed by the Badain Jaran Desert). It extends over an area of approximately 1.2 10^4 km^2 (Zhou, Hu, et al. 2010).

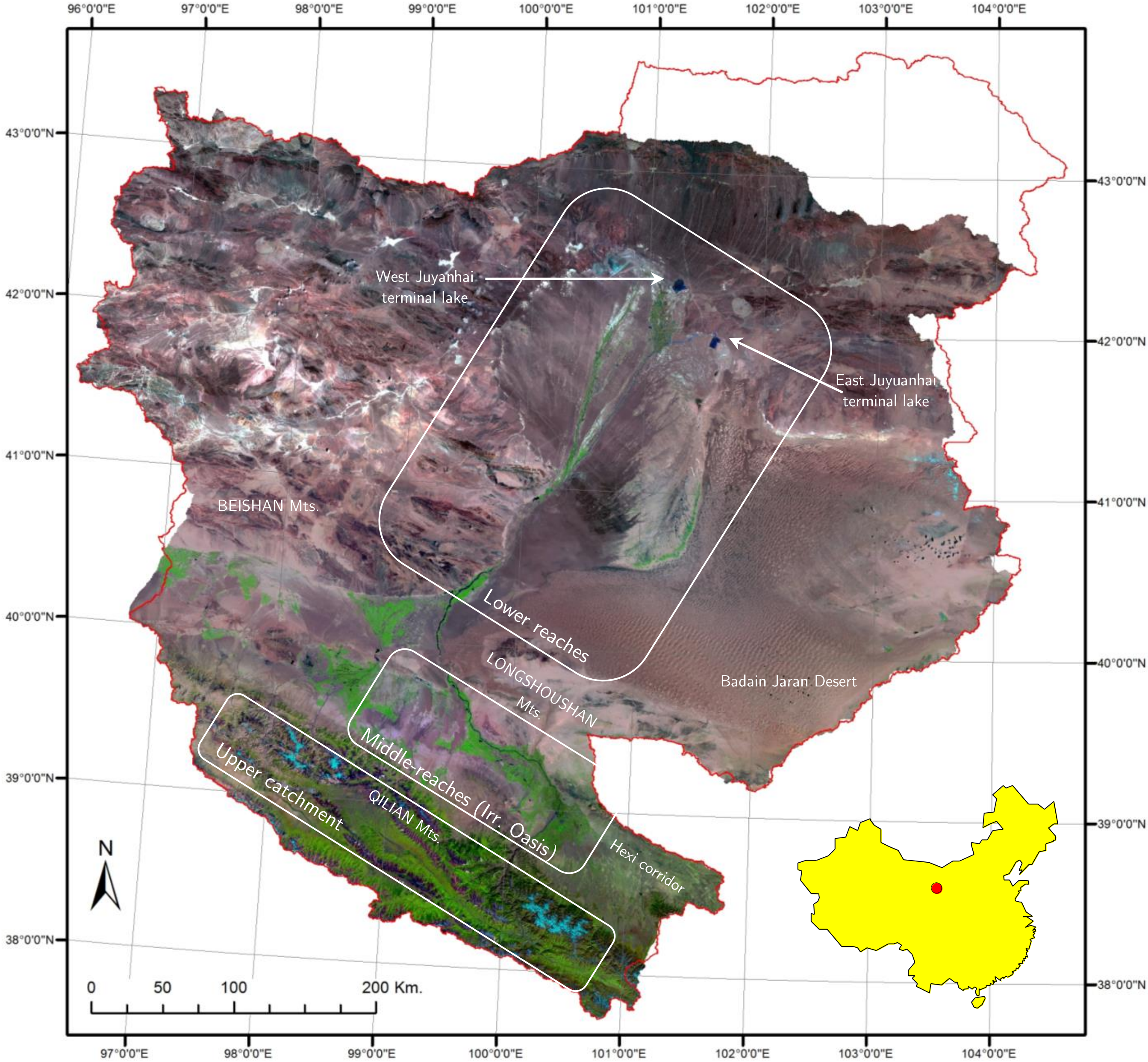

Figure 1: Overview map of the Heihe River Basin. Sources: CAREERI: satellite image, Wikipedia: small China map, Gaofeng, et al. (2009): nomenclature on map.

1.5.1 Why researching in the Heihe Basin

10.4% of the world's land area is covered by inland basins. As many of them are lying in arid climates they have to cope with persisting conflicts over water use between the necessity of growing economic development and ecosystem demand (Li, et al. 2013). The Heihe Basin was chosen as pilot-research area for the current project as it is a typical inland river basin representative for many others of its kind. Knowledge acquired from the Heihe River Basin may therefore be applied to many other inland basins. It is also particularly suited for the current investigation as it has been subject to integrated watershed research over an extensive period of time (Li, et al. 2013).

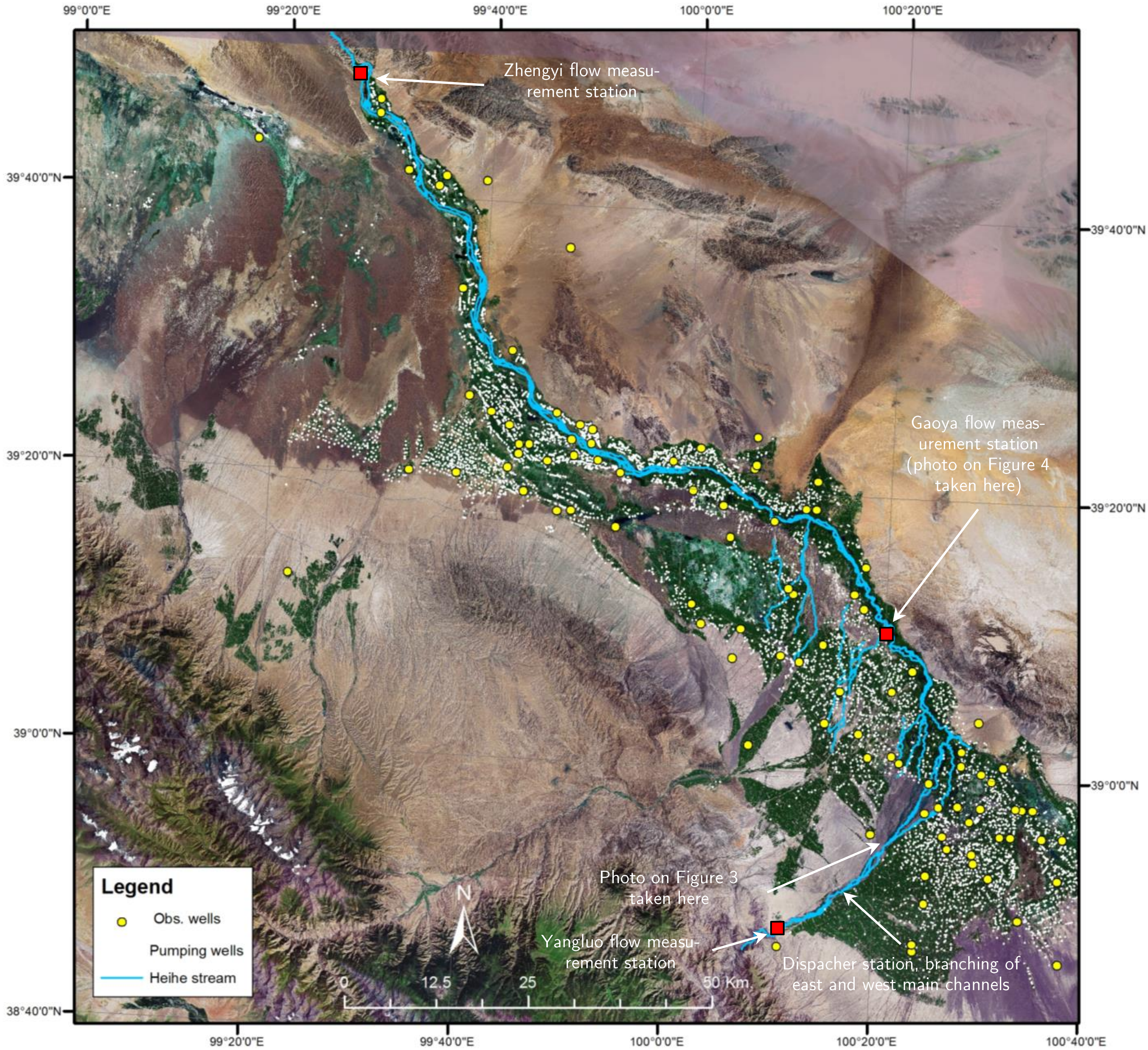

Figure 2: Map of the middle reach of the Heihe River Basin showing the irrigated areas, the Heihe Stream (blue), observation wells (yellow), pumping wells (white) and the flow measurement stations (red squares). (source: CAREERI)

1.5.2 Climate

The climate is of typical continental nature with moderately low precipitation in the range of 100-250mm/year and high potential evaporation ranging from 1200-1800mm/year (Li, et al. 2013). The rainy season extends from May to September.

1.5.3 Streams

Most of the numerous independent streams originating in the upstream Qilian Mountain catchment dry up due to water abstraction for irrigation and seepage into the alluvial fans at the foot of the mountains. The Heihe is the only stream sufficiently large to flow through its middle reaches without drying out (Zhou, Hu, et al. 2010). Its course through the irrigation districts can be seen on Figure 2. The Heihe loses a part of its water to the aquifer in the upstream of the middle reach and is then further downstream recharged by groundwater from that aquifer (Zhou, Hu, et al. 2010). Figure 3 shows a photo of the Heihe taken in the upstream section with little water remaining in the riverbed, Figure 4 shows the situation at the same time further downstream close to Gaoya flow measurement station where the water is sufficient to fill the entire riverbed. The locations where the photos were taken are shown on the map on Figure 2.

Figure 3: Heihe River, braiding stream sections close to the city of Zhangye

Figure 4: Heihe River middle section: Gaoya flow measurement station

1.5.4 Aquifer

Zhou, Hu, et al. (2010) subdivide the landform into two categories: the alluvial plain in front of the mountains in the South and the river valley fine-soil plain in the centre of the oasis. The groundwater is mainly stored in a single layer shallow aquifer in the alluvial plain and in a multi-layer aquifer in the river valley fine-soil plain. The multi-layer aquifer is separated by three aquitards composed of clay, clay-loam and sand. As the aquitards are encountered as lenses, there is no completely impermeable layer extending over the region. Therefore hydraulic interconnectivity of the different layers is given and – at least for water balance purposes - the aquifer can be seen as one continuous multi-layer aquifer, limited transversely by the basin boundary (Zhou, Hu, et al. 2010).

1.6 Scope of work

In this thesis we focus on irrigation water management on regional sub-basin scale. A modelling based approach is adopted to maximize financial profit by taking into account selected environmental and social constraints in order to attain more sustainability for ecosystem services, food security in terms of risk aversion and financial profitability.

The decision variables are the yearly amount and the sourcing (either from the stream or from the aquifer) of the irrigation water of each district. The amount of irrigation water represents the area to be irrigated and therefore the spatial allocation of irrigation water. The temporal dimension comes into play when running the simulation for a consecutive number of years. The interaction between surface and groundwater is considered very important (Chen, et al. 2005) and is modelled by using a distributed numerical groundwater model. The thesis analyses the improvements on selected indicators that can be achieved by better managing the conjunctive use of surface- and groundwater on the level of irrigation districts. The optimal allocation and sourcing is determined using a gradient ascent algorithm to maximize an objective function. The objective function is a weighted aggregate of the different indicators. Before aggregation, the indicators are made non-linear through a simple power function in order to ensure that a more critical indicator value exerts more control on the derivative of the objective function. This non-linearity of the indicators should avoid the absolute domination of one indicator over the others, promote a dynamic equilibrium within the system and prevent the system from falling into a critical state with respect to any single indicator. The model can be perceived as a decision support system which suggests from where irrigation water should be sourced and how it should be allocated to the districts, i.e. which districts should enlarge or reduce their irrigation area. Application of an optimization algorithm instead of a straight-forward controller allows to translate an optimal operation problem into an optimization problem. The idea is to transform the control problem in such a way that an algorithm always finds an optimal solution regardless of changes in the system configuration. Ideally, schemes should be adaptive to changes in the system itself (e.g. development of new wells) as well as to changes in the external forcing on the system (e.g. changes in climate).

2 Methodology

2.1 Field trip

Within the scope of this work I had the opportunity to spend one month at the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) in Lanzhou, China. The institute is part of the Chinese Academy of Sciences (CAS) and has undertaken extensive work and published numerous papers on the Heihe River Basin. During this period I worked with the local project partners Prof. Dr. Li Xin, Dr. Zhou Jian and Mr. Chen Chong (see Figure 5) and visited the middle reach oasis in the Heihe Basin (Figure 6). The close exchange of knowledge and the field trip were extremely useful the get an in-depth understanding of the situation. Much of the information in this report is based on personal conversations with the local project partners.

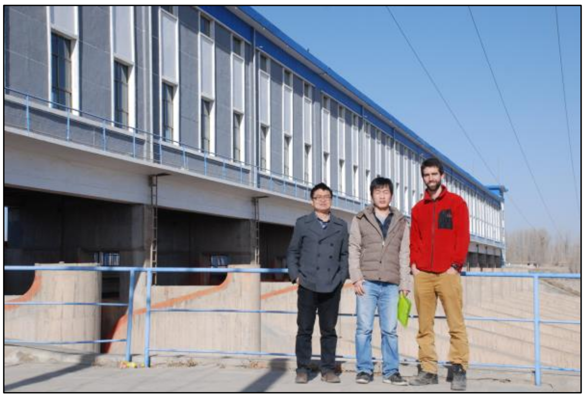

Figure 5: Field trip: in front of the dispatcher station where the east and west main channels branch off from the Heihe main stream. From left to right: Dr. Zhou Jian (CAREERI), Chen Chong (CAREERI) and myself.

Figure 6: Field trip: view on the irrigation districts from a hydropower plant close to the Liyuan River, a tributary of the Heihe.

2.2 Software and model setup

The software used in this work includes the distributed finite-difference groundwater model MODFLOW developed by the U.S. Geological Survey (Version 2005) and the numerical computing environment and programming language MATLAB developed by MathWorks (version R2014a).

The model can be seen as a combination of two sub-models: a physical groundwater model (which was provided by CAREERI) and a decision model. The whole construction is embedded in a MATLAB framework. Interaction of MATLAB with the distributed numerical groundwater model happens via input/output files. As stated in numerous studies, the interaction of groundwater and surface water is of particular relevance (Chen, et al. 2005). A numerical distributed groundwater flow model offers the possibility of including all relevant surface water aspects to some extent. As the irrigation water is sourced from either the groundwater reservoir or the stream, the Heihe River is a central element in the model implemented in MODFLOW via the stream flow module. River and aquifer are connected via the leakage principle. The seepage from surface water irrigation is included into the recharge module. A schematic diagram of the software coupling is shown in Figure 7. The following section will explain how the different elements are designed to interact with each other.

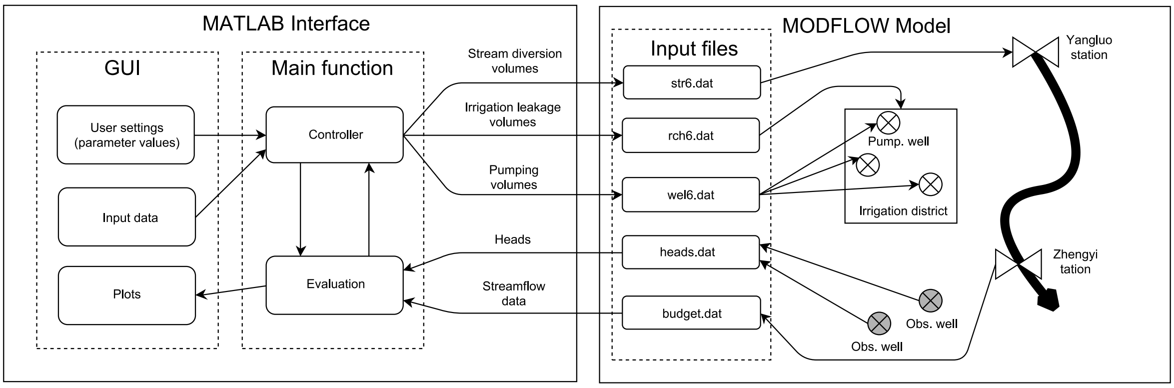

Figure 7: Model coupling: A MATLAB Interface interacts with the numerical groundwater model (MODFLOW) through reading/writing of input/output files. A graphical user interface (GUI) allows easy running of simulations/optimizations and quick visualization of the results.

2.2.1 The irrigation districts

The model considers the irrigation districts as basic functional units for water allocation. A total of 20 irrigation districts are identified in the middle reach of the Heihe River Basin according to topological maps provided by CAREERI. A schematic diagram showing how the districts are arranged with respect to the Heihe Stream is shown on Figure 8. Each irrigation district can be assigned a yearly quota of irrigation water, specifying how much of it is provided from surface water and how much from groundwater. From this follows a total of 40 decision variables. With the amount of irrigation water provided the irrigated area is also fixed defined. The decision as well as the evaluation time step are presently chosen to be 1 year.

2.2.2 Groundwater irrigation

As we note on Figure 2 the pumping wells are densely scattered all over the entire irrigation area. Since no exact numbers for pumping rates are available, it seems reasonable to assume that the applied groundwater irrigation volume is evenly distributed among the wells within an irrigation district. MODFLOW's Well Package is used as specified flux boundary package to simulate this water abstraction. The input file for the Well Package "wel6.dat" is rewritten by MATLAB for each computation and contains pumping rates specified for the current time step.

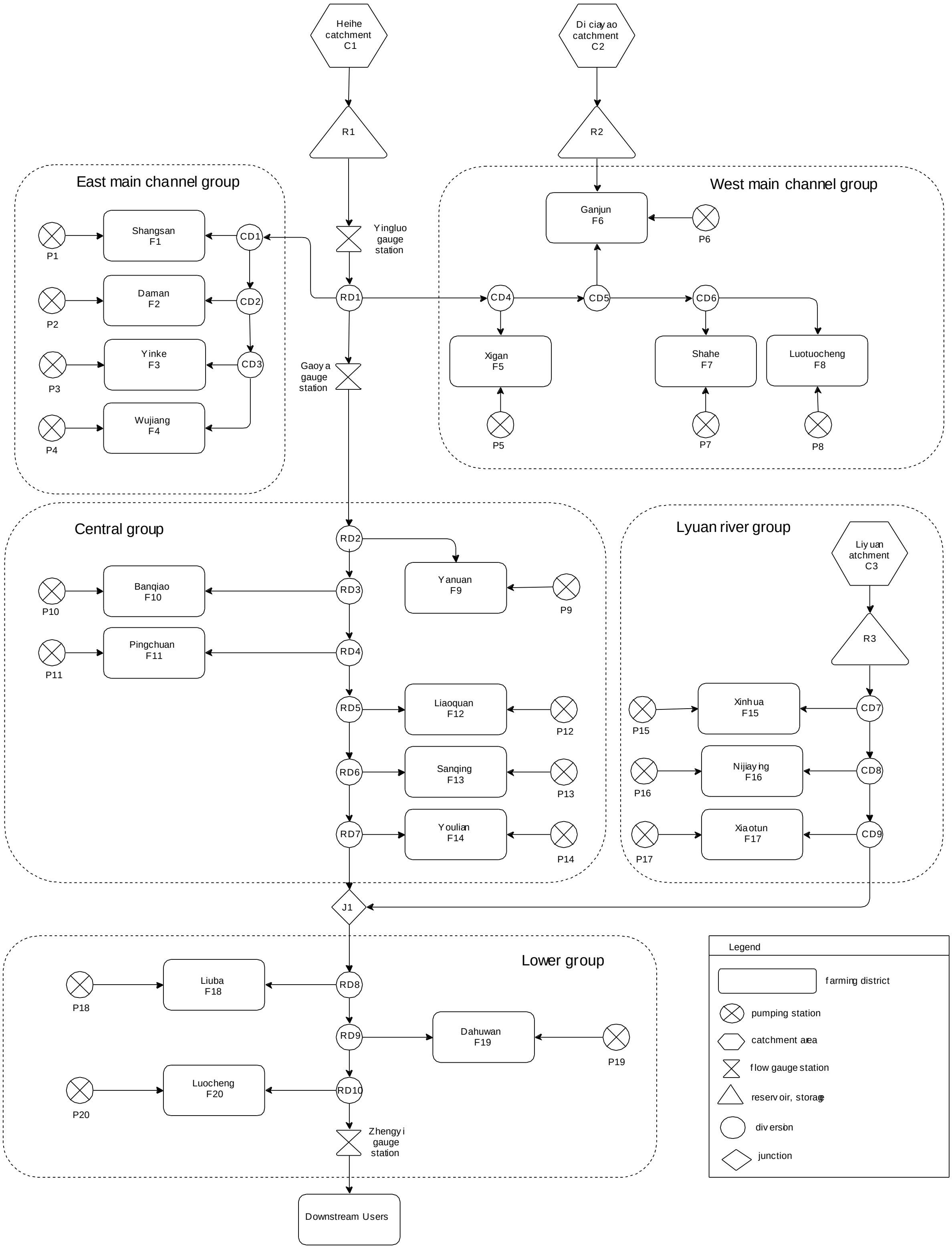

Figure 8: Topological diagram of the Heihe River, the farming districts and the corresponding main channels. This diagram was drawn based on information obtained from CAREERI to understand how irrigation water is routed to the districts. The districts can be subdivided into the ones connected to the east main channel, the ones connected to the west main channel, the central ones, the ones connected to the Liyuan River and the lower ones.

2.2.1 Surface water irrigation

The irrigation water volume from surface water generally refers to water that is abstracted from the Heihe and routed to the irrigation districts using an extensive network of channels. As a vast majority of channels even up to the small ending branches are lined with concrete (see Figure 47 to Figure 50), channel leakage is not considered explicitly but included in the model through seepage of irrigation water. The Heihe Stream is incorporated into the MODFLOW model using MODFLOW's Stream Flow Package. This package uses the kinematic wave equation to simulate flow in a river. The river is subdivided into tributary reaches representing individual cells and segments (grouping of reaches). The groundwater exchange between the stream and the aquifer is computed for each cell as a function of the water level in the stream, the groundwater head and the streambed hydraulic conductance.

Note that there are three districts (Xinhua, Nijiaying and Xiaotun) that do not source irrigation water from the Heihe Stream but from the Liyuan River, a minor tributary of the Heihe. Apparently all the water from the Liyuan River is used to irrigate those districts and there is actually hardly any flow reaching the Heihe. Due to this lack of coupling the Liyuan River was not explicitly included using the Stream Flow Package (as for the Heihe River) in the model. The surface water supply of these three districts is therefore disconnected from the Heihe River in the model, it is simply assumed that all water from the Liyuan River is used for irrigation and no water flows into the Heihe.

The water abstraction of all other districts is located at the main irrigation channel nodes where water is diverted directly away from the Heihe River. A total of 10 diversions are simulated. Figure 9 shows an overview of the stream as it is implemented in MODFLOW. The red cells indicate the locations where irrigation water is diverted.

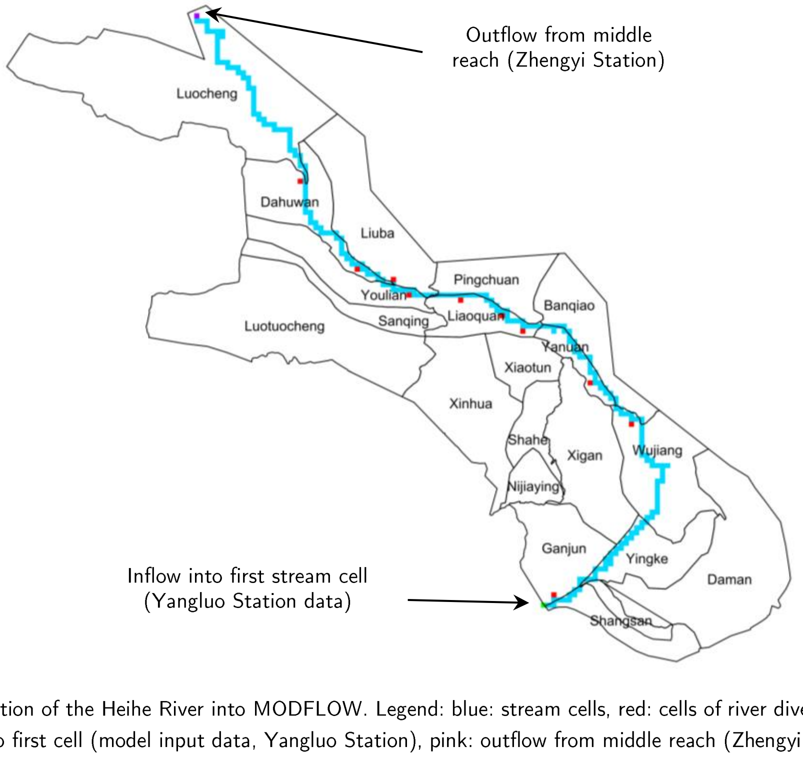

Figure 9: Implementation of the Heihe River into MODFLOW. Legend: blue: stream cells, red: cells of river diversions for irrigation, green: inflow into first cell (model input data, Yangluo Station), pink: outflow from middle reach (Zhengyi Station).

The stream diversion volumes at each diversion node are computed as the sum of the allocated surface water irrigation volumes of the districts connected to the respective branch. The specified stream diversion volumes and the flow into the first cell are then written into the "str6.dat" input file.

2.2.2 *Infiltration of irrigation water*

An important aspect is the recharge of the aquifer from the fraction of irrigation water that percolates into the soil. Flood irrigation (also called surface irrigation) is known to be rather inefficient, the fraction of water used beneficially being only about half of the water delivered (Rogers, et al. 1997). Besides the transpiration and uptake by the plant, there is evaporation from the soil and percolation to deeper soil layers to finally recharge the aquifer. Detailed hydrologic models such as HYDRUS 1D (Simunek, et al. 2005) have been developed and coupled with crop growth models such as WOFOST (Diepen, Wolf und Keulen 1994) to describe soil moisture profiles and infiltration during various stages of crop growth (Zhou, Cheng, et al. 2012). For the purpose of this work we assume a simple proportionality relation between the applied surface- and groundwater irrigation water ($Q_{irr,SW}{}^{D}$, $Q_{irr,GW}{}^{D}$) and the resulting aquifer recharge volume $Q_{rech}{}^{D}$. The factor $f_{rech}{}^{D}$ was set to a value of 0.1

$$Q_{rech}{}^{D} = (Q_{irr,SW}{}^{D} + Q_{irr,GW}{}^{D}) \cdot f_{rech}{}^{D}$$

In reality the situation is way more complex, as the recharge is also a function of time, soil saturation and many other factors.

By dividing by the effective irrigation area A^D of each district one obtains the recharge depth $q_{rech}{}^{D}$.

$$q_{rech}{}^{D} = \frac{Q_{rech}{}^{D}}{A^D}$$

The underlying and simplifying assumption is that the factor $f_{rech}{}^{D}$ in this relation does not vary spatially and temporally. The recharge depth $q_{rech}{}^{D}$ is then written into MODFLOW's Recharge Package input file "rch6.dat" for all cells within the respective district. Figure 10 shows the effective irrigation areas of each district identified based on the GIS data of the irrigation channel networks and the satellite images.

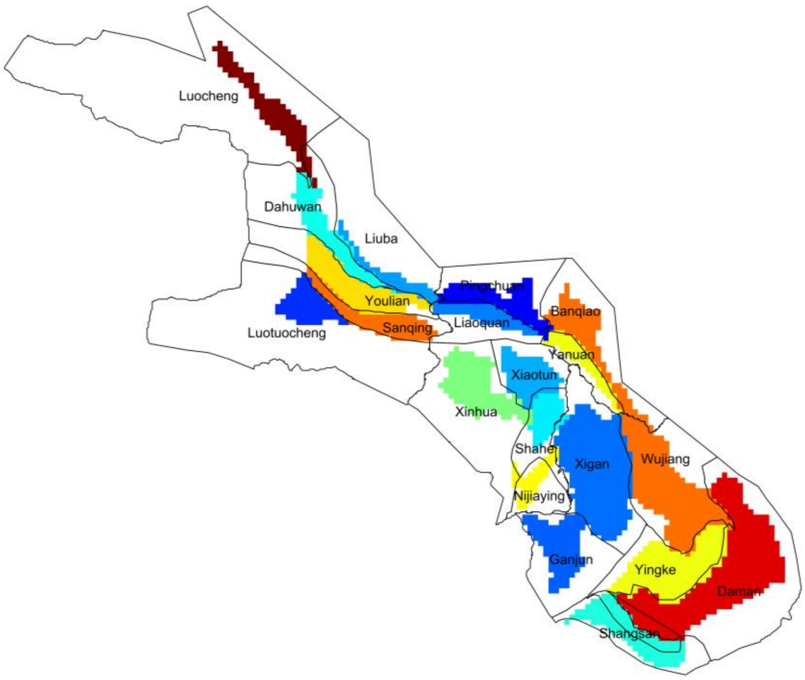

Figure 10: Effective irrigation areas within the districts. They were identified according to GIS data of the irrigation channel network and satellite images showing the irrigated areas.

2.3 State transition function (Groundwater model)

The state variables of the model are the groundwater heads. The state transition function used by MODFLOW is the groundwater flow equation. MODFLOW's Preconditioned Conjugate Gradient Method 2 (PCG2) is used as solver algorithm to compute the new groundwater heads for each time step. Input data can be subdivided into decision variables and disturbances. The decision variables are the yearly volumes of surface water and groundwater irrigation for each of the 20 irrigation districts. This results in a total of 40 decision variables. In the beginning of each year one has to decide how much area to irrigate and where to source the water from. The authorities then supply the corresponding amount of water. As the total irrigation water can be seen as proportional to the irrigated area it is possible to perceive the irrigation area in some way as a decision variable. The reference irrigation water depth of 2010 is computed by dividing the current irrigation volumes of 2010 by the irrigated areas of the districts (Figure 10). The numbers are shown in Table 5 in the Appendix. The area corresponding to a new water allocation is then obtained by dividing the new allocated volumes by this reference depth.

The model disturbance is the inflow from the upstream reservoir into the first cell of the Heihe in the model domain for the current year. This is obviously not known in advance. As the runoff is mainly due to snow-melt processes it could though be possible to make reasonable predictions for the summer runoff based on snow cover observations in the upper catchment. Here is it assumed that perfect knowledge is available. In a future step the decision has to be made under uncertainty with the possibility of correcting decisions with incoming real time data.

2.3.1 Numerical distributed groundwater model

The numerical groundwater model used was provided by Dr. Zhou Jian and Mr. Chen Chong from the CAREERI-Institute of the Chinese Academy of Sciences. The model uses a single unconfined layer on a structured grid of 236x236 cells of 1000m side length each. The model was calibrated by Dr. Zhou Jian and Mr. Cheng Chong using observation data from 26 wells over a period from 1986 to 2008 in monthly time steps. All pumping wells within a grid cell are grouped together and represented by a single pumping well acting on this cell. Although setting up the numerical model was not the task of this thesis, some contributions were made concerning the consistency of data, elimination of data errors, and the convergence of the solver in steady state simulations. For further information and documentation of the model Mr. Chen Chong's Ph. D. thesis should be referred to (Chong 2014).

2.4 Controller (Decision model)

The controller is the core element of the decision model. It is responsible for the allocation and sourcing of surface and groundwater irrigation. The controller adopts a gradient ascent optimization routine in order to maximize an objective function. The objective function is an aggregation of three indicators, one representing the financial profit, one covering an environmental dimension and one expressing a social risk factor. The financial profit is to be maximized. A penalty is given if the impact on the social and environmental indicators is considered negative, and reward is given for a positive impact. The controller can operate within a range constraining the maximal and minimal amount of irrigation water that should be provided to each irrigation district.

2.4.1 *Algorithm*

The optimization is performed iteratively by going stepwise in the ascending direction of the local gradient vector in decision variable space. This vector contains all partial derivatives of the objective function with respect to the decision variables. This method is called 'gradient ascent' or gradient search method. For each iteration the new parameter vector x_{n+1} is computed from the old parameter vector x_n, the increment γ and the gradient of the objective function $\nabla OF(x_n)$ at the point x_n (Brereton 2009).

$$x_{n+1} = x_n + \gamma \cdot \nabla OF(x_n)$$

As the gradient $\nabla OF(x_n)$ cannot be computed analytically for the numerical groundwater model, we must approximate it by computing difference quotients instead of derivatives.

$$\frac{d\,OF(x_{n,D})}{dx_{n,D}} = \frac{OF(x_{n,D} + \Delta x_{n,D}) - OF(x_{n,D})}{\Delta x_{n,D}}$$

The parameters of the optimization routine are set to the following values:

x_0: As an initial estimate the irrigation volumes of 2010 were used, the reason being that this is the most trustworthy parameter set available at the moment. For two districts (Luotuocheng and Nijiaying) zero values were given in 2010, which had to be replaced by plausible non-zero initial values, as zeroes would cause problems for the controller to start.

γ: Set to 10^{12}. Manual calibration by trial and error showed that a value in this order of magnitude leads to reasonable results. The high order of magnitude of this value can be explained by the fact that the partial derivatives are extremely small.

$\Delta x_{n,D}$: Arbitrarily set to 5% of the initial parameter set. It must be sufficiently small to approximate the derivative accurately, but at the same time not too small as otherwise the limited numerical accuracy of the model interferes.

2.4.2 *Constraints*

The total irrigation water quantity supplied to each irrigation district is bounded by upper and lower constraints. The lower constraint avoids to completely refusing water to a certain district. The upper constraint sets a limit to the irrigated area. In fact expansion of irrigated perimeters is officially discouraged since the year 2000. As a reference the irrigation volumes of the year 2010 are used and the lower and upper constraints are set at a factor of 0.5 and 1.5 respectively of those volumes. These factors are chosen arbitrarily without considering the regulations regarding expansion of irrigated perimeters to allow the controller some freedom in the reallocation of the water. If the controller suggests increasing the irrigation above the maximum or below the minimum, surface and groundwater irrigation volumes are corrected so that their sum equals the threshold value (min. or max.). At these two extremes the partitioning of surface and groundwater corresponds to the proportions suggested by the controller before the correction is applied.

2.4.3 *Indicators*

Indicators are the measures to evaluate the model outcome. In accordance with the principle of the three spheres of sustainability we consider three dimensions of impacts: an economic, an environmental and a social dimension. The accounted indicators are not to be considered as comprehensive measures of all impacts affecting the respective component, but rather as one representative feature that is of particular interest in that dimension and possibly representative for others. After the indicators are computed they are mapped onto dimensionless indexes and a non-linearity is induced through a power function. Finally they are aggregated to obtain an objective function which can be maximized by the controller.

2.4.3.1 *Economic indicator* I_{profit}^{glob}

The economic side of the problem feeds back to the ecological side due to the strong demand for irrigation water. The vast unused plains in the basin suggest that for further agricultural expansion water is the limiting factor and not the land. The economic indicator is therefore defined to be the net revenue from irrigation, which should presumably be as high as possible. The real profit itself is a function of revenue and a number of factors such as market prizes and costs of inputs such as seeds, materials, labour, machinery, fertilizer, pesticides, irrigation water etc. The specific cost of all these inputs are assumed fixed and are not analysed within this work except for the cost of irrigation water. For simplicity in the following the net revenue is referred to as 'profit'. The revenue is based on the area that can be irrigated with a given amount of water under the simplifying assumptions that: 1. crop water demand and crop type are constants that do not change over the years. 2. Farmers always aim to apply the same amount of water per unit area. 3. Adjusted revenue per unit area is the same for all districts. 4. Changing the allocated irrigation water quantity will result in farmers increasing or decreasing the crop area proportionally to the change in irrigation water quantity.

The revenue is computed by first computing the area that can be irrigated with the suggested volume of water:

$$A_{irr}^{D} = \frac{\left(Q_{irr,SW}^{D} + Q_{irr,GW}^{D}\right) \cdot}{Q_{irr,std}^{D}}$$

$$I_{rev}^{D} = p_{crop}^{D} \cdot A_{irr}^{D}$$

Where A_{irr}^{D} is the crop area in [m^2], $Q_{irr,SW}^{D}$ and $Q_{irr,GW}^{D}$ the surface– and groundwater irrigation volumes [m^3/year]. The superscript D refers to the district. The standard irrigation amount $Q_{irr,std}^{D}$ as volume per unit area (or depth) [m/year] is computed by dividing the estimated total irrigation volumes in 2010 by the effectively irrigated areas of the district (see Figure 10). It can be seen that large differences exist in the irrigation water volumes applied on the different districts (see Figure 51 and Table 5 in the Appendix). The standard irrigation volume was therefore considered individually according to each district. The following numbers are based on information from the Kick-off Report by Wang and Kinzelbach (2014). The return per unit area p_{crop}^{D} was set to be 2800 Yuan/mu (recall 1mu=666.67m^2).

The cost of surface water is computed based on the price of surface water p_{sw} estimated to be 0.12 Yuan/m^3.

$$I_{cost,SW}^{D} = Q_{irr,SW}^{D} \cdot p_{sw}$$

The cost of groundwater $I_{cost,GW}^{D}$ is computed based on the electric energy required to pump the water from a certain depth.

$$I_{cost,GW}^{D} = p_{power} \cdot \frac{1}{\eta} \cdot \sigma \cdot g \cdot dh^{D} \cdot Q_{irr,GW}^{D}$$

p_{power} is the price of electric power estimated to be 0.4 Yuan/kWh, η the efficiency (estimated to be 0.9 for commercial electric pumps), g the gravitational acceleration of 9.81m/s^2, σ the density of water of 1000kg/m^3, dh^D the average depth to the water table of the respective district D and $Q_{irr,GW}^D$ the groundwater irrigation volume. The effective depth to water is however larger than the average drawdown modelled on the grid cell of 1km^2. For depth smaller than 5m.b.g.l. a value 5m was assumed. To obtain the total cost of groundwater a resource fee of 1 cent RMB per m^3 and the discounted investment cost per m^3 , which lies in the same order of magnitude, have to be added. As the groundwater cost enters only as an index we account for it by the dominant part which is electric power.

The total cost of the irrigation water $I_{cost,tot}^D$ per district is computed as the sum of the cost of surface water $I_{cost,SW}^D$ and the cost of groundwater $I_{cost,GW}^D$.

$$I_{cost,tot}^D = I_{cost,SW}^D + I_{cost,GW}^D$$

The net revenue is then computed from the revenue minus the total cost of irrigation.

$$I_{rev,net}^D = I_{rev}^D - I_{cost,tot}^D$$

The global index value is computed by summing up the net revenue of all districts.

$$I_{profit}^{glob} = \sum_{D=1}^{20} I_{rev,net}^D$$

2.4.3.1 Environmental indicator $I_{Zhengyi}$

As mentioned previously there is a multitude of environmental impacts related to groundwater and stream flow water overexploitation. The key indicator used in this context concerns the Heihe flow leaving the middle reach oasis measured at Zhengyi Station (see location Figure 2). This flow is a crucial element in the current water management. Since 2000 a regulation by the Chinese Ministry of Water Resource is in force that sets an outflow of 0.95 10^9 m^3/year as minimum constraint of water that has to be left for the downstream (Chen, et al. 2014). The main importance of this water lies in its beneficial use for the ecosystem in the lower reach and around the terminal lake of the Heihe. There are possibly also socio-economic aspects as downstream communities also exploit the stream for minor irrigation use, but we consider the environmental side to dominate. The index $I_{Zhengyi}$ corresponds to the computed annual stream flow $Q_{riv,Zhengyi}$ leaving the catchment

$$I_{Zhengyi} = Q_{riv,Zhengyi}$$

2.4.3.2 Social indicator I_{head}^{glob}

As described earlier, the aquifer can be considered as a large subsurface water reservoir able to sustain short term high pumping stress if it is adequately left to recover and properly managed in the long term. A major social problem is seen in the food and income security of the farming communities. In that respect we address the ability of the farmers to resort to excessive groundwater pumping over a short term of time in order to mitigate the impacts of temporal surface water shortages (droughts). This requires that the level of the groundwater should not fall too low, as if a drought happens at an already low groundwater level this would impose additional stress on the system and wells could fall dry. A groundwater level close to the natural level therefore means smaller vulnerability to droughts for the farming communities whereas a low level means higher exposure to the risk of being unable to provide the additional necessary water in case of need. The indicator is therefore computed as the drawdown at the location of selected observation wells (see Figure 11). The observation wells for the indicator computation are selected from the ensemble of real observation wells so to have a representative distribution of observation wells over the entire area. The head indicator I_{Head}^n for each borehole n is computed as follows

$$I_{Head}^n = h_{ini}^n - h^n$$

where h_{ini}^n is the initial head (calculated using the groundwater model as the head at 2010) and h^n the computed head at the location of observation borehole n. The global indicator is then computed from the 13 individual indicators as follows:

$$I_{head}^{glob} = \left[\frac{1}{13}\sum_{n=1}^{13}(I_{Head}^n(I_{Head}^n + DZ)^{AZ})\right]^{1/AZ} - DZ$$

With parameters AZ=20 and DZ=15m. The exponent AZ allows increasing the weight of boreholes with positive drawdowns (lowering water table) as compared to negative drawdowns, which are welcome as the water table is already too low today. The shift DZ ensures all values are positive (up to 15m). The problem remains that, when averaging, positive values can simply be compensated by negative values and so the drawdown is not reflected in the index. The asymmetrical weighting through the exponent AZ helps slightly to increase penalty from positive drawdowns.

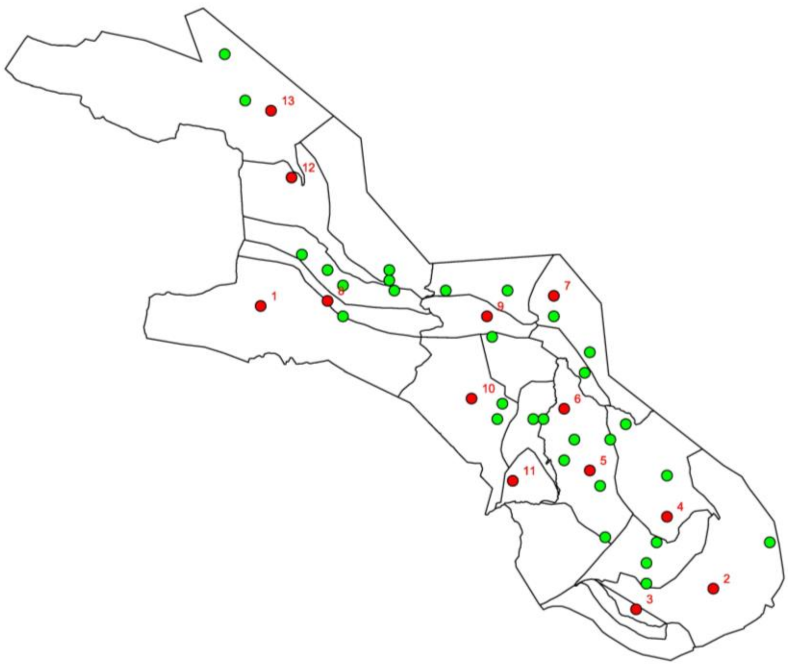

Figure 11: Location of observation wells. Legend: red circles: obs. wells used for indicator. Green circles: remaining obs. wells.

2.4.4 Index mapping

Before computing the objective function the unbounded dimensional indicators I_N are mapped onto bounded non-dimensional indices i_N. We first transform indicator I_N into a linear function ranging from 0 to 2 ($i_{N,lin}(I_N)$). In a second step an exponential function is applied to the index to induce a non-linear behaviour ($i_{N,non-lin}(I_N)$). The mathematical formulation is

$$i_{N,lin}(I_N) = \begin{cases} 0, & I \leq P_1 \\ 2 \cdot (I_N - P_1)/(P_2 - P_1) & \\ 2, & I \geq P_2 \end{cases}$$

$$i_{N,non-lin}(I_N) = i_{N,lin}(I_N)^a - 1$$

Where P_1 and P_2 are the upper and lower threshold values within which we linearize the indicator. For larger or smaller values the index assumes constant values of 2 and 0 respectively. a is the exponent for the non-linear indicator function and is set to 0.3.

The advantage of using these indexes is that they are dimensionless and of the same order of magnitude allowing more efficient comparison of different criteria. A disadvantage is however that outside their boundaries the index assumes a constant value. This implies that when the boundary value is reached, a change in the indicator does not change the index value. In terms of optimization this means the partial derivative of the objective function with respect to some decision variable is zero, and the algorithm cannot further optimize as the new parameter set will be equal to the old one. In the case of reaching the upper bound this is does not matter as we may have achieved a good trade-off already. But if this happens when the indicator drops below the lower bound it will be impossible to recover thereafter. We must therefore ensure that the boundaries are on the one hand chosen sufficiently large in order to include a reasonable range of values, but on the other hand not too large as otherwise the change in index with respect to the change in indicator becomes extremely small. One way out of the dilemma would be to use exponential curves to smoothen out the tails of the indicator so that there is always a minimal slope regardless of the indicator value.

The non-linearization of the indicator is introduced in order to vary the sensitivity of the index over its range. If the sensitivity is constant over the entire range of the indicator, the strongest indicator may possibly solely control the optimization. By inducing the non-linearity, we ensure that when an index value decreases, its sensitivity increases, and vice-versa. Therefore, a lower index value will relatively speaking exert a stronger control on the objective function than a higher index value.

Figure 12 shows the partial value functions for the three indicators profit, head and stream flow. The partial value functions map the indicator onto a dimensionless index. For the profit and head indicator the bounding values P_1 and P_2 are chosen such that the index assumes a neutral value of zero for the reference year 2010. P_1 and P_2 are therefore set symmetrically at a proportion of 0.5 and 1.5 of the 2010 value. For the drawdown the index is centred on the zero point of the indicator, and P_1 and P_2 are set at 10m and -10m respectively. As far as the stream flow index is concerned, the zero value of the index is set at the minimum flow requirement by the government of 0.95 billion m^3/year (Chen, et al. 2014). Here the bounds P_1 and P_2 are defined at a proportion of 0.2 and 1.8 in order to cover the range of plausible values observed in the past.

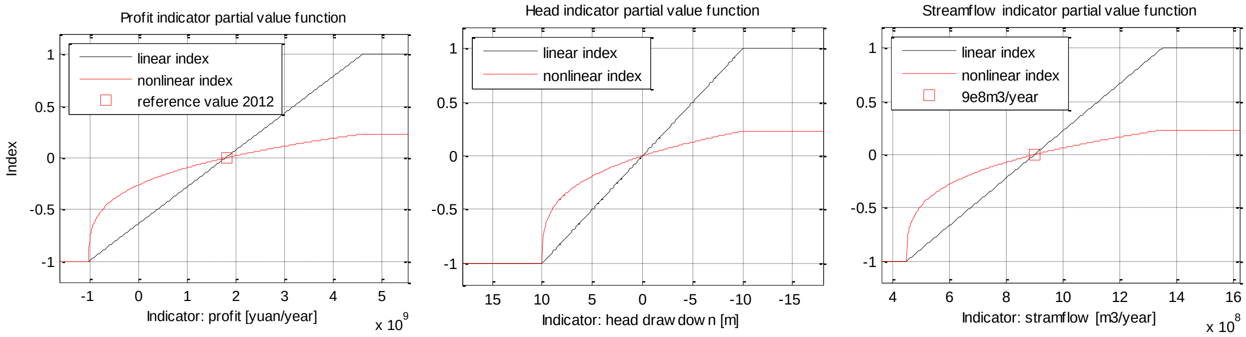

Figure 12: Partial value functions for the three indicators profit, head and stream flow

2.5 Objective function

The objective function OF is an aggregation of the three indices $\mathrm{I}_{\mathrm{profit}}^{\mathrm{glob}}$, $I_{Zhengyi}$ and I_{head}^{glob}:

$$OF = \left(1 - w_{Zhengyi} - w_{head}\right) \cdot \mathrm{I}_{\mathrm{profit}}^{\mathrm{glob}} + w_{Zhengyi} \cdot I_{Zhengyi} + w_{head} \cdot I_{head}^{glob}$$

To allow some flexibility and account for different sensitivity, the indicators $I_{Zhengyi}$ and I_{head}^{glob} are assigned weights $w_{Zhengyi}$ and w_{head}. Each weight should be a value between 0 and 1. The complementary weight of $\mathrm{I}_{\mathrm{profit}}^{\mathrm{glob}}$ is then computed from the condition that the sum of the three weights is 1. It is therefore important to ensure that the sum of $w_{Zhengyi}$ and w_{head} does not exceed 1. The idea of the weights is to keep the objective function in the same order of magnitude regardless of the importance of the single indicators. Otherwise, if the sensitivity of the objective function changes too much, some of the control algorithm parameters would have to be recalibrated.

The objective function is penalized by negative impacts while rewarded by positive impacts on the indicators. If the stream flow for instance assumes values below the minimum flow requirement of 0.95 10^9 m^3/year a penalty is subtracted from the objective function while if it lies above that value a reward contributes positively to the objective function. For the head and profit indicators the zero values correspond to the conditions of 2010. It profit or head indicators drop below those values, the respective indexes will assume negative values while they would turn positive for higher indicator values.

2.6 Input data

The groundwater model input data are the inflow into the first stream cell (stochastic disturbance) and the decision variables (surface and groundwater irrigation volume for each district) provided by the controller or from a historical time series. The coupled control model can be run in two modes:

1. Using the controller:
    a. Using historical data measured at Yangluo Station for the inflow in the first stream cell.
    b. Using generated data (series) for the inflow in the first stream cell.
2. Using historical water allocation data and historical stream flow data measured at Yangluo Station for the inflow in the first stream cell.

2.6.1 Using controller mode and generated input data

When running the model using the controller for water allocation, the stochastic disturbance (inflow into first stream cell) can either be taken from a historic data set or be specified. The graphical user interface allows the generation of a random number or even a random time series. Mean and standard deviation for the normally distributed random number generator can be specified. By default the statistical properties of the observed data series are applied.

2.6.2 Using historical water allocation data

When using historical data a dataset of the period 1986-2012 obtained by CAREERI is applied. It is only possible to consider the historical stream flow data measured at Yangluo Station for the inflow in the first stream cell in this mode. When running the process with historical data the decisions can be evaluated in terms of the indicators and the fulfilment of the 3 objectives.

2.6.2.1 *Stochastic disturbance: stream flow data*

Stream flow data was measured at Yangluo Station. The data was provided to CAREERI by Zhangye Department of Water Resources. The station determines the water level - flow rate curves by measuring velocity profiles with a standard propeller flow meter fixed on a cable crossing the river. Yearly data is aggregated from monthly data.

2.6.2.2 *Decision variables: surface irrigation volumes*

All surface water irrigation data is based on one set of monthly data for each district from the year 2010. The yearly data for 2010 was computed by summing up the monthly data. CAREERI has obtained these data from the Zhangye Department of Water Resources. There is no information about how this data was determined. It is presumably estimated based on experience from the time interval between the opening and closing of a diversion. CAREERI estimated from satellite imagery that the crop area in the years 1986 and 2000 represented 64% and 80% of the crop area in the year 2007, and assumed that the applied irrigation water probably followed the same trend. Therefore a linear interpolation was applied to compute yearly flows for all other years, based on reference crop area indexes of the three specified years.

2.6.2.3 *Decision variables: groundwater irrigation volumes*

Groundwater irrigation data was taken from one set of monthly flow data representing an average over the years 2009-2011. Yearly data for 2009-2011 was computed by summing up monthly data. This data too was obtained by CAREERI from the Zhangye Department of Water Resources. The amounts were apparently estimated partly using measured flows from certain wells and partly from estimates based on power supply for other wells. A total of over 10'000 wells was considered. As no other historical data could be found, the same linear interpolation as for the surface irrigation volumes was applied.

2.7 Simulations

In order to investigate the controller's performance a set of 9 scenarios are simulated. These include simulations using different indicator weights, different inflow data, single and time series simulations.

2.7.1 *Scenarios S1-S6: Different indicator weighting, single year 2010*

As a first step, a set of six scenarios are simulated in order to assess the optimization outcome with respect to different indicator weight combinations. For these scenarios we consider an optimization over one single time step, using input data (river inflow) of the year 2010. The idea is to first test the model for different isolated indicator combinations and verify if the optimization occurs in accordance with the respective indicator characteristics.

Secondly we want to determine what could be a plausible set of suitable indicator weights leading to reasonable optimization results. We hereby presume that not all indicators are equally sensitive to alterations in the decision variables. The sensitivity may however be adapted by changing the indicator weights. An iterative trial-and-error approach is used in order to find a reasonable set of indicator weights.

The first scenario (S1) employs the current allocation of 2010 and is used as benchmark to assess the allocations suggested by the controller. The other scenarios (S2-S6) are conceived to start by only considering the profit maximization (S2), then individually adding head and stream flow constraints (S3, S4), then simulating a scenario including only the constraints and neglecting the profit (S5), and finally a compromise solution were all indicators are considered simultaneously (S6). The scenario definitions are listed in Table 1.

Table 1: Scenarios S1-S6, simulated scenarios using 2010 inflow data with different indicator weighting

Scenario	Brief description	Full description
Using historical data		
S1	Current (or historical)	This scenario is run in the historical data mode. Current water allocation of 2010 is used, the controller is switched off.
Using controller		
S2	Only profit	No constraints on profit optimization by the stream flow and head indicators
S3	Profit and head	Constrain profit by the head indicator
S4	Profit and stream flow	Constrain profit by the stream flow indicator
S5	Stream flow and head (no profit)	Considering stream flow and head indicators, excluding profit from optimization
S6	Compromise	Considering all indicators

2.7.1 Scenarios S7, S8: Different inflow data, single year 2004, 1998 (low, high)

Scenarios S7 and S8 investigate the controller's allocation under conditions of low (S7) and high (S8) inflow from the upstream catchment. Figure 13 shows the course of the measured yearly stream flow at Yangluo Station (mid-reach catchment inflow) and Zhengyi Station (mid-reach catchment outflow) over the period 1986-2012. One can clearly recognize that at the lower lying measurement station of Zhengyi the stream conducts a remarkably smaller amount water than at the upper station of Yangluo. The difference in water is either used for irrigation, lost to direct evaporation, or lost to exchange with the aquifer. It can be observed that in recent years there has been considerably more water than in the 1990s. Researchers from CAREERI claim this may be related to an increase in summer precipitation and a warmer climate in winter (Chen, et al. 2014). There is however uncertainty how the stream flow will evolve in future, and how long the current abundance of surface water will continue. One can see that there is a distinct variability in the data and that there have been numerous years where the outflow at Zhengyi station was smaller than the minimal flow requirement by the government at Zhengyi Station (red line). Two scenarios S7 and S8 are run using different stream inflow data in order to assess how the model allocates water under those conditions. Scenario S7 represents a year with rather reduced stream flow (1.5e9 m^3/year such as 2004) while S8 represents a rear with abundant stream flow (2.1 m^3/year as in the year 1998).

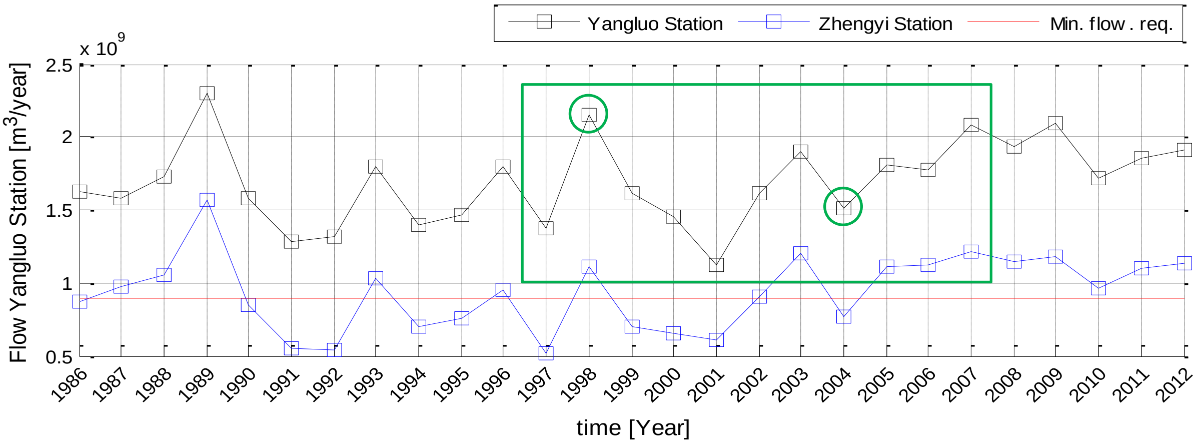

Figure 13: Measured yearly stream flow volumes in the Heihe River at Yangluo Station, Zhengyi Station and minimal flow requirement by the government. Data source: CAREERI. Green circles: data from 2004 was used for low flow scenario S7 while data from 1998 was used for high flow scenario S8. Green rectangle: Time series used for scenario S9.

Table 2 shows an overview of the different computations within scenarios S7 and S8. The performance of the optimized water allocation scenarios S7c and S8c is compared to historical performance of those years, as well as to the performance of the current water allocation (year 2010) under the same inflow conditions.

Table 2: Scenarios S7 and S8, simulated using low and high inflow values

Scenario	Brief description	Full description
S7: Inflow of 1.5e9 m3/year such as 2004		
S7a	2004 historical	Use historical water allocation of the year 2004
S7b	2010 current	Use current water allocation of the year 2010
S7c	Optimized	Optimize water allocation using controller
S8 Inflow of 2.1 m^3/year as in the year 1998		
S8a	1998 historical	Use historical water allocation of the year 1998
S8b	2010 current	Use current water allocation of the year 2010
S8c	Optimized	Optimize water allocation using controller

2.7.2 S9: Real time series 1997-2007

The last scenario S9 investigates the model's water allocation over a time series of 10 years. Historical data from the period of 1997-2007 is chosen as a sample out of the dataset of 26 years of observed flow at Yangluo Station (see Figure 13). The optimized allocation (S9b) is then compared to a simulation using the same inflow data but constantly applying the current allocation of the year 2010. The different sub-scenarios of scenario S9 are listed in Table 3. This scenario shall investigate how the allocation suggested by the controller evolves over time.

Table 3: Scenarios S9, simulation over a time series of years

Scenario	Brief description	Full description
S9: Real time series		
S9a	2010 allocation	Use historical water allocation of the year 2010 for all intervals
S9b	Optimized	Optimize water allocation using controller

3 Results

The following section presents the results of scenarios S1 to S9. First the performance of scenarios S1 to S6 (scenarios with different indicator weighting) with respect to the different indicators is shown on a spider plot (Figure 14). Then the results of each single of these scenarios are briefly presented individually using line plots and thematic maps to show how the optimization routine iteratively adapts the decision variables. Scenario S6 is presented in greater detail, as it represents the alternative which includes all indicators. Scenarios S7 and S8 (low and high inflow) are presented analogously to scenario S6. Finally results of scenario S9 (time series) are illustrated on time series plots. The results are discussed in total in the next chapter.

3.1 Scenarios S1-S6: Different indicator weighting, single year 2010

Scenarios S2-S6 investigate the controller's performance when applying only one or two indicators for the objective function. In Figure 14 one can see that those scenarios all perform remarkably better on the respective indicator(s) that are considered than on the indicator(s) which are weighted zero. We also note that the optimized scenario S6 performs better than the historical scenario S1 on head and stream flow indicators while profit is practically the same. As a first result we see that for the year 2010 a more sustainable choice of water allocation is feasible than the one chosen historically at hardly any loss of profit.

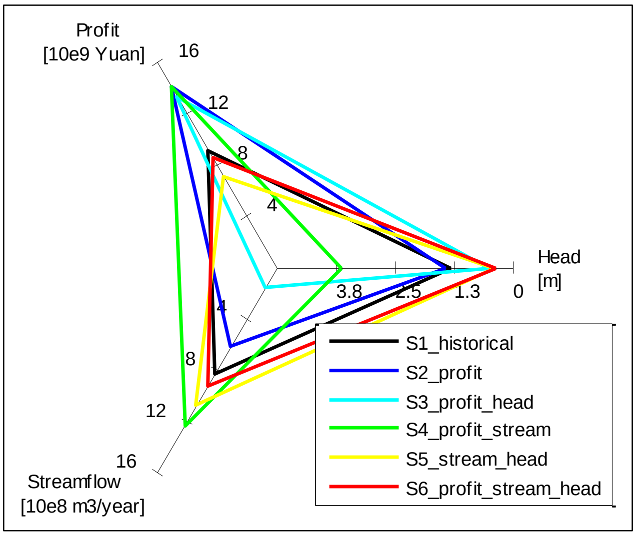

Figure 14: Results of scenario S1 to S6 with respect to the different indicators

The set of plausible weights obtained by trial-and error calibration is shown in Table 4. A total of only about 6 iterative trial simulations were performed to evaluate these parameters, as this is a very time consuming process. While the choice of weights in scenario 2 is trivial, one can see that the difference in weights in scenarios 3 through 6 is rather large. Yet, the results show systematic features. If head is constrained the weight of its indicator has to be large.

Table 4: Results of simulated scenarios using 2010 inflow data with different indicator weighting

Scenario	Brief description	Full description
Using historical data		
S1	Historical	This scenario is run in the historical data mode. Historical water allocation of 2010 is used, the controller is switched off.

Using controller		
S2	Only profit	Weights I_profit=1 I_Zhengyi=0, I_head=0
S3	Profit and head	Weights I_profit=0.05 I_Zhengyi=0, I_head=0.95
S4	Profit and stream flow	Weights I_profit=0.7 I_Zhengyi=0.3, I_head=0
S5	No profit – stream flow and head	Weights I_profit=0 I_Zhengyi=0.03, I_head=0.97
S6	Compromise	Weights I_profit=0.01 I_Zhengyi=0.03, I_head=0.96

3.1.1 S1: current allocation

The results of the current allocation (year 2010) are shown in the following section. The irrigation depth from SW and GW irrigation is plotted in Figure 15. The values are commented on in the section 'Background: irrigated agriculture in the middle reach of the HRB' in the Appendix and are therefore not additionally commented on at this stage. They are plotted here to simplify the comparison at a later stage.

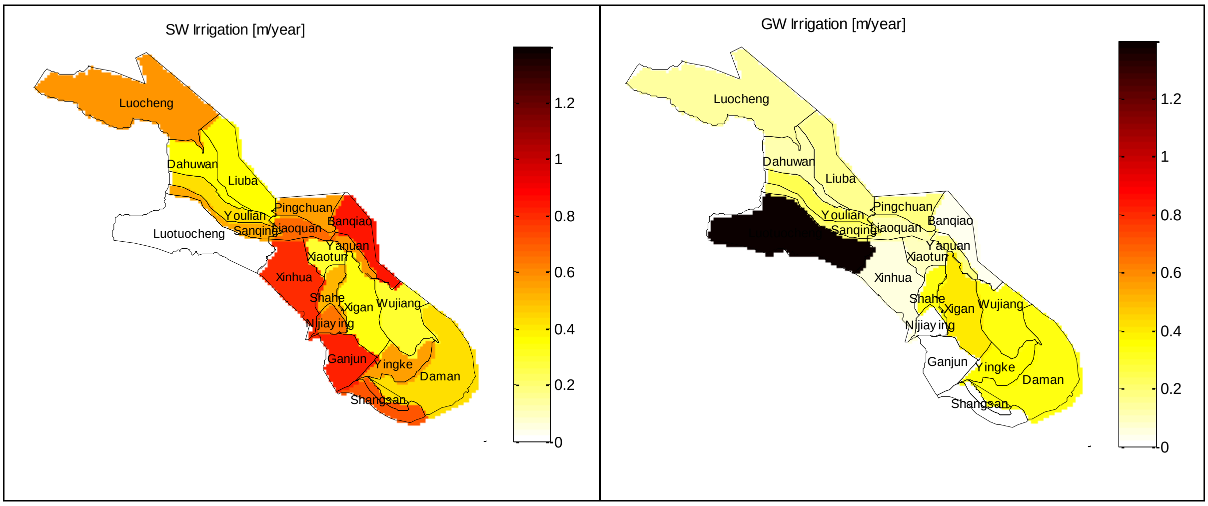

Figure 15: Irrigation depth of SW (left) and GW (right) irrigation for scenario S1.

Figure 16 shows the total irrigation depth and the corresponding area alteration factor. The total irrigation water volume is also already commented on in the Appendix. The area alteration factor is by definition one, as it is defined to be the current irrigation area divided by the area of 2010 (or simply the total irrigation water volume of the current year divided by the volume of year 2010).

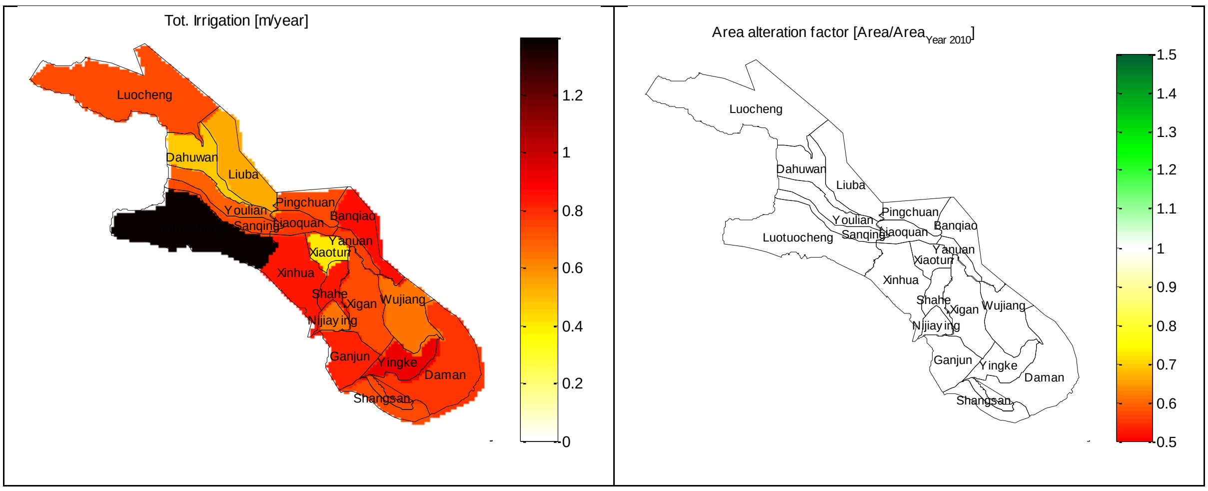

Figure 16: Total irrigation depth (left) and corresponding area alteration factor (right) for scenario S1.

Pumping rates and drawdown for 2010 are shown in Figure 17. One can see that major drawdowns occur in the district of Luotuocheng where GW is the only irrigation water source. In the Liyuan districts and in the east main channel districts minor drawdowns are visible. The drawdowns outside the district perimeters should be ignored, as there are fewer observation wells and the numerical GW model becomes rather inaccurate. Pumping rates are very high in Luotuocheng district where only GW is pumped and moderately high in the upstream districts. The downstream districts have generally lower pumping rates, with some exceptions in Luocheng district. One can see that some pumping wells (i.e. outside Luotuocheng district) assume values of zero. This is due to the fact that for simplicity the groundwater pumping rates of each district are only assigned to the wells lying in the main irrigated area of that district identified on satellite images (see Figure 10). This method includes most of the wells, if a well however lies outside this area it is subsequently not included in the calculations.

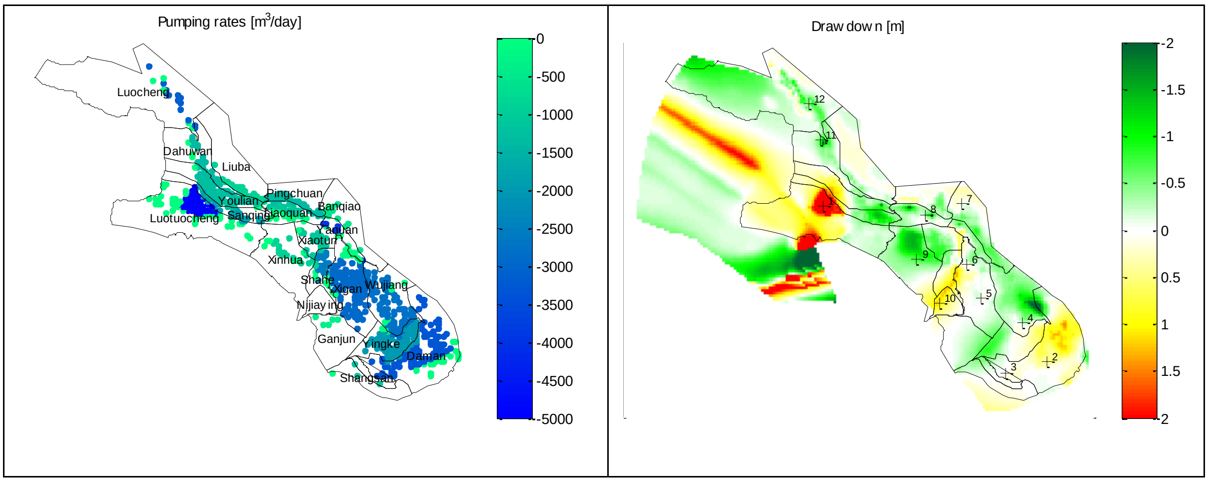

Figure 17: Pumping rates (left) and drawdown (right) for scenario S1.

3.1.2 *S2: only profit*

Figure 18 shows the iteration results for scenario S2. As expected we can see that the profit indicator is obviously maximized at the cost of stream flow and head indicators. One can also see that all variables converge to stable values quickly within less than 10 iterations. Only some minor signs of overshooting can be recognized. The thematic map plots are not shown for this scenario as they are not of particular relevance.

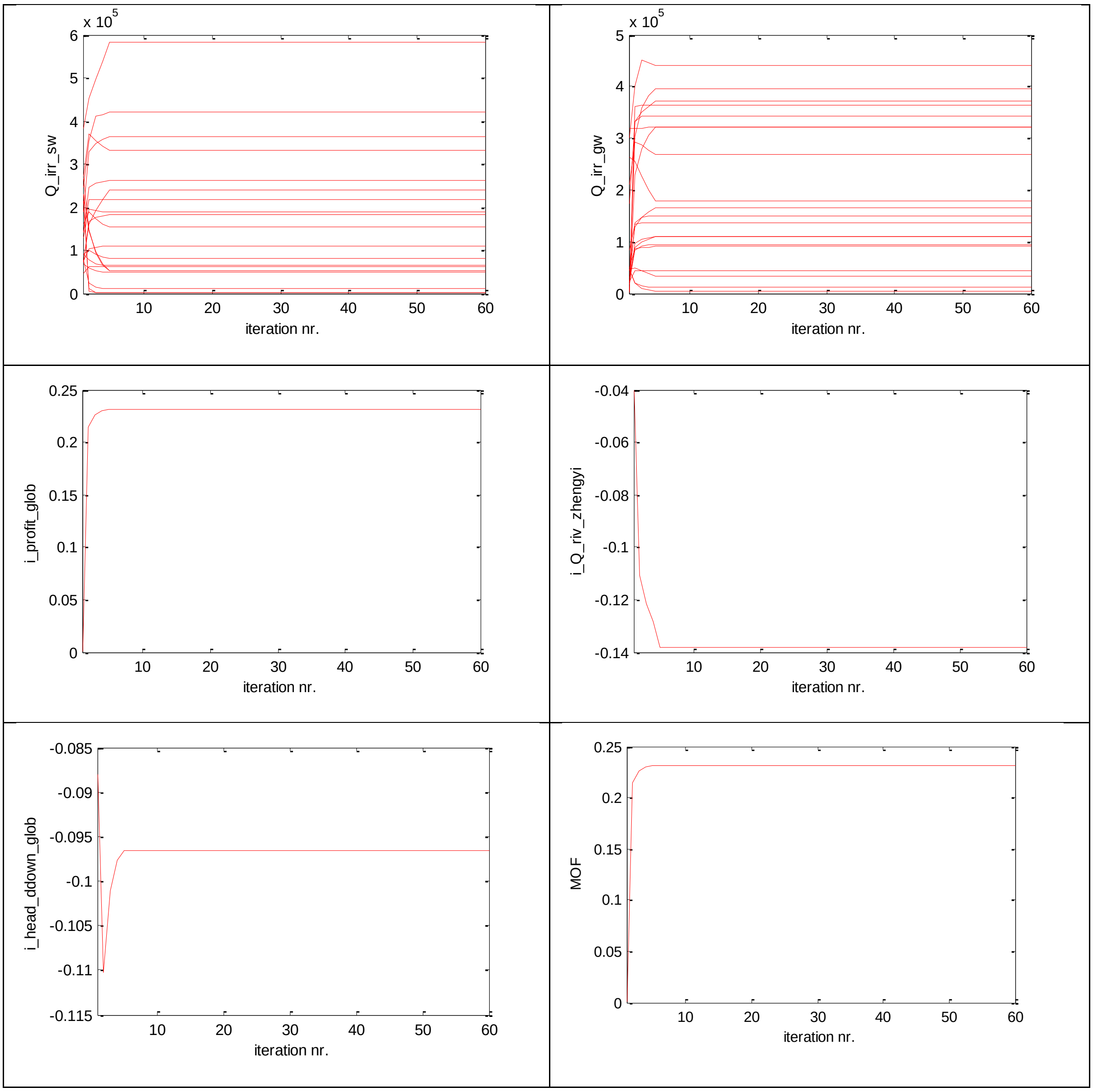

Figure 18: Iteration results for scenario S2

3.1.3 S3: profit and head

Figure 19 displays the results for scenario S3. We note that some decision variables reach equilibrium state faster than others, and by iteration 60 not all of them have yet reached a stable state. The profit and head indicators are clearly maximized at the cost of a decreasing stream flow indicator. The stream flow indicator, being excluded from the objective function, declines until reaching the lower boundary of the index, suggesting serious decline of stream water. The objective function seems to converge towards a stable value towards the end of the optimization.

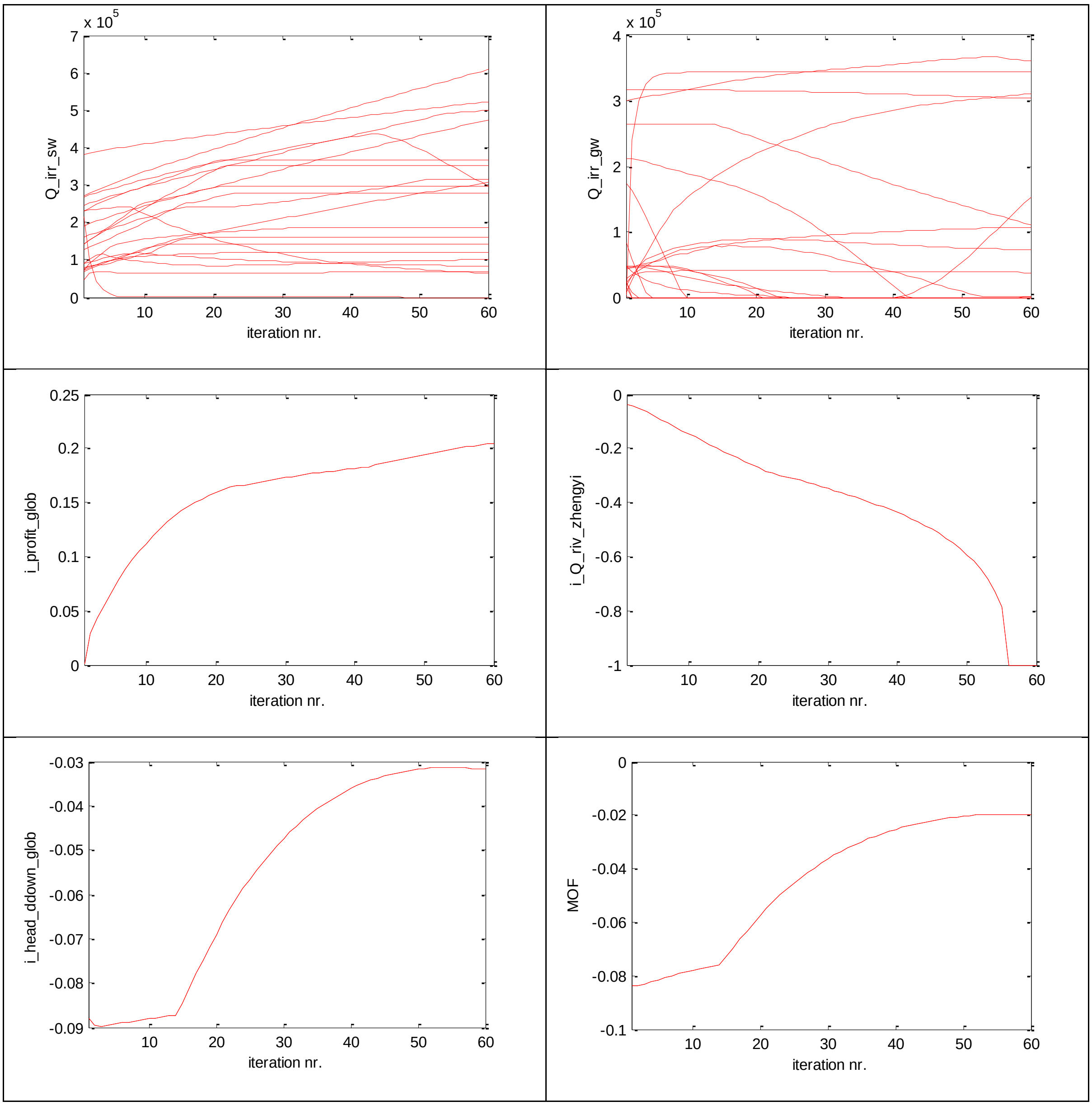

Figure 19: Iteration results for scenario S3

3.1.4 S4: profit and stream flow

The results of scenario S4 are shown in Figure 20. One can see that most decision variables seem to reach equilibrium faster than in scenario S3, but slower than in scenario S4. There are persisting oscillations visible on both SW and GW decision variables from iteration step 20 onwards. The oscillations remain within certain amplitude and do not seem to increase or decrease. The results show how the controller increases profit and stream flow indicators at the cost of the head indicator. The oscillations are a consequence of the stronger weighting of the profit and stream flow indices and could be suppressed by adjustment of weights.

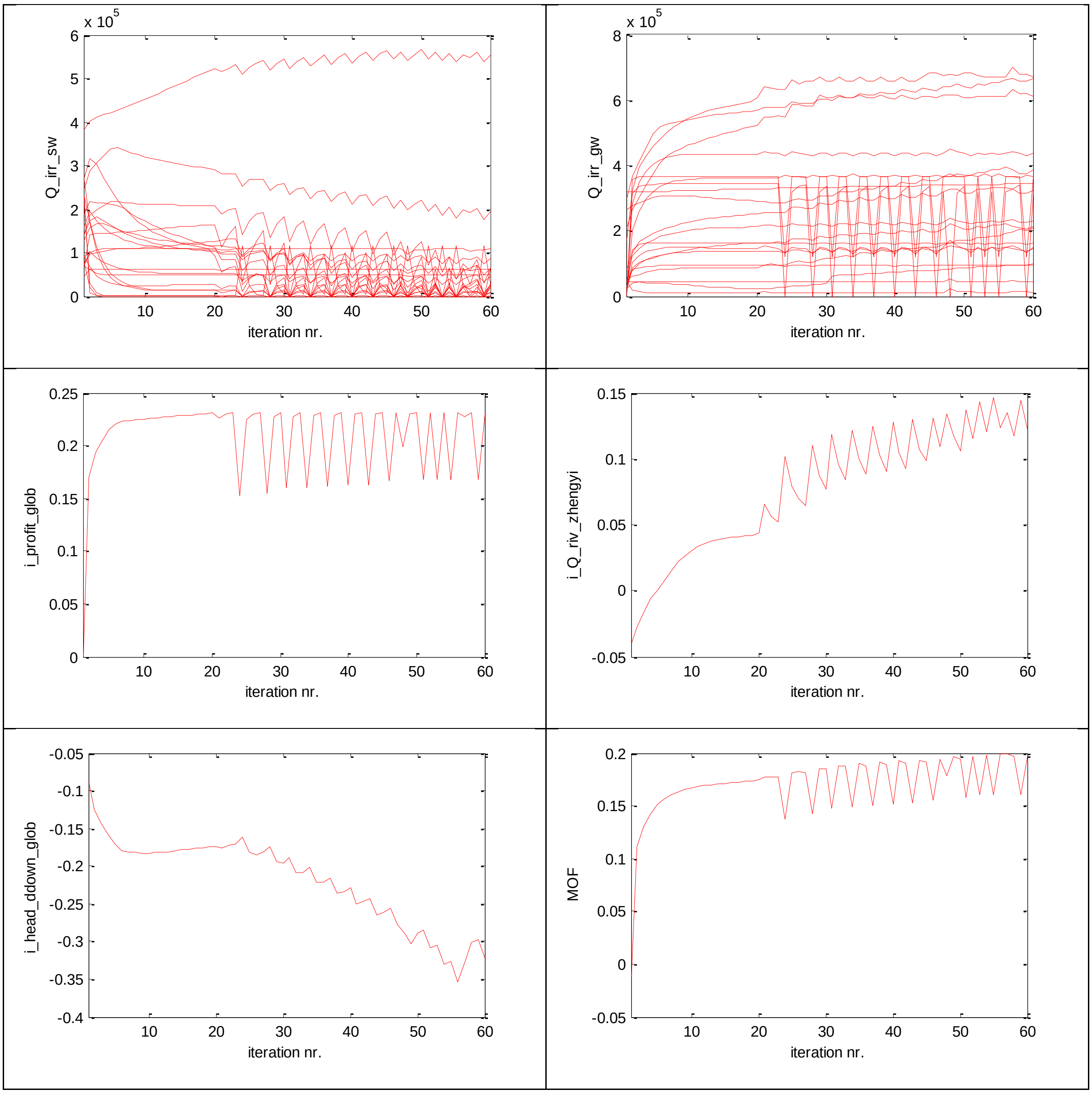

Figure 20: Iteration results for scenario S4

3.1.5 *S5: no profit – stream flow and head*

Figure 21 shows the results of scenario S5. The decision variables do not all seem to converge towards a stable value within the current number of iterations. Some of them do but others increase and decrease in a rather curious manner. The stream flow and the head indicator both increase at the cost of the profit indicator. The steadily increasing head indicator however suggests that the optimization should not be terminated after iteration 60 and that more iterations would allow further improvement of the indicators.

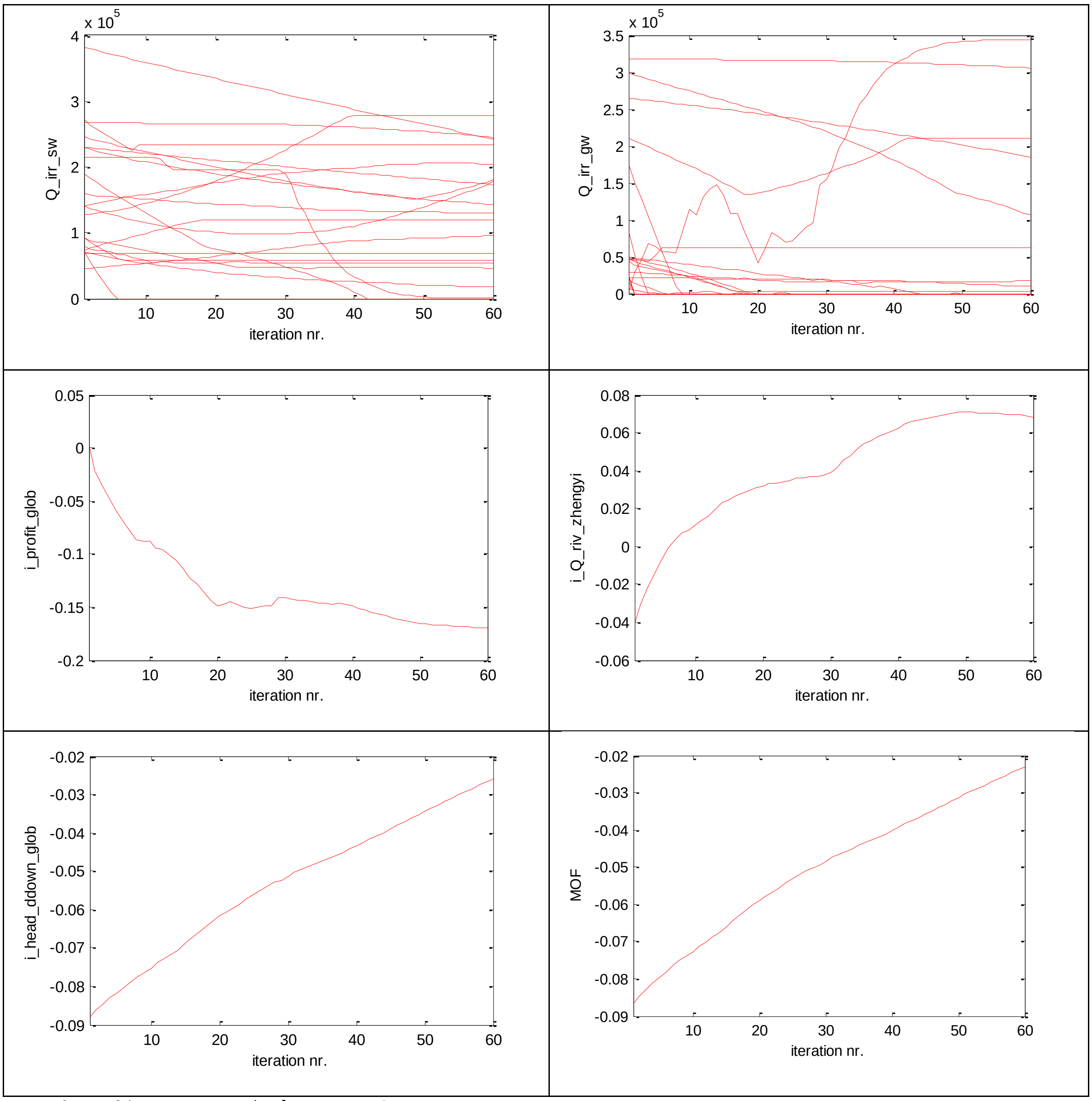

Figure 21: Iteration results for scenario S5

3.1.6 S6: profit, stream flow and head

The results of the compromise scenario that includes all three indicators are shown in Figure 22. One can see that different decision variables adapt at different velocity. The profit and stream flow indices do not converge steadily but fluctuate instead; only the head index seems to converge steadily.

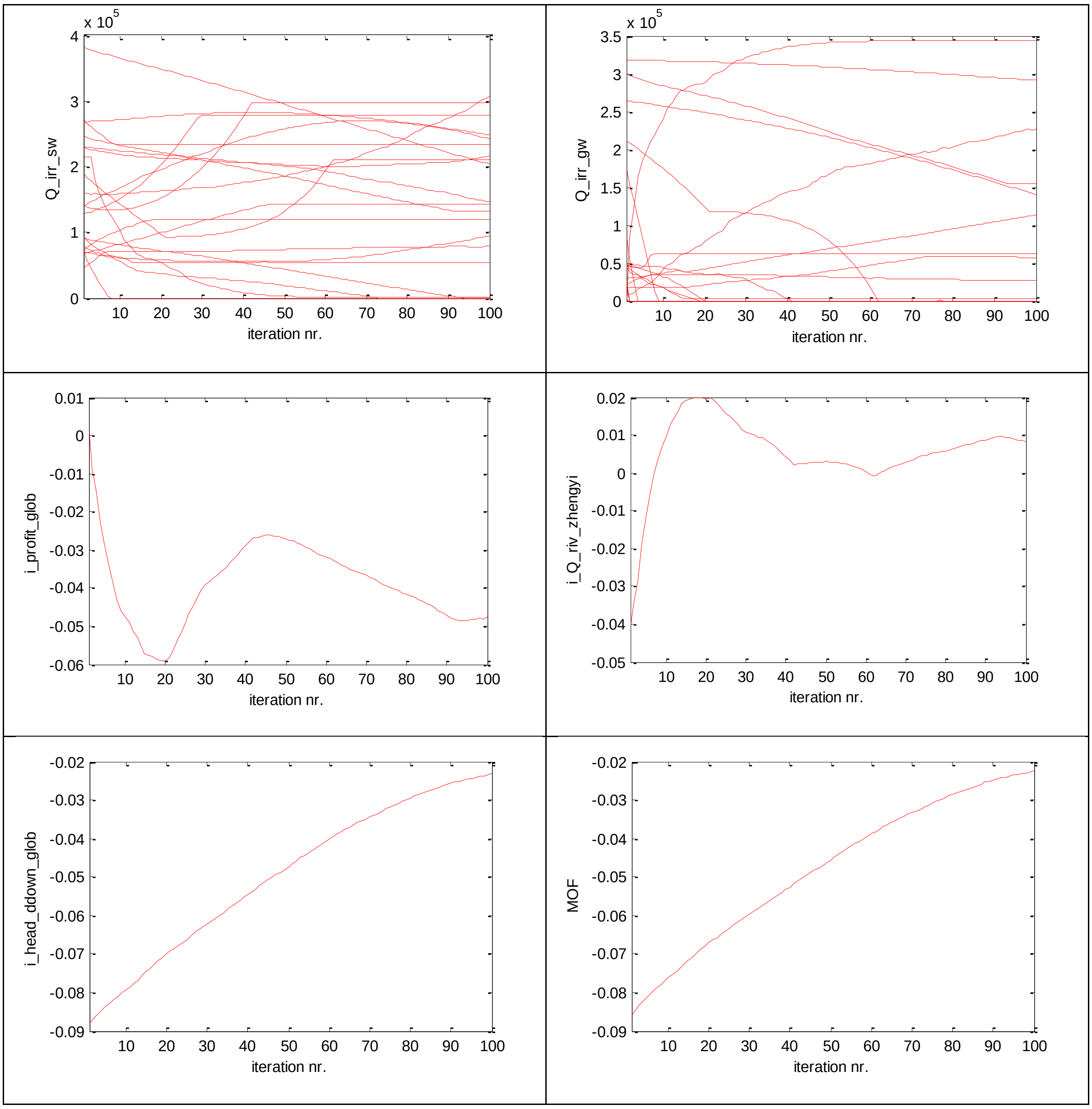

Figure 22: Iteration results for scenario S6

The irrigation depth from SW and GW irrigation is shown in Figure 23. SW allocation does not differ substantially from the current real allocation scenario (S1). Luotuocheng is however now shifting to more SW instead of only GW. In terms of GW use the situation looks quite different compared to the current allocation in scenario S1. The GW irrigation amount is generally reduced; many districts are not using any GW at all. In Luotuocheng district in particular there is much less GW irrigation as response to the increase in SW irrigation.

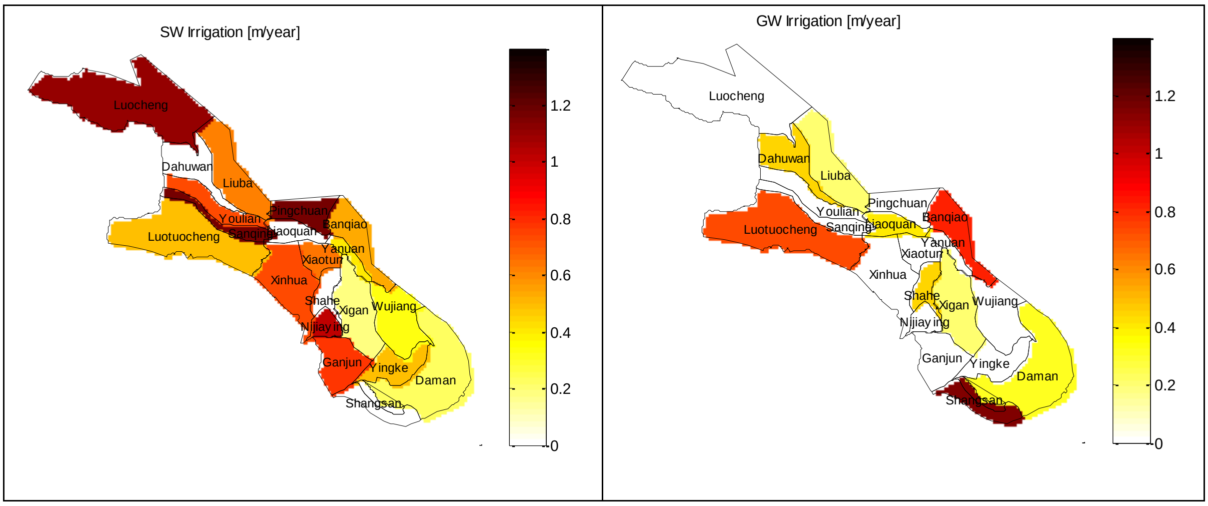

Figure 23: Irrigation depth of SW (left) and GW (right) irrigation for scenario S6

Figure 24 shows the total irrigation depth and the corresponding area alteration factor. Here the overall situation is a bit more differentiated than in the current allocation of scenario S1. Upstream districts generally use less irrigation water and suggest reduction of irrigation land whilst the downstream districts are allocated more water. Drastic cuts are recommended in the districts of Yinke, Wujiang, Xigan, Shahe, Yanuan and Liaoquan.

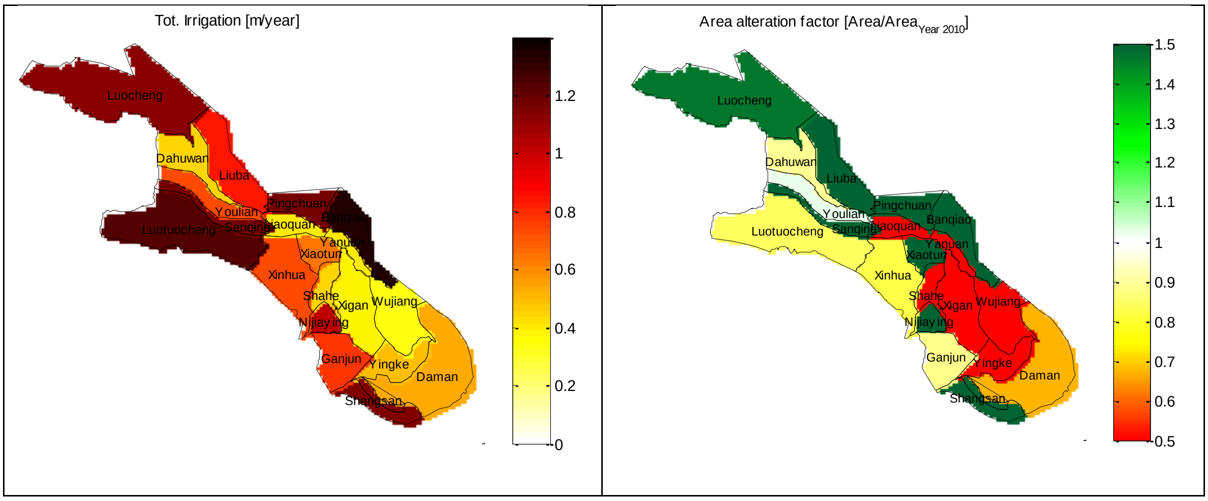

Figure 24: Total irrigation depth (left) and corresponding area alteration factor (right).for scenario S6

The pumping rates and drawdown are shown on Figure 25. Drawdowns appearing in the areas around Luotuocheng as well as in the east main channel districts are still visible but remarkably less pronounced than in the current allocation scenario S1. The pumping volumes vary largely in the east main districts as Daman and Shangsan still employ GW irrigation while their neighbouring districts don't. Also in the central and lower districts the variance is more pronounced.

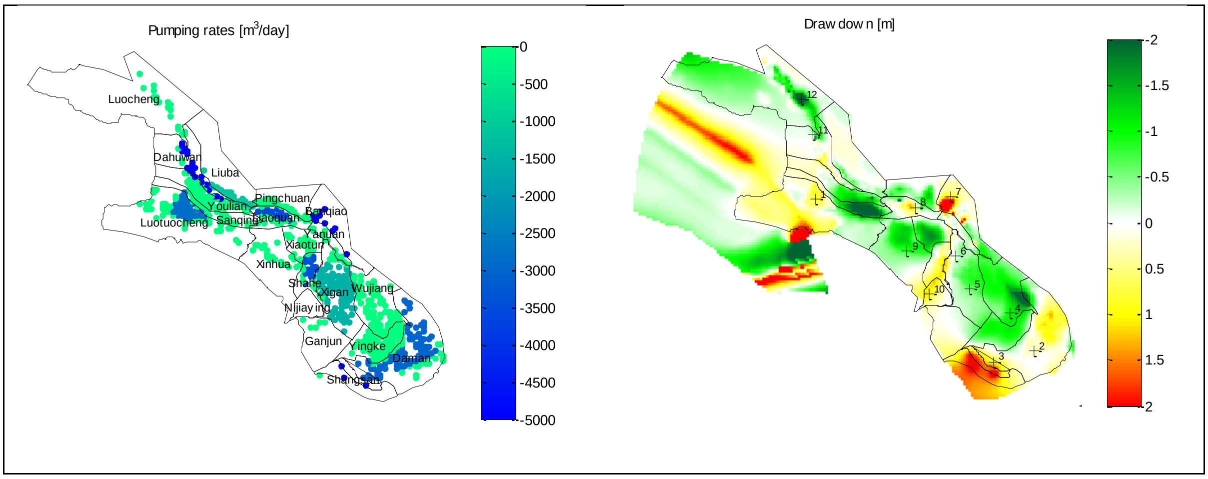

Figure 25: Pumping rates (left) and drawdown (right) for scenario S6.

3.2 Scenarios S7, S8: Different inflow data, single year 2004, 1998 (low, high)

3.2.1 S7: Low inflow

The results of scenario S7 are shown on the spider plot on Figure 26. In this scenario a reduced inflow such as in the year 2004 is simulated. The three scenarios represent the results using the real allocation of 2004 (S7a), the current allocation of 2010 (S7b) and the optimized allocation with the controller (S7c).

We notice that the optimized allocation (S7c) performs remarkably better with respect to stream flow and head indicator than the current allocation (S7b) at the cost of a reduced profit. The optimized scenario (S7c) is almost able to satisfy the minimum flow target of 0.95 billion m^3/year at Zhengyi Station, which is by far missed in the current allocation scenario (S7b). Compared to the historic allocation (S7a) the optimized scenario (S7c) performs slightly better on all three indices but most importantly on the head index.

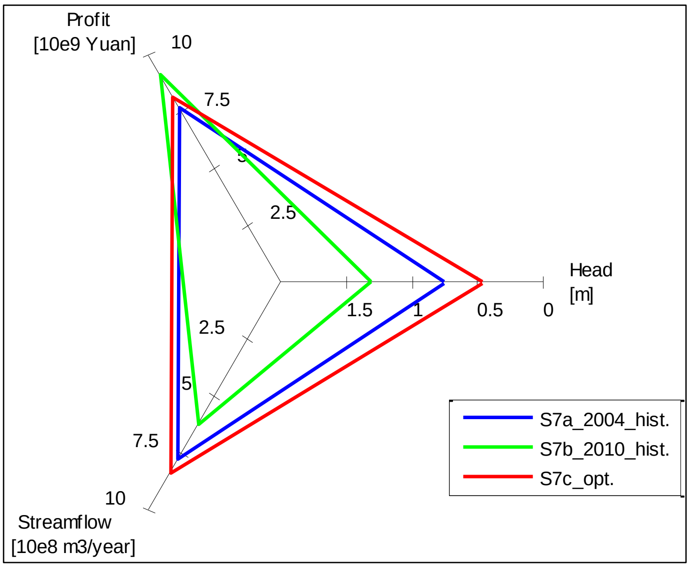

Figure 26: Results of scenario S7 with respect to the different indicators

Figure 27 shows the results during the optimization of scenario S7c. Similar fluctuations in the indices as observed in scenario S6 are visible for the profit and the stream flow indices.

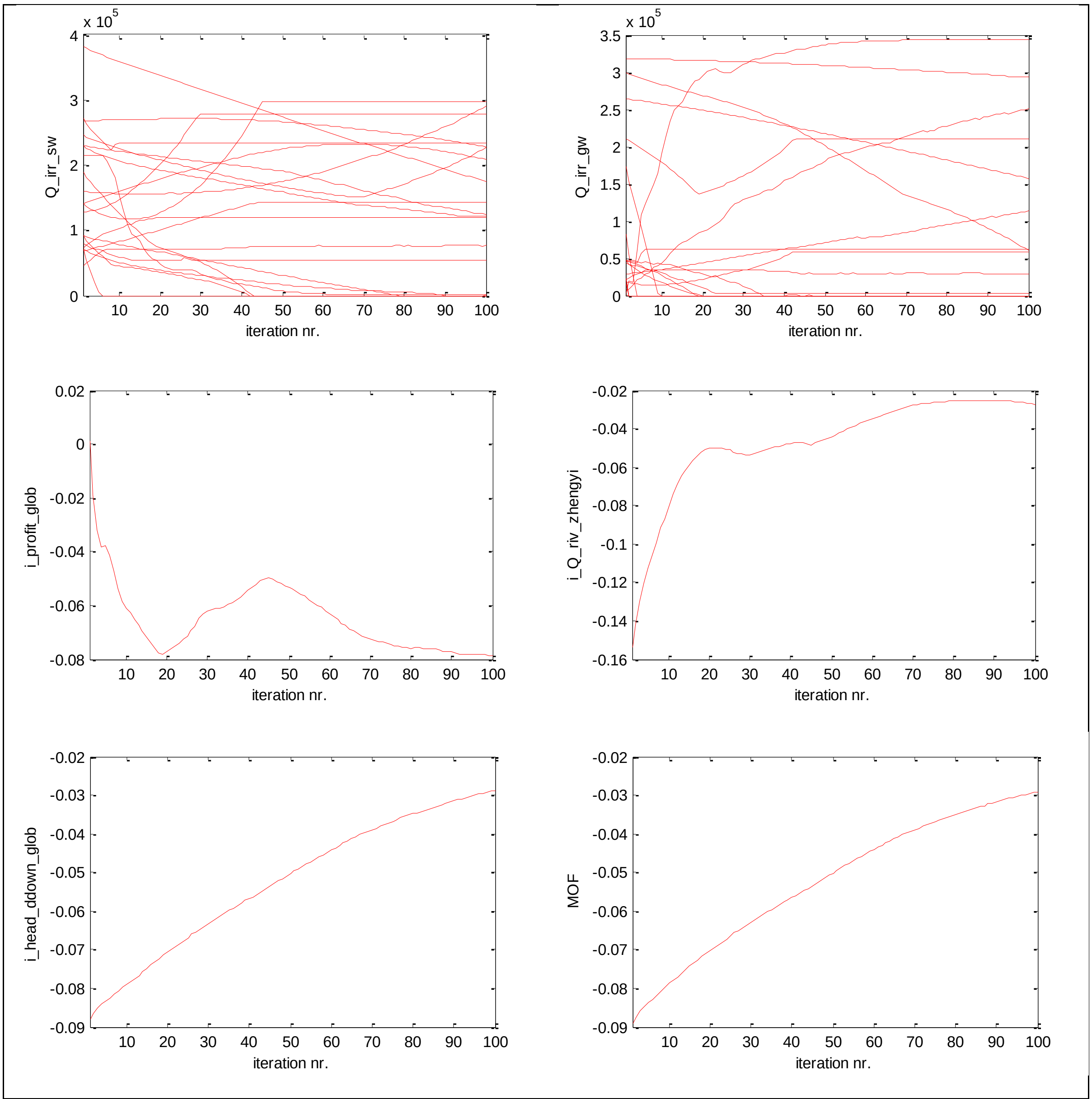

Figure 27: Iteration results for scenario S7c

The irrigation depth of SW and GW irrigation is shown on Figure 28. The distributions look very similar to the one of scenario S6, except that the values are generally a bit smaller and some districts (Luotuocheng, Ganjun and Wujiang) cut down on surface water irrigation.

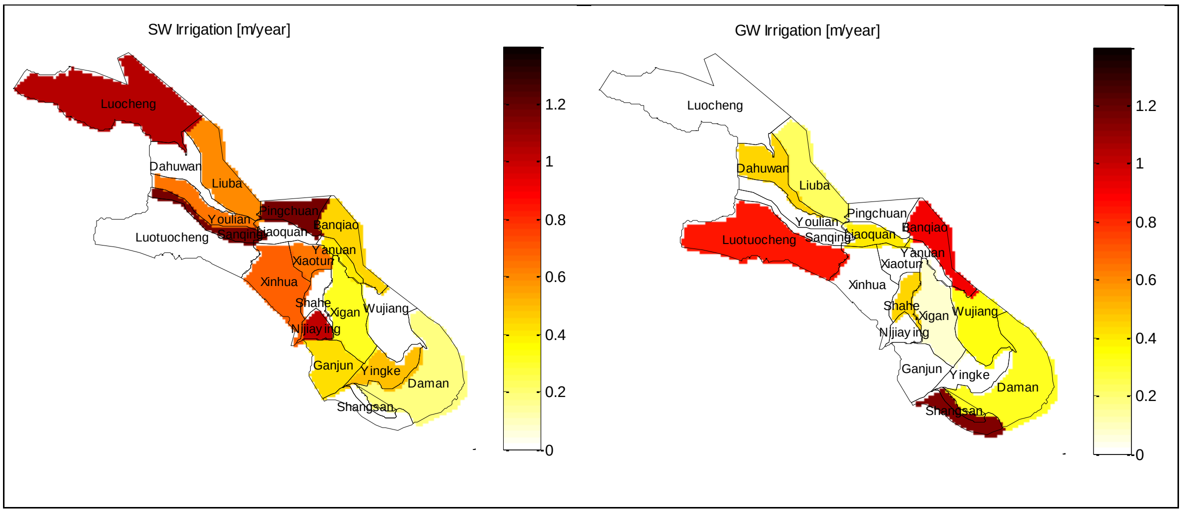

Figure 28: Irrigation depth of SW (left) and GW (right) irrigation for scenario S7c.

Figure 29 shows the total irrigation depth and the corresponding area alteration factor. Also here the overall picture does not change too much except of stronger reductions in the districts of Luotuocheng and Ganjun.

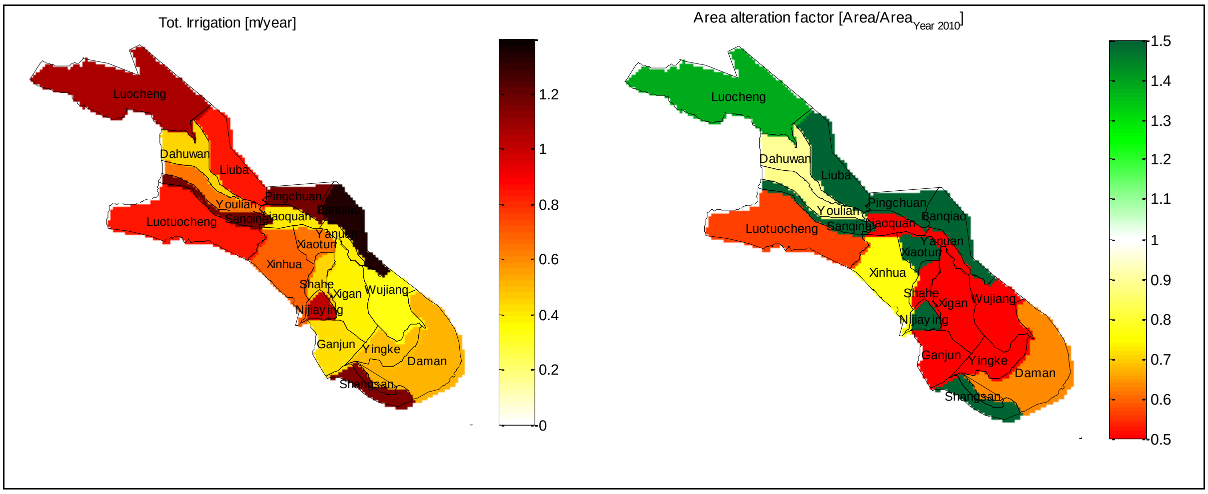

Figure 29: Total irrigation depth (left) and corresponding area alteration factor (right).for scenario S7c.

Pumping rates and drawdown are shown on Figure 30. One can see that drawdowns occur in the east main channel districts, in the Liyuan districts and in parts of Luotuocheng district. The water table rises in the remaining districts, particularly in proximity of the Heihe. The pumping rates look similar as in scenario S6, slightly higher rates are encountered in Wujian, smaller rates in Xigan.

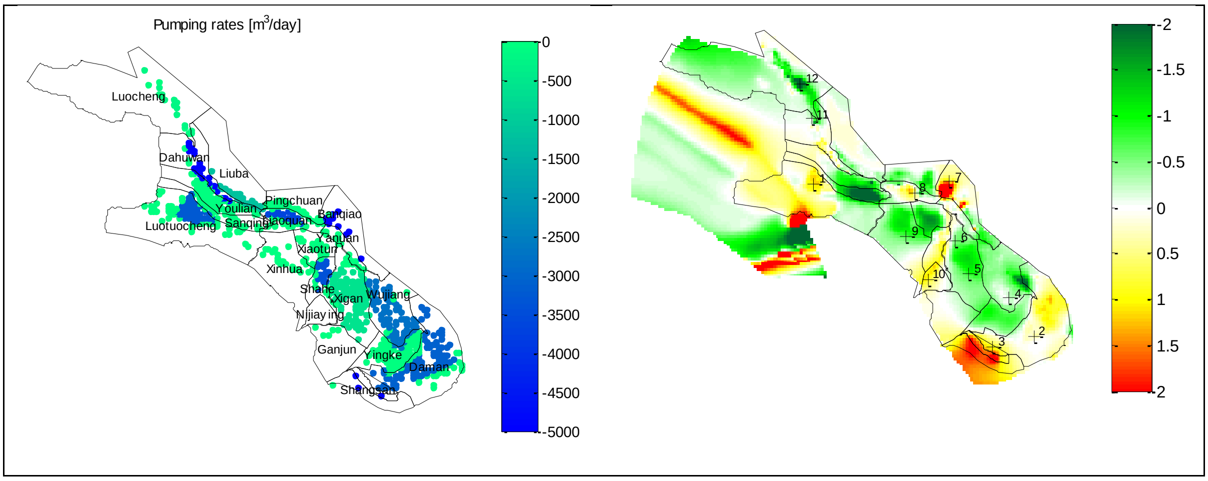

Figure 30: Pumping rates (left) and drawdown (right) for scenario S7c.

3.2.2 S8: High inflow

Figure 31 shows the resulting allocations of scenario S8. A high inflow as encountered in the year 1998 is simulated. The three scenarios represent the results using the real allocation of 1998 (S8a), the current allocation of 2010 (S8b) and the optimized allocation with the controller (S8c).

We note that the optimized allocation S8c performs remarkably better than real allocation (S8a) with respect to the profit. The stream flow indicator is worse off, but as it still lies above the minimum flow target of 0.95 billion m^3/year at Zhengyi Station due to the high inflow from the mountains this is not a problem. Compared to the current allocation of 2010 (S8b) the optimized allocation (S8c) performs about equally good in terms of profit and stream flow but remarkably better with respect to the head indicator.

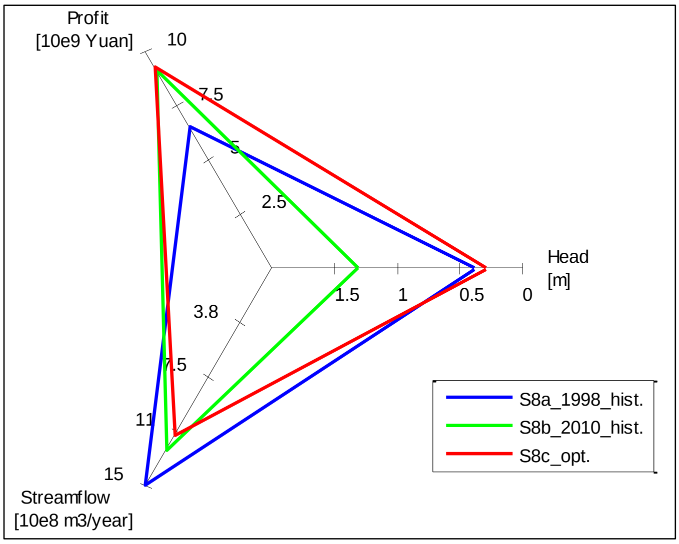

Figure 31: Results of scenario S8c with respect to the different indicators

The results of the optimization of scenario S8c are presented in Figure 32. As noted in many other scenarios previously, strong fluctuations in the profit and stream flow indicators can be observed.

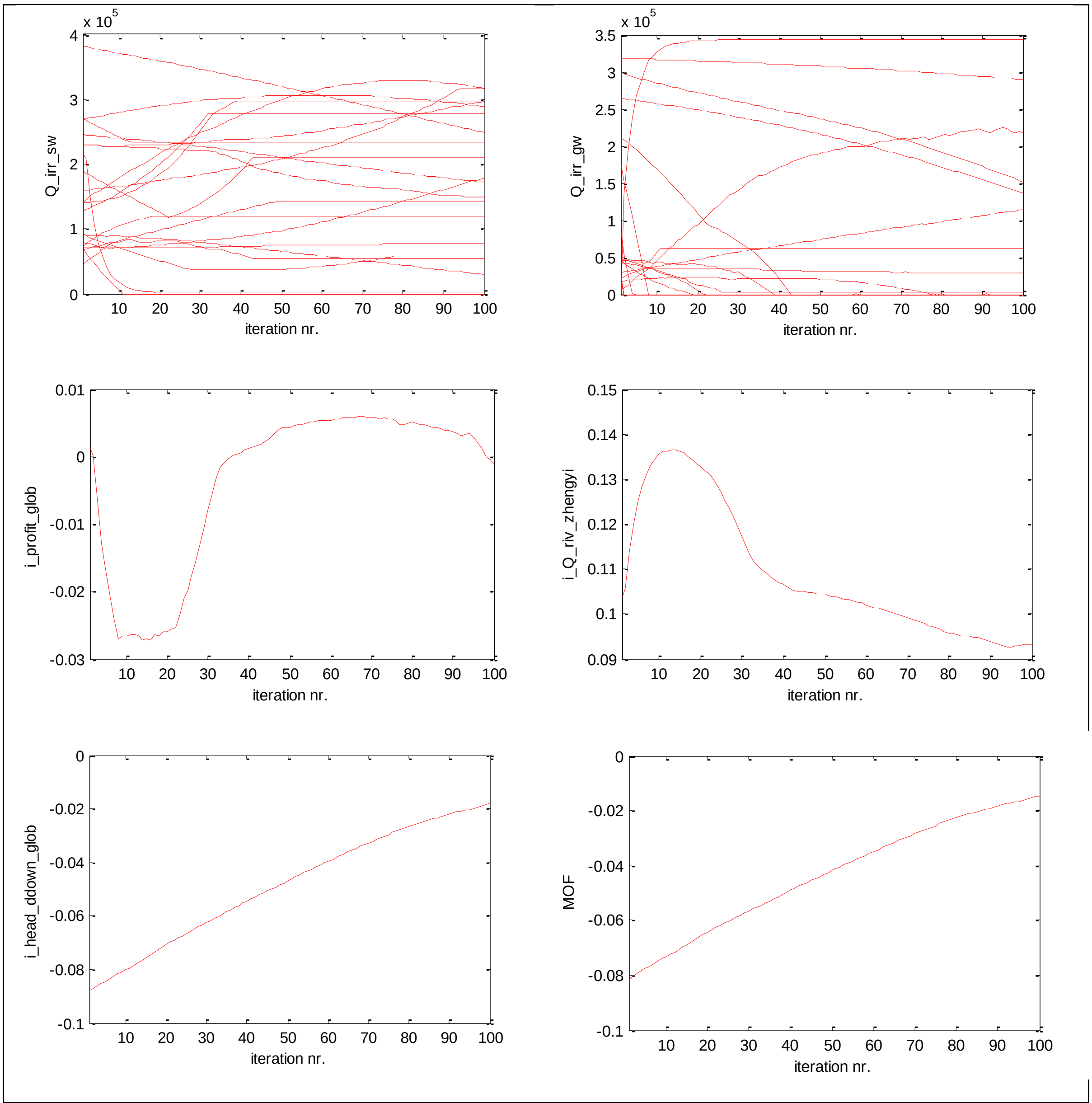

Figure 32: Iteration results for scenario S8c.

Figure 33 illustrates SW and GW allocation of scenario S8c. Also here we note the situation looks similar to scenario S6c as far as the GW allocation is concerned. The SW allocation differs from S6 as more water is allocated to the lower districts as well as to Xinhua and Luotuocheng districts.

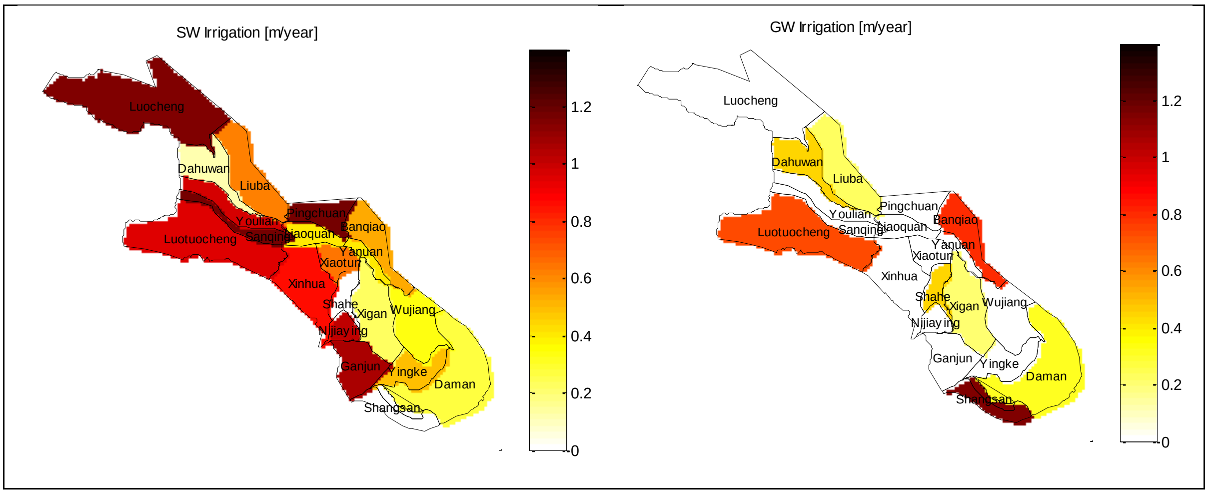

Figure 33: Irrigation depth of SW (left) and GW (right) irrigation for scenario S8c.

Figure 34 shows the total irrigation depth and the corresponding area alteration factor. As can be deduced from the previous figures the total amount of irrigation water increases particularly strongly in Luotuocheng. Compared to scenario S6 expansion of irrigation in some districts that were critical (Luotuocheng, Xinhua, Ganjun, Dahuwan, Youlian) is now possible.

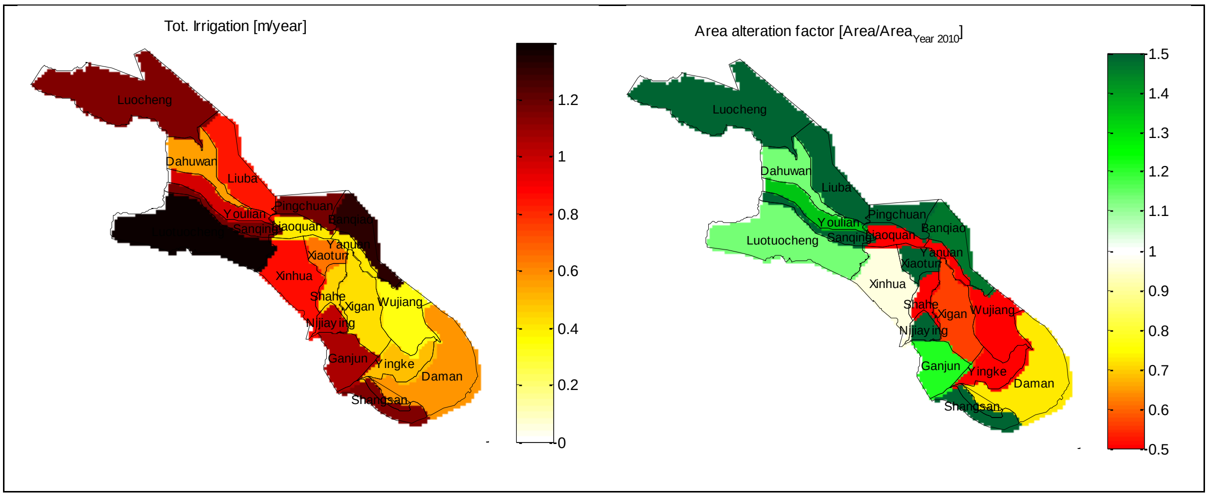

Figure 34: Total irrigation depth (left) and corresponding area alteration factor (right).for scenario S8c.

Pumping rates and drawdown are shown on Figure 35. Compared to scenario S6 the water table is about the same.

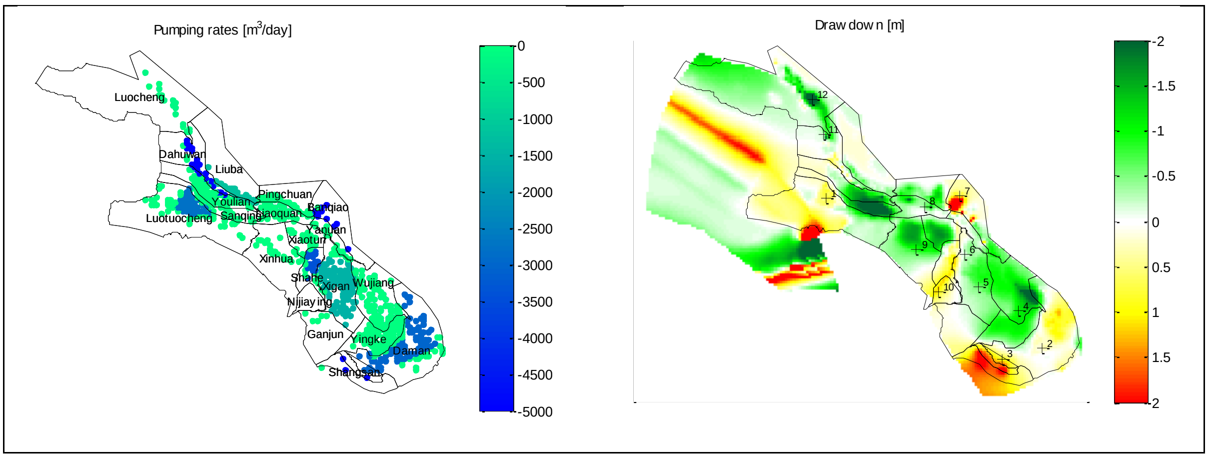

Figure 35: Pumping rates (left) and drawdown (right) for scenario S8c.

3.3 Scenario S9: Time series 1997-2007

Figure 36 to Figure 41 illustrate the results of the time series optimization over the period from 1997-2007. The blue lines represent scenario S9a, using the current 2010 allocation while the red lines represent scenario S9b, the optimized allocation scenario.

On the irrigation water plots in Figure 36 and on the area plot in Figure 37 we see that the controller (S9b) generally allocates less water than the current allocation does (S9a).

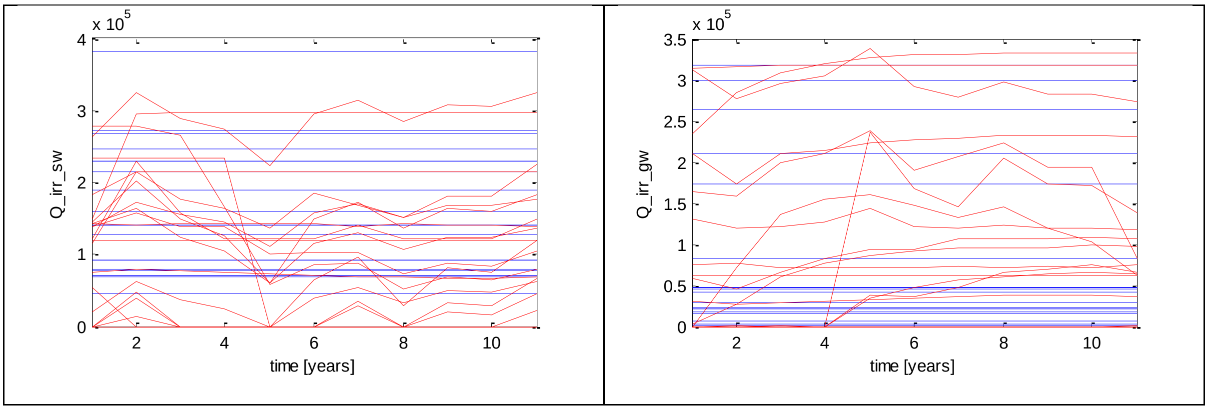

Figure 36: Input data, Q_irr_sw (left) and Q_irr_gw (right) for scenario S9 (legend: blue: 9a, red: 9b).

In Figure 37 we see that the area time series gently follows the trend of the inflow at Yangluo station. The controller seems to consider the amount of inflow water when allocating the irrigation water.

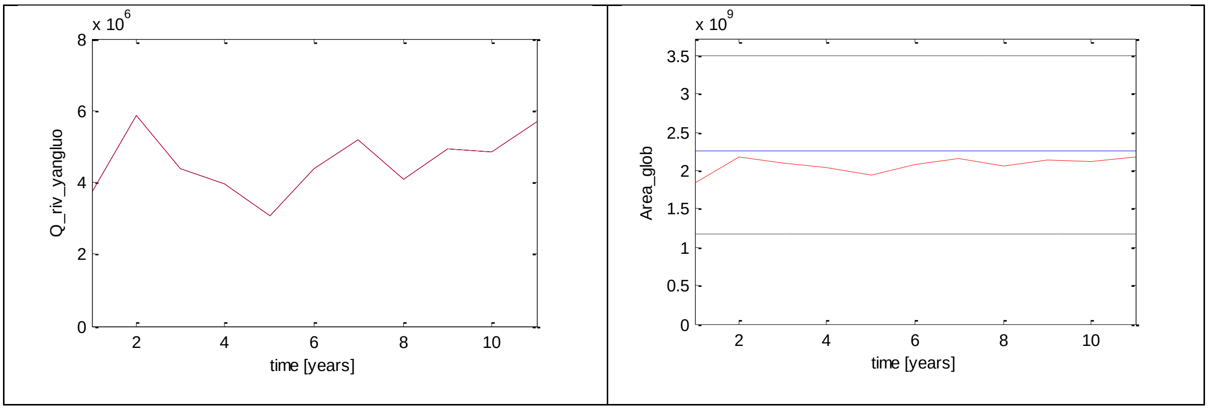

Figure 37: Yangluo stream flow (left) and irrigation area (right) corresponding to the total irrigation water volume for scenario S9 (legend: blue: 9a, red: 9b).

3.3.1 Indicators

On the indicator plots in Figure 38 and Figure 39 we see that the revenue follows the area shown in Figure 37 as the two are proportional to each other. The cost of irrigation follows the same trend, as it depends mainly on the amount of water allocated.

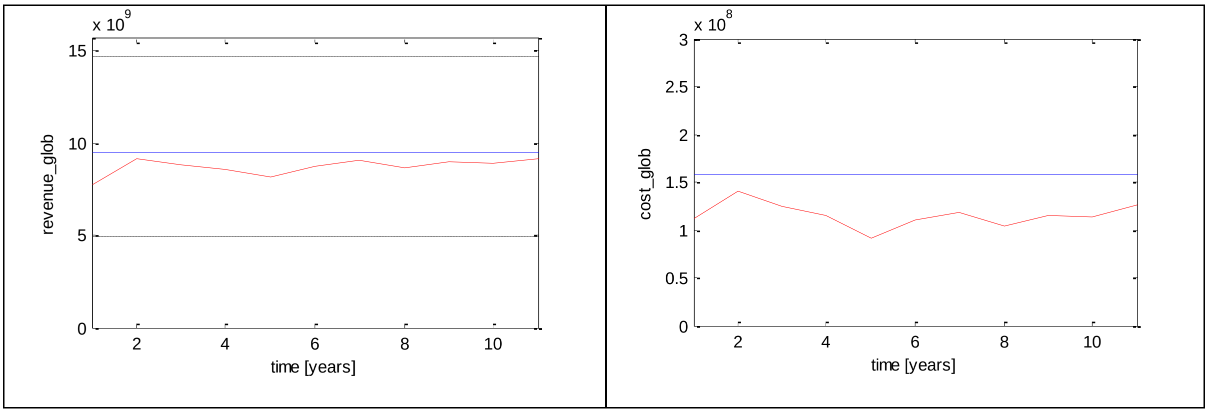

Figure 38: Revenue (left) and total cost of irrigation (right) for scenario S9 (legend: blue: 9a, red: 9b).

The profit plotted on Figure 39 is almost equal to the revenue, as the irrigation water cost only makes up a very small fraction of it.

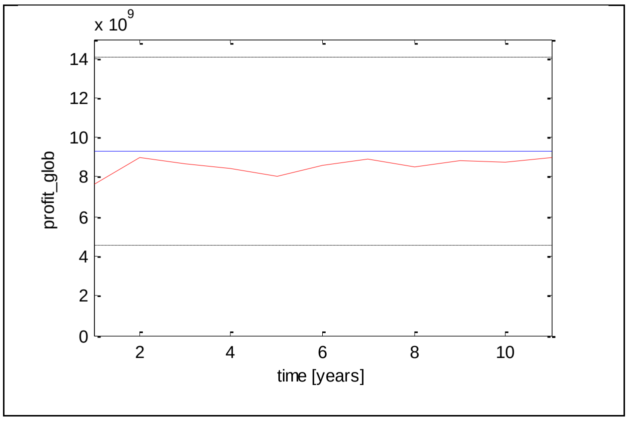

Figure 39: Profit (left) for scenario S9 (legend: blue: 9a, red: 9b).

The stream flow of scenario S9b is remarkably higher than the one of scenario S9a. Particularly in times of low inflow from upstream (around the fifth year) the optimized allocation leaves more water in the stream to practically satisfy the minimum flow target of 0.95 billion m^3/year at Zhengyi Station.

Concerning the head indicator plot we note that generally the heads at the observation wells drift away from the initial value in both directions, implying that at some spots the water table constantly rises, while at others it keeps on declining. Comparing the two scenarios the current allocation scenario (S9a) seems to keep and even slightly increase the head values except of one outlier where the head constantly drops. The observation heads of the optimized scenario S9b are close to the ones of scenario S9a, but outliers are much less pronounced than in scenario S9a, and the largest drawdown is only of magnitude of 6m as compared to 14m in scenario S9a. The controller seems to succeed in preventing strong drawdowns. The levels are still declining but at much slower rate than without the controller.

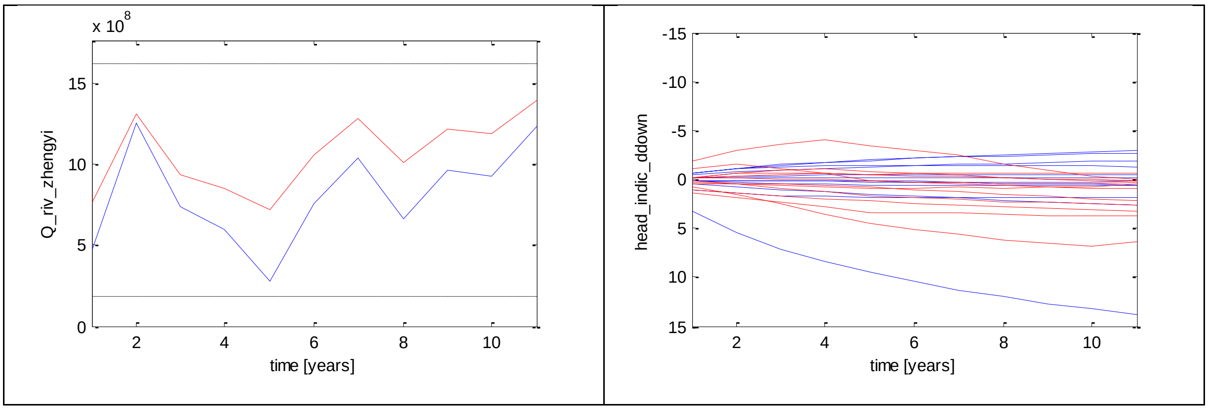

Figure 40: Stream flow indicator (Zhengyi Station, left) and head indicator (right) for scenario S9 (legend: blue: 9a, red: 9b).

3.3.2 Indexes

In terms of stream flow the optimized scenario (S9b) performs significantly better than the current allocation scenario (S9a). The head indicator is still dropping in both cases, suggesting increase in draw-down. The sustainability on the long term with respect to water table recovery is not yet reached. The performance of scenario S9b is however remarkably better than the one of S9a and the head index curve suggests that a stable state with slight tendency of improvement is reached towards the end of the simulation. The declining heads might also be related to the period of low inflow between the second and the seventh year, where water scarcity may lead to more groundwater pumping, as can be seen on Figure 36.

The profit index of S9b obviously lies below the one of S9a as less water is allocated on the whole domain. The objective function strongly correlates to the head index, as this is the index with the strongest weight assigned. On the whole, we can say that the optimized scenario performs remarkably better on the ecological and social indicators (stream flow and stream flow). The price we pay is a cut down on profit in the range of 10-15%.

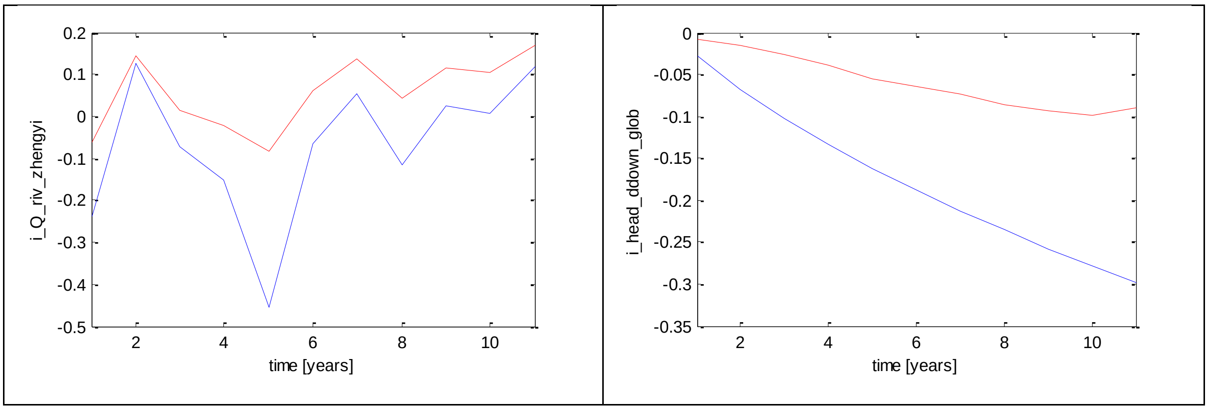

Figure 41: Stream flow index (left) and head index (right) for scenario S9 (legend: blue: 9a, red: 9b).

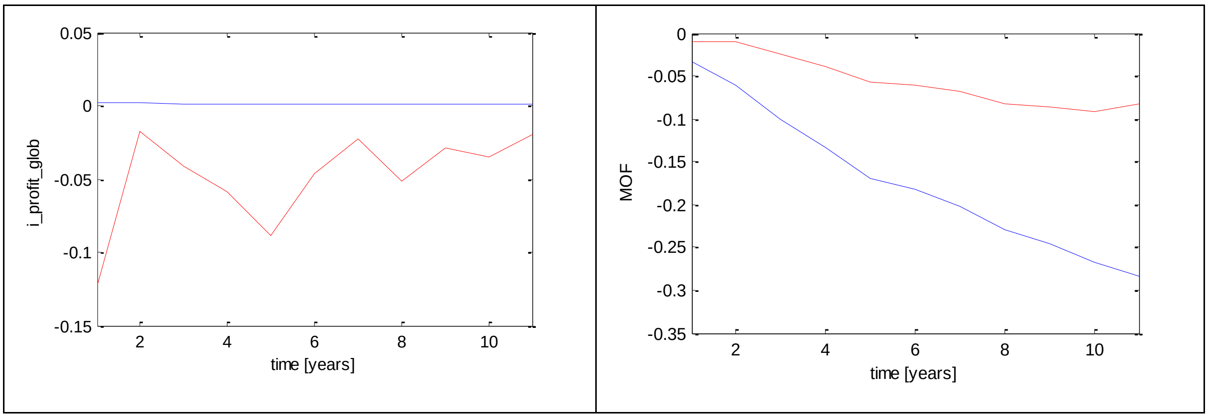

Figure 42: Profit (net revenue) index (left) and objective function (right) (legend: blue: 9a, red: 9b).

4 Discussion

4.1 Scenarios S1-S6: Different indicator weighting, single year 2010

The modelling results using different indicator weights are useful to verify the how the controller operates when only some indicators are used. As expected scenario S2 shows high economic revenue but bad performance on the head and stream flow indices. As it should be, scenarios S3, S4 and S5 achieve good results on the indicators that are considered, and bad performance on the indicator whose weight was set to zero. We can therefore deduce that the controller is to some extent able to direct allocation in a way to maximize a single indicator or an indicator combination that we want. Things become more complicated when trying to combine the three indicators in scenario S6. We see that now the controller is not able anymore to achieve as good performance on the single indicators as it did in scenarios S2-S5 where only one or two indicators were considered. This has two reasons. On one hand the maximum may no longer be unique, as one indicator may compensate for another. On the other hand the problem becomes more constrained and one arrives fast at a Pareto-optimum, where only compromises between indicators are feasible, without the possibility of further improving on all three sustainability criteria. Nevertheless, we can note that the controllers allocation performs better than the current allocation of 2010 (S1) on the stream flow and head indicators, while it yields almost equal results on the profit indicator. The optimizer is therefore able to achieve improvements on some indicators without harassing the other indicator (a more detailed discussion of the optimized scenario S6 follows in Section 4.1.5). This suggests that the current allocation (S1) is not Pareto-dominant with respect to those indices. There must be an ensemble of allocations which do in fact perform better on all three indicator fronts and the controller has shown ability to explore some of these new solutions. The way the indices are computed can however influence the relative performance of an alternative as compared to another one, so the concept of Pareto-dominance hereby is strictly bound to the current index formulation.

4.1.1 Fluctuations

We can observe that in scenario S6 some indicators tend to slowly fluctuate and overshoot. This suggests that the large space of decision variables combined with two of more competing indicators possibly offers a multitude of similarly good solutions. As a consequence the controller may jump from one local maximum to another and the search of the best solution is not trivial anymore. The oscillations may also be due to the non-linearity of the indices. Smoothing out the approach to the bounds may be able to suppress them. Problems of faster oscillations are encountered only in scenario S4 (profit and stream flow indicator maximization). The problem may be related to the increment γ of the gradient ascent algorithm being too large and causing numerical instability by constantly overshooting around the equilibrium point. It could possibly be helped by using a more advanced maximum search for example the Marquardt-Levenberg algorithm.

4.1.2 Weight sensitivity

The weights adopted after the manual calibration by trial and error show that the different indicators have a very different sensitivity, and that appropriate weighting is essential in order to even out these differences. The profit indicator, being directly proportional to the amount of allocated water, is very sensitive. The stream flow indicator is less sensitive as the amount of stream flow reduction is only proportional to the amount of surface irrigation water and not directly to the amount of groundwater (only through exchange of the stream with the aquifer and through pumping of wells close to the river). The head indicator is the most insensitive and needs the strongest weighting (almost 100 times of the profit indicator) as the response of the heads to the amount of irrigation water only very small.

4.1.3 Number of iterations

The decision variable plots showed that different decision variables are changed at different velocity. This seems to make sense as their impact on the indicators may differ strongly. While in scenarios S2 and S4 they converge very quickly in the other scenarios they need much more time to converge. It is obvious that optimization of an objective function composed of 3 indicators in a 40 dimensional parameter space allows for compensation between indicators and thus makes the optimum search more difficult than in the case where there is only one indicator (S2).

4.1.4 Solution characteristics

When looking at the decision variable values that the solutions tend to converge to, we note that in most of the cases they lie on the limits that have been defined by the constraints. The idea of non-linearizing the indices in order to achieve a dynamic equilibrium between conflicting indicators does not produce the desired outcome. Reasons could be that the indicators are partly not conflicting, that some indicators are still stronger than others, that the non-linearity is still too weak or that the equilibrium point lies outside of the constraints.

4.1.5 S6: compromise scenario

The comparison of the optimized allocation (S6) with the current real allocation of the year 2010 (S1) shows that the controller can successfully improve the current allocation and sourcing of the water. Stream flow can be increased and drawdowns reduced without really impacting the total amount of irrigation water used, but solely by different sourcing and allocation of the water available among the districts.

The allocation suggested by the controller generally decreases the amount of GW pumping, particularly in Luotuocheng. This seems reasonable as Luotuocheng is the district where currently only GW irrigation is applied and steep drawdowns are encountered. Through shifting to more SW irrigation these drawdowns could be significantly reduced. Some drawdowns nevertheless increase in the region of Shansan district where the controller increases irrigation rates. Concerning the total amount of irrigation and the corresponding irrigation area the upstream districts are recommended to cut down on irrigation while the lower ones can expand their irrigation perimeters. This may be due to the fact that the stream loses water to the aquifer in the upstream while it is recharged from the aquifer further downstream, as described by Zhou, Hu, et al. (2010). As for the stream flow it should not make a substantial difference where along the stream water is abstracted. The groundwater abstraction in the upper districts seems to have more severe impacts on the head indicator as the ones further downstream, where the aquifer recharges the stream. As the profit indicator is essentially equal to the one in scenario S1, the decrease in irrigation perimeter in the upper districts seems to even out the increase of irrigation water proposed for the downstream districts. One can deduce that the regional allocation of the water therefore seems to have crucial impacts on these indicators, presumably mostly on the head indicator. A strict limitation of irrigation perimeters suppresses the exploration of such solutions. By leaving some flexibility it is thus possible to improve some relevant environmental and social aspects.

4.2 Scenarios S7, S8: Different inflow data, single year 2004, 1998 (low, high)

4.2.1 S7: Low inflow

Scenario S7c shows the controllers water allocation under low inflow conditions. When comparing, the historical allocation scenario of 2004 (S7a) has to be treated with care as the irrigation water volumes in the past are per se smaller due the fact that there was less irrigated area than there is now. The optimized allocation (S7c) shows a clear response by the controller to predefined ecological and social needs and performs remarkably better than the real allocation of 2004 (S7a) in terms of head and stream flow at the cost of less profit. The target of 0.95 billion m^3/year at Zhengyi Station is almost reached and drawdown reduced to a third. Comparing to scenario S7b which applies the current water allocation of 2010, the optimized scenario performs slightly better on all indices, particularly on the head index. The overall picture of scenario S7c however looks similar to the allocation of scenario S6, which suggests that this allocation is also suitable in years of lower flow. Some minor changes are made by reducing SW irrigation in Luotuocheng and Ganjun and shifting to more SW irrigation instead of GW irrigation in Wujiang district.

4.2.2 Scenario S8: High inflow

For high flow conditions, due to the lower historical irrigation water volumes, scenario S8a performs substantially better on stream flow and head indicator than both other scenarios at the cost of less economic benefit. The optimized allocation scenario S8c is able to substantially improve the head indicator compared to scenario S8b though keeping about the same amount of stream flow and profit. The reduction in stream flow compared to the historical allocation of 1998 (S8a) is not critical as the stream flow is still greater than the minimum flow target of 0.95 billion m^3/year at Zhengyi Station. Also here the allocation resembles the one of S6, changes are made by increasing the SW in Luotuocheng and Xinhua.

4.2.3 General remarks

The optimized allocations S7c and S8c closely resemble the allocation of S6. The sensitivity of the allocation scheme with respect to the river inflow therefore seems not to be very large. In both cases the parameter set of weights used in S6 leads to good results with respect to the indicators. The performance of the optimized allocations (S7c, S8c) seems more satisfactory than the one of the historical allocations (S7a, S8a) and the current allocation of 2010 (S7b, S8b).

4.3 Scenario S9: Time series 1997-2007

Scenario S9 showed that the controller is able to work on a time series of data. The optimized allocation performs substantially better in terms of stream flow and head indicator, at the cost of a slightly reduced profit. The residual stream flow could be significantly increased by about +150% in times of low inflow, and by about 20% in the remaining years. The extreme drawdowns could be reduced, while the biggest drawdown is of 14m in scenario S9a it is of only 6m in scenario 9b. These improvements however required a reduction in irrigation water in the range of 10-15%. The price we pay for the improvements on head and stream flow seems to be small compared to the benefits obtained from the optimized allocation regarding stream flow and drawdown. After 10 years the head values could not yet recover to a higher level than in the beginning and some declining trends still persist, but the improvement compared to using the current allocation (S9a) is considerable.

5 Conclusions

The modelling results show that the gradient ascent algorithm is successfully able to improve allocation and sourcing of irrigation water in the mid-reach of the Heihe Basin with respect to three (economic, ecological and social) indicators.

Fundamental improvements are made by increasing the amount of surface water allocated to Luotuocheng district while reducing its groundwater irrigation volumes. This allows to drastically reduce strong drawdowns in that area and therefore decrease the vulnerability to droughts of the local farming communities exposed to the risks of the declining groundwater table. By redistributing more water in the downstream districts and generally cutting down on irrigation water in the upstream districts the residual stream flow in the Heihe for downstream ecological needs can be slightly increased without changing the total amount of irrigation water and thus essentially keeping economic revenue at its current level.

The time series simulation showed that the application of the controller over a period of 10 years leads to remarkably smaller drawdowns than when using the current water allocation of 2010 (extremes at 6m instead of 14m). The controller is able to react to surface water availability and residual stream flow can be substantially increased particularly in times of surface water scarcity by up to 150%.

The three indexes have proven to react with different sensitivity to alterations of irrigation water volumes. Adequate weighting before aggregating to the objective function is required to even out these differences and produce the desired outcome. The different scenarios showed that the solution of the allocation problem most often is found to coincide with the upper or lower area constraints defined for the respective district.

The high numbers of degrees of freedom for the optimization routine requires long computation time. Convergence of the decision variables is sometimes very slow so that numerous iterations are required. When optimizing only one or two criteria the approximation the search of the optimum occurs more smoothly than in the multi-criteria-space, where sometimes competing indexes tend to fluctuate making the optimal allocation ambiguous and questionable. The overall results are to be treated with care as they are all based on a groundwater model whose quality is explicitly not investigated in this thesis. In addition we must bear in mind that the current simulations are executed for yearly time steps. To evaluate the long-term water balance one should analyse the allocation under steady-state conditions and possibly include some climate change scenarios.

The procedure of programming the MATLAB interface and coupling it with MODFLOW is a very work-intensive process but allows great freedom in the design of the evaluation and optimization of the situation compared to the use of ready-made software. The interface could thus be specifically adapted to the local conditions.

Some major improvements in the yearly allocation and sourcing of irrigation water could be identified and disclose the potential of a coordinated conjunctive use of surface and groundwater. The findings of this work should encourage the water authority to reflect on the current irrigation water allocation strategy in the mid-reach of the Heihe River Basin and consider a regional shift of the irrigation perimeters. The tool developed in this master thesis could be used to evaluate and legitimate new allocation policies by showing the improvements that can be made. The adopted approach could also be applied to other areas facing similar problems.

Of course the thesis makes a number of simplifying assumptions and these could be in a future approach be eliminated. Water saving irrigation as an alternative as well as different choice of crops would be options that should be open for optimization. The option of artificial recharge could be introduced. The perfect knowledge of the year to come, which was assumed here, should be replaced by a probabilistic approach with an estimate of summer flows from snow pack data and in order to react to flows which are different from the prediction a real time component could be introduced in the controlling system working at a smaller time step (e.g. 2 months) in real time.

6 Recommendations for further research using the model

The limited amount of time available for this master thesis leaves room for improvement and closer investigation of numerous features. Amongst these the following aspects are considered particularly interesting, there may be many others not mentioned here.

Firstly, investigations on steady state simulations would be very interesting to analyse the long term effects of some allocation schemes with respect to the overall water balance.

The recharge of the aquifer related to seepage from irrigation water is currently modelled to happen instantaneously as fix percentage of the applied irrigation water volume. It would be interesting to investigate to what extent this simplification can be justified, or whether it would be adequate to include a more complex relation (e.g. as function of time, depth, soil moisture...)

The current time horizons for decision making and for evaluation are both equal to one year. As groundwater processes do often occur exceedingly slow it should be considered to extend the evaluation time horizon in order to account for delayed impacts. Possible delays in aquifer recharge from seepage water mentioned above could for instance require longer evaluation horizons.

The inflow from the upstream catchment measured at Yangluo Station is currently assumed as deterministic prediction. This flow may be strongly influenced by the snow melt processes in the catchment, and additionally influenced by the release scheme of the upstream reservoir.

The prediction may be accurate only to some degree. It would be worth to consider stochastic distributions instead of deterministic values to get an impression on the uncertainty of the model prediction and related risk of a certain allocation scheme.

A refinement to a finer temporal resolution (e.g. seasons or months) would allow to incorporate seasonal effects. Temporal availability of irrigation water is very crucial for irrigation. A finer time scale would allow exploring new sets of solutions for the controller algorithm. It would though also bring much more complexity into the problem as the degrees of freedom of the system would drastically increase. This would require formulating additional constraints and considerably improving the controlling algorithm. The question remains whether this increase in flexibility justifies the necessary additional complexity that has to be added to the model, and whether the value of the model prediction increases.

7 Acknowledgements

I would like to express my gratitude to Prof. Dr. Wolfgang Kinzelbach for his precious support and advice and proofreading. I would also like to thank the project partners Prof. Li Xin, Dr. Zhou Jian and Mr. Chen Chong from the Cold and Arid Regions Environmental Research Institute in Lanzhou, China for their patience when answering all my questions and their helpfulness and hospitality during my visit to China. Thanks also to Corine Uhlmann for proofreading and to Jakob Anz for his inspiring ideas and comments.

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http://www.mathworks.com/matlabcentral/fileexchange/22708-spider-plot-tool

9 Appendix

9.1 Background: irrigated agriculture in the middle reach of the Heihe River Basin

This section shall give some more in-depth information about irrigated agriculture in the middle reach of the Heihe River Basin. It synthesizes knowledge gained during the site visit field trip, talks with local project partners and literature research.

9.1.1 Crops and agriculture

As can be seen on Figure 43 agriculture in the Heihe Basin consists of small scale farming. The actual size of a single field patch is often no more than 1 mu (Chinese unit, corresponds to 666.67m^2), and one person commonly cultivates up to 4-5 patches (Wang und Kinzelbach 2014). Figure 44 shows a local farmer in the Sanqing District interviewed during the site visit field trip.

78% of the total water consumption in the basin can be attributed to irrigation of the farmland of which 90% is located in the middle reach oasis (Chen, et al. 2005). The main crops are maize (80-90%) and vegetables (10-20%). The majority of the maize (about 75%) is used for seed production (Kickoff Report Heihe Project, Wang and Kinzelbach 2014). Figure 45 and Figure 46 illustrate the greenhouses used for indoor vegetable growing.

Figure 43: Agricultural fields in the Sanqing district

Figure 44: Interview with farmer from Sanqing (from left to right: Mr. Chen Chong, Dr. Zhou Jian and the local farmer)

Figure 45: Greenhouses for vegetable farming

Figure 46: Greenhouses for vegetable farming

9.1.2 Water distribution

The distribution of irrigation water occurs by means of a sophisticated dendritic channel network. Channels are mostly trapeziform-shaped profiles lined with concrete with diameters ranging from 30cm up to several meters, depending on the order of the channel. Pictures of the various channel sizes can be seen on Figure 47 to Figure 50. Through river diversions water is branched off from the Heihe main stream at different locations and routed into the different irrigation districts. A topological scheme of the main channels in the branching network is shown on Figure 8 in Section 2.2. Two main (Eastern and Western) channels branch off from a dispatcher station located on the alluvial fan shortly after the Heihe enters the middle reach (denoted as RD1 on Figure 8, location marked on Figure 2). The eastern channel distributes water in the entire eastern region (Districts Shansan, Daman, Yinke and Wujian) whereas the western channel feeds the districts of Xigan, Shahe, Ganjun and interestingly enough also the faraway district of Luotuocheng. Most of the remaining districts (central districts and lower districts) are branching off their water directly from the Heihe further downstream. The districts in the Liyuan group are branching off their water from the Liyuan stream. It is presumed that there is essentially no remaining water in the Liyuan River due to this practice. Gates for routing water into a district are operated automatically in the large channels and partly manually in the smaller channels. The amount of water to be routed is measured through the time interval between opening and closing of the gates and level in the channel.

Figure 47: Second order irrigation channel

Figure 48: First section of the east main channel

Figure 49: Small irrigation channels in the Sanqing district

Figure 50: East main channel diversion

9.1.3 *Irrigation technique*

Crops are mostly irrigated using traditional flood and furrow irrigation. This is the current practice as more advanced water saving irrigation techniques are often not affordable for the farmers. The efficiency is often poor, as large amounts of water are lost to evaporation and seepage. Water is routed to the fields about 7-9 times per year during the growing season from May to September with intervals of some weeks in between. Drip irrigation is gradually adopted especially by farmers working directly with seed companies.

9.1.4 *Groundwater irrigation*

While surface water irrigation can be seen as centralized system regulated, operated and maintained by governmental institutions, groundwater irrigation is largely decentralized. Bore wells are located within the irrigation area. They are mostly by the farmers. Recently a resource fee has been introduced of 1 Fen per cubic meter (Kickoff Report Heihe Project, Wang und Kinzelbach 2014). The implementation requires metering of groundwater use. Figure 2 shows the location of the numerous pumping and observation wells in the area.

9.1.5 *Institutional framework*

The following sections are based on the article by Chen, et al. 2005 which closely describes an assessment of the water resources in the basin. Three levels can be differentiated in the institutional framework: the decision-making level, the executive level and the user level. Decision making takes place at the State Council and the Ministries. Governmental organizations subordinate to them are in charge of the executive tasks. The Heihe River Basin Administrative Bureau (HRBAB) is responsible for development of water resources in the entire Heihe River Basin. The irrigation districts (ID) are then responsible for operation, maintenance and distribution from the main canals to the smaller branches. At local level Water User Associations (WUA) have been established for fee collection, operation and maintenance of tertiary channels. Any farmer can be member in a local WUA. More control and responsibility is being transferred from government to the non-governmental WUA, however farmers seem to be hesitant to take over responsibility from government.

9.1.6 *Water allocation scheme and pricing*

Water allocation within the district is discussed by the representatives of the respective WUAs. The request is then forwarded to the IDs which collect the requests from all the WUAs, and then to the Water Resources and Hydropower Bureau (WRHB) which finally delivers the water into the main channels. The pricing of 0.07 Yuan/m^3 set by the Water Resources and Hydropower Bureau (WRHB) cannot cover operation and maintenance costs. By subsidizing around 30-40% of the operation and maintenance costs food prices can be kept low in urban areas and compete on international markets. Fee collection takes place at WUA level, the money is then forwarded to the ID and then to the WRHB. Salaries to the members of these institutions provide incentives for the fee collection.

9.1.7 *Water markets: a pilot project in Zhangye district*

A pilot attempt to establish a water market was launched in 2002 in the district of Zhangye City. The purpose was to establish a Water User Right system with tradable quotas. Its objective was to increase efficiency through better allocation of the water and encourage water-saving activities. The government also invested in water saving irrigation systems and water meters in order to accurately monitor and charge for water and therefore encourage its economical use. Farmers would obtain water user rights (WUR) based on the size or their land.

The project was claimed to be successful with respect to the water saving and monitoring measures and irrigation water demand could be reduced. Farmers were however still reluctant to trade their WUR and a real water market could not establish. The study conducted by Zhang (2007) points out a number of problems. Firstly, the farmers had to completely use or sell their water quotas every year as they were not refundable. Another issue was that groundwater withdrawal could not be monitored, and many farmers just reduced their surface water use at the cost of more groundwater pumping, which lead to drying up of wells and shrinking of oases. Generally the findings were that management, legal, administrative and fiscal barriers to WUR trading were stronger than geographical, technical and cultural barriers.

9.1.8 Real time monitoring, modelling and controlling project

A new project is currently being initiated by ETH Zürich (Switzerland) in cooperation with partners at CAREERI (China), HydroSolutions GmbH (Switzerland), GEOPRAEVENT AG (Switzerland). It aims at preventing further decline of the water table in the district of Luotuocheng where in recent years excessive groundwater pumping activities have lowered the water table by up to 20m (Zhou, Wang, et al. 2014). Pumping wells are currently being equipped with an electronic metering and controlling system which allows the farmers to extract a predefined quota of water using an IC-card. Knowledge about the consumed electricity can be used as a further instrument estimate and verify the pumping volumes. Monitoring data would be automatically transferred to a control centre. A decision support system would allow optimally allocating the irrigation water quotas in order to maintain and even try to recover groundwater level. The project is currently in its starting phase. If it proves to be successful it could be implemented in the entire basin in a second step.

9.1.1 Current irrigation water volumes and depth

Figure 51 shows district-wise the amount of surface water, groundwater and total irrigation water (sum of the two) per unit area applied. The exact values can be read off from Table 5. The values are computed by dividing the irrigation water volumes of the year 2010 by the irrigated agricultural area of the respective district. This area does not correspond to the entire district area as may be suggested by the figures, but strictly to the area where irrigation is applied (see Figure 10).

Most districts seem to apply more surface water than groundwater. There is no clear spatial pattern visible to explain the different values of the individual districts. In Luotuocheng district, however, the opposite is the case. Data suggests that no surface water is currently used and all irrigation water is sourced from the aquifer. It is known that some surface water is infiltrated during winter in order to recharge the aquifer. Besides Luotuocheng, the eastern districts including Xigan on the western side of the Heihe main stream seem to apply slightly more groundwater than the remaining districts.

If we trust the data, we note that the quantity of total irrigation water applied per unit area also differs from district to district. Possible reasons could be for instance different crop types, different irrigation efficiencies or different groundwater depth. Zhou, Wang, et al. (2014) refer to different irrigation water requirements for maize and wheat, and lower water use efficiencies for districts with crop interplanting.

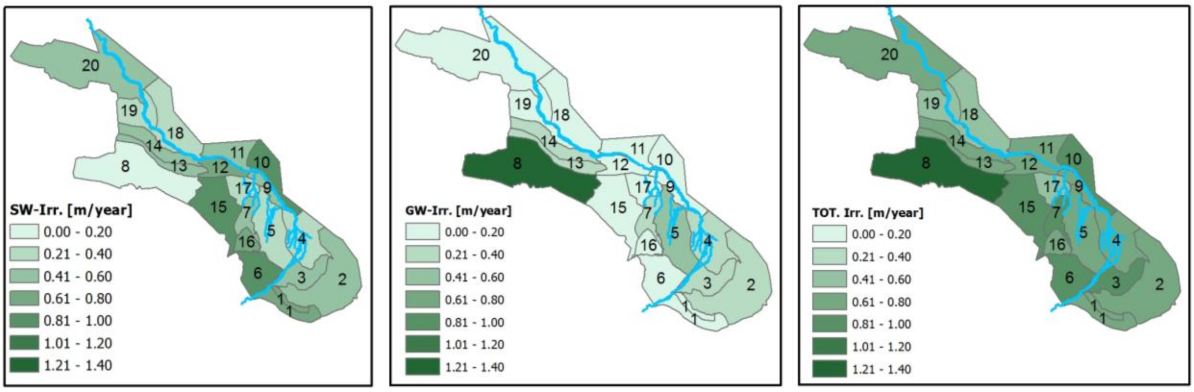

Figure 51: Amount of surface water (SW), groundwater (GW) and total irrigation water (TOT) applied in the year 2010 (Source: CAREERI)

Table 5: Irrigation water quantities applied in the year 2010 (Source: CAREERI)

District name	Nr.	District area [km^2]	Percent of total area [%]	Irrigation Volume [m^3/year			Irrigation Amount [m/year]		
				SW	GW	Tot.	SW	GW	Tot.
Shangsan	1	109	4.7	7.8E+07	1.2E+06	7.9E+07	0.72	0.01	0.73
Daman	2	333	14.3	1.4E+08	1.2E+08	2.6E+08	0.42	0.35	0.77
Yingke	3	176	7.6	9.9E+07	6.3E+07	1.6E+08	0.56	0.36	0.92
Wujiang	4	229	9.8	6.9E+07	7.7E+07	1.5E+08	0.30	0.34	0.64
Xigan	5	270	11.6	9.0E+07	1.1E+08	2.0E+08	0.33	0.40	0.74
Ganjun	6	102	4.4	8.4E+07	6.3E+05	8.5E+07	0.82	0.01	0.83
Shahe	7	51	2.2	2.6E+07	1.7E+07	4.3E+07	0.51	0.33	0.84
Luotuocheng	8	69	3.0	0.0E+00	9.6E+07	9.6E+07	0.00	1.40	1.40
Yanuan	9	49	2.1	2.9E+07	8.6E+06	3.7E+07	0.58	0.18	0.76
Banqiao	10	101	4.3	8.4E+07	2.5E+06	8.7E+07	0.83	0.02	0.86
Pingchuan	11	93	4.0	5.1E+07	1.7E+07	6.9E+07	0.55	0.19	0.74
Liaoquan	12	51	2.2	3.3E+07	6.6E+06	4.0E+07	0.66	0.13	0.79
Sanqing	13	87	3.7	4.7E+07	1.8E+07	6.4E+07	0.54	0.20	0.74
Youlian	14	119	5.1	5.1E+07	3.0E+07	8.2E+07	0.43	0.25	0.69
Xinhua	15	123	5.3	9.8E+07	5.9E+06	1.0E+08	0.80	0.05	0.85
Nijiaying	16	43	1.8	2.8E+07	0.0E+00	2.8E+07	0.65	0.00	0.65
Xiaotun	17	81	3.5	2.5E+07	8.1E+06	3.3E+07	0.31	0.10	0.41
Liuba	18	46	2.0	1.7E+07	7.8E+06	2.4E+07	0.36	0.17	0.53
Dahuwan	19	93	4.0	3.3E+07	1.1E+07	4.4E+07	0.36	0.12	0.47
Luocheng	20	101	4.3	5.8E+07	1.5E+07	7.3E+07	0.58	0.15	0.72
Area weighted average				7.5E+07	5.0E+07	1.3E+08	0.49	0.26	0.75

9.1 Model architecture

The controller is programmed in MATLAB using object oriented language. This allows keeping the overview over a large set of variables and methods, and efficiently passing on variables and functions between the different subroutines. As a principle this MATLAB code could also be applied to other groundwater models, it is however tailor-made for the current Heihe MODFLOW model and a number of alterations would have to be made to the code for application to other cases. The Graphical User Interface (GUI) captures the different user settings and then runs the "MAIN_file.m" script. After computation it applies the plotting functions contained in the "class_plotter_GUI.m" file to generate the respective plots. The "MAIN_file.m" script linearly executes a number of encapsulated scripts that deploy methods declared in the class files. A brief description of the class-, script- and function definition files is given Table 6

Table 6: Main class definition files, functions and scripts written for the model found in the "matlab_folder" on the DVD attached to this report.

Class definition files	
class_BS.m	Properties: general settings Methods: setting of directories, computation of zoning matrices
class_con.m	Properties: controller variables Methods: relevant methods for gradient ascent algorithm
class_DV_all.m	Properties: contains the historical input data Methods: none
class_eval.m	Properties: evaluation parameters, ranges, weights Methods: computation of indicators and indices
class_plotter_GUI.m	Properties: plotting font type and font size Methods: various plotting functions
class_processing.m	Properties: none Methods: functions used to pre/post process data
class_reader_writer.m	Functions to read out and write MODFLOW output and input data.
class_state.m	Properties: relevant results of a single MODFLOW run Methods: minor operations executed on result variables
class_state_eval.m	Properties: evaluation results of a single MODFLOW run Methods: none
class_various_funct.m	Properties: none Methods: various methods that cannot be attributed to any other class
Scripts & functions	
Data_district_vertices.m	Vertices of all districts, required for plotting thematic maps
data_p1.m	Historical water allocation and river flow data
GUI.fig	Figure file for the graphical user interface
GUI.m	Main file for the Graphical User Interface
M_controller.m	Performs optimization by using the gradient ascent algorithm.
M_delete_files.m	Before running, the simulation deletes old output files, so that in no case these might be misunderstood as being current simulation results.
M_Evaluator......m	Various functions used to evaluate the results of the different scenarios.
M_post_process.m	Reads out simulation results, computes depth and drawdown as well as stream flows.
M_pre_process.m	Processes recharge, well and stream data according to the decision variables.
M_reset_files.m	Resets basic files, recharge file, stream flow file
M_runner.m	Pre-processes the data, runs MODFLOW, post processes the data, computes indicators and indices and the objective function and spatial maps of the parameters (later required for the plots).
MAIN_file.m	Main executing file, initializes variables, sets directories, loads input data, deletes old data ("M_delete_files.m")
MAIN_file_runner.m	This file can be used to manually run the simulation without using the graphical user interface.
Spider.m	Function by Michael Arant used to create the spider plots

A more detailed overview on the different computational steps and the hierarchical employment of those scripts and classes is illustrated in Figure 52.

9.1.1 Running the model

In order to run the model, first copy the entire folder named "Model" provided on the DVD included at the end of this report onto the local drive. Running the model requires the installation of MATLABr2014a. Open the subfolder "Coupled_Model\matlab_folder" as your current directory in MATLAB, then run the script GUI.m to open the graphical user interface.

If you don't have MATLABr2014a installed, it is still possible to run the model by first installing the Runtime environment "MyAppInstaller_mcr" which is free and included on the DVD in the folder "MRC". After successful installation run the file "Heihe_control_Model_V1.exe" which can be found in the subfolder "Coupled_Model\matlab_folder" from your windows file explorer.

The subfolders contain the following data:

- input_data_folder: Input data for the model (actually not used anymore as the input data is now in the "matlab_folder")
- matlab_folder: all main matlab files
- model_folder: MODFLOW model files
- modeldata_folder: other relevant data used in the computations
- modeldata_reset: files used to overwrite other files contained in the "model_folder"
- modflow_folder: MODFLOW2005 exe file.

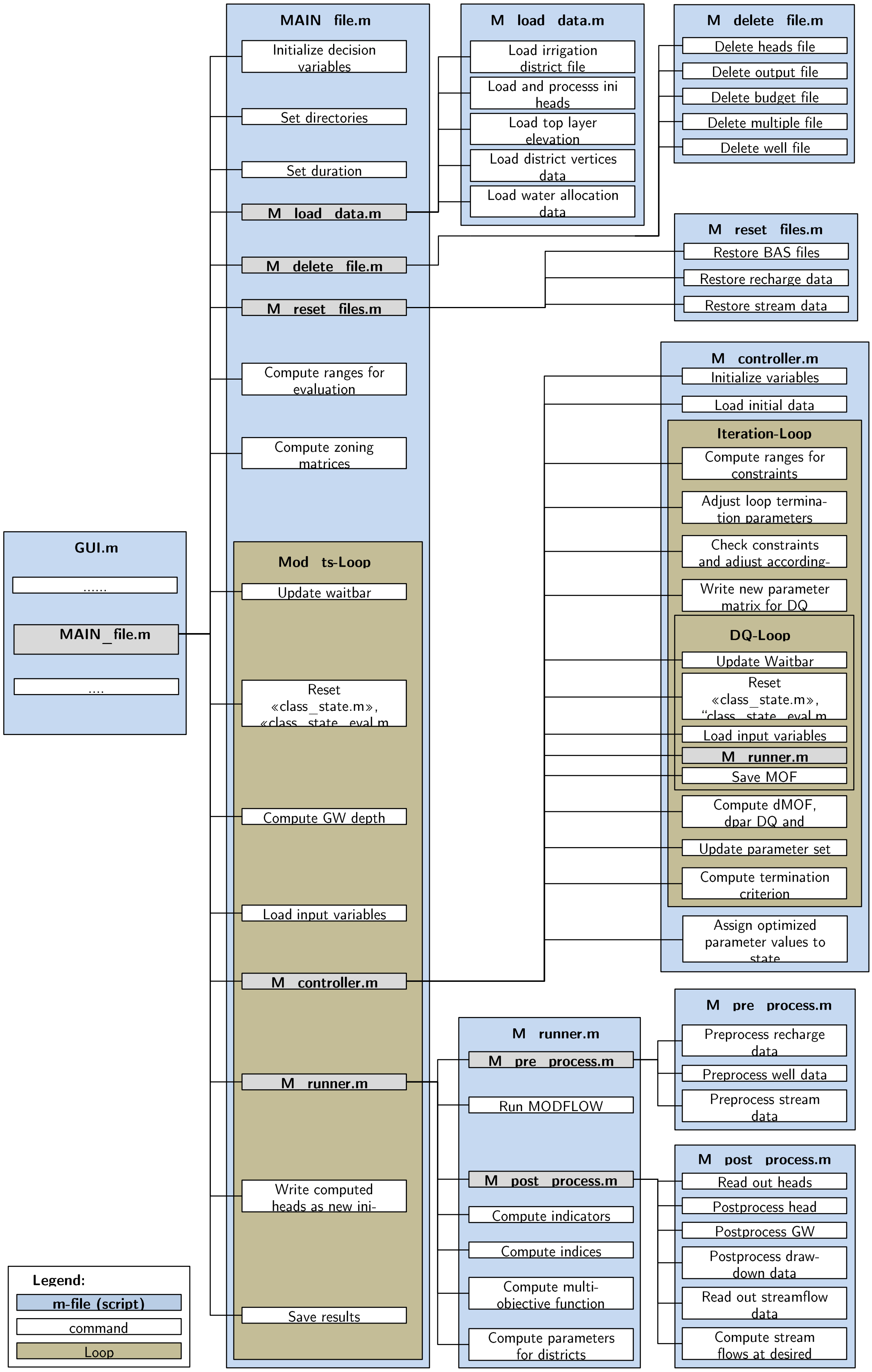

Figure 52: Model architecture

9.2 Graphical User Interface (GUI)

As the evaluation of a model outcome requires the comparison of a large number of different variables, a graphical user interface was developed. This allows quickly switching between different plots and at the same time keeping an overview of the current settings. After a successful model run the results are routinely saved into a new subfolder named after current date and time of the simulation execution. To open a previously saved model result, click the "Load" pushbutton and select the "simulation_result_variables.fig" file in the respective subfolder. The "simulation_result_variables.mat" contains an array with all the variables displayed in the figures. When this file is loaded in MATLAB the simulation results' matrices can be accessed in the "handles.m"-structure. A more detailed description of the GUI is given in the Appendix

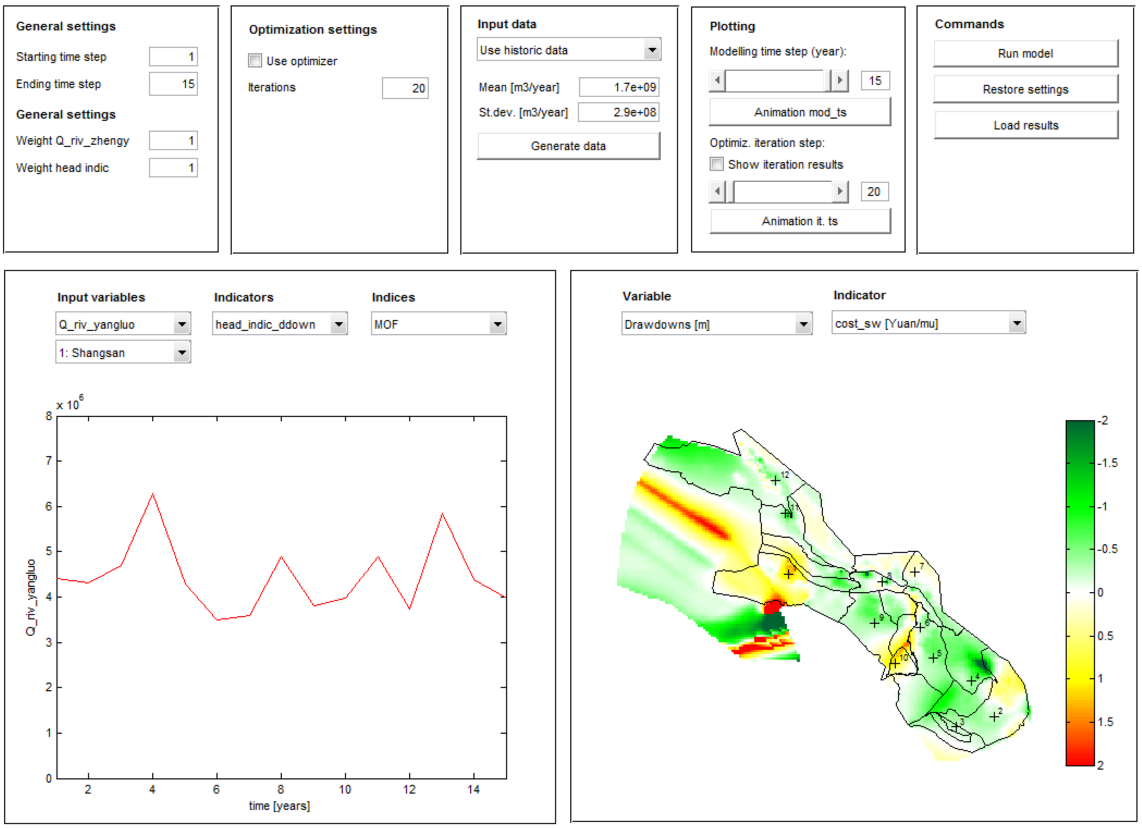

Figure 53: Graphical user interface

9.3 Detailed description of the Graphic User Interface (GUI)

9.3.1 Control panel

The control panel contains the main settings for simulating and plotting as well as some command buttons. Most of them are self-explanatory, the following section gives a brief description of each one.

9.3.1.1 General settings

Edit text "Starting time step": time step when simulation should begin. This is only of relevance when using the historic data as input data as otherwise a new stochastic series is generated and the starting time step may not be of particular interest. Note that historic data is only available for 27 years, so when using historic data the value shall be a positive integer in the range of 1 to 27.

Edit text "Ending time step": time step when simulation shall be terminated, this value must be greater than or equal to the starting time step value. When using historic data this value shall not be greater than 27, as there is not historic data available beyond that point. To optimize only one single time step set the value equal to the starting time step value.

Edit text "Weight Q_riv_zhengyi indic.": this indicates the weight assigned to the Q_riv_zhengy indicator. Ensure this is a positive real number. Consult the section regarding definition of the multi-objective function for detailed description

Edit text "Weight head indic.": this indicates the weight assigned to the head indicator. Ensure this is a positive value. Consult the section regarding definition of the multi-objective function for detailed description. The sum of both indicator weights should not exceed 1.

9.3.1.2 Optimization setting

Checkbox "Use optimizer": click this tick box to enable the optimizing algorithm. This is required when evaluating a generated input data series. If disabled, the model will automatically use historic data

Edit text "Iterations": specify the number of iterations to be performed.

9.3.1.3 Inflow data

Popup menu "historical data": select whether to use historical data or generated data as input. When using generated data the optimizer has to be switched on, as the decision variables are then not a-priori known.

Edit text "Mean" and "St.dev": statistical properties of the random generated inflow data series.

Pushbutton "Generate data": this generates the inflow data using the statistical properties described previously.

9.3.2 Plotting

Edit text "Modelling time step (year)": define which time step should be plotted on the figure(s). The value should be in the range defined previously in the general settings.

Scrollbar: Click to toggle between different time steps.

Pushbutton "Animation mod_ts": use this button to generate a quick slideshow-movie of the plots for the different modelling time steps (mod_ts) to better visualize the temporal evolution of specified parameters.

Checkbox "Show iteration results": use this button to switch between the iteration results within one single time step and the results of the overall temporal evolution over the modelled time steps.

Edit text "Optimiz. iteration step": define which iteration step should be plotted on the figure(s). The value should be a positive integer smaller or equal to the iteration number.

Scrollbar: click to toggle between the different iteration steps.

Pushbutton "Animation it_ts": use this button to generate a quick slideshow-movie of the plots for the different iteration steps to better visualize the evolution of specified parameters during the iteration procedure.

9.3.3 Commands

Pushbutton "Run model": click to start the simulation. A general check for errors will be performed in the beginning.

Pushbutton "Restore all": reset all settings to default values.

Pushbutton "Load results": opens a file browser which allows selecting a previously generated model figure (".fig"). After each successful model run the results are automatically saved in a subfolder named after the date and time of its execution.

9.3.4 Figure Panel (left side)

9.3.4.1 Input variables

First popup-menu: plot surface water or groundwater irrigation volumes for all 20 districts or the inflow at Yangluo Station.

Second popup-menu: plot irrigation volumes district-wise.

9.3.4.2 Indicators

Popup-menu: select which indicator to plot. Besides the three indicators used to compute the objective function one can also visualize the cost and the area corresponding to the current irrigation scheme.

9.3.4.3 Indexes

Popup-menu: visualize the computed indexes.

9.3.5 Figure Panel (right side)

9.3.5.1 Variables

Popup-menu: visualize the spatial distribution of different model parameters.

9.3.5.2 Indicators

Popup-menu: visualize the spatial distribution of different indicators.