Optimizing conjunctive use of surface water and groundwater for irrigation in arid and semi-arid areas: an integrated modeling approach

Xin Wu*, Bin Wu ,Yi Zheng, Yong Tian, Chunmiao Zheng

College of Engineering, Peking University, Beijing 100871, China; *E-mail: wuxin31911@163.com

Background

- Conjunctive use of surface water (SW) and groundwater (GW) for irrigation is critical to water and food security in arid and semi-arid areas.
- Simulation-optimization (SO) analysis is desired by water resource management, but hardly applicable for complex integrated SW-GW models.
- This study adopted a surrogate-based approach to optimize the conjunctive use of SW and GW in the Zhangye Basin (northwest China) based on integrated SW-GW modeling.

Study area and hydrological model

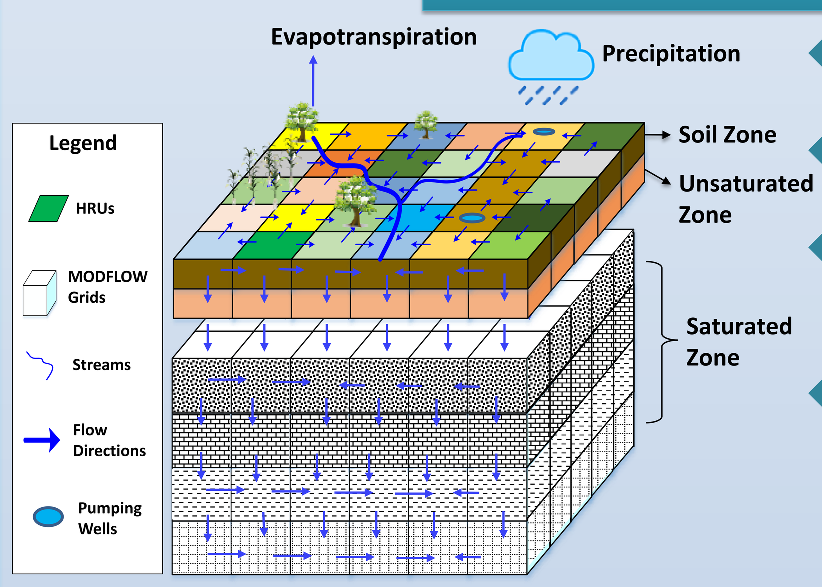

Fig. 1 Model structure of GSFLOW

- **Zhangye Basin** (ZB) is the midstream part of Heihe River Basin (HRB).
- Farmlands in ZB consumes 90% of the total water supply in this area.
- Environmental flow regulation has been implemented for the main Heihe River, based on a water allocation curve (Fig. 3), and stimulated the groundwater pumping in ZB.
- A GSFLOW (an integrated model developed by USGS) model has been established for ZB (104 sub-basins; 588 HRUs; five subsurface layers with 9,106 active MODFLOW cells, 1km×1km, in each; 01/01/2000-12/31/2008).

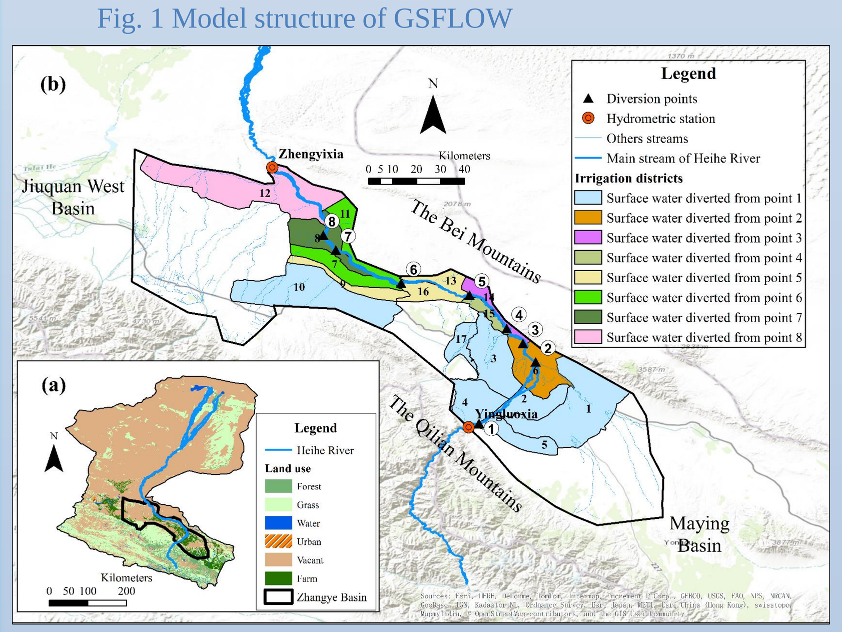

Fig. 2 The study area: (a) Heihe River Basin; (b) Zhangye Basin, midstream of HRB, irrigation districts and 8 diversion points.

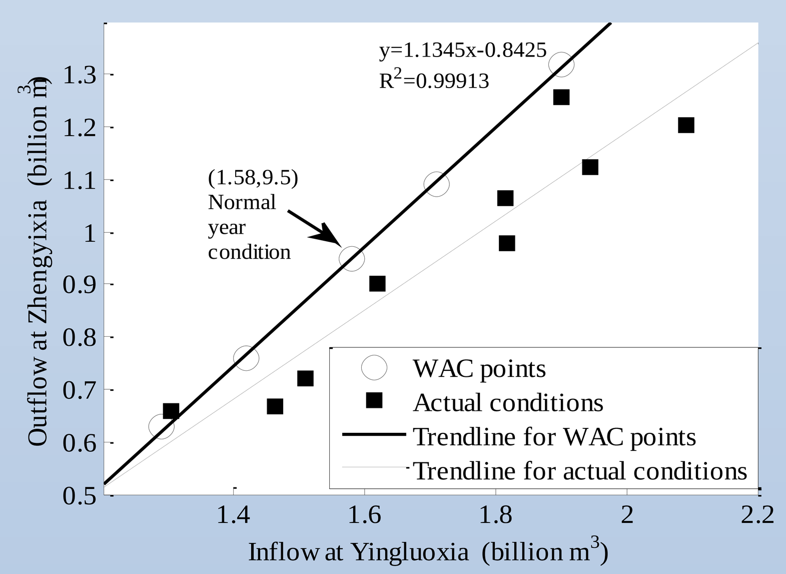

Fig. 3 Water allocation curve (WAC)

Optimization scheme

- **Basic assumptions**: 1) the total irrigation demand of each irrigation (estimated from historical data) is met; 2) GW is applied to adjacent fields and subjects to little seepage and ET losses.
- **Decision variables** (**X**) : proportions of surface water (from 8 diversion points along the main river) in total irrigation water. In **spatial** optimization, **X** is a vector of the 18 districts (Fig. 2). In **temporal** optimization, **X** is a vector of 12 months.
- **Objective function**: maximizing the annual saturated storage change (ΔS).
- **Major constraints**: 1) the environmental flow limit at Zhengyixia is met ($R \geq R_0$, see Table 1); and 2) amount of water diversion does not exceed the available flow at the diversion points (Q_{ik}).

$$\max_{\mathbf{X}} \Delta S(\mathbf{X})$$
$$s.t.$$
$$R(\mathbf{X}) \geq R_0$$
$$\sum_{j=1}^{18} z_{jk} d_{ij} \leq Q_{ik}, \forall i,k$$

Table 1. Optimization scenarios with different flow limits and irrigation demands. Scenario A's represent "no-flow-decrease" situation, and Scenario B's represent the WAC regulation situation.

Flow limit R_0	Actual Demand	10% reduction	20% reduction	30% reduction
Current flow	A1	A2	A3	A4
WAC	B1	B2	B3	B4

Where d_{ij} denotes the surface water diversion for i_{th} district in j_{th} month, and z_{jk}=1 is the indication that the j_{th} district is served by k_{th} diversion point, otherwise z_{jk}=0.

Algorithm

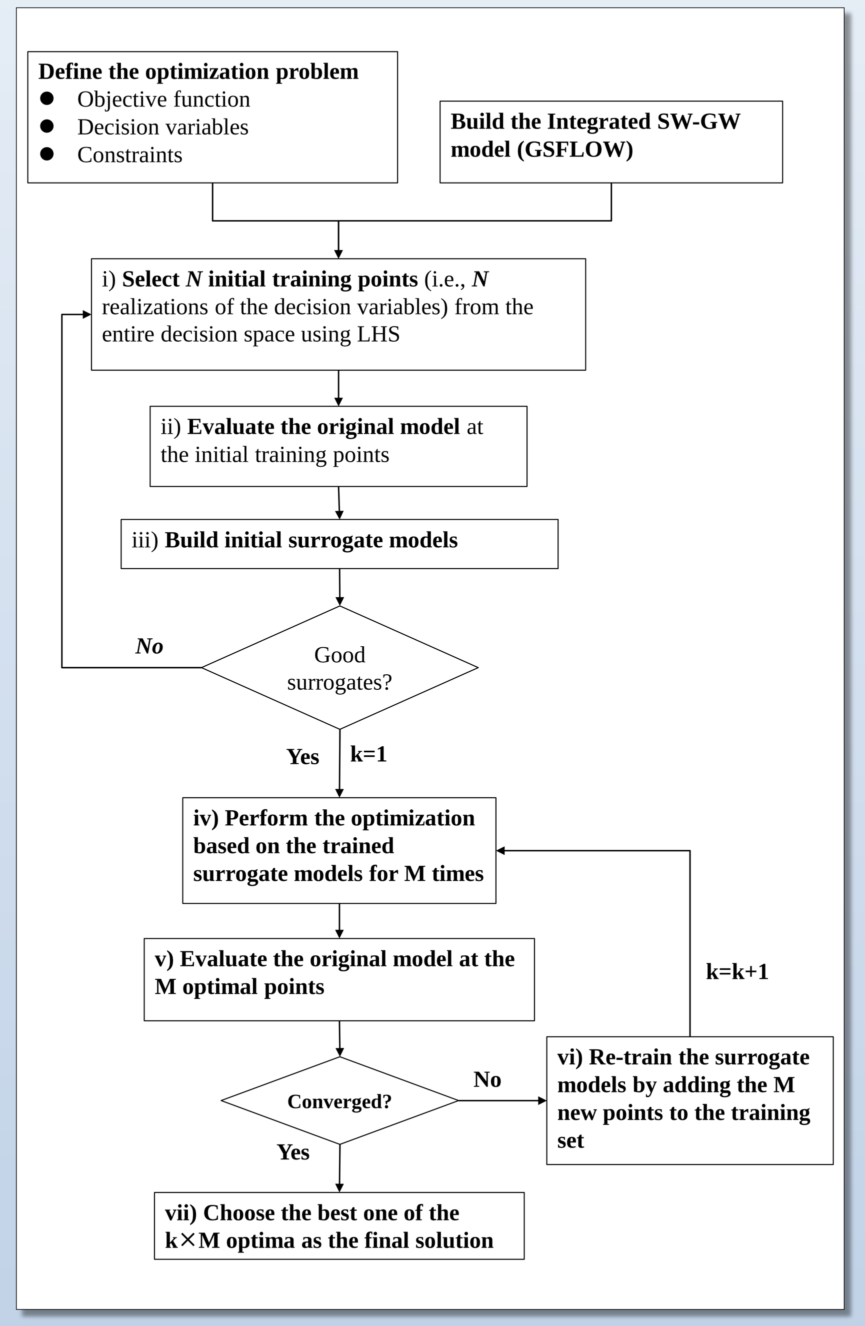

Fig. 4 Flow chart for SOIM

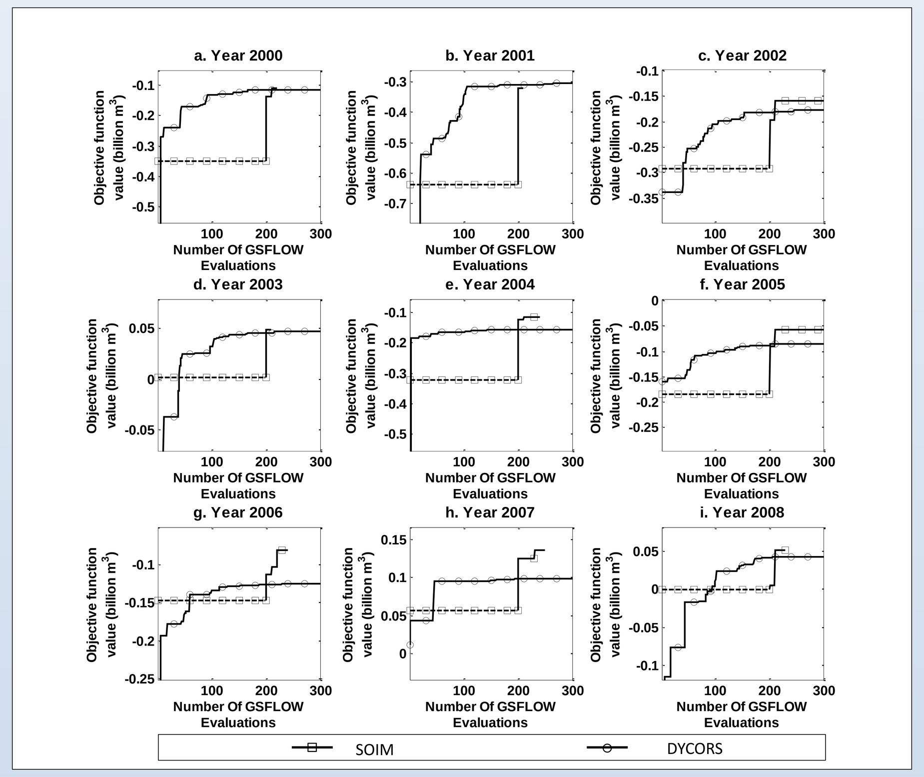

Fig. 5 Evolution of the objective function value during the spatial optimization by both SOIM and DYCORS, Scenario A1. The dashed portion of the SOIM curves represents the 200 initial training runs of GSFLOW.

- DYCORS (Regis and Shoemaker, 2005) was applied in both spatial and temporal optimizations.
- A new surrogate-based optimization approach, named SOIM (Wu et al., 2015) , was developed and compared with DYCORS in the spatial optimization.
- Both approaches are effective and efficient in dealing with the time-consuming global optimization.

Major Results

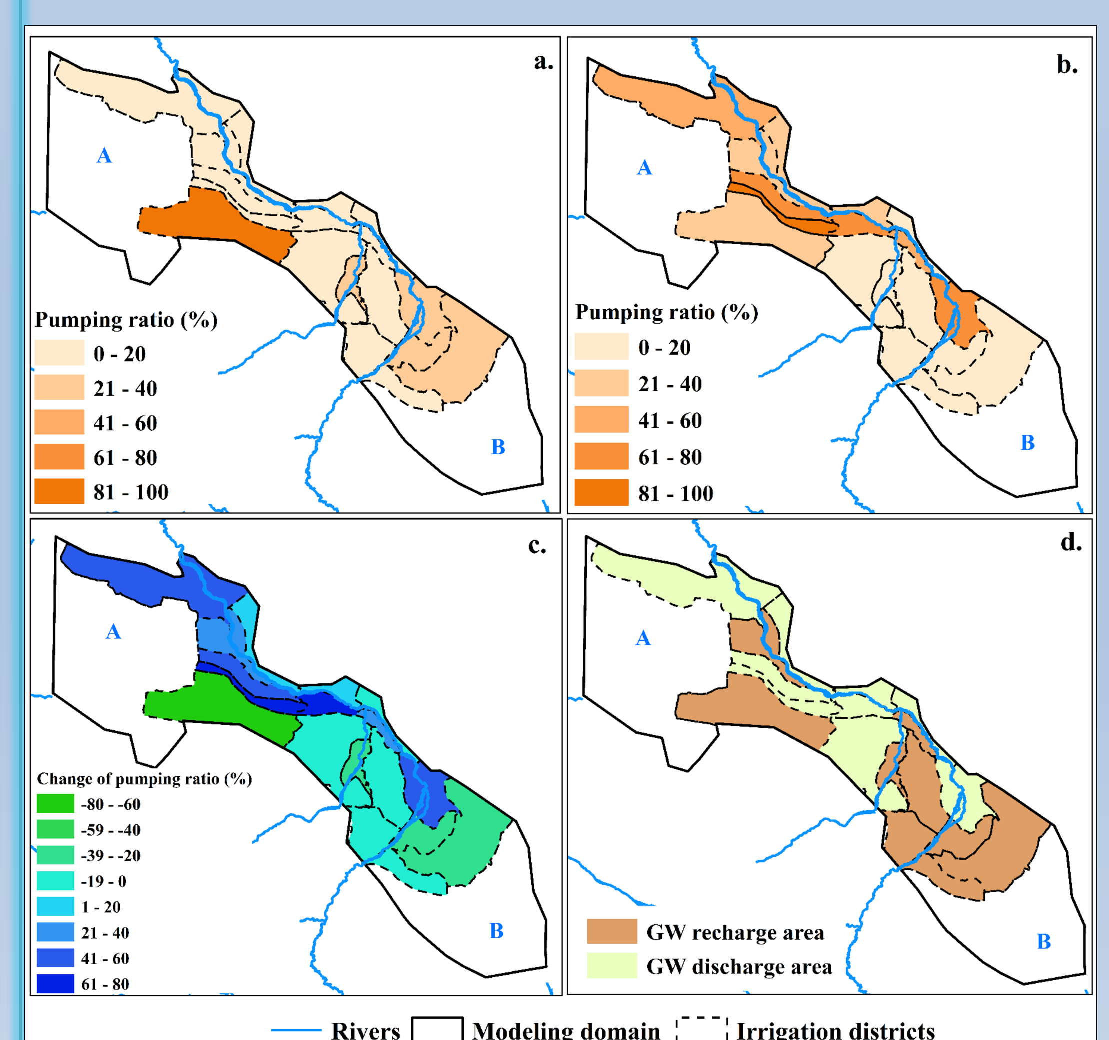

Fig. 6 Spatial patterns of the pumping ratios at the 18 irrigation districts. (a): actual pumping ratios in year 2002; (b): optimized pumping ratios for Year 2002 in Scenario A1; (c): change of the ratios after the optimization; (d): distribution of groundwater discharge and recharge areas.

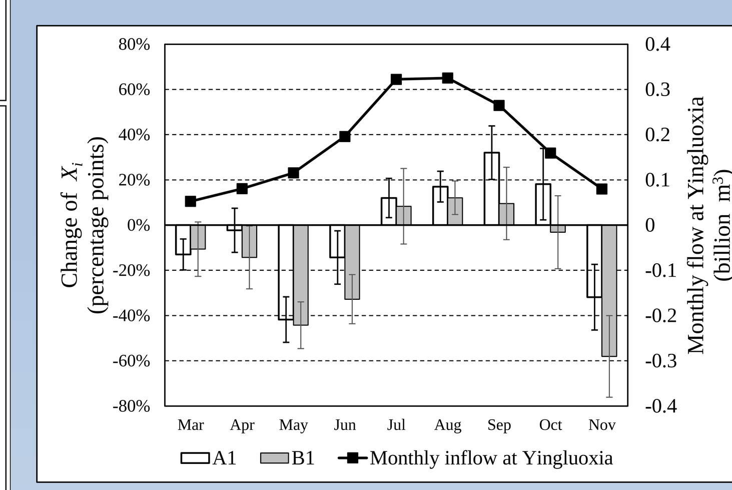

Fig. 7 Changes of the surface water percentages (X_i) before and after the temporal optimization. Other scenarios demonstrate the same pattern.

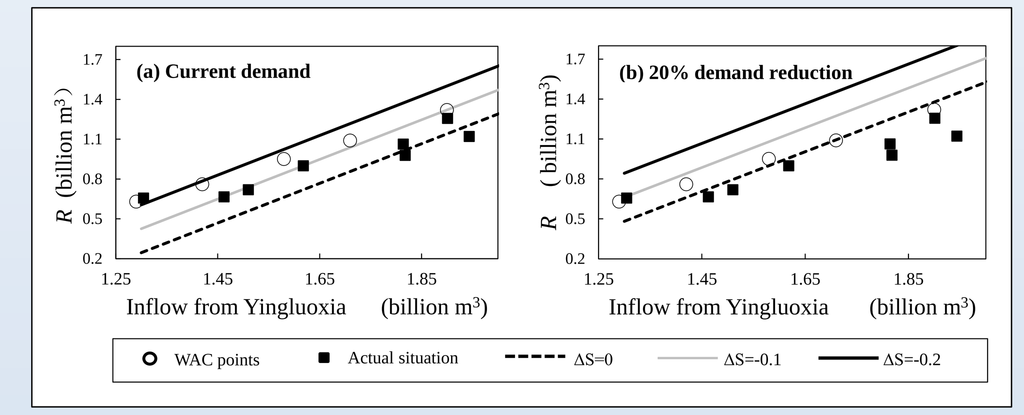

Fig. 8 Optimized relationships between the outflow R and the inflow (a) considering the current irrigation demand; and (b) 20% demand reduction.

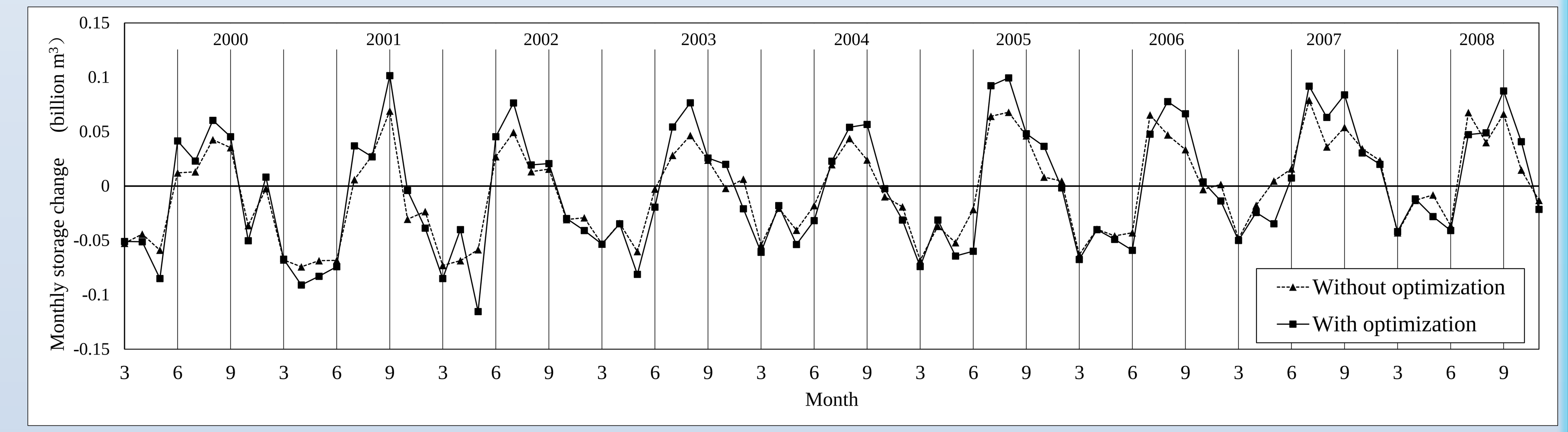

Fig. 9 Monthly saturated storage changes with and without the optimization in temporal optimization, Scenario A1.

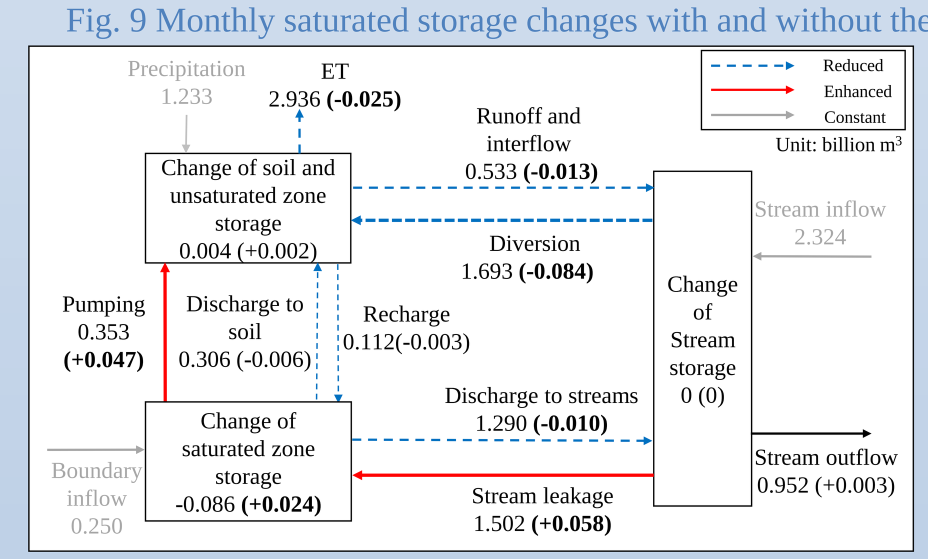

Fig. 10 Comparison of water budget of non-optimized and optimized situation of A1 in temporal optimization, as an average of the 9 years. Surface water diversion is partly replaced by 'Stream leakage-pumping' path to avoid unbeneficial ET. In this process the aquifer behaves like an reservoir that stores water in flood season and releases water through pumping in dry seasons.

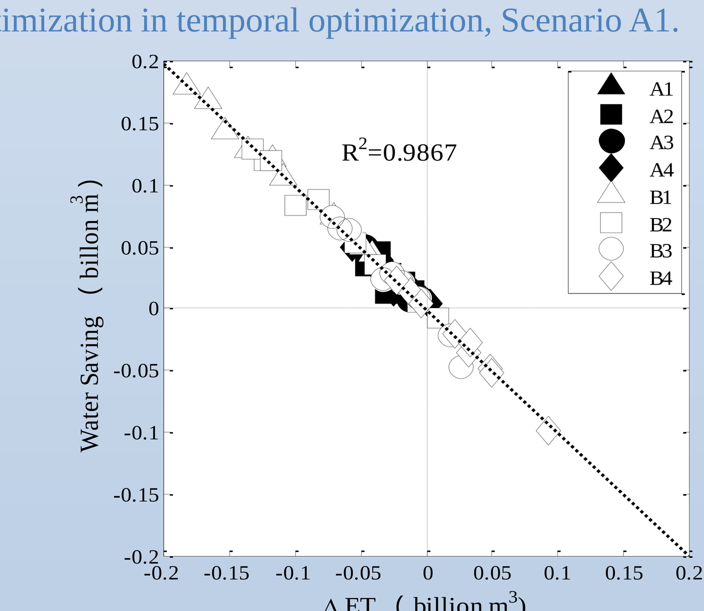

Fig. 11 ET and water saving of all the 72 cases (9 years, 8 scenarios) in temporal optimization. Water saving is defined as the change of (ΔS+R) after optimization. The points are almost on the 1:-1 line, and the nuance comes from slight change of soil and unsaturated zone.

Conclusions

- The surrogate-based approaches are promising.
- Optimized conjunctive use of groundwater and surface water can lead to reduction of non-beneficial ET and save water resources at the basin scale.
- It has been suggested that, in ZB, SW diversion could be enhanced in the flood season and reduced in the dry season. Spatially, GW pumping could be increased in groundwater discharge zones.
- If the current water management regime persists, at least a 20% reduction of irrigation demand is necessary to meet the WAC limits, which is a challenge to the food and water security of ZB.

References

- Regis, R.G., Shoemaker, C.A., 2005. Constrained global optimization of expensive black box functions using radial basis functions. Journal of Global Optimization 31, 153-171.
- Wu B., Zheng Y., Wu X., Tian Y., Han F., Liu J., Zheng C.,2015.Optimizing water resources management in large river basins with integrated surface water-groundwater modeling: a surrogate-based approach. Water Resources Research. (*in press*)

Acknowledgement

We'd like to thank Dr. Juliane Mueller and Christine A. Shoemaker for providing us her Matlab code of DYCORS. We are also grateful to the support from the National Natural Science Foundation of China (NSFC) (No. 91125021; No. 91225301; No. 41371473). The data set was provided by Cold and Arid Regions Science Data Center in Lanzhou, China (http://westdc.westgis.ac.cn)