XVIII World Water Congress
International Water Resources Association (IWRA)

IWHR

黑河流域水-生态环境-社会经济耦合模拟及互馈关系研究

Water-Ecology-Economy Nexus in Endorheic River Basin under Changing Environment

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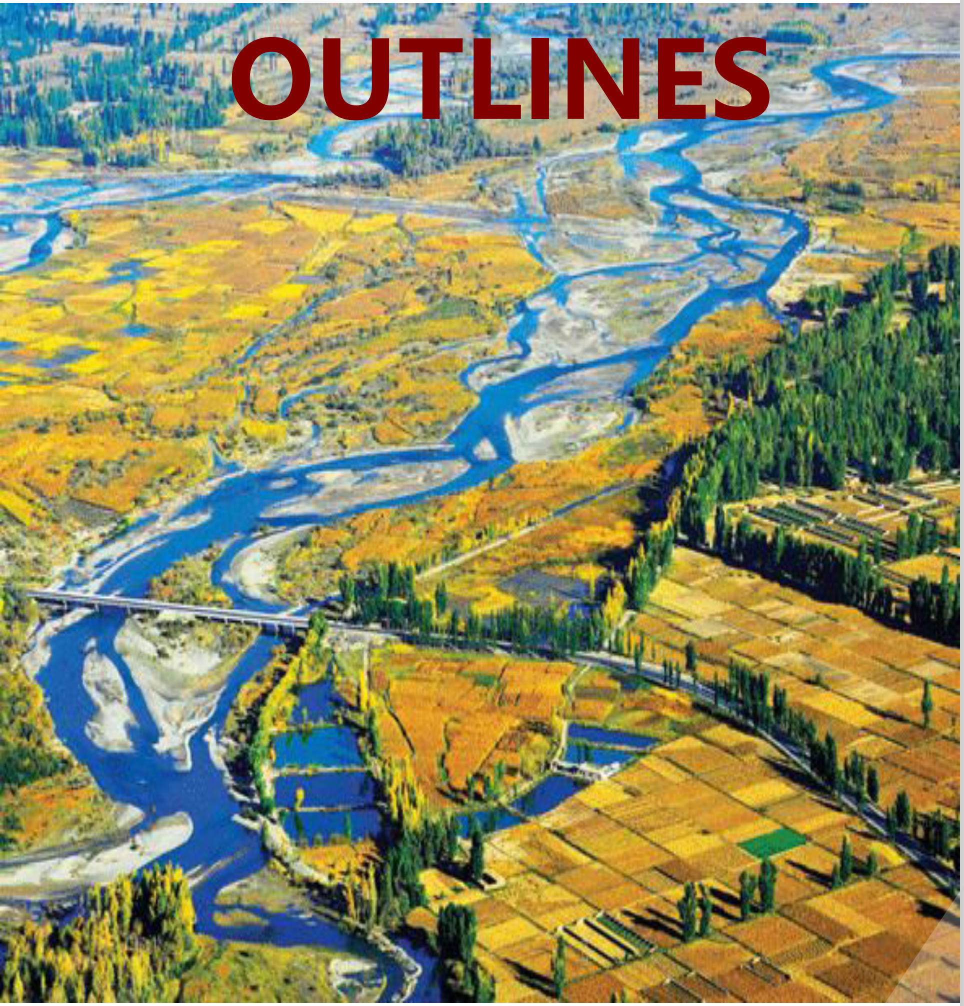
OUTLINES



01 Introduction

02 Methodology

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04 WES Nexus under changing environment

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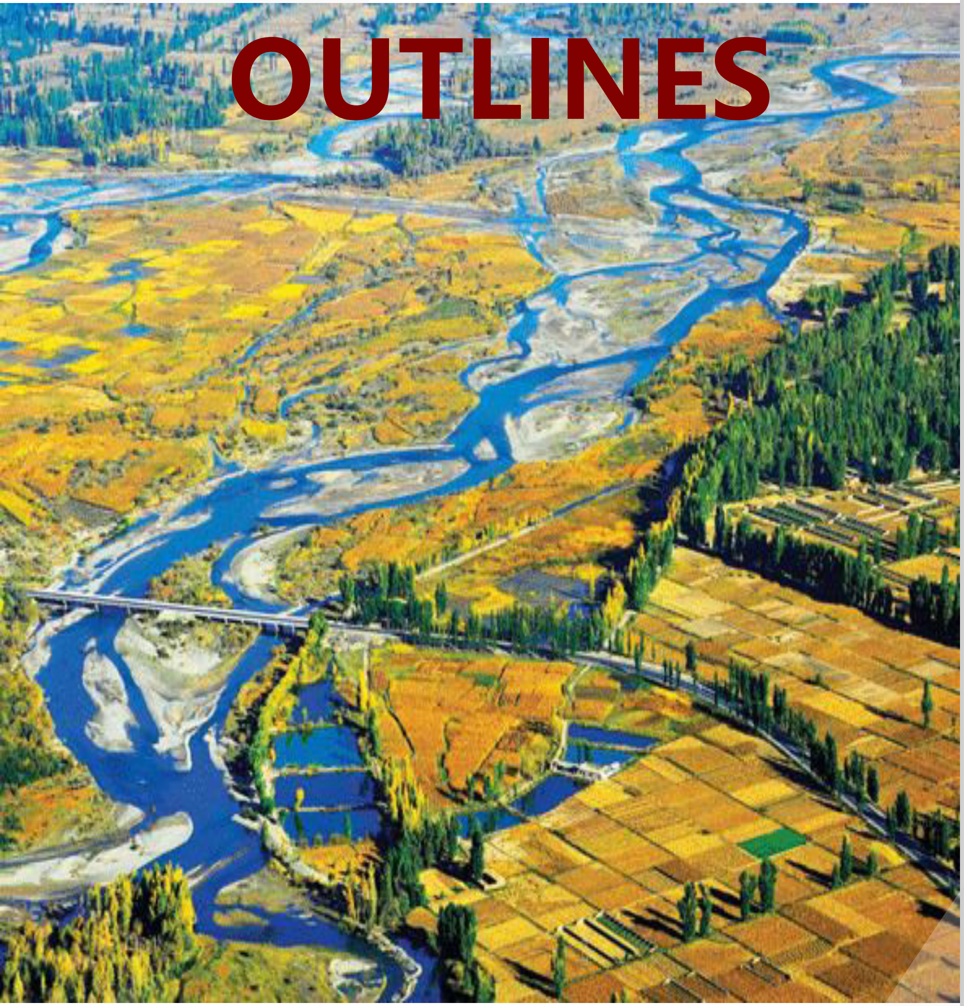
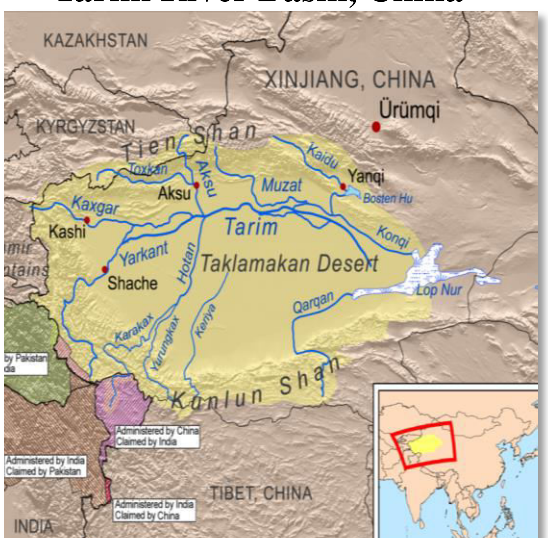


Background

Volga River Basin, Russia

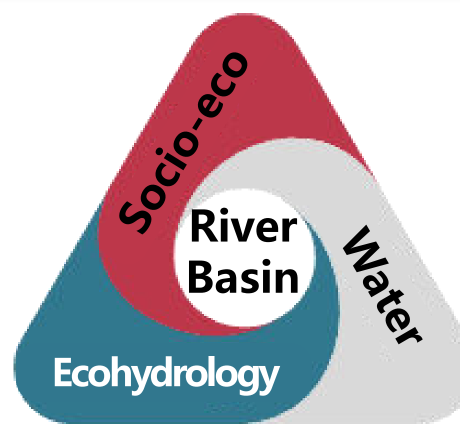
Amu Darya River Basin, Central Asia

Tarim River Basin, China



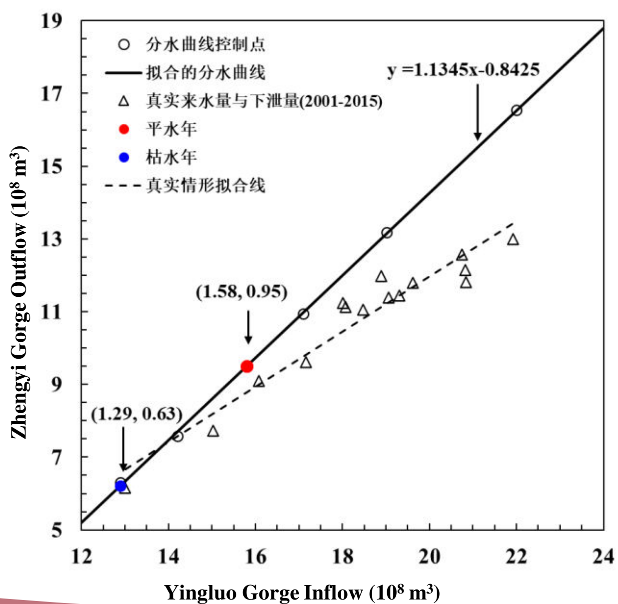
RS of Aral Sea, 2000-2018

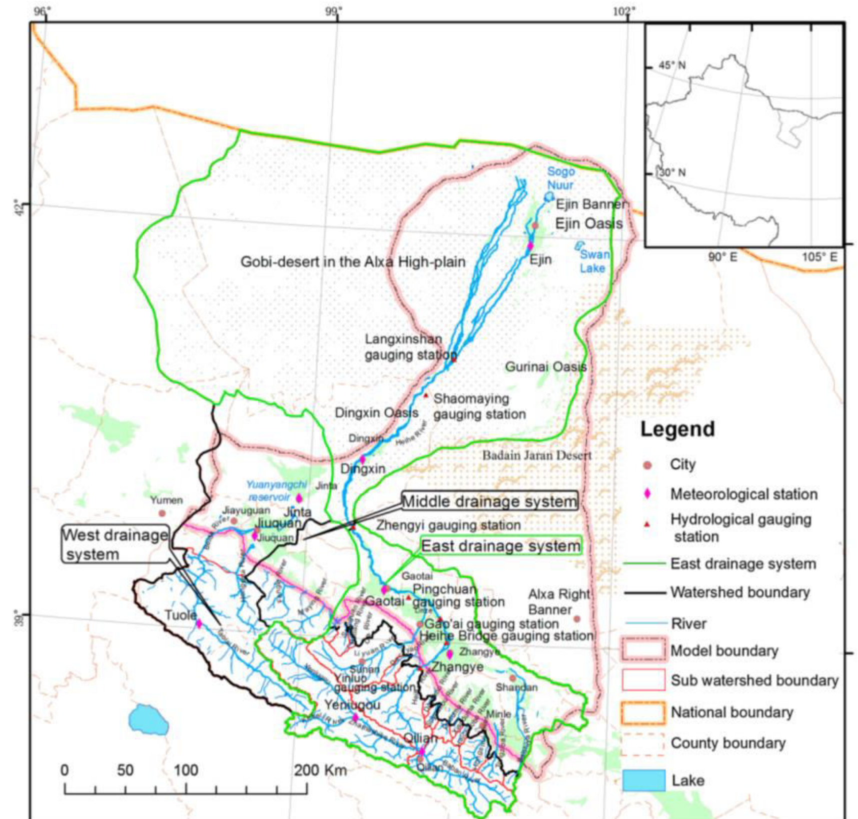
- ☐ The impact of **climate change** and **human activities** has caused rapid changes in the natural water cycle.
- ☐ **Endorheic river basins** worldwide are characterized by a pervasive balance between ecology, environment and economic development.
- ☐ The Aral Sea was once the fourth largest lake in the world, and recently its volume has decreased by **almost 85%**.

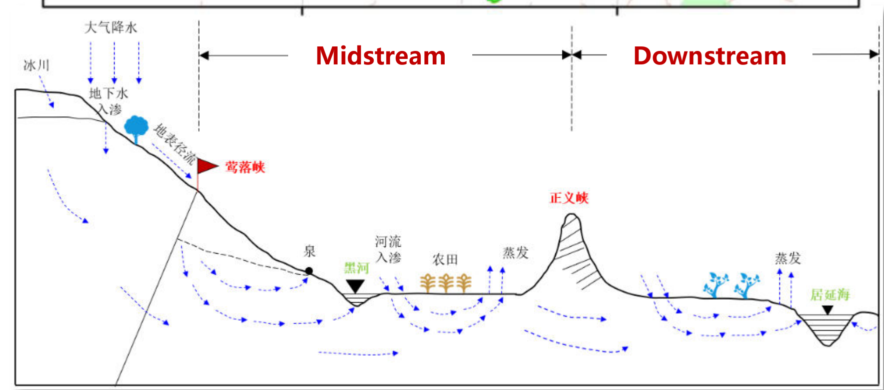


Background (Heihe River Basin)

- China's **second largest endorheic river**, with a total area of about 130,000 km^2;
- The upper and middle reaches of the basin are bounded by **Yingluo Gorge**, and the middle and lower reaches are bounded by **Zhengyi Gorge;**
- Large-scale agricultural irrigation activities in the midstream;
- Conflict of ecological water demand in the downstream;
- Ecological Water Diversion Project (EWDP).







Background (SDGs)

River basin management & SDGs:

- SDG 6.5: Implement integrated water resources management at all levels;
- SDG 6.6: Protect and restore water-related ecosystems;
- SDG 13.2: Integrate climate change measures into national policies, strategies and planning.

Background (nexus)

Table 1 | Nexus examples and direct relationships to SDGs

Nexus example	SDGs
Food-energy-water nexus[32]	2, 7, 6
Water-food-energy-climate nexus[128]	6, 2, 7, 13
Food-energy nexus[129]	2, 7
Food-water nexus[130]	2, 6
Energy-water nexus[131]	7, 6
Energy-economic growth-CO_2 nexus[132]	7, 8, 13
Water- energy-land nexus[67]	6, 7, 2
Energy-water-food-education nexus[133]	7, 6, 2, 4
Water-energy-people nexus[134]	6, 7
Women-water nexus[135]	5, 6
Energy-poverty-climate nexus[136]	7, 1, 13
Food, energy, water, and health nexus[137]	2, 7, 6, 3
Tourism growth-water security nexus[138]	9, 6
Food-biodiversity nexus[139]	2, 14, 15
Mining-water nexus[140]	12, 6
Nexus between financial autonomy, service provision, stakeholder participation and the resultant allocation of water[141]	17, 6
Nexus of climate change, water and food security, energy and social justice[142]	13, 6, 2, 7, 16
Nexus between water service provision and property development[143]	6, 12
Renewable energy consumption-economic growth[144]	7, 12
Urban-water-energy-climate nexus[145]	11, 6, 7, 13

Each example has indirect linkages with many other SDGs as illustrated by food-energy-water nexus' linkages with all SDGs in Fig. 1. Credit (symbols): United Nations.

Systematic Nexus research is an important method for realizing integrated watershed management and is an important topic in the field of SDG research.

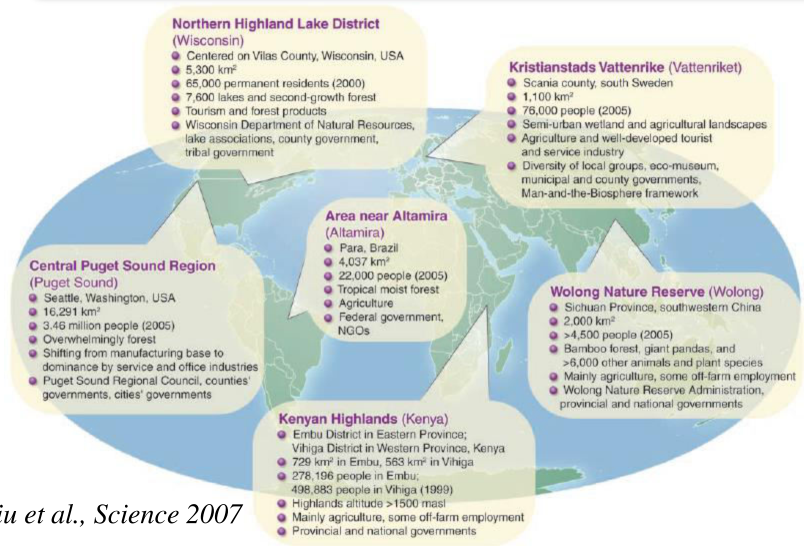
It refers to the interactions between multiple systems and the relationships that exist between them in terms of Synergy or Tradeoff.

Water-Energy-Food nexus, as a typical research paradigm, provides ideas for similar mutual-feedback studies.

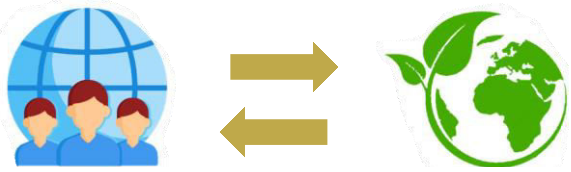
Liu et al., Nature Sustainability (2018)

Background

Complexity of coupled human and natural systems



Liu et al., Science 2007



- Coupled Human-Water System *(Liu et al., 2007; Konar et al, 2019);*
- Hydrologic-Economic Models *(Harou et al, 2009)*;
- Socio-Hydrology (*Sivapalan et al, 2012);*
- Nature-Society Dualistic Cycle, NSDC （*Wang hao*）

Water & Economic development research

- Coupling of economic optimization models with hydrological models（*Ahrends et al., 2008*）
- Human Systems Modeling and Natural Systems Modeling（*Bijl et al., 2018*）
- Coupling of Input-Output Models with Water Quality Models（*Guan et al., 2008*）
- Coupling System Dynamic Models with Nonlinear Differential Equations（*Dadson et al., 2017*）

Social policy, resource management

- Hydrology combined with social sciences（*Massuel et al., 2018*）
- Operational decision making considering climate change（*Mason et al., 2018*）
- Socio-hydrological model of subjective decision-making by users（*Kuil et al., 2018*）
- Historical geographical knowledge and statistical methods（*Wescoat et al., 2018*）

Background

Quantitative research based on multi-system integrated simulation for inland river basins is rare, and the following aspects are worth exploring in depth:

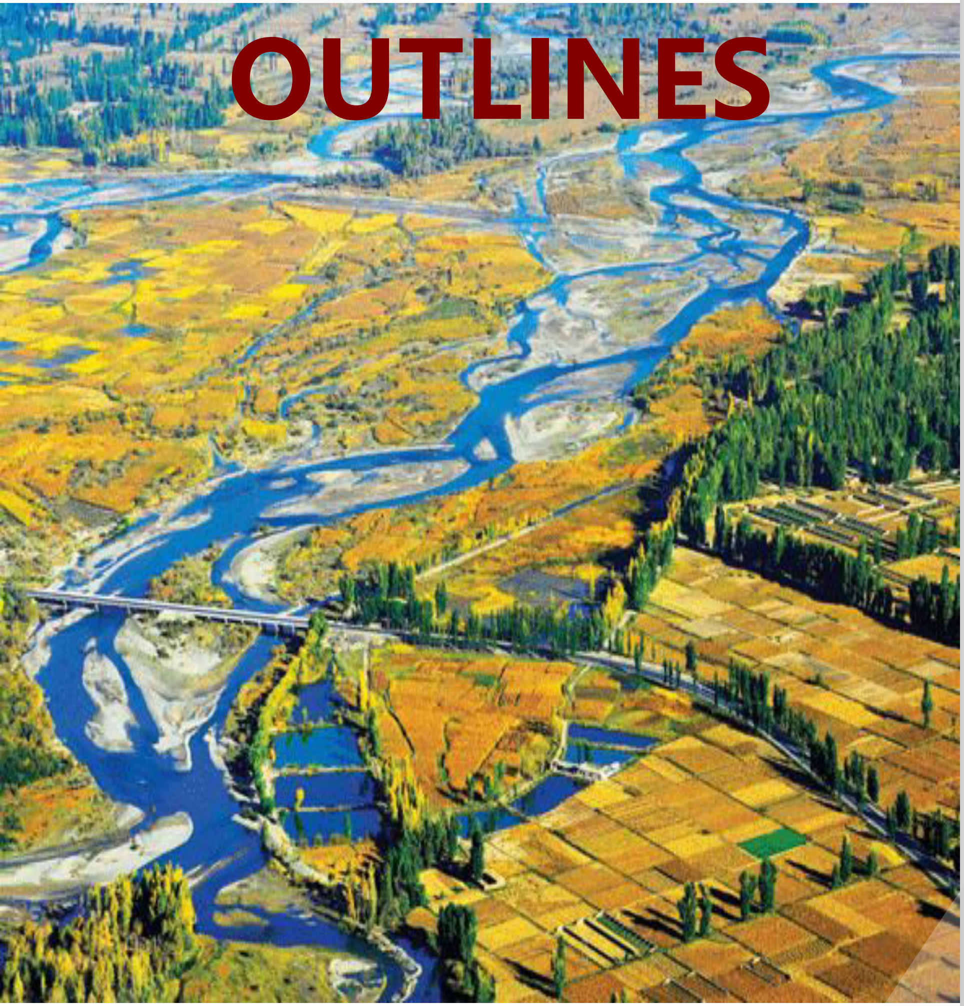
(1) Integrated simulation of two-way mutual feedback coupling between ecohydrological and socio-economic processes

Previous studies often focus on one-way influence or constraints between different systems, and there is still a lack of studies on two-way coupling between natural and social systems.

(2) Systematic evolution under the synergy of future climate change and socio-economic development.

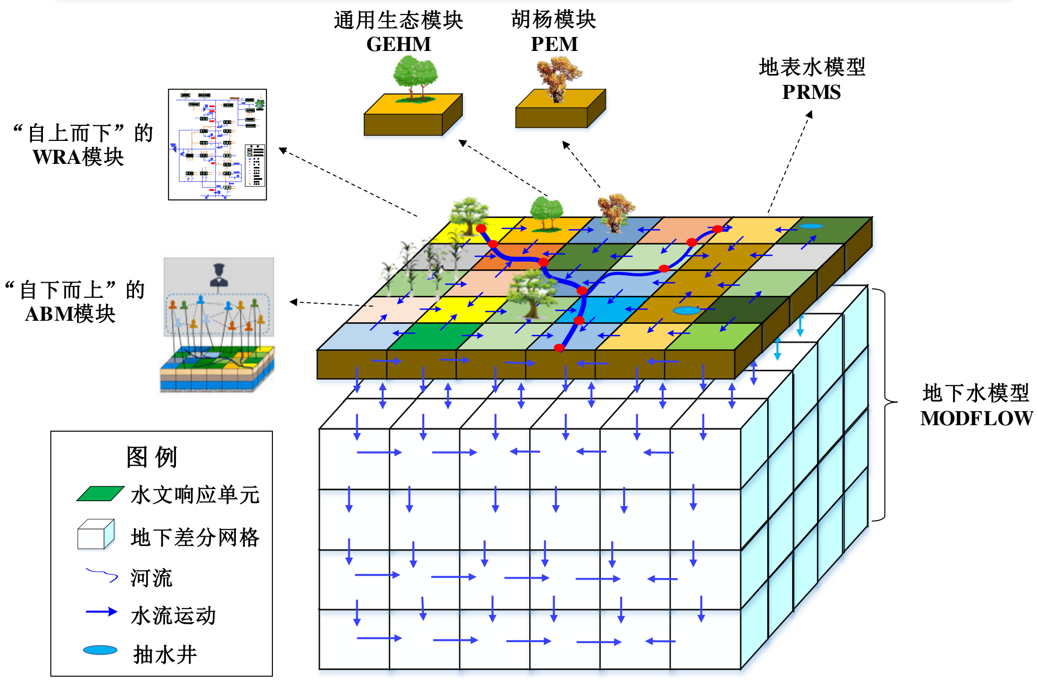
Although the changes in ecohydrological processes driven by climate change and socio-economic development have been discussed, the feedback effect of ecohydrological processes on socio-economics has rarely been quantitatively investigated and is even more rare in inland river basins.

OUTLINES



Model Basics （HEIFLOW）

Hydrological-Ecological Integrated watershed-scale FLOW model (HEIFLOW model)



Model Functions:

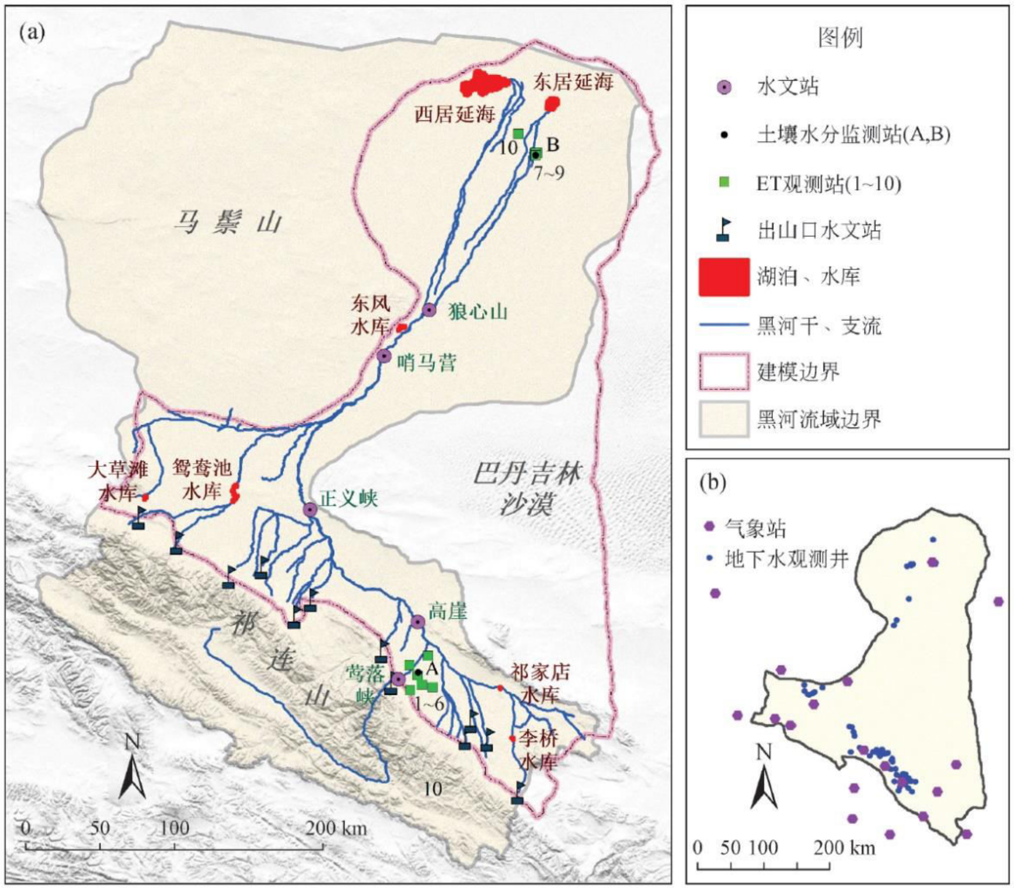
- ☐ Developed on the framework of the coupled surface water-groundwater model GSFLOW
- ☐ Simulation of water cycle processes
- ☐ Modeling vegetation ecological processes
- ☐ water resource allocation
- ☐ Agricultural irrigation
- ☐ Integrated water resources-agriculture-ecology model

Model History：

1. **Hydrodynamic module;** *Tian et al., EMS (2018)*
2. **GEHM Module ; PEM Module ;** *Sun et al., WRR (2018); Li et al., EM (2017)*
3. **WRA Module;** *Zheng et al., EMS(2020)*
4. **AMB Module;** *Du et al., JoH (2020)*
5. **Reorganization of the soil water Module;** *Han et al., JoH (2021)*
6. **land-use dynamics update;** *Tian et al., EMS (2018)*

Model Basics（HEIFLOW)

Modeling Scope Overview

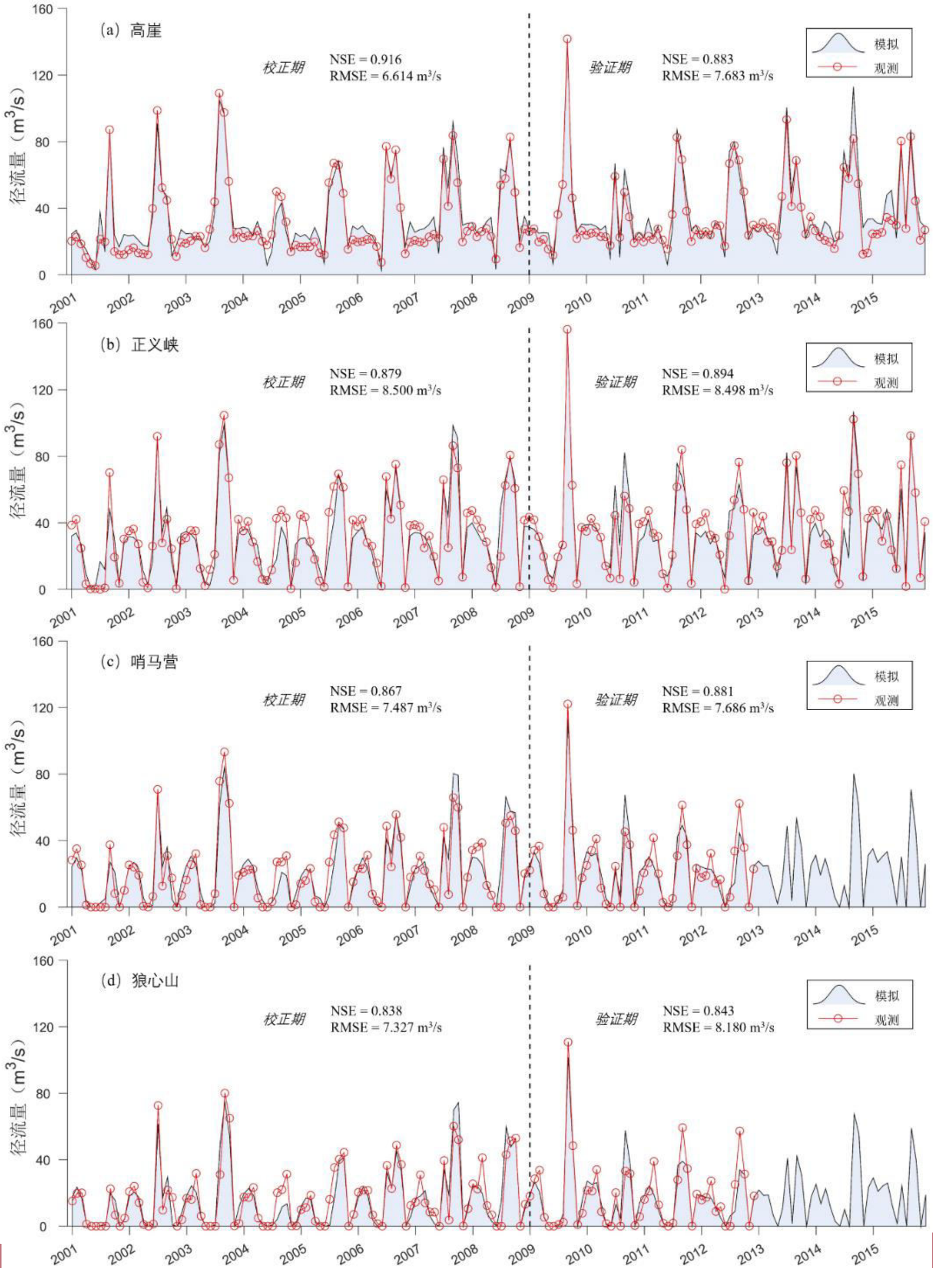


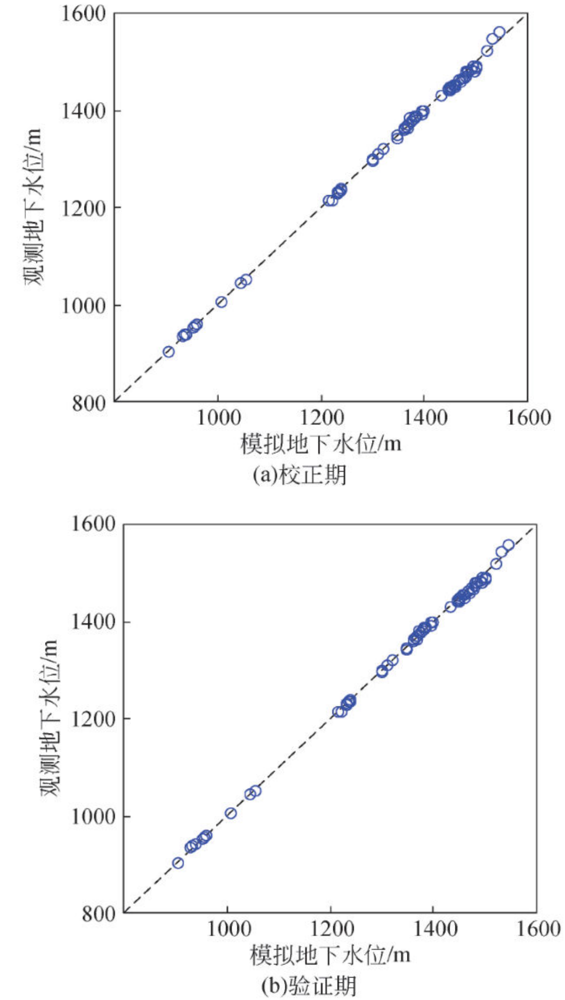
Modeling Overview

- The modeling area is 90,589 km^2;
- The modeling area includes the middle and some lower reaches of the Black River Basin;
- The surface fraction was generalized to 90,589 1 km × 1 km HRU grids;
- The underground part is divided into: one submersible aquifer, two confined aquifers and two weakly permeable aquifers;
- The river network is divided into 116 channels and 3,119 reaches based on confluence relationships and channel characteristics;
- The simulation period of the HEIFLOW model is 2000-2015, with 2000 as the warm-up period, 2001-2008 as the calibration period, and 2009-2015 as the validation period.

Model Validation

Simulation results for mainstem river flow

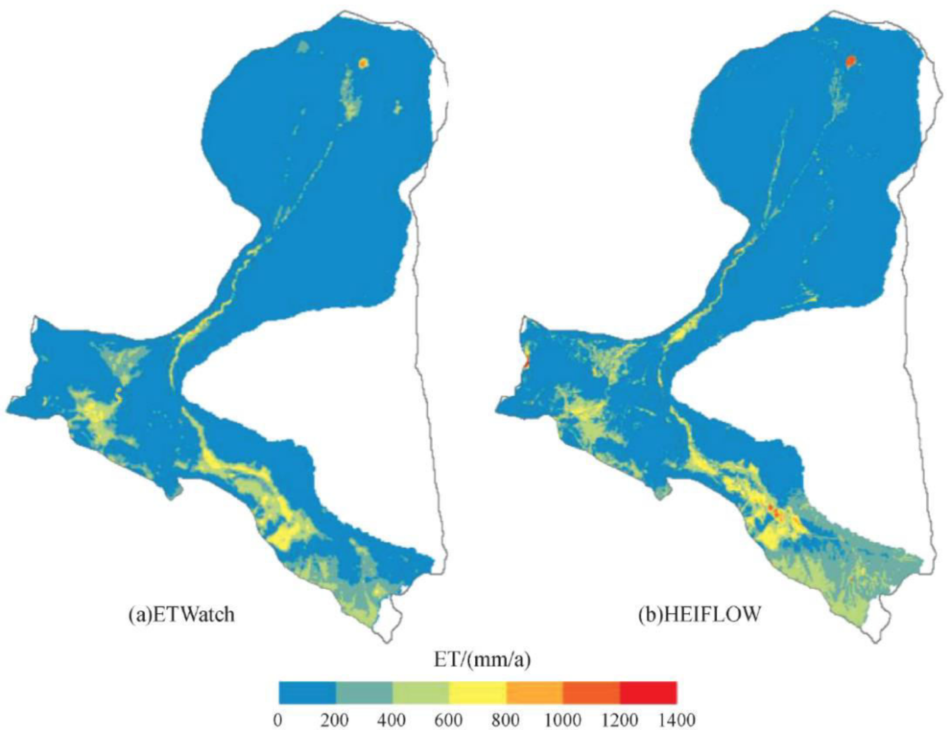




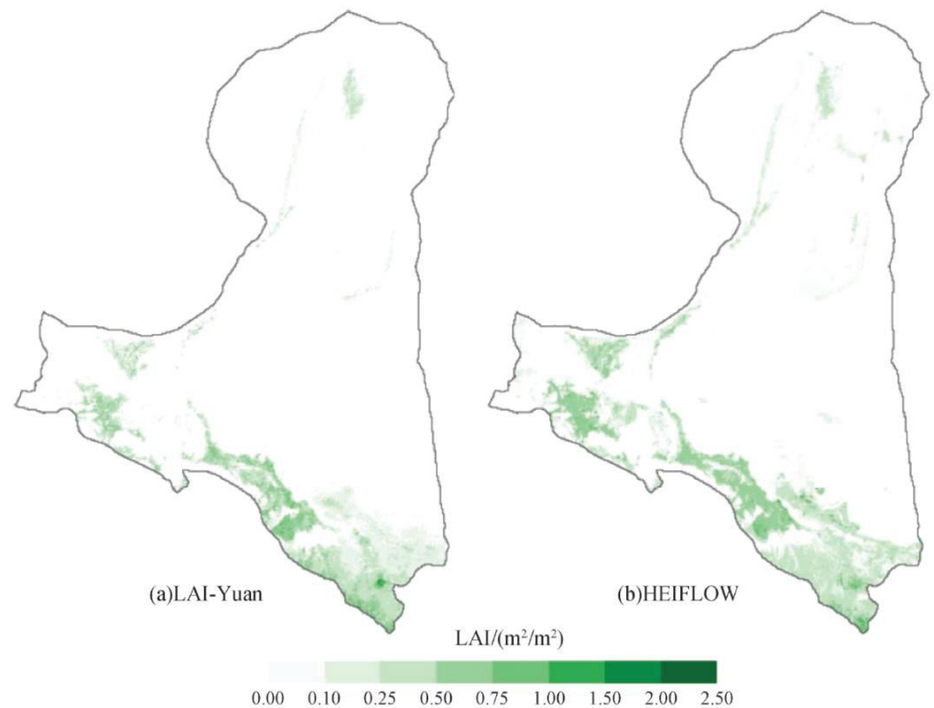
Simulation results of Groundwater level (a) Correction period (b) Validation period

Model Validation

Spatial distribution of mean annual ET (a) Remote sensing (b) HEIFLOW

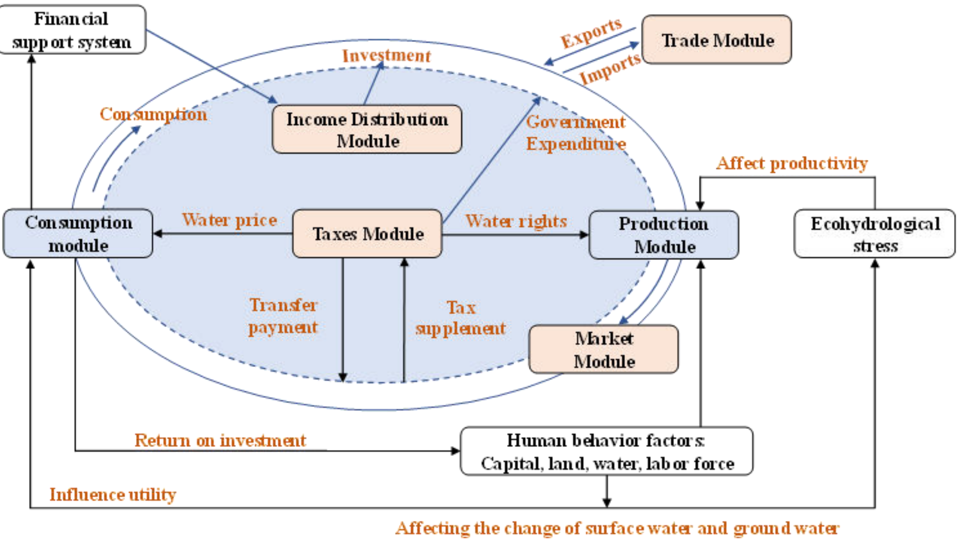


Spatial distribution of mean LAI (a) Remote sensing (b) HEIFLOW

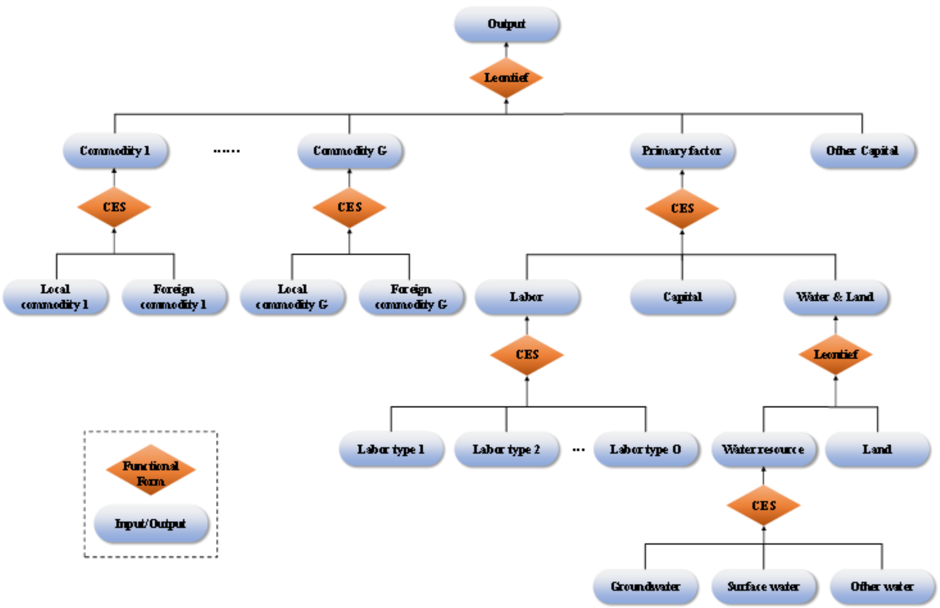


Overall, the HEIFLOW model basically **reproduced** the eco-hydrological processes under the influence of anthropogenic activities in the historical period, and its performance in the **validation** period demonstrated that the model can **reliably predict** the response of eco-hydrological processes under different climatic conditions and anthropogenic activities driven in the future.

Model Basics（WESIM）



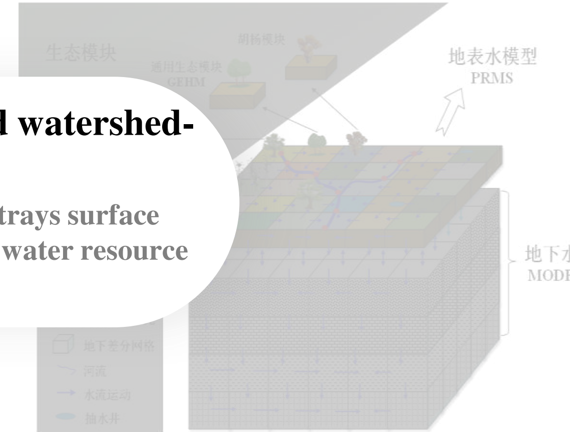
Water Economic Society Integrated Model (WESIM)



Production structure of the WESIM model

- The WESIM model is based on the theory of optimal allocation of resources and empirical economics, with survey data and **multi-region input-output tables (MRIO)** as the main data basis.
- **The WESIM model** describes the substitution relationship between different types of water resources by fixing the production function of substitution (CES) and effectively predicts the changes in water use after the implementation of water resources policies.
- The WESIM model uses multi-layer nested **Leontief functions** and **CES functions** to describe water and land resources in the model.

Integration Model（HEEIM）

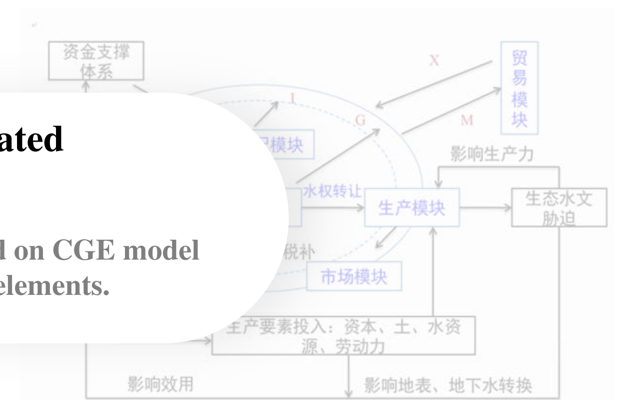


Hydrological-Ecological-Economic Integrated Model（HEEIM）

Ability to represent differences in spatial hydrogeology and resource distribution and to track seasonal dynamics of water resources in time

Hydrological-Ecological Integrated watershed-scale FLOW model（HEIFLOW）

Distributed eco-hydrological model that portrays surface water - groundwater - ecological processes - water resource utilization.



Water Economic Society Integrated Model（WESIM）

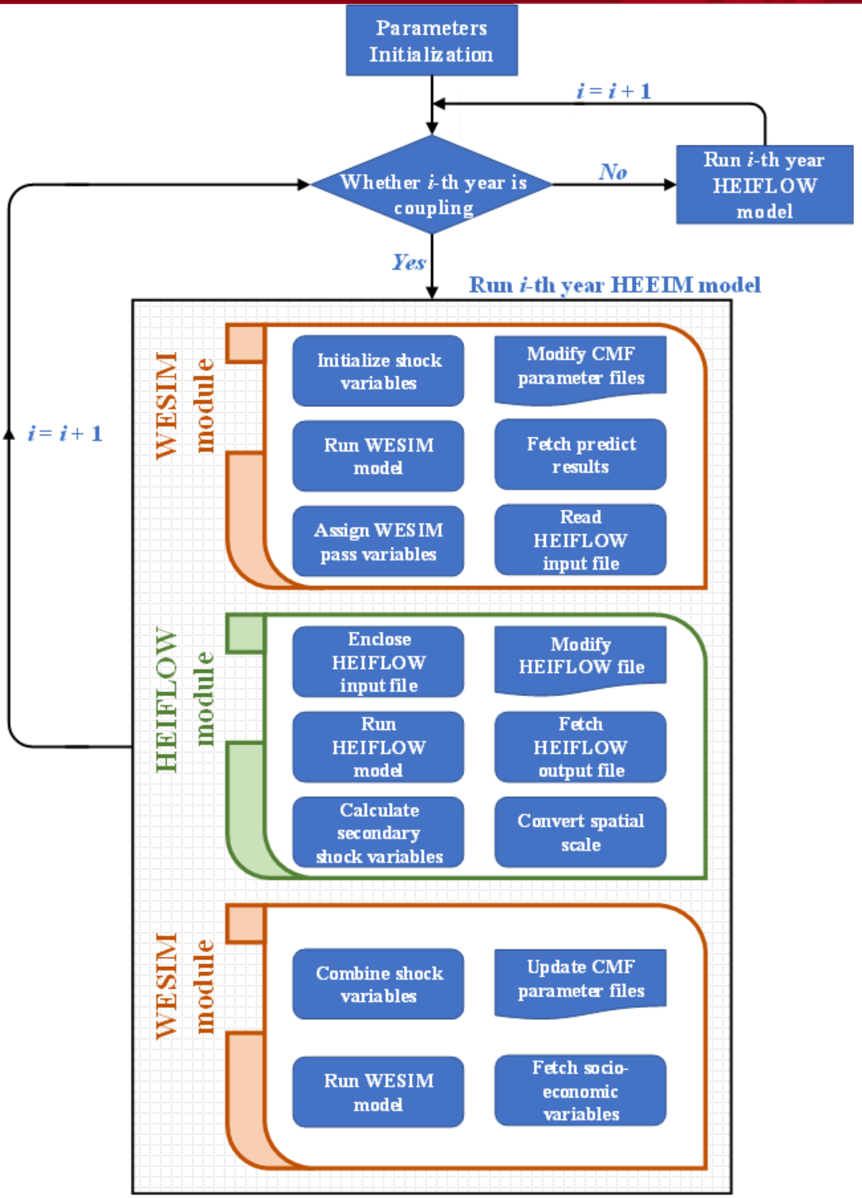
Economic and social system model based on CGE model embedded with water and soil resource elements.

- Ecohydrological process models provide information on water distribution and spatial and temporal variability for socio-economic modeling studies
- Socio-economic system parameters also provide external drivers for ecohydrological evolution;
- Realizing the two-way coupling of natural and socio-economic systems

Bidirectional coupling process

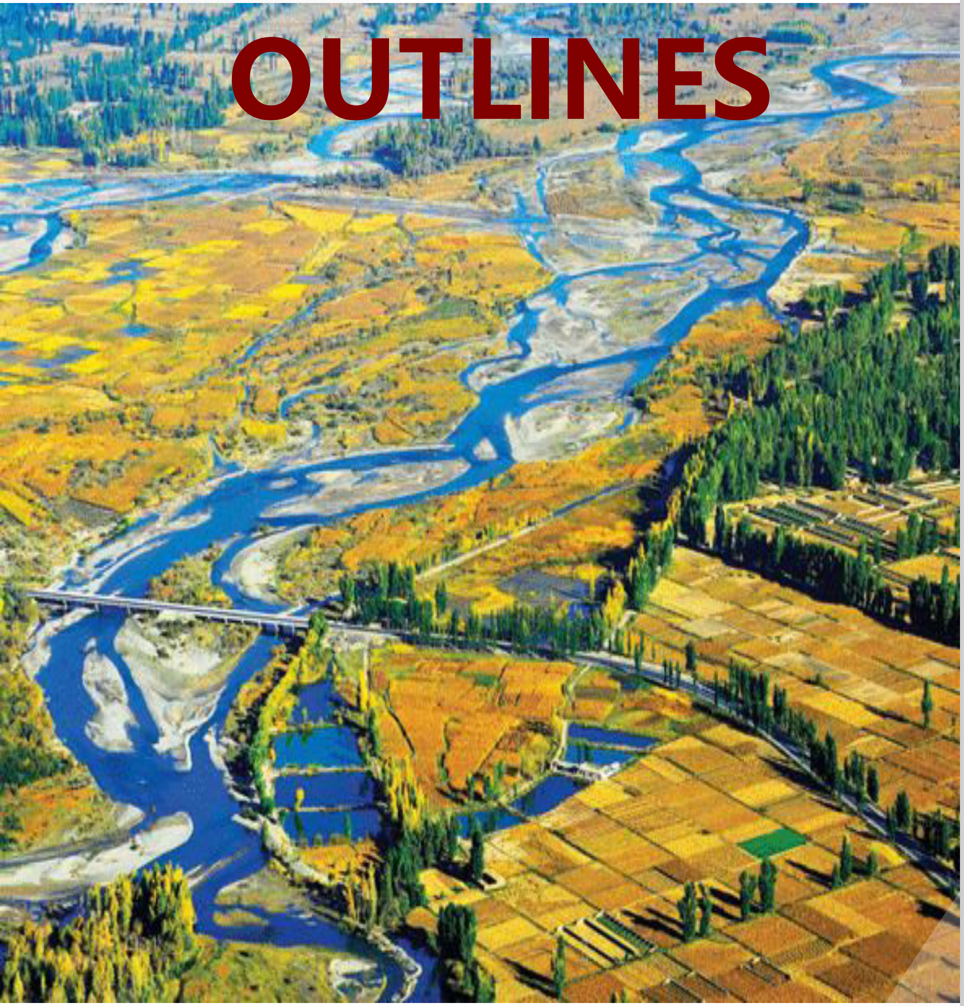
|-- main.m	main program
|--pre_file	Prepare shock variables, coupling status, year and other variables
|--| integrate_model.m	Cycle in year
|--|	Judging the coupling state
|--cmf_modify.m	Recall and modify socioeconomic model shock files
|--WESIM. shock	read shock variable
|--term.cmf	Modify the shock file
|--runTERM.m	Run the WESIM model
|--read_har.R	R language program file to read the result of har.file
|-- read_SL4.R	Read WESIM model file and write out data
|-- allocate_WESIM_output.m	Assign transfer variables and perform spatial scale conversion
|--readpars_wra.m	Extract corresponding information of irrigation area
|-- modify_HEIFLOW_input.m	Modify corresponding variables
|--writepars_wra.m	Write to parameter file
|--HEIFLOW_startfile.m	run the HEIFLOW model
|--readanimation_out.m	Read the output file animation.out.nhru
|--runTERM2.m	Run the WESIM model again
|--end_file	Integrated Model run ends
|--|	end loop

Sketch of the coupled model catalog



Model Coupling Framework

OUTLINES



Management policy scenario

□ Scenarios for water price regulation

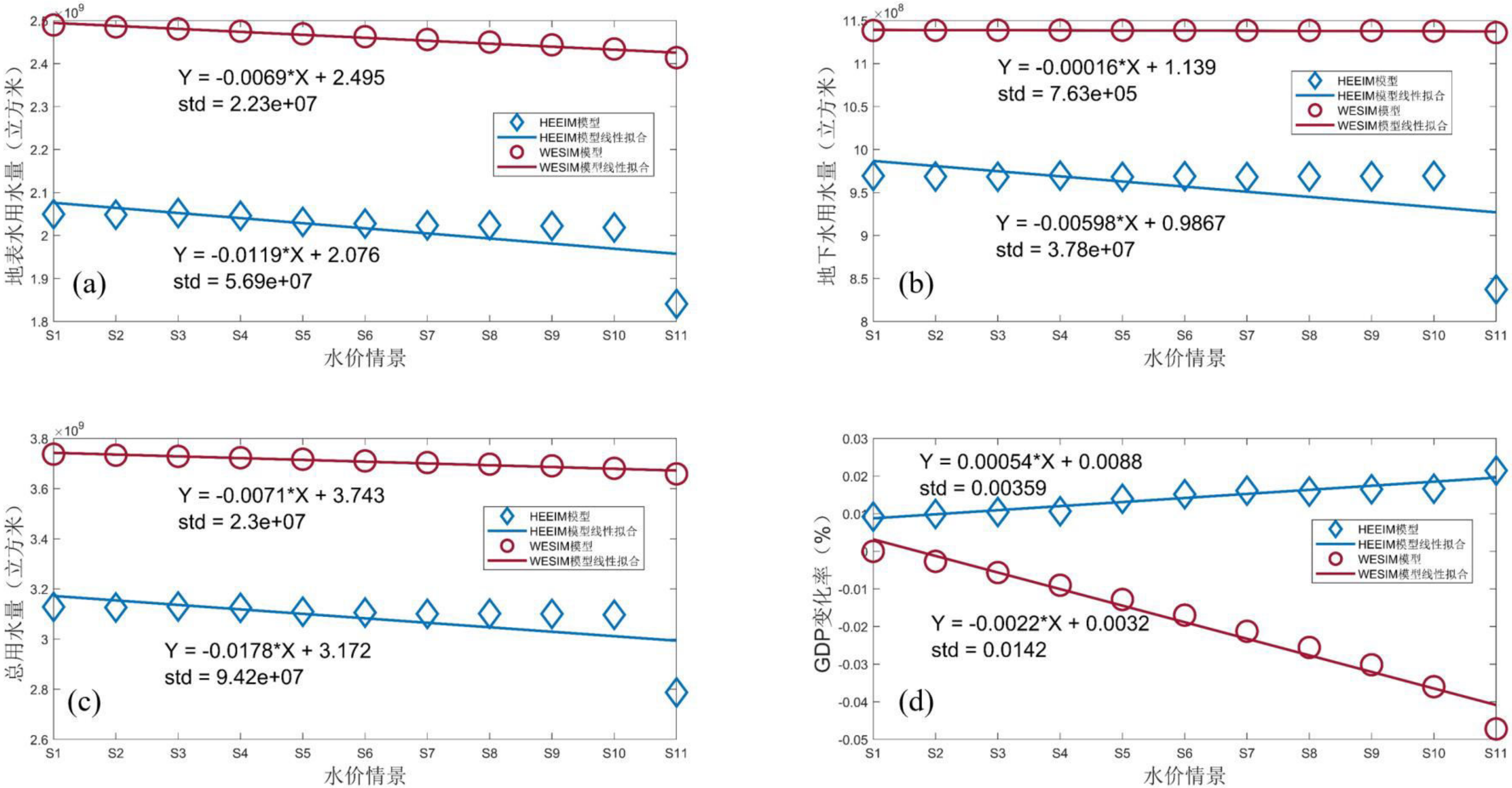
情景	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
地表水水价变动（%）	0%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%

□ Scenarios for managing groundwater depth reduction constraints

情景	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
降深（米）	0.1	0.5	1	1.5	2	3	4	6	8	10

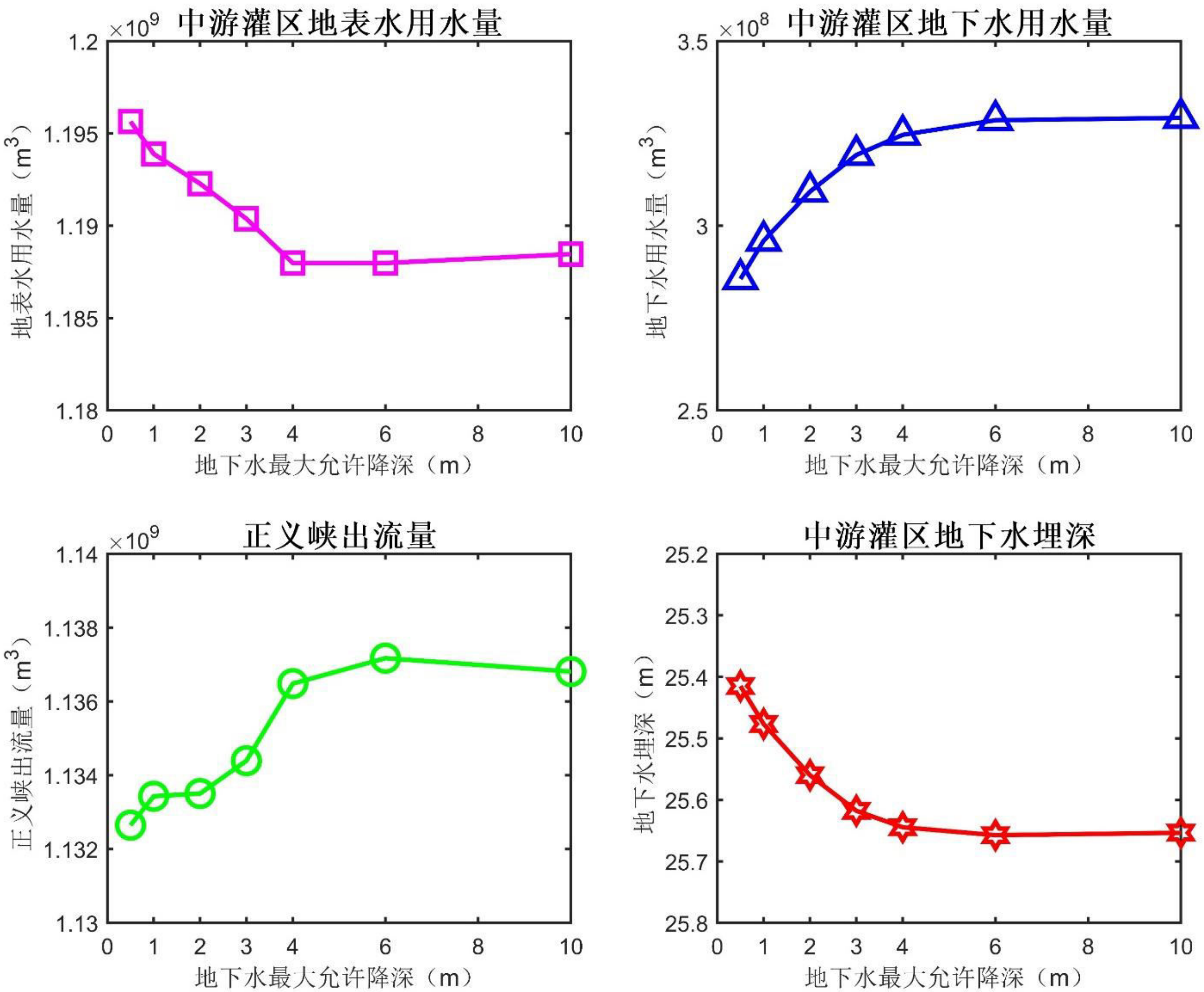
Groundwater Depth Constraint

(a) Surface water use (b) Groundwater use (c) Total water use
(d) Change in GDP response to water price policy



- **The HEEIM coupled model is more robust to the simulation results of economic variables.**

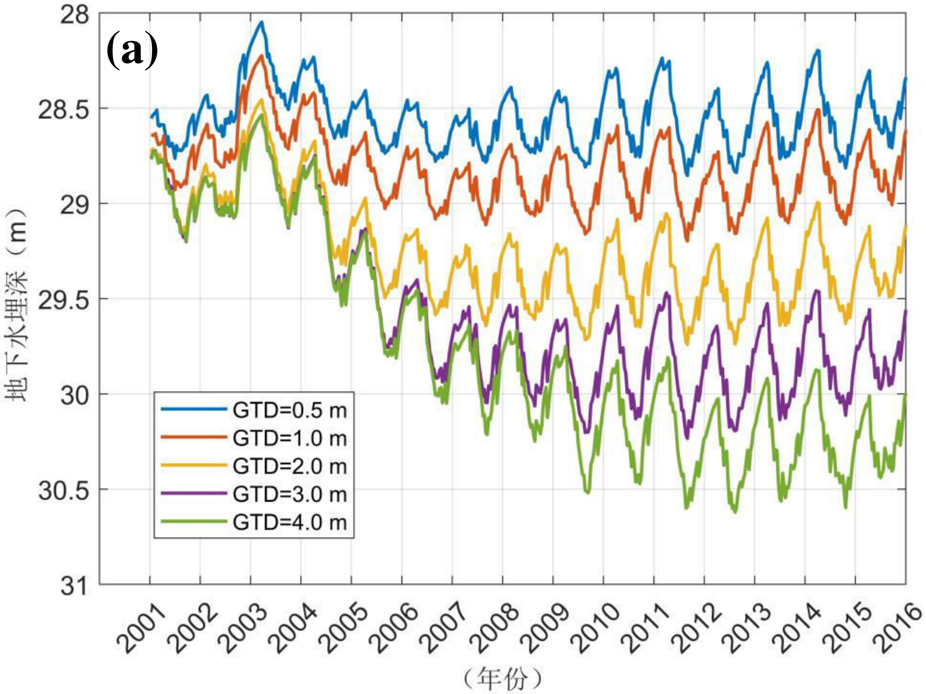
Groundwater Depth Constraint



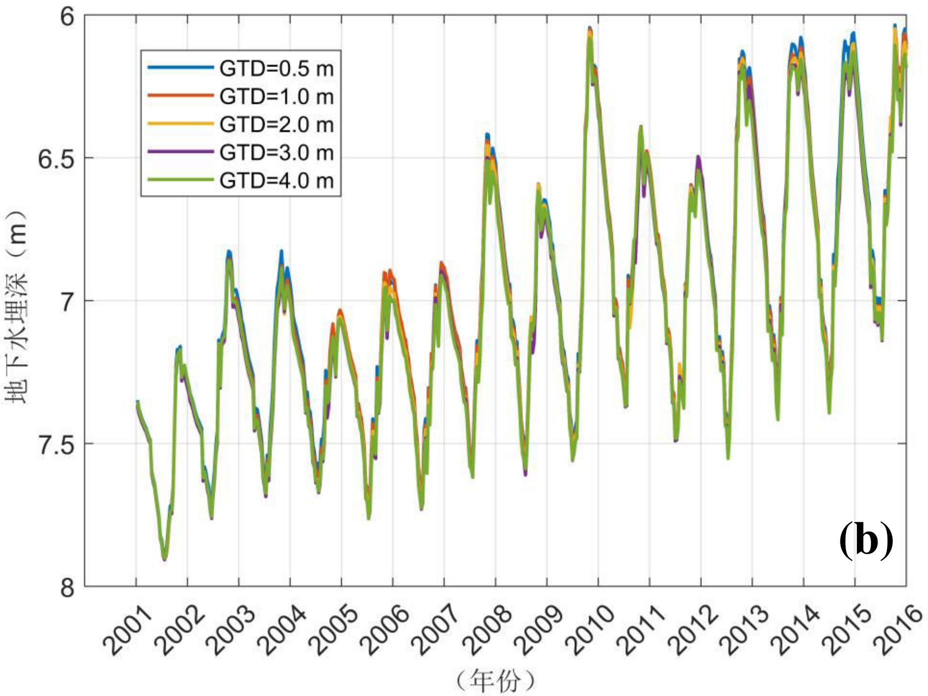
Response of hydrologic variables to a constrained scenario of groundwater depth reduction

- When the groundwater drop depth constraint is less than 4 m, the changes of each index are more obvious, the surface water consumption gradually decreases, the groundwater consumption keeps increasing, the outflow of Zhengyi Gorge increases, and the groundwater depth increases.
- At groundwater drop depth constraints of 4-10 m, all indicators entered a stabilization period.
- When the impacts of water management policies on hydrological processes in the basin are in the **nonlinear interval**, there is a need to scientifically assess the impacts of the policies on agricultural water use and ecosystems in the basin.

Groundwater Depth Constraint



(a) Response process of groundwater depth to water management policies in Luotuo City Irrigation District

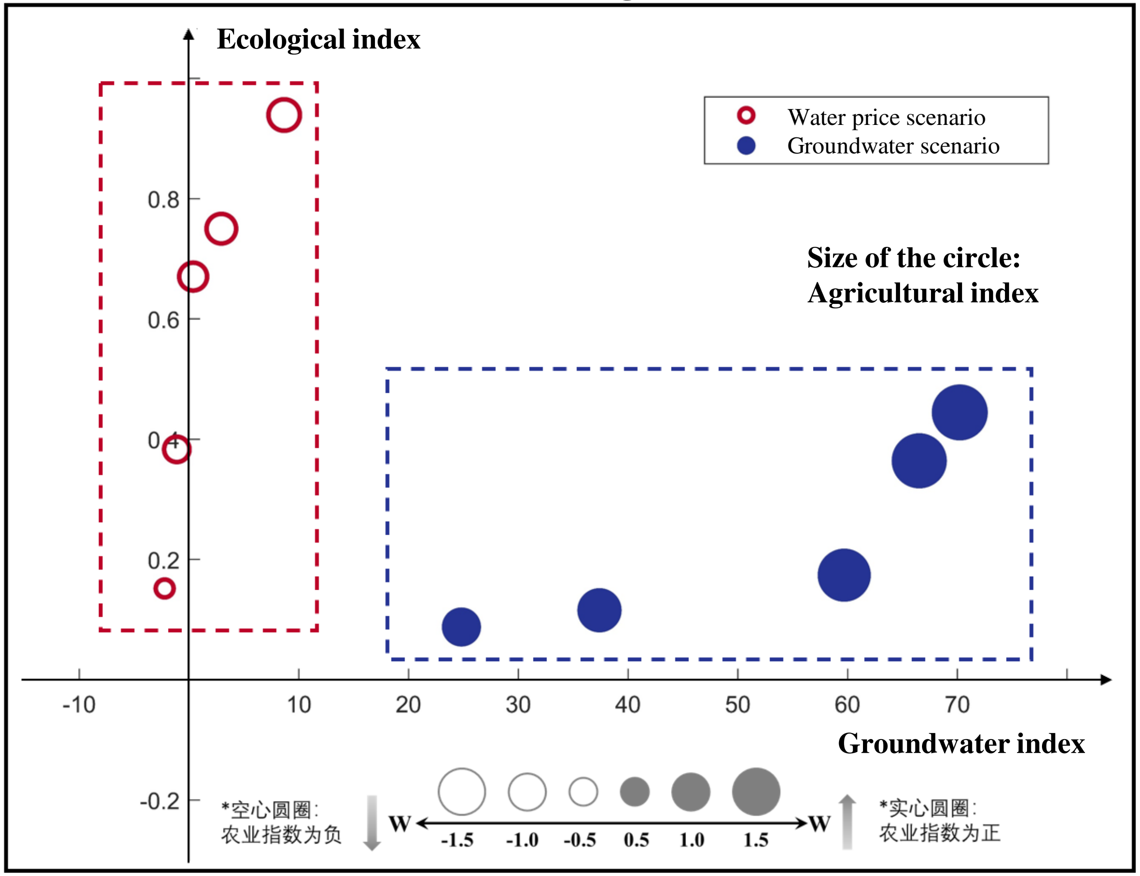


(b) Response process of groundwater depth to water management policy in Yanuan Warm Irrigation District

- The response of groundwater levels to water management policies is characterized by different characteristics.
- The impact of water management policies on groundwater levels will not be immediate and there will be some policy response time.

System nexus

Covariation of water, ecological, and agricultural indices under different management scenarios

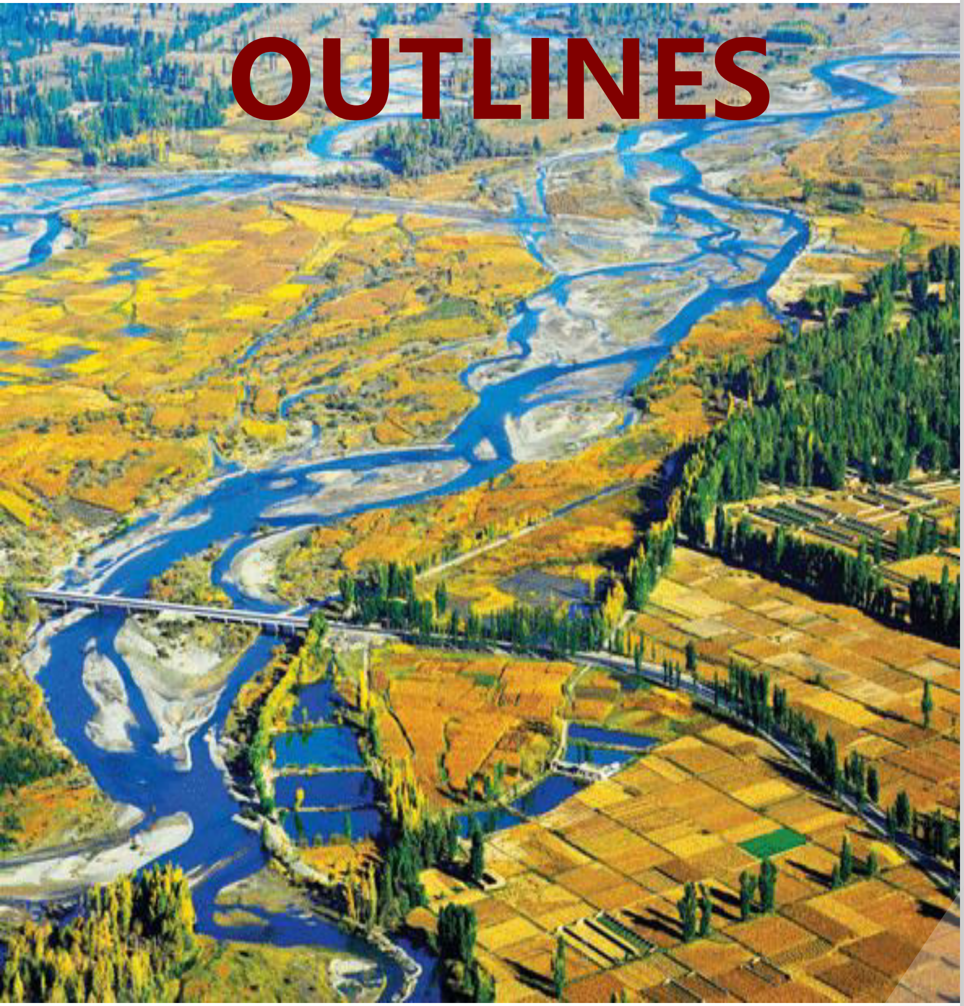


$$CI = 100 \cdot \frac{var_s - var_b}{|var_b|}$$

- var_s is the value of the variable in the scenario and var_b is the value of the variable in the baseline scenario;
- **Groundwater index** using midstream groundwater level changes （ΔGWL_{mid}）；
- **Ecological index** using the ecological downstream flow of the Zhengyi Gorge （$Flow_{zyx}$）；
- **Agricultural index is** calculated using midstream farmland vegetation evapotranspiration （T_{mid}）。

- In the surface water price regulation scenario, there is a **synergistic relationship** between downstream ecological indices and midstream groundwater, however, this synergistic relationship comes at the cost of reduced agricultural production in the midstream.
- The groundwater level drop depth constraint scenario improves the midstream agricultural index and groundwater index while promoting downstream ecological flows and contributing to the restoration of the downstream ecosystem.

OUTLINES



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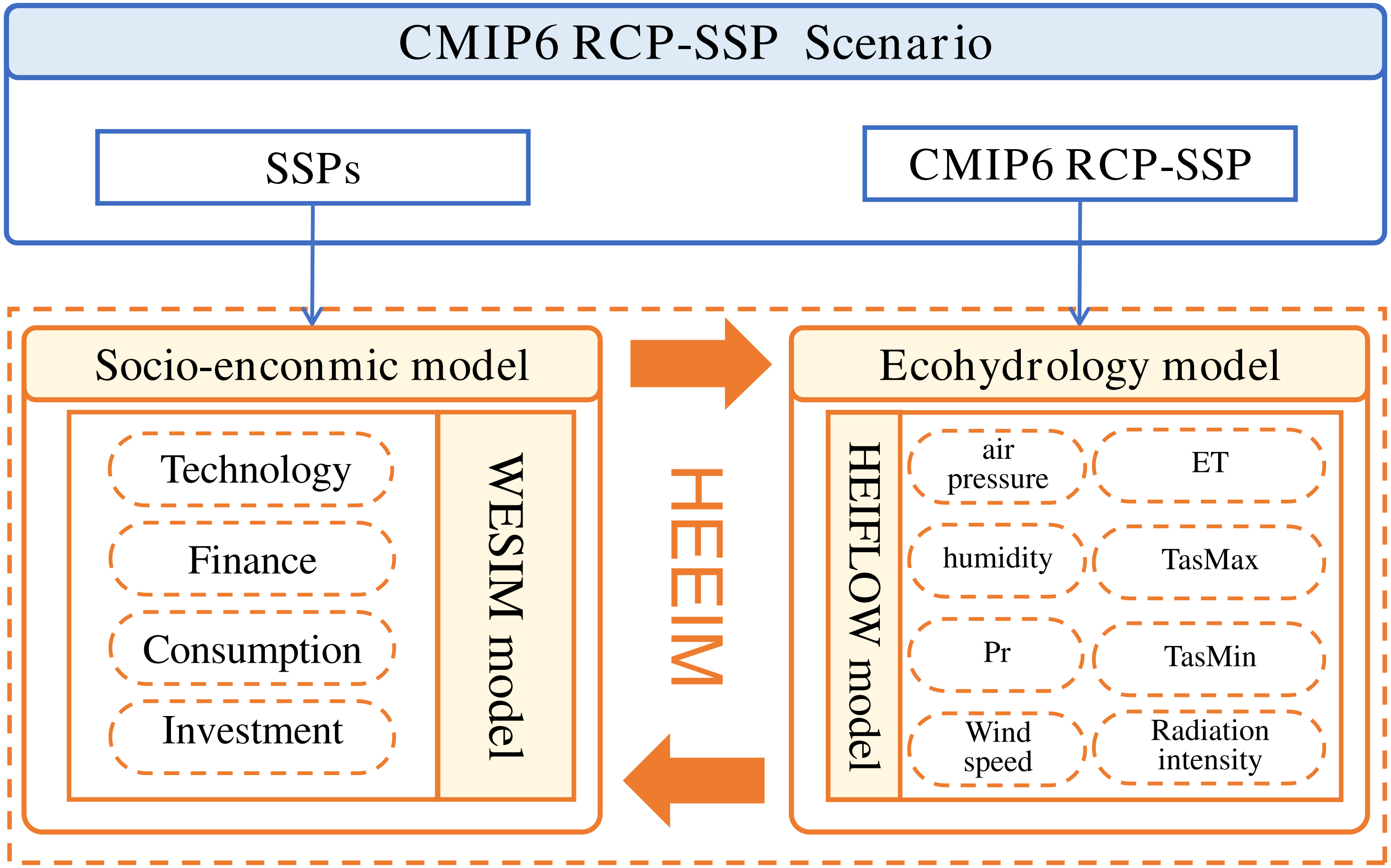
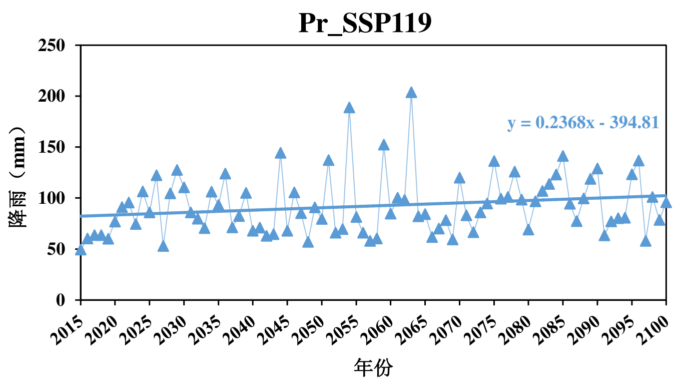
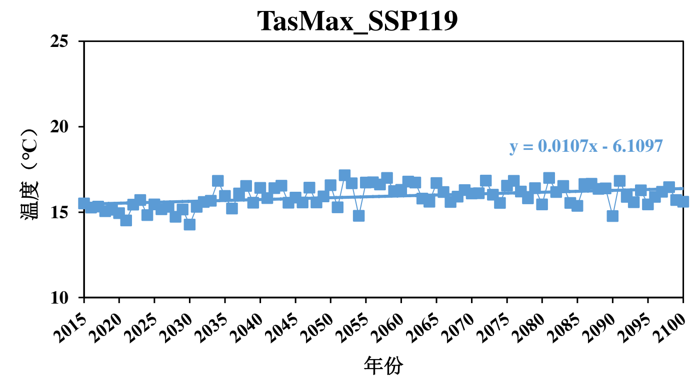
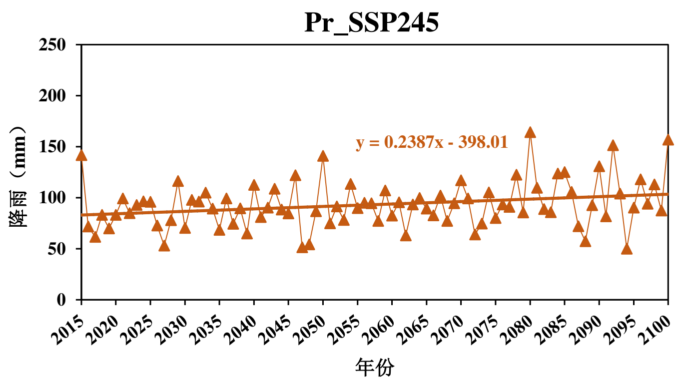
WES Nexus under changing environment

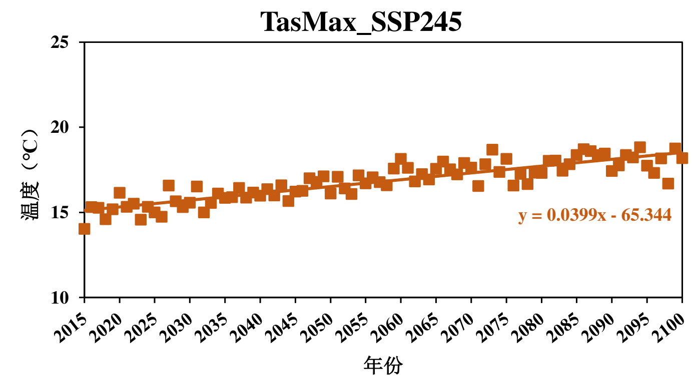


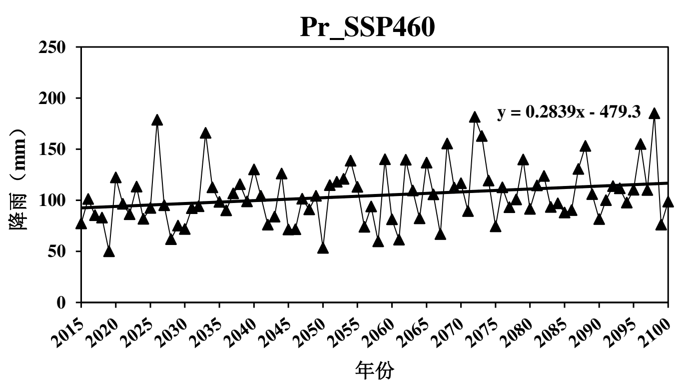
WES Nexus under changing environment

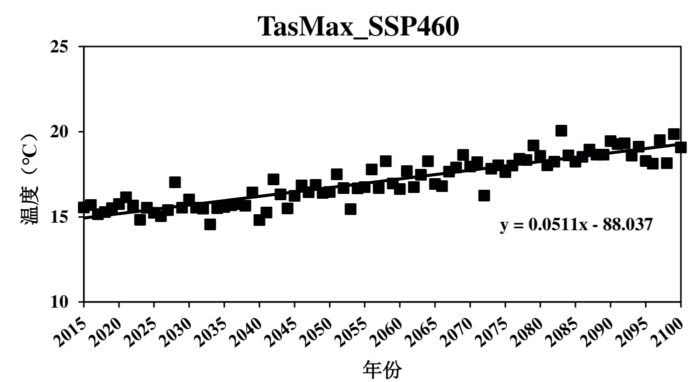








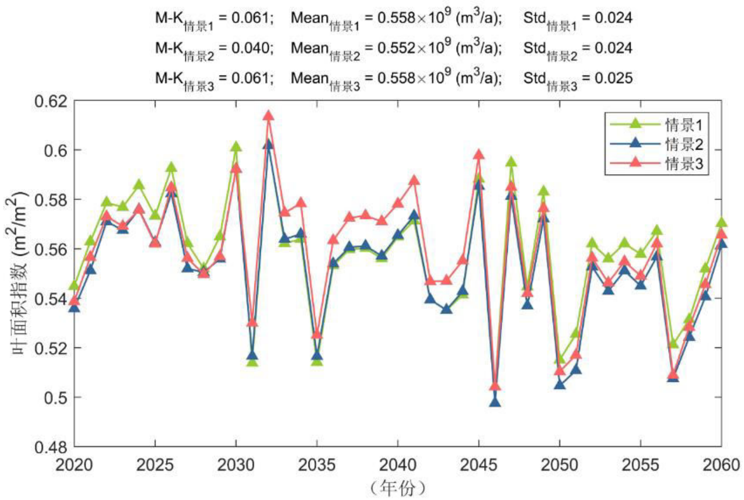




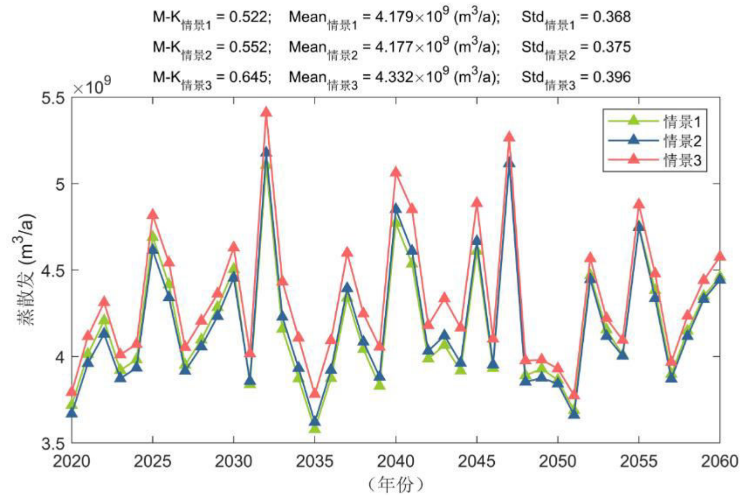
Precipitation（Pr）

Maximum temperature（TasMax）

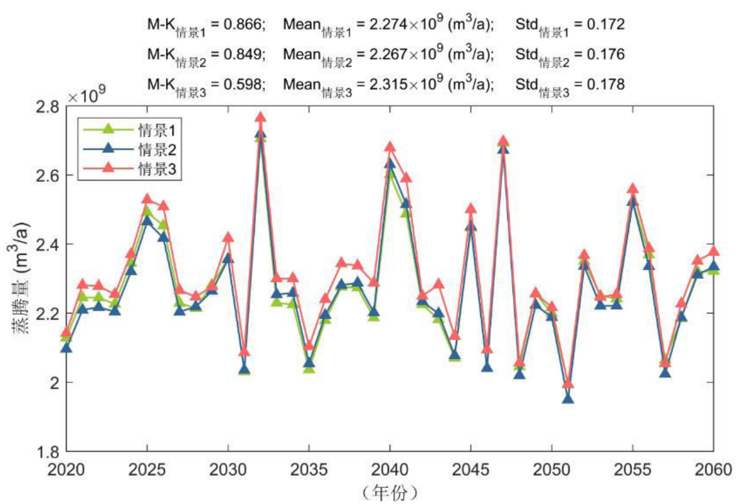
Coupled evolution of ecohydrological variables



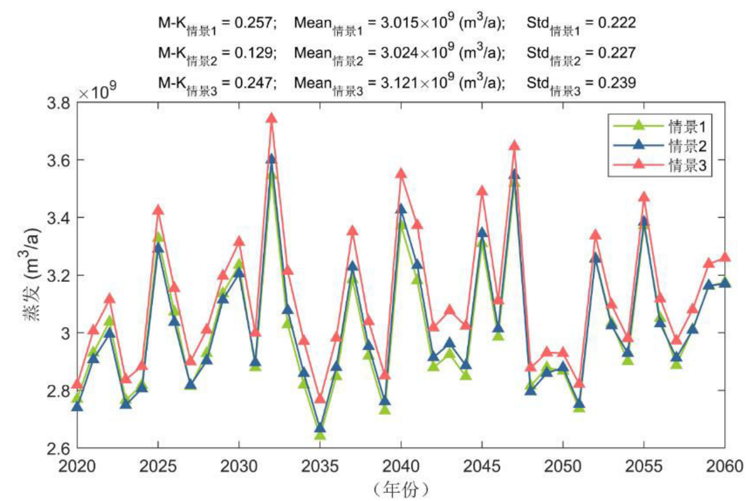
LAI evolution under different scenarios



ET evolution under different scenarios



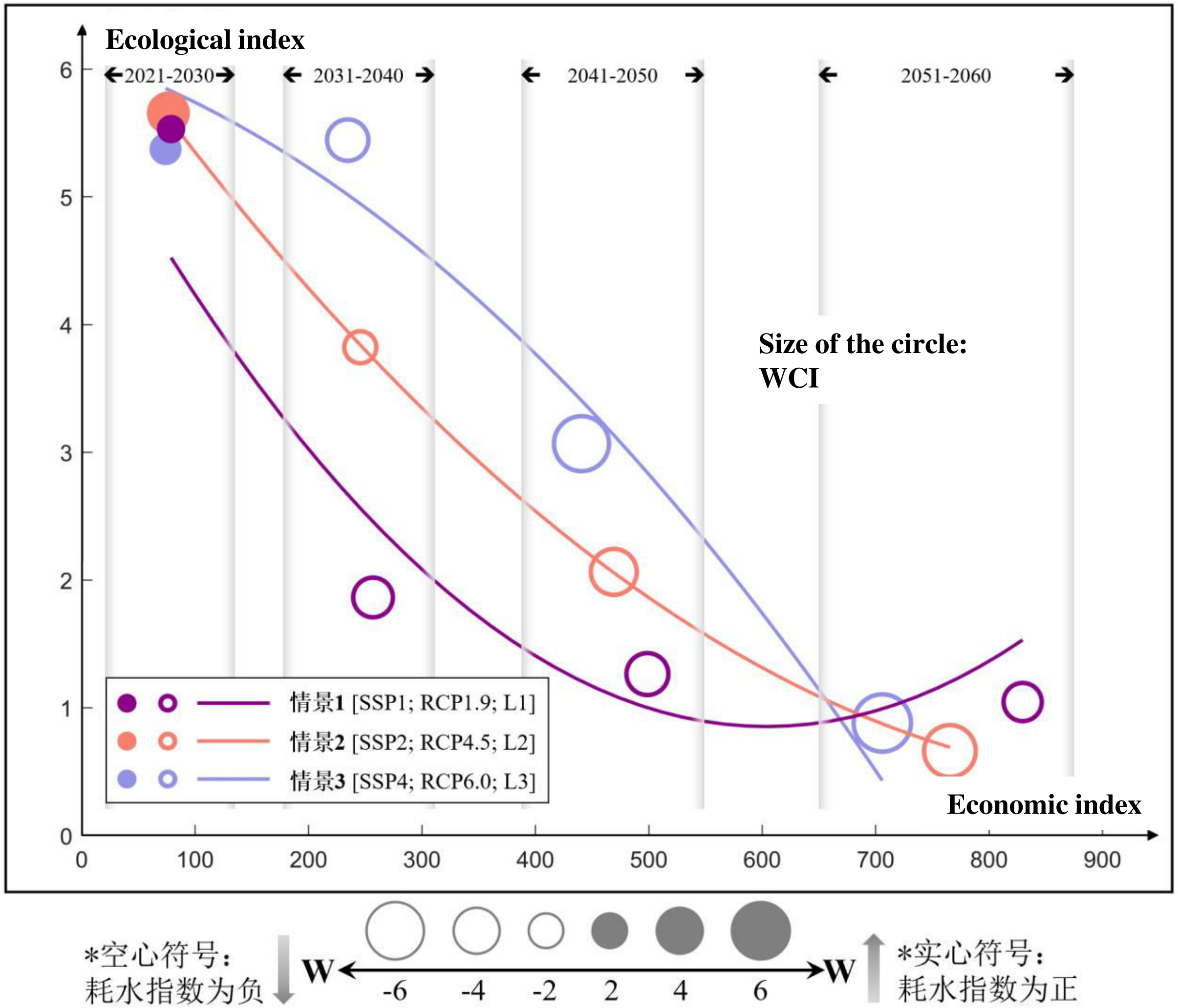
Transpiration evolution under different scenarios



Evaporation evolution under different scenarios

- For ET, E, and T, the values under Scenario 3 are all higher than the other two scenarios. This is due to the fact that the SSP460 radiative forcing scenario included in Scenario 3 has the highest warming of the three scenarios.

System nexus



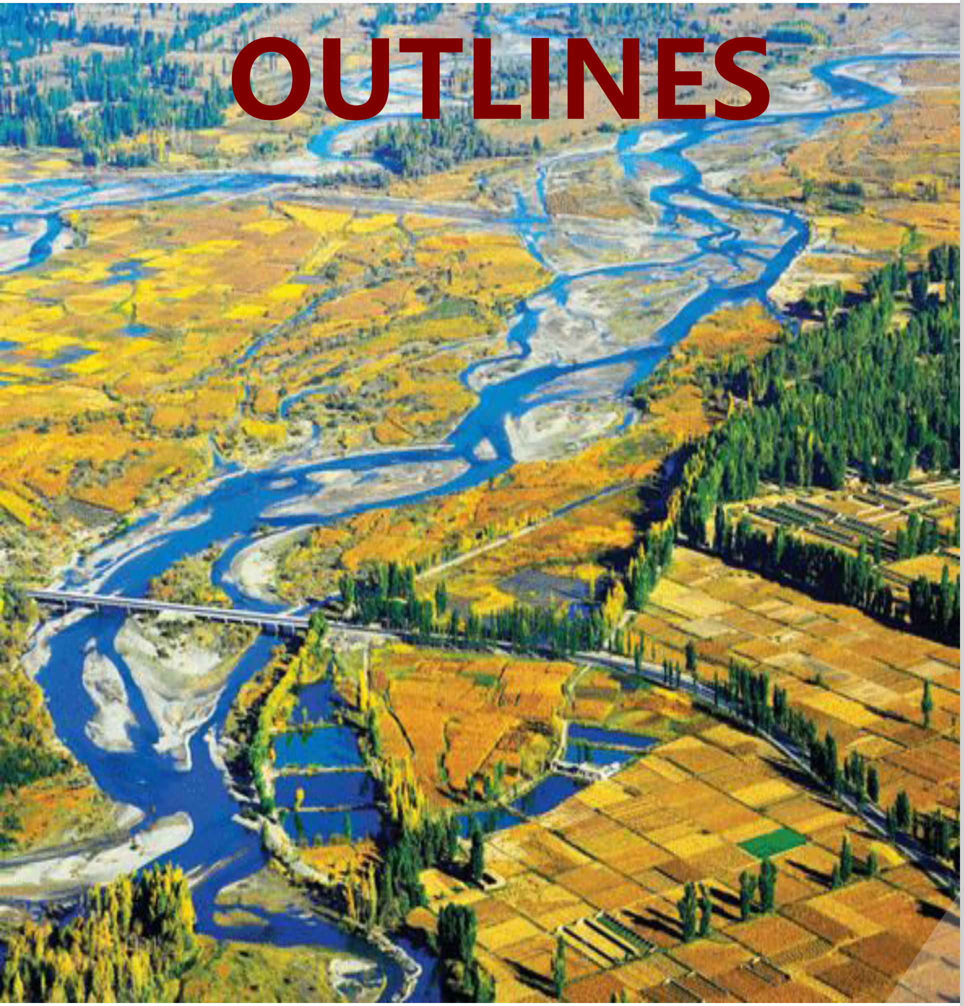
Covariance of water consumption index, ecological index and economic index under different scenarios

$$CI = 100 \cdot \frac{var_t - var_{2020}}{|var_{2020}|}$$

- In the visionary development, the ecological and water consumption indices (WCI) show a **synergistic effect**, i.e. the water consumption index decreases when the ecological index decreases.

- All three scenarios show a trend of **increasing economic indices**, which also implies economic development at the expense of ecological development.

- Under the industrial restructuring driven by technological progress, the **water use efficiency** of economic development has been improved.


OUTLINES

Conclusion

① In the study of management policy-driven water-ecology-socioeconomic nexus, it was found that the relevant hydrological variables showed a certain non-linear response to the management policy of groundwater level-depth constraints, while the impacts of hydrological processes in the watersheds showed different superposition effects as they accumulated over time. In the surface water price regulation scenario, there is a synergistic relationship between the downstream ecological index and midstream groundwater, however, this synergistic relationship comes at the cost of reduced agricultural production in the midstream.

② With regard to the study of the water-ecology-socioeconomic nexus under changing environments, results found that the ecological index and the water consumption index showed a synergistic change effect, and the water use efficiency of the economic development was improved under the industrial restructuring driven by technological progress, and the future economy showed a trend of sustained growth, but this is at the cost of ecological development.

Outlook

(1) On the resilience analysis of the future water-ecological-socioeconomic system of the Hehei River Basin.

From the perspective of coordinated development of coupled water-ecology-economy systems, the study of the resilience of complex systems is explored to assess the risk of breaking the security boundary of the system in future scenarios.

(2) On the future development management of watersheds incorporating AI technologies.

- More accurate alternative models are built by training deep neural network models, LSTM models to reduce the system error.
- Based on the fusion of data-driven models with physical process models.

Thanks for your attention!

Hope for your suggestions

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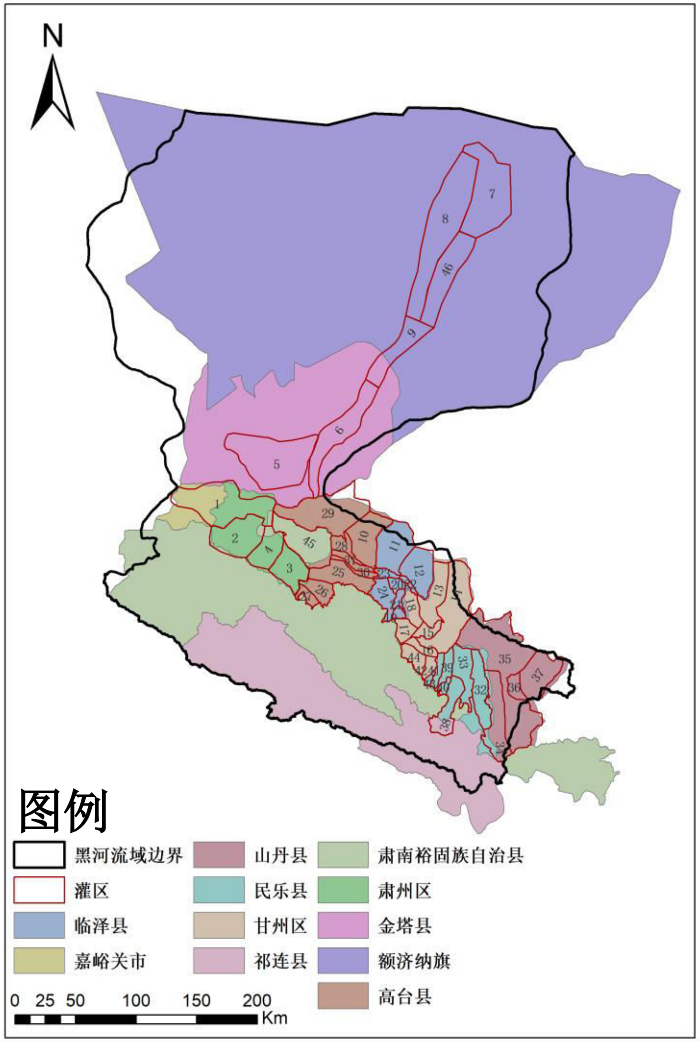

黑河中下游灌区与行政区的空间映射

灌区编号	灌区名称	灌溉类型	灌区编号	灌区名称	灌溉类型
1	北大河灌区	河水、井水混灌	24	新华灌区	河水、井水混灌
2	洪水坝河灌区	河水、井水混灌	25	骆驼城灌区	纯井水
3	中马营河灌区	河水、井水混灌	26	新坝灌区	纯河水
4	丰乐河灌区	河水、井水混灌	27	红崖子灌区	纯河水
5	金塔灌区	河水、井水混灌	28	沙河灌区	河水、井水混灌
6	鼎新灌区	河水、井水混灌	29	罗城灌区	河水、井水混灌
7	额济纳绿洲灌区	河水、井水混灌	30	三清灌区	河水、井水混灌
8	西河灌区	河水、井水混灌	31	友联灌区	河水、井水混灌
9	东风灌区	河水、井水混灌	32	童子坝灌区	河水、泉水混灌
10	六坝灌区	河水、井水混灌	33	益民灌区	河水、井水混灌
11	平川灌区	河水、井水混灌	34	霍城灌区	河水、泉水混灌
12	板桥灌区	河水、井水混灌	35	马营河灌区	河水、井水混灌
13	乌江灌区	泉水、河水、井水混灌	36	寺沟灌区	河水、井水混灌
14	大满灌区	河水、井水混灌	37	老军灌区	河水、井水混灌
15	盈科灌区	河水、井水混灌	38	海潮坝灌区	纯河水
16	上三灌区	纯河水	39	大堵麻东干灌区	河水、井水混灌
17	甘浚灌区	河水、井水混灌	40	小堵麻灌区	河水、井水混灌
18	西干灌区	河水、井水混灌	41	大堵麻西干灌区	河水、井水混灌
19	倪家营灌区	河水、井水混灌	42	安阳灌区	纯河水
20	小屯灌区	纯泉水	43	酥油口灌区	纯河水
21	沙河灌区	河水、井水混灌	44	花寨子灌区	纯河水
22	鸭暖灌区	河水、泉水混灌	45	明花灌区	纯井水
23	蓼泉灌区	河水、泉水混灌	46	东风灌区	河水、井水混灌