Grain yield analysis under climate change and water resources constraints

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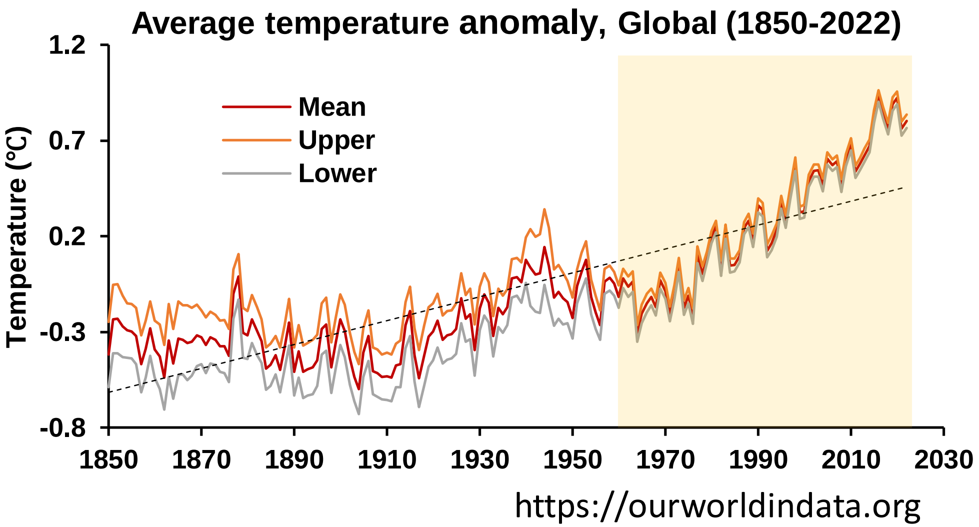
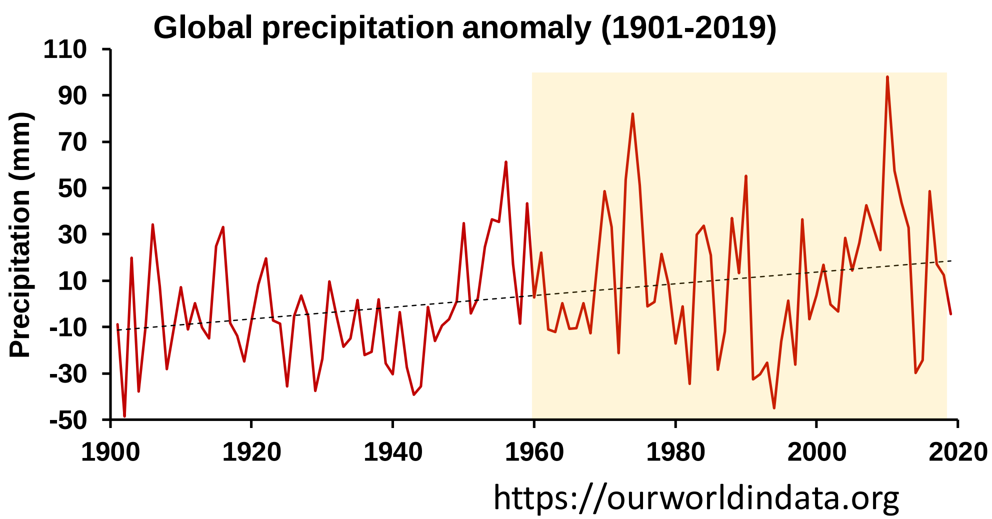
1. Introduction



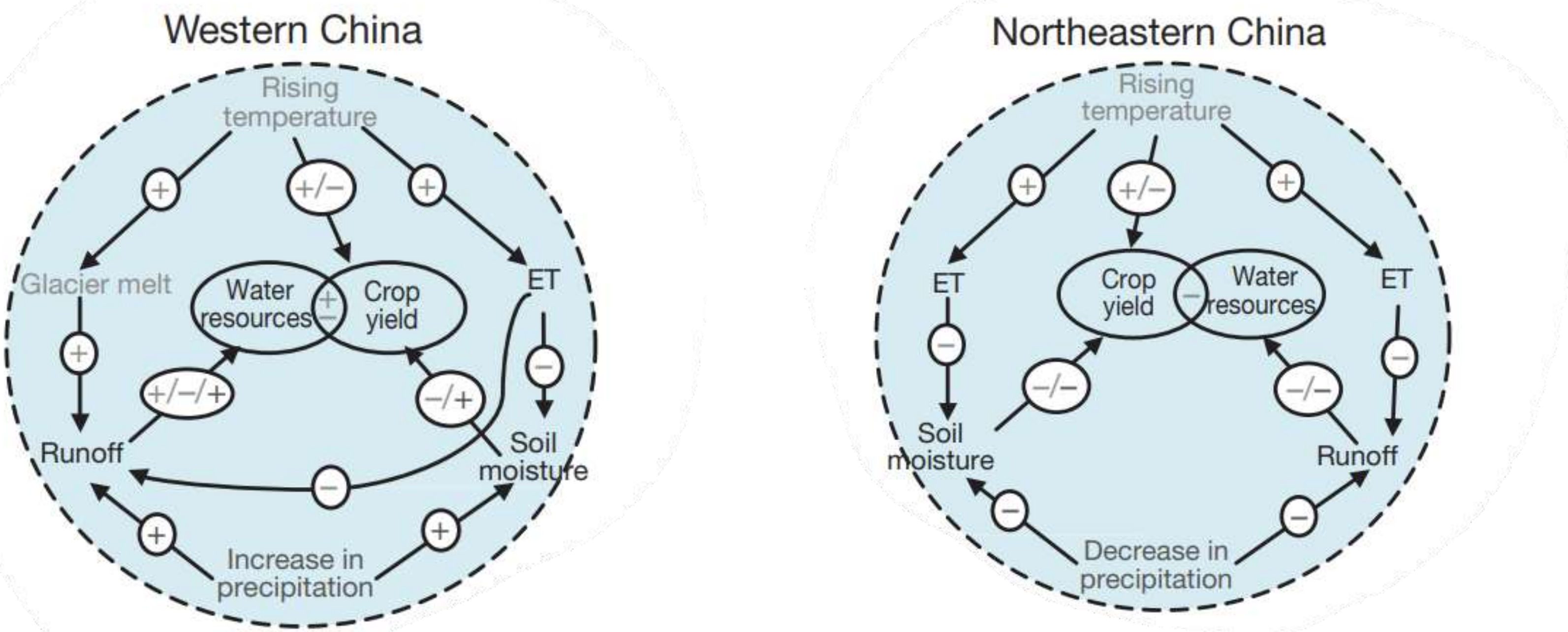
- The global average temperature presents a remarkable increase
- The temperature has increased by 0.56 ℃ since 1990



- Similarly, global precipitation shows a growing trend
- Meanwhile, the precipitation has an evident inter-annual fluctuation

1. Introduction

- As temperature rises and precipitation becomes more variable, changes in regional water demand and supply are expected to increase the likelihood of water shortage for many areas and uses, such as agriculture

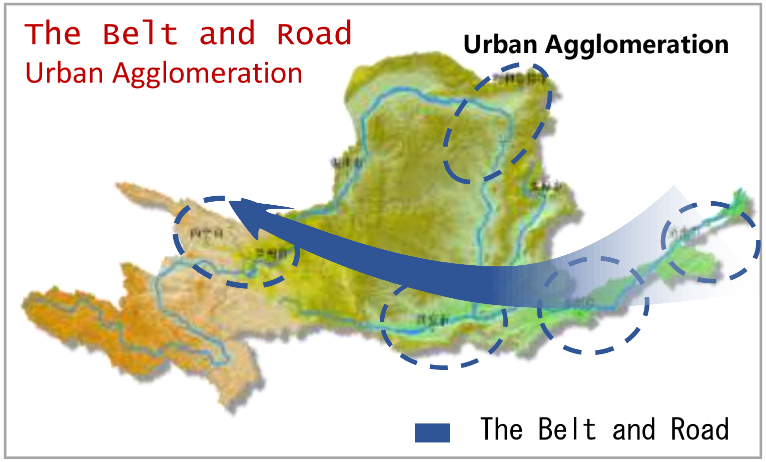


Schematic diagram of climate change and its potential impacts on water resources and agriculture in China. *Piao et al. (2010, Nature)*

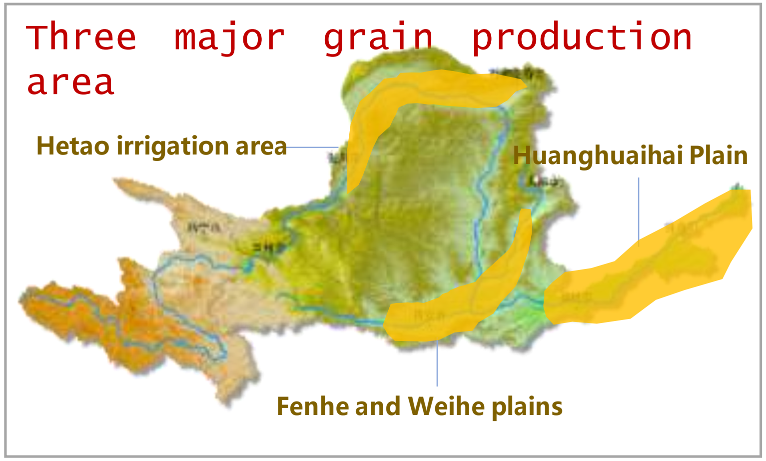
This work aims to investigate the impact of climate change on grain yield

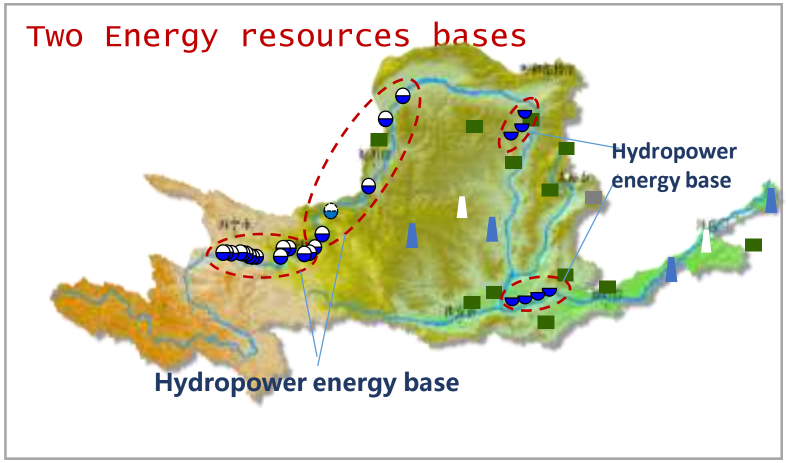
1. Introduction

- Case study: Yellow River Basin



- ✓ The second longest river in China
- ✓ 5,400 km in length, 745,000 km^2
- ✓ accounts for 13% of the total cultivated area
- ✓ holds only 3% of the country's water resources
- ✓ nourishes more than 150 million people with drinking water and irrigation



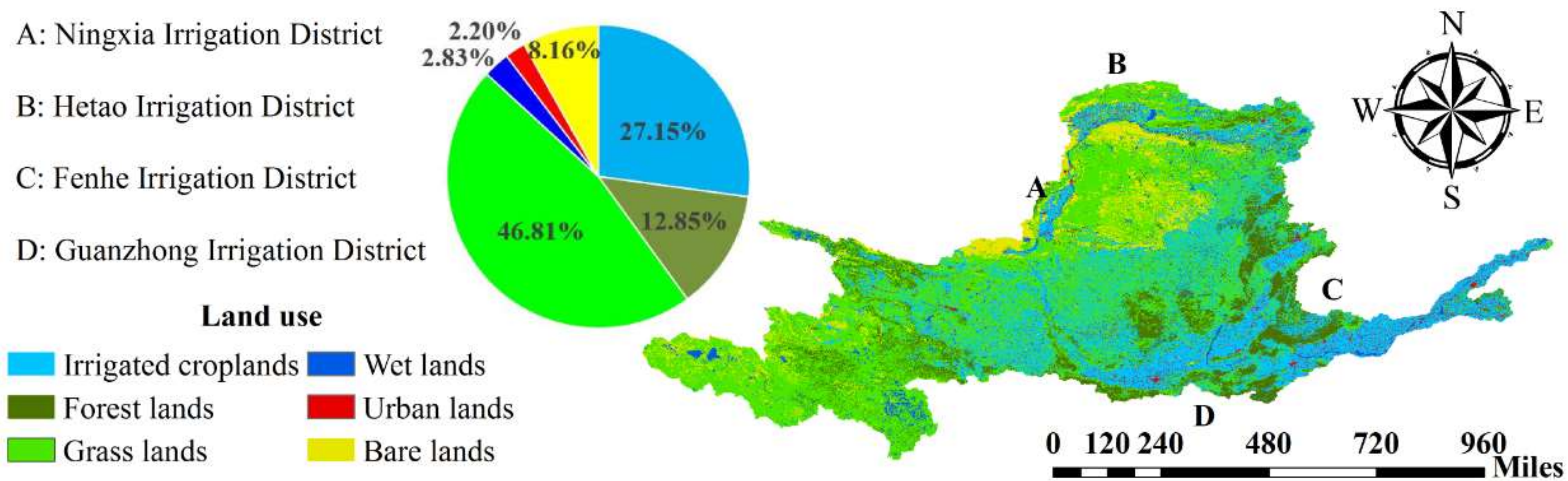


1. Introduction

- Case study: Yellow River Basin

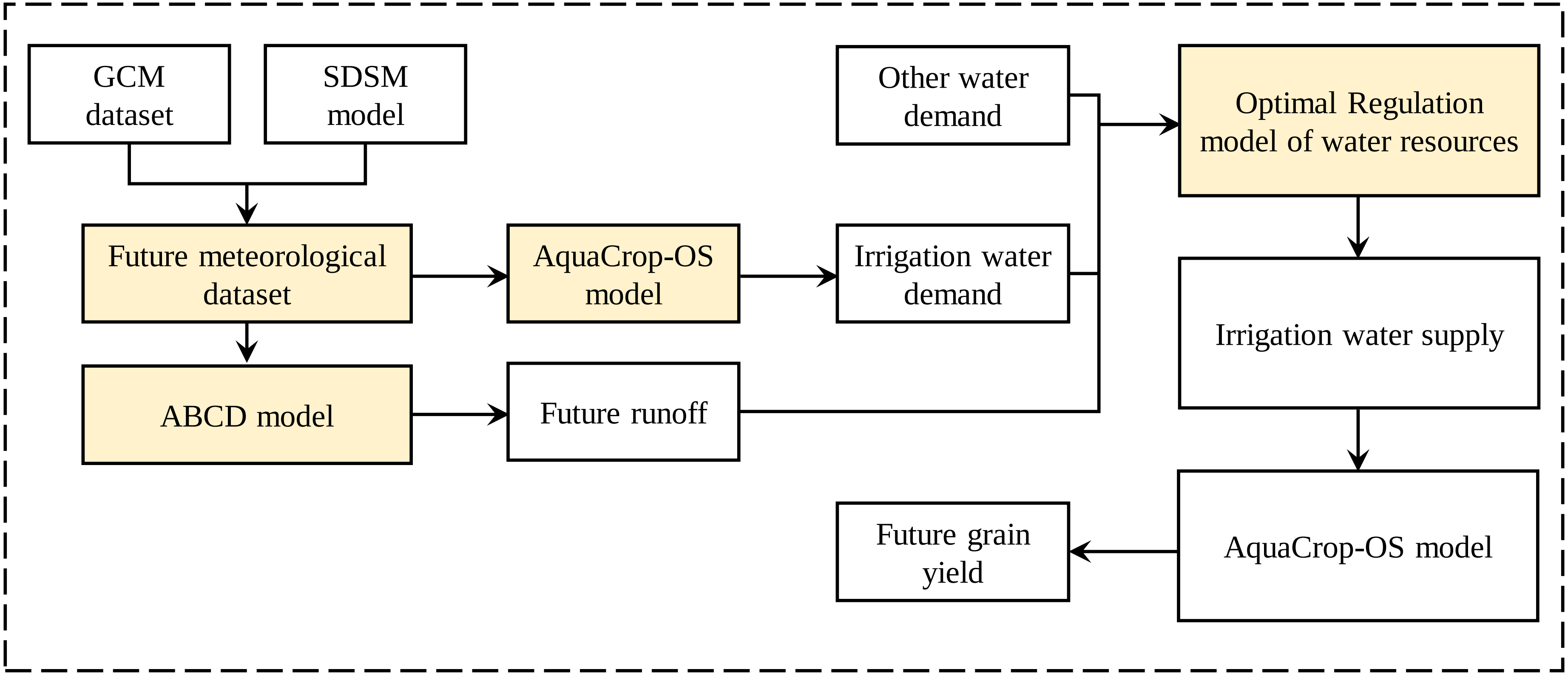
✓ The development and utilization rate of surface water in the Yellow River Basin has reached 86% and 71%, far exceeding the carrying capacity of water resources in the Yellow River

✓ Climate change is increasingly challenging the security of the water resources of the basin



2. Methodology and Model Construction

- Framework modeling the basin-scale water management
- Core Parts: Climate model, hydrological model, Crop growth model, Reservoir operation model, Water resources allocation model

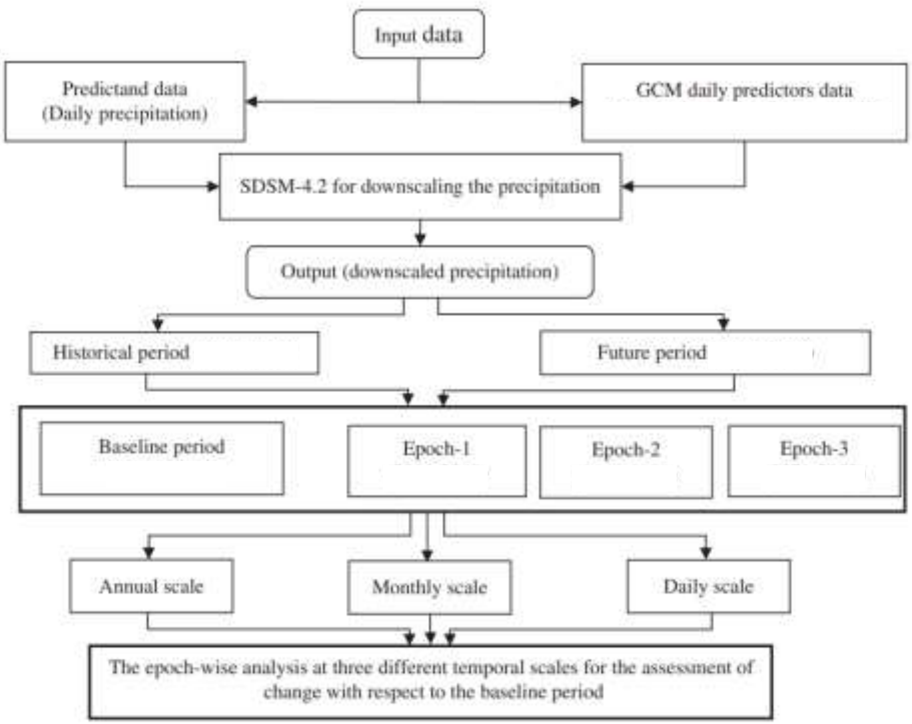


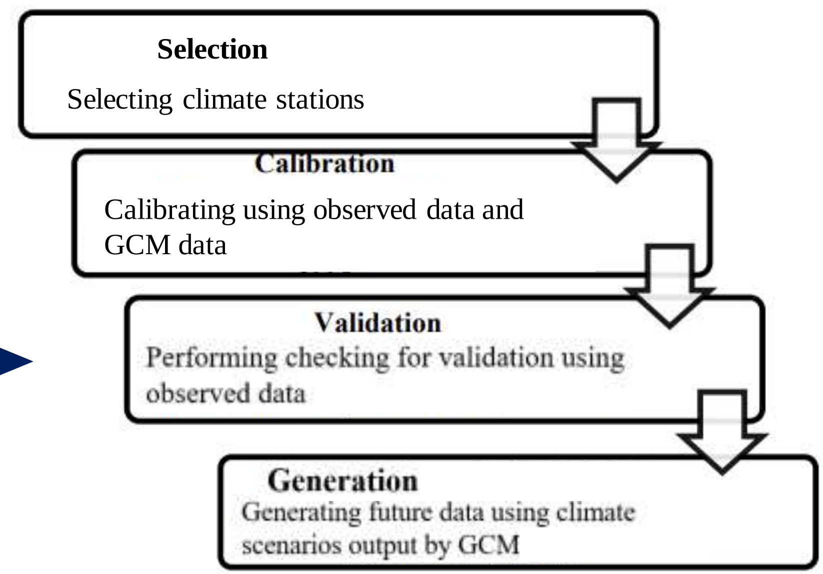
2. Methodology and Model Construction

✓ Climate model

- Three climate models: CanESM2, GFDL_ESM2G, and MIROC_ESM_CHEM
- Three emission scenarios: RCP2.6, RCP4.5, and RCP8.5
- Statistical down-scaling model (SDSM) is used to downscale the regional climate

Schematic diagram of SDSM





Pichuka and Maity (2017, Hydrological Sciences Journal)
Hassan et al (2017, Journal of Engineering Research and Education)

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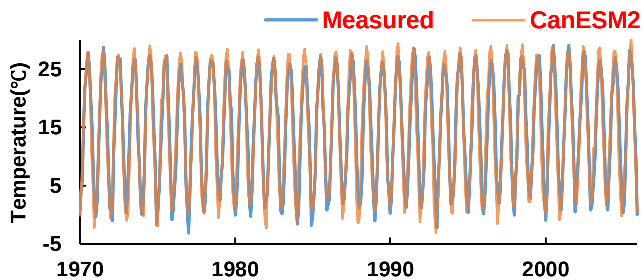

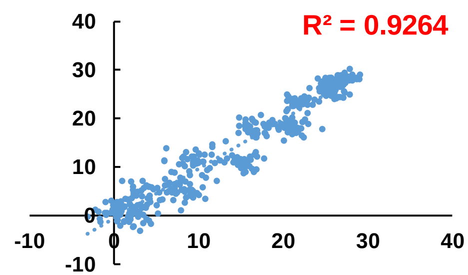

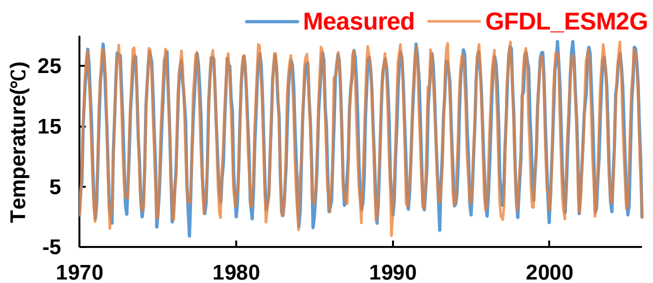

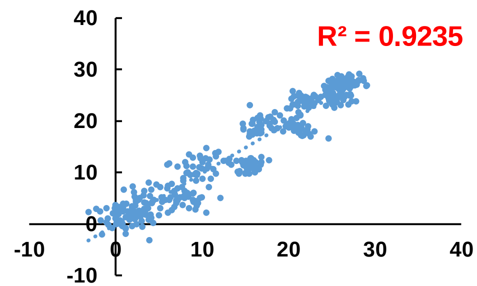

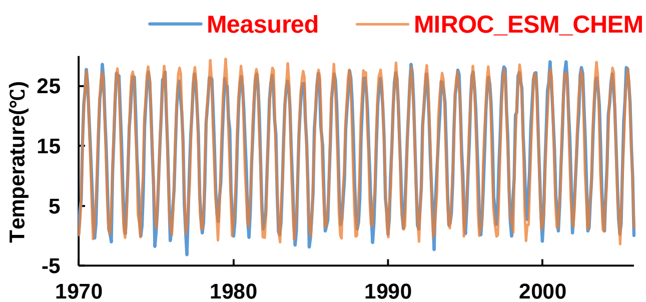

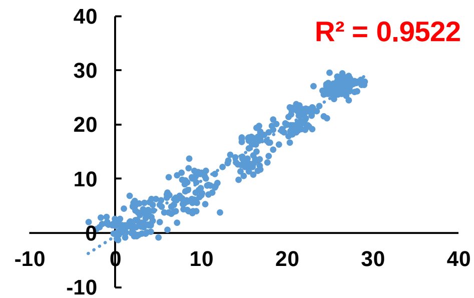

Observed and downscaled monthly maximum temperature during 1970-2005

* coefficient of determination (R^2)

2. Methodology and Model Construction

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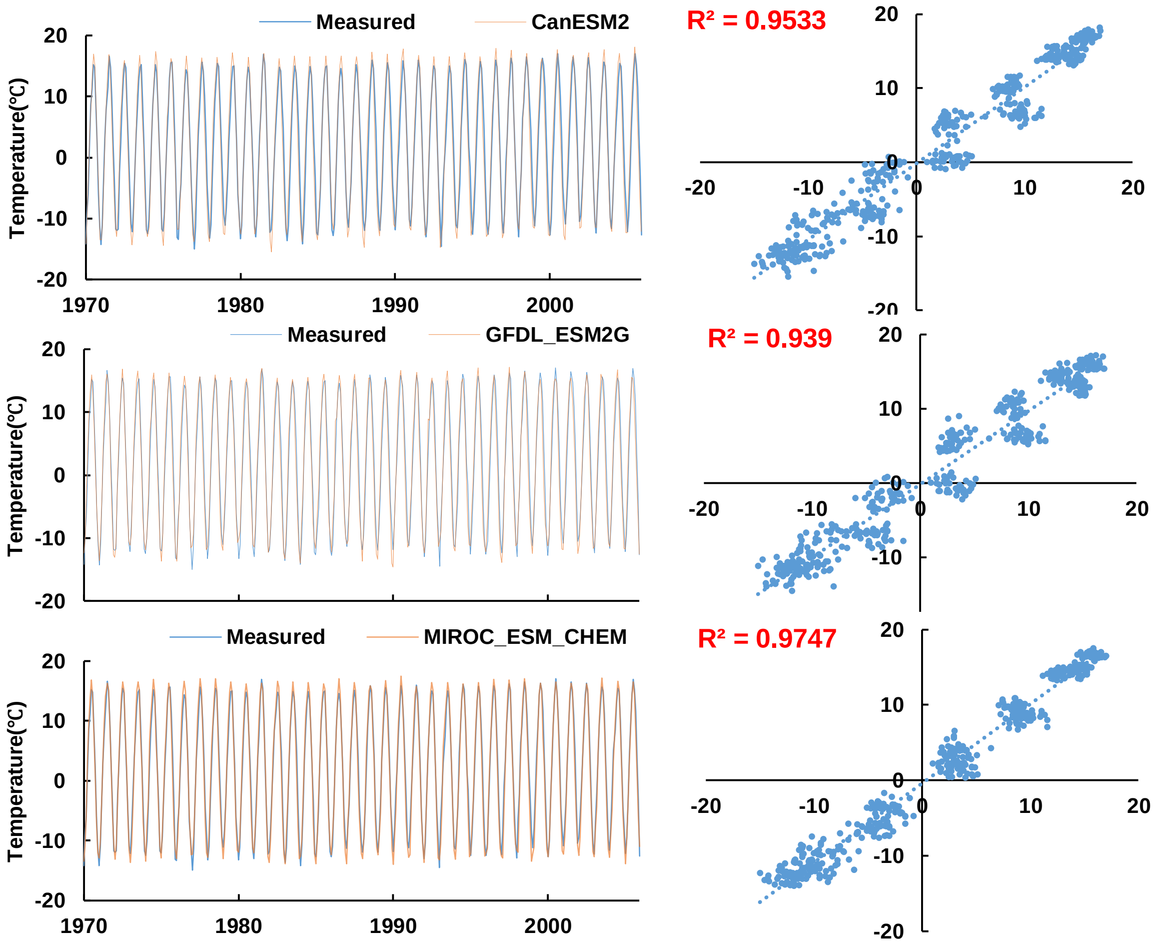

Observed and downscaled monthly minimum temperature during 1970-2005

2. Methodology and Model Construction

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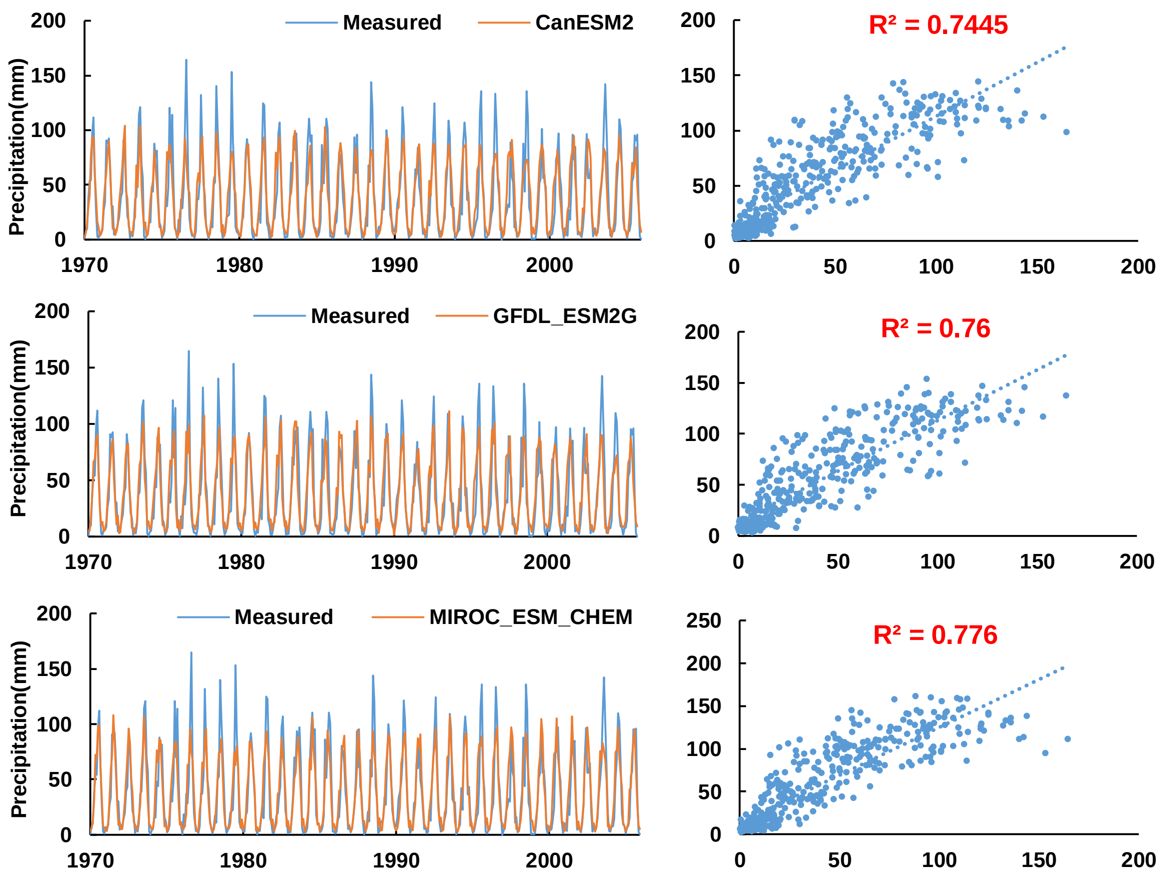
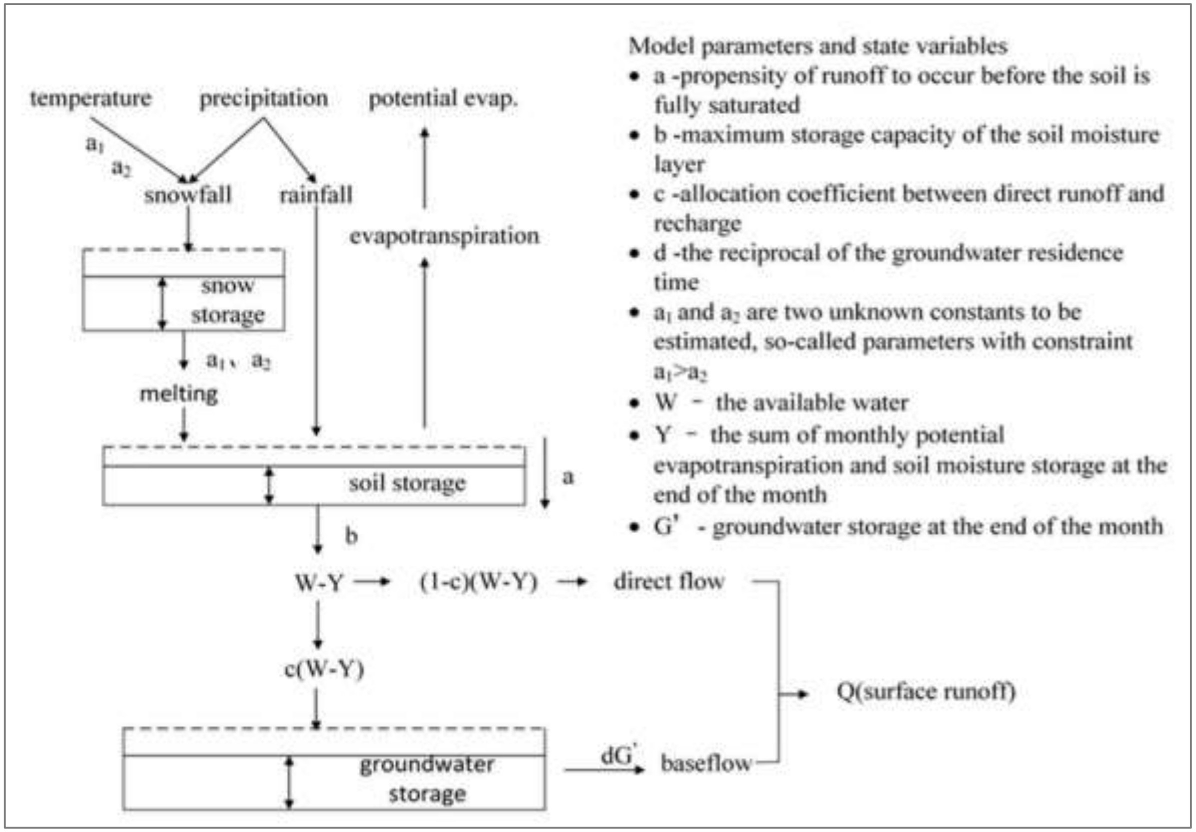


Observed and downscaled monthly precipitation during 1970-2005

2. Methodology and Model Construction

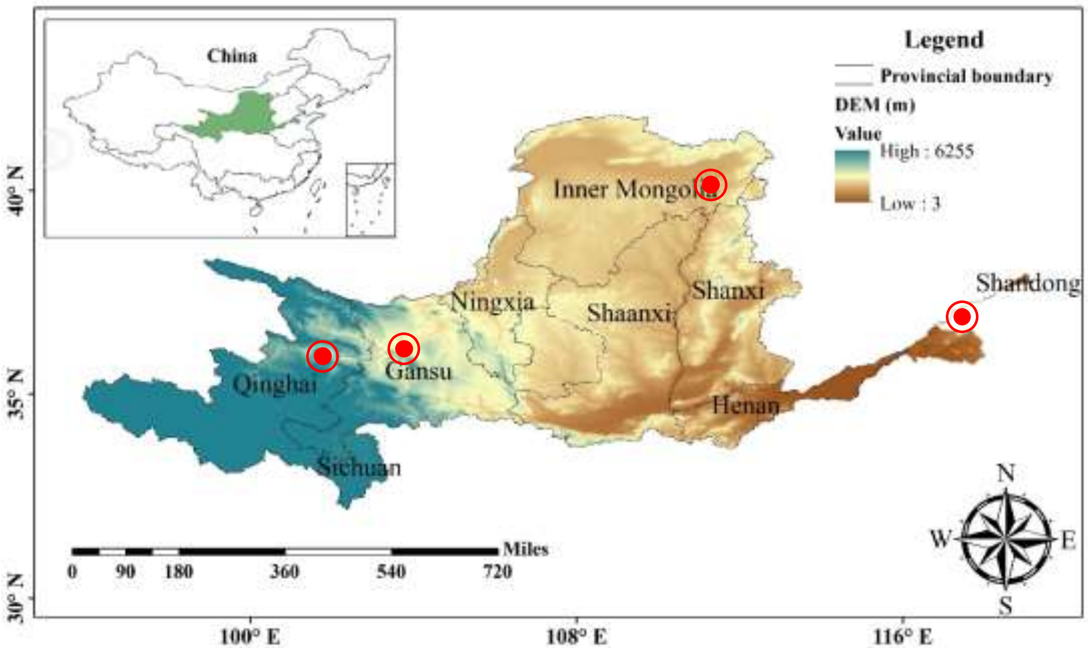
✓ Hydrologic model

- ABCD model: a simple, nonlinear hydrologic model with four parameters which accepts precipitation and potential evaporation as input, producing streamflow as output
- The modified model incorporating temperature-dependent hydrological processes for cold regions



2. Methodology and Model Construction

✓ Hydrologic model



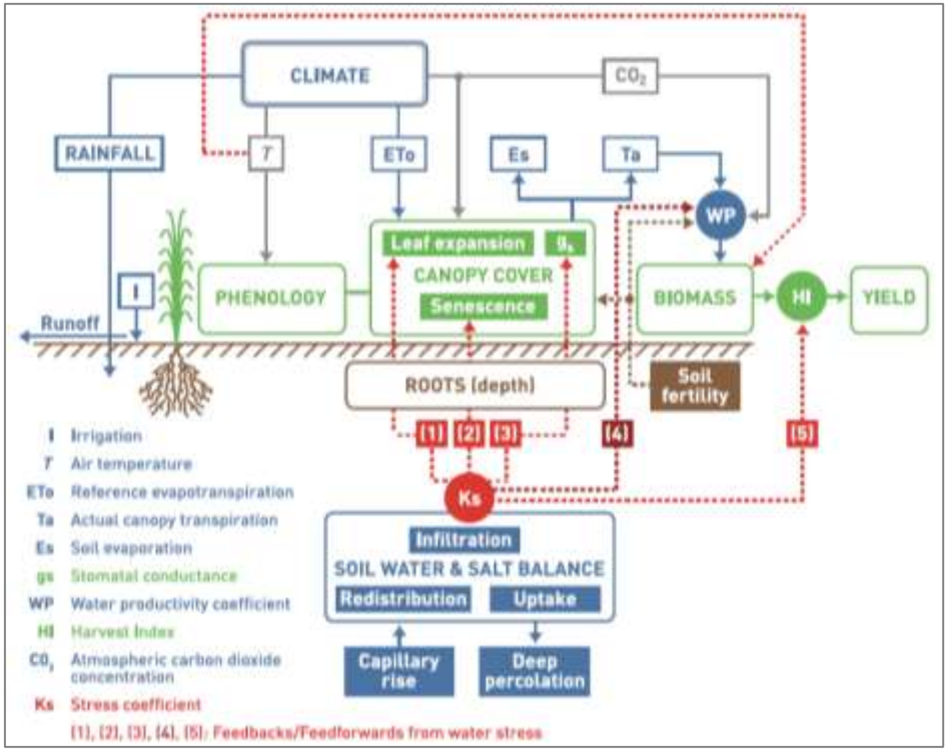
Station	Validation period (1991-2000)	
	NSE	R^2
Tangnaihai	0.65	0.85
Lanzhou	0.72	0.88
Toudaoguai	0.61	0.87
Lijin	0.56	0.75

Station	Calibration period (1975-1990)	
	NSE	R^2
Tangnaihai (TNH)	0.71	0.87
Lanzhou	0.79	0.89
Toudaoguai (TDG)	0.62	0.8
Lijin	0.61	0.75

- Observed streamflow data at TNH, Lanzhou, TDG and Lijin stations
- The NSE values are almost all higher than 0.60 (except the Lijin station) in the calibration and validation periods

2. Methodology and Model Construction

✓ Crop-growth model

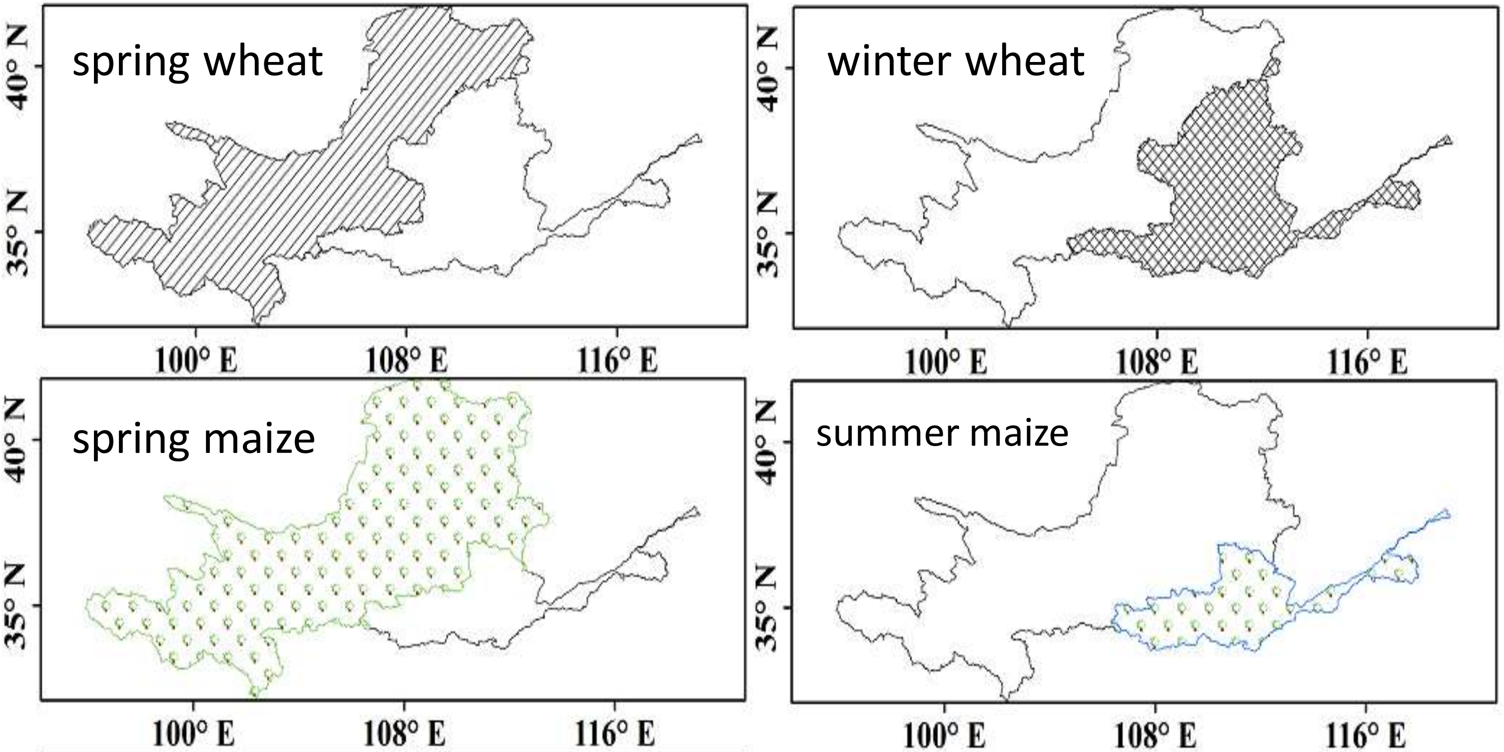


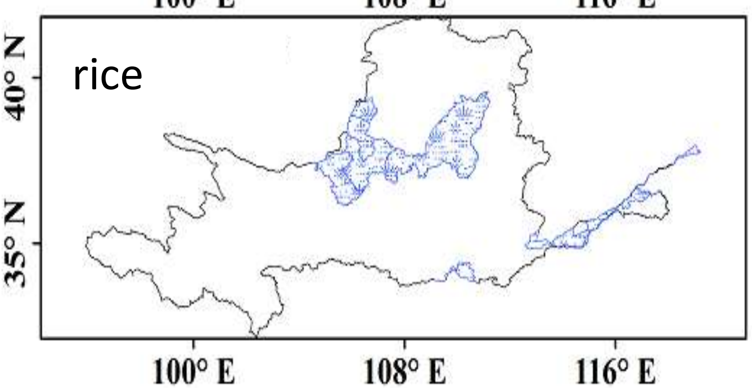
Flowchart of AquaCrop indicating the main components of soil-plant-atmosphere continuum
Steduto et al. (2009, FAO, Rome)

- AquaCrop model
- a water-driven process-based multi crop simulation model developed by FAO.
- The model is simple to use, requires fewer input data, and has a high level of simulation precision, making it a useful tool for forecasting crop yield under deficit irrigation and water management

2. Methodology and Model Construction

✓ Crop-growth model





- Spatial distribution of main crops in the Yellow River Basin
- Main crops: spring maize, summer maize, spring wheat, winter wheat, rice

2. Methodology and Model Construction

✓ Crop-growth model

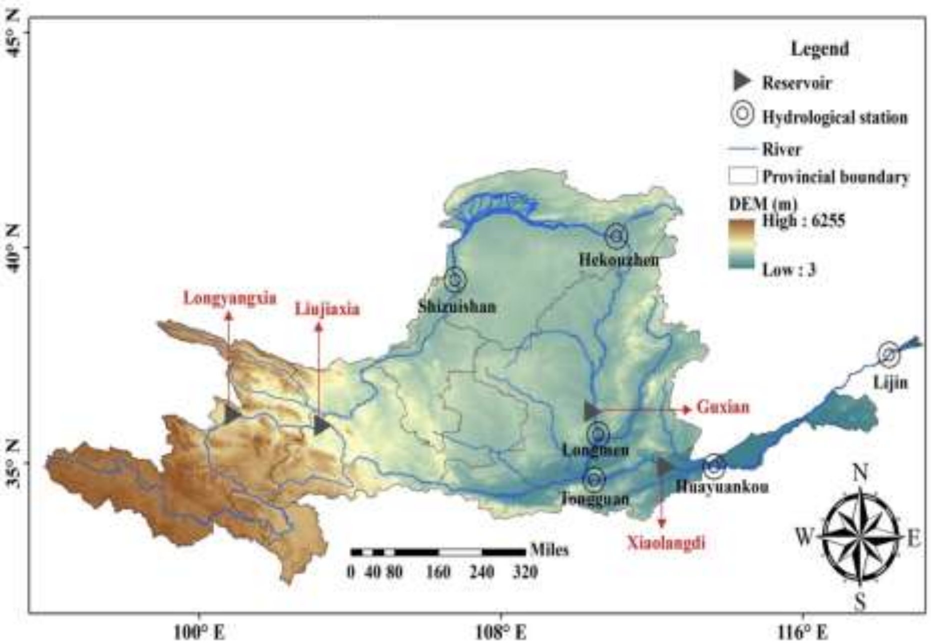
- Grain yield data of 69 cities in the Yellow River Basin are used to calibrate the Aquacrop model
- To reduce computation burden, the accuracy of the model is tested by comparing the simulated crop yield and statistical crop yield in the normal and dry years of precipitation

Performance of the Aquacrop model in the Yellow River Basin

Index	Winter wheat		Spring wheat		Summer maize		Spring maize		Rice	
	50%	75%	50%	75%	50%	75%	50%	75%	50%	75%
R^2	0.97	0.98	0.97	0.98	0.92	0.96	0.84	0.91	0.92	0.91
NRMSE	9.14	8.31	8.64	8.79	8.03	5.18	16.12	13.63	5.66	5.95
d	0.99	0.99	0.99	0.99	0.96	0.98	0.90	0.95	0.95	0.94

2. Methodology and Model Construction

✓ **Reservoir operation model** and water resources allocation model



1 Upstream region

- ✓ Long Yangxia--Multi-year regulation
- ✓ La Xiwa--Runoff regulation
- ✓ Li Jiaxia-- Runoff regulation
- ✓ Gong Boxia-- Runoff regulation
- ✓ Ji Shixia-- Runoff regulation
- ✓ Liu Jiaxia--Annual regulation

2 Midstream region

- ✓ Wan Jiazhai--Seasonal regulation
- ✓ Gu Xian--Annual regulation

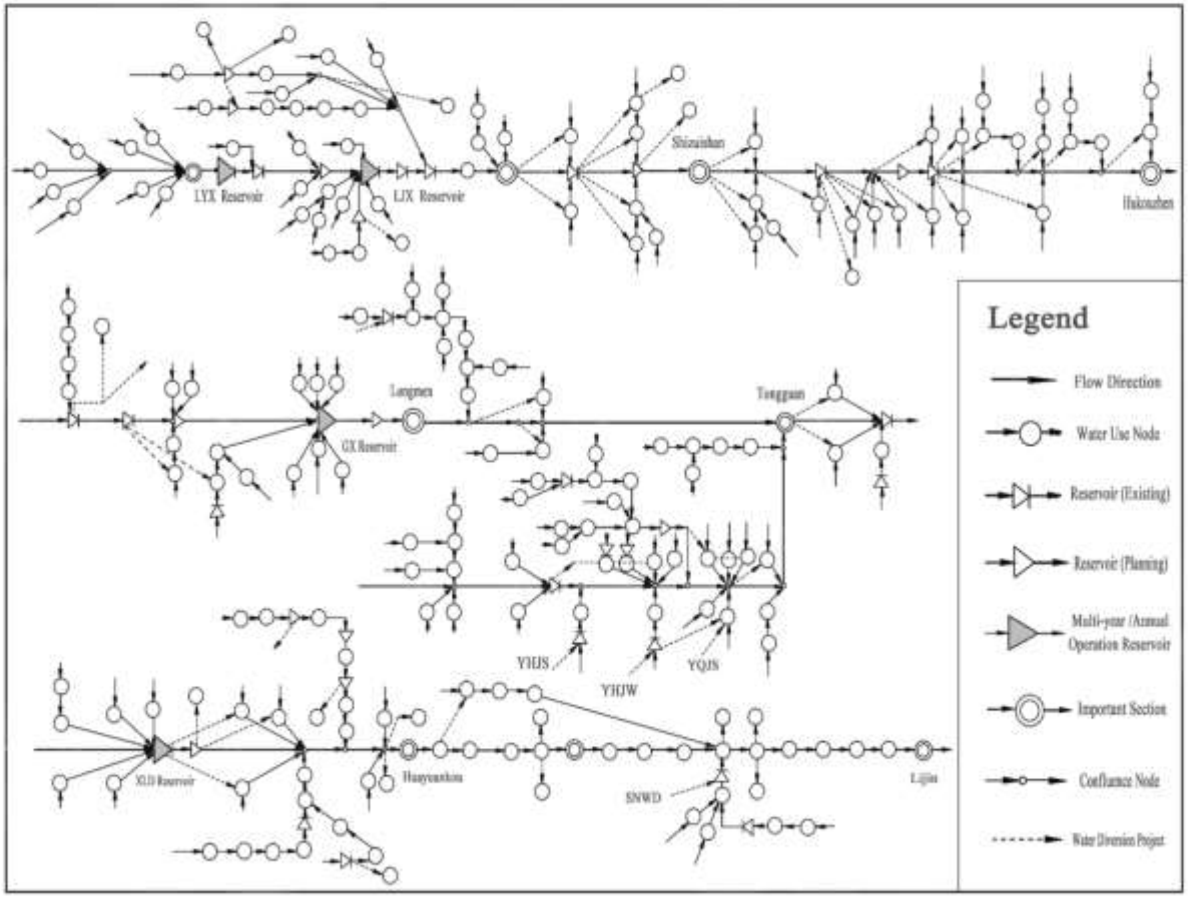
3 Downstream region

- ✓ San Menxia-- Runoff regulation
- ✓ Xiao Langdi--Annual regulation

- The Longyangxia, Liujiaxia, Guxian and Xiaolangdi cascade reservoirs are used
- Guxian is under planning and construction and expected to be completed in 2030

2. Methodology and Model Construction

✓ Reservoir operation model and **water resources allocation model**



Nodes map of the Yellow River Basin

- There are 524 water users (157 domestic, 146 industrial, 57 ecological, and 164 agricultural water users) in the water use nodes.

2. Methodology and Model Construction

✓ Reservoir operation model and water resources allocation model

- Objective

1. Volume — the amount of water shortage — $\left(\sum_{i=1}^{I}\sum_{t=1}^{T}\gamma(i,t)\left(Q_d(i,t)-Q_s(i,t)\right)\Delta t\right)$

+

2. Time dimension — temporal variance of water shortage rate — $\left(\sqrt{\frac{1}{T}\cdot\sum_{t=1}^{T}\left(R-\bar{R}\right)^2}\right)$

+

3. Space dimension — spatial variance of water shortage rate — $\left(\sqrt{\frac{1}{S}\cdot\sum_{s=1}^{S}\left(R-\bar{R}\right)^2}\right)$

↓

$$F=\min\left(\sum_{i=1}^{I}\sum_{t=1}^{T}\gamma(i,t)\left(Q_d(i,t)-Q_s(i,t)\right)\Delta t\right)\left(\sqrt{\frac{1}{T}\cdot\sum_{t=1}^{T}\left(R_t-\bar{R}_T\right)^2}\right)\left(\sqrt{\frac{1}{S}\cdot\sum_{s=1}^{S}\left(R_s-\bar{R}_S\right)^2}\right)$$

2. Methodology and Model Construction

✓ Reservoir operation model and water resources allocation model

- Constraints

(1) Water balance between nodes

$$Q_{down,t} = Q_{up,t-1} \times \frac{t}{T} + Q_{up,t} \times \frac{(T-t)}{T} + q_{add,t} + q_{return,t} - q_{divers,t} - q_{loss,t}$$

(2) Reservoir water balance

$$V(m,t+1) = V(m,t) + \left(QI(m,t) - QO(m,t)\right) \times \Delta t$$

(3) Constraints on reservoir storage and release

$$Vmin(m,t) \le V(m,t) \le Vmax(m,t) \qquad Qmin(m,t) \le QO(m,t) \le Qmax(m,t) \qquad Nmin(m,t) \le N(m,t) \le Nmax(m,t)$$

(4) Ecological water supply constraint

Constraint on water demand for the ecological environment in Lijin

Month	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Flow (m^3/s)	800	1000	1000	1500	300	200	50	50	300	300	400	300

2. Methodology and Model Construction

✓ Reservoir operation model and water resources allocation model

- Constraints

(5) Ice-jam prevention constraint

Ice jams occur in Lanzhou from November to the following March and in Huayuankou from December to the following April
so the discharge from Liujiaxia reservoir must comply with flood-control limitations from November to March, as does the discharge from Xiaolangdi reservoir from December to April.

Critical flow value for ice-jam prevention at Lanzhou and Huayuankou in different periods (m^3/s).

Section	Critical value	December	January	February	March
Lanzhou	Q_{maxlan}	700	700	700	500
	Q_{minlan}	500	400	550	100
Huayuankou	Q_{maxhua}		600	400	
	Q_{minhua}		500	300	

2. Methodology and Model Construction

✓ Reservoir operation model and water resources allocation model

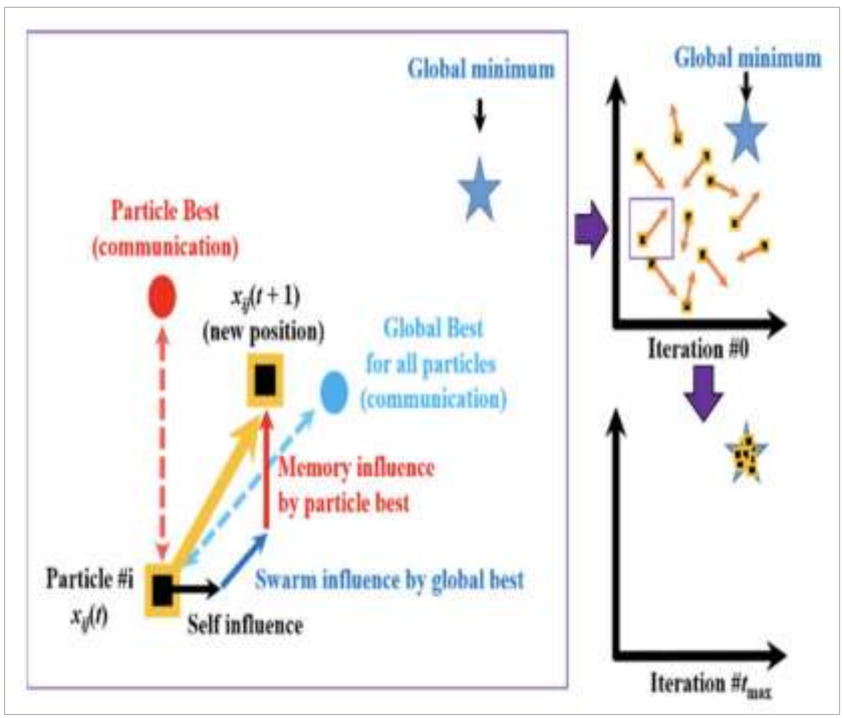
4 reservoirs × 30 years × 12 months/year = 1440 decision variables

164 agricultural water users × 30 years × 12 months/year = 59040 decision variables

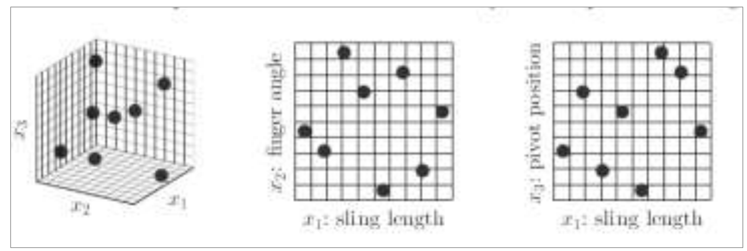
- Solution

Outer Layer: Optimal Operation Model of Cascade Reservoirs

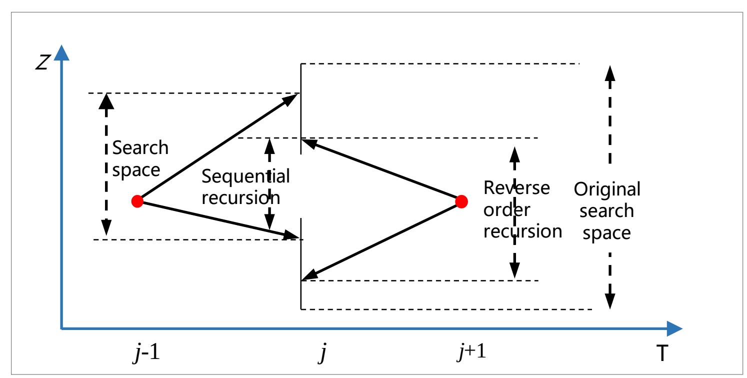
Particle swarm optimization (PSO) algorithm



Space-filling Latin Hypercube sampling plan



Search space reduction strategy



2. Methodology and Model Construction

✓ Reservoir operation model and water resources allocation model

- Solution

Inner Layer: Optimal Allocation Model of Water Resources

1. Objective Minimum spatial variance of water shortage rate $\left(\sqrt{\frac{1}{S}\cdot\sum_{s=1}^{S}\left(R-\bar{R}\right)^{2}}\right)$

2. The priority of water resource allocation is setted as follows: domestic, industrial, ecological, and agricultural water

3. Sequential quadratic programming (SQP) is employed to solve the water resources allocation model
It is powerful enough for real problems because it can handle any degree of non-linearity including non-linearity in the constraints

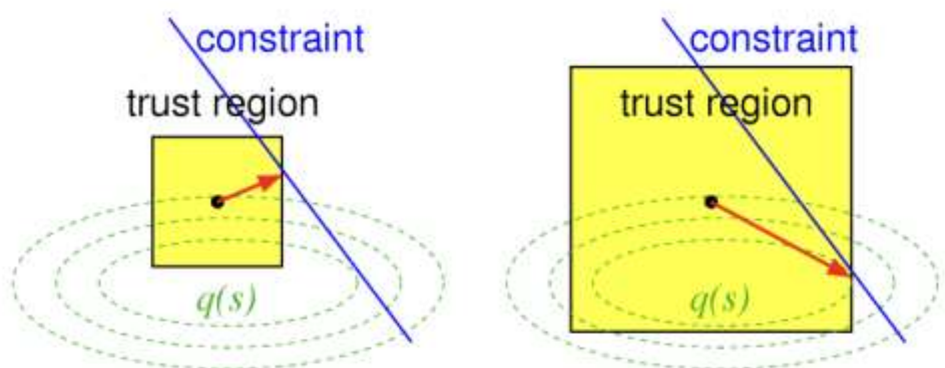
SQP: Sequential Quadratic Programming

Newton method to solve the KKT conditions

$$\min_{\mathbf{x}} \quad f(\mathbf{x}) \qquad \text{s.t.} \quad \mathbf{h}(\mathbf{x}) = \mathbf{0}$$

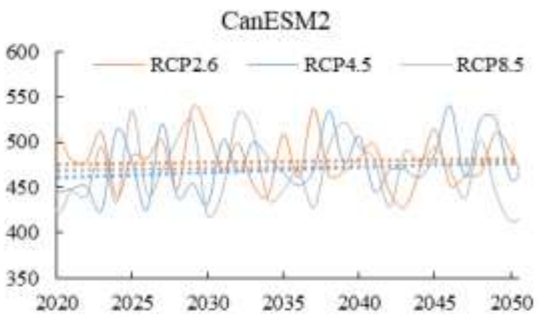
KKT points: $\frac{\partial L}{\partial \mathbf{x}} = \frac{\partial f}{\partial \mathbf{x}} + \boldsymbol{\lambda}^T \frac{\partial \mathbf{h}}{\partial \mathbf{x}} = \mathbf{0}^T$

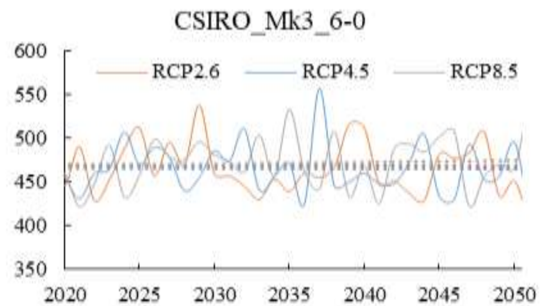
Newton: $$\begin{bmatrix} \frac{\partial^2 L}{\partial \mathbf{x}^2} & \frac{\partial^2 L}{\partial \mathbf{x}\partial \boldsymbol{\lambda}} \\ \frac{\partial^2 L}{\partial \boldsymbol{\lambda}\partial \mathbf{x}} & \frac{\partial^2 L}{\partial \boldsymbol{\lambda}^2} \end{bmatrix} \begin{Bmatrix} \Delta \mathbf{x} \\ \Delta \boldsymbol{\lambda} \end{Bmatrix} = -\begin{Bmatrix} \frac{\partial L}{\partial \mathbf{x}} \\ \frac{\partial L}{\partial \boldsymbol{\lambda}} \end{Bmatrix}$$

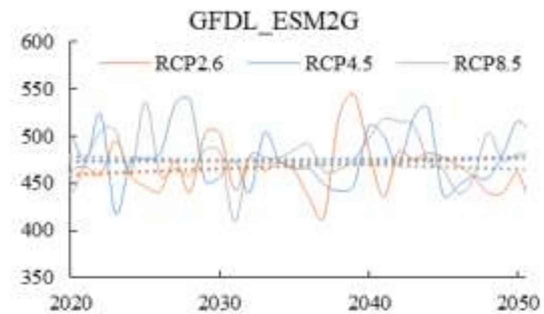


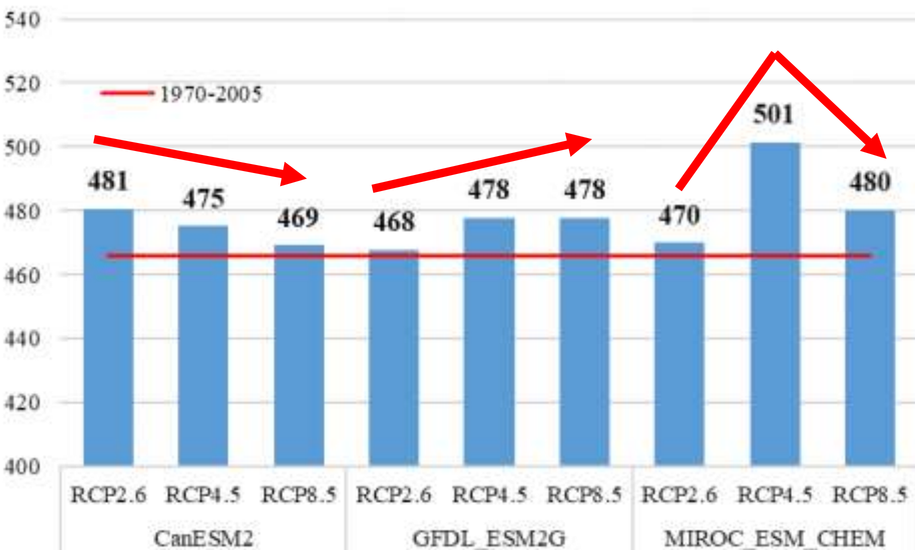
3. Results

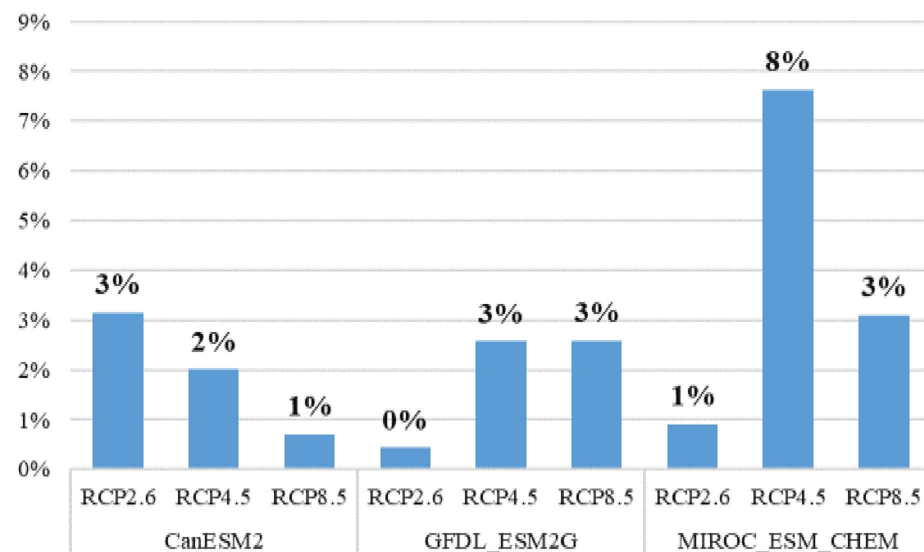
- ✓ Projections of three GCMs are used to analyze future climate change in 2020-2050 for YRB
- ✓ **Precipitation** doesn't increase or decrease with the emission scenarios (RCP2.6, RCP4.5, RCP8.5)
- ✓ The projected annual precipitation (2020-2050) is expected to rise slightly as compared to the baseline of 1970-2005
- ✓ The largest increase is 8% under the MIROC_ESM_CHEM climate model, RCP4.5





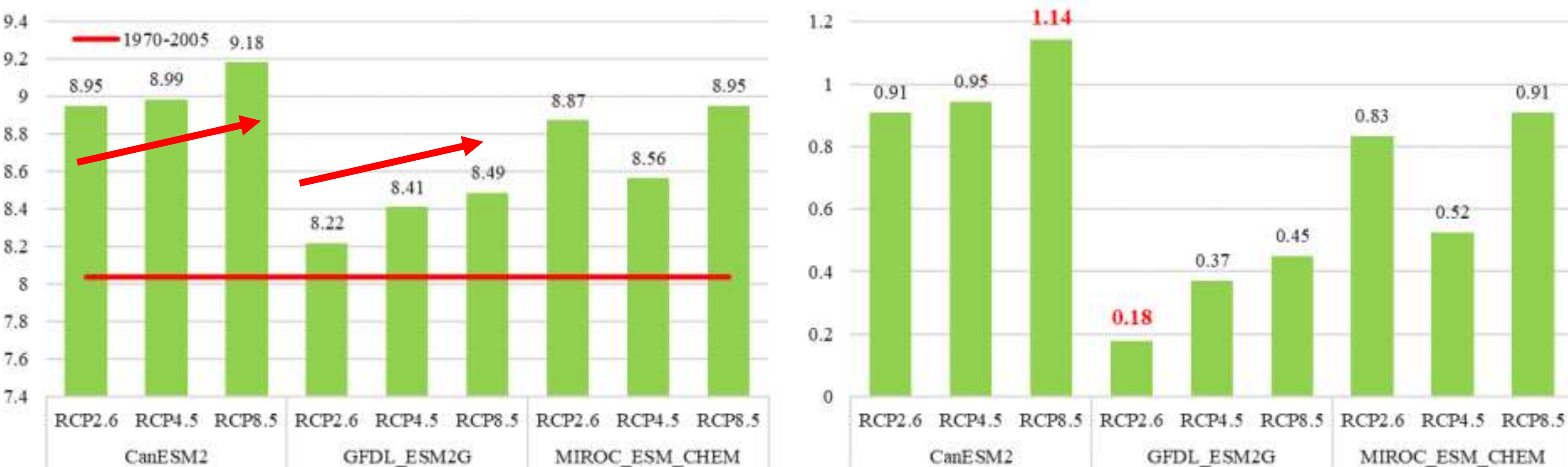






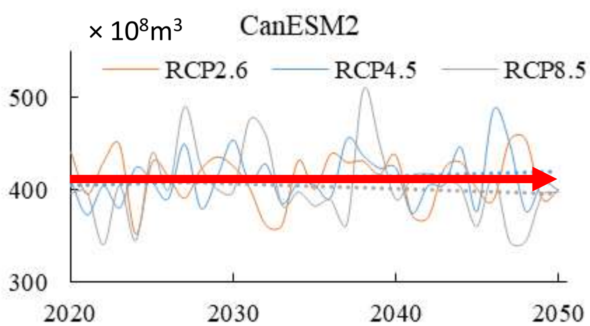
3. Results

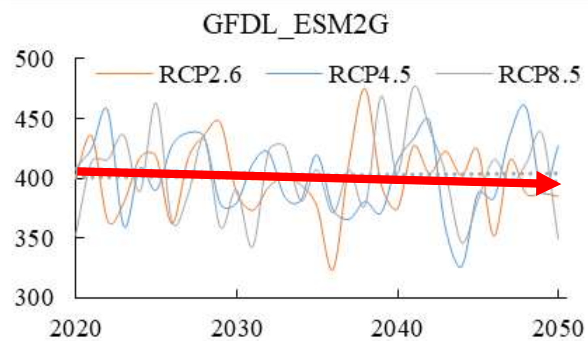
- ✓ All GCM model results show a **temperature** increase compared to the baseline of 1970-2005
- ✓ The largest increase is 1.14 °C under the CanESM2 climate model, RCP8.5

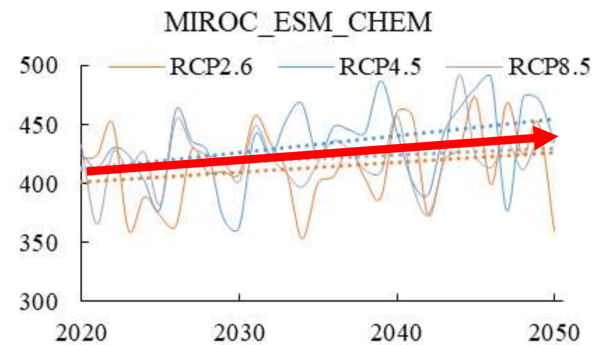


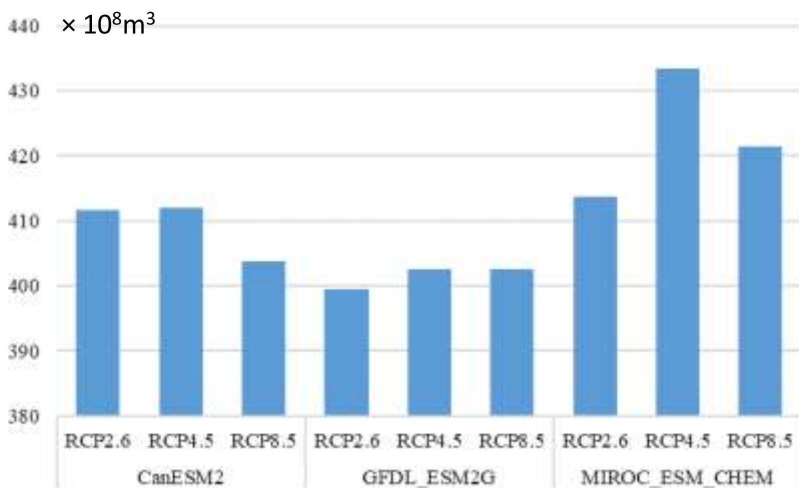
3. Results

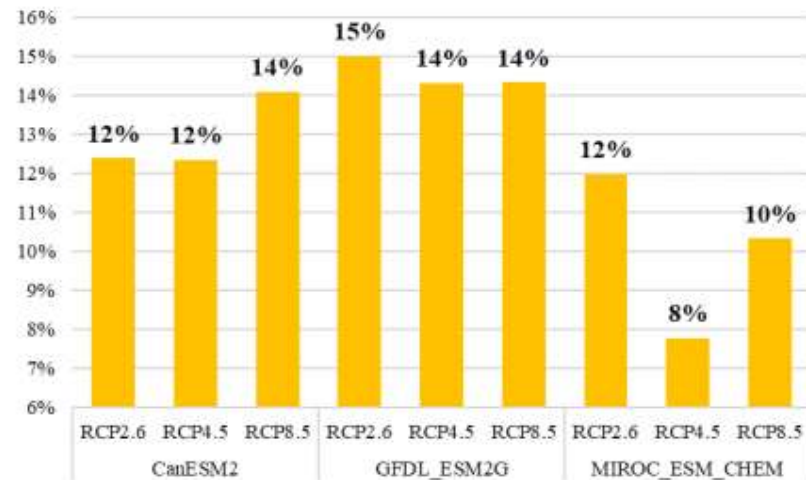
- ✓ The estimated average annual **runoff** in the Yellow River Basin is lower than that in the baseline of 1970-2005 (470 × $10^8 m^3$)
- ✓ The decrease of annual runoff ranges from 8% to 15%



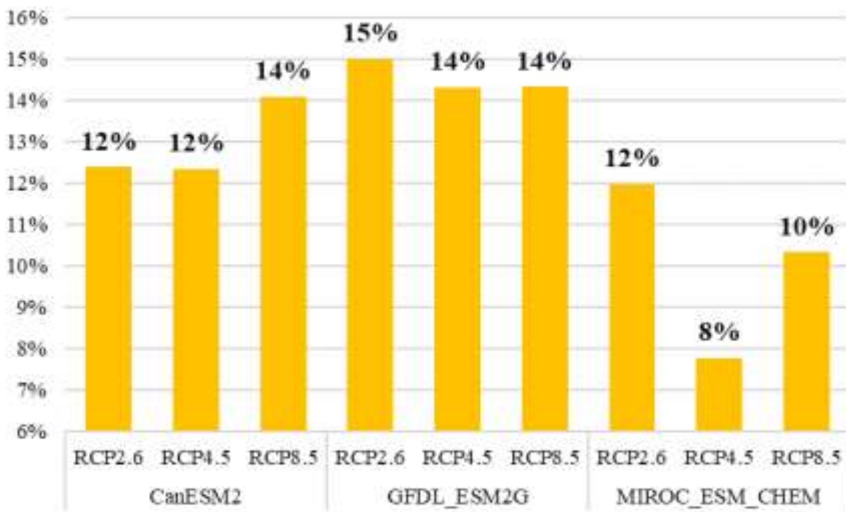


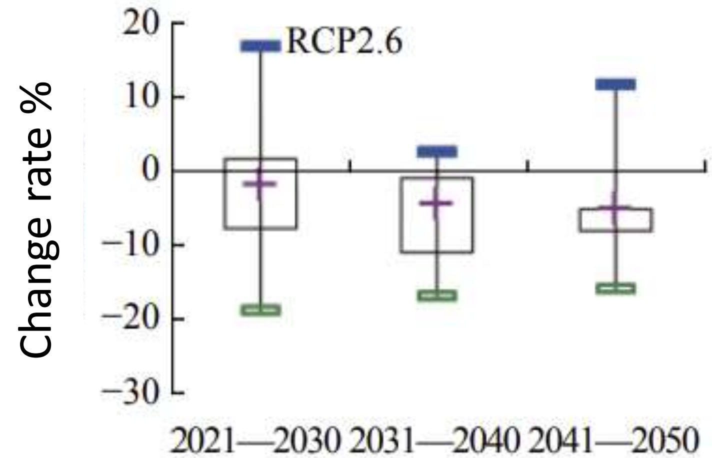


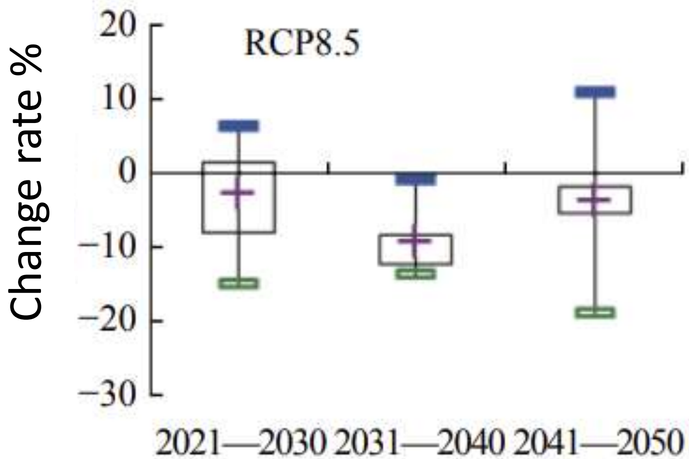


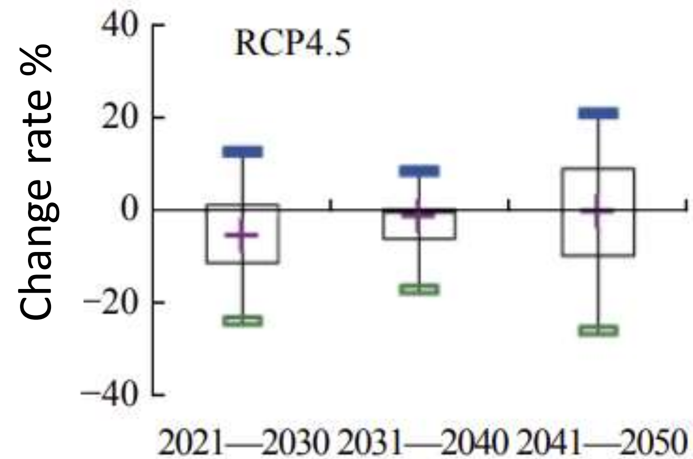


3. Results



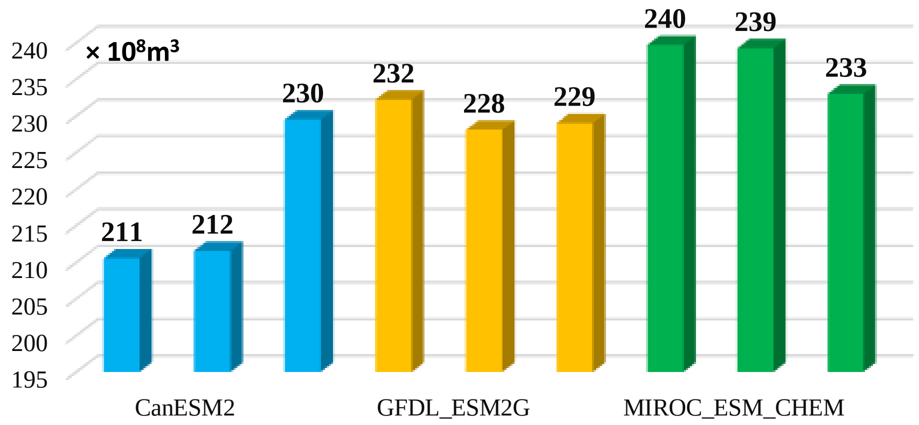


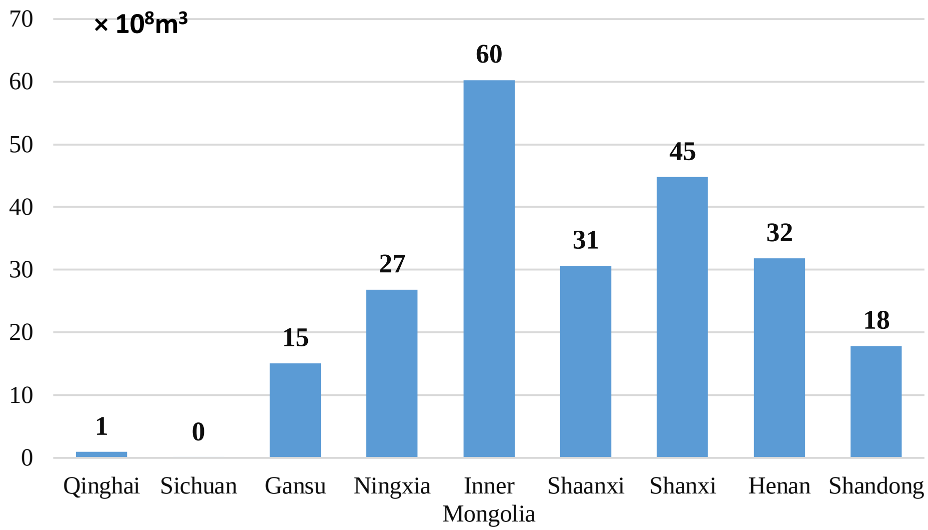




Wang et al. (2020, Hydro-Science and Engineering)

3. Results





- ✓ The **irrigation water demand** in the Yellow River Basin changes remarkably with the climate models
- ✓ The average annual irrigation water demand ranges from 211 to 240 × $10^8 m^3$ (290 × $10^8 m^3$ under the present situation from Yellow River Water Resources Commission)
- ✓ The irrigation water demand is greater under GFDL_ESM2G and MIROC_ESM_CHEM than CanESM2
- ✓ Especially under the CanESM2 model, the difference between maximum and minimum irrigation water demand is nearly 20 × $10^8 m^3$
- ✓ The irrigation water demands of Inner Mongolia, Shanxi and Henan are in the top three

3. Results

- ✓ The **irrigation water shortage rate** ranges from 34% to 45% under different climate models
- ✓ The average grain yield under climate change is 97 million tons in the Yellow River Basin
- ✓ The climate model has relatively remarkable impact on grain yield. The difference between maximum and minimum grain yield reaches to 16 million tons (17% of the 97 million tons)

Climate model	Emission scenario	Agricultural water supply($10^8 m^3$)	Water deficient ratio (%)	Grain yield (10^6 ton)
CanESM2	RCP2.6	192.55	35.33	101.17
	RCP4.5	177.16	38.81	98.89
	RCP8.5	172.6	43.39	99.33
GFDL_ESM2G	RCP2.6	208.56	35.34	104.84
	RCP4.5	202.87	33.79	98.4
	RCP8.5	195.89	37.86	99.69
MIROC_ESM_CHEM	RCP2.6	199.31	37.62	93.01
	RCP4.5	175.4	45.10	88.53
	RCP8.5	183.97	37.89	92.30

4. Conclusion

- ✓ The essence of water resources management model under climate change is a coupled natural and human model. The climate model, hydrologic model, crop growth model, reservoir operation model, and water resources allocation model are the key components of the model.
- ✓ The precipitation and temperature in the Yellow River Basin both increase under different climate models.
- ✓ The changes of difference of temporal-spatial precipitation and temperature under climate change leads to the decreasing runoff in the Yellow River Basin.
- ✓ The grain yield in the Yellow River Basin presents a remarkable difference between different climate models. The uncertainty embedded in climate models should attract considerable attention.

THANKS FOR YOUR KIND ATTENTION