State Key Laboratory of Numerical Modelling for Atmospheric Sciences
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A quasi three-dimensional variably saturated groundwater flow model for climate modeling

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Outline

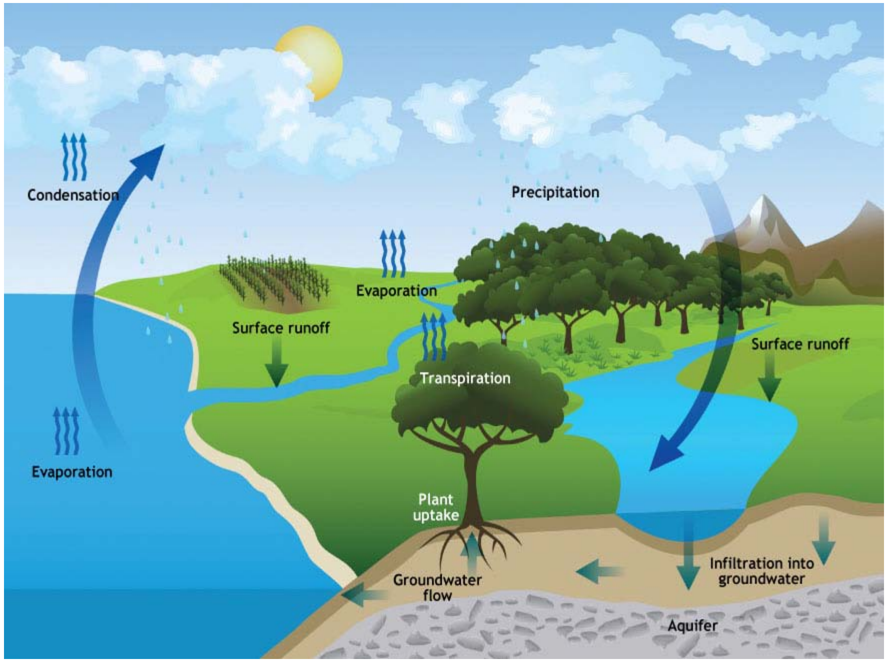
- Motivation
- A quasi three-dimensional variably saturated groundwater flow model
- Model validations
- Summary and discussion

Motivation

- Dynamic variations in the water table over a region directly influence soil moisture at the surface, latent and sensible heat fluxes;
- Developing an appropriate groundwater-soil water interaction model including lateral flow for climate modeling will facilitate accurate estimation of water table depths and the improvement of simulations in land surface processes and climate;

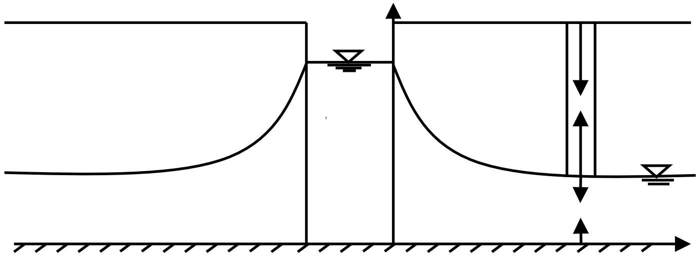
However

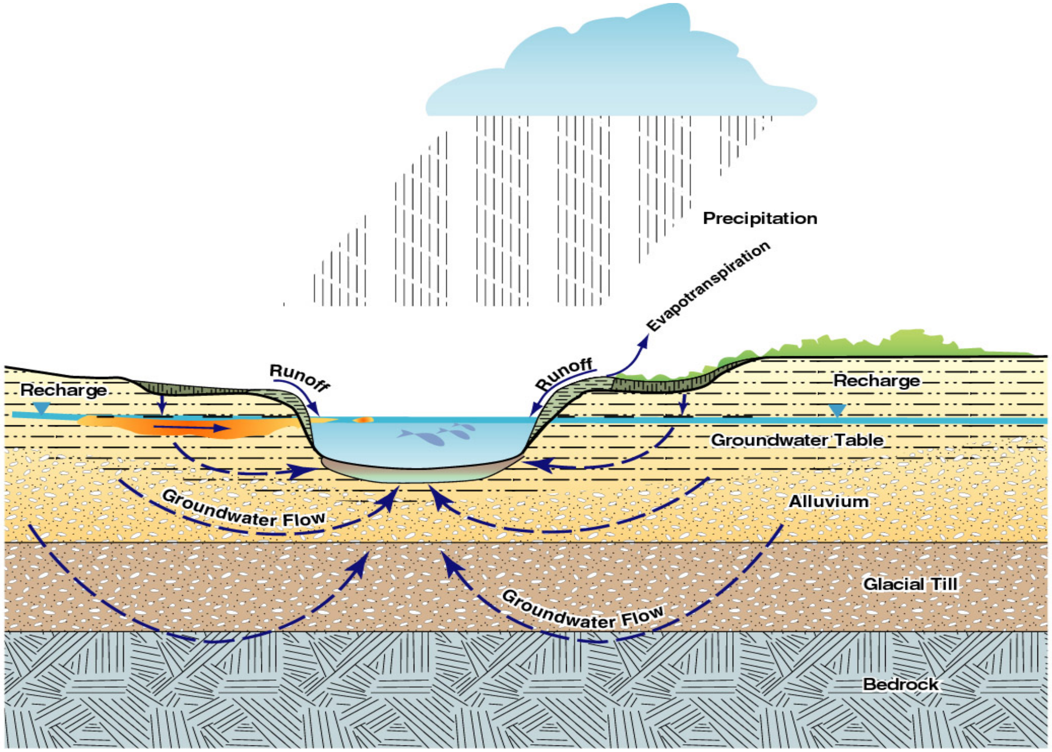
- Most of current land surface models for climate modeling do NOT consider lateral flow .



Current LSMs for climate modeling requires:

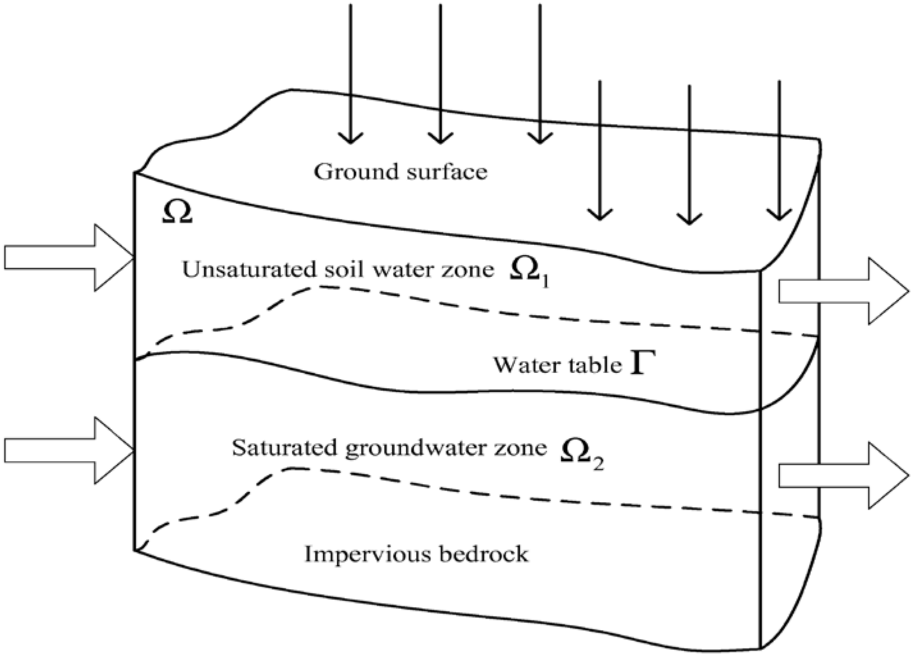
- Better representation of spatial heterogeneity to realistically simulate water-energy-land use interactions across spatial scales(including the interactions between land hydrological processes and climate, lateral flow of groundwater);
- Improved accuracy in simulating the physical systems for better predictions of future climate change and impacts.
- Groundwater-soil water interaction model for climate modeling should include vertical flow lateral flow and can be used in the current land surface models.





The purpose of this study

- A quasi three-dimensional numerical model for flow of soil water and groundwater is constructed for climate modeling.
- Synthetic experiments by the model were conducted to test the sensitivities of the model, comparison of the simulation by the model and that by a full three-dimensional model;
- A case of stream water conveyance in the lower reaches of Tarim River was then applied to validate the model;
- A numerical experiment by the model for Tarim River Basin was conducted to discuss the latent flow for large-scale high-relief topography with stream water conveyance.



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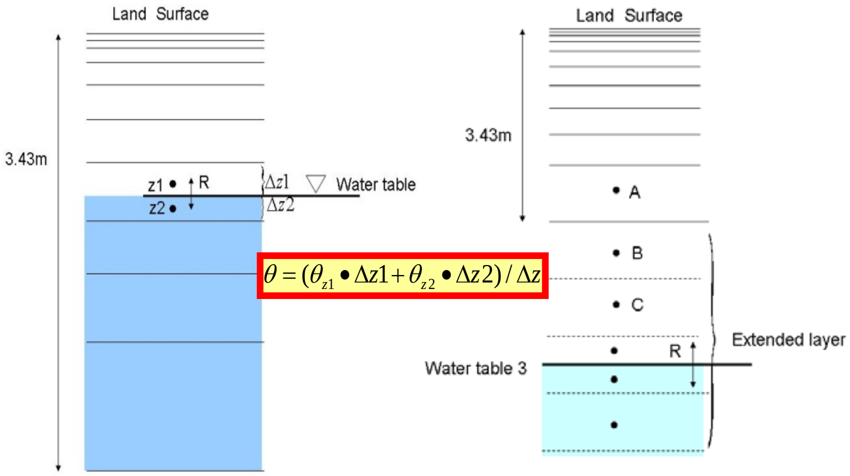
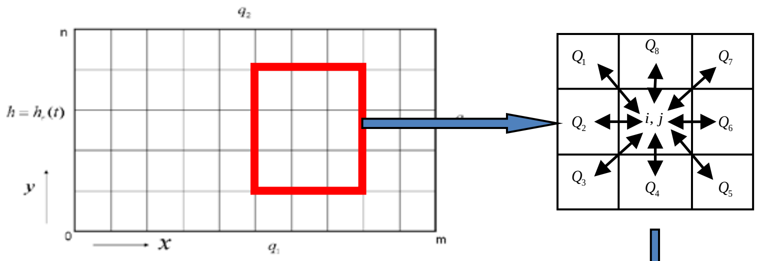
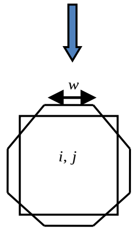
A quasi-3D variably saturated groundwater flow model

- A quasi 3-D groundwater model is constructed for climate modeling by dividing 3-D soil water and groundwater flow into an unsaturated soil water flow and a horizontal groundwater flow;
- It consists of a one-dimensional unsaturated soil water flow model with the water table as the moving boundary using an adaptive grid structure, a two-dimensional groundwater flow model for the horizontal domain, and an interface model.





Plan view of datum plane.



$$\frac{dS_g}{dt} = \Delta x \Delta y q + \sum_{1}^{8} Q_n - Q_r$$

Zhenghui Xie, Zhenhua Di, Zhendong Luo, Qian Ma, A quasi three-dimensional variably saturated groundwater flow model for climate modeling, ***Journal of Hydrometeorology***, DOI: 10.1175/JHM-D-10-05019.1, 2012.

A quasi-3D variably saturated groundwater flow model

- **The moving boundary problem for the interaction between soil water and groundwater**
- **A quasi three-dimensional model framework for the interaction between soil water and groundwater**
    A. The one-dimensional unsaturated soil water flow model for a vertical soil column
    B. The two-dimensional groundwater flow model
    C. The connection equation
- **An adaptive grid structure for the unsaturated soil water flow model with water table as the moving boundary**
- **The quasi three-dimensional model numerical algorithms**

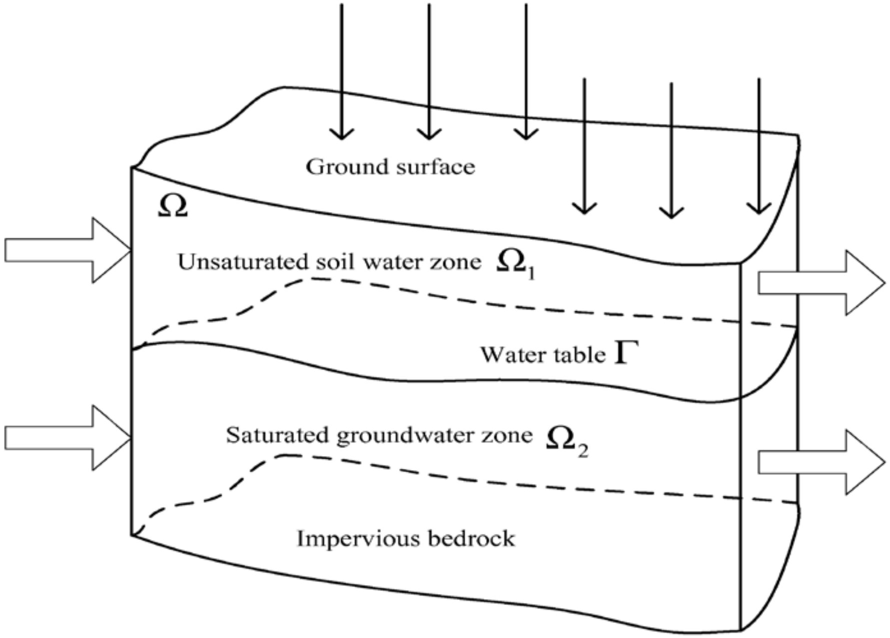
The moving boundary problem

- **The moving boundary problem for the interaction between soil water and groundwater**

$$\frac{\partial\theta}{\partial t}-\nabla\cdot\left(D(\theta)\nabla\theta\right)-\frac{\partial K(\theta)}{\partial z}=g(x,y,z)$$

$$S_s\frac{\partial\psi}{\partial t}-\nabla\cdot\left(K_s\nabla\psi\right)-g(x,y,z)=0$$

$$V_n=\left(q_s-q_u\right)\cdot\mathbf{n}(t)$$



The equations with initial and boundary conditions are formulated into the three-dimensional moving boundary problem.

A quasi-3D model framework

- **A quasi three-dimensional model framework for the interaction between soil water and water, groundwater**

A. The one-dimensional unsaturated soil water flow model for a vertical soil column

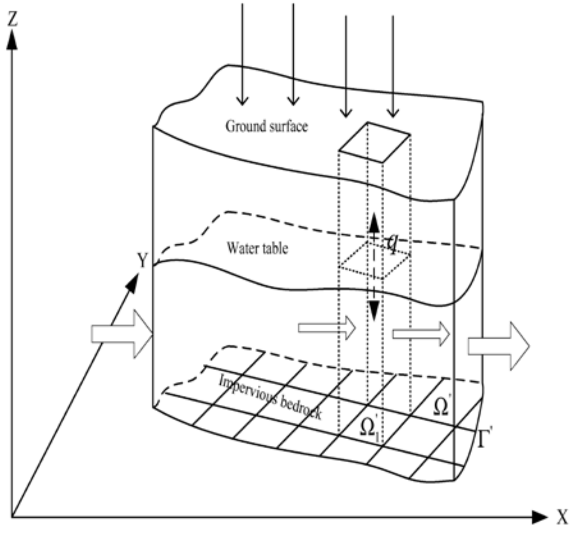
$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right]-\frac{\partial K(\theta)}{\partial z}+f_1(x,y,z,t)$$

B. The two-dimensional groundwater flow model

$$n_e\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K_s h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_s h\frac{\partial h}{\partial y}\right)-q_{z=h(x,y,t)}(x,y,z,t)+f_2(x,y,t)$$

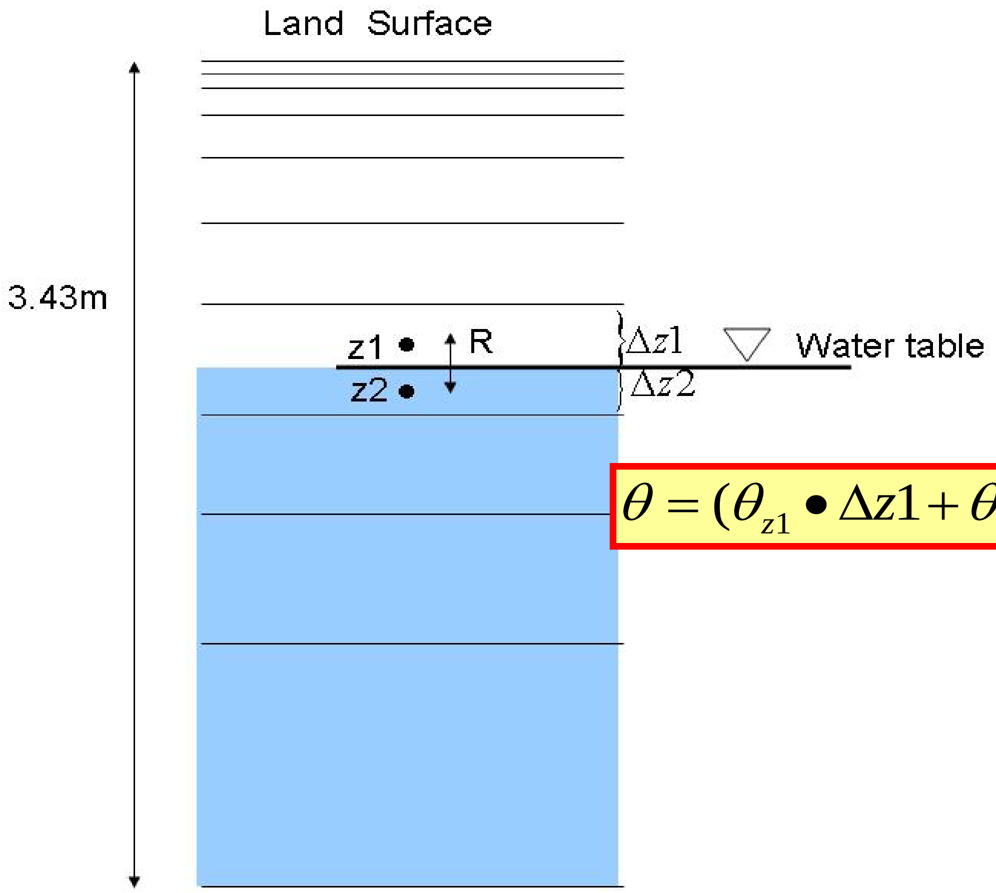
C. The connection equation

$$q_{z=h(x,y,t)}(x,y,z,t)=\int_{h(x,y,t)}^{H(x,y)}\frac{\partial\theta}{\partial t}dz+q_{z=H(x,y)}(x,y,z,t)$$



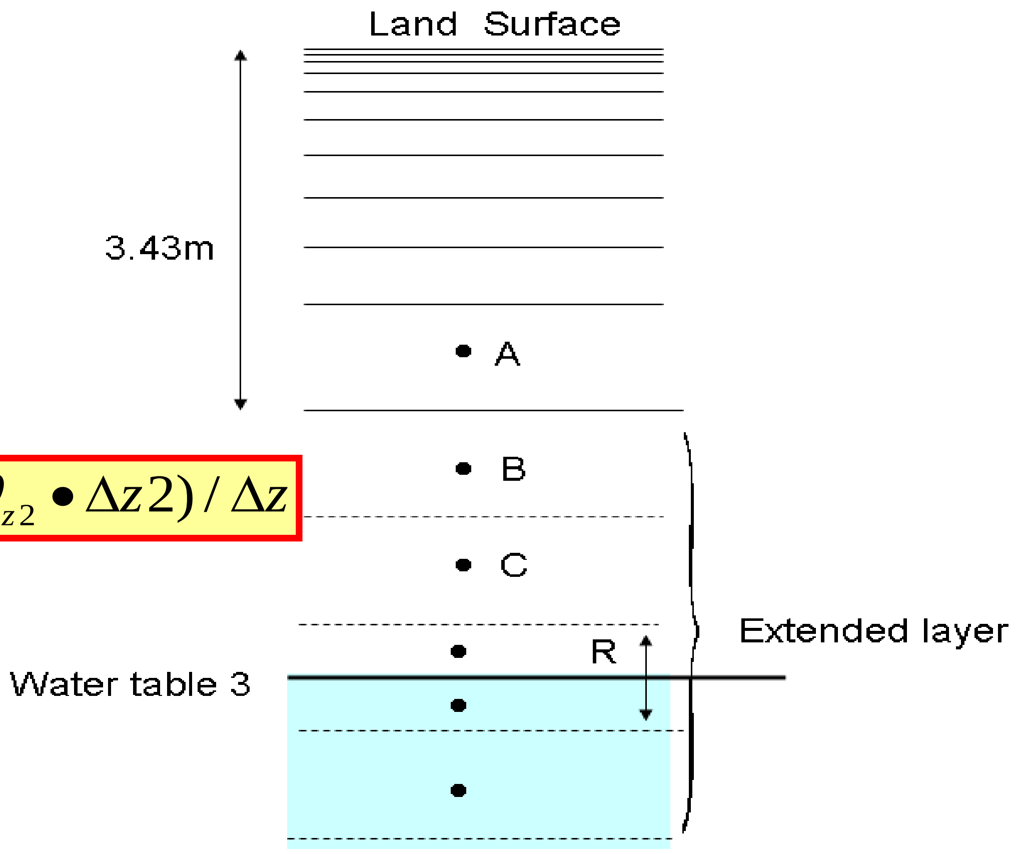
(a)

An adaptive grid structure for the soil water model



Soil water flux across the water table in the ten-layer soil column

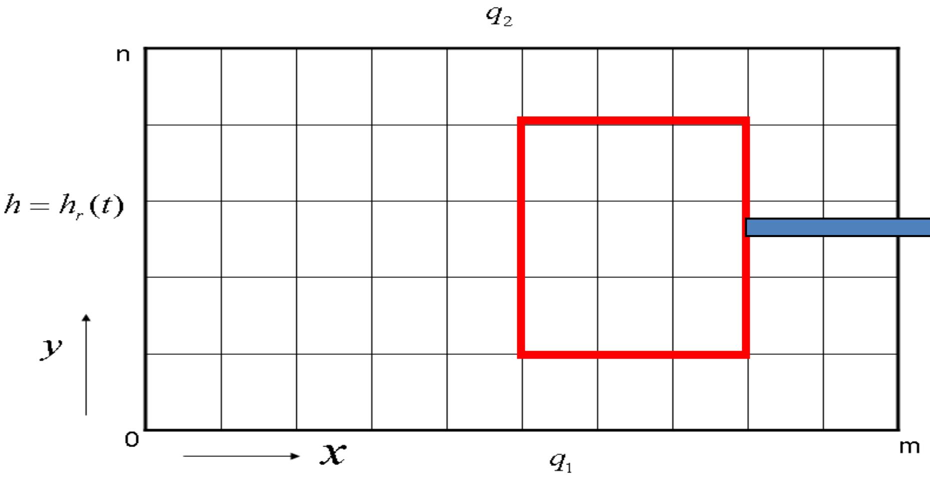
$$\theta = (\theta_{z1} \bullet \Delta z1 + \theta_{z2} \bullet \Delta z2) / \Delta z$$

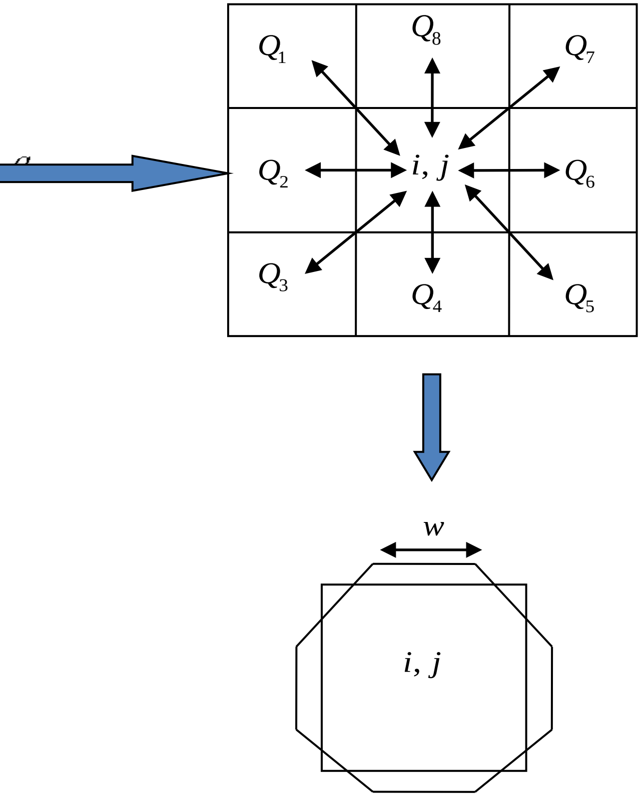


The extended soil column and soil water flux across the water table

- **An adaptive grid structure for the unsaturated soil water flow model with water table as the moving boundary**

Two-dimensional groundwater flow model in level direction

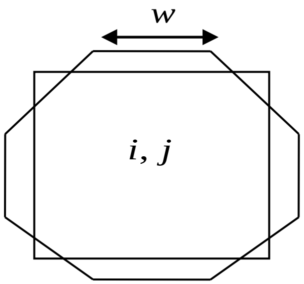




Plan view of datum plane.

$$\frac{dS_g}{dt} = \Delta x \Delta y q + \sum_{1}^{8} Q_n - Q_r$$

Two-dimensional groundwater flow model in level direction



$$w = \Delta x\sqrt{0.5tg(\pi/8)}$$

$$Q_n = wT_n\left(\frac{h_n - h}{l}\right)$$

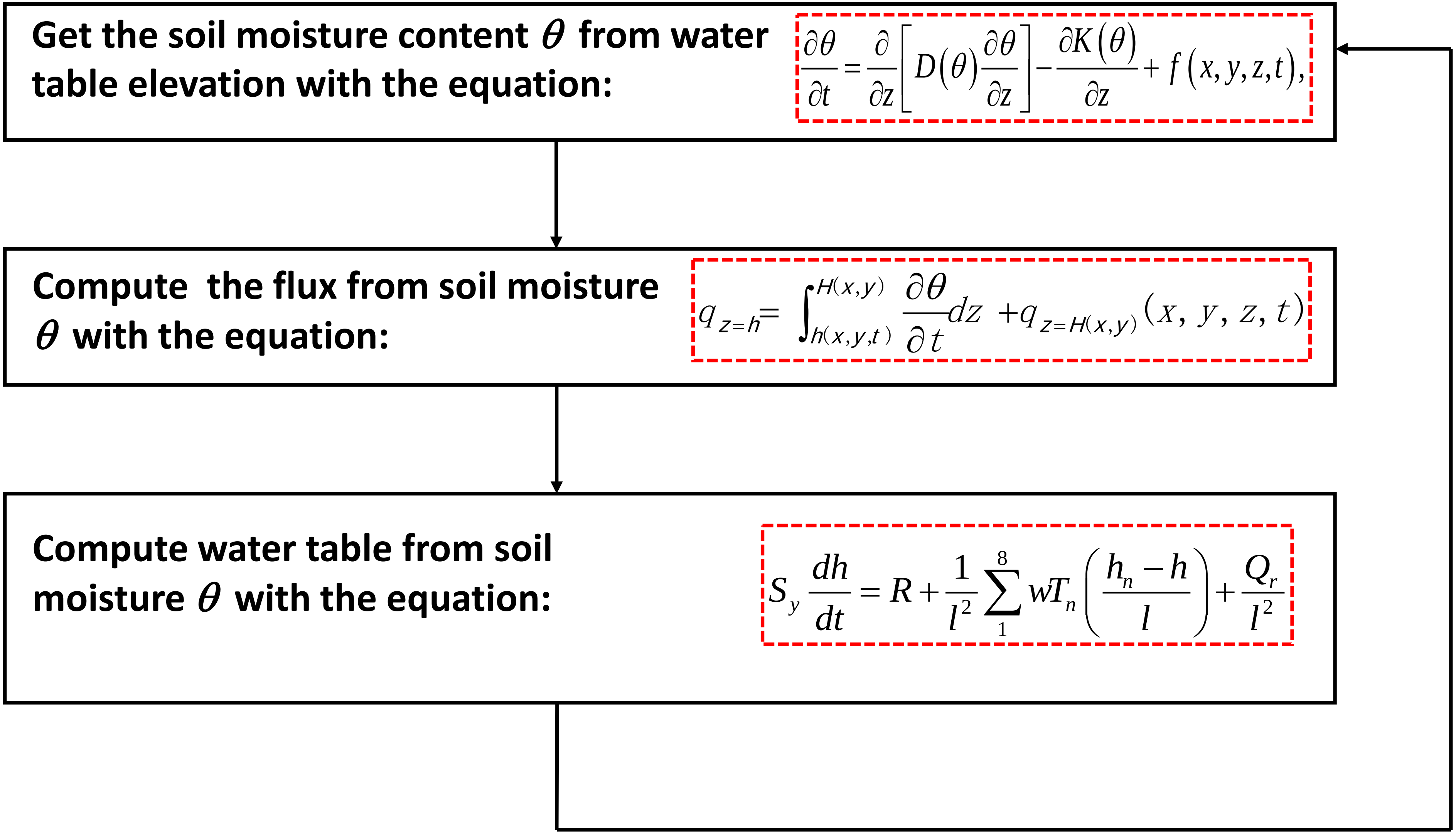
$$T_n = \int_{d_n}^{\infty} K_n dz = \int_{d_n}^{\infty} K_s \exp(-z/f)dz = K_s f e^{-d_n/f}$$

$$f = \frac{a}{1+b\beta}, \qquad 当 \quad \beta \le 0.16$$

$$f = 5m, \qquad 当 \quad \beta > 0.16$$

$$\boxed{S_y\frac{dh}{dt} = R + \frac{1}{l^2}\sum_{1}^{8} wT_n\left(\frac{h_n - h}{l}\right) + \frac{Q_r}{l^2}}$$

The quasi three-dimensional model numerical algorithms



Get the soil moisture content θ from water table elevation with the equation:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right]-\frac{\partial K(\theta)}{\partial z}+f(x,y,z,t),$$

Compute the flux from soil moisture θ with the equation:

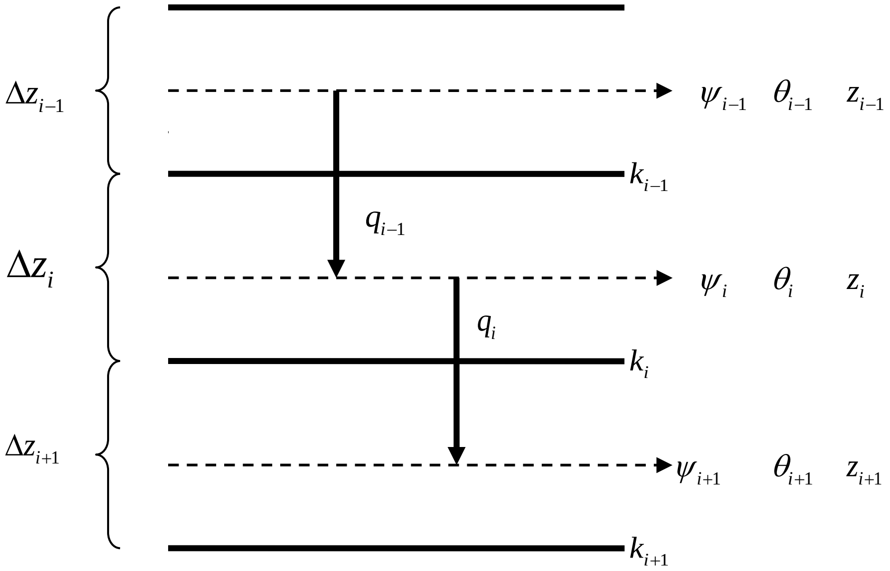
$$q_{z=h}=\int_{h(x,y,t)}^{H(x,y)}\frac{\partial\theta}{\partial t}dz+q_{z=H(x,y)}(x,y,z,t)$$

Compute water table from soil moisture θ with the equation:

$$S_y\frac{dh}{dt}=R+\frac{1}{l^2}\sum_1^8 wT_n\left(\frac{h_n-h}{l}\right)+\frac{Q_r}{l^2}$$

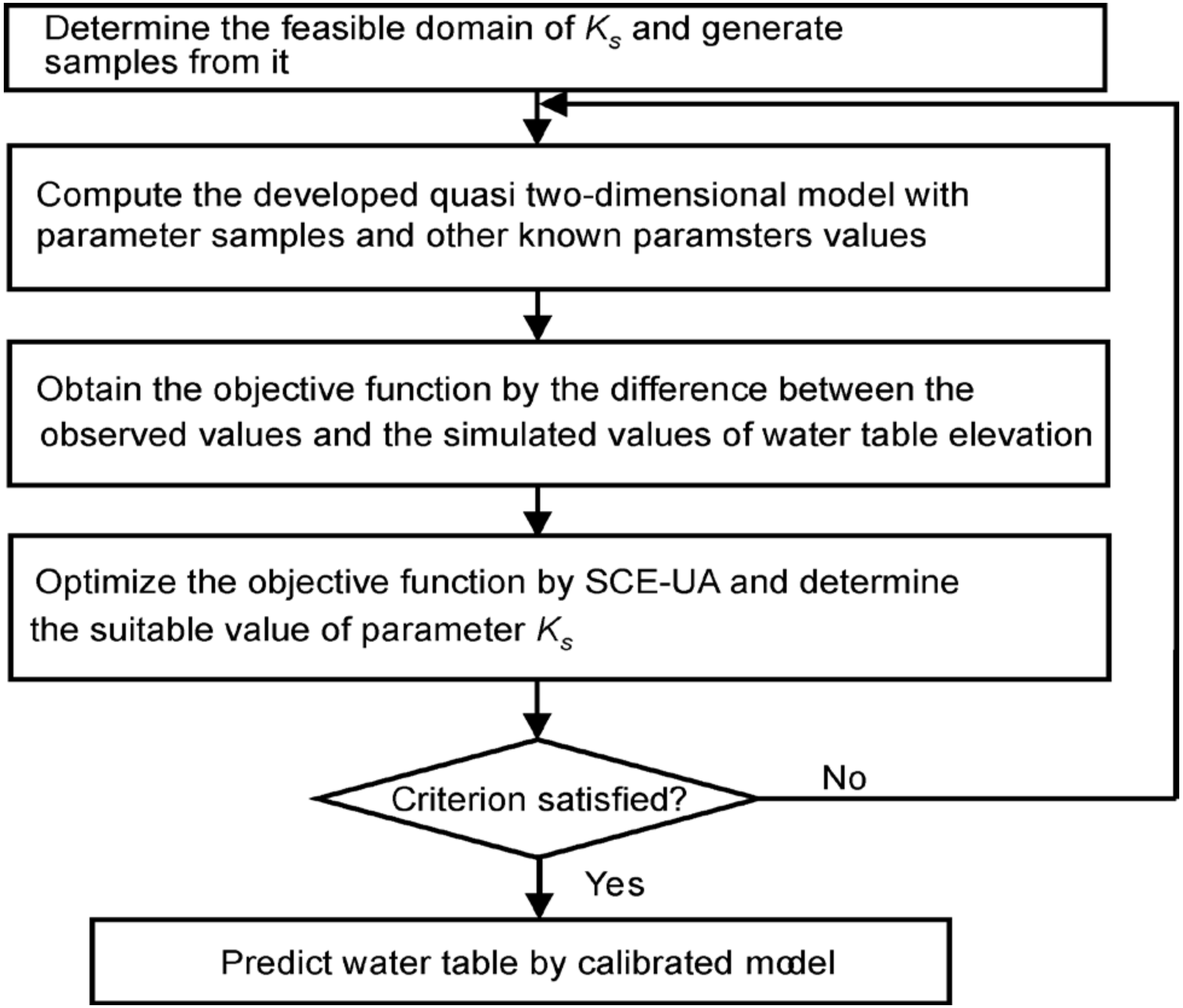
How to couple the soil water and ground water in Community Land Model

- **Based on ten-layer structure of the soil column with 3.43 m depth in CLM and water table as the bottom boundary condition of unsaturated flow equation, the coupling of soil water and groundwater can be implemented adopting the adaptive grid refinement method.**
- **The ten-layer soil structure in CLM**



A schematic representation of numerical scheme for soil moisture in CLM

Flowchart for water table prediction based on SCE-UA



Determine the feasible domain of K_s and generate samples from it

Compute the developed quasi two-dimensional model with parameter samples and other known paramsters values

Obtain the objective function by the difference between the observed values and the simulated values of water table elevation

Optimize the objective function by SCE-UA and determine the suitable value of parameter K_s

Criterion satisfied?

No

Yes

Predict water table by calibrated model

An estimation scheme of water table depth based on model and parameter calibration method SCE-UA

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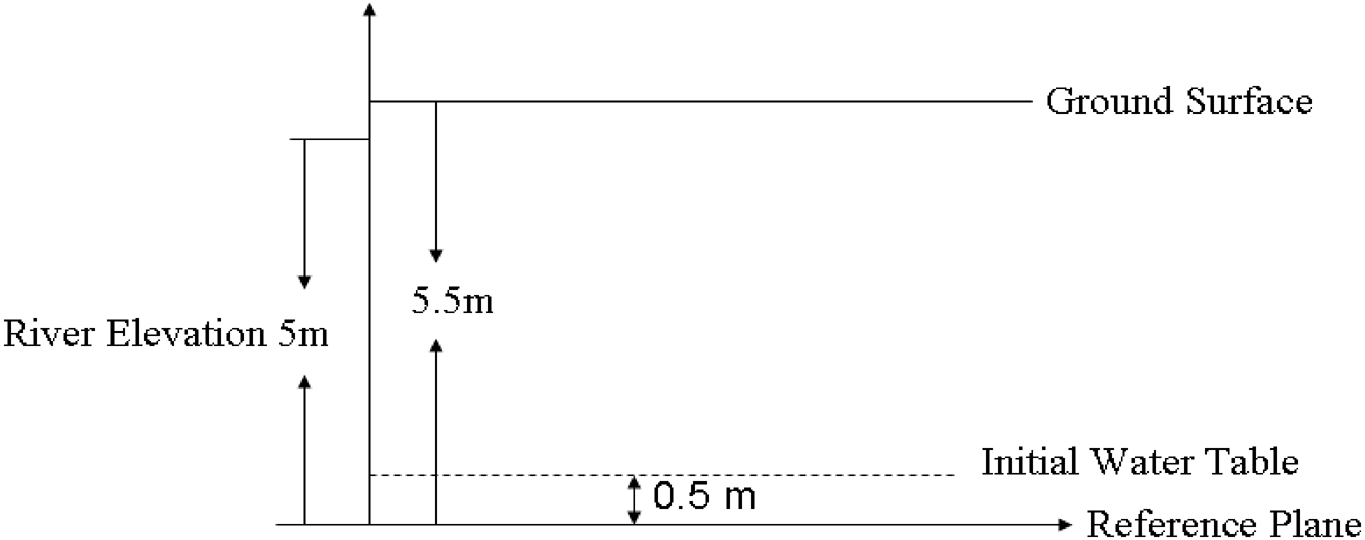
Sensitivities of model parameters

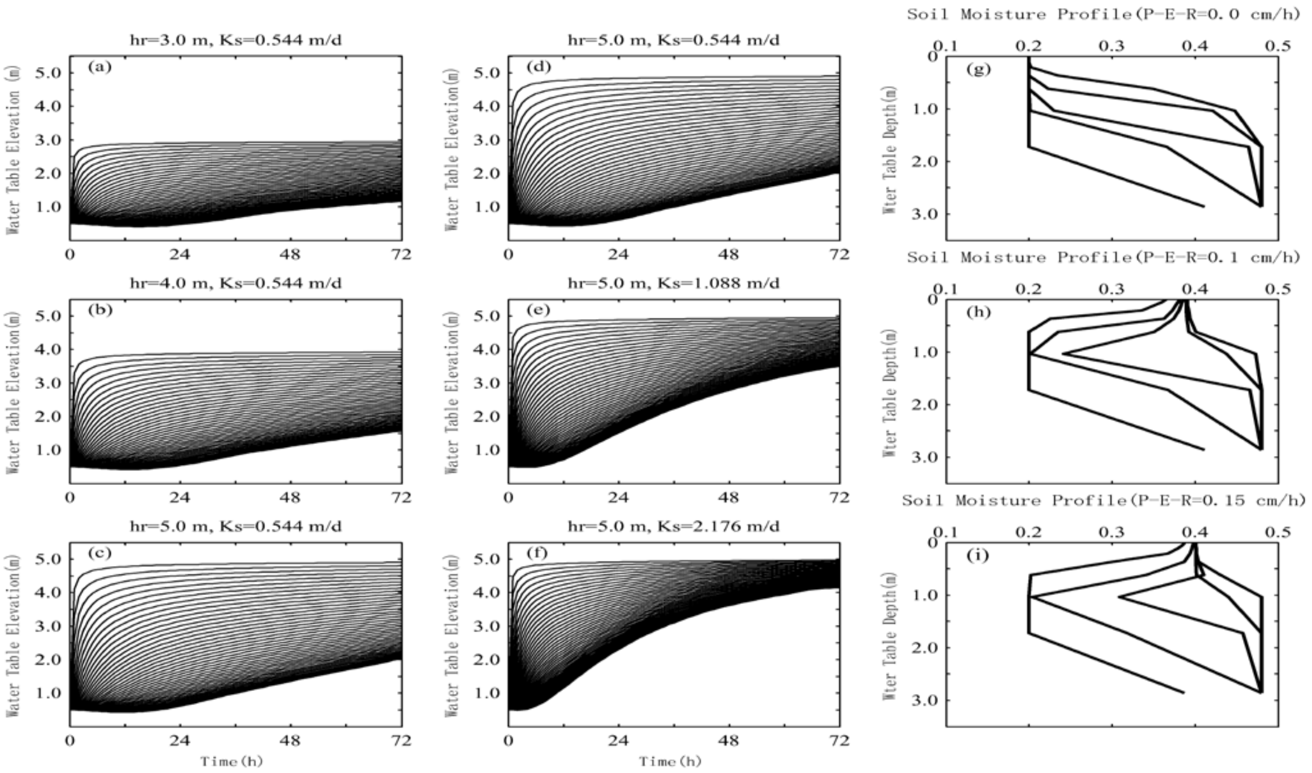
- The study domain is an aquifer near river bank with 50 m length from river bank, 10 m width paralleling river bank, and 5.5 m depth from the ground surface；
- The river surface is 5 m from the reference plane. The initial water table depth is 5 m . The vertical soil parameters value are adopted:

$$\theta_s = 0.48,\ \psi_s = -200mm,\ K_{s1} = 6.3\times10^{-3}mms^{-1}\ \theta_0 = 0.2$$

- **The cross-section of the study domain**



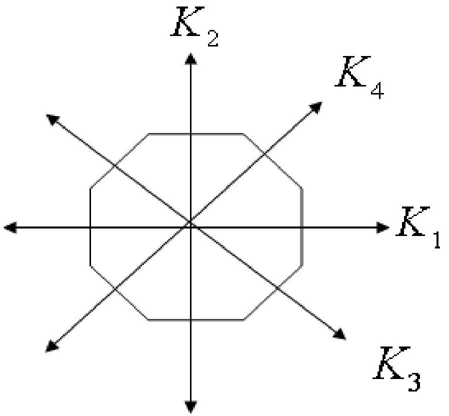
Sensitivities of model parameters

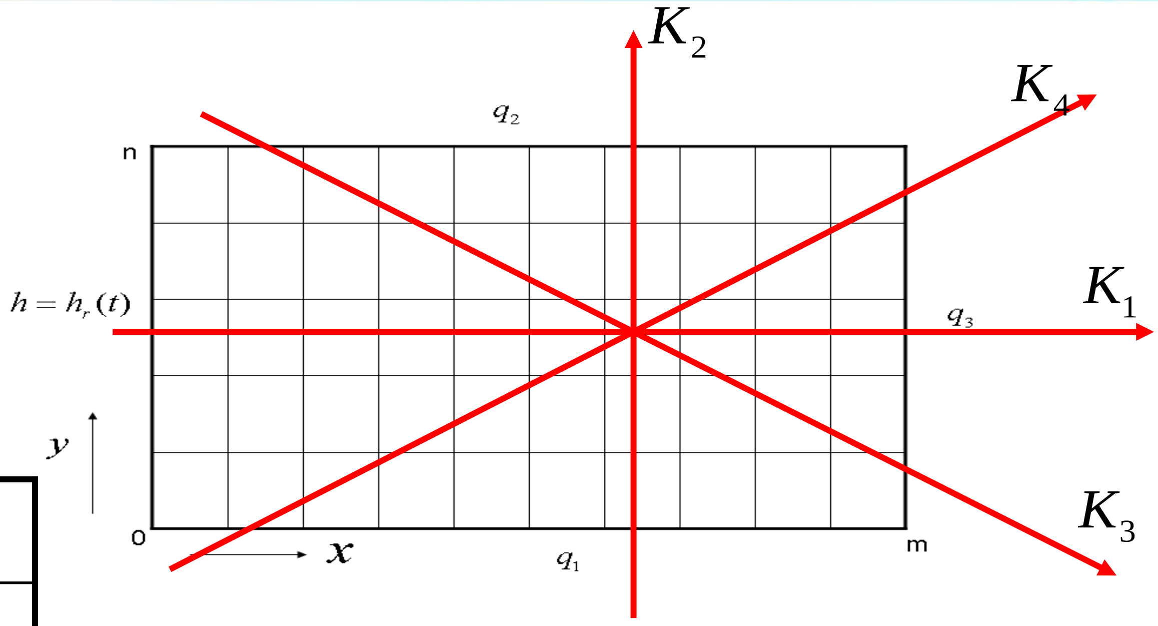


- ●(a)-(c) water table elevation profile curves of each grid nodes in three days with different river elevation;
- ●(d)-(f) water table elevation with different surface hydraulic conductivity ;
- ●(g)-(i) soil moisture profiles of soil column 20 m far from river for different infiltration fluxes.

- The water table increases as river elevation increases due to that a high river elevation enhances the hydraulic gradient between the river cell and study cells, making the groundwater flow stronger;
- The difference in water table elevations for grid cells with different distances from the river decreases as the hydraulic conductivity increases due to that the increased groundwater hydraulic conductivity reduces the response time of the flow exchange between grid cells;
- Both soil moisture content and water table elevations increase as surface infiltration increases.

Anisotropic hydraulic conductivity



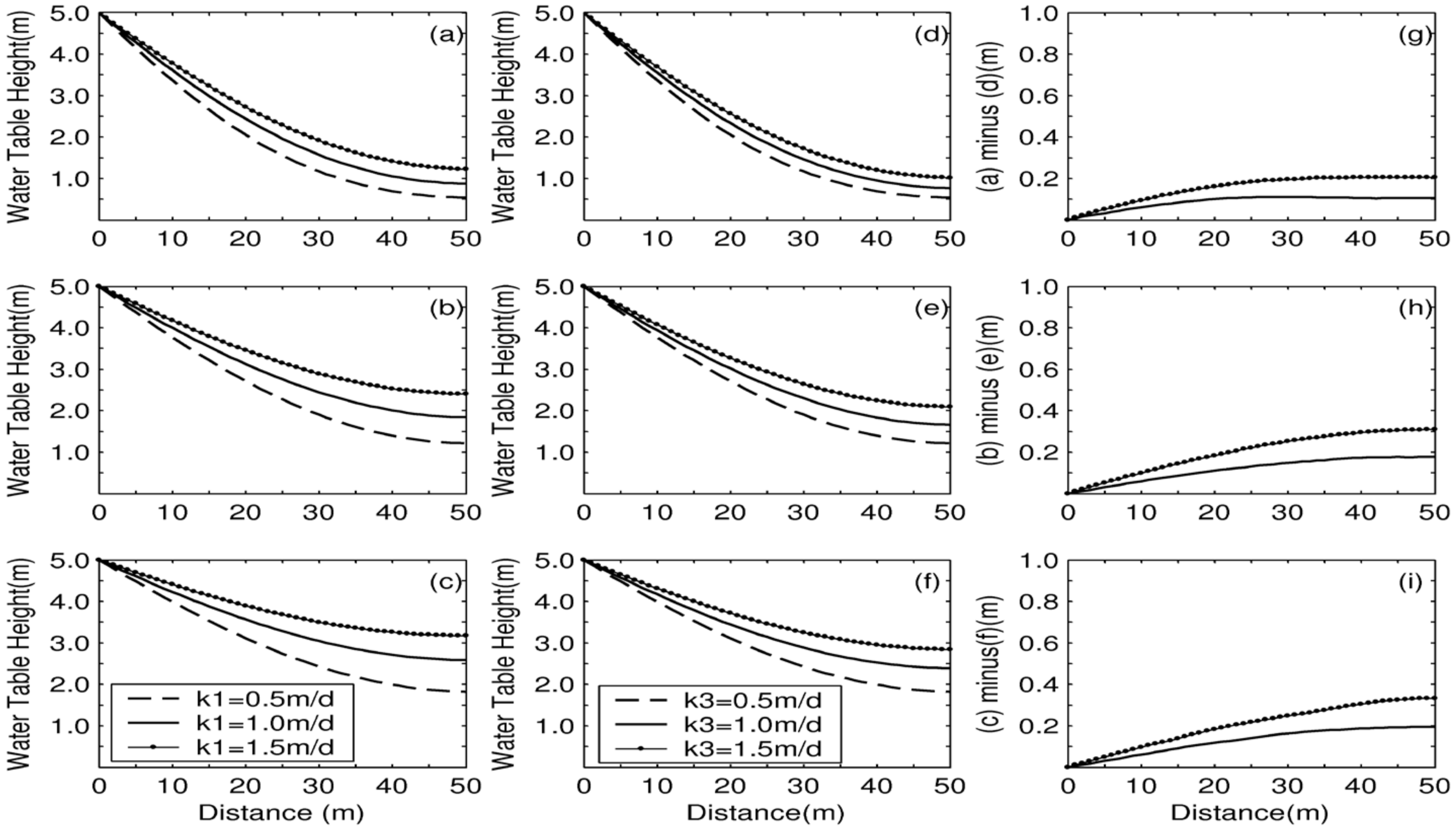


Exp. / Cond.	test1	test2	test3	test4
K_1	0.5 1.0 1.5	0.5	0.5	0.5
K_2	0.5	0.5 1.0 1.5	0.5	0.5
K_3	0.5	0.5	0.5 1.0 1.5	0.5
K_4	0.5	0.5	0.5	0.5 1.0 1.5

$$Q_n = wK_s fe^{-d_n/f}\left(\frac{h_n - h}{l}\right)$$

- Anisotropic hydraulic conductivity in the horizontal direction is examined

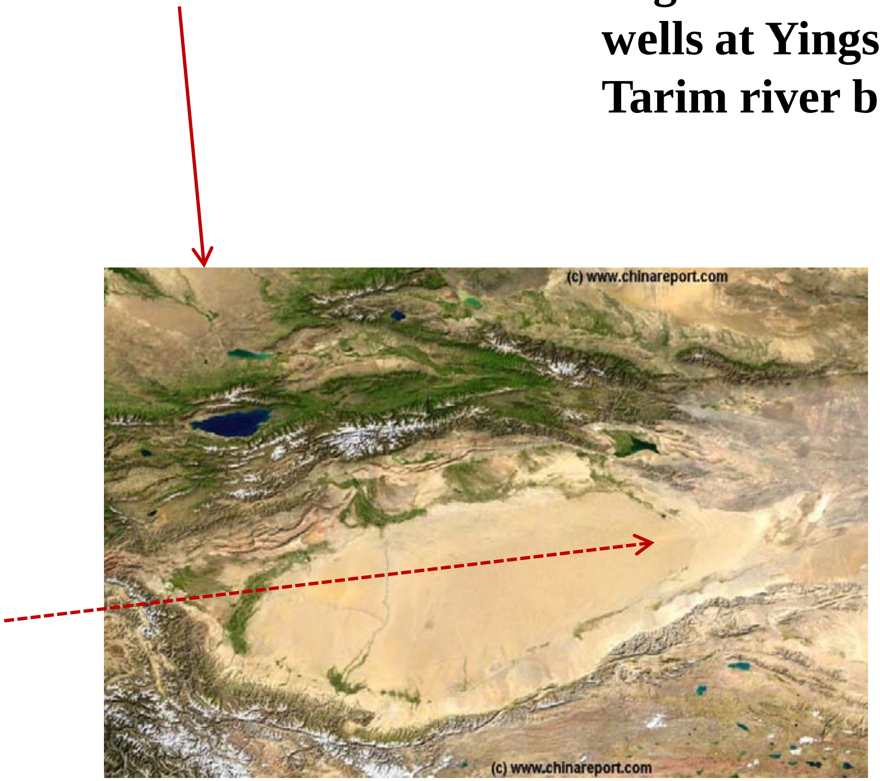
Anisotropic hydraulic conductivity



Water table elevation profile curves of the first day, the second day, and the third day, respectively for different Ks

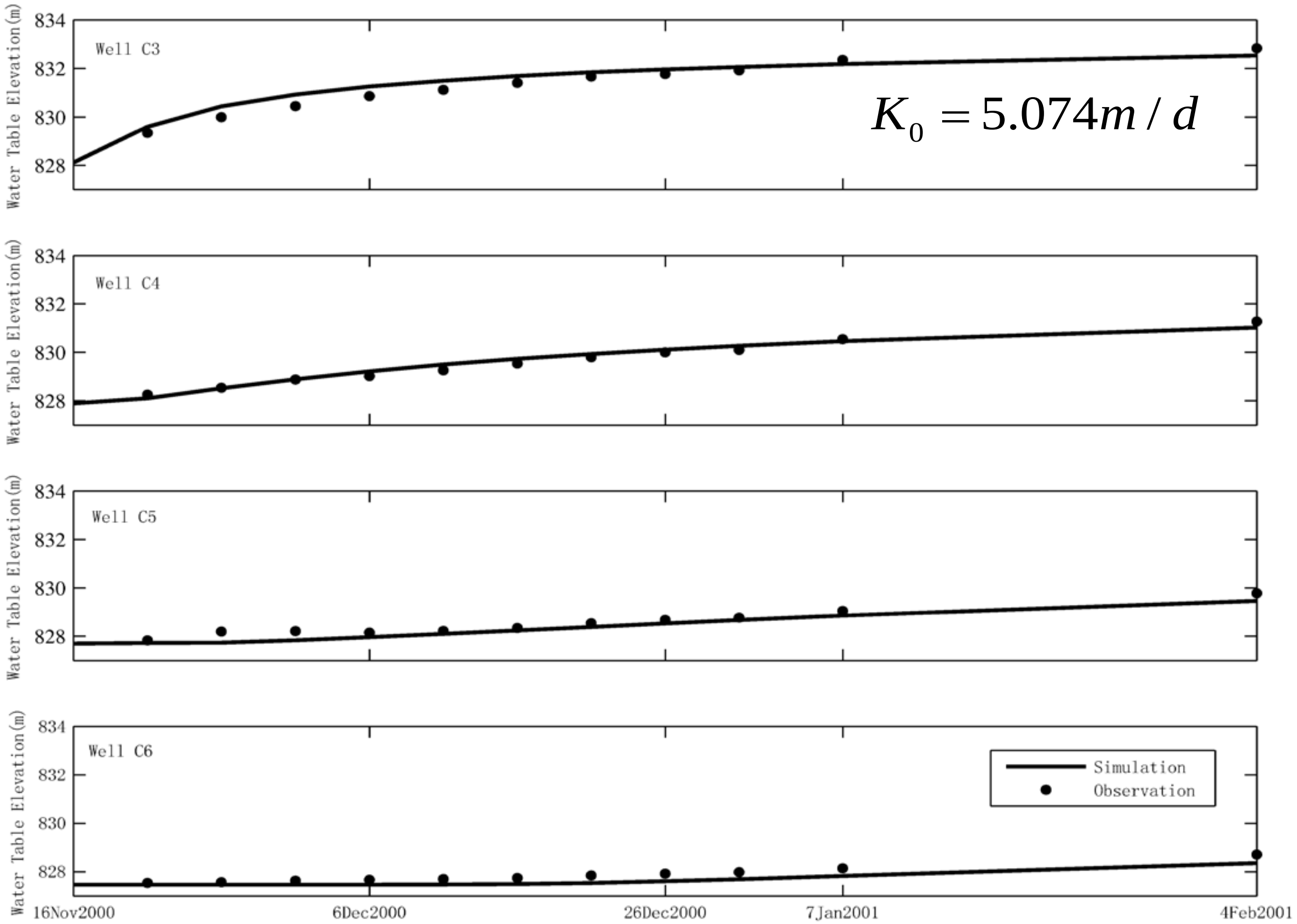
A case for validating model

A schematic representation of groundwater-monitoring wells at Yingsu section, Tarim river basin



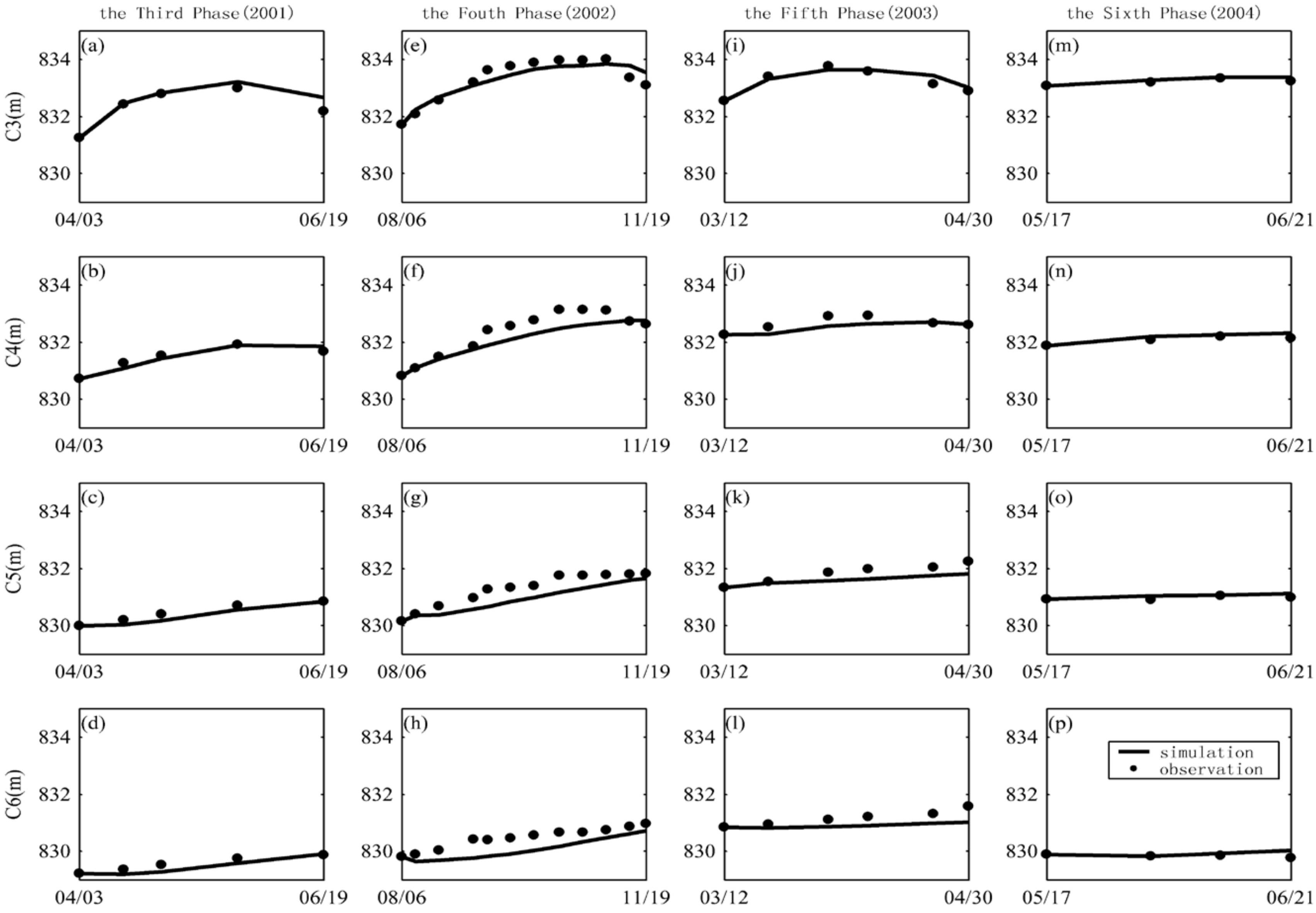
- A water conveyance project in the lower reaches of the Tarim River has been implemented since May, 2000, groundwater on the river sides along a river can be recharged laterally from stream water to sustain the ecological balance of riparian zone.
- The key issue of elevating water table reasonably is how to accurately predict the water table depth under the interaction between soil water and groundwater with stream water transferred.

Calibration phase (the 2th water conveyance period



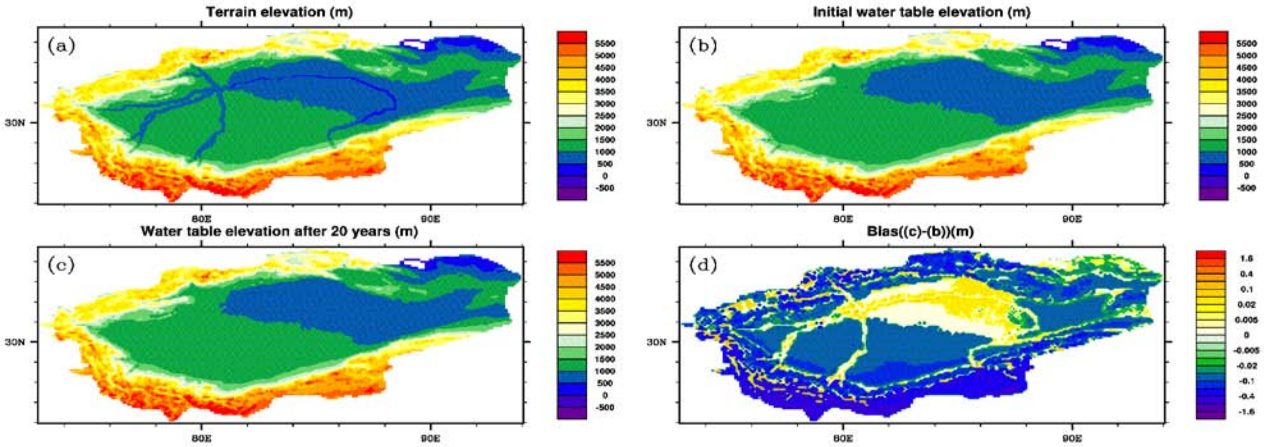
- **Time series of the observed and simulated water table elevations for wells C3, C4, C5and C6, respectively.**

Water table elevations for wells C3, C4, C5and C6



A numerical experiment for Tarim River Basin

- A numerical experiment by the model for Tarim River Basin was presented to test the model on simulation of the effects of lateral groundwater flow for large-scale high-relief topography with stream water conveyance, assuming that their vertical exchange flux to be zero at the surface;
- A grid size of 10 km was selected. The initial water table elevation is assumed to be 20 m below the land surface except that the river elevation is assumed to be 1.0 m below the land ;
- The groundwater hydraulic conductivity for the surface soil K0=10 m d-1, the e-folding length f =120， the boundary condition for the Basin is assumed to be zero flux.



$$\Delta t = 20 day, \Delta x = \Delta z = 10 km$$

$$K_s = 10 m / day, timestep = 365$$

Initial the depth to the water table 20m, river water table= -1m

The groundwater flows from high altitude to low altitude and water table have an increasing trend around river channel. Due to the initial water table elevation differences between grid cells corresponding to the differences of terrain height, the groundwater in high altitude areas supply for low altitude areas. A stable river elevation supplies to water table near river bank, which results in elevation of water table near river bank. The model has the potential to be used in large-scale groundwater latent flow.

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Summary and discussion

- In this study, a quasi three-dimensional numerical model for predicting the water table and soil moisture content simultaneously is established by dividing into one-dimensional vertical soil water flow in unsaturated soil columns and two-dimensional horizontal groundwater flow in the saturated zone;
- For each unsaturated soil column, a new soil layer structure is presented, and an adaptive grid refinement method is applied to model the soil moisture content at the cell nodes;
- Synthetic experiments and numerical experiments showed the robustness of the developed model and demonstrated its feasibility and efficiency, and that the model has the potential to be used in large-scale groundwater latent flow.

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THANKS

National Key Laboratory of Numerical modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)

Institute of Atmospheric Physics (IAP),Chinese Academy of Sciences (CAS)

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