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Article

Large-scale and high-performance groundwater flow modeling and simulation for water resource management in the Yellow River basin, China

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Abstract: A large-scale full-3D water circulation model, which covered with the whole Yellow River Basin (YRB) from source to mouth, was developed to predict the available groundwater resource next 20 years. Reproducibility of YRB model had been verified by using the measured groundwater levels or the existing literature information. Future prediction was carried out based on the scenarios required from 2010’s and 2020’s water demand and supply data provided by China Geological Survey (CGS).

As a result, it was found that ground settlement caused by groundwater pumping during next 20 years reaches up to 4.0m in Hebei. When we consider recovering groundwater levels to state of 1980’s, it is clear that we need to depend on alternative water resources instead of groundwater resources. Even if we have restricted groundwater pumping immediately, amount of such alternatively required water resources will be 10.5 billion tons per year. Furthermore, if we didn’t employ any restriction for it during next 20 years, more than 21.4 billion tons per year of water resources will be required as an alternative. These are corresponding to 6.4% and 9.8% of water demand in annually, respectively.

Keywords: Yellow river, water resource, numerical simulation, groundwater, ground settlement

1. Introduction

In the upstream areas of Huang He (Yellow river, China), available groundwater resources are limited because there are a few basin structures which can be reservoir of groundwater. So much of water for daily life and agriculture is depending on the surface water, most of which is river water. Consequently, although the amount of surface water which flowing into the downstream has been reduced, much more water is available from large scale groundwater basin. This means that there are different patterns of water use in the upstream and downstream of Yellow river basin.

Dry-up of the yellow river, which became well known recently in the world, may be one of the serious aspects which exposed as the background of unbalance of water supply and overuse in the uneven distribution of water resources. In order to understand the water resource problems in the yellow river basin mentioned above, we need to consider a whole water circulation as a system from the upstream to the downstream with the relation to each other. Utilization of the integrated numerical model which is able to simulate the whole watershed from headwaters to river mouth would become one of the effective approaches.

In this study, large-scale, full-3D water circulation model, covered with the whole yellow river basin of 1,600,000 km^2, was developed for the future prediction of the available groundwater resource after 20 years. (Mori *et al*., 2007) Various field data such as topography, hydrogeology, meteorology and monitoring information were incorporated to this model. Total grid-block number is about 1,400,000. Fully-coupled simulations of surface water and groundwater were carried out on the PC cluster computer. Simulated results were compared with the observed data which obtained from China Geological Survey (CGS) and reproducibility of the constructed model was discussed and verified through the technical workshops conducted in China and Japan.

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2. Full-3D numerical modeling of the Yellow River basin (YRB)

2.1 Study area

Study area for numerical modeling is about EW 2,200×NS1,100 km from headwaters to the mouth (Fig. 1). This area is not exactly the same with the well known yellow river watershed and is including some additional area especially in the downstream area. Downstream area of yellow river basin we often see in literatures is limited in the neighborhood around the river. However, much larger area including Hebei Plain was defined in this study. The watershed is often estimated from mainly topography, but that is not always restricted by topography only. Especially when we emphasize on groundwater flow, hydrogeological feature such as lithofacies distribution, seasonal change of groundwater, human activity and water use and so on, also become important aspects to determine watershed boundary.

Therefore, our study area was defined as yellow river basin including Hebei Plain and we call it here ‘Yellow Rive Basin (YRB)’ which is different from general use.

2.2 Governing equations of geosphere fluid-flow

Water and gas movement in geosphere affect each other and is receiving various impacts from land surface condition change. It goes without saying that surface water has a high relation with such geosphere fluid movement.

In generally, it is difficult to solve simultaneously both surface water and groundwater movements because of large difference of fluid velocity. Tosaka *et al*. (2000) enable large scale 3D flow problem to solve numerically by introducing a new mathematical formulation for the fully coupling of surface and underground fluid flow. In there diffusion wave approximation was applied for surface water flow and expressed formally it same type of equations with generalized Darcy’s equation for the multi-phase fluid flow in geosphere.

When we consider an air-water two phase fluid flow in land surface and in geosphere for the modeling of water circulation processes, governing equations basing on the generalized Darcy’s law are as followings.

$$\nabla\left(\frac{Kkr_g}{\mu_g B_g}\nabla\Psi_g\right)-q_{gS}=\frac{\partial}{\partial t}\left(\phi\frac{S_g}{B_g}\right)$$

$$\nabla\left(\frac{Kkr_w}{\mu_w B_w}\nabla\Psi_w\right)-q_{wS}=\frac{\partial}{\partial t}\left(\phi\frac{S_w}{B_w}\right)$$

Where, these equations represent mass balance

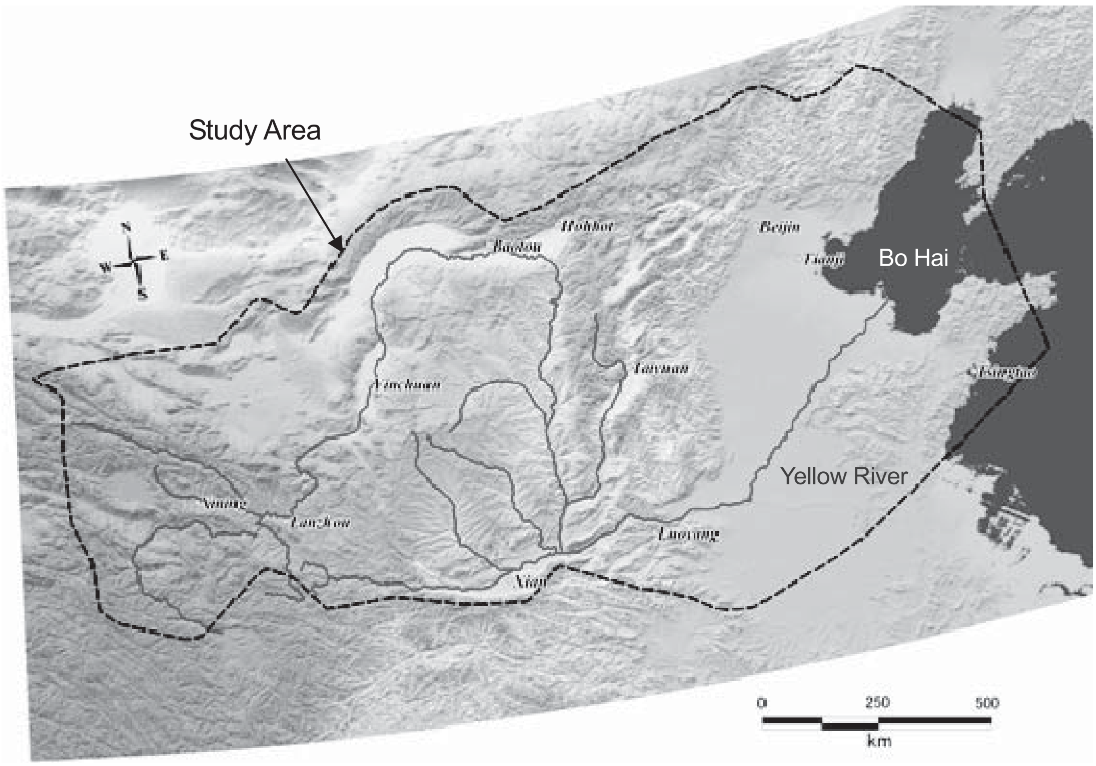


Fig. 1 Study area of Yellow River basin (YRB).

for gas phase and water phase, respectively. Ψ_p is total potential for p phase (Pa). K is intrinsic permeability (m^2), k_{rp} is relative permeability for p phase(-), μ_p is viscosity of p phase ($Pa \cdot s$), B_p is formation volume factor of p phase(m^3/m^3), ϕ is porosity(-), S_p is saturation (m^3/m^3), and q_p is unit volume at standard state with production or injection rate ($m^3/m^3/s$). Subscript p indicates fluid phase water (w) and gas (g).

In the coastal areas, in order to take into consideration interaction between freshwater and seawater, it is necessary to introduce an advective-dispersion equation for brine in addition to two-phase flow equations mentioned above. That is,

$$\nabla\left(\frac{Kkr_wR_s}{\mu_wB_w}\nabla\Psi_{cw}\right)+\nabla\left(D_s\nabla\frac{R_s}{\alpha_{cw}}\right)-q_{cS}=\frac{\partial}{\partial t}\left(\phi\frac{S_wR_s}{B_w}\right)$$

where, R_s represents brine concentration in water phase(m^3/m^3), D_s *is* dispersion coefficient which combined molecular diffusion and mechanical dispersion (m^2/s) and q_{cS} is unit volume at standard state with production or injection rate of brine per unit time ($m^3/m^3/s$).

Combined with further supplementary equations, these equations can be solved numerically. Primary variables to be solved here are a) air phase pressure, b) water saturation, and c) brine concentration.

2.3 Numerical simulation method

Integral Finite Difference Method (IFDM) with upstream weighting was employed to descretize the governing equations spatially as shown in previous section. Then we can obtain hepta-diagonal Jacobian matrix arising from the conventional 7-point expansion for 3D problem. The 3×3 sub-Jacobian are formed as the each element of hepta-diagonal Jacobian matrix. Total degree of freedom for this equation system becomes NEQ×NNBLK. In where, NEQ and NNBLK represent number of unknown (primary variables) and gird-block number, respectively.

The non-linearities associated with compressible multi phase fluid flow problem were dealt with the Newton-Raphson iterative scheme and fully-implicit temporal descretization. The preconditioned conjugate residual matrix solver was applied to solve equation system. The nested factorization method, which takes full advantages of hierarchies of tri-diagonal structure of Jacobian in incomplete factorization, is used as the pre-conditioner.

In order to achieve efficient and practicable computation time in large-scale 3D problem, successive the locking process (SLP) which excludes unchanged grid-block dynamically during Newton-Raphson iteration and the domain decomposition (DD) on cluster computer are used.

3. Basic specification of the YRB numerical model

3.1 Full 3D grid-block system and primary setting of numerical simulation

The corner-pointed 3D grid-block system of YRB is shown in Fig. 2. Total grid number is 1,413,600 which have 70,680 grid-blocks in each 2D plane (EW 372 x NS190). Grid-block system in plane was designed so that main stream of Yellow river and topographic feature are finely represented. Spatial resolution of grid-block system in plane is approximately 0.1 deg (approx.10 km). The 20 layers in depth direction were assigned from land surface to 20km depth. The size of grid-blocks gradually increases with depth.

The lower part of Fig. 2 shows the bird view of hydrologeological structure incorporated to 3D grid-block system. Basic formation is a) isopachs of Quaternary deposits, b) basement, c) faults, and d) depth dependency of rock permeability. Upper surface of basement was estimated from the existing geothermal flux distribution. That is, basement was defined as the deep place than brittle-plastic boundary of bedrock and fluid mobility in basement was not considered (intrinsic permeability equal zero).

The elevation of brittle-plastic boundary was assumed to be depth where the geo-temperature becomes 380°C using geothermal gradient estimated from geothermal flux distribution. Inclinations of major faults were modeled by typical angles for each fault type as followings; normal fault 70°, lateral fault 90°, and reverse fault 50°(Muraoka *et al*., 2007). In Hebei plain which is located in downstream of YRB, four major aquifers, inter-bedded clay formation and fan deposit were taken into consideration as the groundwater basin structure.

Basic specifications of YRB numerical model are shown in Table 1.

3.2 Procedure of numerical simulations

To reproduce the full-coupled behavior of surface water and air-water two phase flow in geosphere, initialization of the 3D field was carried out based on basic specifications listed above firstly. That is, we consider completely-water saturated condition in underground without any surface water on land surface. Starting from this condition, air-water two phase flow was traced by time transient simulation. During this simulation, groundwater levels in the mountainous area gradually decrease and also unsaturated zone is developed with the air-water displacement through grand surface. At the same time, groundwater discharge in the lower place was happened and then river flows are formed by such discharged water. Finally, fluid flow in the whole field achieves equilibrium state with the given condition such as precipitation, topography, and

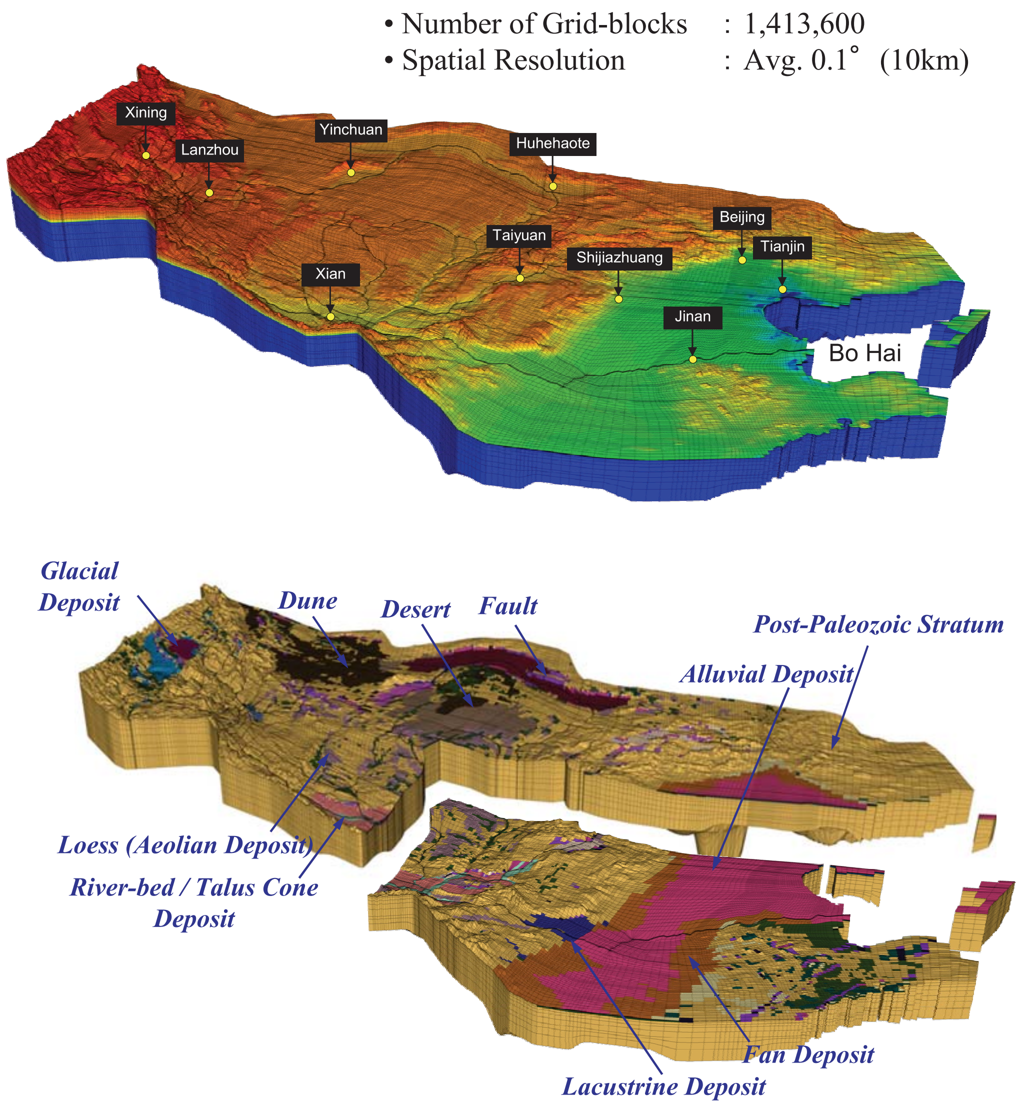


Fig. 2 Three dimensional grid-block system of YRB model

geologic structure and so on. From these equilibrium state, numerically obtained groundwater level or flow rate are compared with actual observed data to confirm reproducibility of numerical model. If simulated results couldn't match with the observation, various conditions such as geological structure or precipitation data are improved based on assumptions identified from differences between simulation result and observed data with the trial and error runs.

The following data was used to make matching and discuss the reproducibility of simulation results.

- Observed groundwater level; totally 96 monitoring points from Qinghai Province to Shandong Province along Yellow River.
- Conceptualized large-scale groundwater flows estimated from stable isotopes data of hydrogen and oxygen
- C^{14} age determination
- Aquifer structures and groundwater monitoring data of major groundwater basins provided by CGS
- Existing data from literatures; river flow rate, drawdown of groundwater levels, and so on.

After the good matching was attained between simulation and observation from initialization processes, then fluctuation of groundwater level and river flow rate by daily participation and water use are reproduced. Finally, amount of available groundwater resources for the next 20 years is predicted based on the water supply and demand planning published in China.

Table 1　Basic specification for YRB model

			Basic specification	Note
Basic specification	Period considered		Natural state（Before 1960），1980～2020	
	Study areas		EW 2,200 km×NS 1,100 km（1,600,000 km^2）× depth 20 km	
	Number of grid-block		1,413,600（372×190×20）	
	Spatial resolution		Average 0.1°(10 km)	
Topography	DEM		SRTM3 (land), ETOPO2 (sea bottom)	1), 2)
Meteorological condition	Precipitation		Based on precipitation datasets for 1978-2003(Yatagai A, *et al*, 2005)	
	Temperature		Based on observed data during 1971-2000 and 1951-1990	
	Evapotranspiration		Potential evapotranspiration estimated from Harmon equation based on temperature distribution	
	Atmospheric pressure		Standard atmospheric pressure according to the elevation	
Fluid conditions	Surface water flow		Linearized diffusion wave approximation	
	Groundwater flow		Generalized-Darcy's law for multi-phase fluid-flow	
	Fluid phase		Water/air two phase flow system	
	Fluids	Water phase	Density：1.0 [g/cm^3] Viscosity：1.0E-5 [Pa・s] Compressibility：0.45[GPa^{-1}]	
		Gas phase	Density：1.3E-3 [g/cm^3] Viscosity：1.1E-5 [Pa・s] Compressibility：As formation volume factor	
Hydrogeology	Geological settings		Pre-Quaternary basement, Quaternary deposit, Penetration basement, and major Faults (Muraoka H.,2007, Zhang.Z., *et al*, 2001a,b)	
	Permanently frozen soil		As the impervious soil layer above EL.4300m (Ikeda A.,*et al*, 2007)	
	Absolute permeability		*See Table.2*	
	Relative permeability		As the function of water saturation	
	Capillary pressure		As the function of water saturation	
Others	Water use		Based on statistical data(Lin X. and Wang J.,2006, Ichinose T. *et al.*,2007, Zhang.Z., et al, 2001a,b)	
	Land use		Rice paddies, irrigated fields, grass lands, forests, permanent snow fields, deserts, salt lands, cold deserts, bare lands, lakes and dams, major cities (20 categories)	
	Boundary conditions		Bo Hai bay: constant sea level condition Lateral: no flow condition Surface: atmospheric pressure and precipitation distribution and surface flow condition	

1) National Aeronautics and Space Administration(NASA) http://www2.jpl.nasa.gov /srtm/

2) National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/image

Table 2 Hydraulic Parameters

Geology		Thickness 〔m〕	Permeability 〔cm/s〕		Effective Porosity 〔%〕
			Horizontal	Vertical	
Igneous rock			1.0×10^{-5}		10
Cenozoic Sediment			1.0×10^{-3}		20
Lake Deposit	Upper	0 - 500	1.0×10^{-4}		15
	Lower	500 –	1.0×10^{-5}		10
Loess			1.0×10^{-4}		15
Fluvial deposit	Upper	0 – 500	1.0×10^{-3}		20
	Lower	500 -	1.0×10^{-4}		15
Talus deposit	Upper	0 – 500	1.0×10^{-3}		20
	Lower	500 -	1.0×10^{-4}		15
Sand dunes			1.0×10^{-3}		20
Deserts	Upper	0 – 300	1.0×10^{-2}		25
	Lower	300 –	1.0×10^{-3}		20
Glacial deposit			1.0×10^{-4}		15
Fan Deposit			1.0×10^{-4}		20
Alluvial Deposit	Surface soil	0 – 10	1.0×10^{-1}		20
	1st aquifer	10 – 50	1.0×10^{-1}	1.0×10^{-2}	20
	interbedded clay		—	1.0×10^{-7}	—
	2nd aquifer	50 - 145	1.0×10^{-3}	1.0×10^{-4}	20
	interbedded clay		—	1.0×10^{-7}	—
	3rd aquifer	145 – 300	1.0×10^{-2}	1.0×10^{-3}	20
	interbedded clay		—	1.0×10^{-7}	—
	4th aquifer	300 –	1.0×10^{-4}	1.0×10^{-5}	10

4. Results and discussions

4.1 Full-sale groundwater flow system in YRB

A full-scale groundwater flow system of Yellow river basin without any human activity was reproduced by initialization procedure mentioned above.

Results of numerical simulation shown here have been improved by comparing with the actual observed groundwater levels and existing data from literatures, and then discussed in the internal workshops between CGS and AIST. Based on these activities, groundwater flow in YRB is described here.

Fig. 3 shows the simulated streamlines obtained from particle tracking simulation with initialization results. Although 3D streamlines was actually computed using groundwater velocity field, projected streamlines onto the 2D surface plane was represented here. Each streamline doesn't distinguish surface water flow and groundwater flow and is including both of them.

Travel time and distance along flow paths were calculated for each streamline and we found that a) long travel time with short distance of flow path in the upstream area and b) short travel time with long distance of flow path in the downstream area. These tendencies are consistent with the conceptualized groundwater flows system estimated from hydrogen/oxygen stable isotope or water quality measurements by Uchida *et al*. (2007).

In northern part of midstream area in Hetao Plain, a former river channel changing the direction from north to east along the current river channel is clearly reproduced. The groundwater flow from south to north meet with another groundwater flows comes from northern mountainous area. Discharge area is formed around former river channel. Actually many springs and lakes can be seen in Hetao plain. Groundwater

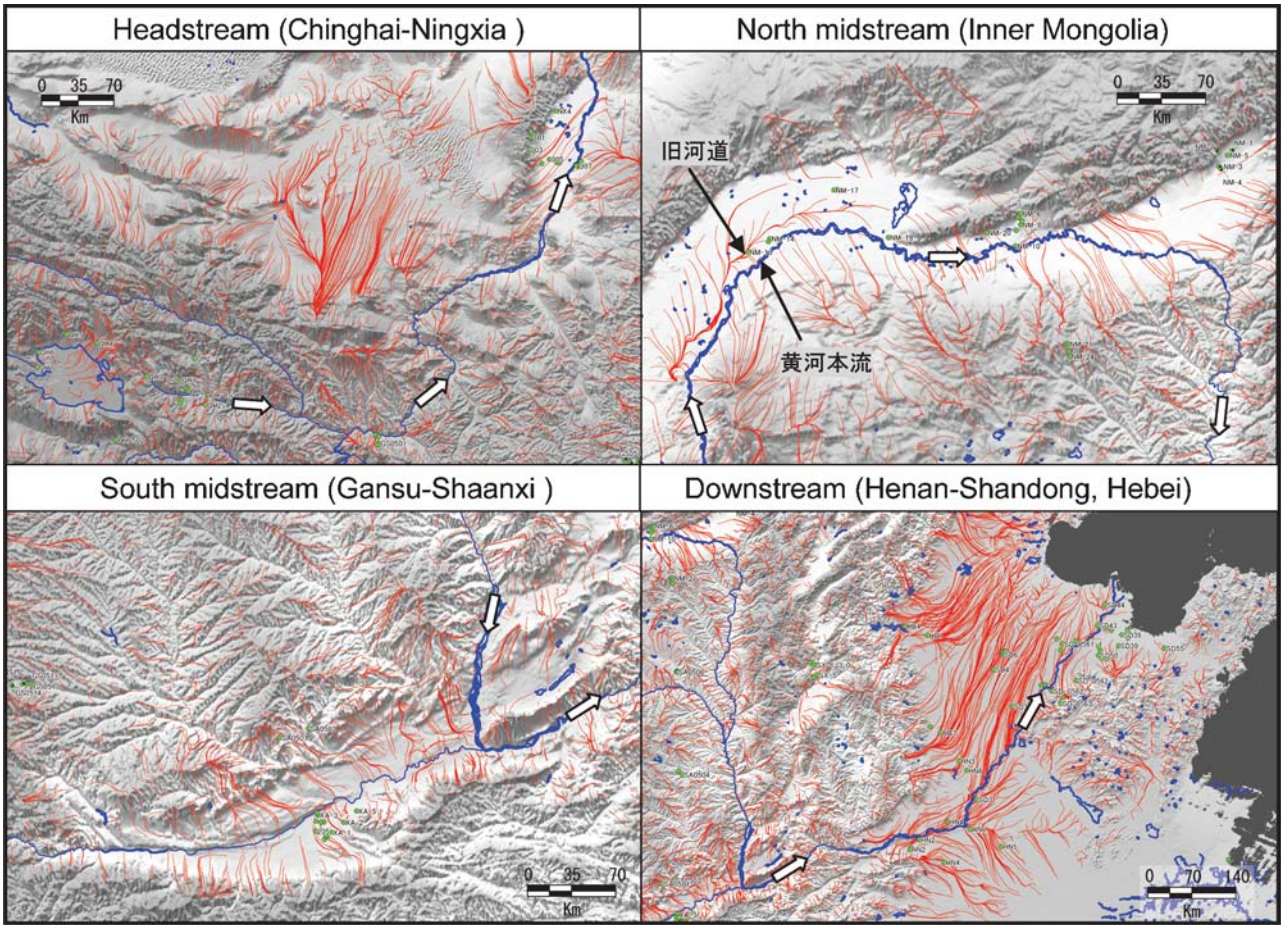


Fig. 3 Simulated Streamline (Red lines) from source to mouth (Blue line show main stream of Yellow river)

flow in the downstream area shows that travel time is almost shorter than that in the upstream area. But travel distances of groundwater flow becomes several hundred kilometers totally, relatively stable groundwater flow is formed in the permeable aquifers. Mainstream of Yellow river around here is ceiling river due to sediment transport comes from upstream. Recharged groundwater from river bed is supplying water to the aquifer in Hebei plain. Similar characteristics of former river channel which can be seen in case of Hetao Plain exist in also Hebei plain. Changes of river channels are clearly recognized with Henan Province as heel (origin) point. These results are consistent with other historical evidences.

Fig. 4 shows potential distribution of YRB as bird's eye view and cross sectional potential distribution from uppermost region to the mouth of the river. Distance of this cross section is totally 1,700 km along from Xining in upstream area to Tianjin in downstream area. Only grid-blocks except basement are shown in this picture. Vector plots of groundwater flow represent flow directions only. Since length of all vectors is identical, information about magnitude of flow velocity is not included in this picture.

From these result, we can found that recharged groundwater in the upstream regions almost goes into the deep underground and discharges into the lower place. Since topographic slope change is complex around upstream area, the recharged groundwater seems to discharge into the close valley. There are many springs in such valley. In other words, deep groundwater in the upstream area does not move directly to the river mouth and it can be considered that Yellow river basin is comprised from many closed local basins.

4.2 Groundwater flow and water use in major groundwater basins

Based on the results of initialization for the whole YRB, simulated groundwater distribution were compared with the observed data focusing on the major groundwater basins such as Yinchuan, Hetao, Guanzhong, and Hebei Plains.

Many wells have been installed for the long-term groundwater monitoring in Hebei plain. Drawdown

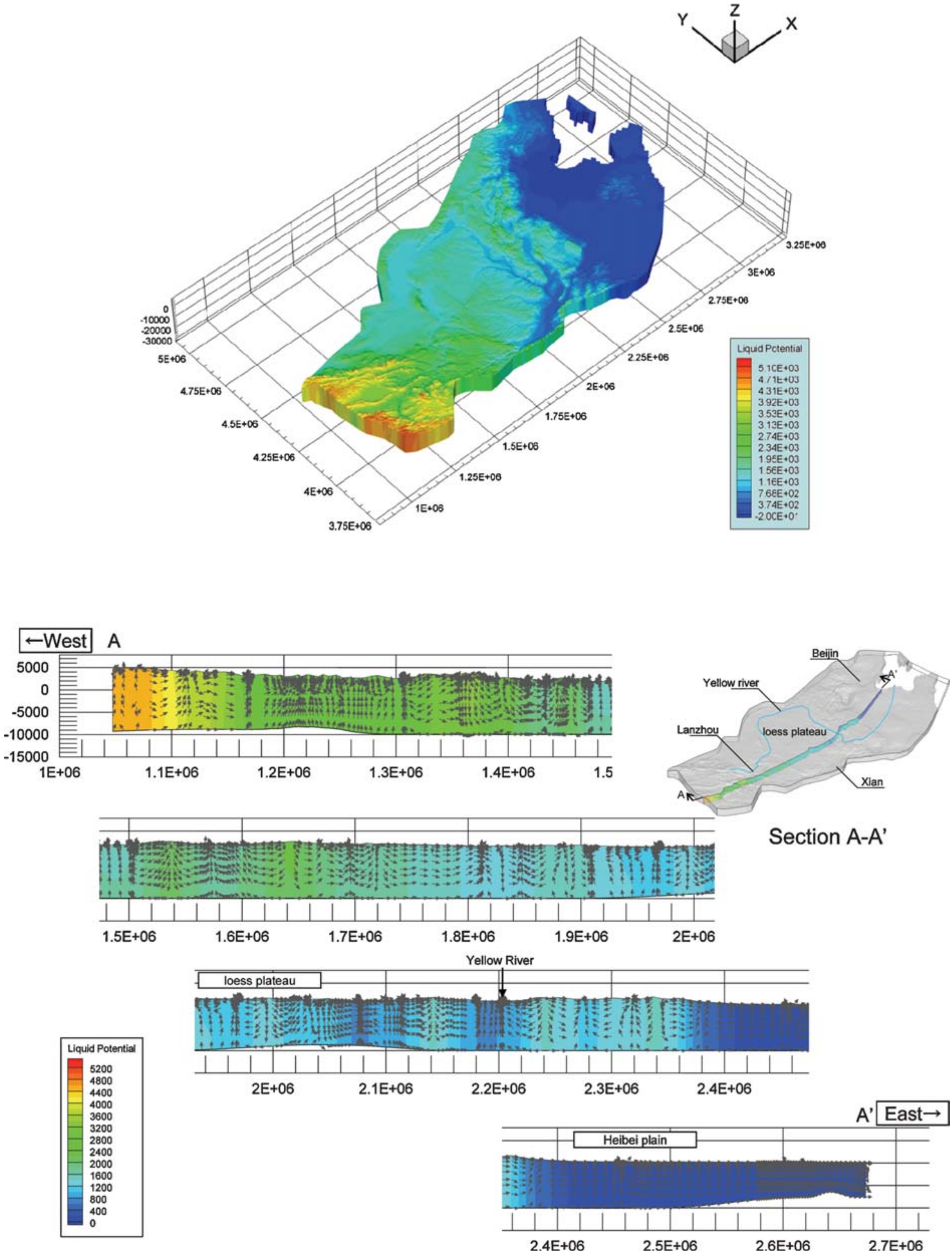
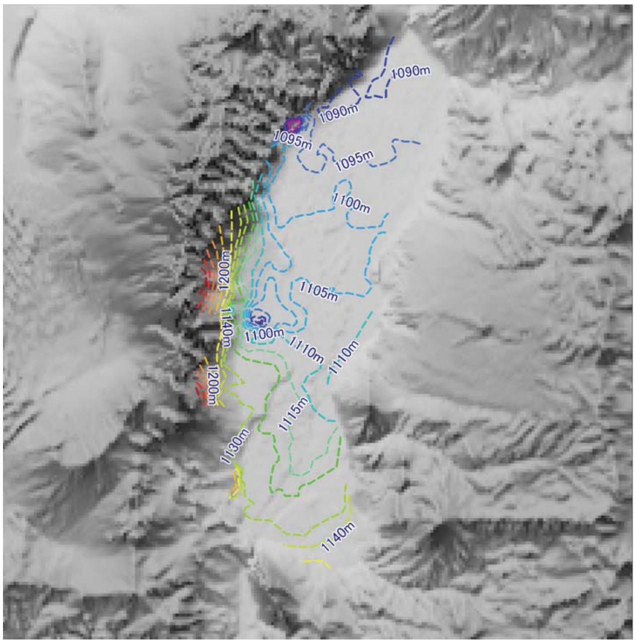
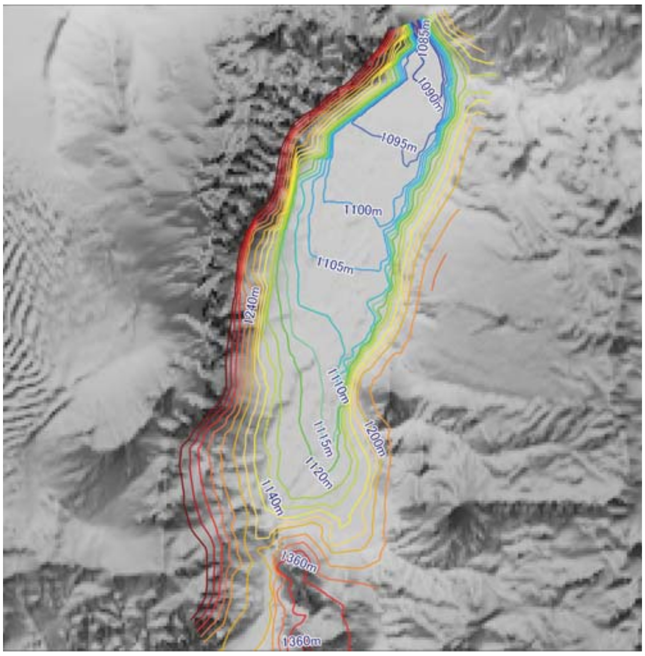


Fig. 4 Groundwater flow and potential distribution in AA' section



(a) Observed groundwater level in 1960's



(b) Reproduced groundwater level without any human activities

Fig. 5 Comparison between observed and reproduced groundwater in deep confined aquifer in Yinchuan plain of groundwater level and its spatial distribution due to withdrawing in deep and shallow aquifers are available for 1960s, 1980s and 2000s. Based on these monitoring data, we have estimated the amount of groundwater pumping rate by reproducing the groundwater drawdown at each date using numerical simulation.

Fig. 5 shows unconfined groundwater level in Yinchuan Plain. Thickness of quaternary deposits in Yinchuan Plain is estimated to be over 2,000 m. According to the existing geological maps provided by CGS, which was based on a number of boreholes information, four primary aquifers are recognized in this plain. Fig. 5(a) is unconfined groundwater distribution in 1960's and groundwater drawdown in place caused by pumping can be recognized. Simulated result without pumping is shown in another picture (b). Comparison of these results indicates reasonably consistent major groundwater flow and hydraulic gradient (approx. 3E-4).

In similar way, observed shallow groundwater levels in Hebei plain is compared with the simulated result (Fig. 6).

Geological survey and groundwater monitoring using over 10,000 boreholes for shallow and deep groundwater has been conducted in Hebei Plain. There are four major aquifers in Hebei plain and it is considered that groundwater is produced from all of them. Especially No.1 and No.3 aquifers which is thick sand and gravel layer are major sources of water supply (Zhang *et al*., 2001a).

From the comparison shown in Fig. 6, we can see reasonable match between observation and simulation. Especially both relatively large hydraulic gradient restricted by recharged groundwater at the backland and small hydraulic gradient from central plain to Bohai Bay is finely reproduced. Good matching represented here were attained by a number of trial and error runs focusing on the modeling of aquifer structures and its hydraulic properties. Actually we found that distribution and permeability of fan deposit could be important aspects which restrict primary groundwater flow in Hebei plain.

As mentioned above, shallow and deep potential distribution in Hebei plain in 1960s, 1980s, and 2000s are available from existing boreholes survey. Although actual groundwater use is not fully understood, we can estimate the rate of groundwater pumping by using such observation-based potential distribution. That is, groundwater drawdown during 20 years from 1960 to 2000 has reproduced by trial and error matching calculations. Fig. 7 shows the reproduced deep potential distribution in 2000's with observation. Distribution of groundwater drawdown by pumping around the central area in plain shows good agreement with each other. In similar way, comparison for shallow potential distribution was reproduced and pumping rate was estimated.

The results of groundwater drawdown for 40 years from 1960 to 2000 for shallow and deep groundwater as compared with the existing data by Zhang *et a*l (2001a,b) are summarized in Table 3. Simulated results are consistent with such existing pumping data.

4.3 Future prediction for available groundwater Resource

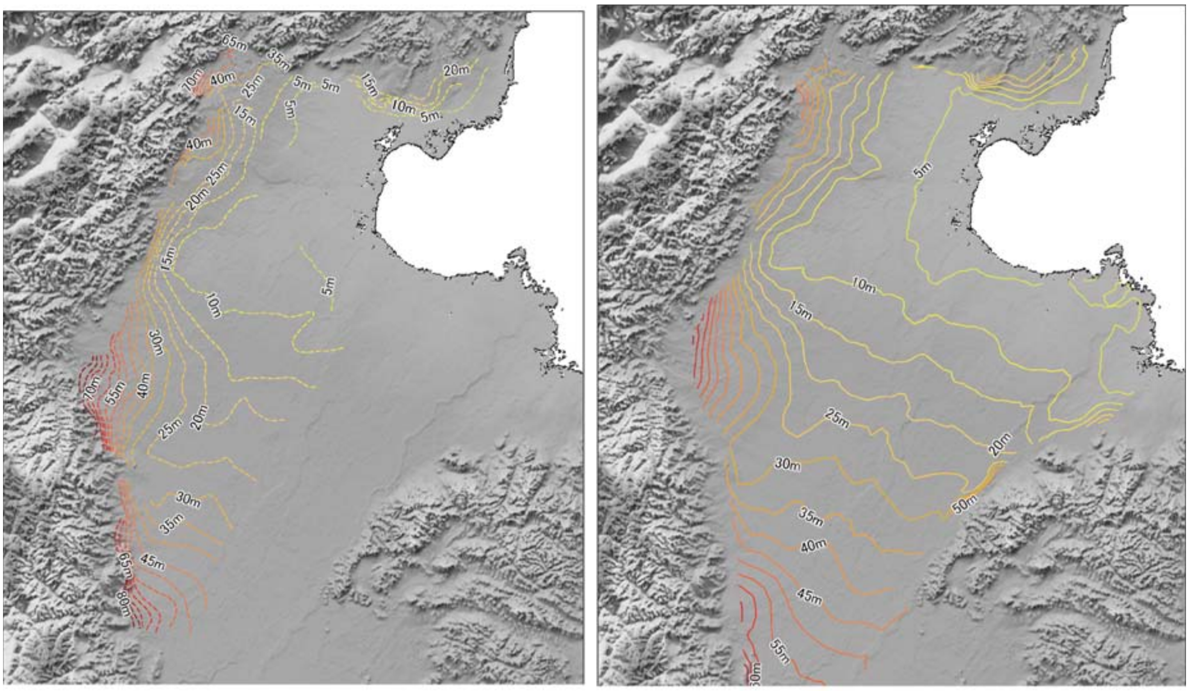
Scenario-based simulations for the prediction of available groundwater resources in YRB after 20 years have carried out. Groundwater use in future was based on Lin *et al*. (2006). In there, available data of water use is basic unit for each Chinese province. Since province area is too large, there is a possibility that the areal or local responses by groundwater withdrawing disappear if we use such data directly. Therefore, several assumptions associated with the relationship between groundwater pumping rate and the areal and depth distribution of quaternary or transmissibility of each aquifer were introduced firstly. Then the amount of groundwater use by pumping for each more local prefecture was derived from the base unit data mentioned above. (Fig. 8).

Fig. 9 shows deep and shallow groundwater level changes at Dezhou and Xingtai in Hebei plain. Two scenarios for different water use were defined. One is to keep the rate of groundwater pumping until 2020 (Scenario-1). Another one is to instantaneously cease any groundwater use after 2004 (Scenario-2).

As to groundwater level response in deep confined aquifer, we have found that the deep groundwater level gradually decrease from EL.-30m to -50m below during 20 years in future (Scenaio-1). In case of Scenario-2, deep groundwater level quickly recovered after 2004 and period to recover is less than 5 years.

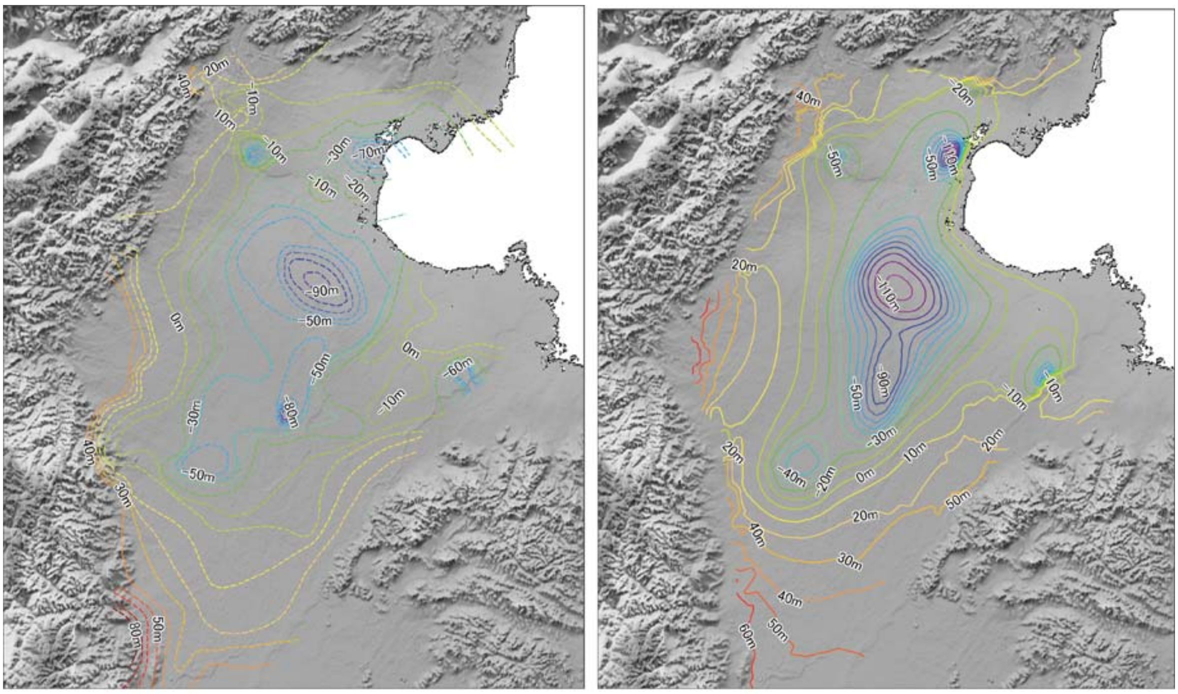
On the other hand, as to groundwater level response in shallow unconfined aquifer, reproduced result for the past 20 years doesn't match the observed data. Simulated groundwater almost keeps constant level and we couldn't see the tendency of decreasing with time. One of the reasons of this disagreement against observed data is strongly depending on the pumping condition we use by basic unit for local prefectures. Withdrawing from even local prefecture unit might decrease the response of groundwater level.

Fig. 10 shows spatial distribution of deep groundwater level in Hebei plain. Around central area of Hebei plain shows large decreasing of groundwater level. This result shows that deep groundwater level might decrease until EL.-100m in 2020. Seawater intrusion, ground settlement and alkaline soil are well known as the features of groundwater failure which might restrict critical production rate. The irreversible ground settlement by squeeze and shrinkage of the



(a) 1960's (b) Equilibrium state without any human activities

Fig. 6 Comparison between observed and reproduced groundwater in shallow unconfined aquifer in Hebei plain



(a) 2000's (b) Decreased groundwater table by pumping

Fig. 7 Comparison between observed and reproduced groundwater in deep confined aquifer in Hebei plain

Table 3 Comparison of the estimated pumping rate and groundwater drawdown with the literature data

		Simulated result		Literature (Zhang, et al 2001a)
		Before 1980	1980-2000	1975-1984
Pumping Rate [Hundred million m^3/y]	Shallow	27.2	65.3	91.68
	Deep	8.5	12.1	8.905
Groundwater Drawdown [m/y]	Shallow	0.3		0.11-0.67
	Deep	2.6		1.44-3.33

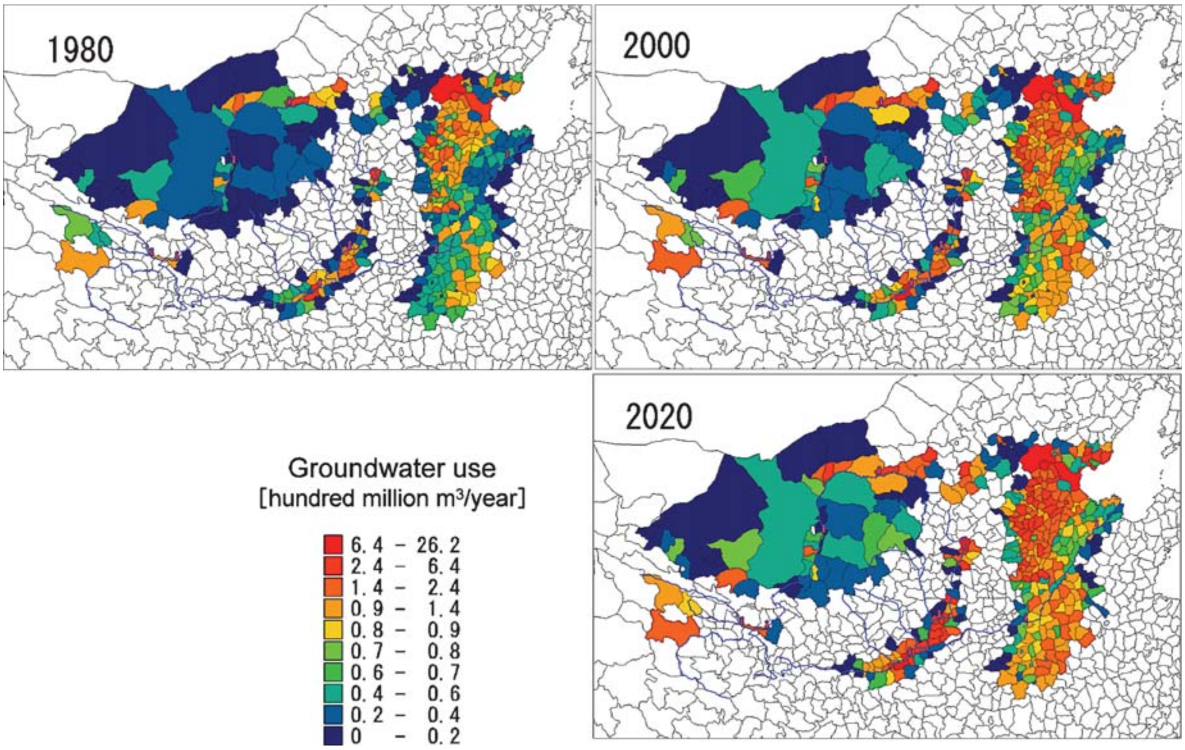


Fig. 8 Amount of groundwater use in YRB (Yellow river basin)

pressurized aquifers is concerned.

Base on these predicted deep groundwater level, we have preliminary estimated the amount of ground settlement by using 1-dimensional consolidation theory. A deep groundwater level here is the third aquifer where pumping are most actively done in Hebei plains. Cray thickness within aquifer we use here is approximately 60m obtained from exsiting data by Zhang, *et al.* (2001a). Volumetric compressibility is assumed to be 7.5E-8 (1/*Pa*) as the general value in Japan Geotechnical Society (1982).

Fig. 11 shows the reproduced and predicted responses of accumulated ground settlement at the point that appears remarkable decreasing in deep groundwater level in Hebei plain during 1980 to 2024. Pumping rate is also shown in same picture. From these result, we can find that the total amount of ground settlement caused by decreasing deep groundwater level might be 4.0m in 2024. This corresponds to twice or more of Cangzhou where serious groundwater settlement was observed in 1995. Although pumping rate during 1998 to 2003 was decreasing, it was not clear if there was a groundwater regulation by Chinese government.

A hypothesis was considered that restoring the groundwater level to more good condition in 1980's in order to decrease the ground settlement. In case of such

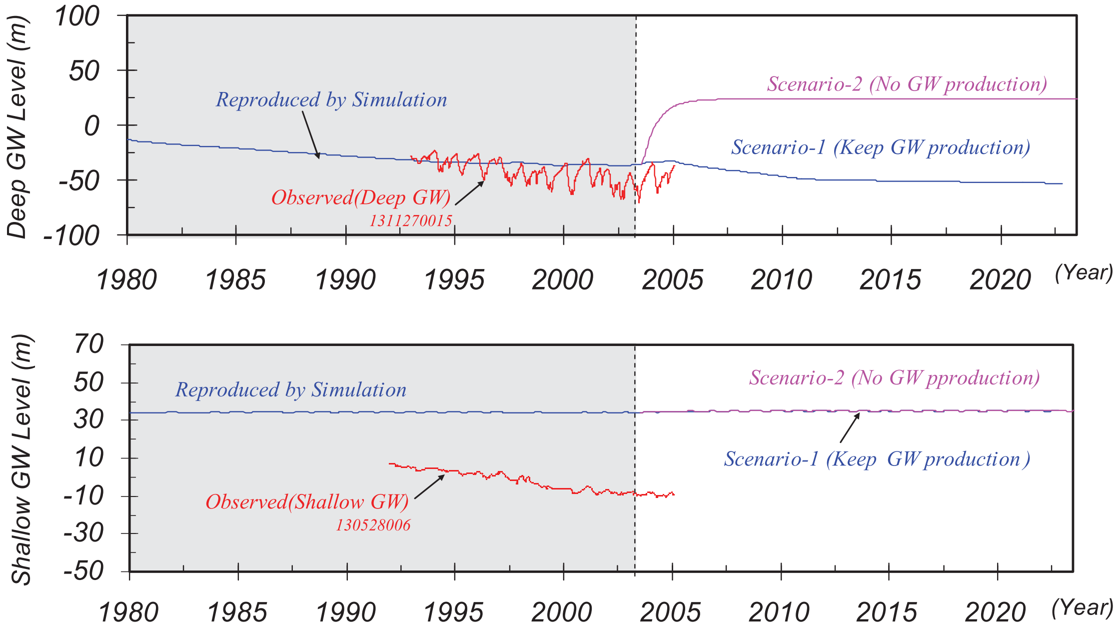


Fig. 9　Simulated groundwater level responses in shallow and deep aquifer (Hebei plain)

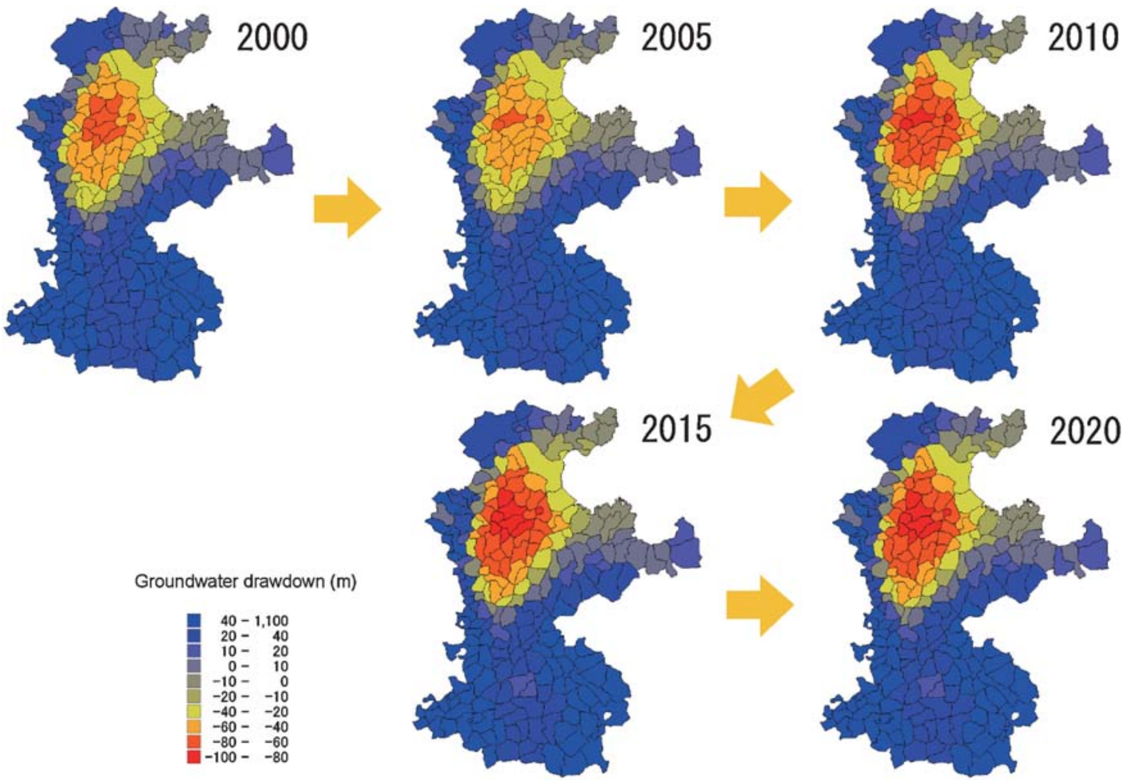


Fig. 10　Contour of groundwater drawdown in deep aquifer (Hebei plain)

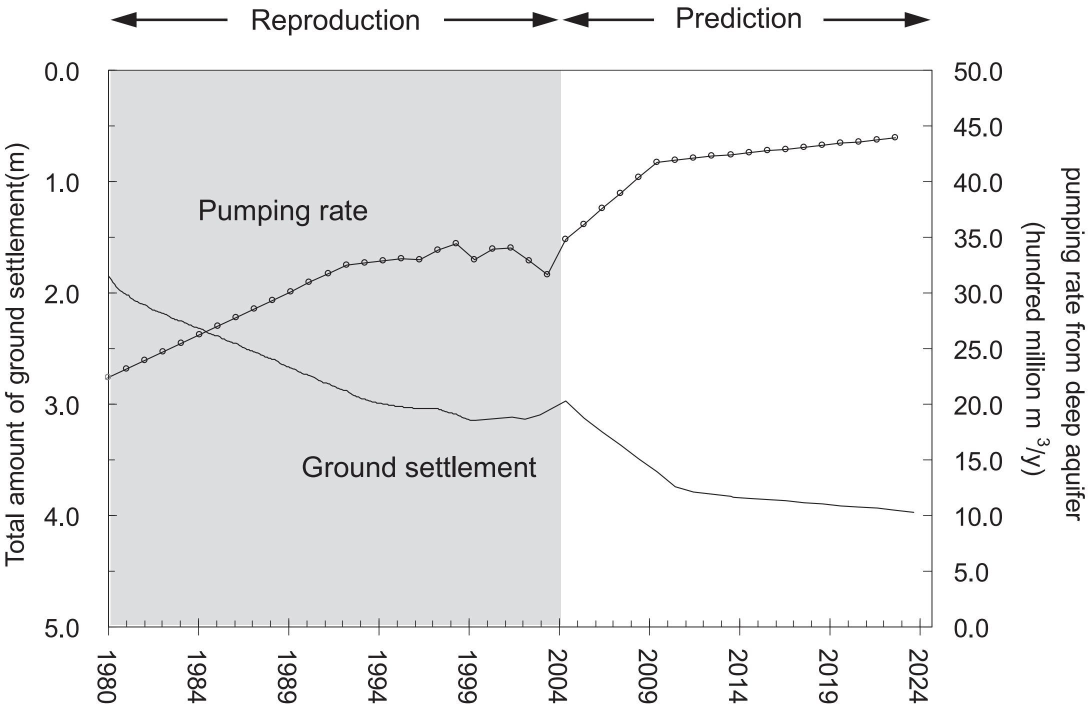


Fig. 11 Numerically reproduced and predicted ground settlement in Hebei plain

situation, if we start to restrict groundwater pumping from 2004, we need to reduce approximately 10.5 hundred million tons groundwater per year. When we assume to keep the pumping for 20 years and beginning restriction from 2024, it is required to reduce 21.4 hundred million tons groundwater per year, and we have to prepare for substitutive water resource. This amount corresponds to approximately 10% of total amount of water use in 2024.

5. Summary

A full-dimensional groundwater circulation model was developed to understand current status and future of groundwater resources in Yellow River basin. Although detailed data or information as to geology and water use were not always enough, high performance numerical model based on current available data was completed. The simulated results were compared with the observed groundwater level measured by CGS and AIST. Reasonable match between observation and simulation was attained.

What we can find through this modeling study is that the recharged groundwater in the upstream area almost goes into the deep underground and discharges into the lower place where is apart from several kilometers. Since topographic slope change is complex around upstream area, the recharged groundwater seems to discharge into the close valley. In other words, deep groundwater in the upstream area does not travel directly to the river mouth and it can be considered that Yellow river basin is comprised from many relatively closed local basins.

During 5 years for this project, various data such as topography, geology, meteorology, land use and water use had been incorporated into the 0.1 degree high resolution full-3D numerical model which is one of mission of this project.

As a result, we could describe groundwater flow system of the whole scale of Yellow River Basin and its characteristic feature mentioned above was reproduced. Therefore, it was confirmed that locally-more detailed groundwater basin models nested from the whole-scale model could be available in order to support effective managements of groundwater resources.

What is important thing here is to continue to improve and maintain this numerical model itself with field monitoring for a long term and to share knowledge obtained from such nature-based modeling for the society. So it is required to expand this project into the postal stage of RR2002.

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中国黄河流域圏における水資源管理のための大規模地下水流動モデリングと高性能数値シミュレーション

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要　旨

黄河源流から河口に及ぶ2,200km×1,100km（約160万km^2）の領域について，地下水資源量評価のための三次元地下水循環モデルを構築した．構築モデルによる過去20年間の流況再現シミュレーションの結果は，多数の水位観測データや既存の文献データなどとの比較を通じて検証された．地下水資源量評価のための将来20年の流況予測は，中国側より提示された2010年及び2020年の水需要予測値をベースに幾つかのシナリオに対して実施した．
その結果，河北省の被圧水位低下によって引き起こされる地盤沈下量は最大4.0mに達すると推定された．1980年当時の被圧地下水状態へ回復させ，地盤沈下の進行を抑制することを考えた場合，直ちに揚水規制を行ったとして年間10.5億m^3，現状を放置し20年後になると年間21.4億m^3以上の地下水資源を他の代替水源に頼らなければならない事態が予測される．この量はその年の地下水総利用量に対して，それぞれ6.4%，9.8%に相当するものである．