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Impact of Irrigation on Hydrologic Change in Highly Cultivated Basin

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1. Introduction

With the development of regional economies, the water use environment in the Yellow River Basin, China, has changed greatly (Fig. 1). The river is well known for its high sediment content, frequent floods, unique channel characteristics in the downstream (where the river bed lies above the surrounding land), and limited water resources. This region is heavily irrigated, and combinations of increased food demand and declining water availability are creating substantial pressures. Some research emphasized human activities such as irrigation water withdrawals dominate annual streamflow changes in the downstream in addition to climate change (Tang et al., 2008a). The North China Plain (NCP), located in the downstream area of the Yellow River, is one of the most important grain cropping areas in China, where water resources are also the key to agricultural development, and the demand for groundwater has been increasing. Groundwater has declined dramatically over the previous half century due to over-pumping and drought, and the area of saline-alkaline land has expanded (Brown and Halweil, 1998; Shimada, 2000; Chen et al., 2003b; Nakayama et al., 2006).

Since the completion of a large-scale irrigation project in 1969, noticeable cessation of flow has been observed in the Yellow River (Yang et al., 1998; Fu et al., 2004) resulting from intense competition between water supply and demand, which has occurred increasingly often. The ratio of irrigation water use (defined as the ratio of the annual gross use for irrigation relative to the annual natural runoff) having increased continuously from 21% to 68% during the last 50 years, indicating that the current water shortage is closely related to irrigation development (Yang et al., 2004a). This shortage also reduces the water renewal time (Liu et al., 2003) and renewability of water resources (Xia et al., 2004). This has been accompanied by a decrease in precipitation in most parts of the basin (Tang et al., 2008b). To ensure sustainable water resource use, it is also important to understand the contributions of human intervention to climate change in this basin (Xu et al., 2002), in addition to clarifying the rather complex and diverse water system in the highly cultivated region.

The objective of this research is to clarify the impact of irrigation on the hydrologic change in the Yellow River Basin, an arid to semi-arid environment with intensive cultivation.

Combination of the National Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2008a, 2008b, 2009, 2010, 2011a, 2011b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Watanabe, 2004, 2006, 2008a, 2008b, 2008c; Nakayama et al., 2006, 2007, 2010, 2011) with complex components such as irrigation, urban water use, and dam/canal systems has led to the improvement in the model, which simulates the balance of both water budget and energy in the entire basin with a resolution of 10 km. The simulated results also evaluates the complex hydrological processes of river dry-up, agricultural/urban water use, groundwater pumping, and dam/canal effects, and to reveal the impact of irrigation on both surface water and groundwater in the basin. This approach will help to clarify how the substantial pressures of combinations of increased food demand and declining water availability can be overcome, and how effective decisions can be made regarding sustainable development under sound socio-economic conditions in the basin.

2. Material and methods

2.1 Coupling of process-based model with complex irrigation procedures

Previously, the author developed the process-based NICE model, which includes surface-unsaturated-saturated water processes and assimilates land-surface processes describing the variations of LAI (leaf area index) and FPAR (fraction of photosynthetically active radiation) from satellite data (Fig. 2) (Nakayama, 2008a, 2008b, 2009, 2010, 2011a, 2011b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Watanabe, 2004, 2006, 2008a, 2008b, 2008c; Nakayama et al., 2006, 2007, 2010, 2011). The unsaturated layer divides canopy into two layers, and soil into three layers in the vertical dimension in the SiB2 (Simple Biosphere model 2) (Sellers et al., 1996). About the saturated layer, the NICE solves three-dimensional groundwater flow for both unconfined and confined aquifers. The hillslope hydrology can be expressed by the two-layer surface runoff model including freezing/thawing processes. The NICE connects each sub-model by considering water/heat fluxes: gradient of hydraulic potentials between the deepest unsaturated layer and the groundwater, effective precipitation, and seepage between river and groundwater.

In an agricultural field, NICE is coupled with DSSAT (Decision Support Systems for Agro-technology Transfer) (Ritchie et al., 1998), in which automatic irrigation mode supplies crop water requirement, assuming that average available water in the top layer falls below soil moisture at field capacity for cultivated fields (Nakayama et al., 2006). The model includes different functions of representative crops (wheat, maize, soybean, and rice) and simulates automatically dynamic growth processes. Potential evaporation is calculated on Priestley and Taylor equation (Priestley and Taylor, 1972), and plant growth is based on biomass formulation, which is limited by various reduction factors like light, temperature, water, and nutrient, et al. (Nakayama et al., 2006; Nakayama and Watanabe, 2008b; Nakayama, 2011a).

In this study, the NICE was coupled with complex sub-systems in irrigation and dam/canal in order to develop coupled human and natural systems and to analyze impact of irrigation on hydrologic change in highly cultivated basin. The return flow was evaluated from surface drainage and from groundwater, whereas previous studies had considered only surface drainage (Liu et al., 2003; Xia et al., 2004; Yang et al., 2004a). The gross loss of river water to irrigation includes losses via canals and leakage into groundwater in the field, and can be estimated as the difference between intake from, and return to the river.

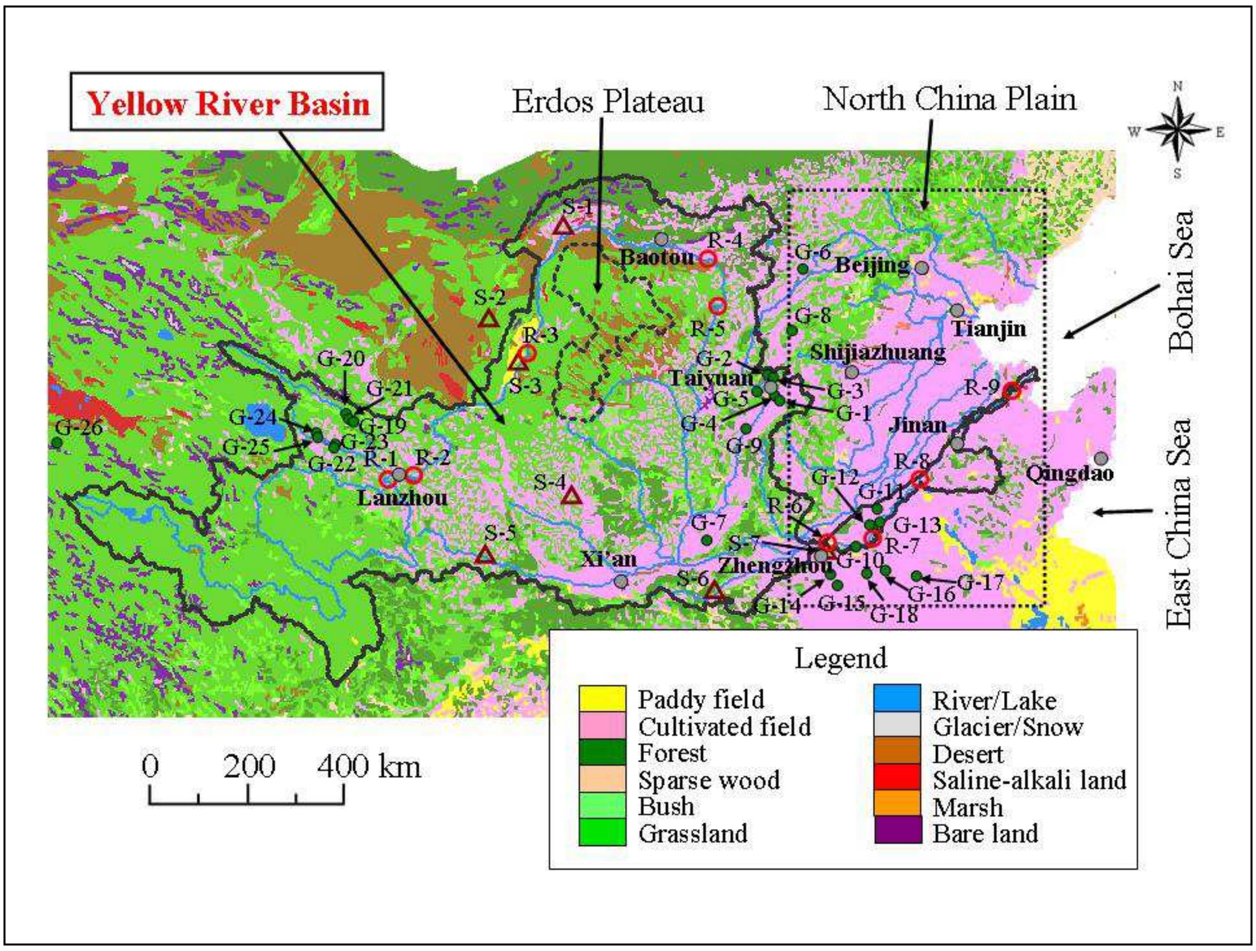

Fig. 1. Land cover in the study area of the Yellow River Basin in China. Bold black line shows the boundary of the basin. Black dotted line is the border of the North China Plain (NCP), which includes the downstream of the Yellow River Basin. Verification data are also plotted in this figure: river discharge (open red circle), soil moisture (open brown triangle), and groundwater level (green dot).

Irrigation withdrawals in the basin account for about 90% of total surface abstraction and 60% of groundwater withdrawal (Chen et al., 2003a). The model was improved for application to irrigated fields where water is withdrawn from both groundwater and river, and therefore the river dry-up process can be reproduced well. As the initial conditions, the ratios of river to aquifer irrigation were set at constant values. In the calibration procedure, these values were changed from initial conditions in order to reproduce the observation data as closely as possible after repeated trial and error (Oreskes et al., 1994). A validation procedure was then conducted in order to confirm the simulation under the same set of parameters, which resulted into reproducing reasonably the observed values. Spring/winter wheat, summer maize, and summer rice were automatically simulated in sequence analysis mode in succession by inputting previous point data for each crop type (Wang et al., 2001; Liu et al., 2002; Tao et al., 2006) and spatial distribution data (Chinese Academy of Sciences, 1988; Fang et al., 2006). The deficit water in the irrigated fields was automatically withdrawn and supplied from the river or the aquifer in the model in order to satisfy the observed hydrologic variables like soil moisture, river discharge, groundwater level, LAI, evapotranspiration, and crop coefficient. So, NICE simulates drought impact and includes the effect of water stress implicitly. Details are given in the previous researches (Nakayama et al., 2006; Nakayama and Watanabe, 2008b; Nakayama, 2011a, 2011b).

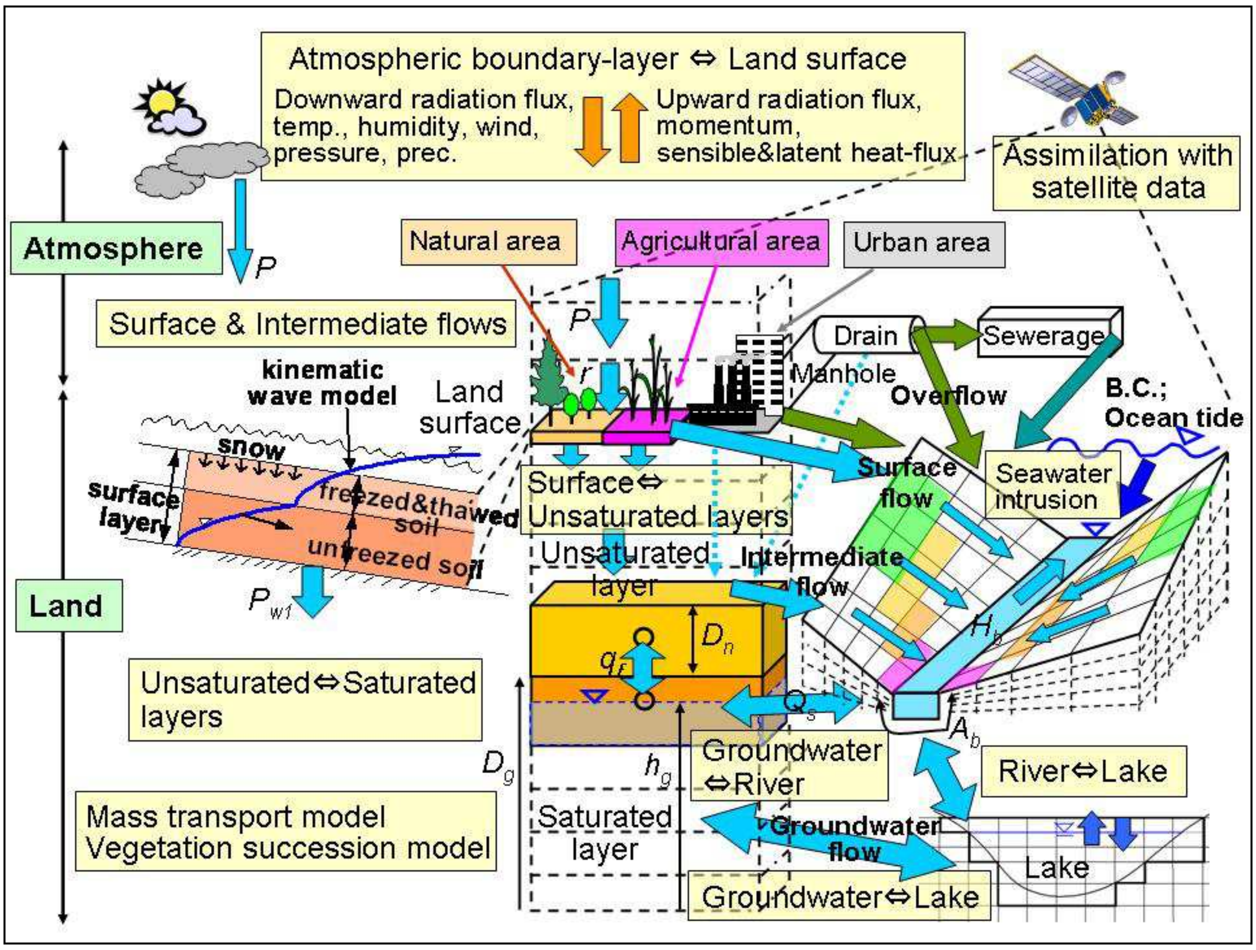

Fig. 2. National Integrated Catchment-based Eco-hydrology (NICE) model.

Another important characteristics of the study area is that there are many dams and canals to meet the huge demand for agricultural, industrial, and domestic water use (Ren et al., 2002) (Fig. 1), and exist six large dams on the main river (Yang et al., 2004a). Because there are few available data on discharge control at most of these dams, the model uses a constant ratio of dam inflow to outflow, which is a simpler approach than that of the storage-runoff function model (Sato et al., 2008). There are also many complex canals in the three large irrigation zones (Qingtongxia in Ningxia Hui, Hetao in Inner Mongolia, and Weisan in Shandong Province), in addition to the NCP, making it very difficult to evaluate the flow dynamics there. Because it is impossible to obtain the observed discharge and data related to the control of the weir/gate at every canal, it is effective to estimate the flow dynamics only in main canals as the first approximation when attempting to evaluate the hydrologic cycle in the entire basin in the same way as (Nakayama et al., 2006; Nakayama, 2011a). Therefore, NICE simulates the discharge only in a main canal assuming that this is defined as the difference in hydraulic potentials at both junctions similar to the stream junction model (Nakayama and Watanabe, 2008b). The dynamic wave effect is also important for the simulation of meandering rivers and smaller slopes, because the backwater effect is predominant (Nakayama and Watanabe, 2004). When a river flow is very low and almost zero at some point in the simulation, the dynamic wave theory requires a lot more computation time and sometimes becomes unstable. Therefore, the model applies a threshold water level of 1 mm to ensure simulation stability and to include the dry-up process. The model also includes the seepage process which is decided by some parameters such as hydraulic conductivity of the river bed, cross-sectional area of the groundwater section, and river bed thickness. Details are described in Nakayama (2011b).

2.2 Model input data and running the simulation

Six-hour reanalysed data for downward radiation, precipitation, atmospheric pressure, air temperature, air humidity, wind speed at a reference level, FPAR, and LAI were input into the model after interpolation of ISLSCP (International Satellite Land Surface Climatology Project) data with a resolution of 1° x 1° (Sellers et al., 1996) in inverse proportion to the distance back-calculated in each grid. Because the ISLSCP precipitation data had the least reliability and underestimated the observed values at peak times, rain gauge daily precipitation data collected at 3,352 meteorological stations throughout the study area were used to correct the ISLSCP precipitation data. Mean elevation of each 10-km grid cell was calculated from the spatial average of a global digital elevation model (DEM; GTOPO30) with a horizontal grid spacing of 30 arc–seconds (~1 km) (USGS, 1996). Digital land cover data produced by the Chinese Academy of Sciences (CAS) based on Landsat TM data from the early 1990s (Liu, 1996) were categorized for the simulation (Fig. 1). Vegetation class and soil texture were categorized and digitized into 1-km mesh data by using 1:4,000,000 and 1:1,000,000 vegetation and soil maps of China (Chinese Academy of Sciences, 1988, 2003). The author's previous research showed that these finer-resolution products are highly correlated with the ISLSCP (Nakayama, 2011b). The geological structure was divided into four types on the basis of hydraulic conductivity, the specific storage of porous material, and specific yield by scanning and digitizing the geological material (Geological Atlas of China, 2002) and core–sampling data at some points (Zhu, 1992).

The irrigation area was calculated from the GIS data based on Landsat TM data from the early 1990s (Liu, 1996), and the calculated value agrees well with the previous results from that period (Yang et al., 2004a) (Table 1), as described in Nakayama (2011b). Most of the irrigated fields are distributed in the middle and lower regions of the Yellow River mainstream and in the NCP (Fig. 3). The agricultural areas in the upper regions and Erdos Plateau are dominated by dryland fields. Spring/winter wheat was predominant in the upper and middle of the arid and semi-arid regions, and double cropping of winter wheat and summer maize was usually practised in the middle and downstream and in the NCP's relatively warm and humid environment (Wang et al., 2001; Liu et al., 2002; Fang et al., 2006; Nakayama et al., 2006; Tao et al., 2006). The averaged water use during 1987-1988 at the main cities in the Yellow River Basin and the NCP (Hebei Department of Water Conservancy, 1987-1988; Yellow River Conservancy Commission, 2002) was directly input to the model. In the 1990s, return flow was as much as 35% of withdrawal in the upper and 25% in the middle, but close to 0% in the downstream (Chen et al., 2003a; Cai and Rosegrant, 2004). The return flows at Qingtongxia and Hetao irrigation zones are 59% and 25% of withdrawal, whereas that at Weisan irrigation zone is close to 0%, because the river bed is above the level of the plain (Chen et al., 2003a; Cai and Rosegrant, 2004). This information was also input into the model.

At the upstream boundaries, a reflecting condition on the hydraulic head was used assuming that there is no inflow from the mountains in the opposite direction (Nakayama and Watanabe, 2004). At the eastern sea boundary, a constant head was set at 0 m. The hydraulic head values parallel to the observed ground level were input as initial conditions for the groundwater sub-model. As initial conditions, the ratios of river and aquifer irrigation were set at the same constant values as in the above section. In river grids decided by digital river network from 1:50,000 and 1:100,000 topographic maps (CAS, 1982), inflows or outflows from the riverbeds were simulated at each time step depending on the difference in the hydraulic heads of groundwater and river. The simulation area covered 3,000 km by 1,000 km with a grid spacing of 10 km, covering the entire Yellow River Basin and the NCP. The vertical layer was discretized in thickness with depth, with each layer increased in thickness by a factor of 1.1 (Nakayama, 2011b; Nakayama and Watanabe, 2008b; Nakayama et al., 2006). The upper layer was set at 2 m depth, and the 20th layer was defined as an elevation of –500 m from the sea surface. Simulations were performed with a time step of 6 h for two years during 1987–1988 after 6 months of warm-up period until equilibrium. The author first calibrated the simulated values including irrigation water use in 1987 against previous results, and then validated them in 1988. Previously observed data about river discharge (9 points; Yellow River Conservancy Commission, 1987-1988), soil moisture (7 points of the Global Soil Moisture Data Bank; Entin et al., 2000; Robock et al., 2000), and groundwater level (26 points; China Institute for Geo-Environmental Monitoring, 2003) were also used for the verification of the model (Fig. 1 and Table 2) in addition to values published in the literature (Clapp and Hornberger, 1978; Rawls et al., 1982). Details are described in Nakayama (2011b).

Reaches[a]	Irrigation area (x 10^4 ha)	
	GIS database (Liu 1996)	Previous research (Yang et al. 2004a)
Above LZ	46.8	39.5
LZ – TDG	342.1	344.1
TDG – LM	43.0	53.4
LM – SMX	295.6	281.3
SMX – HYK	59.2	60.6
Below HYK	160.7	155.0
Sum	947.3	933.9

[a]Abbreviation in the following; LZ, Lanzhou (R-1);
TDG, Toudaoguai (R-4); LM, Longmen; SMX, Sanmenxia;
HYK, Huayuankou (R-6).

Table 1. Comparison of irrigation area in the simulated condition with that in the previous research.

No.	Point Name	Type	Lat.	Lon.	Elev.(m)
R-1	Lanzhou	River Discharge	35°55.8'	103°19.8'	1794.0
R-2	Lanzhou	River Discharge	36°4.2'	103°49.2'	1622.0
R-3	Qingtongxia	River Discharge	38°21.0'	106°24.0'	1096.0
R-4	Toudaoguai	River Discharge	40°16.2'	111°4.2'	861.0
R-5	Hequ	River Discharge	39°22.2'	111°9.0'	861.0
R-6	Huayuankou	River Discharge	34°55.2'	113°39.0'	104.0
R-7	Lankao	River Discharge	34°55.2'	114°42.0'	73.0
R-8	Juancheng	River Discharge	35°55.8'	115°54.0'	1.0
R-9	Lijin	River Discharge	37°31.2'	118°18.0'	1.0
S-1	Bameng	Soil Moisture	40°46.2'	107°24.0'	1059.0
S-2	Xilingaole	Soil Moisture	39°4.8'	105°22.8'	1238.0
S-3	Yongning	Soil Moisture	38°15.0'	106°13.8'	1130.0
S-4	Xifengzhen	Soil Moisture	35°43.8'	107°37.8'	1435.0
S-5	Tianshui	Soil Moisture	34°34.8'	105°45.0'	1196.0
S-6	Lushi	Soil Moisture	34°0.0'	111°1.2'	675.0
S-7	Zhengzhou	Soil Moisture	34°49.2'	113°40.2'	99.0
G-1	Shanxi-1	Groundwater Level	37°44.0'	112°34.2'	772.51
G-2	Shanxi-2	Groundwater Level	38°0.7'	112°25.8'	831.10
G-3	Shanxi-3	Groundwater Level	37°58.0'	112°29.6'	788.96
G-4	Shanxi-4	Groundwater Level	37°47.3'	112°31.3'	779.03
G-5	Shanxi-5	Groundwater Level	37°43.2'	111°57.5'	780.51
G-6	Shanxi-6	Groundwater Level	40°3.4'	113°17.4'	1059.73
G-7	Shanxi-7	Groundwater Level	34°56.9'	110°45.1'	346.73
G-8	Shanxi-8	Groundwater Level	38°47.1'	112°44.0'	823.18
G-9	Shanxi-9	Groundwater Level	37°7.6'	111°54.2'	733.24
G-10	Henan-1	Groundwater Level	34°48.2'	114°18.2'	73.40
G-11	Henan-2	Groundwater Level	35°42.0'	115°1.3'	52.20
G-12	Henan-3	Groundwater Level	35°31.0'	115°1.0'	53.30
G-13	Henan-4	Groundwater Level	35°31.0'	115°12.5'	54.00
G-14	Henan-5	Groundwater Level	34°1.5'	113°50.8'	66.80
G-15	Henan-6	Groundwater Level	33°49.0'	113°56.3'	63.91
G-16	Henan-7	Groundwater Level	34°4.1'	115°18.2'	47.20
G-17	Henan-8	Groundwater Level	33°55.9'	116°22.3'	31.90
G-18	Henan-9	Groundwater Level	34°48.2'	114°18.2'	52.60
G-19	Qinghai-1	Groundwater Level	36°35.5'	101°44.7'	2321.17
G-20	Qinghai-2	Groundwater Level	37°0.0'	101°37.9'	2506.94
G-21	Qinghai-3	Groundwater Level	36°58.5'	101°38.9'	2474.63
G-22	Qinghai-4	Groundwater Level	36°34.3'	101°43.9'	2346.37
G-23	Qinghai-5	Groundwater Level	36°32.2'	101°40.5'	2451.32
G-24	Qinghai-6	Groundwater Level	36°43.1'	101°30.3'	2425.32
G-25	Qinghai-7	Groundwater Level	36°41.9'	101°30.9'	2383.98
G-26	Qinghai-8	Groundwater Level	36°14.8'	94°46.6'	3007.81

Table 2. Lists of observation stations for calibration and validation shown in Fig. 1.

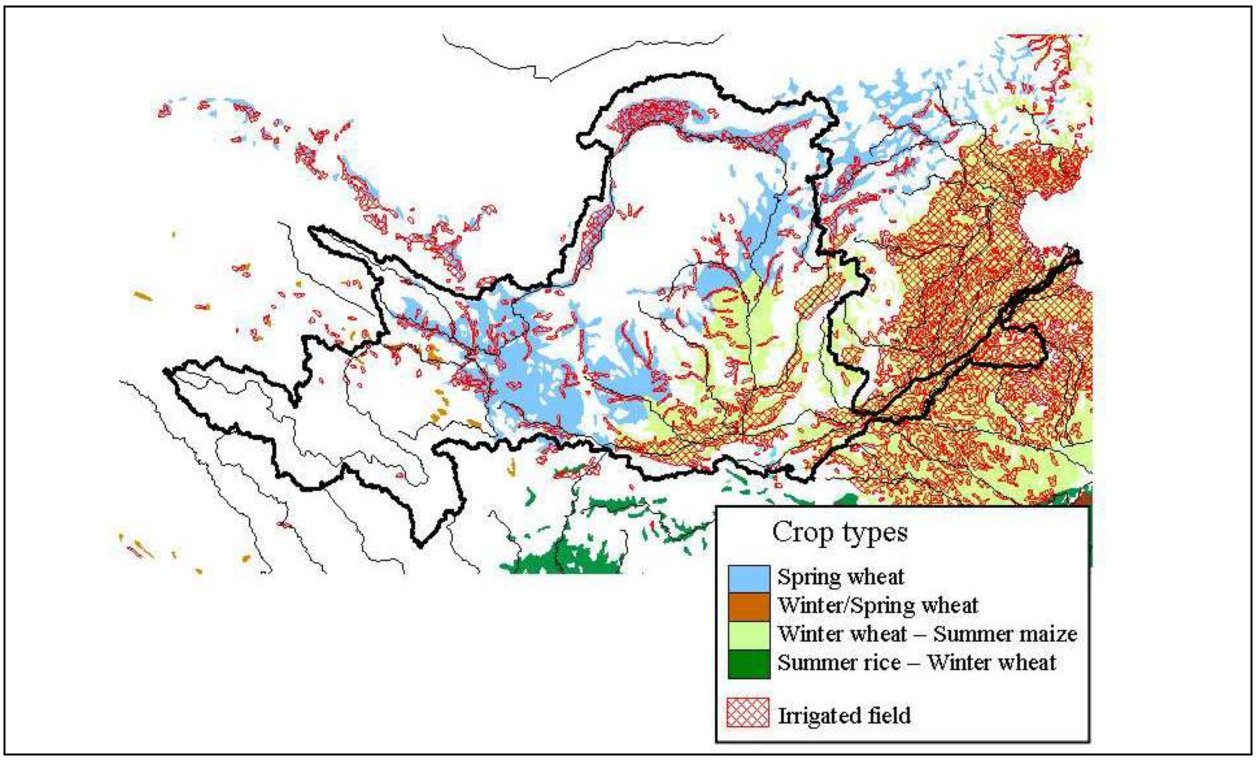

Fig. 3. Crop types in the agricultural areas. Irrigation areas are also overshaded. Irrigated fields cover most of the NCP for double cropping of winter wheat and summer maize in addition to three large irrigation zones.

3. Result and discussion

3.1 Verification of hydrologic cycle in the basin

The irrigation water use simulated in 1987 was firstly calibrated against previous results (Cai and Rosegrant, 2004; Liu and Xia, 2004; Yang et al., 2004a; Cai, 2006), showing a close agreement with the results of Cai and Rosegrant (2004). Then, the simulated value in 1988 was validated with the previous researches (Table 3), which indicates that there was reasonable agreement with each other and that irrigation water use is higher in large irrigation zones (LZ-TDG), along the Wei and Fen rivers (LM-SMX) in the middle, and in the downstream (below HYK). The results also show a high correlation between irrigation area and water use: r^2 = 0.986 (Chen et al., 2003a) and r^2 = 0.826 (Liu and Xia, 2004). Details of calibration and validation procedures are described in Nakayama (2011b).

The actual ET simulated by NICE reproduces reasonably the general trend estimated by integrated AVHRR NDVI data (Sun et al., 2004), which may give a good support on the predictive skill of the model (Fig. 4a-b). Although there are some discrepancies particularly for the lowest ET area (EP < 200 mm/year) mainly because of the banded colour figures, the simulated result reproduces the characteristics that the value is lowest in the downstream area of middle and on the Erdos Plateau—less than 200-300 mm per year (except in the irrigated area)—where vegetation is dominated by desert and soil is dominated by sand, and increases gradually towards the south-east. The simulated result also indicates that this spatial heterogeneity is related to human interventions and the resultant water stress by spring/winter cultivation in the upper/middle areas (Chen et al., 2003a; Tao et al., 2006), and winter wheat and summer maize cultivations in the middle/downstream (including the

Wei and Fen tributaries) and the NCP (Wang et al., 2001; Liu et al., 2002; Nakayama et al., 2006). Although the satellite-derived data are effective for grasping the spatial distribution of actual ET, there are some inefficiencies with regard to underestimation in sparsely vegetated regions (Inner Mongolia and Shaanxi Province) and overestimation in densely vegetated or irrigated regions (source area and Henan Province), as suggested by previous research (Sun et al., 2004; Zhou et al., 2007), which the simulation overcomes and improves mainly due to the inclusion of drought impact in the model. Details are described in Nakayama (2011b).

The model also simulated effect of irrigation on evapotranspiration at rotation between winter wheat and summer maize in the downstream of Yellow River (Fig. 4c). Because more water is withdrawn during winter-wheat period due to small rainfall in the north, the irrigation in this period affects greatly the increase in evapotranspiration. The simulated result indicates that the evapotranspiration increases predominantly during the seasons of grain filling and harvest of winter wheat with the effect of irrigation. In particular, most of the irrigation is withdrawn from aquifer in the NCP because surface water is seriously limited there (Nakayama, 2011b; Nakayama et al., 2006). This over-irrigation also affects the hydrologic change such as river discharge, soil moisture, and groundwater level in addition to evapotranspiration, as described in the following.

<table>
<tr><th rowspan="2">Reaches[a]</th><th colspan="5">Irrigation water use (x 10^9 m^3)</th></tr>
<tr><th>Simulated value (1988)[b]</th><th>Cai and Rosegrant 2004 (2000)[b]</th><th>Liu and Xia 2004 (1990s)[b]</th><th>Yang et al. 2004a (1990s)[b]</th><th>Cai 2006 (1988-1992)[b]</th></tr>
<tr><td>Above LZ</td><td>1.5</td><td>2.9</td><td rowspan="2">13.2</td><td rowspan="5">18.9</td><td rowspan="2">12.4</td></tr>
<tr><td>LZ – TDG</td><td>6.8</td><td>12.2</td></tr>
<tr><td>TDG – LM</td><td>1.1</td><td>1.0</td><td rowspan="3">6.0</td><td rowspan="3">4.8</td></tr>
<tr><td>LM – SMX</td><td>10.4</td><td>7.3</td></tr>
<tr><td>SMX – HYK</td><td>2.0</td><td>2.4</td></tr>
<tr><td>Below HYK</td><td>8.4</td><td>10.6</td><td>10.8</td><td>9.5</td><td>11.2</td></tr>
<tr><td>Sum</td><td>30.2</td><td>36.4</td><td>30.0</td><td>28.5</td><td>28.4</td></tr>
</table>

[a]Abbreviation in the following; LZ, Lanzhou (R-1); TDG, Toudaoguai (R-4); LM, Longmen; SMX, Sanmenxia; HYK, Huayuankou (R-6).
[b]Value in parenthesis shows the target year in the simulation and the literatures.

Table 3. Validation of irrigation water use simulated by the model with that in the previous research.

The model could simulate reasonably the spatial distribution of irrigation water use after the comparison with a previous study based on the Penman-Monteith method and the crop coefficient (Fang et al., 2006) not only in reach level but also in the spatial distribution, as described in Nakayama (2011b). In particular, simulated ratios of river to total irrigation

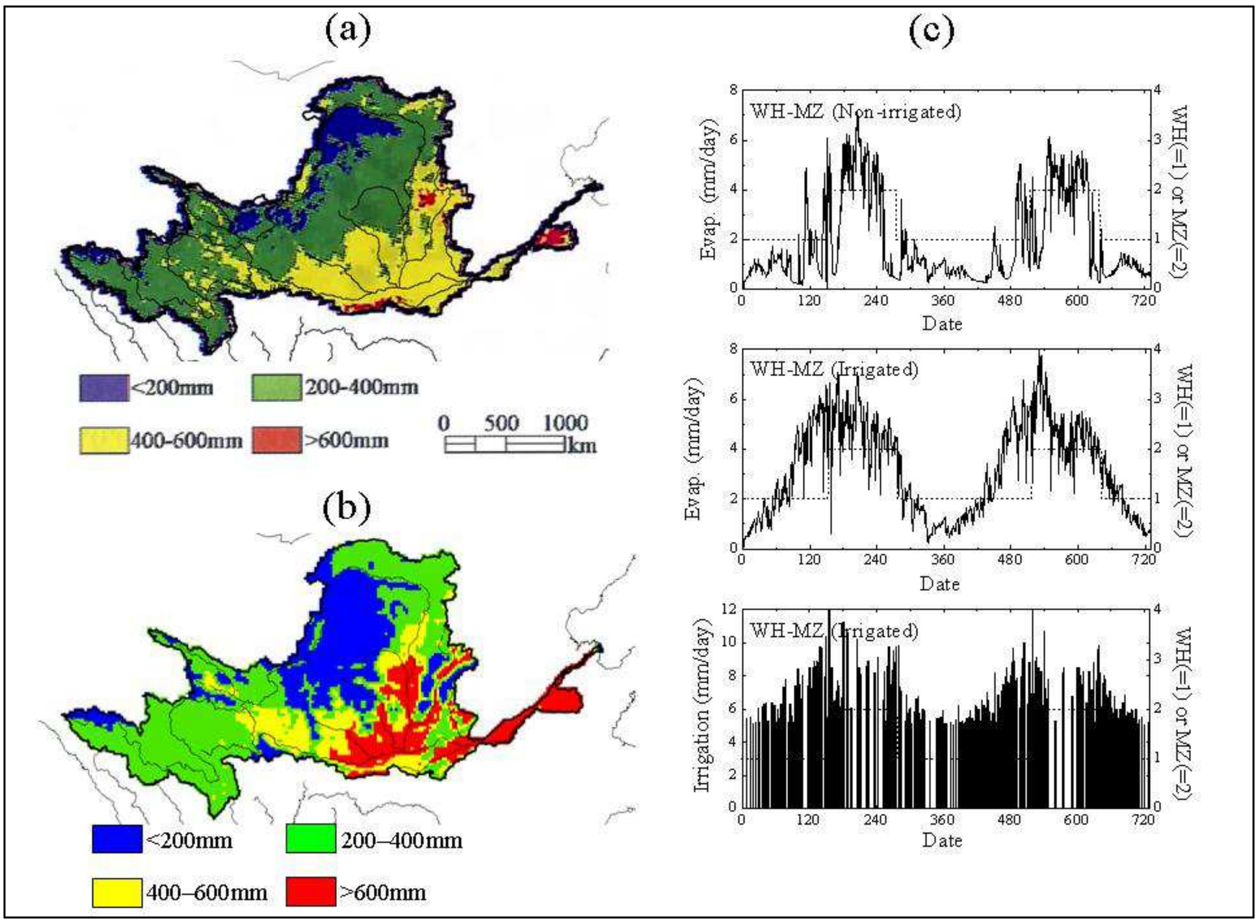

Fig. 4. Annual-averaged spatial distribution of evapotranspiration in 1987; (a) previous research; (b) simulated result; and (c) simulated value about impact of irrigation on evapotranspiration at rotation between winter wheat and summer maize. In Fig. 4c, right axis (dotted line) shows a period of each crop (WH; wheat, and MZ; maize).

(=river + aquifer) showed great variation and spatial heterogeneity in the basin. Fig. 5 shows the effect of over-irrigation on the decrease in river discharge on the downstream. The model reproduces reasonably the observed discharge for a low flow, and sometimes dry-up in the downstream (Yellow River Conservancy Commission, 1987-1988) with relatively high correlation r^2 and Nash-Sutcliffe criterion (NS; Nash and Sutcliffe, 1970) because the model includes the irrigation procedure and dynamic wave effect (Nakayama and Watanabe, 2004) in the model (Fig. 5b). The discharge decreases seriously in the downstream area mainly because of the water withdrawal for agriculture, which is more than 90% of the total withdrawal (Cai, 2006). At the downstream point at Lijin (R-9 in Table 2), the river discharge dries out during the spring mainly because most of the water is used for the irrigation of winter wheat in correspondence with the great increase in evapotranspiration shown in Fig. 4c. The model also indicated that the effect of groundwater irrigation is predominant in the downstream (data not shown), mainly on account of intensified water-use conflicts between upstream and downstream, and between various sectors like agriculture, municipality, and industry (Brown and Halweil, 1998; Nakayama, 2011a, 2011b; Nakayama et al., 2006). The smaller change in groundwater level in the upper was largely attributable to its unsuitability for crop production and the higher dependence of irrigation on surface water, as described previously (Yellow River Conservancy Commission, 2002).

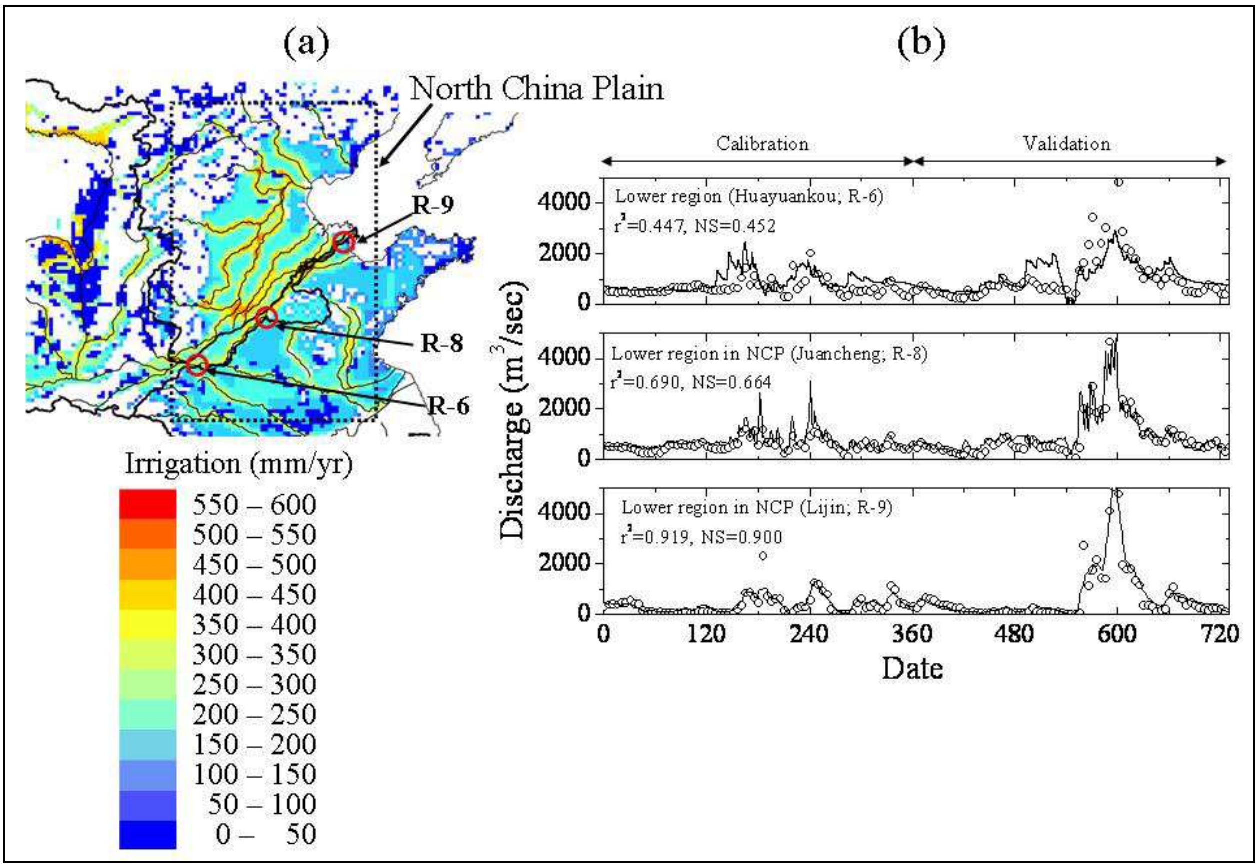

Fig. 5. Decrease in discharge caused by over-irrigation in the downstream region; (a) simulated result of river irrigation in 1987; (b) river discharge at the downstream. In Fig. 5b, solid line is the simulated result with irrigation, and circle is the observed value.

The simulated groundwater levels and soil moisture contents were calibrated and validated against observed data (Entin et al., 2000; Robock et al., 2000; China Institute for Geo-Environmental Monitoring, 2003) shown in Fig. 1 and Table 2 (data not shown). Although the correlation of groundwater level relative to the surface was not as good (r^2 = 0.401) as that of the absolute groundwater level (r^2 = 0.983) and the simulated value showed a tendency to overestimate the observed value in the calibration procedure for 1987, the simulation reproduced well the general distribution (BIAS = -21.2%, RMSE = 5.6 m, RRMSE = -0.468, MSSS = 0.356) (Nakayama, 2011b). This disagreement was due to the difference in surface elevation on the point-scale and mesh-scale (scale dependence), and the resolution of the groundwater flow model (changes in elevation from 0 m to 3000–4000 m in the basin). Because the simulated level is the hydraulic head in an aquifer, it might take a larger value than the land surface, particularly for a grid cell near or on the river. Another reason is that the irrigation water use simulated by the model might be underestimated because automatic irrigation supplied the water requirement for crops in order to satisfy the observed soil moisture, river discharge, groundwater level, LAI, evapotranspiration, and crop coefficient, which was theoretically pumped up from the river or the aquifer in the model. In reality, it has a possibility that farmers might use more irrigation water than the theoretical water requirement for crops if possible though there were not enough statistical or observed data to support it. The simulated water level decreases rapidly around the source area, indicating that there are many springs in this region. It is very low in the downstream (below sea level in some regions) because of the low elevation and overexploitation, as is the case in the NCP (Nakayama, 2011a, 2011b; Nakayama et al., 2006). The soil moisture is higher in the source area and in the paddy-dominated Qingtongxia Irrigation Zone (data not shown), corresponding closely with the distribution of the groundwater level. Details are described in Nakayama (2011b).

3.2 Impact of irrigation on hydrologic changes

Scenario analysis of conversion from unirrigated to irrigated run predicted the hydrologic changes (Fig. 6). The predicted result without irrigation generally overestimates the observed river discharge (Fig. 6a) and this effect is more prominent in the middle and downstream, as supported by reports that the difference between natural and observed runoff is larger downstream (Ren et al., 2002; Fu et al., 2004; Liu and Zheng, 2004). The difference between simulations considering and not considering irrigation strongly supports previous studies from the point of view that the influence of human interventions on river runoff has increased downstream over the last five decades (Chen et al., 2003a; Liu and Xia, 2004; Yang et al., 2004a; Cai, 2006; Tang et al., 2007) (Table 3), as also represented by the decline of water renewal times (Liu et al., 2003) and water resource renewability (Xia et al., 2004). This difference is greatly affected by complex irrigation procedures of various crops, which are roughly represented by spring/winter wheat in the upper-middle, and double cropping of winter wheat and summer maize in the middle-downstream regions (Wang et al., 2001; Liu et al., 2002; Fang et al., 2006; Nakayama et al., 2006; Tao et al., 2006).

Because there is some time lag between periods of increase in irrigation and decrease in runoff, the river discharge does not necessarily decrease in the winter and sometimes decreases in the summer. Further, the discharge sometimes increases slightly in the flood season, which indicates that the precipitation in irrigated fields sometimes responds quickly to flood drainage. Although both r^2 and NS have relatively low values across the basin (max: r^2 = 0.447, NS = 0.452), the simulated results with irrigation reproduce these characteristics better, and the statistics for MV (mean value), SD (standard deviation), and CV (coefficient of variation; CV = SD/MV) generally agree better with the observed values, as also supported by the better reproduction of other components of the hydrologic cycle, such as annual ET (Fig. 4) (data not shown in the case without irrigation) and irrigation water use (Fig. 5a, Table 3). The simulated result considering irrigation also reproduces the observed data for a low flow, and sometimes dry-up in the same way as Fig. 5b (Zhang et al., 1990; Yang et al., 1998; Ren et al., 2002), being attributable to inclusion of the dynamic wave effect in NICE, which other previous NICE series were unable to reproduce. Furthermore, the model improves the reproduction of river discharge in the basin in comparison with previous research (Yang and Musiake, 2003), where the ratio of absolute error to the mean was more than 60% at Huayuankou hydrological station, one of the worst such cases on a major river in Asia. The major reason for this disagreement is artificial water regulation such as reservoirs, water intakes, and diversions, which the model generally includes in addition to the extreme annual variation in flood seasons (Nakayama and Watanabe, 2008b).

Scenario analysis also predicts the groundwater level change and indicates that the effect of groundwater over-irrigation is predominant in the middle and downstream (Fig. 6b), where surface water is seriously limited, as shown in Fig. 5b and described in section 2.1 (Yellow River Conservancy Commission, 2002). The predicted result indicates a serious situation of water shortage in the downstream region and the NCP where groundwater level degrades over a wide area (Brown and Halweil). The result also implies that the model accounts for intensified water-use conflicts between upstream and downstream areas, and between agriculture, municipal, and industrial sectors (Brown and Halweil, 1998; Shimada, 2000; Chen et al., 2003b; Nakayama et al., 2006). These analyses of the impact of human intervention on hydrologic changes present strong indicatives of the seriousness of the situation, and imply the need for further correct estimation and appropriate measures against such irrigation loss and the low irrigation efficiency described previously (Wang et al., 2001). Details are described in Nakayama (2011b).

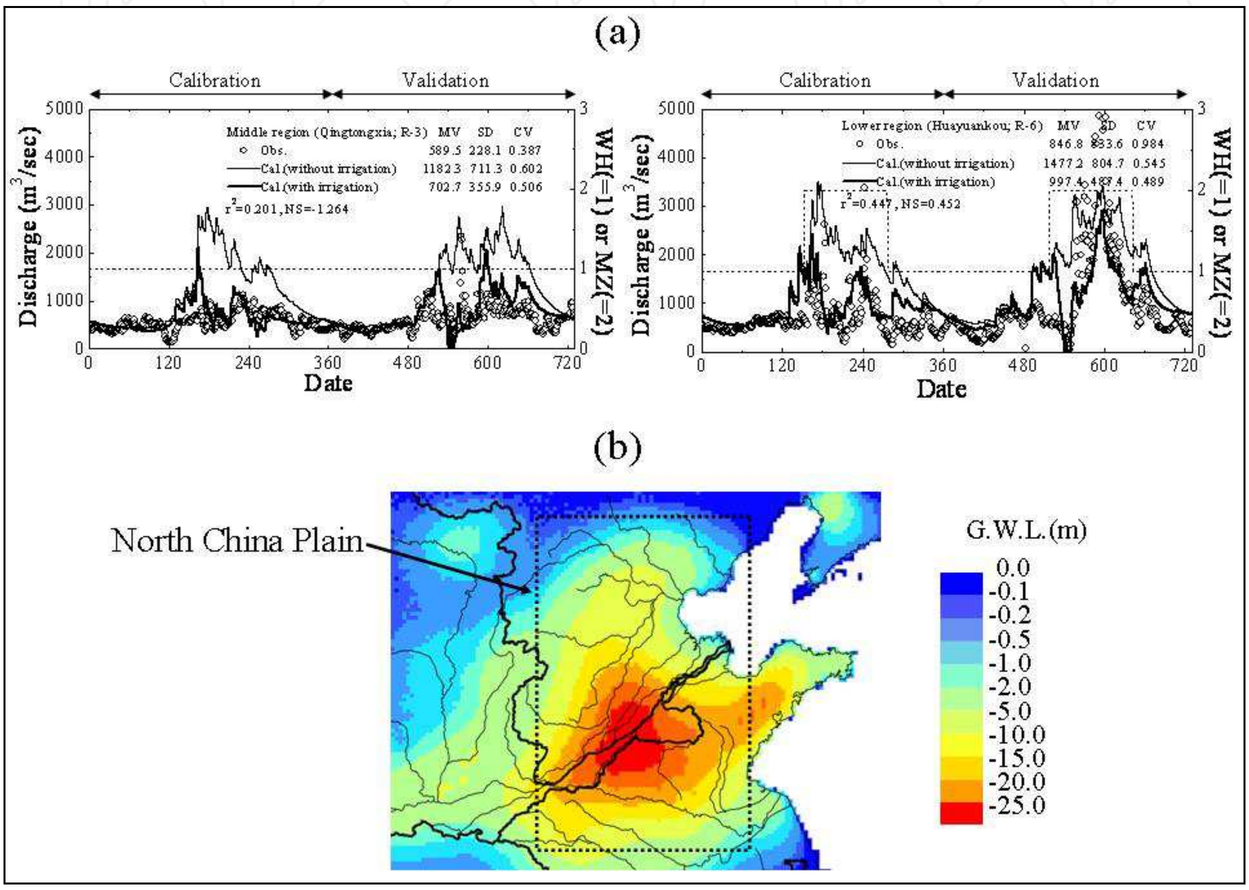

Fig. 6. Scenario analysis of conversion from unirrigated to irrigated run; (a) prediction of river discharge at the upper-middle (R–3; Qingtongxia) and the lower (R–6; Huayuankou) in Fig. 1 and Table 2; (b) groundwater level change in the middle-downstream regions. In Fig. 6a, circles show observation data; solid line is the simulated result without irrigation effect; bold line is the simulated result with irrigation. Right axis (dotted line) shows a period of each crop (WH; wheat, and MZ; maize) in the same way as Fig. 4c.

3.3 Discussion

Water scarcity and resource depletion in the downstream and the NCP, referred to as the 'bread basket' of China, is becoming more severe every year against increased crop production based on irrigation water, in addition to the expansion of municipal and industrial usage (Nakayama, 2011a; Nakayama et al., 2006). The simulated result shows the discharge was affected greatly by the rapid development of cities and industries and the increase in farmland irrigation (Fig. 6), which is closely related to severe groundwater degradation owing to the high clay content of the surface soil (Nakayama et al., 2006;

Nakayama, 2011a, 2011b). Because the dry-up of river reaches and groundwater exhaustion have been very severe so far (Chen et al., 2003b; Xia et al., 2004; Yang et al., 2004a), it is urgently necessary to perform effective control of water diversions (Liu and Xia, 2004; Liu and Zheng, 2004); the results simulated by NICE can be taken as strong indicatives of the seriousness of the situation. There are some reasons for the gap between irrigation water use (Fig. 5a) and groundwater level distribution (Fig. 6b). Firstly, the simulated levels have a temporally averaged distribution, and it takes some time for water levels to reach equilibrium after the boundary conditions have changed. This in turn affects the replenishment of groundwater from adjacent regions in addition to the heterogeneity of three-dimensional groundwater flow. Secondly, irrigation water is drawn not only from groundwater but also from river, and the ratio of river to total irrigation changes spatio-temporally in the basin (Fig. 5b); more river irrigation is drawn in the upper, and most of the irrigation depends on groundwater in the downstream, particularly in the NCP. This effect is clearly evident in comparison with the simulated results and the degradation value in the downstream is smaller that that in Fig. 6b.

Though the simulation reproduced reasonably hydrologic cycle such as evapotranspiration (Fig. 4), irrigation water use (Fig. 5a and Table 3), groundwater level, and river discharge (Fig. 5b and Fig. 6a), there were some discrepancies due to very complex and inaccurate nature of water withdrawal in the basin. In particular, the model achieved a relatively reasonable agreement though the model tried to calibrate and validate irrigation water use during only two years against other studies focusing on irrigation during long period (Fig. 5a and Table 3), which might lead to a substantial bias on model parameters. Because the objective of this study is primarily to evaluate the complex hydrological processes and reveal the impact of irrigation on hydrologic cycle in the basin through the verification during a fixed period, it is a future work to run model for the long period in the next step. At the same time, it will be of importance to derive better estimates of water demand in agricultural and urban areas during the long period by using more detailed statistical data, GIS data, and satellite data in longer period. Although the geological structure in the model included the general characteristics of several aquifers by reference to previous literature (Geological Atlas of China, 2002), the detailed structure of each aquifer layer was simplified as much as possible (Nakayama and Watanabe, 2008b; Nakayama et al., 2006). It will be necessary to obtain more precise data for the complex channel geometry of both natural and artificial rivers, soil properties, and geological structure. The spatial and temporal resolution used in the simulation also requires further improvement in order to overcome the problem of scale dependence and to improve verification and future reliability (Nakayama, 2011b).

Simulated results about the impact of irrigation on evapotranspiration change show a heterogeneous distribution (Fig. 4a-b). In particular, the irrigation of winter wheat increases greatly evapotranspiration, which is supplied by the limited water resources of river discharge and groundwater there (Fig. 5). This implies that energy supply is abundant relative to the water supply and the hydrological process is more sensitive to precipitation in the north, whereas the water supply is abundant relative to the energy supply and sun duration has a more significant impact in the south (Cong et al., 2010). The NICE is effective to provide better evaluation of hydrological trends in longer period including 'evaporation paradox' (Roderick and Farquhar, 2002; Cong et al., 2010) together with observation networks because the model does not need the crop coefficient (depending on a growing stage and a kind of crop) for the calculation of actual evaporation and simulates it directly without detailed site-specific information or empirical relation to calculate effective precipitation (Nakayama, 2011a; Nakayama et al., 2006). It is further necessary to clarify feedback and inter-relationship between micro, regional, and global scales; Linkage with global-scale dynamic vegetation model including two-way interactions between seasonal crop growth and atmospheric variability (Bondeau et al., 2007; Oleson et al., 2008); From stochastic to deterministic processes towards relationship between seedling establishment, mortality, and regeneration, and growth process based on carbon balance (Bugmann et al., 1996); From CERES-DSSAT to generic (hybrid) crop model by combinations of growth-development functions and mechanistic formulation of photosynthesis and respiration (Yang et al., 2004b); Improvement of nutrient fixation in seedlings, growth rate parameter, and stress factor, etc. for longer time-scale (Hendrickson et al., 1990). These future works might make a great contribution to the construction of powerful strategy for climate change problems in global scale.

Importance is that authority for water management in the basin is delineated by water source (surface water or groundwater) in addition to topographic boundaries (basin) and integrated water management concepts. In China, surface water and groundwater are managed by different authorities; the Ministry of Water Resources is responsible for surface water, while groundwater is considered a mineral resource and is administered by the Ministry of Minerals. In order to manage water resources effectively, any change in water accounting procedures may need to be negotiated through agreements brokered at relatively high levels of government, because surface water and groundwater are physically closely related to each other. Furthermore, the future development of irrigated and unirrigated fields and the associated crop production would affect greatly hydrologic change and usable irrigation water from river and aquifer, and vice versa (Nakayama, 2011b). The changes seen in this water resource are also related to climate change because groundwater storage moderates basin responses and climate feedback through evapotranspiration (Maxwell and Kollet, 2008). This is also related to a necessity of further evaluation about the evaporation paradox as described in the above. Although the groundwater level has decreased rapidly mainly due to overexploitation in the middle and downstream (Nakayama et al., 2006; Nakayama, 2011a, 2011b), regions where the land surface energy budget is very sensitive to groundwater storage are dominated by a critical water level (Kollet and Maxwell, 2008). The predicted hydrologic change indicates heterogeneous vulnerability of water resources and implies the associated impact on climate change (Fig. 6).

Basin responses will also be accelerated by an ambitious project to divert water from the Changjiang to the Yellow River, so-called, the South-to-North Water Transfer Project (SNWTP) (Rich, 1983; Yang and Zehnder, 2001). It can be estimated that the degradation of crop productivity may become severe, because most of the irrigation is dependent on vulnerable water resources (McVicar et al., 2002). Further research is necessary to examine the optimum amount of water that can be transferred, the effective management of the Three Gorges Dam (TGD) in the Changjiang River, the overall economic and social consequences of both projects, and their environmental assessment. It will be further necessary to obtain more observed and statistical data relating to water level, soil and water temperatures, water quality, and various phenological characteristics and crop productivity of spring/winter wheat and summer maize, in addition to satellite data of higher spatiotemporal resolution describing the seasonal and spatial vegetation phenology more accurately. The linear relationship between evapotranspiration and biomass production, which is very conservative and physiologically determined, is also valuable for further evaluation of the relationship between changes in water use and crop production by coupling with the numerical simulation and the satellite data analysis. Furthermore, it is powerful to develop a more realistic mechanism for sub-models, and to predict future hydrologic cycle and associated climate change using the model in order to achieve sustainable development under sound socio-economic conditions.

4. Conclusion

This study coupled National Integrated Catchment-based Eco-hydrology (NICE) model series with complex sub-models involving various factors, and clarified the importance of and diverse water system in the highly cultivated Yellow River Basin, including hydrological processes such as river dry-up, groundwater deterioration, agricultural water use, et al. The model includes different functions of representative crops (wheat, maize, soybean, and rice) and simulates automatically dynamic growth processes and biomass formulation. The model reproduced reasonably evapotranspiration, irrigation water use, groundwater level, and river discharge during spring/winter wheat and summer maize cultivations. Scenario analysis predicted the impact of irrigation on both surface water and groundwater, which had previously been difficult to evaluate. The simulated discharge with irrigation was improved in terms of mean value, standard deviation, and coefficient of variation. Because this region has experienced substantial river dry-up and groundwater degradation at the end of the 20th century, this approach would help to overcome substantial pressures of increasing food demand and declining water availability, and to decide on appropriate measures for whole water resources management to achieve sustainable development under sound socio-economic conditions.

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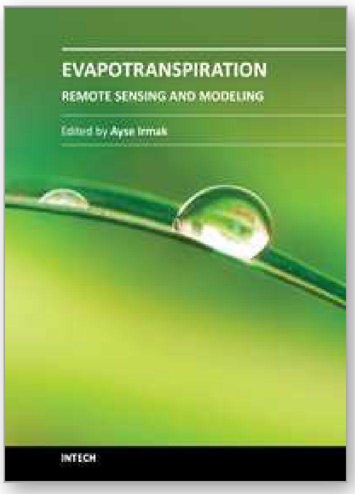

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This edition of Evapotranspiration - Remote Sensing and Modeling contains 23 chapters related to the modeling and simulation of evapotranspiration (ET) and remote sensing-based energy balance determination of ET. These areas are at the forefront of technologies that quantify the highly spatial ET from the Earth's surface. The topics describe mechanics of ET simulation from partially vegetated surfaces and stomatal conductance behavior of natural and agricultural ecosystems. Estimation methods that use weather based methods, soil water balance, the Complementary Relationship, the Hargreaves and other temperature-radiation based methods, and Fuzzy-Probabilistic calculations are described. A critical review describes methods used in hydrological models. Applications describe ET patterns in alpine catchments, under water shortage, for irrigated systems, under climate change, and for grasslands and pastures. Remote sensing based approaches include Landsat and MODIS satellite-based energy balance, and the common process models SEBAL, METRIC and S-SEBS. Recommended guidelines for applying operational satellite-based energy balance models and for overcoming common challenges are made.

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