Challenges and Adaptive Strategies of Water Resources Change in the Yellow River Basin under the Changing Environment

YANGWEN JIA[1], CUNWEN NIU[1], YAQIN QIU[1], CHUNFENG HAO[1,2,3]

1 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, 1 Yu-Yuan-Tan South Road, Beijing 100038, China. Email:jiayw@iwhr.com, jiaywangwen@163.com; Phone: 861068785616; Fax: 861068483367

2 Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

3 Beijing IWHR Technology Co., Ltd., Beijing 100038, China

Abstract：To quantify the water resources change, identify the main challenges and provide management suggestions in the Yellow River Basin, the distributed hydrology model WEP-L is utilized with combinations of statistical analysis of hydro-meteorological data and remote-sensing data. The results show that climate variation, soil conservation and water use facilities are main reasons for the water resources decrease in the basin, and an interesting finding is the groundwater resources unrepeated with the surface water resources has increased contrasting to the obvious decrease of surface water resources. Adaptive strategies for ensuring water resources security in the basin are suggested from the aspects of comprehensive water-saving, optimal water resources allocation, and legislation-institution arrangements etc.

Introduction. This study aims to quantify the water resources change, identify the main challenges and provide management suggestions in the water-stressed Yellow River Basin under the changing environment.

The Yellow River is the second longest river in China. Map of the Yellow River basin is shown in Fig.1. The area of the basin is 795,000 km^2. After running through the Tibet Plateau, the Loess Plateau and the North China Plain, the river runs into the Bohai Sea at last. The headstream of the Yellow River is covered by snow and frozen soil for the whole year. The area upstream to Lanzhou city is the main source of the river runoff, and about 54% of the river runoff is from this area. The vast expanse of desert distributes in the area from Lanzhou to Toudaoguai, the dividing line of the upper reaches and middle reaches. Downstream to Toudaoguai, the Yellow River runs through the Loess Plateau, where most of the sand of the basin produces because of the rainstorm frequently occurring in flood season besides the loose soil texture and sparse vegetation. The vegetation in the area from Longmen to Huayuankou is dense because of the abundant rain. The riverbed of most trunk stream is above the ground downstream to Huayuankou, the dividing line of the middle reaches and lower reaches. A small quantity of water flows into the river in this area.

The Yellow River basin has been playing very important roles in the social-economy development of China. According to statistics (China Water Resources Bulletin, 2015), the annual average precipitation in the basin is 446 mm, the annual average naturalized river runoff is 58 billion m^3, the total population is 119 million people, the total GDP is 5750 billion RMB Yuan, and the total water use is 39.6 billion m^3 in 2015. In addition, 12 reservoirs (total volume 56.3 billion m^3) at the main river and 170 reservoirs (total volume 10 billion m^3) at tributaries were constructed; large amount of soil conservation facilities including 1390 small reservoirs, over 11,200 silt arresters and over 4 million ponds were established in the basin; and irrigation area increased to 7.3 million ha from 0.8 million ha in 1950s. These human activities not only changed hydrological processes but also impacted availability and compositions of water resources.

Under the impacts of strong human activities and climate change, the water resources situation in the Yellow River Basin has greatly changed. The existing main issues include: 1) the annual average runoff at the Tongguan gauge station (the conjunction point of the Weihe tributary and the main stream) since 2010 has decreased by 34% compared with that from 1919 to 1959, and the sediment has decreased by 94%; 2) the continuously-increased socio-economic water use has caused insufficient environment flow in rivers and groundwater overexploitation; 3) the urbanization progress since 1980s has led to urban inundation and water quality deterioration problems in cities like Xi'an and Jinan. It is highly desired to quantify and attribute the water resources decrease and to study the adaptive strategies of water resources management.

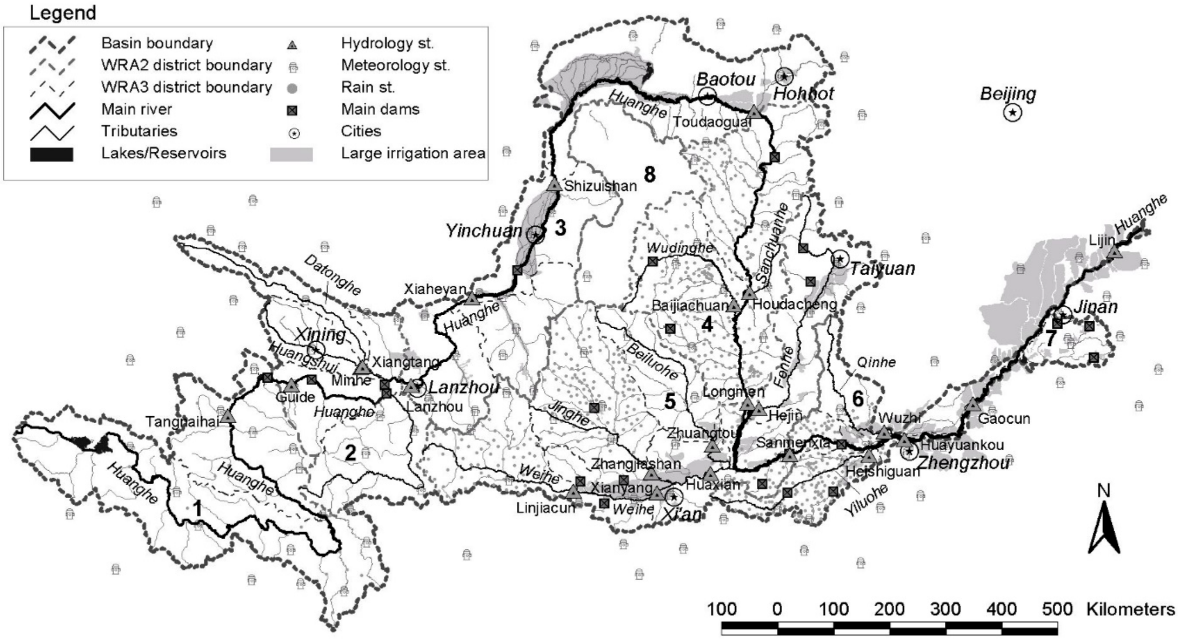

Fig.1 Map of Yellow River basin. Numbers (1-8) in the figure are codes of 8 WRA2 districts. WRA2 represents the 2nd level national water resources assessment sub-basin in China, WRA3 means the 3rd level one (a further subdivision of WRA2), and WRA1 means the 1st level one. The Yellow River basin is one of total 10 WRA1 districts in China.

Methodology and Data. The distributed hydrology model WEP-L with combinations of statistical analysis of hydro-meteorological data and remote-sensing data are adopted to address the above-mentioned issues. Both natural hydrological processes and water utilization processes are depicted in the model, and the observed flow series at main gauge stations are used to validate the model.

The distributed hydrological model water and energy transfer processes in large river basins (WEP-L) (Jia et al., 2006, 2012) is based on the WEP model, which has been successfully applied to several watersheds in Japan, Korea, and China with different climate and geographic conditions (Jia et al., 2001) and was developed in a national key basic research project of China. The WEP-L model adopts contour bands as the calculation units to fit large river basins.

For the vertical structure of WEP-L, each calculation unit has nine layers: from top to bottom, an interception layer, a depression layer, three upper soil layers, a transition layer, an unconfined aquifer and two confined aquifers. To consider the sub-grid heterogeneity of land use, the mosaic method which reflects the composition of different land uses within a calculation unit is employed. Mean water fluxes over a calculation unit are obtained by averaging over all land use types in that unit. For the simulation of hydrological processes, evapotranspiration is calculated using the Penman-Monteith equation, infiltration excess during heavy rain is simulated using a generalized Green-Ampt model, and saturation excess during the remaining periods is simulated through balance analysis in unsaturated soil layers. Runoff routings for land and rivers are carried out by applying the one dimensional kinematic wave approach from upstream to downstream. For groundwater flows, multilayered aquifers are numerically simulated in mountainous and plain areas separately with consideration of water exchange with surface water, soil moisture and streamflow. Snow melt is simulated employing a temperature index.

In the case of anthropogenic components, the water consumption in each calculation unit is calculated on the basis of the population and water consumption per capita which is determined from the statistical materials of water consumption in a sub-basin. Water leakage is calculated from water consumption and the leakage rate of the water supply system. Sewerage is obtained by deducting leakage from water consumption. The groundwater withdrawal is divided into domestic consumption, industrial consumption, and irrigation consumption. Domestic water consumption is calculated according to the annual regional statistical data and the population distribution, and industrial water consumption is calculated on the basis of the gross domestic product (GDP) distribution. Irrigation water consumption is calculated on the basis of the annual statistical data, irrigation area, and irrigation rule. Details of the model and its application are given by Jia et al. (2001, 2006, 2012).

The sources of meteorological and hydrological data are the National Climate Bureau of China (NCBC) and the Yellow River Water Conservancy Commission (YRWCC). The source of DEM is GTOPO30 data developed by the US Geological Survey's EROS Data Center, which can be downloaded from the website: http://edcdaac.usgs.gov/gtopo30/gtopo30.asp. Land use data of five periods (1970s, 1980s, 1990s and 2000) are obtained using the Landsat TM data and the statistical data in the yearbooks of administrative districts, and monthly vegetation information (LAI and area fraction of vegetation) from 1982 to 2000 is obtained using the NOAA-AVHRR data. The soil data including map of soil types and correspondent characteristic parameters are from National Second Soil Survey Data and Soil Types of China. The hydrogeology data of aquifers including hydrogeology unit subdivision, permeability and storage coefficient are from the Distribution Map of Hydrogeology in China and the Second-time Countrywide Comprehensive Water Resources Planning in China. Water use and social-economy data of the Hai River Basin are from the Second-time Countrywide Comprehensive Water Resources Planning in China. The statistical units of the data are the national administrative prefecture or municipality.

Results and Discussion. This study carries out continuous simulations of 45 years (1956–2000) in the variable time steps (from 1 h to 1 day), 21 years (1980–2000) of which is selected as calibration period. The calibration is performed on a basis of ''try and error''. The calibration parameters include maximum depression storage depth of land surface, soil saturated hydraulic conductivity, hydraulic conductivity of unconfined aquifer, permeability of riverbed material, Manning roughness, snow melting coefficient, and critical air temperature for snow melting. After the model calibration, all parameters are kept unchanged, continuous simulations from 1956 to 2000 are performed to verify the model by using the observed monthly and daily discharges at 23 main gage stations in the basin (Fig.1). Monthly discharges of 45 years at representative stations in the main river are shown in Fig. 2.

The scope of water resources assessed in the traditional approach includes surface water and groundwater, both of which exist in gravity-driven form. However, unsaturated soil moisture in vegetation root zones and intercepted precipitation on vegetation are effective to ecology. Thus these parts of evapotranspiration, i.e., the precipitation directly utilized by ecosystem should also be considered into water resources assessment. The traditional water resources can be called as "special water resources" or "blue water", and those including the precipitation directly utilized by ecosystem (or "green water") can be called as "general water resources".

Table 1 shows assessment results of the special water resources in the whole basin correspondent to various periods of meteorological data under the condition of historical land cover and water use. It can be seen that under the driving of "natural-artificial" dualistic forces, water resources compositions changed obviously: the surface water resources from 1980 to 2000 decreased by 6.9% than that from 1956 to 1979, the non-overlapped groundwater resources increased by 21.4% than that from 1956 to 1979, and the total special water resources from 1980 to 2000 decreased by 3.1% than that from 1956 to 1979.

The impacts of land cover and water use conditions on water resources can be seen from Table 2 and Table 3: compared with those values under historical land cover condition, (1) total special water resources under Year-2000 land cover condition decreased by 2.0 billion m^3 yr^{-1}, among which the surface water resources decreased by 4.1 billion m^3 yr^{-1}, and the non-overlapped groundwater increased by 2.1 billion m^3 yr^{-1}; (2) the precipitation directly utilized by ecosystem increased by 11.4 billion m^3 yr^{-1}; and (3) the general water resources increased by 9.4 billion m^3 yr^{-1}. The decrease of the surface water resources can be explained by that the soil conservation and farmland construction in the basin strengthened vertical infiltration process and weakened runoff generation, and the increase of the non-overlapped groundwater is because of the increase of net exploitation of groundwater.

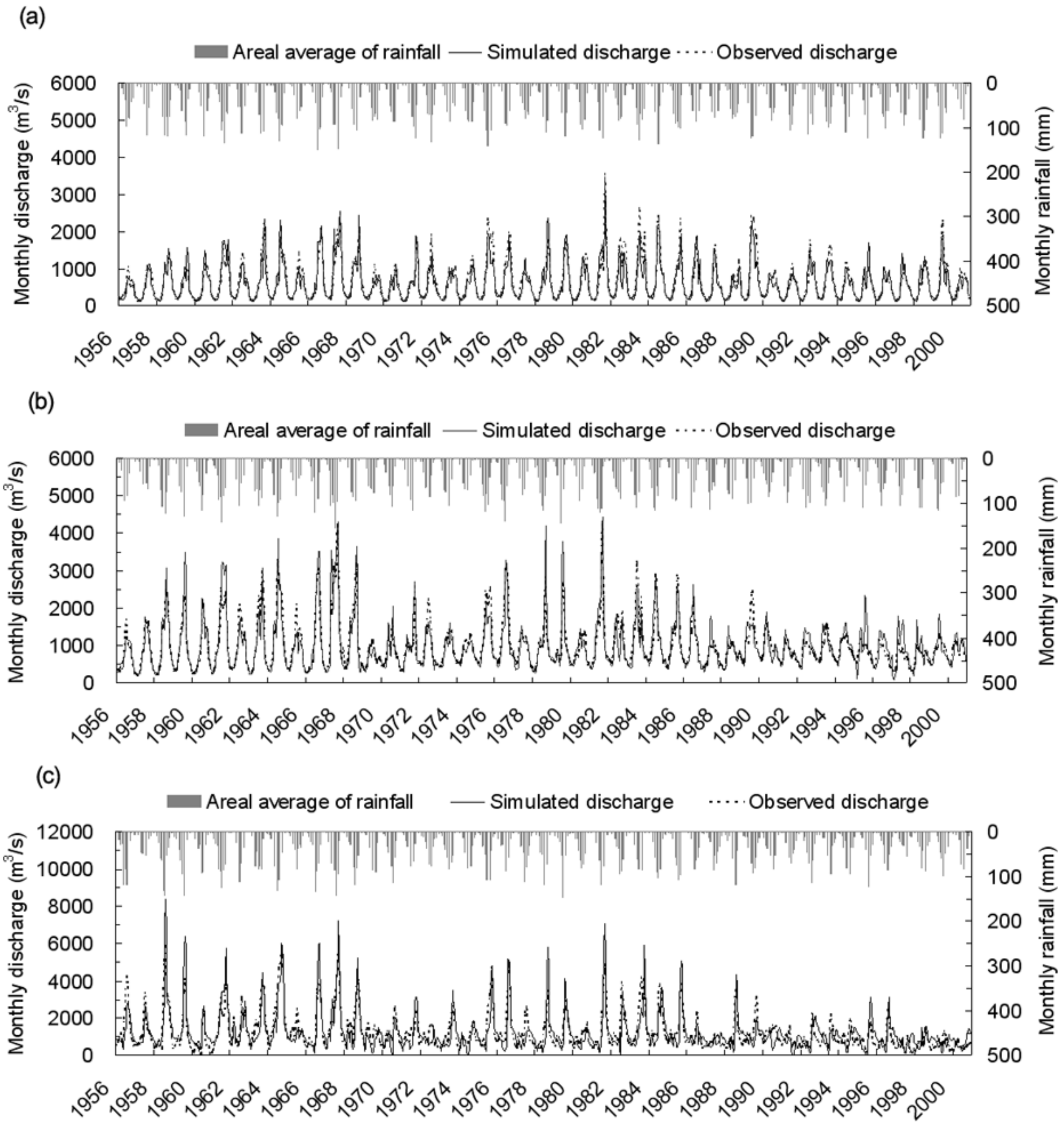

Fig.2 Verification of simulated monthly discharges at: (a) Tangnaihai station, (b) Lanzhou station, and (c) Huayuankou station of the main river

Table 1 Assessed special water resources correspondent to various periods of meteorological data under condition of historical land cover and water use（unit: billion m^3 yr^{-1}）

Meteorological periods	Precipitation	Surface water resources	Groundwater resources		Total special water resources
			Total	Non-overlapped with surface water	
1956－1959	378.88	60.86	37.28	6.94	67.80
1960－1969	374.38	65.02	38.30	8.97	73.99
1970－1979	354.34	56.98	39.65	11.20	68.17
1980－1989	353.75	61.40	39.58	10.99	72.39
1990－2000	335.76	52.49	39.37	12.28	64.77
1956－1979	366.78	60.94	38.69	9.62	70.56
1980－2000	344.43	56.71	39.47	11.68	68.39
1956－2000	356.30	58.94	39.06	10.67	69.62

Table 2 Assessed water resources of WRA districts under condition of historical land cover and water use （unit: billion m^3 yr^{-1}）

WRA2 district name	Surface water	Total groundwater	Non-overlapped groundwater	Special water resources	Precipitation directly utilized by ecosystem
Whole basin	58.94	39.06	10.67	69.62	196.62
Upstream Longyangxia	22.33	6.77	0.18	22.51	20.73
Longyangxia - Lanzhou	12.35	3.77	0.23	12.59	21.89
Lanzhou - Hekouzhen	1.99	5.83	3.37	5.35	23.31
Hekouzhen - Longmen	4.11	3.70	0.53	4.64	27.54
Longmen - Sanmenxia	11.48	11.62	2.93	14.42	69.99
Sanmenxia - Huayuankou	4.23	3.54	0.78	5.01	17.62
Downstream of Huayuankou	2.14	1.98	1.16	3.30	10.84

Table 3 Assessed water resources of WRA districts under condition of Year-2000 land cover and water use（unit: billion m^3 yr^{-1}）

WRA2 district name	Surface water	Total groundwater	Non-overlapped groundwater	Special water resources	Precipitation directly utilized by ecosystem
Whole basin	54.87	40.42	12.77	67.64	208.01
Upstream Longyangxia	21.01	6.53	0.19	21.21	23.28
Longyangxia - Lanzhou	11.28	3.70	0.34	11.61	23.23
Lanzhou - Hekouzhen	1.85	5.86	3.52	5.37	23.92
Hekouzhen - Longmen	4.23	4.00	0.69	4.92	28.82
Longmen - Sanmenxia	10.45	12.51	3.90	14.35	72.36
Sanmenxia - Huayuankou	3.92	3.51	1.10	5.03	20.98
Downstream of Huayuankou	1.80	2.36	1.40	3.20	10.95

Based the above-results, the special water resources (blue water) especially the surface water resources in the basin were decreased under the impacts of climate change, land cover change and water use increase, which threatens the water resources security in the basin. Adaptive strategies for ensuring the water resources security are suggested from the aspects as follows:

(1) Comprehensive water-saving: the water use efficiency in the Yellow River Basin is still lower than developed countries and the neighboring Haihe River. For example, based on China Water Resources Bulletin (2015), the water use per 10000 RMB Yuan GDP is 69 m^3 in the basin whereas it is 43 m^3 in the neighboring basin, and the irrigation water per ha is 5010 m^3 in the basin whereas it is 3165 m^3 in the neighboring basin. It is desired to adopt a comprehensive water-saving measure to raise the water use efficiency in the basin, which includes restructuring industry sectors and adjustment of cropping patterns, propaganda of water-saving technology and facilities, utilization of un-traditional water sources like treated wastewater and brackish water, raising the water-saving awareness of public and adopting rational virtual water strategy. In addition, as the basin is both a major base for energy production and a major base for food production, the nexus of water-energy-food should be considered.

(2) Control of groundwater overexploitation: the Weihe Plain around Xian City and the Fenhe Plain around Taiyuan City are the seriously groundwater-overexploited regions. The groundwater overexploitation not only caused geological hazards but also reduced river base flows. Strict control strategy of groundwater overexploitation is required to adopt including shut-in of wells, surface water substitution and water fees raising etc.

(3) Ecological sponge city construction: the concept gives priority to the protection and rehabilitation of natural environment in urban planning and construction to ensure their ecosystem service function of water. It is devoted to find ecologically suitable alternatives to transform urban infrastructures into green infrastructures so these could capture, control and use rain water in an ecologically-sound way. Moreover, it promotes the renovation of drainage systems, the improvement of connectivity of water systems, the division of rainwater and sewage water pipe network, and other modern engineering measures to address urban water problems. The multi-objective whole-process integrated rainwater management of sponge cities is expected to be achieved through infiltration, stagnation, storage, purification, utilization and discharge, so as to use the full potential of rainwater under the premise of not suffering urban flooding.

(4) Optimal allocation and regulation of water resources: the purpose is both guarantee the security of water supply in cities and rural areas and guarantee river eco-environment flows. In add to comprehensive water-saving and reuse of treated wastewater, it is desired to carry out joint

allocation and regulation of local surface water, local groundwater, diverted water from the Hanjiang River to the Weihe River and water supply from the Yellow River downstream to the areas of Henan, Shandong and Hebei Provinces outside the Yellow River Basin.

(5) legislation-institution arrangements: it includes updating water rights allocation, water pricing, and environmental flow guarantee policy etc. The present water rights allocation scheme of the Yellow River was promulgated in 1987 by the State Council of China. The water supply-demand situation has greatly changed after nearly 40 years, especially considering the increase of water demand in the upstream and middle-stream regions and the implementation of the South-to-North Water Transfer (SNWT) projects in the downstream regions. Therefore, updating the water rights allocation scheme is highly desired to adapt to the present status. Water pricing is an important measure to water management, but the water pricing standards are still low in the basin. The policies for rational water charges of industry water use, domestic water use and irrigation water use are needed to update. In addition, although environmental flows at key river sections have been studied, environmental flow guarantee policy is desired including compensation mechanism for stakeholders who contribute to the increase of environmental flow, and punishment mechanism for those who cause the decrease of environmental flow.

Conclusions. The study results show that climate variation, soil conservation and water use facilities are main reasons for the water resources decrease in the basin, and water resources evolution rules are summarized, including surface water and groundwater change, and blue water (special water resources) and green water (utilized by ecosystem) etc. An interesting finding is the groundwater resources unrepeated with the surface water resources has obviously increased contrasting to the obvious decrease of surface water resources. Adaptive strategies for ensuring water resources security in the basin are suggested from the aspects of comprehensive water-saving, control of groundwater overexploitation, ecological sponge city construction, optimal water resources allocation, and legislation-institution arrangements including updating water rights allocation, water pricing, environmental flow guarantee mechanism etc. The study is believed to be of a referential value for policy-making in the water management in the Yellow River basin under the changing environment.

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