Optional Water Development Strategies for the Yellow River Basin: Balancing Agricultural and Ecological Water Demands

Ximing Cai and Mark W. Rosegrant
International Food Policy Research Institute (IFPRI), Washington DC
International Water Management Institute (IWMI), Colombo, Sri Lanka

Abstract

The Yellow River basin is of utmost importance for China in food production, natural resources management, and socioeconomic development. Water withdrawals for agriculture, industry and households in the past decade have seriously depleted ecological water requirements in the basin, of which agriculture is the major player. This paper presents a modeling scenario analysis of some water development strategies to harmonize water withdrawal demand and ecological water demand in the Yellow River Basin through water saving and inter-basin water transfer. A global water and food analysis model, IMPACT-WATER, including the Yellow River Basin as one of the modeling units, is applied for the analysis. It is found that there is little space for resolving the conflict between agriculture water demand and ecological water demand in the basin, if the current practices of water use continue. Strong tradeoffs exist between irrigation water use and ecological water use and the tradeoffs will become more intensive in future years with population growth, urbanization and industrial development, and food demand increases in the YRB. Substantial pressure exists in the basin to improve water demand control and water saving, and for consideration of other measures including inter-basin water transfer through the South-North-Water Transfer (SNWT) project. Scenario analysis in this paper concludes that increasing water use efficiency to a feasible level first and then supplementary water availability by the SNWT may provide a solution to water management of the YRB in the next 25 years.

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1. INTRODUCTION

The Yellow River (YR), or Huanghe, is the second longest river in China. In total, the river flows over 5,400 km, passes through 9 provinces and autonomous regions and drains an area of 745,000 km^2. The Yellow River basin is of utmost importance for China in terms of food production, natural resources, and socioeconomic development: it covers 7 percent of China's land area and supports 136 million people, or 11 percent of China's population. The total cultivated area in the basin is 12.9 million hectares, about 13 percent of the total cultivated area in China, but the basin holds only 3 percent of the country's water resources. The river also feeds over 50 cities along the basin each with a population over 500,000 people and significant amounts of water supplied to chemical and oil industry and mining in the middle and lower reaches. Figure 1 shows the location of the Yellow River Basin (YRB) in China and the division of upper, middle and lower stream of the basin.

Similar to other regions in the world, human demand on natural resources has increased rapidly over the last decades, while the aquatic and riparian ecosystems have degraded, resulting in loss of high-quality water, productive soil, and diverse ecological functions that are critical for plant and animal communities. Since the founding of the People's Republic of China, over 3,100 large, middle and small-sized reservoirs have been built in the basin, with a total storage up to 58 km^3 in 1997, and over 70 km^3 in 1999 after Xiaolangdi Reservoir, a huge reservoir located in the middle stream was put into use. The total storage is now greater than the long-term average annual runoff in the river (58 km^3 based on hydrologic series during 1919-1975).

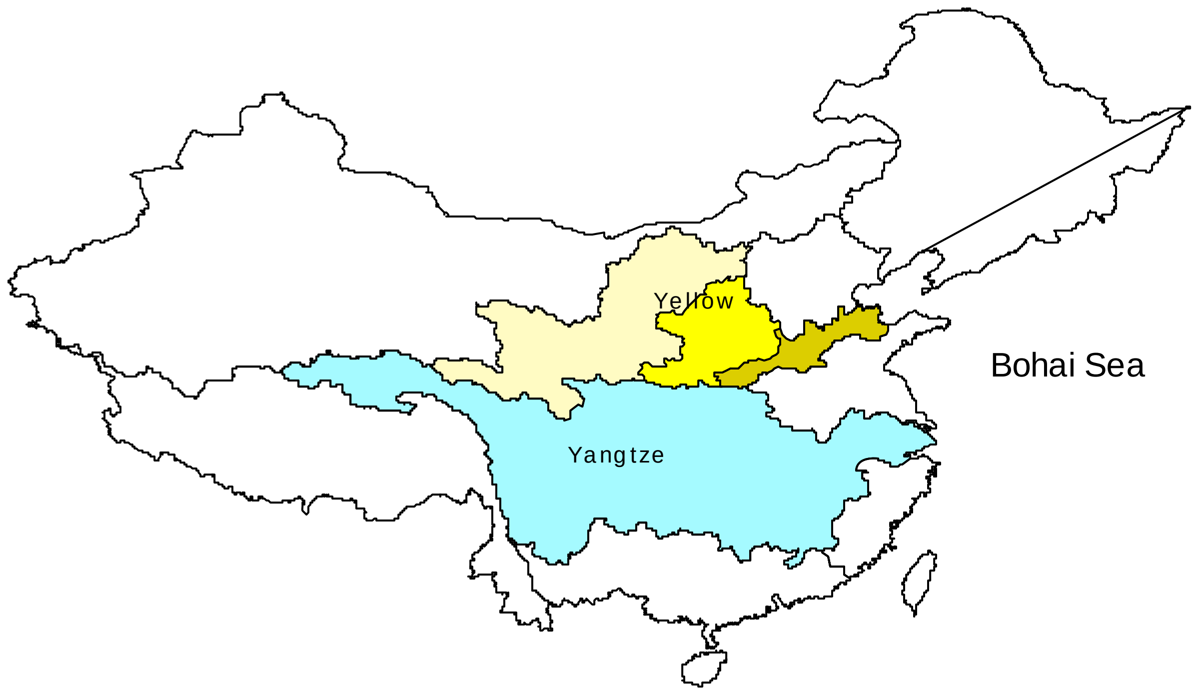

Figure 1: The location of the Yellow River Basin in China, with boundaries of upper, middle, and lower streams

Table 1: Water uses by sector by source in the YRB in 1998, 1999, and 2000.

Year	Withdrawals: By Source: Surface Water	Withdrawals: By Source: Ground Water	Withdrawals: By Source: Total	Withdrawals: By Sector: Ag.	Withdrawals: By Sector: Ind.	Withdrawals: By Sector: Domestic: Urban	Withdrawals: By Sector: Domestic: Rural	Withdrawals: By Sector: Total	Depletion: By Sector: Ag.	Depletion: By Sector: Ind.	Depletion: By Sector: Domestic: Urban	Depletion: By Sector: Domestic: Rural	Depletion: By Sector: Total	Depletion/ Withdrawal: Total
1998	37	12.7	49.7	40.5	6.1	1.6	1.5	49.7	31.3	2.9	0.8	1.5	36.5	0.73
1999	38.4	13.3	51.7	42.6	5.7	1.8	1.5	51.7	33.8	3.0	1.0	1.5	39.3	0.76
2000	34.6	13.5	48.1	38.1	6.3	2.1	1.6	48.1	30.6	3.2	1.2	1.6	36.6	0.76
Average	36.7	13.2	49.8	40.4	6.0	1.8	1.5	49.8	31.9	3.0	1.0	1.5	37.4	0.75
Share	74%	26%	100%	81%	12%	4%	3%	100%	85%	8%	3%	4%	100%	

Sources: 1998-2000 YRCC Water Bulletin

Table 2: Water balances in the YRB in 1998, 1999, and 2000

Year	Total renewable water (TRW)	Consumption (WC)	Basin outflow (BO)	Storage change	WC / TRW	BO / TRW
		(km3)				
1998	54.9	39.5	10.1	5.3	71.9%	18.4%
1999	56.3	40.4	6.2	9.7	71.8%	11.0%
2000	48.4	44.0	4.2	0.2	90.9%	8.7%
Average	53.2	41.3	6.8	5.1	77.6%	12.8%

Sources: 1998-2000 YRCC Water Bulletin

The expansion of irrigated area has been especially rapid, rising from 0.8 million hectares in year 1950 to 7.5 million hectares in 2000 (Li, 2002a). Irrigation growth, together with rapid growth of industrial and municipal water uses have resulted in dramatic increases in water withdrawal in all provinces located in the basin, and in the entire basin, it has been tripled since 1950. Table 1 gives water uses by sector and by source in three recent years, 1998, 1999, and 2000, in both withdrawal and consumption. As can be seen, agriculture is the dominant water user in the basin, covering over 80 percent of total water withdrawal and total water consumption. Another characteristic of water uses in the basin is that the fraction of consumption (ratio of consumption to withdrawal) is higher than that in many other basins in the world, with an average in 1998-2000 as high as 75 percent, which is significantly higher than the world average 46 percent (in 1995) assessed by Rosegrant and Cai (2002). The high consumption in the YRB is due to the high fraction of agricultural water use, almost full use of return flow in the downstream irrigation districts through conjunctive use of cannels and wells (YRCC, 1998-2000), and the large fraction of water loss (about half of the total consumption is categorized as non-beneficial, see detailed discussion later). Table 2 lists the total consumption (including water consumed during production process and non-process consumption such as river evaporation and use by non-agricultural vegetation), basin outflow to the ocean, and storage change in 1998, 1999 and 2000. The fraction of total consumption is as high as 77 percent of the total runoff, as an average figure of the three years; and outflow accounts only 13 percent.

Water withdrawal has been even greater than the amount of the total renewable water, indicating significant reuse of water. For example, water withdrawal in 2000 is 110 percent of the total water resource in 2000. This ratio, called criticality ratio, shows a degree of the water use intensity. The higher the criticality ratio, the more intensive the use of river basin water and lower the water available for instream ecosystems. Hence at high criticality ratios, water usage by downstream users can be impaired, and during low flow periods, the chance of absolute water shortages increases. There is no objective basis for selecting a threshold between low and high water stress, but the literature indicates that criticality ratios equal to or greater than 0.4 are considered “high water stress,” and 0.8 “very high water stress” (Alcamo, Henrichs, and Rösch 2000).

River desiccation has occurred due to excess water withdrawal and consumption. The most striking evidences are flow cutoffs experienced in the main channel downstream of the river during 1972-1998, which caused serious problems to water supply and ecosystems in the downstream area. In the 27 years, flow in the main channel was cut off in 21 years, accumulated to 1050 days; and occurred every year in the 1990’s with both time and river reaches extended. In 1997, there was no flow out of the basin in 226 days accumulated through the year, and the river dried up to Kaifeng, about 600 km from the outlet, or about 11 percent of the entire length of the river. Starting in 1999, the government of China has strengthened the “Water Allocation Programme”, which specifies water withdrawal quotas for provinces along the basin, and the status has been improved and there has been no absolute flow cut-off since then. However, flow for ecological uses, especially for sediment flushing, is still far below the required amounts.

The major ecological and environmental water requirements for the YRB, particularly in the downstream, include flow for wetland ecosystems and groundwater recharge in the costal area to prevent seawater intrusion and flow for sediment flushing. According to the estimation of the Yellow River Conservation Commission (YRCC), the average flow rate at Lijing Station (close to the river mouth) should be 300 m^3/s, the minimum flow rate 50 m^3/s, and the total volume in the non-flooding season should be 5 km^3, which is about 10 percent of the 8-month non-flooding period during the 11-year successive droughts from 1922 to 1932. The delta ecosystems were basically sustained during this period under such flow rate and volume (Hong Shangchi, YRCC, personal communication, 2002), and therefore this flow rate and volume are then assumed to be the minimum ecological flow requirement.

The flow requirement for sediment flushing is recognized as the largest ecological and environmental flow requirement in the YRB. The most challenging engineering aspect of managing the river is without doubt the control of the exceptionally high sediment load that the river carries in its lower reaches (Leung, 1996). Through thousands of years, excessive sediment deposits have raised the riverbed several meters over the surrounding grounds; it is as much as 10 m above the city level of the ancient capital, Kaifeng, on its southern bank, where the level embankments are 13 km apart. Over the last 50 years, sediment deposit in the downstream channel is estimated as 10 billion tons, resulting in 2 - 6 m increase of the riverbed level (Li, 2002b). The accumulated sediment deposit has aggravated the threat of flooding. For example, in 1996, flow passing Huayuankou (a hydrologic station at the river section established as the beginning of the downstream) at a peak rate of 7,600 m^3/s made the river level rise to 94.7 m, which is 0.9 m higher than that caused by a flow rate of 22,300 m^3/s in 1958 at the same station. Therefore, for the Yellow River, flow required for sediment flushing is unique and important. It is estimated that sediment flushing requires 15 km^3 of flow in the downstream channel during the flooding season in which most of the sand is loaded to the river channel (Zhu and Zhang, 1999).

Other ecological requirements for the Yellow River include water to be stored within small catchments in the middle stream area with heavy-and-coarse sediment yield in order to reduce sand load to the main channel; water from the major tributaries or the main channel to recharge groundwater in regions where groundwater is over drafted; and stream flow to dilute wastewater discharge in the non-flooding season. The amount for these requirements is relatively small compared to flow required for downstream wetland ecosystems and sediment flushing. According to Zhu and Zhang (1999), flow blocked within the small catchments in the middle stream to prevent soil erosion was 1.0 km^3 in 1997.

The total ecological flow requirement is then estimated as 21 km^3 in one year, including 15 km^3 for sediment flushing in the flooding season, 5 km^3 for the downstream ecosystems in the non-flooding season, and 1 km^3 discounted from the main channel runoff due to soil erosion control, as discussed above. This amount is mainly determined by some objective measure, while, in many western countries, environmental water requirements are determined rather by a combination of legislative, regulative and legal procedures tempered by social values and only partly predicated on scientifically justified criteria (Zhu et al., 2003). Research will be needed in the future for new ecological water definition and accounting. Moreover, one of the major purposes of Xiaolangdi Reservoir, with a storage about 12.6 km^3 is to regulate flow and sediment transport in the downstream channel, which is expected to control both intra-year seasonal flow and inter-year flow for downstream sediment flushing and ecosystems maintenance more efficiently (Li, 2002b).

Ecological restoration for sustainable water development has been given a high priority by the new Chinese Water Law (2002), and ecological restoration must be undertaken according to the Law in areas where ecosystems are seriously deteriorated. As noted above, in the YRB agriculture uses the majority of the water, and is mainly responsible for the depletion of flow needed for downstream sediment flushing and ecosystems. Therefore, the task of agricultural water savings is now made more pressing in order to reserve water to serve ecological and environmental functions. Due to the limit of runoff in the basin, for a long-term plan, inter-basin water transfer is under consideration to supplement water sources in the YRB in the dry season. The South-North Water Transfer (SNWT) project diverting water from the Yangtze River in South China (see Figure 1 for the location of the Yangtze, whose annual runoff is about 15 times of the YR's) to North China is already under construction, which makes water supplementation to the Yellow River Basin possible in the future.

This paper presents a modeling scenario analysis for some water development strategies designed to harmonize water withdrawal demand and ecological water demand in the Yellow River Basin through water saving and inter-basin water transfer. In the rest of the paper, we first describe the modeling method and definition of the analytical scenarios based on data assessments of 1995 and projections of 1996-2025. Following that, results are presented, showing tradeoffs between agricultural and ecological water uses and the impacts of feasible water saving and possible inter-basin water transfer. Conclusions are derived at the end.

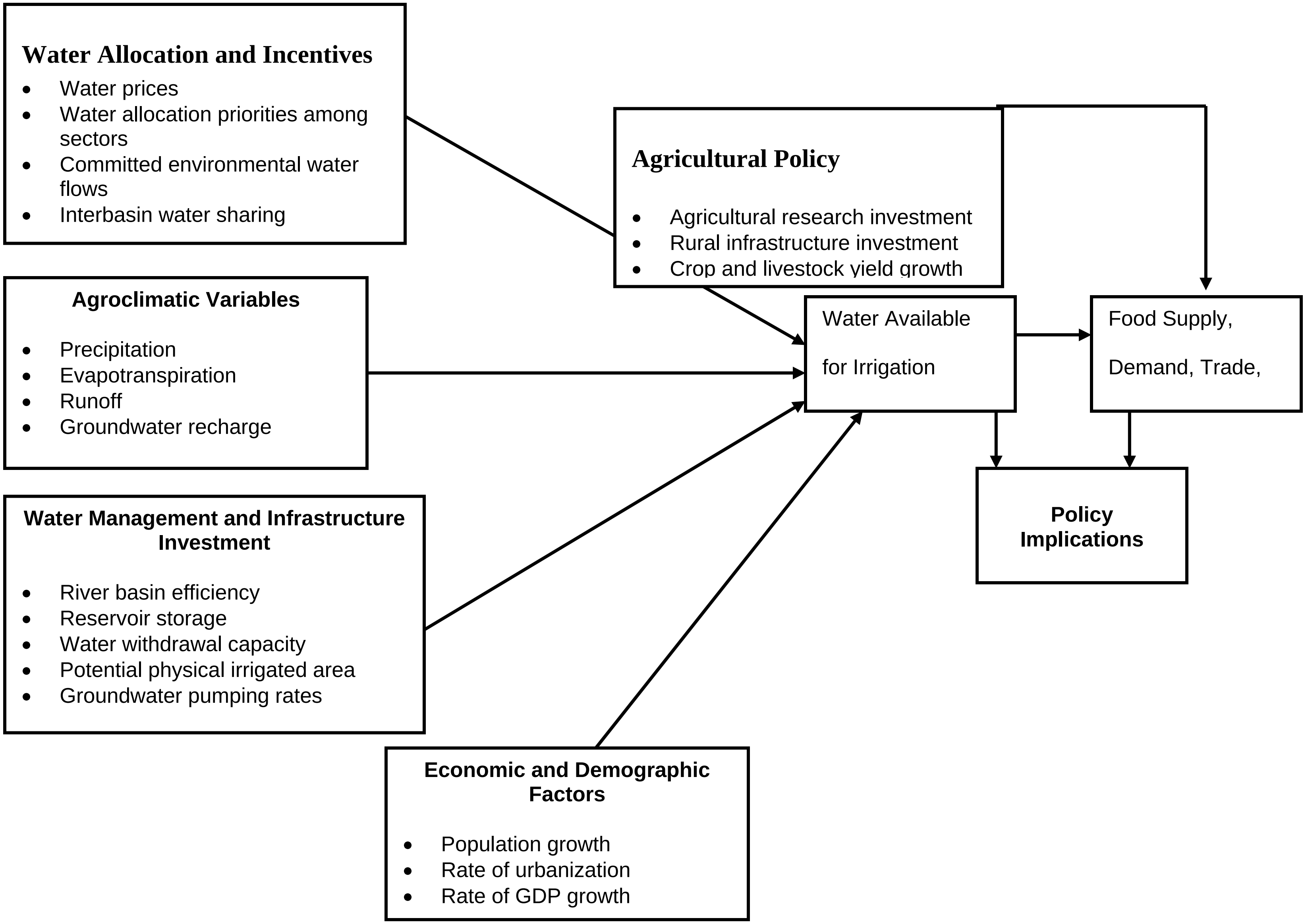

Figure 2: IMPACT-WATER: Driving forces for scenario analysis

2. METHODOLOGY

An integrated water and food model with the YR as one of the 69 modeling units in the global scope is applied for this study (Rosegrant, Cai and Cline, 2002). The global modeling framework—IMPACT-WATER—combines an extension of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Rosegrant et al., 2001) with a newly developed Water Simulation Model (WATER, Cai and Rosegrant, 2002), based on state-of-the-art global water databases and models, integrated basin management, field water management and crop water modeling. The model attempts to project and analyze how water availability and demand would evolve over the next three decades (from a base year of 1995), taking into account the availability and variability in water resources, water supply infrastructure, and irrigation and non-agricultural water demands, as well as the impact of alternative water policies and investments on water supply and demand. The driving forces for scenario analysis are shown in Figure 2.

In the WATER module, water available for food production is simulated as a function of precipitation, runoff, water supply infrastructure, and socioeconomic and environmental policies. Crop water demand and water supply for irrigation are simulated, taking into account the year-by-year hydrologic fluctuations, irrigation development, growth of industrial and domestic water uses, environmental and other flow requirements (committed flow), and water supply and use infrastructure. Committed environmental and ecological flows are treated as a pre-determined hard constraint in water supply, and off-stream water supply for domestic, industrial, livestock, and irrigation sectors are determined through two steps. The first step is to determine total water that could be depleted in each time period (month) for various off-stream uses, and the second is to determine water supply for different sectors. Assuming domestic water demand is satisfied first, followed in priority by industrial and livestock water demand, irrigation water supply is the residual claimant. Moreover, irrigation water supply is further allocated to different crops in the basin based on crop water requirements and profitability.

In the IMPACT module, crop harvested areas and yields are calculated through crop-wise irrigated and rainfed area and yield functions. These functions include water availability as a variable, through which IMPACT is connected with the global water simulation model (WATER). The following section focus on the definition of the scenarios used for this study, while a detailed description of the modeling method can be found in Rosegrant, Cai and Cline (2002).

Table 3: Estimation of beneficial irrigation water consumption in the YRB

	(1)	**(2)**	**(3)**	**(4)**	**(5)=(4)-(3)**	**(6)**	**(7)=(6)*(5) /10^5**
	ETC **(mm)**	***Yr***	***ETA*** **(mm)**	***PE*** **(mm)**	***IW*** **(mm)**	***AI*** **('000ha)**	***WI*** **(km3)**
Rice	762	0.82	659	307	352	296	1.04
Whest	335	0.93	313	99	214	3,070	6.58
Maize	603	0.91	560	263	297	883	2.62
Other cereals	663	0.86	575	291	284	128	0.36
Soybeans	541	0.91	494	283	211	431	0.91
Potatoes	571	0.80	469	280	189	191	0.36
Sweet potatoes	571	0.82	477	280	197	291	0.57
Other roots and tubers	571	0.82	458	280	178	15	0.03
Other crops	587	0.90	528	278	250	1,329	3.33
Total			(N/A)			6,634	15.80

Sources and Notations:

(1) *ETC* potential crop evapotranspiration, (2) *Yr* relative crop yield, Cai and Rosegrant (1999).
(3) *ETA* actual crop evapotranspiration: $ETA = ETC^{*} [1 - (1\text{-}Yr)/Ky]$ in which *Ky* is the crop response coefficient to water stress (FAO, 1979).
(4) *PE*: Effective rainfall, Cai and Rosegrant (1999).
(5) *WI*: Irrigation water requirement in mm.
(6) *AI*: Irrigated area
(7) *WI*: Irrigation water requirement in km^3

3. SCENARIO DEFINITION

Three terms are introduced before we define the analytical scenarios, agricultural water use efficiency, irrigation water supply reliability and irrigation crop production reliability. These terms are used in the definition of scenarios and the result presentation in the following contexts.

Agricultural Water Use Efficiency (AWUE)

We use effective efficiency at the river basin scale (Keller, Keller, and Seckler, 1996) to represent irrigation water use efficiency, which is a ratio of beneficial irrigation water consumption (*BIWC*) to total irrigation water consumption (*TIWC*):

$$AWUE = \frac{BIWC}{TIWC} \qquad (1)$$

BIWC refers to actual crop evapotranspiration of all crops over one year in the entire basin, and *TIWC* is equal to *BIWC* plus non-beneficial water consumption or depletion including evaporation loss, salt and other pollutant sinks and economically non-recoverable seepage. *TIWC* is assessed as 30.4 km^3 in 1995 in the YRB; and *BIWC* is estimated as shown in Table 3 based on hydrologic parameters, irrigated areas and yields, and empirical relations and assumptions, which are illustrated in the notation of Table 3. The *BIWC* is estimated as 15.8 km^3. By Equation 1, *AWUE* is calculated as 0.52. It should be noted that the estimated *AWUE* represented as effective efficiency is higher than the efficiency value estimated by Chinese irrigation experts, 0.3 ~ 0.4, which is represented by classical irrigation efficiency (Qian and Zhang, 2001). Although the classical efficiency concept is appropriate for irrigation system design and management (Doorenbos and Pruitt, 1977), it could lead to erroneous conclusions and serious mismanagement of scarce water resources if it is used for water accounting at a larger scale. This is because the classical approach ignores potential reuses of irrigation return flows (Keller, Keller, and Seckler, 1996). The effective efficiency takes into account of potential reuses of irrigation return flows. Reuses of irrigation return flows have been undertaken in the YRB widely. Table 4 shows irrigation water withdrawals and return flows in different river reaches in 2000 assessed by YRCC (2000). In the upper stream reaches (above Toudaoguai), return flow is as high as 35 percent of the withdrawal, which obviously provides a "source" for middle and downstream water withdrawal. While in the downstream reaches (below Huayuankou), return flow cannot come back to the main channel because of the riverbed is much over the ground. However, water is recycled and reused through the well-developed canal-well systems in the downstream areas (Li Huian, YRCC, personal communication, 2002).

Table 4: Year 2000 Withdrawal and Depletion along YR reaches (bcm)

Reaches	Withdrawal	Depletion	Return flow	Depletion / Withdrawal	Return flow / Withdrawal
Above LZ	4.0	2.9	1.1	73%	27%
LZ-TDG	18.8	12.2	6.6	65%	35%
TDG-LM	1.0	1.0	0.1	91%	9%
LM-SMX	9.3	7.3	2.0	79%	21%
SMX-HYK	3.2	2.4	0.8	75%	25%
HYK-LJ	10.8	9.9	0.9	92%	8%
Below LJ	0.7	0.7	0.0	100%	0%
Inland sub-basins	0.2	0.2	0.0	84%	16%
Sum/Average	48.1	36.6	11.5	76%	24%

Sources: 2000 YRCC Water Bulletin

Irrigation Water Supply Reliability (***IWSR***)

IWSR is defined as the ratio of actual irrigation water supply (*AIWS*) to the potential irrigation water requirement (*PIWR*), with *AIWS* represented by total irrigation water consumption (*TIWC*):

$$IWSR = \frac{AIWS}{PIWR} = \frac{TIWC}{PIWR} \tag{2}$$

and *PIWR* is estimated by:

$$PIWR = \sum_{c}\sum_{st}\left(kc^{c,st} \cdot ET_{0}^{st} - PE^{c,st}\right)\cdot AI^{c} \cdot (1 + LR) / AWUE \tag{3}$$

in which *c* is the index for crops, and *st* is the index for crop growth stages, *kc* is the crop coefficient, *LR* is the salt leaching factor, which is characterized by soil salinity and irrigation water salinity, and other items has been defined in the notation of Table 3.

With *WUE* = 0.52, *LR* = 0.15 and data given in Table 4, *PIWR* is estimated as 34.5 km^3, and by Equation (2), *IWSR* of the YRB in 1995 is calculated as 0.88. For years 1996-2025, *IWSR* is an output from the model as shown in the result section.

Irrigated Crop Production Reliability (***ICPR***)

ICPR is defined as a ratio of actual irrigated crop production (*AICP*) to the potential irrigated crop production (*PICP*):

$$ICPR = \frac{AICP}{PICP} \tag{4}$$

In this study, we assess this item for cereal crops as a whole. *AICP* in the YRB is assessed as 15.8 million tons in 1995, with actual yield as 3.6 metric tons per hectare and actual harvested area as 4.4 million hectare (Gunaratnam and Kutcher, 1997). The potential yield is 4.0 metric tons per hectare or 10 percent higher than the actual yield, and potential harvested area is 4.6 million hectares, or 4 percent higher than the actual harvested area (Cai and Rosegrant, 1999).

Thus *PICP* is estimated as 18.2 million tons. By Equation (4), *ICPR* is calculated as 0.87. For years 1996-2025, *ICPR* is an output from the model, as shown in the result section.

Table 5: Data assessemnts (1995) and projections (2025)

	1995	**2025**
Population (million)	136	155
GDP per capita (US$/person)	544	2,330
Industrial water demand (km3)	2.49	5.25
Domestic water demand (km3)	1.85	3.43
Gross irrigated area (million ha.)	6.63	8.37
Agricultural water demand (km3)	29.42	33.34
Total demand (km3)	33.76	42.02
Reservoir storage (km3)	58	87.5
Basin efficiency	0.52	0.59

Source : Rosegrant, Cai and Cline (2002)

Five scenarios are defined for this paper. The first one is a business-as-usual scenario (BAU) which projects the likely water and food outcomes for a future trajectory based on the recent past, whereby current trends for water investments, water prices, and management are broadly maintained. Table 5 shows assessments in 1995 and projections in 2025 of key parameters under BAU. Since the downstream ecological flow requirement for sediment flushing and ecosystems is approximately equal to the basin outflow to the ocean, we use the basin outflow to represent the ecological water use. Under BAU, there is no specification set for the basin outflow, which basically reflects the practices during the last decade. That is to say, irrigation water withdrawals were driven by crop water demand under low water use efficiency and were not constrained by the downstream ecological flow requirement. The BAU assumes this status continues in the future 25 years although the withdrawals have been constrained more or less by the Water Allocation Programme in recent years.

The second scenario, ecological scenario (ECO) assigns higher priority on ecological flow requirement than agriculture, assuming the downstream ecological flow requirement will be satisfied as much as possible after 2001, i.e., the basin outflow should not be less than 20 km^3, as discussed before. The two scenarios BAU and ECO are used to explore tradeoffs between agricultural water demand and ecosystem water demand. The next three scenarios attempt to search possible measures to match both agricultural and ecological water demand, which are defined as below:

- ECO-WUE, ECO with large improvement of irrigation water use efficiency, assuming the effective efficiency in the basin will gradually increase to 0.76 by 2025 from 0.52 in 1995. According to the assessment of Rosegrant, Cai and Cline (2002), *WUE* as effective efficiency up to 0.76 is at a high level compared to other basins in the world. For example, the effective efficiency in California basins is assessed as 0.77 in 1995. These increases will be accomplished by substantial improvement of water demand management and large investment for advanced irrigation systems.
- ECO-SNWT, ECO with source supplement from the SNWT project, assuming that up to 4.0 km^3 of water can be provided to the YRB by the SNWT in the dry season by 2010, and 9.0 km^3 by 2015. The amounts follow the goal of the first stage and the second stage of the western route of SNWT, respectively (Li, 2002a).
- ECO-WUE-SNWT, ECO with a more feasible improvement of irrigation water use efficiency and possible water supplement by the SNWT project, assuming AWUE

increases to 0.67 by 2010 (and this value stays to 2025), followed by the same water supplement from the SNWT project as specified under ECO-SNWT.

Under all scenarios**,** the projected hydrologic regime between 1996 and 2025 is modeled based on data (including precipitation, evapotranspiration, and runoff) from the period between 1961 and 1990 from WaterGap 2.0, Kassel University, Germany (Alcamo et al. 1998). In this study we use the global model IMPACT-WATER but focus on the YRB only, and assumptions and projections for other units under all these scenarios follow business-as-usual conditions described by Rosegrant, Cai and Cline (2002).

4. RESULT ANALYSIS

Modeling results from the five scenarios defined above are compared in terms of irrigation water supply reliability, irrigated crop production reliability, cereal production, and satisfaction of ecological water requirement. First we examine the tradeoffs between irrigation water use and ecological water use, based on the outputs from BAU and ECO; next we discuss optional water development strategies which aim to match both agricultural water demand and ecological water demand in the next 25 years, based on outputs from ECO-WUE, ECO-SNWT, and ECO-WUE-SNWT.

To show the tradeoffs between irrigation water use and ecological water use, Figure 3 plots the *IWSR* under BAU and ECO, and Figure 4 plots the basin outflows, both for the period of 1995-2025. As can be seen, under BAU without control on the basin outflow, irrigation water demand will be almost fully matched, except in a few years, there will be minor water shortage for irrigation. However, in most years (16 years out of 25 years during 2001-2025), basin outflow will be below the target level (20 km^3) and it is below 10 km^3 in 6 years.

Under ECO with higher priority on ecological flow requirement, a much different picture compared to BAU can be seen from Figures 3 and 4. Basin outflows will match the expected value except for small deficits in a few years, while the *IWSR* shows a declining trend and drops to 0.5 in some years. Such drops in irrigation may not mean a disaster for the entire basin, but in some sub-areas with relatively less water availability, substantial vulnerability to water shortage may hit the irrigated crops.

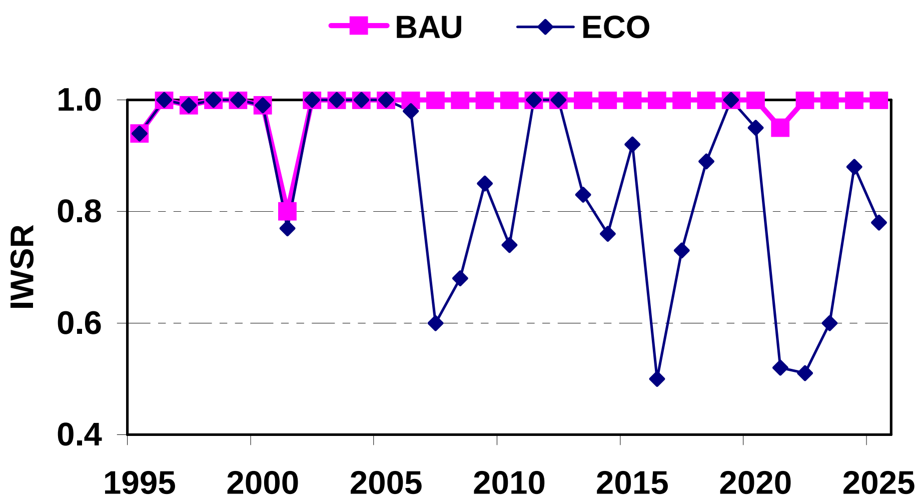

Figure 3: Compare *IWSR* between BAU and ECO

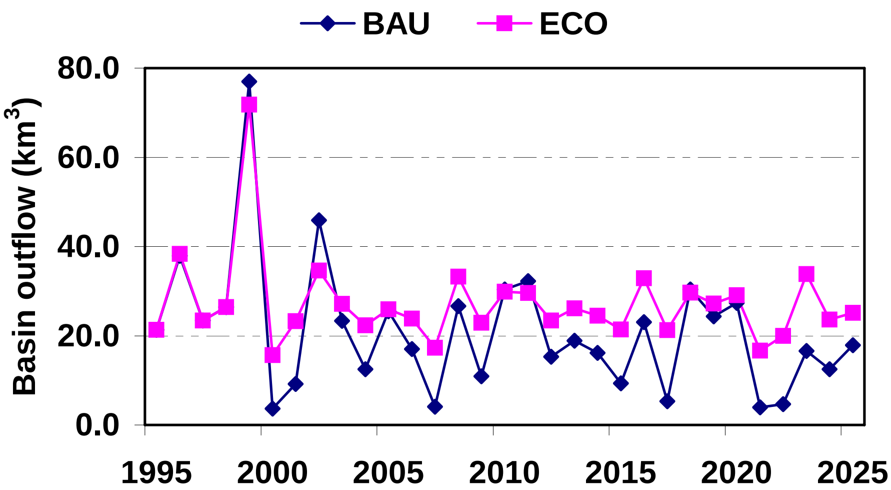

Figure 4: Compare basin outflows between BAU and ECO

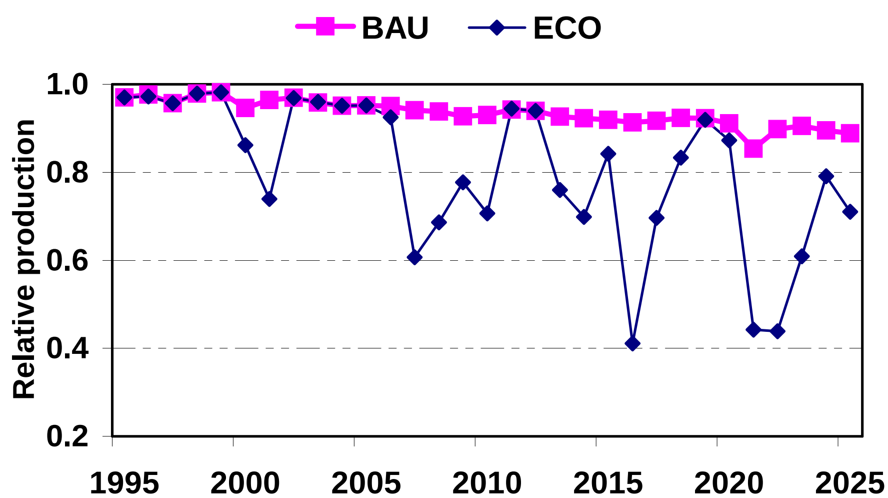

Figure 5: Compare *ICPR* between BAU and ECO

It should be noted that, the hydrologic time series used in this analysis do not include the consecutive drought periods such as 1922-1933 and 1990-2002 (Chen, 2002). With such consecutive drought periods, the basin outflow will be reduced substantially, as observed in the 1990's. Including more complete hydrologic series to represent more complete climate variability and even climate change is beyond the purpose of this paper and will be an important research topic in future research.

Figure 5 shows the irrigated crop production reliability (*ICPR*) regarding all cereal crops as a whole, which consumes over 65 percent of total irrigation water in the YRB. Under BAU, the value of *ICPR* is over 0.9; under ECO, we can see large variability and a significant declining trend of the *ICPR*. The *ICPR* will be as low as 0.4 in some years after 2015, which means the total irrigated cereal production will decline by 60 percent of the potential production without water stress. Moreover, although the *IWSR* is almost 1.0 in most years under BAU, which means little water shortage; but the *ICPR* shows a slight declining tread. This is because the *IWSR* accounts for *seasonal* irrigation water supply reliability ignoring irrigation water supply in individual crop stages; however, the IMPACT-WATER model accounts the effects of water shortage in individual crop growth stages in the calculation of irrigated crop production. The declining trend of the *ICPR* implies a growing effect on crop production from water stress in individual crop growth stages, due to growing non-irrigation water demand (Table 4).

Table 5 shows cereal production and basin outflow as annual average of 2011-2015 and 2021-2025 under BAU and ECO. From BAU to ECO, the ratio of the cereal production decrease over the basin outflow increase is calculated. During 2011-2015, each increase of 1000 m^3 basin outflow will result in cereal production loss of 0.67 metric ton; and during 2021-2025, the same increase of basin outflow will result in cereal production loss of 0.81 metric ton. The increase of the tradeoff is due to the higher potential irrigated area, yield and production in later years than those in earlier years; and the same water stress will then result in larger production loss. Cereal production will be nearly one third lower in 2021-25 under ECO, compared to BAU (Table 6).

Table 6: Compare irrigated cereal production and basin outflow under BAU and ECO

	Cereal production (million metric tons)		Annual basin outflow (km^3)		Chg. of food/ Chg. Of outflow
	BAU	**ECO**	**BAU**	**ECO**	**($mt/1000m^3$)**
2011-2015	27.1	24.3	22.6	26.7	0.67
2021-2025	32.0	21.7	11.1	23.8	0.81

Source: IMPACT-WATER projection, Rosegrant, Cai and Cline (2002).

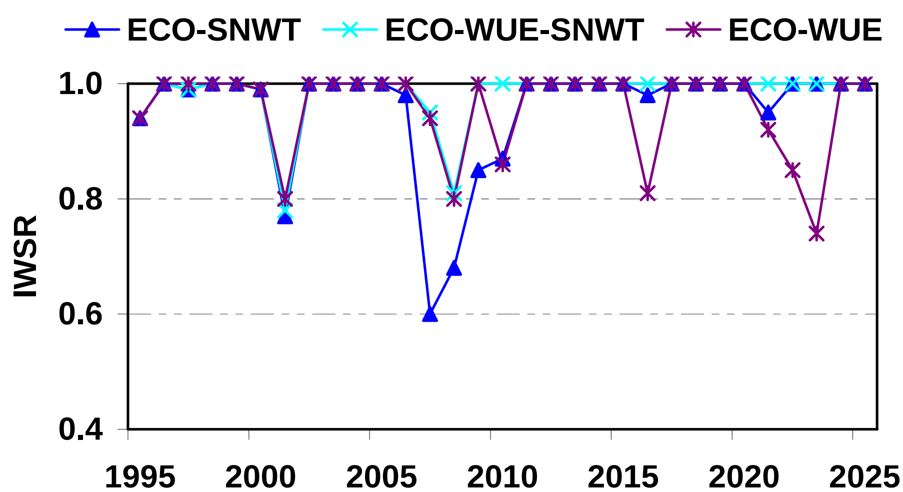

Figure 6: Compare *IWSR* between ECO-SNWT, ECO-WUE, and ECO-WUE-SNWT

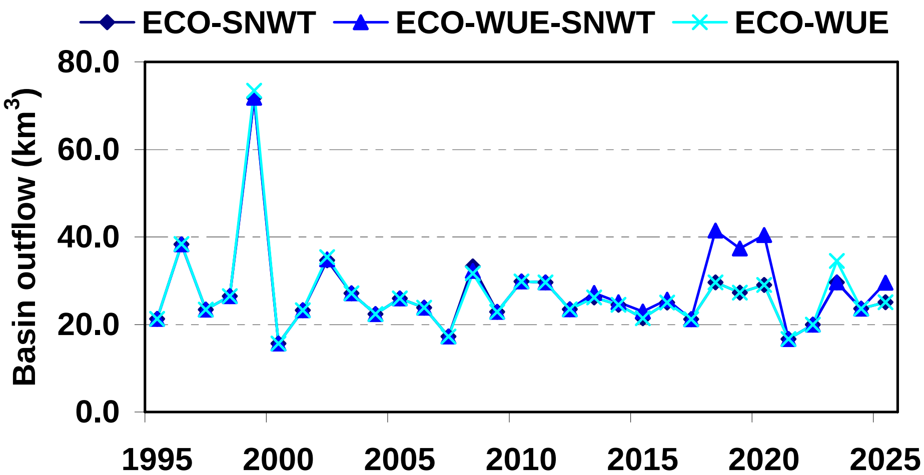

Figure7: Compare basin outflows between ECO-SNWT, ECO-WUE, and ECO-WUE-SNWT

The three scenarios with improvement of water use efficiency, water supplement from the SNWT, or both are discussed in the following. As shown in Figure 6, under ECO-SNWT, the same declines of *IWSR* will occur as under the ECO before the SWNT water supplement is realized in 2010; and some drops may still occur even after the SWNT water supplement is realized after 2015. Under ECO-WUE, although the drops are smaller than those under ECO, they are still significant especially in later years when potential irrigation water demand becomes larger. Under ECO-WUE-SNWT, similar *IWSR* values as those under BAU are achieved. In terms of basin outflows, ECO-WUE and ECO-SNWT will result in basin outflows equal to those under ECO, and ECO-WUE-SNWT will result in even higher basin outflows than ECO in later years, as shown in Figure 7. Correspondingly, Figure 8 shows the *ICPR* under the three scenarios. As can be seen, only ECO-WUE-SNWT can achieve the irrigated food production reliability as achieved under BAU. Therefore, ECO-WUE-SNWT will match the irrigation water demand as BAU and match the ecological flow requirement even better than ECO. Cereal production and annual basin outflow as average values during 2011-2015 and 2021-2025 under the thee ECO scenarios are presented in Table 7, which shows that ECO-WUE-SNWT is better than other two in terms of both cereal production and basin outflow.

Table 7: Compare irrigated cereal production and basin outflow under ECO-WUE, ECO-SNWT and ECO-WUE-SNWT

	Cereal production (million metric tons)			Annual basin outflow (km^3)		
	ECO-WUE	**ECO-SNWT**	**ECO-WUE-SNWT**	**ECO-WUE**	**ECO-SNWT**	**ECO-WUE-SNWT**
2011-2015	27.6	27.1	27.6	25.0	25.0	25.7
2021-2025	29.4	32.0	32.3	24.0	23.0	24.2

Source: IMPACT-WATER projection, Rosegrant, Cai and Cline (2002).

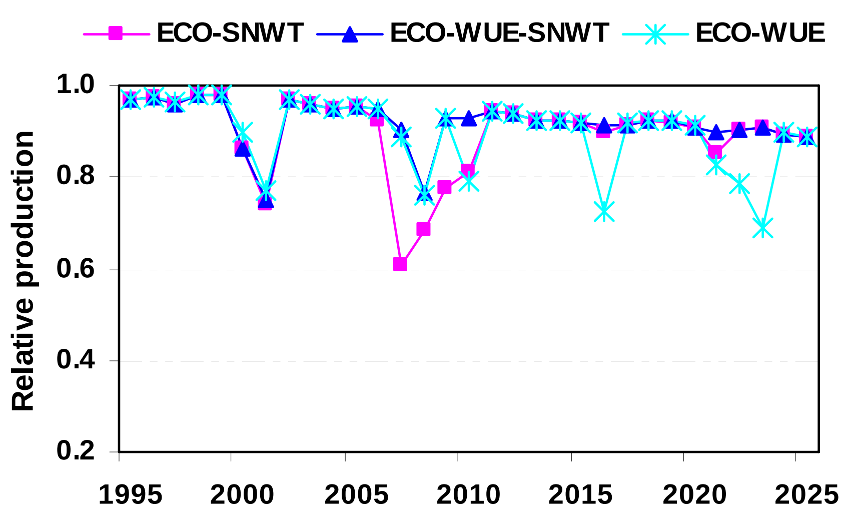

Figure 8: Compare *ICPR* between ECO-SNWT, ECO-WUE, and ECO-WUE-SNWT

5. CONCLUSIONS AND DISCUSSIONS

Water withdrawals in the past decade have seriously depleted ecological water requirements in the YRB. One may argue that this is mainly due to the consecutive droughts with declining precipitation and runoff during 1991-2002, with an annual average renewable water only about 47.6 km^3 (Chen, 2002), 10.4 km^3 below the long-term average renewable water 58.0 km^3, based on hydrologic series 1919-1975. However, even with time series (1961-1990), which exclude the consecutive droughts, ecological flow will continually be depleted if the current water use practices continue with agricultural water withdrawal driven by demand but not constrained by downstream ecological requirement. Therefore, there is little space for flexibility in sustaining both agriculture water demand and water demand for the ecosystems, if the current water use practices continue. The system will be highly vulnerable especially when the successive droughts during 1990-2000 and during 1922-1932 occur.

With water becoming increasingly scarce, continued high flow diversions would become self-defeating. In the YRB, sediment accumulation due to insufficient flow for sediment flushing in the downstream river channel makes the middle and downstream of the basin more vulnerable to flooding damage than ever. Groundwater overdraft is found in the middle stream area and can likewise lead to the loss of an important water source for human uses in the future. Flow depletion has already led to recession of ecological systems in the delta area, on which people there depend for living.

Strong tradeoffs exist between irrigation water use and ecological water use. Considering population growth, urbanization and industrial development, and food demand increase in the YRB, water demand is expected to grow continually, which will make the tradeoffs more intensive in future years. Substantial pressure exists in the basin to drive water demand control, water saving, and consideration of other measures including inter-basin water transfer through the South-North-Water Transfer (SNWT) project. Scenario analysis in this paper concludes that plausible improvement of irrigation water use efficiency solely cannot fully solve the problem of the YRB that may rise in the next 25 years, i.e., being not able to match both the irrigation water demand and ecological water demand. The SNWT water supplement as planned cannot solve the problem solely either. Increasing the WUE to a feasible level first and then implementing the water supplement by the SNWT may provide a better solution, as shown by the modeling results. Making big improvements in water use efficiency in the YRB, as well as in other basins, will require site-specific analysis and implementation. *AWUE* depends on improvements both in water-saving technologies and in the institutions governing water allocation, water rights, and water quality. Technical improvements include advanced irrigation systems such as drip irrigation, sprinklers, conjunctive use of surface and groundwater, and precision agriculture, including computer monitoring of crop water demand. The key issue for agricultural water saving in the YRB is to reduce non-beneficial water depletion especially in upper and middle regions. Different water conservation measures should be taken for different regions from upstream to downstream according to their current practices. For irrigation districts in Ningxia and Neimeng (Ning-Meng), water requirement for salt leaching needs to be carefully checked to see if there is any potential to reduce water withdrawal; in some subregions of Neimeng, water is withdrawn to crop fields after crop harvesting to maintain soil moisture for next crop season, which covers 40 percent of total water withdrawal in this region according to the estimation of the YRCC. Research is needed to examine if that amount of water is used efficiently. In downstream regions, combined canal and well systems have been efficient in enhancing water recycling and these practices can be further explored, including increasing the capacity for large-scale conjunctive surface-groundwater uses and maintaining water quality requirement during water recycling. In terms of irrigation water saving technology, improvements in irrigation canal linings may be more important in the upper (Ningxia) and middles of the Yellow River, because canal leakage raises groundwater levels along with salinity levels and because leakage increases evaporation. In lower reaches, canal leakage may beneficially recharge groundwater. The potential benefits from canal lining improvements may be greatest near main river channels, because the groundwater table there is already high and any recharge from leakage may increase salinity levels. The cost-effectiveness of these interventions must also be carefully assessed.

Managerial improvements include the adoption of demand-based irrigation scheduling systems and improved equipment maintenance. Institutional improvements involve the establishment of effective water user associations and water rights, the creation of a better legal environment for water allocation, and the introduction of higher water prices. Great care must be taken in designing a water pricing system for agriculture in the YRB, in which agriculture is the dominant water use at least in the near future. Direct water price increases are likely to be punitive to farmers because water plays such a large role in their cost of production. Better alternatives would be pricing schemes that pay farmers for reducing water use, and water rights and water trading arrangements that provide farmers or water user associations with incentives to reduce wasteful water use.

This paper is based on some empirical results and assumptions from other studies, such as the assessment of ecological water demand irrigation water demand. These are expected to be updated or improved in future research. A new methodology for determining appropriate ecological water demand might be used to examine the current objective method; crop pattern changes and agricultural research will change the irrigation water demand. Moreover, flow regulation through the storage system may increase water availability, while on the other hand it may affect the ecosystems in the basin too. Future research on these issues is needed for further verification of the conclusions derived from this paper.

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