Impact of Global Change on Large River Basins: Example of the Yellow River Basin

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Abstract
The Yellow River Basin (YRB), the breadbasket of China, is characterized by severe water scarcity. Local climatic conditions make the basin one of the driest areas of China, and rapid socioeconomic development has led to excessive water abstraction. Climate change is expected to add further pressure on water resources. The Yellow River Conservancy Commission projects that climate change may result in annual water shortages of 9 km3 by 2020, and up to 26 km3 in very dry years. Similarly, the International Food Policy Research Institute's IMPACT model shows a decline in availability of water for irrigation in the YRB under climate change. We also find that large food-producing basins, such as the YRB, can strongly impact global food prices. We run two scenarios of reduced irrigation water availability in the YRB under climate change, which reflect Chinese estimates of future dry-season water shortages. Under these scenarios, international prices for wheat, maize and rice increase by between 3 and 10 percent by 2030. To address escalating water shortages that affect economic growth and food security in the basin, and to reduce potentially adverse impacts on global food markets, managers will need to strengthen water demand management and increase agricultural water productivity.

Keywords: Yellow River basin, water shortages, climate change

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1 Introduction

1.1 The Economic Importance of the Yellow River Basin

The Yellow River basin (YRB) is the second longest river in China, after the Yangtze. Its basin, stretching from the Bayangela Mountains in western China to the Bohai Sea, is the breadbasket of China and the cradle of Chinese civilization (Xue, Sun, and Ringler 2010). Although it contains only 2 percent of national water resources, in 2000 it generated 16 percent of Chinese grain production and 12 percent of the country's gross domestic product (GDP; Xue, Sun, and Ringler 2010). The section of the basin between the Fen and Wei Rivers in the middle reaches is one of the main production areas for cotton and grains in China. In the last few decades, industry, including mining, has developed rapidly. The YRB is now home to the largest mining operations in China, and big investments have poured into the development of coal-based power generation as part of the national energy development plan (Xue, Sun, and Ringler 2010).

The rapid industrialization and urbanization of the YRB in the last few decades are correlated with population growth. The total population of the YRB area was at 96.3 million at the end of the 1980s and 107 million at the end of the 1990s (Wang, Liu, and Ma 2010). Today the basin is the main water source for the north and northwest of China, servicing more than 50 cities and 420 counties and a population of between 120 and 200 million people, about 9 percent of China's total (Ringler et al. 2010).

1.2 Evidence of Water Shortages and Their Causing Factors

Particular climatological conditions make the YRB one of the driest areas in China. The natural annual average runoff amounts to 53.5 km^3, and the annual renewable water resources per capita are estimated at 588 m^3, less than one-third of the average for the whole of China (Li et al. 2010). A decrease in precipitation dating from the 1950s, and competition over water resources for irrigation—to satisfy the country's grain self-sufficiency policy of 95 percent—and for urban industrial development are at the heart of water shortages in the basin.

The most striking evidence of water scarcity has been the interruption of river flow, which affected the main channel near the delta for 22 years in the period between 1972 and 1998. In 1997 the Yellow River did not reach the Bohai Sea for a total of 226 days, and the river dried up to Kaifeng, 600 km from the river mouth (Ringler et al. 2010). In the past 20 years numerous droughts struck the upper and middle reaches in the basin, causing significant reductions in grain yields. In 1994 the drought caused a loss in agricultural production of 6 million metric tons, and more recently, from winter 2008 to spring 2009, drought affected more than 75,000 hectare in the provinces of northern China, causing damage to the wheat crops (Li et al. 2010).

The agriculture sector currently accounts for 80 percent of total water withdrawals, with the industrial and domestic sectors dividing the remaining 20 percent (Giordano et al. 2004; Li et al. 2010; Xu et al. 2005). During the last 50 years irrigated areas in the YRB have increased more than 350 percent, and agricultural water use has increased by more than 250 percent; water demand from industry and domestic use has grown even more steeply (Ringler et al. 2010).

Competition over water resources is also fueled by the growing appreciation for ecosystem services and the consequent effort to maintain environmental flows. Furthermore, a minimum water flow of 15 km^3 must be kept in the river during the flood season to flush the vast amount of sediment downstream (Xu et al. 2005; Ringler et al. 2010; Li et al. 2010). The Yellow River has the highest sediment load in the world, averaging 38 kg/m^3; in conditions of low flow, sediments can accumulate and become a cofactor in causing damaging floods (Li et al. 2010).

Environmental externalities such as runoff from industry and agriculture are a source of additional pressure, because poor water quality limits suitability for a number of uses. The growing problem of competing demands is compounded by low water-use efficiency in the main sectors (agriculture, industry, and domestic sector), due to an aging distribution system and to a water management and allocation process that is still inadequate (Li et al. 2010).

The YRB has been at the forefront of innovation in water management. The 1987 YRB water allocation plan was the first of its kind, but in the first 10 years, problems of implementation and lack of clearly defined water rights exacerbated the conflict between users, caused water overuse, and led to the crisis of the late 1990s. In response, the Yellow River Conservancy Commission (YRCC) implemented in 1998 the Unified Water Flow

Regulation of the YRB, which defined monthly allocations for each province (Shen and Speed 2009; Zhao et al. 2009). Since then, no flow cutoff has occurred but water shortages are increasing (Xue, Sun, and Ringler 2010).

Climate change is poised to worsen future water availability in the YRB (Piao et al. 2010). At least one study in the past has reported that climate is the dominant factor in determining the declines in runoff in the lower reaches of the YRB (Fu et al. 2004). The following sections describe the impact of global change on water resources in the YRB and how this may then affect global food markets.

2 Impact of Global Change on the Yellow River Basin

2.1 Climate Change Effects on Stream-Flow in the YRB

China's climate has been warming at least for the past five decades, and the north has been doing so faster than the south (Piao et al. 2010). To investigate the impact of climate change on future stream-flows in the Yellow River, the B2 emission scenario from the Intergovernmental Panel on Climate Change (IPCC) was used to drive the HadCM3 Global Circulation Model (GCM) and estimate changes in daily maximum and minimum air temperatures and precipitation between a baseline period (1961–1990) and three future periods: the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099). The B2 storyline and scenario family characterizes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with slowly increasing population and intermediate economic development. It is considered a very moderate scenario.

As the spatial resolution of GCMs is too coarse to represent local-level biophysical dynamics, such as precipitations and hydrological processes, statistical downscaling was used to transfer the outputs of the HadCM3 model to two catchments in the YRB. The downscaled climate parameters (both temperatures and precipitation) were then used to drive the Soil and Water Assessment Tool (SWAT) hydrological model to simulate future changes in stream-flow (Li et al. 2010). The two study areas were the upper catchment of the YRB north of Lanzhou station, the least affected by anthropogenic activities, and the Wei River basin, a tributary of the Yellow River (Figure 1). Together these two areas, denoted as UMR-YRB (upper-middle reaches of YRB), contribute up to 75 percent of the total water resource of the YRB.

Downscaling analysis applied to the whole UMR-YRB shows a gradual increment in both minimum and maximum temperatures from 2020 to 2080, with an increase of up to 4°C in 2080. Minimum air temperatures show a smaller trend of increase compared with maximum temperatures, except in 2020 (Table 1). Average precipitation decreases up to 7 percent by 2050 and up to 9 percent by 2080 (Table 1).

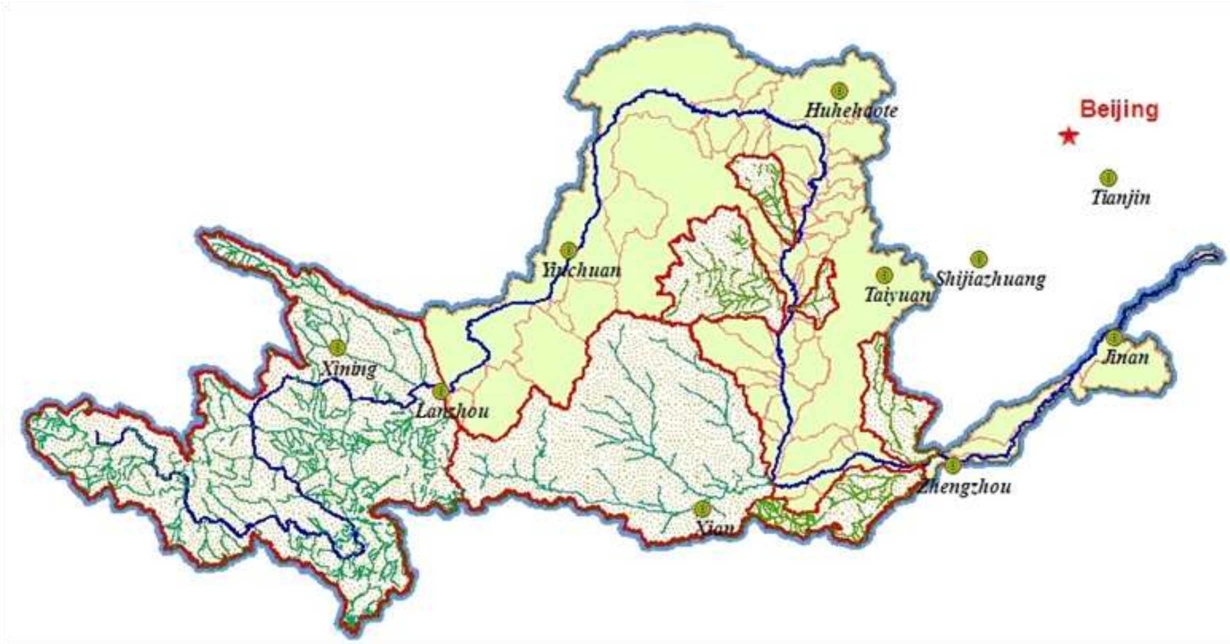
Table 1. Increment of daily maximum and minimum temperatures, and decrease in precipitation in future periods compared with baseline

Parameter	Baseline	Future scenarios		
		2020s	2050s	2080s
Daily Tmax（℃/d）	13.5	0.4	1.9	4
Daily Tmin（℃/d）	0.6	0.5	1.6	2.7
Annual precipitation（mm/yr）	451.3	–81.9	–32.2	–41.3

Source: Li et al. 2010

Notes: Tmax = maximum temperature; Tmin = minimum temperature. These projections apply to the UMR-YRB, the area including both catchments under study.

Figure 1. Yellow River basin, with headwaters region and Wei River basin

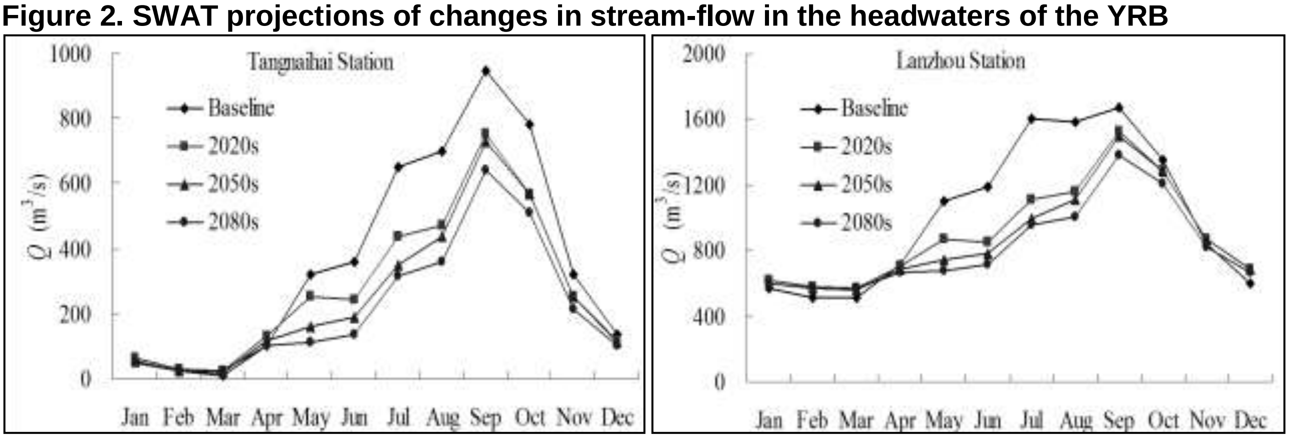


Source: College of Water Sciences, Beijing Normal University

Notes: The blue line indicates the Yellow river. The area circled in red upstream of Lanzhou station is the Headwaters region of the YRB. The area circled in red to the south of the basin is the Wei River basin.

Based on the SWAT analysis, the combination of higher temperatures and lower precipitation levels will reduce the stream-flow in the upper catchment of the YRB, both at Tangnaihai and Lanzhou stations (Figure 2). The stream-flow will decrease of as much as 88.61 m^3/sec (9.0 percent), 116.64 m^3/sec (21.9 percent), and 151.62 m^3/sec (29.2 percent) at Tangnaihai station; and 117.05 m^3/sec (5.8 percent), 154.08 m^3/sec (9.0 percent), and 200.03 m^3/sec (12.6 percent) at Lanzhou station in the 2020s, 2050s, and 2080s, respectively. For the Wei River basin, SWAT simulations seem to indicate a stream-flow decrease of up to 6.6 percent before 2020, and an increase in stream-flow beyond that date (Table 2). Thus, even under the relatively moderate and precipitation-abundant HadCM3 B2 scenario, climate change may affect future regional water supply in the basin (Xu, Zhao, and Li 2009).

Figure 2. SWAT projections of changes in stream-flow in the headwaters of the YRB



Source: Xu, Zhao, and Li 2009; Li et al. 2010.

Note: Q = stream-flow.

Table 2. Annual mean runoff and change rate at different stations in the future

Station	Sim. status-quo	2010s		2020s		2030s		2050s	
		Sim.	Rate(%)	Sim.	Rate(%)	Sim.	Rate(%)	Sim.	Rate(%)
Qin'an(m^3/s)	2.47	2.44	–1.20	2.28	–7.67	2.78	12.65	2.60	5.31
Wushan(m^3/s)	7.17	6.80	5.13	6.58	8.21	7.53	5.02	7.50	4.62
Yuluoping(m^3/s)	18.84	17.53	–6.96	17.56	–6.81	18.81	–0.18	18.14	–3.71
Xianyang(m^3/s)	69.81	68.37	–2.07	64.86	–7.09	76.97	10.25	72.39	3.69
Wei River basin ($\times 10^8 m^3/a$)	54.75	53.00	–3.210	51.13	–6.62	59.53	8.731	56.14	2.53

Source: Li et al. 2010.
Note: Sim. = simulated.

2.2 Impacts of Climate Change on the Supply and Demand Balance

To assess the impacts of changes in stream-flow on the water supply-and-demand balance in the YRB, we linked the SWAT model results with the water simulation model of the YRCC, the basin authority overseeing management of water resources in the YRB.

The YRCC model uses forecasts of socioeconomic and demographic development of the basin to simulate the spatial and temporal use of water resources in the entire YRB and to project changes in water supply and demand. Two scenarios, one with and one without climate change, were taken into consideration, and supply and demand were projected to 2020.

In a condition without climate change, the YRCC simulation projects an increase of total water demand to 52 km^3 by 2020 and nearly 55 km^3 by 2030 (Table 3). Demand will increase for the domestic and industrial sectors, as well as for both in-stream and off-stream environmental needs, whereas demand for the rural production sector (all types of irrigation, fishponds, and livestock) is projected to decline slightly. Water shortages will mostly affect agriculture, still the largest water user in 2020 and lowest on the priority scale in most provinces.

With a water supply estimate of 44.58 km^3 by 2020, which is equivalent to the average of 1956–2000, the basin will experience a water shortage of 7.5 km^3 and a water deficiency ratio of 14.5 percent (this is calculated as: water shortage/water demand x 100) (Table 4). Under this water scarcity situation, it will be hard to maintain the water flow of 15–22 km^3 necessary for sediment flushing in the lower reaches of the YRB (Li et al. 2010).

When considering climate change conditions projected to 2020, the annual surface flow of the Yellow River is reduced, average annual water shortages increase to 9.08 km^3, and the water deficiency ratio rises from 14.5 percent to 17.4 percent (Table 4).

As can be expected, the worst conditions would be registered under a drier-year scenario, as this triggers a combination of lower runoff and higher water demand in agriculture. Without taking climate change into consideration, annual average water shortages in the basin under a 75 percent and a 95 percent exceedance frequency for dry conditions would increase from 7.5 km^3 to 12.11 km^3 and 20 km^3, respectively. With climate change, these values would rise to 15.44 km^3 and 25.68 km^3, respectively (Table 4; Li et al. 2010).

Table 3. Domestic, production, and ecological water demand projections (km^3)

Level year	Domestic water demand	Water demand of production sector			Ecological water demand	Total
		Urban[a]	Rural[b]	Subtotal		
Current Year	2.945	7.667	37.622	45.289	0.345	48.579
2020	4.119	11.22	36.18	47.4	0.594	52.113
2030	4.889	12.673	36.424	49.097	0.746	54.733

Source: Li et al 2010

Notes: a = industry, including construction and tertiary; b = cropland, pastures, livestock, and irrigation.

Table 4. The Yellow River basin water supply-and-demand balance for 2020 (km^3)

Conditions	Scenarios	Water demand in the basin	Surface water supply in the basin	Water shortage in the basin	Water shortage ratio in basin (%nt)	Enterin g into the sea
Annual Average conditions	Not considering climate change	52.11	44.58	7.53	14.5	18.88
	Considering climate change	52.11	43.03	9.08	17.4	17.70
	Difference	0	–1.55	1.55	2.9	–1.18
75%	Not considering climate change	53.17	27.44	12.11	22.77	16.51
	Considering climate change	53.17	24.11	15.44	29.04	13.83
	Difference	0	–3.33	3.33	6.27	–2.68
95%	Not considering climate change	57.28	23.63	20.00	34.92	8.41
	Considering climate change	57.28	17.95	25.68	44.83	4.61
	Difference	0	–5.68	5.68	9.91	–3.80

Source: Li et al. 2010.

3 Global Impacts of Water Shortages in the Yellow River Basin

Most of the irrigation water in the YRB, and in China in general, is used for the production of basic staple crops. While agricultural area in China is expected to continue to contract and irrigated area to barely increase in the next decades, irrigation in the YRB is expected to account for an increasing share, 18 percent, of the national total during the coming decades, as a result of declines in irrigated rice production in other Chinese river basins (IFPRI 2009).

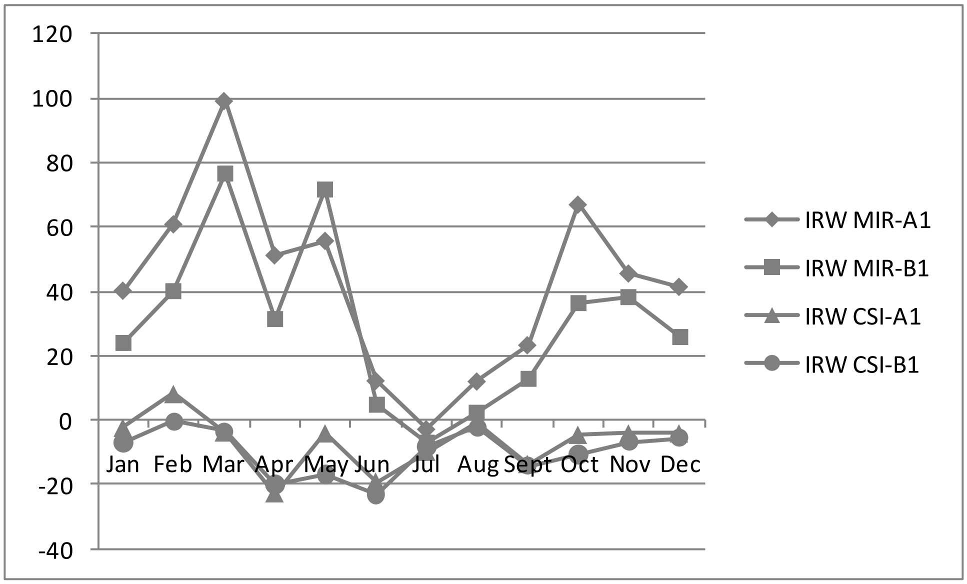
However, during 1988–1992, irrigation water use in the basin declined by 1.5 km^3 while urban-industrial use increased by 2.4 km^3. Further declines in allocation of water to irrigation will eventually result in food production declines, with serious implications for food security and farmer incomes.

A 2009 companion study suggests that reduced irrigation may impact the rural poor in the YRB in several ways (Ahmed et al. 2009). The study shows that water irrigation coverage is a statistically significant determinant of per capita household income, and a 10 percent increase in coverage of surface irrigation reduces the incidence of poverty by 5 percent. Based on the international poverty line of US$1.25 per day, the ratio of poor households in nonirrigated villages in the YRB is double compared with irrigated villages, and irrigated provinces like Shandong, Inner Mongolia, and Henan have a higher concentration of nonpoor compared with nonirrigated provinces. The benefits of irrigation water on a community are also reflected in the social and health dimensions, as irrigated villages have higher school enrollment rates and better access to safe drinking water (Ahmed et al. 2009).

Because the YRB is also a food production center of global importance, a decline in irrigation and food production may have far-reaching effects for global food prices and trade. To assess the impacts of changes in irrigation water availability on global food markets, we implement two alternative irrigation scenarios with the IMPACT global food and water projections model (Rosegrant et al. 2008). One scenario reduces irrigation water availability in the YRB for all crops by 30 percent up to 2030, maintaining the same reduction share thereafter; and the second scenario reduces availability further, up to 50 percent by 2030, to reflect the growing water shortages simulated in the YRCC model. Both scenarios were implemented as gradual linear reductions of irrigation water availability.

Moreover, both scenarios were modeled under historic climate and with climate change. The climate change conditions used as input to the IMPACT model were derived from the global circulation model CSI driven by the B1 emission scenario. The CSI-B1 scenario is among the most dry scenarios for the YRB (Figure 3; Nelson et al.), but at the global level CSI-B1 is a relatively moderate scenario in terms of increases in minimum and maximum temperatures and average annual precipitation. CSI is the abbreviation for the CSIRO-Mk3.0 Global Circulation Model.

Figure 3. Changes in water availability across four scenarios in 2050, compared with long-term historic flows, YRB

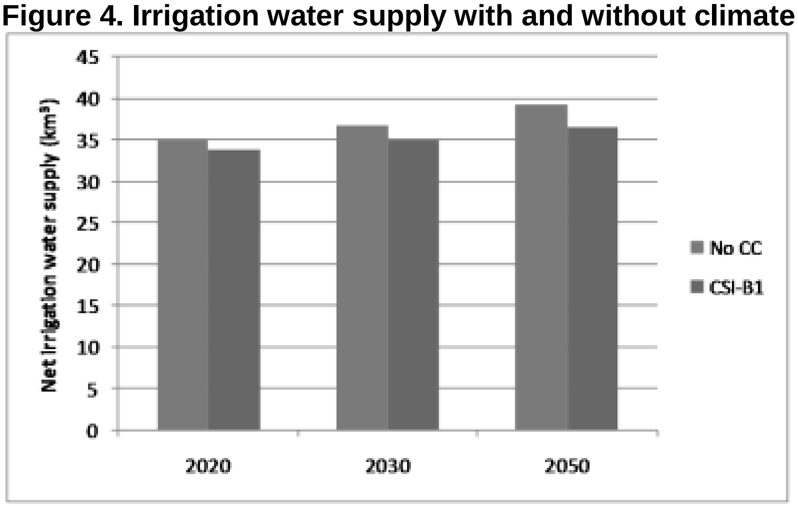


Source: Nelson et al.

Note: B1 and A1 are emission scenarios; MRI and CSI are two different GCMs; IRW = internal renewable water. Values above the 0 line indicate increase in availability, below 0 a decrease in availability.

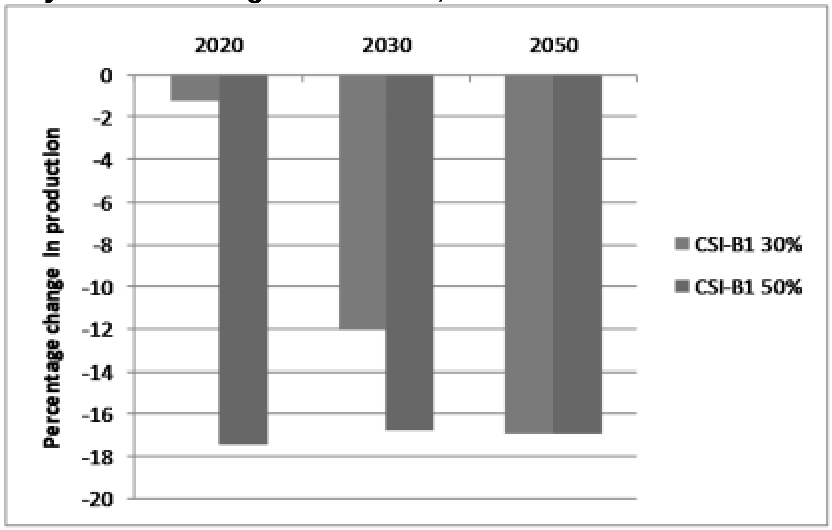
IMPACT results show that irrigation water availability in the YRB is always lower under the CSI-B1 scenario compared with conditions without climate change (Figure 4), even before forcing the 30 percent and 50 percent reduction in irrigation. In both scenarios (no climate change and CSI-B1) we see also small increases in total irrigation water supply across time, as a result of continued, albeit small, expansion in irrigated area. In 2050 the irrigation water is 39.4 km^3 for the no-climate-change scenario and 36.6 km^3 for the CSI-B1 scenario. With climate change and a 50 percent reduction in water available for irrigation, the production of irrigated cereals drops by 17 percent compared with the base CSI-B1 climate change conditions (Figure 5). The impacts of a 30percent reduction are more gradual, but they also cause nearly a 17percent reduction in production of irrigated cereals by 2050.

Figure 4. Irrigation water supply with and without climate change, YRB



Note: CC = climate change.

Figure 5. Change in cereals production under reduced irrigation water availability compared to only climate change conditions, YRB



Note: CSI-B1 30% = scenario with 30 percent reduction of irrigation on top of climate change conditions. CSI-B1 50% is the second scenario with 50 percent reduction. Irrigated cereals production (rainfed production is much smaller) changes under irrigation water availability reduction in the YRB of 30% and 50%, compared with the CSI-B1 scenario.

Table 5 presents the impact that changes in YRB irrigation water availability can have on global food prices: By 2030, international wheat prices are 6percent higher under climate change conditions and irrigation water reduction of 30 percent, compared to a scenario with only climate change conditions. Maize prices are 4percent higher, and rice prices are 3percent higher. If irrigation water availability were 50 percent lower by 2030, price hikes would be even higher: 9percent for wheat, 10 percent for maize, and 6percent for rice.

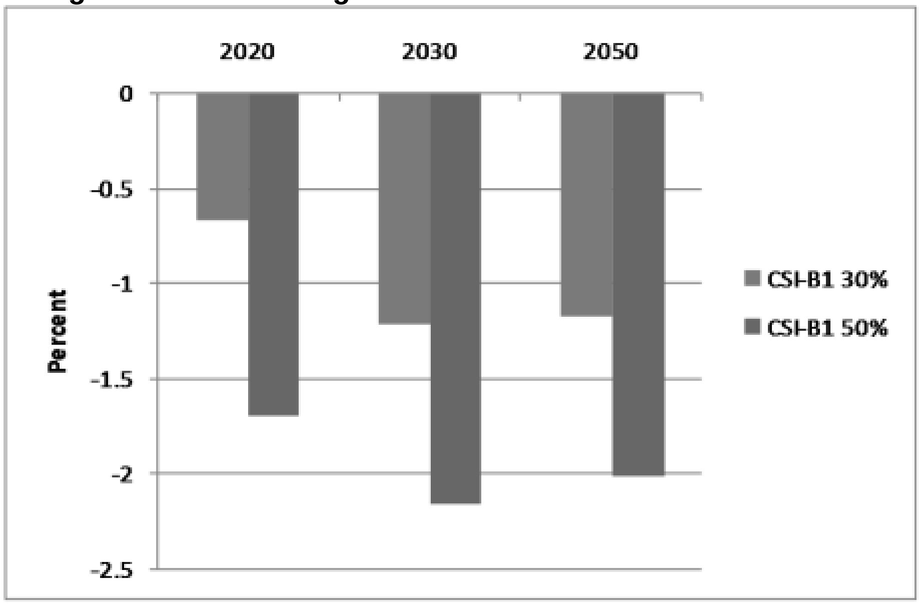
Table 5. International cereal prices under reduced irrigation water availability, YRB, climate change scenario

	CSI-B1	**CSI-B1 30%**	**CSI-B1 50%**	**CSI-B1**	**CSI-B1 30%**	**CSI-B1 50%**
Crops	**2030**	**2030**	**2030**	**2050**	**2050**	**2050**
Rice	272.15	281.17	287.58	316.49	324.37	332.00
Wheat	161.25	170.40	175.86	180.742	191.44	196.00
Maize	138.84	144.51	152.88	166.00	173.79	181.84

Note: Prices are in U.S. dollars per metric ton (real 2000 values). CSI-B1 30 percent and CSI-B1 50 percent indicate the CSI-B1 scenario with irrigation water reduced by 30 percent and 50 percent, respectively.

Higher food prices, in turn, depress food demand with adverse impacts on those who still spend sizable shares of total expenditures on food items, particularly in sub-Saharan Africa. Figure 6 shows changes in calorie availability per capita per day for the group of developing countries, under climate change with irrigation reduced of 30 percent (CSI-B1 30%) and 50percent (CSI-B1 50%), compared with the regular climate change scenario CSI-B1. By 2030, calorie availability in developing countries declines by 1.2 percent and 2.2 percent under a 30 percent and 50 percent irrigation water reduction, respectively.

Figure 6. Percent change in kcal per capita per day in developing countries under climate change and reduced irrigation



Note: CSI-B1 30% and CSI-B1 50% indicate the CSI-B1 scenario with irrigation water reduced by 30% and 50% , respectively.

4 Directions to Adapt to Global Change in the Yellow River Basin

Responding to extreme water scarcity in the YRB requires a variety of interventions. Improvement of water rights and development of water markets need to go in parallel with the implementation of water-saving measures, particularly in agriculture, and the completion of water transfer schemes. Any plan to succeed will require a high level of institutional and technical integration and plans to improve the implementation rate of laws and regulations down to the local level.

4.1. Technology Options to Reduce Water Shortages in the YRB

During the last two decades water use efficiency has improved in the YRB, yet it still falls very short of that in developed countries, suggesting that large improvements can still be made. The intensity of industrial water use has decreased from 876 m^3 of water withdrawal per 10,000 renminbi (RMB) of GDP in 1980 to 104 m^3 in 2006, a reduction of 88 percent. In the developed world this value is below 50 m^3 (Li et al. 2010).

According to the YRCC, the expansion of technologies to increase water use efficiency across the agriculture, industry, and urban-domestic sectors could produce water savings of up to 5.69 km^3 and 7.64 km^3 in 2020 and 2030, respectively (Table 6; Li et al. 2010; Xue, Sun, and Ringler 2010), and could lower total water withdrawals per 10,000 RMB of GDP from 354 m^3 in 2008 to 71 m^3 in 2030, with an annual rate of decline of 6.9 percent (Li et al. 2010).

In the industrial sector, water savings are expected to originate from the adoption of advanced technologies and by improving water recycling rates, which will reach 72.3 percent in 2020 and 83.5 percent in 2030 (in the developed world this value is currently between 80 percent and 85 percent). In the urban-domestic sector, engineering measures can improve water use efficiency, and losses can be reduced by disconnecting illegal water connections.

In agriculture, water savings can originate from the modernization of irrigation systems through the introduction of canal lining and the extension of microirrigation, as well as by adjusting planting dates and expanding less-water-intensive crops (e.g., maize or millet) while reducing the area used for wheat. According to YRCC experts, these water-saving strategies could be extended to 3.6 million hectare by 2020 and to an additional 2 million hectare by 2030, resulting in total irrigation water savings of 4 km^3 and 5.4 km^3, respectively (Table 6; Li et al. 2010). In 2009, 7.6 percent of net irrigated area in China was under microirrigation, compared with less than 0.1 percent in 1991 (ICID 2010).

Table 6. Proposed water savings in YRB

Level year	Industrial water savings	Agricultural water savings	Urban domestic water savings	Total
2020	1.53	4.04	0.12	5.69
2030	2.05	5.42	0.17	7.64

Source: Li et al. 2010.

Even if successfully implemented, these measures will not be enough to solve the water shortage problems in 2020, with or without the added stress of climate change (compare Table 6 and Table 3). Thanks to the financial resources mobilized by China's economic development, the government officially launched in 2002 the South-North Water Transfer Project, which could bring up to 50 km^3 of water from the Yangtze to the north of China through western, middle, and eastern routes (Pietz and Giordano 2009; Yang and Zehnder 2005). The eastern and middle routes will cross the Yellow River and continue their course to the north to provide water for the dry regions in the Haihe and Huaihe River basins in Beijing, Tianjin, Hebei, Henan, and Shandong, with limited benefits for the YRB. The western route could instead pour nearly 20 km^3 of water directly into the Yellow River, enough to irrigate an additional 1.3 million hectare of agricultural land in the basin. However, economic, engineering, and ecological concerns will prevent this route from development in the foreseeable future (Li et al. 2010).

4.2. Policy Options to Improve Efficiency: Control of Demand, Water Permits, and Rights

Water-saving options that focus on technological solutions and on the supply side of water management can contribute but will not be enough to single-handedly solve the water challenges brought about by socioeconomic development and climate change. The major necessary change to improve water use efficiency is a transition from control of supply to control of demand. The 2002 water law commenced this transition for the whole of China through the establishment of a water permit system and the introduction of the concept of water rights.

The current system of water allocation and distribution of water rights in the YRB is very sophisticated (Calow, Howarth, and Wang 2009). The combined effectiveness of the unified water flow regulation of 1998, water permits, water pricing, and pilot projects to establish water markets has the potential to reduce water demand; but each of these initiatives faces impediments.

4.2.1 Unified Water Allocation and Water Pricing

The Unified Water Allocation Regulation of 1998 managed to stop the flow of interruptions in the YRB. In essence, the regulation enacted a water transfer from the northern upstream provinces of the basin to the southern, more water-deprived, provinces. Before the unified regulation, water was treated as an open-access resource, and users could abstract as much as they wanted (Wang and Zhang 2010). This meant that the upstream provinces of Qinghai, Gansu, Ningxia, and Inner Mongolia, closer to the headwaters of the Yellow River, were using much more water per capita than the downstream provinces of Shaanxi, Shanxi, Henan, and Shandong (Wang and Zhang 2010). Irrigation districts in the upstream provinces were forced to cut water supply and lost revenues originating from collection of water fees from farmers. In the year 2000, under pressure from water suppliers in the upstream provinces and concerned about the apparent lack of funds to maintain the irrigation network, the government raised water prices.

Managers of irrigation districts have no incentives to work toward improvement of water use efficiency because their wages are solely dependent on collection of water fees, thus on the amount of water used. Moreover, water pricing seems to have limited applicability to control water use in the YRB. Although prices have been increased fivefold since the 1990s, water is still considered underpriced; but further increases would weigh prohibitively on the productive capacity of farmers, and therefore the government is reluctant to continue raising prices (Xue, Sun, and Ringler 2010). A possible alternative would be to introduce a scheme that pays farmers for reducing water use.

4.2.2 Pace of the Reforms and Incentives for Water Savings

In the YRB, water management reform includes mechanisms that generate monetary incentives for those village water managers that succeed in reducing water use. However, the system is plagued by the slow implementation of water reforms, a major problem in the YRB and across China. As an example, details on how to make operative the 2002 Water law, including key regulations on the method of collection of water resources fees, were not issued until 2006 for many provinces of the YRB (Wang and Zhang 2010)

Based on the water reforms approved since the early 1990s farmers are subject to paying a double water fee. One is based on the owned area to be irrigated, and the second is a volumetric fee based on estimates of the water needs compiled before the farming year. The village water manager collects water use fees from the farmers and pays them to the irrigation district. In the reform regulation, water managers are entitled to keep as excess profit the difference between the volumetric fee exacted from the farmers and the fee actually due to the irrigation district, calculated based on the real water use (based on a per-cubic-meter charge). However, a field survey across 51 villages in four irrigation districts in Ningxia and Henan provinces found that only in 46 percent of the villages were the managers actually offered this type of incentive from the village leadership (Xue, Sun, and Ringler 2010).

The main reason behind this failing is that although the water reform commands a transition in the management of water at the village level, from collective management to water user associations or to a hired independent and external manager, this transition is not complete in the YRB. In the surveyed regions, in 85 percent of cases the board of the water user association was the village leadership itself, and the remaining 15 percent appointed a manager that had very close ties with the village leadership. This minimizes the difference between the associations and collective management and undermines the system of monetary incentives—the intention of the reforms—that would have encouraged the managers to save water (Xue, Sun, and Ringler 2010). Econometric analysis performed on the survey data showed that independently from the form of management (water user association or contractor), water use per hectare of wheat was reduced by nearly 1,000 cubic meters (about 20 percent of the previous use) when managers faced positive incentives (Xue, Sun, and Ringler 2010). The inconsistent application of incentives across provinces results in significant differences in water savings on a village basis.

To rectify the situation, the YRCC should exert a level of authority it still does not have. Although the Ministry for Water Resources trusted upon the YRCC control over water allocation within the basin, the water law does not specify the powers of the YRCC in matters of "administrative enforcement, supervision, and punishment, and the relationship between YRCC and local governments remains unclear" (Wang and Zhang 2010, page 13).

4.2.3 Water Permits, Water Rights, and Water Markets

Regional administrations (i.e., provinces and prefectures) employ water use permits to allocate water among water abstractors—those who directly abstract water from watercourses or aquifers. Permits are issued most often to legal entities like industries and to public supply systems such as urban water utilities and irrigation districts[1] (Shen and Speed 2009). These public systems supply end users like farms or individuals, based on factors such as availability of water, amount of irrigable land, and crop requirements (Shen and Speed 2009).

The permit system also needs to be adjusted. The 2006 Water Permit Regulation establishes that the issuance of a permit must be in accord with the general water allocation plans, which in essence sets a cap on total abstractions. However, the way allocation plans define rights does not allow water managers to readily verify whether an application for a water permit is acceptable based on the targets of the plan (Wang and Zhang 2010).

Although permits assigned to entities and supply systems are usually unambiguous, the allocation to single users is not, and it thwarts the development of water markets. Farmers often do not know how much water they are entitled to, and when the rights (i.e., the individual water entitlement) are understood, they often are not documented or protected; therefore, water availability is not reliable (Shen and Speed 2009). The precise definition and enforcement of water rights is critical to developing a water market.

There is also a legal issue still standing. Both the 2002 Water Law and the 2006 Water Permit Regulation recognize the concept of water rights, but they do not allow transferability of these rights, although they consent that the water saved through the application of new technologies be exchanged between users. The result is an unclear set of rules. In some regions of the YRB, experiments have been conducted on water rights transfers from the agriculture to the industry sector, but these experiments were driven by the local government and were not the result of free-market mechanisms (Liu and Speed 2009; Shen and Speed 2009).

5 Conclusions

The economies of nations and the welfare and food security of their people are linked through the international trade system. The 2008 crisis triggered by spikes in food prices exemplified the volatility of global food markets. The market is particularly small for grains, as only a handful of countries, including Canada and the United States, Australia, and Argentina, are net exporters (FAO 2006). As a result, even modest shifts in supply and demand can cause significant shifts in prices.

Large food-producing river basins like the YRB are major players in global food markets. As climate change unfolds, it is vital to analyze how shifts in temperatures and precipitation will impact water resources, irrigation, and food production in these river basins and how local effects may ripple through the system and affect global food security. We used the expertise of three institutions, Beijing Normal University, YRCC, and IFPRI, and their models to provide an answer to these questions in relation to the YRB.

The YRB has already been affected by drought and water shortages, as a result of climatic conditions and competition for water resources originating from the rapid socioeconomic development in the country and in the region. Our analysis reveals that in the course of this century climate change may affect the stream-flow of two regions of the Yellow River that account for approximately three-fourths of total runoff in the basin. Using these data as input, the YRCC water supply-and-demand model shows that climate change may result in annual water shortages of 9 km^3 by 2020. If considering extremely dry years, this value may increase to water deficits of 15 to 26 km^3.

IFPRI's IMPACT model also demonstrates that water availability declines in large food-producing basins such as the YRB can strongly impact international food prices as well as calorie availability in developing countries. We implement two scenarios of reduced irrigation water availability in the YRB (declines by 30percent and 50 percent), which reflect Chinese estimates of future dry-season water shortages in the YRB. We find that by 2030, under YRB irrigation water reduction of 30 percent, international wheat prices are 6percent higher, percentmaize prices are 4percent higher, and rice prices are 3percenthigher. If irrigation water availability were 50 percent lower by 2030, price increases would be even higher: by 9percent for wheat, 10percent for maize, and 6percent for rice. Furthermore, calorie availability in developing countries declines by 1.2percent and 2.2 percent under a 30 percent and 50 percent irrigation water reduction, respectively, by 2030.

To preserve economic growth and food security in the basin and to reduce potentially adverse impacts on global food markets, managers will need to tackle inefficient water use. Technological advances are important but insufficient to meet projected gaps in water supply; and megaprojects, such as the South-North Water Transfer Project, face significant obstacles for implementation in addition to unknown ecological feedbacks (particularly the western route that would relax some of the water constraints in the YRB). The focus will thus need to remain on measures to control water demand as well as on increased agricultural and crop water productivity. Although water management reforms, such as water pricing and the unified water flow regulation, were successful in bringing the YRB back from the brink after the water crisis of the late 1990s, there is still an annual water shortage estimated at 3 km^3 (World Bank 2007; Xue, Sun, and Ringler 2010). A working system of incentives is critical to support the shift toward control of demand.

Despite all the difficulties, there is reason for optimism. During the last 30 years, thanks to the increase in water productivity, China's grain production has more than doubled, while total agricultural water use has decreased by 3 percent (Jia, Lin, and Lv 2010). Grain output growth was stronger in drier regions, including in parts of the YRB.

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