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Global Water Demand and Supply Projections
Part 2. Results and Prospects to 2025

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Abstract: *This paper provides the results from the modeling framework presented by Cai and Rosegrant (2002), including projections of water demand and supply for domestic, industrial, livestock, and irrigation water use at the basin or country level in the global scope, during 1995 to 2025. Water demand is projected to grow rapidly for domestic and industrial uses, and relatively slowly for agriculture. The developing world is projected to have much higher growth in total water demand than the developed world, and about 93 percent of the additional demand will occur in developing countries. Moderate increases are projected for water supply capacity expansion, management improvement, and irrigation development. It is found that for the developing world, there will be increasing scarcity of water for irrigation, with a declining fraction of potential irrigation demand being met over time. Particularly large declines are found in dry basins that face rapid growth in domestic and industrial sectors. Variability in irrigation water supply due to climate variability tends to increase over time. Following presentation of the "best-estimate" baseline scenario, alternative scenarios are examined for changes in infrastructure investment, non-irrigation water demand growth, and groundwater pumping.*

Keywords: *Irrigation, water demand, water supply, water shortage.*

Introduction

Several overviews of global water resources have been published in recent years. These are based on global datasets, global models, and/or observed records. Margat (1995) studied the global water situation during 1990 and 2025 and developed a set of global maps indicating regional variability of various water-related characteristics. Raskin et al. (1995) examined how the water situation would look if the world would follow a "business as usual" scenario, based on the anticipated economic development measured in terms of GDP growth and its past correlation with water demands. Gleick (1993) provided comprehensive global water resources assessments including both water supply by various sources and water demand of various sectors. Seckler et al. (1998) developed scenarios of water demand and supply up to 2025, identified countries and regions that would face serious water shortage in next 25 years, and discussed potential solutions to eliminate water scarcity, including improving irrigation water use effectiveness and water supply expansion (also see Chaturevedi, 2000). Shiklomanov (2000) made a critical analysis of the present situation of the global water resources assessment, and presented the results of the assessments for the 20th century and projections for future water supply for domestic, industrial, and agricultural needs. The World Resources Institute (WRI, 2000) publishes water supply and demand data series by country, which have been updated year by year. The Economic and Social Council (ECOSOC) presented a Comprehensive Assessment of the Freshwater Resources of the World to the UN (ECOSOC, 1997). Future water scenarios were also assessed under the World Water Vision project, which had involved many international and national research and consulting agencies and institutes. Results from these scenarios were synthesized in Cosgrove and Rijsberman (2000).

This paper attempts to extend past work and presents new assessments and projections of water demand and supply of domestic, industrial, livestock, and irrigation sectors from 1995 to 2025 in 69 individual or aggregated basins in the world, based on the results from an integrated water and food model described in Cai and Rosegrant (2002, this issue). Data preparation, assumptions, and exogenous driving forces are discussed in the next section, followed by results and analysis.

Data Preparation, Assumptions, and Exogenous Driving Forces

Data Requirements and Preparation

Extensive data is required for the purpose of this paper (also see the data requirements in Cai and Rosegrant, 2002). The information is drawn from highly disparate databases in agronomy, economics, engineering, and pub-

Table 1. Input Data Classification

Category	*Items*	*Sources*
Infrastructure	Reservoir storage	ICOLD (1998)
	Withdrawal capacity	WRI(2000), Gleick (1993)
	Groundwater pumping capacity	WRI (2000)
	Water distribution, use, and recycling situation	World Water Vision (WWV) Scenario Development Panel
Hydrology	River basin delineation	Revenga et al. (1998)
	Precipitation	Climate Research Unit (CRU), University of East Anglia
	Reference Evapotranspiration	Ctr. for Envin. Sys. Res. (CESR), Kassel University
	Runoff	Ctr. for Envin. Sys. Res. (CESR), Kassel University
	Groundwater recharge	WRI (2000)
	Committed flow	Own estimation, Vorosmarty et al. (1996)
	Water pollution	World Development Indicators (2000, World Bank), Global Monitoring for Environmental Security (GMES) database
Agronomy	Crop growth stages	Rice provided by Food and Agriculture Org., wheat and maize by International Maize and Wheat Improvement Center (CIMMYT), other crops by USDA (1998).
	Crop evapotranspiration coefficients(k_c)	FAO (1998), Doorenbos and Pruitt (1977)
	Yield-water response coefficient (k_y)	Doorenbos and Kassam (1979)
Socioeconomic Factors	Domestic, industrial, and livestock water use in 1995	Shiklomanov (1999), ESCAP (1995), Solley et al. (1998).
	Population growth, GDP growth	World Development Indicators (2000, World Bank)
Water Policies	Committed flows	Own estimation
	Int. water sharing agreement	WRI(2000)
	Water demand growth and water supply expansion	Alternative scenarios, from various assessments and projections

lic policy. Table 1 shows the major data items and their sources, which are classified into five classes: water supply infrastructure, hydrology, agronomy, socioeconomic, and water policies. The data have been prepared for river basins (in China, India, and the US), countries and regions. Some data and parameters have been estimated for a 30-year time horizon, including precipitation, runoff, and evapotranspiration; others are calibrated for the base year and are then projected for the future years, including irrigated crop area, reservoir storage, water withdrawal capacity etc. As indicated in Table 1, some of the data are directly collected from other sources, some are processed based on other sources, and some are synthesized or estimated by the authors based on the available information in related literature. A geographic information system (GIS) is used to integrate these parameters with the spatial units modeled. For example, a GIS program is used to generate basin-wide parameter values originally represented in a grid format. Other data are given in smaller spatial units (for example, counties in China and USA, districts in India), and the GIS program is used to aggregate the data at the smaller scales into the basin scale.

Assumptions and Exogenous Driving Forces

Before presenting the baseline – or best estimate – projections for water supply and demand, the baseline estimates and projections of some important policy, investment, technological, and behavioral parameters that drive water demand and supply in different sectors are described in this section.

Climate and Hydrology

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. 2000). Climate scenarios are defined based on this series to assess the impact of hydrologic uncertainty. Thirty climate scenarios operate under the same other assumptions, but with various year sequences as given below:

Scenario 1: 1961, 1962... 1990
Scenario 2: 1962, 1963... 1990 1961
Scenario 3: 1963, 1964... 1990, 1961, 1962
Scenario 30: 1990, 1961 ...1988, 1989

Projected results are reported in terms of averages across the thirty scenarios, for each year between 1996 and 2025.

Water Use Efficiency - Basin Efficiency (BE)

Depending on the local conditions in the irrigation system, agronomic, technical, managerial, and institutional improvements can have large positive impacts on irrigation system water use efficiencies (Batchelor, 1999). However, improvement in river basin efficiency is more difficult, since much of water "lost" from individual irrigation systems is in the form of return flows that are reused downstream. Rapid improvement in basin efficiency would require significant commitment to water policy reform and investment – a commitment not apparent in current trends in the water sector. Under the baseline scenario, it is projected that basin efficiency will improve relatively slowly. The values of *BE* for selected countries and regions in 1995 and 2025 are shown in Table 2. In 1995, the average *BE* was assessed at 0.56 globally, 0.54 in developing countries, and 0.64 in developed countries. By 2025, the average *BE* is projected to reach 0.65 worldwide, 0.64 in developing countries and 0.71 in developed countries, representing relatively small, but important, improvements over efficiency levels in 1995. Relatively high increases in *BE* are projected for developed and developing countries in which renewable water supply infrastructure is highly developed, including India, China, and Western Asia and Northern Africa (WANA), while smaller increases are projected for areas where water supply facilities are still fairly underdeveloped, including Sub-Saharan Africa and Southeast Asia. Excluding China and India, the developing countries are projected to display slow improvements in *BE*, from 0.53 in 1995 to 0.56 in 2025. On a global basis, the improvement of water use efficiency in the baseline saves the equivalent of eight percent of global water consumptive demand in 2025 relative to what it would be if effective basin efficiency remained constant. The amount of water saved through improved *BE* is almost equal to the total irrigation water depletion in the U.S. in 1995 (124 km^3), where about 27.6 million hectares of crop land is irrigated; and is very close to the total irrigation water depletion in Central Asia and the rest of former Soviet Union in 1995, where 33.2 million hectares of crop land is irrigated.

Maximum Allowed Water Withdrawals (MAWW)

Actual water withdrawals are constrained by withdrawal capacity and environmental water use requirements, as well as by water availability. Total water withdrawal capacity in the base year is estimated based on Gleick (2000), Shiklomanov (2000), and WRI (2000). Total global water withdrawals were 3,722 km^3 in 1995, representing 7.8 percent of global renewable water resources, of which 2,796 km^3 were in developing countries and 926 km^3 were in developed countries. Surface water withdrawal in 1995 was 2,905 km^3, and groundwater pumping was 817 km^3.

Many countries and basins exploit their groundwater reserves at a rate substantially exceeding recharge, leading to the conclusion that current rates of exploitation will not be sustainable over the projection period. In future years, a slight decline in groundwater pumped is assumed for particularly over-exploited aquifers in northern India, northern China, WANA, and the western states in the U.S, corresponding to 3.0 km^3 lower pumping in these countries by 2025. Nevertheless, these regions are projected to continue overpumping, but at slightly reduced levels. Conversely, some aquifers worldwide are currently underutilized because of a lack of investment to reach the depths required to extract sufficient water; extraction from these wells on a sustainable basis could improve water supplies. Therefore, we project a gradual increase in extraction for areas with more plentiful groundwater resources. On balance, net global groundwater pumping is projected to increase gradually to 922 km^3 by 2025 (20.9 percent of total global water withdrawals), up from 817 km^3 in 1995 (21.9 percent of total water withdrawals). Despite reductions in groundwater pumping in the most severely mined regions of China and India, these two countries are projected to increase total groundwater extractions by 27 km^3 and 14 km^3, or 11 percent and 9 percent, respectively, Sub-Saharan Africa will increase extractions by 20 km^3, and other countries by 44 km^3. These assumed

Table 2: Underlying Factors Influencing Water Supply in 1995 and 2025 for Selected Countries and Regions

	Storage Increase		*SMAWW[a] Increase*		*GMAWW[b] Increase*		*Basin Efficiency*	
Countries/Regions	*(km^3)*	*Annual Rate (%)*	*(km^3)*	*Annual Rate (%)*	*(km^3)*	*Annual Rate (%)*	*1995*	*2025*
China	157	0.62	145	0.87	27	0.71	0.54	0.68
India	135	1.55	134	0.80	14	0.23	0.57	0.70
USA	0	0.00	48	0.41	3	0.09	0.72	0.78
South Asia	12	0.90	62	0.66	1	0.05	0.54	0.65
Southeast Asia	37	0.84	78	1.27	9	1.15	0.47	0.55
Sub-Saharan Africa	74	0.61	50	2.14	20	1.01	0.44	0.50
Latin America	62	0.47	87	1.15	12	0.61	0.44	0.51
WANA[c]	81	0.72	51	0.66	2	0.12	0.68	0.75
Developing World	577	0.66	635	0.88	86	0.46	0.54	0.64
Developed World	44	0.16	128	0.47	20	0.28	0.64	0.71
World	621	0.45	763	0.77	105	0.41	0.56	0.65

a: SMAWW = Surface maximum allowed maximum water withdrawal; b: GMAWW = Groundwater maximum allowed water withdrawal;
c: Western Asia and Nothern Africa..

increases of pumping are assessed based on current pumping (WRI, 2000), potential groundwater availability (WRI, 2000), and other technical and financial factors (Shah et al., 2000).

Surface and groundwater *MAWW* are projected to 2025, respectively, according to the current water withdrawal capacity, the growth of water demand, physical constraints on pumping, and projected investments in infrastructure in future years. Table 2 shows the annual growth rate of surface and ground *MAWW* between 1995 and 2025 for selected countries and regions.

Reservoir Storage

For most basins and countries, surface reservoir storage in the base year is estimated based on values from the International Committee of Large Dams (ICOLD, 1998), while ESCAP (1995) provide estimates for countries that are not members of ICOLD. Changes in reservoir storage to 2025 are based on assessments by Wallingford (2000), and on our estimates of future investments in storage. The total global reservoir storage for irrigation and water supply is estimated at 3,428 km^3 in 1995 (47 percent of total reservoir storage for all purposes), and is projected to reach 4,049 km^3 by 2025, representing a net increase of 621 km^3 over the next 25 years. Only 44 km^3 of the net storage increase will be in developed countries, with the major increases occurring in China, with a storage increase of 15.0 percent or 157 km^3; India, with an increase of 58 percent to 135 km^3; Sub-Saharan Africa, with an increase of 22 percent to 74 km^3; Asian countries excluding China and India, with an increase of 36 percent to 132 km^3; and Latin American countries, with an increase of 17 percent to 62 km^3 (Table 2).

Irrigated Area

Two concepts need to be distinguished with respect to irrigated area: potential irrigated area and actual or realized irrigated area. Potential irrigated area is the area that can be irrigated in the absence of any water supply constraints at the prevailing level of irrigation infrastructure and commodity prices. Actual irrigated area is the irrigated area harvested under the prevailing hydrological conditions in any given year. Potential and actual irrigated area by crop in 1995 is modeled based on data from FAO (1998). Developing countries rely substantially more on irrigated area than do developed countries: 38 percent of total cereal area in the developing world is irrigated, compared to 18 percent of total cereal area in the developed world. Growth rates for potential irrigated area between 1995 and 2025 are estimated based on FAO (1998) and on IFPRI's estimation of the impact of investment in irrigation infrastructure (Rosegrant et al., 2001). Actual irrigated area is a function of the potential and the availability of water. Table 3 shows the projected increase in actual irrigated harvested area and increase between 1995 and 2025. Area growth is projected to be slow, with a total increase of 19 million hectares for irrigated cereals by 2025, and total irrigated harvested area will rise from 355 million hectares in 1995 to 417 million hectares in 2025.

Population and Income Growth

Population and income growth will remain important determinants of domestic and industrial water demand, as well as agricultural water demand through the food supply and demand balances. The world population of three billion people in 1960 doubled to six billion by 1999, with population growth rates peaking at 2.1 percent annually between 1965 and 1970, and declining progressively since then to 1.4 percent annually between 1997 and 1998 (World Bank, 2001). Further declines in global population growth rates are projected, with birth rates declining in many regions, and declines in mortality rates leveling off. Population growth for selected countries and regions is shown in Table 3. GDP growth rate disparities among countries in

Table 3. Underlying Factors Influencing Water Demand: Projected Change 1995 to 2025 for Selected Countries and Regions

	Population Increase		*GDP[a] Increase*		*Irrigated Area Increase*		*Livestock Production Increase*
Countries/Regions	*(Million)*	*(%)*	*(US$ per capita)*	*(%)*	*(Million ha.)*	*(%)*	*(%)*
China	261	21.3	2,390	355	4.9	6.9	122
India	395	42.5	1,123	281	9.7	25.1	143
USA	58	21.9	24,405	93	0.7	6.4	31
South Asia	630	50.7	909	237	11.2	19.1	143
Southeast Asia	201	42.0	2,332	198	1.7	8.6	136
Sub-Saharan Africa	525	98.4	125	45	3.5	8.6	157
Latin America	212	45.0	3,942	110	2.3	25.7	87
WANA	215	66.1	1,495	88	1.9	18.4	87
Developing World	2,801	47.3	1,808	167	2.4	5.1	116
Developed World	57	4.6	17,787	98	26.0	13.5	16
World	2,138	37.9	3,562	74	28.4	11.9	56

a: GDP = gross domestic product

the developing world are projected to remain high. Growth rates will be highest in East and Southeast Asia, ranging between 3.5 and 6.0 percent per year; while lower GDP growth for Sub-Saharan Africa is projected to be between 3.2 and 3.8 percent between 1995 and 2025 (Table 3).

Committed Flow for Environmental, Ecological, and Navigational Uses

Committed flow is estimated as a portion of total renewable water, ranging from 15 percent to 50 percent, depending on availability of runoff and relative demands of these instream uses in different basins (Cai and Rosegrant, 2002). Some basins already have legislative requirements for environmental and instream flows. In the California water basin in the model, legal committed flows represent 46 percent of renewable water. In river basins that have high hydropower generation and navigation requirements, the fraction of committed flow is high. For example, the portion is estimated 48 percent for Yangtze River Basin in China and 47 percent for Brazil. In the dry areas in developing countries, the portion is limited to 15 percent to 20 percent.

Water Demand and Supply Assessments and Projections

Water demand can be defined and measured in terms of withdrawals and actual consumptive uses, also called depletion (Box 1 in Cai and Rosegrant, 2002). Water withdrawal is the most commonly estimated figure. Consumptive use or depletion best captures the actual use of water, and most of the analysis below will utilize this concept. Table 4 shows total water withdrawal and ratio of water withdrawal to total renewable water, in 1995, 2010, and 2025 for selected basins, countries, and regions.

Total global water withdrawals are projected to total 4,794 km^3 in 2025, a 23 percent increase above total withdrawals of 3,906 km^3 in 1995. The increase in projected withdrawals is much higher in developing countries, rising from 2,762 km^3 in 1995 to 3,528 km^3 in 2025, a 28 percent increase. The global projection is consistent with other recent projections to 2025, including the Alcamo et al. (1999) medium scenario of 4,580 km^3, the "business-as-usual" scenario of Seckler et al. (1999) of 4,569 km^3, and the forecast of Shiklomanov (2000) of 4,966 km^3 (not including reservoir evaporation).

The ratio of water withdrawal to total renewable water can be used as an indicator of water stress at the basin level. Total global water withdrawals in 2025 will represent approximately 10 percent of total renewable water resources, a modest increase above the 8 percent in 1995. While the ratio of total withdrawals to total resources in Australia and Oceania, South America, and Africa and North America (not including the U.S.) will be less than 5 percent between 2021 and 2025, it will range between 20 and 30 percent in the U.S., Europe, and major countries in Asia such as India and China. In median hydrologic years, the ratio is over 100 percent in some basins and countries, including the Rio Grande and Colorado River Basins in the U.S., the Haihe and inland river basins in China, river basins in northwestern India, Pakistan, and most countries in WANA. A ratio of over 100 percent implies considerable water reuse in these areas, with water withdrawals placing a high stress on environmental and ecological water demand in terms of both quantity and quality. While water stress will not be particularly excessive at the global level, a number of regions will face significantly worsening water stress over the next 25 years.

Non-Irrigation Water Demand - Consumptive Use

Table 5 shows non-irrigation water demand (consumptive use) by sector for selected basins, countries, and regions, in 1995, 2010 and 2025. Domestic water demand (including municipal and rural domestic) in the world is 169 km^3, 235 km^3, and 290 km^3 in 1995, 2010, and 2025, respectively, showing an increase of 75 percent between

Table 4. Total Water Withdrawal and Total Withdrawal as a Percentage of Total Renewable Water (%), Estimated 1995 and Projected to 2025, for Selected Countries and Regions

	Total Supply in Withdrawal			*Total Withdrawal as a Percentage of Renewable Water (%)*		
Countries/Regions	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*
China	679	771	858	26	30	33
India	674	750	813	30	33	36
USA	497	524	533	24	25	26
South Asia	1,027	1,142	1,235	24	27	29
Southeast Asia	203	242	289	4	4	5
Sub-Saharan Africa	128	166	215	2	3	4
Latin America	298	355	411	2	2	3
WANA[a]	236	263	297	69	77	87
Developed	1,144	1,232	1,274	9	9	10
Developing	2,762	3,145	3,528	8	9	10
World	3,906	4,378	4,794	8	9	10

1995 and 2025. Most of the increase (about 92 percent) is projected for developing countries, which is the result of higher population growth rate in developing countries (Table 2) and relatively rapid increase of per capita water use from the existing low levels due to income growth (see Table 3). About 97 percent of population growth will be in developing countries, and per capita water use in developing countries is projected to increase from 73 liters per day in 1995 to 102 liters per day in 2025. Developed countries as a group have only about 4.6 percent increase of population between 1995 and 2025 and a relatively small increase in per capita water use (from 132 to 145 liters per day). Per capita domestic water use is projected to decline in the developed countries with the highest per capita water demand, due to conservation and technological improvements. As a result, total domestic water demand in developed countries grows much more slowly than in developing countries, from 60 km^3 in 1995 to 70 km^3 in 2025. Domestic water demand is 8.4 percent (178 km^3) of the total in 1995. By 2025, it will be 12.3 percent (311 km^3) of the total.

Global industrial water demand is 157 km^3 in 1995, 7.2 percent of the total; by 2025, it is projected to be 236 km^3, 8.9 percent of the total. The major increase in industrial water demand (79 percent) is also in the developing countries. In 1995, industrial water depletion in the developed world (97 km^3) is much higher than that in the developing (57 km^3). However, by 2025, industrial water demand in the developing world is projected to increase to 122 km^3, over the level of the developed world (114 km^3). Intensity of industrial water use (water demand per $1,000 GDP) for selected basins, countries, and regions, in 1995, 2010, and 2025 is shown in Table 6. The industrial water use intensity will decrease significantly over the world, especially for developing countries (where initial intensity levels are very high), due to improvement in water-saving technology and demand policy in this sector. However, the increase of total industrial production still leads to an increase in total industrial water demand.

Direct water consumption by livestock is very small, but due to the rapid increase of livestock production, especially in developing countries, livestock water demand is projected to rise to 64 km^3 in 2025, 72 percent more than the 37 km^3 in 1995. While the developed world has only a 19 percent increase of livestock water demand between 1995 and 2025, from 15 km^3 to 18 km^3, livestock water demand is projected to double in the developing world, from 22 km^3 to 45 km^3. Livestock water demand is only 1.7 percent of the total water demand (depletion) in 1995. By 2025, it will be 2.6 percent of the total.

Irrigation Water Demand - Consumptive Use

The potential demand or consumptive use for irrigation water is defined as the irrigation water requirement to meet full evapotranspirative demand of all crops included in the model over the full potential irrigated area. Potential demand is thus the demand for irrigation water in the absence of any water supply constraints. Actual irrigation consumptive use is the realized water demand, given the limitations of water supply for irrigation. The proportion of potential demand that is realized in actual consumptive use is irrigation water supply reliability index (IWSR), which is defined as the ratio of water supply available for irrigation over potential demand for irrigation water. The average potential and actual irrigation water demands and the IWSR resulting from the 30 climate scenarios are shown in Table 7. Compared to other sectors, the growth of irrigation water demand is much lower, with 13.6 percent growth in potential demand between 1995 and 2025 in developing countries and a slight decline in potential demand in developed countries.

Sub-Saharan Africa is projected to have the highest percentage increase in potential irrigation water demand, from 69 km^3 in 1995 to 87 km^3 in 2025, or an increase of 28 percent; Latin America will experience the second highest, from 107 km^3 in 1995 to 129 km^3 in 2025, or an increase rate of 21 percent. Each of these regions has a high percentage increase in irrigated area from a relatively small

Table 5: Consumptive Use of Water (km^3) in the Non-irrigation Sectors, Estimated 1995 and Projected to 2025, for Selected Countries and Regions

	Domestic			*Industry*			*Livestock*			*Total Non-Irrigation*		
Countries/Regions	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*
China	30.0	48.5	59.3	13.1	24.7	31.2	3.4	5.3	7.4	46.5	78.5	97.9
India	21.0	32.2	41.0	7.2	13.8	15.8	3.3	5.3	8.2	31.5	51.3	64.9
USA	24.2	27.2	29.2	32.6	38.1	36.2	4.4	5.1	5.7	61.3	70.4	71.1
South Asia	28.0	43.3	57.7	9.1	17	20.5	5.1	7.9	12.1	42.1	68.2	90.3
Southeast Asia	13.9	21.9	30.4	11.2	15.5	20.9	1.7	2.9	4.1	26.8	40.3	55.3
Sub-Saharan Africa	9.5	15.9	23.8	0.9	1.5	2.4	1.6	2.6	4.1	12.0	20.1	30.4
Latin America	18.2	25	30.8	17.9	25.2	30.0	6.9	9.4	12.5	43.0	59.7	73.3
WANA	7.1	10.2	13.1	4.6	6.9	8.6	1.8	2.5	3.3	13.5	19.6	25.0
Developed	58.7	64.4	68.6	94.7	112.8	113.9	15.3	16.9	18.1	168.6	194.1	200.6
Developing	110.6	170.1	221.7	62.2	98.5	121.8	21.8	32.1	45.4	194.5	300.8	388.9
World	169.2	234.6	290.2	156.9	211.3	235.7	37.0	49.0	63.6	363.1	494.9	589.5

Table 6. Per Capita Domestic Water Demand and Industrial Water Use Intensity, Estimated 1995 and Projected to 2025, for Selected Countries and Regions

	Per Capita Domestic Water Demand			*Industrial Water Use Intensity*		
	(l/day/person)			*(m³ per $1000 GDP)*		
Countries/Regions	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*
China	67	97	109	16.0	12.1	6.2
India	62	79	86	19.6	16.3	7.9
USA	250	247	242	4.7	3.4	2.1
South Asia	62	77	85	19.3	16.2	8.0
Southeast Asia	82	103	126	16.3	13.4	8.7
Sub Saharan. Africa	50	59	64	6.3	6.3	5.8
Latin America	107	118	124	10.6	8.7	5.9
WANA	60	65	67	8.4	7.2	5.1
Developed	132	140	145	4.3	3.5	2.5
Developing	73	93	102	13.2	0.5	6.4
World	86	102	109	5.9	5.1	3.6

1995 level. India is projected to have by far the highest absolute growth in potential irrigation water demand, 66 km^3 (17 percent), due to relatively rapid growth in irrigated area from an already high level in 1995. WANA will have an increase rate of 18 percent (28 km^3, mainly in Turkey), and China 4 percent (12 km^3).

Water for Irrigation: Increasing Scarcity

Actual consumptive use of irrigation water worldwide is projected to grow more slowly than potential consumptive use, from 1,430 km^3 in 1995 to 1,485 km^3 in 2025, an increase of only 3.9 percent (Table 7). In developing countries, consumptive use for irrigation increases from 1,162 km^3 in 1995 to 1,214 km^3 in 2025, an increase of 4.4 percent. Therefore, it is critically important that irrigation water demand in developing countries will be increasingly supply-constrained, with a declining fraction of potential demand being met over time.

This tightening water-supply constraint is shown by the irrigation water supply reliability index (IWSR). For developing countries, the IWSR declines from 0.80 in 1995 to 0.71 in 2025 (Table 7). Relatively dry basins that face rapid growth in domestic and industrial demand, that experience slow improvement in river basin efficiency, or that have rapid expansion in potential irrigated area without adequate increase in storage or withdrawal capacity show even greater declines in water supply reliability. For example, in the Yellow River Basin in China, which mainly grows wheat and maize, the IWSR is projected to decline from 0.80 to 0.70, and in the Ganges of India, the IWSR declines from 0.83 to 0.70. China and India each experience more severe increases in water scarcity than the developing countries as a whole. In the developed world, water-scarce basins such as the Colorado and White-Red basins in the United States, also face increasing water scarcity in the future. However, the developed countries as a whole show a sharp contrast to the developing world, with irrigation water supply projected to grow faster than potential demand in the developed world, partially compensating at the global level for shortfalls in the developing world. Over the full projection period, irrigation water supply in the developed world increases by 7 .0 km^3, while the corresponding demand decreases by 5.0 km^3. Irrigation demand in the developed world as a whole declines because basin efficiency increases sufficiently to more than offset the very small increase in irrigated area. As a result, after initially declining from 0.86 to 0.84 in 2010, the IWSR improves to 0.89 in 2025 due to slowing domestic and industrial demand growth in later years (and actual declines in total domestic and industrial water use in the United States and Europe) and improved efficiency in irrigation water use. The divergence between trends in the developing and developed countries indicates that agricultural water shortages will become worse in the former even as they improve in the latter, providing a major impetus for the expansion in virtual water transfers through agricultural trade.

By 2025, basins and countries with IWSR less than 70 percent (30 percent of water shortage relative to the potential irrigation demand) will include the Haihe River Basin; the Yellow River Basin; most basins in India, including the Indus River Basin and the Ganges River Basin; Central Asia; Mexico; Argentina; Nigeria; northern Sub-Sahara Africa (SSA); eastern SSA; Egypt; other WANA; Bangladesh; Pakistan; and some southeastern Asia countries. IWSR remains above 85 percent in most developed countries and basins (the value of IWSR in Eastern Europe and Russia will increase significantly from 60 to 70 percent in 1995 to 85 percent in 2021 to 2025) because of declining water demand for domestic and industrial uses. However, even when the IWSR remains relatively high over time, irrigation is susceptible to considerable downside risk. Some basins in the U.S, including the Colorado, Rio Grande, downstream Mississippi, Missouri, Texas Gulf,

Table 7. Potential and Actual Consumptive Use of Water for Irrigation and Irrigation Water Supply Reliability, Estimated 1995 and Projected to 2025, for Selected Countries and Regions

	Potential Irrigation Consumption			*Actual Irrigation Consumption*			*Irrigation Water Supply Reliabilityindex (IWSR)*		
Countries/Regions	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*	*1995*	*2010*	*2025*
China	279.4	288.3	291.2	244	227	233	0.87	0.77	0.76
India	399.6	441.8	465.9	321	320	329	0.80	0.72	0.69
USA	132.6	133.6	130.9	124	118	120	0.93	0.88	0.90
South Asia	604.8	657.0	691.0	484	489	498	0.80	0.73	0.71
Southeast Asia	98.2	103.3	106.3	85	88	91	0.86	0.82	0.83
Sub Saharan Africa	68.5	78.2	87.3	50	55	62	0.73	0.65	0.67
Latin America	106.8	122.4	128.8	88	89	96	0.82	0.73	0.75
WANA	156.1	170.4	184.2	122	126	137	0.78	0.72	0.71
Developed	312.8	314.4	308.2	268	263	275	0.86	0.84	0.89
Developing	1,444.8	1,548.7	1,615.6	1,162	1,165	1,214	0.80	0.73	0.71
World	1,757.6	1,863.1	,1923.8	1,430	1,429	1,485	0.81	0.75	0.74

and White-Red-Arkansas River basins have IWSR as low as 60 percent in some dry years in the latter stages of the projection period, which means as much as 40 percent of irrigation water demand cannot be satisfied in those years.

River basins in northern China display different water supply trends than those in the south. The ratio of water supply to demand in northern China is projected to remain below 0.8 in most years, and will fall as low as 50 percent in some dry years. Southern China will have IWSR above 85 percent in most years, although this ratio falls as low as 50 percent in some particularly dry years.

IWSR falls as low as 30 percent to 40 percent in some basins in western and northwestern India, particularly after 2015. Dramatic drops to approximately 30 percent may occur in some dry years or years with uneven intra-year rainfall distribution in other Indian basins. For the major cereal production basin, the Ganges, IWSR is projected to decline from 83 percent in 1995 to below 0.67 by 2025.

Countries in Latin America will basically maintain their base year water supply reliability measuring 75 percent in Mexico, Brazil, Argentina, and Columbia and 85 percent in other Latin American countries – with Mexico undergoing slight declines. Countries in Sub-Saharan Africa are projected to have widely varying agricultural water supply conditions. Nigeria will have low reliability of 57 percent along with considerable downside variance; Northern SSA will undergo a slight decline from 74 percent in 1995 to 69 percent in 2025; Central and Western SSA will undergo a larger decline from 90 percent to 80 percent; and Southern and Eastern SSA will maintain an average annual reliability of 77 percent with a relatively high variance. In WANA, the year-to-year variability is relatively small, but all those countries will experience declining reliability over the projection period, from 75 percent to 69 percent in Egypt, 80 percent to 76 percent in Turkey, and 76 percent to 70 percent in other WANA countries.

Among South Asian countries, Bangladesh will experience the highest variance in water supply reliability around an average of 75 percent between 1995 and 2010, declining to 70 percent between 2010 and 2025. Pakistan and other South Asian countries (not including India) have relatively low variances, but average reliability is projected to decline from 80 percent to 70 percent in Pakistan and from 88 percent to 83 percent in other countries. All Southeast Asia countries have high water supply variability, but high reliability, with averages of between 67 and 88 percent, depending on the country and time period, with variances widening in the latter years of the projection period. In East Asia outside of China, South Korea is projected to have a high variance in annual water supply reliability and a high average of 85 percent to 95 percent. Other East Asian countries maintain an average reliability of 85 percent prior to 2010 and 80 percent subsequently.

Causes of Water Supply Constraints

Different causes lie behind water shortages in different countries. In the modeling framework, the causes of water shortages can be classified as source limits and infrastructure constraints. Source limits for irrigation water supply may come from fluctuation of natural sources (precipitation and runoff), and from increased non-irrigation water demands including domestic, industrial, and environmental water demand. Infrastructure constraints can be due to insufficient reservoir storage or withdrawal facilities. The relative importance of these factors in a specific basin can help prioritize the need for different water development policies, including infrastructure investment or investments and policy reform that enhance basin efficiency. In the model, the relative importance of these factors can be identified through the constraint equations related to each of the factors such as infrastructure capacity, environment requirement, and source balance. After the model is solved, the status of all the constraints can be examined, as well as the IWSR. If IWSR is below 0.95 and one of the corresponding constraints is contingent (reaching the lower or upper bound), then we conclude that water shortage is caused by the factor(s) with the contingent constraint(s). For example, if IWSR is 0.85, and water supply reaches the source limit, then the water shortage is caused by the source limit.

In the U.S., source limits occur in the Rio Grande and Colorado River basins in some dry years. Late in the projection period, the Missouri, Texas Gulf, and White-Red-Arkansas River basins may suffer water shortages of up to 40 percent in some dry years in order to maintain non-irrigation demands and environmental water requirements. In China, serious source shortages could occur in the Haihe River Basin, inland basins of Northwest China, the Yellow River Basin, and the Huaihe River Basin. The Huaihe River Basin and the Yellow River Basin will also have infrastructure constraints in some dry years (when water requirement from irrigation is large in order to make up for lack of rainfall) due to reaching the limits of withdrawal capacity. Although it is seemingly paradoxical that withdrawal capacity would be a constraint when water supply is low, low rainfall also increases the proportion of crop water demand that must be met from irrigation. Australia will also have source shortages in some dry years. Basins in South and Southeast China will have a dramatic drop (as much as 50 percent) in water supply in some years due to a lack of storage capacity that can deliver water to the dry season.

In India, infrastructure constraints will cause water shortages of as much as 60 to 70 percent in some basins in western and northwestern India after 2015, especially due to insufficient reservoir storage, and the same problem may occur in some basins in South and East India where internal rainfall distribution is uneven. The Ganges River basin will be constrained by storage and water withdrawal capacity in later years, particularly after 2015.

For other developed countries and regions, including Western Europe, Eastern Europe (including Russia), Australia, Oceania, and Japan, agricultural water shortages in some dry years mainly will be due to the need to meet environmental and other non-irrigation demands and water withdrawal capacity limitations.

Many Latin American countries will face water withdrawal capacity constraints, and Mexico and Argentina will require more storage for intra and inter-year regulation in later years. Outside of Egypt, the WANA countries require more storage, and Turkey is also constrained by the water withdrawal capacity limit. Egypt will have substantial source problems, particularly after 2010. All Sub-Saharan African regions and most Asian countries need more storage and/or larger withdrawal capacity to meet growing demands for water.

Variability in Irrigation Water Demand and Supply

Climate variability leads to variability and risk to irrigation water supply availability under existing and projected water supply infrastructure. As shown in the previous section, low rainfall years can lead to severe water shortages even in regions in which water is relatively plentiful in most years. Water supply variability in a specific year can be assessed based on the multiple climate runs, or through changes in year-to-year variation in supply for a single climate run. Variability in irrigation water supply tends to be higher at smaller spatial scales, because as the size of the spatial unit increases, local variability within the component spatial units of the larger spatial unit is often counterbalanced by negative covariation between the component spatial units. This tendency is shown in Figure 1, which shows the standard deviation in irrigation water supplies from the 30 different climate scenarios at three spatial scales, the Luni River Basin in India, all-India, and the world. The variability, as shown by the standard deviation in irrigation water supply, decreases as spatial scale increases. However, very importantly, variability in irrigation water supply will increase over time at all spatial scales. From 1995 to 2025, the standard deviation (variance divided by mean) of irrigation water supply increases from 4.1 percent to 5.0 percent in the world, 7.2 percent to 9.4 percent in India, and from 34.2 percent to 37.2 percent in the Luni River Basin. Figure 2 shows the increase in variability even more dramatically for the year-to-year irrigation water supply in the Ganges River Basin under the climate regime of 1961–1990. Irrigation water supply variability in Ganges – and more generally in many relatively dry basins – becomes larger in later years due to the increase in non-irrigation water demand combined with water supply constraints.

The degree and impact of irrigation water supply variability depends on climate variability, the degree of water scarcity, and the adequacy of water supply infrastructure. It is a fundamental problem that, in general, irrigation water supply variability increases precisely in those basins in which water scarcity is severe and increasing, such as river basins in the US, WANA, and northern China and India. Under these conditions, natural climate variability can cause severe shortages in irrigation water supply. On the other hand, in basins where water supply is relatively

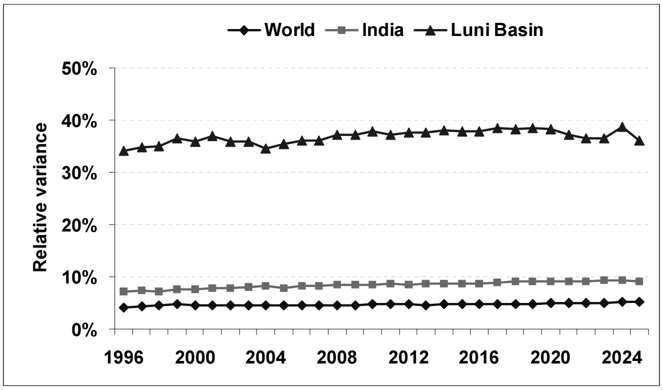

Figure 1. Coefficients of variation (ratio of standard deviation over average) of irrigation water supply for the world, India and the Luni River Basin (India).

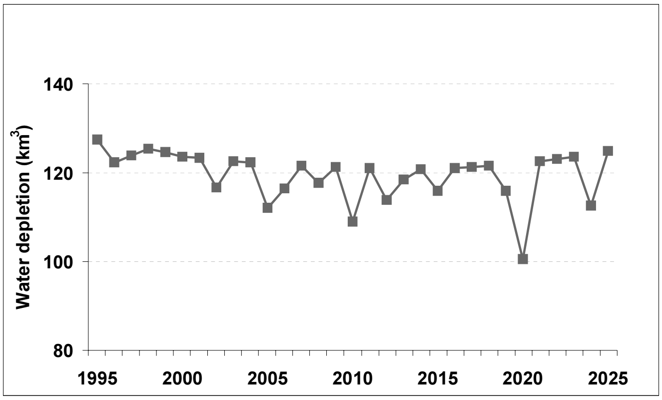

Figure 2. Irrigation water depletion (assessed in 1995; projected for 1996-2025) in Ganges River Basin in India (under the climate regime of 1961-1990).

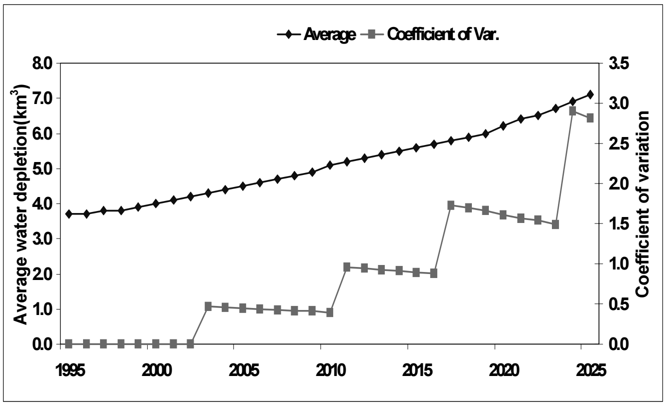

Figure 3. Coefficient of variation of irrigation water supply and the average supply in Nigeria during 1995-2025.

plentiful, the impact of climate variability may be low because inadequate water storage and withdrawal facilities are the dominant constraint on water supply even in dry years. In such basins or countries, annual climate variability barely affects agricultural water supply, although further development of water supply infrastructure will raise water supply variability along with the average supply level due to climatic variability at higher levels of water supply. This situation is typified by Nigeria, where the variability in irrigation water supply is very small until late in the projection period, when growth in both demand and supply bring source limitations into play (Figure 3).

Alternative Scenarios

The baseline scenario shows increasing scarcity of irrigation water. But deterioration in policy reform and investment in the water sector could further worsen long-term prospects for irrigation water supply. In this section alternative scenarios are compared to the baseline (BAS).

Low Growth in Investment (LINV)

This scenario explores the impact of low investment in water supply infrastructure and management. Due to global and regional environmental concerns and financial problems in some developing countries, projected levels of infrastructure investment and water management improvement may not be achieved over the projections period. This scenario assumes that any improvements in these drivers due to already committed investments and water management reforms will be offset by faster depreciation of existing infrastructure including more rapid siltation of reservoirs and that reservoir storage for irrigation and water supply, water use efficiency, and MAWW are therefore maintained at the levels prevailing in 2000.

Low Groundwater Pumping (LGW)

This scenario is applied to assess the impact of elimination of groundwater overdraft throughout the world. Many regions in the world, including northern India, northern China, some countries in WANA, and the western U.S. have experienced significant groundwater depletion due to pumping in excess of groundwater discharge. In any given aquifer, groundwater overdraft occurs when the ratio of pumping to recharge is greater than one. However, given the large macro-basins utilized in the global model and the unequal distribution of groundwater resources in these basins, there will be areas within these basins where available groundwater resources are subject to overdraft, even if the whole-basin ratio shows pumping to be less than recharge. Postel (1999), drawing upon several sources, estimates that the total annual global groundwater overdraft is 163 km^3. Utilizing this estimate of groundwater overdraft as a benchmark with our model, the threshold point at the whole-basin level at which localized groundwater overdraft occurs is set at 0.55. Under this benchmark, a number of important basins and countries experience groundwater overdraft in the base year, including the Rio Grande River Basin and the Colorado River Basin in the western U.S., where the ratio of annual groundwater pumping to recharge is greater than 0.6, the Haihe River Basin in northern China, where the ratio is 0.85; several river basins in northern and western India with ratios in excess of 0.8; Egypt, with a ratio greater than 1.0; and other WANA, with a ratio of 0.8.

The LGW scenario assumes that groundwater overdraft in those countries/regions that are currently using their water unsustainably will be phased-out over the next 25 years through a reduction in the ratio of annual groundwater pumping to recharge at the basin or country level to 0.55. Compared to levels in 1995, under the LGW scenario groundwater pumping in these countries/regions will decline by 163 km^3, including a reduction by 11 km^3 in the U.S., 30 km^3 in China, 69 km^3 in India, 29 km^3 in WANA and 24 km^3 in other countries. The projected increase in pumping for areas with more plentiful groundwater resources remains virtually the same as under the baseline scenario, and total global groundwater pumping in 2025 falls to 753 km^3, representing a significant decline from the value in 1995 of 817 km^3 and from the baseline 2025 value of 922 km^3.

High Domestic and Industrial Water Demand (HDI)

This scenario explores the possible impact of higher domestic and industrial water demand growth. Higher domestic and industrial water demands than projected under the baseline scenario could arise due to high population growth, rapid urbanization, and less effective water saving and recycling technologies, particularly in developing countries. Industrial demand is increased by reducing the rate of decline in water use intensity due to technological change (i.e. reducing the absolute value of the negative time coefficient, γ); domestic water is increased by increasing the income demand elasticity for domestic water. Compared to the baseline level of 506 km^3 in 2025, domestic and industrial water demand (depletion) under the HDI scenario is projected to reach 642 km^3, accounting for 31 percent of the available water for all demands. Under this scenario, global domestic and industrial water depletion in 2025 will be double the value in 1995, and 26 percent more than the domestic and industrial depletion under the baseline scenario in 2025.

The alternative scenarios – LINV, LGW, and HDI – reduce the availability and reliability of water supply. Under LINV, even non-irrigation water demand will not be satisfied in basins in northeast India (Chotanagapur and Brahmaputra), most countries in Sub-Saharan Africa, Columbia, and some countries in Southeast Asia. Current water storage and withdrawal capacity is low in these basins, countries, and regions, and reduced future investments are a severe constraint.

The reduction in the amount of water available for irrigation is large under these more water-stressed scenarios, with the biggest reductions in the developing countries. Figure 4 compares the irrigation water supply projections for developing countries under alternative scenarios, showing the substantial reduction in water for irrigation by 2025. Compared to the baseline scenario, the reduction of irrigation water supply in 2021/25 is 282 km^3, 97 km^3, and 82 km^3 for the developing world under LINV, HDI, and LGW, respectively (and 27 km^3, 56 km^3, and 3 km^3, for the developed world, respectively).

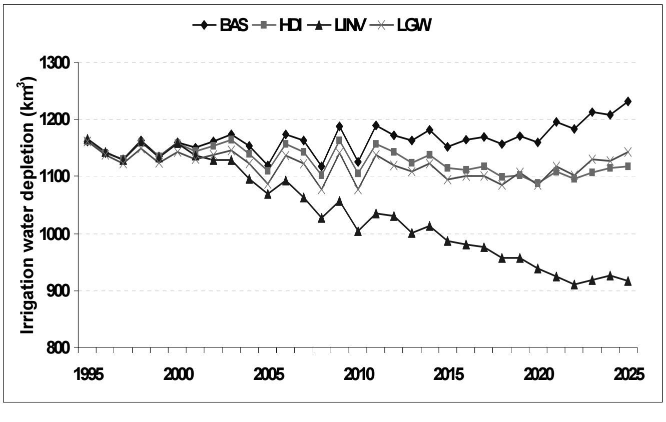

Figure 4. Irrigation water depletion for the developing world under alternative scenarios (under the climate regime of 1961–1990).

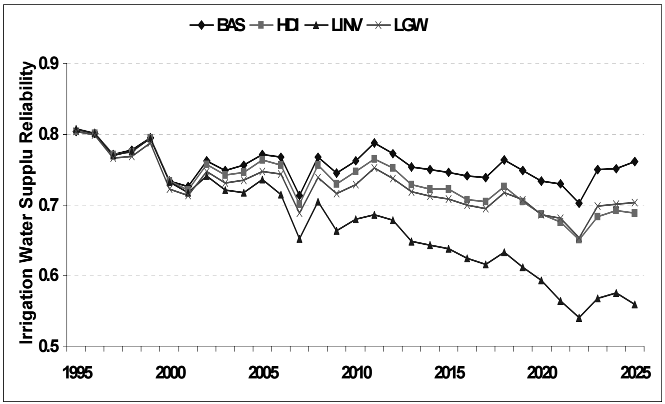

Figure 5. Irrigation water supply reliability (IWSR) for the developing world under alternative scenarios (under the climate regime of 1961–1990.

The fall in irrigation water availability under LINV results in a severe decline in IWSR in the developing world (Figure 5). Under the LINV scenario, IWSR is only 0.55 in 2025, lower than in 1995, and 0.20 below the baseline value in 2025. The LGW scenario has smaller impacts on these large regional averages than the other alternative scenarios, because the impacts are concentrated in the basins that have overdrafting of groundwater, but the impacts within the overdrafting basins are severe. In the Ganges basin, the IWSR is projected to decline on average between 2021 and 2025 from 0.71 in the baseline to 0.60 in the LGW scenario. In the Indus basin IWSR falls from 0.78 to 0.61, and within China, IWSR falls from 0.60 to 0.44 in the Haihe River Basin and 0.73 to 0.51 in the Yellow River Basin. In WANA, IWSR falls from 0.72 to 0.64.

Conclusions

Water demand is projected to grow rapidly for domestic and industrial uses and relatively slowly for agriculture. The developing world is projected to have much higher growth in total water demand than the developed world, accounting for more than 90 percent of the additional demand for water in the baseline scenario. Moderate increases are projected for water supply capacity expansion and management improvement and irrigation development. Assuming that non-irrigation water demand will receive priority over irrigation demands, actual global irrigation water consumption will increase by only 4.4 percent in developing countries, much lower than the increase in potential demand of 12 percent. As a result, a declining fraction of demand will be met over time, with irrigation water supply reliability declining from 0.79 in 1995 to 0.71 in 2025, and even greater declines in drier basins that face rapid growth in domestic and industrial sector. Moreover, variability in irrigation water supply in developing countries is projected to increase over time as non-irrigation demand increases rapidly while water supply and storage infrastructure increases relatively slowly. However, for the developed world, the increase of irrigation water supply is projected to outpace the increase of demand, due to improved efficiency in water use and continued slowdown in non-irrigation demand.

Alternative scenarios show that investments in water and irrigation management will play a critical role in determining future irrigation water supply; that non-irrigation water demand that is even higher than the baseline projection will put additional stress on irrigation water supply; and that phasing groundwater overdraft out will have large impacts on irrigation water supply in those regions with significant overdraft of groundwater. But even the baseline scenario shows that the pressure on water supplies in much of the world will likely increase significantly in the coming decades.

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