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Global Water Resources: Vulnerability from Climate Change and Population Growth

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The future adequacy of freshwater resources is difficult to assess, owing to a complex and rapidly changing geography of water supply and use. Numerical experiments combining climate model outputs, water budgets, and socioeconomic information along digitized river networks demonstrate that (i) a large proportion of the world's population is currently experiencing water stress and (ii) rising water demands greatly outweigh greenhouse warming in defining the state of global water systems to 2025. Consideration of direct human impacts on global water supply remains a poorly articulated but potentially important facet of the larger global change question.

Greenhouse warming continues to dominate the world's science and policy agenda on global change. One fundamental concern is the impact of this climate change on water supply (*1, 2*). The question of how human society directly influences the state of the terrestrial water cycle has received much less attention, despite the presence of the socioeconomic equivalent of the Mauna Loa curve, namely, rapid population growth and economic development. Our goal in this report is to identify the contributions of climate change, human development, and their combination to the future state of global water resources.

Assessments of water vulnerability traditionally have been cast at the country or regional scale (*2–5*). Although recent work has focused on individual drainage basins and subbasins (*1, 6, 7*), to the best of our knowledge, no global-scale study has articulated the geographic linkage of water supply to water demand defined by runoff and its passage through river networks. We present a high-resolution geography of water use and availability, analyzing the vulnerability of water resource infrastructure (*8*) to future climate change, population growth and migration, and industrial development between 1985 and 2025. We consider explicitly how the topology of river systems determines the character of sustainable water supply and its use by humans.

Mean annual surface and subsurface (shallow aquifer) runoff, accumulated as river discharge (*Q*), is assumed to constitute the sustainable water supply to which local human populations have access (*9*). We mapped the distribution of population with respect to relative water demand (RWD) defined as the ratio of water withdrawal or water use to discharge. We consider the domestic and industrial sectors (DI/*Q*), irrigated agriculture (A/*Q*), and their combination (DIA/*Q*) on a mean annual basis. Each ratio determines the degree to which humans interact with sustainable water supply and provides a local index of water stress. Values on the order of 0.2 to 0.4 indicate medium to high stress, whereas those greater than 0.4 reflect conditions of severe water limitation (*10*). We also constructed a water reuse index (ΣDIA/*Q*), defined as the ratio of aggregate upstream water use relative to discharge. We consider vulnerability with respect to sustainable water resources only. We make no explicit tabulation of nonsustainable supplies or withdrawals, such as the mining of groundwater, although we can draw inferences about such activities by analyzing RWD. We do not explicitly model human adaptation to climate change or development pressure, but we do incorporate estimates of future water use efficiency offered in other studies.

A recent version of the Water Balance Model (WBM) (*11*) was used to compute contemporary and future runoff at 30′ grid resolution (latitude by longitude). Runoff fields were constrained by monitoring data, and converted to discharge by integrating along digitized rivers (*12, 13*). Climate change fields were from the Canadian Climate Center general circulation model CGCM1 and Hadley Center circulation model HadCM2 used in the current Intergovernmental Panel on Climate Change (IPCC) assessment (*14*). Global means for contemporary (1961–90) runoff and river discharge were computed by the WBM using off-line atmospheric forcings from HadCM2 and CGCM1. Predictions were in substantial agreement with runoff fields based on observed discharge (*13, 15*). Results from HadCM2/WBM and CGCM1/WBM were used to predict incremental differences between contemporary and future runoff and discharge for individual grid cells. These differences were then applied to a baseline (*13*) to generate the future patterns of runoff (*16*). Mean global runoff varied in response to climate change from an increase of <1 mm year^{-1} (HadCM2/WBM) to a decrease of 17 mm year^{-1} (CGCM1/WBM) (*17*). With each runoff field, more substantial changes could be found at local and regional scales. CGCM1/WBM gave the strongest climate change signal, and we use it to exemplify key findings derived from both models.

Domestic and industrial water demand was determined by population and per capita use statistics. The geography of contemporary urban and rural population was developed from a 1-km data set (*18*). Future population distribution was determined from projections of the percent change in total, rural, and urban population from 1985 to 2025 (*19*) applied to the 1-km urban and rural population maps. Country-level water withdrawal statistics (*19*) were used to estimate contemporary water demands, but they first required standardization and spatial disaggregation (*20*). The geography of agricultural water demand was computed from irrigated land area and national use statistics (*21*). Future demands for all sectors were based on population growth, economic development, and projected changes in water use efficiency (*22*). Water withdrawals at 30′ resolution were geographically linked to digital river networks and corresponding discharge estimates.

The contemporary condition is represented by 1985, the year that is most compatible with the time span represented by the runoff climatology and historical water use statistics. Against this benchmark we formulated three scenarios to quantify the contributions of climate change and development pressure to the degree of relative water demand in 2025. The first scenario (Sc1) varied climate but fixed the magnitude and spatial distribution of human population and water withdrawals at 1985 levels. Sc2 applied projected water demands for 2025 but used runoff and discharge based on contemporary climate. Sc3 changed both climate and water demand. Total water use per capita is projected to decrease from 640 to 580 m^3 year^{-1} between 1985 and 2025. The impacts of human development under Sc2 and Sc3 will therefore generally reflect population growth and migration as opposed to intensification of water use, though results will be location specific. In relation to (*5*), our calculation of global water use in 2025 is conservative, 4700 km^3 year^{-1} compared to 5200 km^3 year^{-1}.

We compared our calculations to country-level data typically applied in global water assessments. Our national-scale aggregates of gridded DIA/*Q* and a recent global assessment by the United Nations (*10*) place almost the same fraction of the world's 1995 population under similar levels of water stress (Table 1). In both studies, one-third of the total population of

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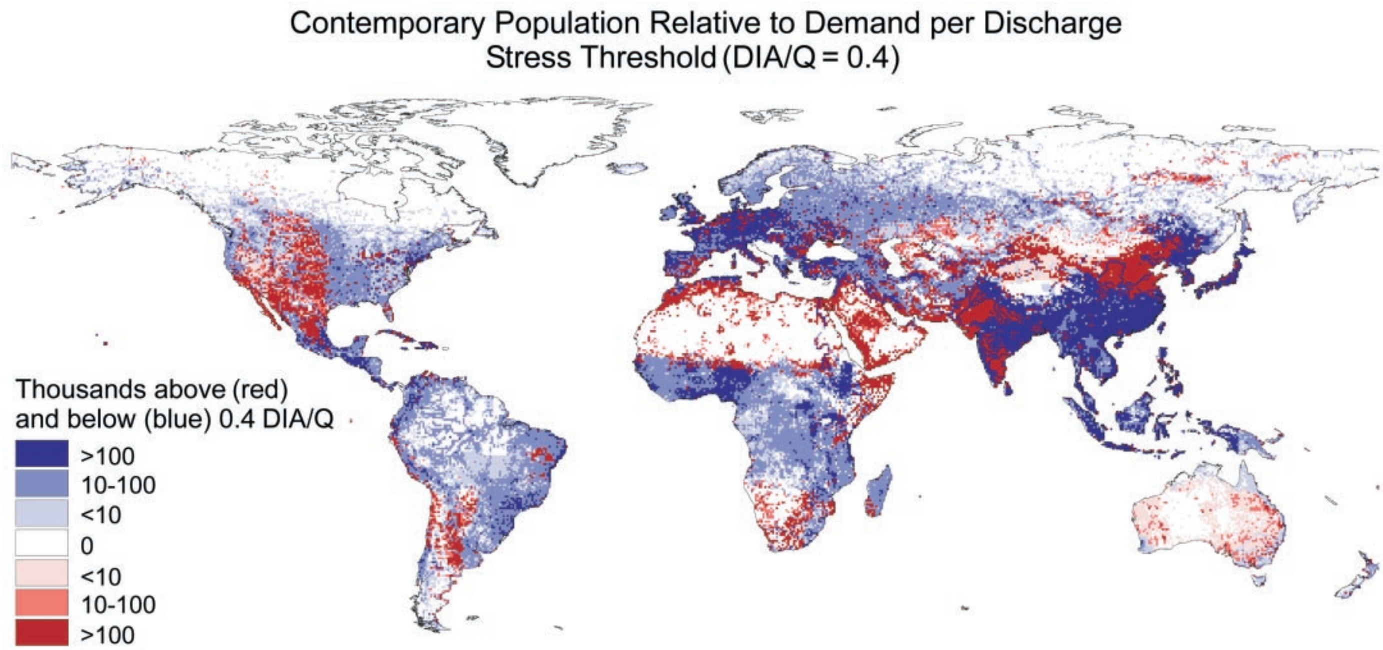

Fig. 1. The global distribution of population in 1985 with respect to the relative water stress threshold of DIA/Q = 0.4 indicating severe water scarcity (*10*). A 30′ spatial resolution is used. This mapping reflects a mean global runoff of ~40,000 km^3 year^{-1} and aggregate water withdrawals of 3100 km^3 year^{-1}. These estimates are highly dependent on contemporary water use statistics, which reflect a degree of uncertainty. Recent reviews (*5, 36*) show year 2000 global water withdrawals from assessments made even as late as 1987 to vary by >1300 km^3 year^{-1}. National-level water use statistics (*18*) for some countries are decades old. Runoff estimates for some regions may also be biased (*9,13*). Results should be viewed with appropriate caution.

Table 1. Contemporary world population living under progressive levels of relative total water demand (DIA/Q). The thresholds and definitions of water stress are as defined by the United Nations (UN) (*10*). Results shown here contrast national-level summaries (~10^2 entries) against grid-based tabulations (~10^4 to 10^5 entries). Indices given are for 1995.

Water stress	DIA/Q (unitless)	Total population (billions)		
		Country-level		Grid-based
		UN	This study*	This study
Low	<0.1	1.72	1.95	3.16
Moderate	0.1 to 0.2	2.08	1.73	0.38
Medium-high	0.2 to 0.4	1.44	1.54	0.37
High	>0.4	0.46	0.45	1.76

*Total water demand, runoff, and population at 30′ grid spatial resolution were each summed to the national scale, and corresponding aggregates were then computed.

Table 2. Cumulative distribution of worldwide population with respect to ranked values of relative water demand for domestic and industrial sectors (DI/Q) generated by the CGCM1/WBM model. Each entry represents the population at or exceeding the indicated DIA/Q level from 30′ resolution data.

DI/Q (unitless)	Cumulative population (billions)			
	Contemporary	Sc1	Sc2	Sc3
1.0	0.9	0.8	1.9	1.6
0.4	1.2	1.0	2.4	2.2
0.2	1.4	1.3	2.8	2.7
0.1	1.7	1.6	3.2	3.2
0.01	2.9	2.9	5.4	5.4
0.001	4.1	4.1	7.0	7.0
0.000	4.8	4.8	8.0	8.0

5.7 billion lives under conditions of relative water scarcity (DIA/Q > 0.2), and ~450 million people are under severe water stress (DIA/Q > 0.4). A summary based on individual grid cells (Table 1) shows that a much larger population (an additional 1.3 billion) now lives under a high degree of water stress that national-level totals, especially for large countries, fail to articulate. Use of 30′ grids (n = 59,132) captures much more of the spatial heterogeneity in water use, discharge, and RWD (Fig. 1). Water stress transcends national boundaries and is apparent today across arid and semiarid regions as well as in many densely populated parts of the humid tropics and temperate zone.

We find that the primary determinants of changing levels of RWD, and hence vulnerability to water stress, through the early part of this century will be the growth and economic development of human population. We base this conclusion on contrasts between the cumulative distributions of global population, ranked by DI/Q and A/Q, for each of the scenarios tested (Table 2). Under CGCM1/WBM, we see almost no difference between cumulative population distributions represented by the contemporary baseline and by climate change scenario Sc1. In contrast, Sc2 shows a large effect from human development with substantial increases over 1985 in accumulated population for all levels of DI/Q. The additional climatic effects represented by Sc3 fail to elicit a substantial departure from the Sc2 distribution. Although more people are predicted in 2025 to be living in relatively water-rich areas, under Sc3 the highly vulnerable population with DI/Q > 0.4 increases to >2 billion, an 85% increase in relation to the vulnerable population in 1985. This condition is determined almost exclusively by population and development pressure.

For agriculture, overall results are similar (Table 3). The population distribution here refers to the number of people dependent on irrigated water withdrawals (*21*), and changes in either remote demand or local available discharge influence A/Q under contrasting scenarios. The effect of Sc1 produces little change from 1985, and the aggregate impact of increasing water demands under Sc2 and Sc3 is apparent. For 1985, we estimate that almost 2 billion people are dependent on irrigated lands with A/Q values of >0.4. For 2025, under Sc3 this number rises to >3 billion. Irrigation thus supports 40% of the population in 1985 (and will potentially support the same percentage in 2025) on cropland with A/Q values of >0.4, suggesting a substantial nonsustainable water use and major global vulnerability, even under present-day conditions.

Our findings are further supported by calculations expressed as continental- and global-scale totals (Table 4). For the globe, climate change under Sc1 increased DIA/Q values by <5%. In contrast, rising water demands alone (Sc2) increased DIA/Q by 50%, whereas Sc3 combining both climate and development effects produced relative increases of 60%. Over individual continents, climate-induced changes in DIA/Q varied from a 4% decrease to a 12% increase, which were in all cases much smaller than changes corresponding to population and economic growth.

Continental- and global-scale summaries mask potentially important regional patterns of water abundance and scarcity. We accumulated water demand and water supply and calculated ΣDIA/Q along main-stem rivers to establish an aggregate imprint of water use intensity and competition across watersheds. Even rivers in close proximity show distinct patterns of ΣDIA/Q and of sensitivity to future changes in climate and water demand (Fig. 2). The Chang Jiang River (China) follows a pattern of sensitivity under which both climate change and population pressures increase the water reuse index along virtually the entire main stem. Under Sc3, we see a severalfold increase in ΣDIA/Q over contemporary conditions, an impact determined in large measure by climate change. The neighboring Yellow River also displays a progressive intensification of ΣDIA/Q in the downstream direction but with an aggregate use of water well in excess of the entire basin's discharge, even for the baseline condition. Future development pressure (Sc2) exacerbates the situation, whereas climate change has an apparent beneficial effect by lowering values of ΣDIA/Q over the entire main stem, thereby counteracting the increases associated with future population growth. As a result, future ΣDIA/Q values are lowered substantially. Despite the projected improvement, there is likely to be a sustained and severe pressure on water supplies in this basin. Contemporary conditions along this river are already more severe than indicated, because of rapid increases in water use and decreases in discharge into the 1990s (*23*), which are not reflected by the 1985 benchmark.

When results are examined at the grid-cell level, an even richer set of responses emerges. The increase or decrease in ΣDIA/Q for each scenario in relation to conditions in 1985 was used to develop a geography of changing relative water demand (Fig. 3). Climate change alone (Sc1) produces a mixture of responses, both positive and negative, that is highly region

Table 3. Same as Table 2, except showing the cumulative distribution of worldwide population that is dependent on contemporary water use for irrigated agriculture at different levels of relative demand (A/Q). Dependent populations were linked to irrigation water demands within individual countries; table entries are derived from gridded 30′ data.

A/Q (unitless)	Cumulative dependent population (billions)			
	Contemporary	Sc1	Sc2	Sc3
1.0	1.5	1.4	2.7	2.7
0.4	1.9	1.8	3.4	3.3
0.2	2.2	2.1	4.0	3.9
0.1	2.6	2.5	4.7	4.7
0.01	3.8	3.8	6.7	6.6
0.001	4.5	4.5	7.6	7.6
0.000	4.8	4.8	8.0	8.0

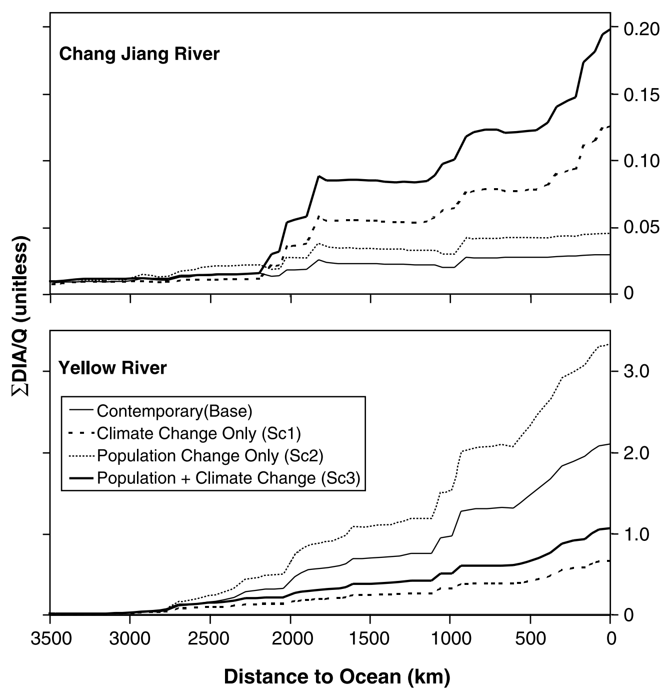

Fig. 2. The imprint of accumulated relative water demand from all sectors (ΣDIA/Q) plotted as a function of downstream distance along two major rivers in eastern Asia. The contemporary setting is contrasted against the three scenarios of potential conditions in 2025 simulated by CGCM1/WBM. Trajectories are unique for individual main-stem rivers and involve a complex interplay between the geography of river discharge and water use. An increase in this index along the downstream direction accompanies an increase in accumulated water demand, a decrease in discharge, or both, whereas a lowering of the curve reflects dilution from local runoff or less impacted tributaries. ΣDIA/Q is an index of water competition and reuse as well as a surrogate for potential water quality problems.

Table 4. Continental and global summaries for population, irrigable land, sustainable water supply defined as discharge (Q), and relative all-sector water demand (DIA/Q) tabulated for the contemporary condition and simulated by CGCM1/WBM. Percentages assigned to the change in DIA/Q (ΔDIA/Q) are relative to the 1985 contemporary baseline.

Area	Population (millions)		Irrigated cropland (1000 km^2)	Observed Q (km^3 year^{-1})	Contemporary DIA/Q (unitless)	2025 Q (km^3 year^{-1})	Predicted ΔDIA/Q (%)		
	1985	2025					Sc1	Sc2	Sc3
Africa	543	1440	118	4,520	0.032	4,100	10	73	92
Asia	2930	4800	1690	13,700	0.129	13,300	2.3	60	66
Australia/Oceania	22	33	26	714	0.025	692	2.0	30	44
Europe	667	682	273	2,770	0.154	2,790	−1.9	30	31
North America	395	601	317	5,890	0.105	5,870	−4.4	23	28
South America	267	454	95	11,700	0.009	10,400	12	93	121
Globe	4830	8010	2520	39,300	0.078	37,100	4.1	50	61

specific. Expanded water use by itself (Sc2) increases relative ΣDIA/*Q* for broad regions of the globe, although small clusters of grid cells showing relative decreases appear in areas of rural-to-urban migration, as in Russia. The large continental areas with elevated ΣDIA/*Q* values under Sc3 reflect well the patterns of increase associated with Sc2. Interactions between population growth and climate change result in some notable net decreases in ΣDIA/*Q*, which are large enough to reverse the relative water scarcity suggested by Sc2, as in Mexico and much of central Asia. The overall pattern, however, is one of pandemic increase.

The major increases in relative water demand documented here reveal that much of the world will face substantial challenges to water infrastructure and associated water services. Potentially large economic costs are likely to be associated with the implementation of response strategies (e.g., expansion of facilities, new water-pricing policies, innovative technology, and mismanagement) or the consequences of inaction (e.g., deterioration of water quality and reduction in irrigated crop yields) (*24, 25*). Where sustainable water supplies are at a premium, the challenges also include curtailment of economic activities, abandonment of existing water facilities, mass migration, and conflict in international river basins (*25–27*).

Many parts of the developing world will experience large increases in relative water demand. In water-rich areas such as the wet tropics, the challenge will not be in providing adequate quantities of water, but in providing clean supplies that minimize public health problems (*28*). Arid and semiarid regions face the additional challenge of absolute water scarcity. Projected increases in scarcity will be focused on rapidly expanding cities. Much of the world's population growth over the next few decades will occur in urban areas, which are projected to double in size to near 5 billion between 1995 and 2025 (*29*) and face major challenges in coping with increased water pollution and incidence of waterborne disease (*5, 10, 19, 25, 29*).

We conclude that impending global-scale changes in population and economic development over the next 25 years will dictate the future relation between water supply and demand to a much greater degree than will changes in mean climate. To secure a more complete picture of future water vulnerabilities, it will be necessary to consider interactions among climate change and variability, land surface and groundwater hydrology, water engineering, and human systems, including societal adaptations to water scarcity [see (*30, 31*)]. Pursuit of this question will be limited by outdated and nonexistent socioeconomic data and information from a progressively deteriorating global network of hydrometric monitoring stations (*32*) unless a vigorous commitment is made by the water sciences community to collect, standardize, and widely disseminate such information. In light of our findings, an integrated approach bringing together the climate change, water resources, and socioeconomic communities appears essential to future progress.

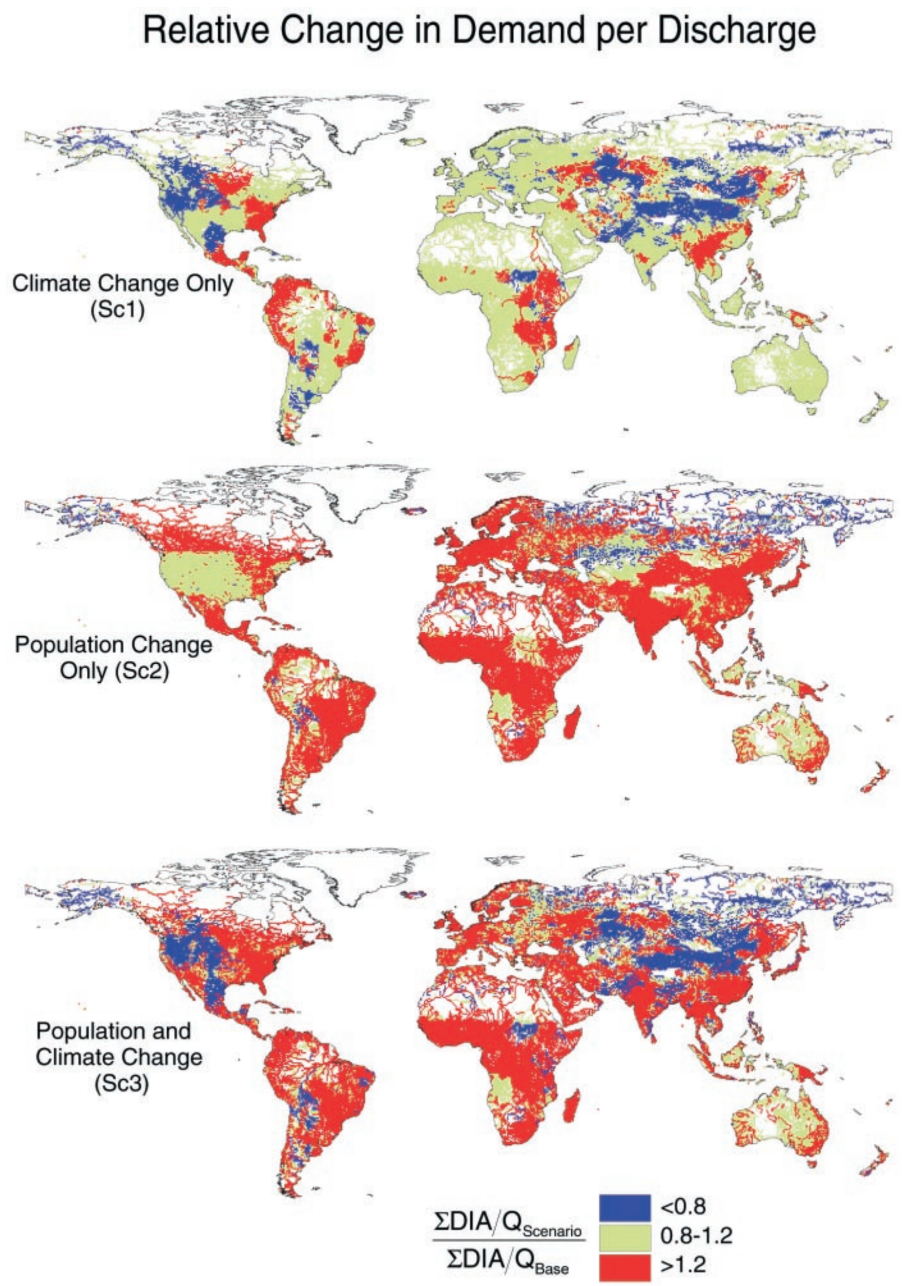

Fig. 3. Maps of the change in water reuse index (ΣDIA/*Q*) predicted by the CGCM1/WBM model configuration under Sc1 (climate change alone), Sc2 (population and economic development only), and Sc3 (both effects). Changes in the ratio of scenario-specific ΣDIA/*Q* ($\Sigma DIA/Q_{Scenario}$) relative to contemporary ($\Sigma DIA/Q_{Base}$) conditions are shown. A threshold of ±20% is used to highlight areas of substantial change.

References and Notes

1. N. Arnell *et al.*, in *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change*, R. T. Watson *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1996), pp. 325–363.
2. Z. Kaczmarek *et al.*, in *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change*, R. T. Watson *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1996), pp. 469–486.
3. M. Falkenmark, *Water Int.* **16**, 229 (1991).
4. M. I. L'vovich and G. F. White, in *The Earth as Transformed by Human Action*, B. L. Turner *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1990), pp. 235–252.
5. I. Shiklomanov, Ed., *Assessment of Water Resources and Water Availability in the World: Scientific and Technical Report* (State Hydrological Institute, St. Petersburg, Russia, 1996).
6. J. Alcamo *et al.*, in *World Water Scenarios: Analyses*, F. R. Rijsberman, Ed. (Earthscan, London, 2000), pp. 204–242.
7. J. C. van Dam, Ed., *Impacts of Climate Change and Climate Variability on Hydrological Regimes* (Cambridge Univ. Press, Cambridge, 1999).

8. "Water resource infrastructure" refers to water source, distribution, and treatment systems. We assume that wherever there is a resident human population or irrigated cropland, there will be a corresponding water infrastructure. Changes in water demand due to population growth and industrialization or in water supply due to climate change will define the vulnerability of water infrastructure and the human population that is dependent on these systems.
9. S. L. Postel *et al.*, *Science* **271**, 785 (1996).
10. United Nations, *Comprehensive Assessment of the Freshwater Resources of the World* (overview document) (World Meteorological Organization, Geneva, 1997).
11. C. J. Vörösmarty, C. A. Federer, A. Schloss, *J. Hydrol.* **207**, 147 (1998).
12. C. J. Vörösmarty, B. Fekete, M. Meybeck, R. Lammers, *Global Biogeochem. Cycles* **14**, 599 (2000).
13. B. M. Fekete *et al.*, *Global, Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances*, *Report 22* (World Meteorological Organization–Global Runoff Data Center, Koblenz, Germany, 1999).
14. Data are from the IPCC Data Distribution Centre, Deutsches Klimarechenzentrum (Max-Planck-Institut) in Hamburg, Germany, and the Climatic Research Unit at the University of East Anglia in Norwich, UK. CGCM1GSa1 and HadCM2GSa1 (GSa, ensemble of greenhouse gas plus sulfate aerosol integrations) scenarios were obtained from http://ipcc-ddc.cru.uea.ac.uk/cru_data/datadownload/download_index.html. Scenarios represent a 1% per year increase in CO_2-equivalent forcing and sulfate aerosol dampening. Original data at 3.75° by 3.75° (latitude by longitude) for CGCM1 and at 2.5° by 3.75° for HadCM2 were bilinearly interpolated to 30′ resolution. Monthly forcings were applied to the WBM, and a statistically equivalent daily time step was used to integrate over time and compute water budget variables, including runoff.
15. Simulated water budgets combined with discharge data from several hundred recording stations in (*13*) yielded a mean global runoff of 300 mm year^{-1} or a discharge of 39,300 km^3 year^{-1}; CGCM1/WBM computed respective values of 319 mm year^{-1} and 41,900 km^3 year^{-1}, whereas HadCM2/WBM gave 302 mm year^{-1} and 39,600 km^3 year^{-1}, respectively.
16. The approach taken is that used in climate impact studies on net primary production by VEMAP Members [*Global Biogeochem. Cycles* **9**, 407 (1995)].
17. The values are statistically significant ($P < 1 \times 10^{-6}$) with the Wilcoxon sign test.
18. A 1-km gridded polygon file [*Arc World Supplement*, 1:3 M scale digital map (ESRI, Redlands, CA, 1995)] defined the spatial extent of 242 countries for which country-level population statistics were available (*19*). We defined urban spatial extents as a set of geographically referenced city polygons with demographic data (n = 1858) (*33*) and distributed the remaining country-level urban population evenly across 1-km pixels classified as city lights from remote sensing (*34*). Lacking digital data to the contrary, we distributed rural population uniformly among digitized points representing populated places [*Digital Chart of the World*, 1:1 M scale digital map (ESRI, Redlands, CA, 1993)] falling outside of urban spatial extents. A total of 155 countries simultaneously showed water demand data and discharges greater than zero and fell within our 30′ digitized land mass. The remaining 87 countries were mostly small islands and were not considered. For the contemporary setting, we account for 99.7% of the global population (*19*); 98.4% of the total is assigned water use statistics.
19. *World Resources: A Guide to the Global Environment 1998–99* (World Resources Institute, Washington, DC, 1998).
20. National and sectoral water use statistics were from (*19*). The mean reporting year was 1986, but the range was from 1970 to 1995. National statistics were normalized to year 1985 by applying usage trends recorded in corresponding regional time series (*5*). Domestic water demand was computed on a per capita basis for each country and distributed geographically with respect to the 1-km total population field. Industrial usage was applied in proportion to urban population. Grid-based aggregates at 30′ resolution were then determined for domestic plus industrial water demand.
21. Country-level totals for agricultural water demand were distributed onto 30′ grid cells on the basis of the fraction of each grid cell classified as irrigated land from (*35*) and prorated on the basis of the ratio of unrealized potential evapotranspiration (i.e., the potential minus the estimated actual) to the potential from (*13*). Irrigation-dependent population was determined by proportionally assigning national-level population to the corresponding irrigated areas in each country. We reason that entire national populations (and not simply local farmers and agribusiness) benefit from the food and fiber (destined for domestic or export markets) and income produced from irrigated land. A/Q uses mean annual discharge. These relative water demand estimates are thus conservative and assume highly effective storage of surface water for irrigation, such as through reservoir impoundment. We consider irrigated agriculture because it is a major component of water resource infrastructure that is subject to changes in the availability of net runoff. Rain-fed agriculture falls outside this definition, and we have not treated it here.
22. Rates of increase in water demand to 2025 from regional estimates (*5*) were applied to the 1985 water withdrawal data set. Future changes in population and urban-to-rural ratios (*19*) were used to shift the geography of water demands. The distribution of irrigable lands was fixed to that observed under contemporary conditions. Projected water withdrawals in (*5*) are dependent on water use efficiencies that both increase and decrease for different parts of the world. These estimates were made through extensive consultation of country-level studies and trend analysis based on per unit agricultural, municipal, and industrial water withdrawals; assumptions regarding future technology adoption; and economic capacity to institute efficiency changes.
23. J. Milliman and R. Mei-e, in *Climate Change: Impact on Coastal Habitation*, D. Eisma, Ed. (CRC Press, Boca Raton, FL, 1995), pp. 57–83.
24. S. Postel, *Interciencia* **10**, 290 (1985).
25. P. Gleick, *The World's Water: The Biennial Report on Freshwater Resources (1998–99)* (Island, Washington, DC, 1998).
26. T. Homer-Dixon, *Int. Secur.* **19**, 5 (1994).
27. M. Falkenmark and J. Rockström, *Ambio* **22**, 427 (1993).
28. M. Bonell *et al.*, *Hydrology and Water Management in the Humid Tropics* (Cambridge Univ. Press, Cambridge, 1993).
29. *World Resources: A Guide to the Global Environment 1996–97* (World Resources Institute, Washington, DC, 1996).
30. D. Conway *et al.*, *Ambio* **25**, 336 (1996).
31. K. M. Strzepek *et al*, in *World Water Scenarios: Analyses*, F. R. Rijsberman, Ed. (Earthscan, London, 2000), pp. 120–159.
32. J. C. Rodda, in *Water: A Looming Crisis* (International Hydrological Program, United Nations Educational, Scientific, and Cultural Organization, Paris, 1998).
33. W. Tobler *et al.*, *The Global Demography Project*, *Technical Report TR-95-6* (National Center for Geographic Information and Analysis, Santa Barbara, CA, 1995).
34. C. Elvidge *et al.*, *Int. J. Remote Sens.* **18**, 1373 (1997).
35. P. Döll and S. Siebert, *A Digital Global Map of Irrigated Areas, Report A9901* (University of Kassel, Kassel, Germany, 1999).
36. P. Gleick, in *World Water Scenarios: Analyses*, F. R. Rijsberman, Ed. (Earthscan, London, 2000), pp. 27–37.
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Overpressure and Fluid Flow in the New Jersey Continental Slope: Implications for Slope Failure and Cold Seeps

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Miocene through Pleistocene sediments on the New Jersey continental slope (Ocean Drilling Program Site 1073) are undercompacted (porosity between 40 and 65%) to 640 meters below the sea floor, and this is interpreted to record fluid pressures that reach 95% of the lithostatic stress. A two-dimensional model, where rapid Pleistocene sedimentation loads permeable sandy silt of Miocene age, successfully predicts the observed pressures. The model describes how lateral pressure equilibration in permeable beds produces fluid pressures that approach the lithostatic stress where overburden is thin. This transfer of pressure may cause slope failure and drive cold seeps on passive margins around the world.

Rapid sediment loading (>1 mm year^{-1}) is documented as a source of overpressure (P^*, pressure in excess of hydrostatic) in basins around the world (*1*, *2*). A suite of models describe how overpressure is generated during rapid deposition (*3–6*). These models quantify the rock properties and sedimentation rates required to generate and maintain overpressure. Mass and volume measurements of wet and dry core samples provide porosity data (*7*) that we use to document overpressures on the New

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REVIEW

Global Hydrological Cycles and World Water Resources

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Water is a naturally circulating resource that is constantly recharged. Therefore, even though the stocks of water in natural and artificial reservoirs are helpful to increase the available water resources for human society, the flow of water should be the main focus in water resources assessments. The climate system puts an upper limit on the circulation rate of available renewable freshwater resources (RFWR). Although current global withdrawals are well below the upper limit, more than two billion people live in highly water-stressed areas because of the uneven distribution of RFWR in time and space. Climate change is expected to accelerate water cycles and thereby increase the available RFWR. This would slow down the increase of people living under water stress; however, changes in seasonal patterns and increasing probability of extreme events may offset this effect. Reducing current vulnerability will be the first step to prepare for such anticipated changes.

All organisms, including humans, require water for their survival. Therefore, ensuring that adequate supplies of water are available is essential for human well-being. Although our planet is often called the "Blue Planet," warnings of increasing water scarcity in the world are common. However, unlike oil, water circulates, forming closed hydrologic cycles. The amount of water will not diminish on shorter than geological time scales (*1*). Given this background, how could water scarcity become a widespread reality within a few decades (*2*)?

A common explanation is that even though there is a lot of water on Earth, only about 2.5% is fresh water, and because most of that water is stored as glaciers or deep groundwater, only a small amount of water is easily accessible. This answer is only partly correct: Rather than looking only at the stocks of water resources, assessments should concentrate mainly on the flows (Fig. 1) (*1*, *3*–*5*). The amount of water stored in all the rivers in the world is only 2000 km^3, much less than the annual water withdrawal of 3800 km^3/year (Fig. 1). Clearly, a more adequate measure of water availability is the 45,500 km^3/year of annual discharge, which flows mainly through the rivers from continents to the sea.

What Is the Meaning of a Circulating Resource?

Unlike most other natural resources, water circulates naturally. When it evaporates, it changes from liquid to gas and eventually recondenses as a liquid. Water assimilated during photosynthesis becomes part of carbohydrates stored in plants, but ultimately reverts to water again by decomposition.

When used, water loses properties such as purity, heat content, and potential gravitational energy, but eventually, most degraded water resources are refreshed by natural processes in the hydrological cycle, which is mostly driven by solar energy. When considering water flux as the most relevant measure of water resources, the speed of water circulation becomes crucial. Mean residence times of water molecules—i.e., how long they stay in a given reservoir—can be estimated by dividing the volume of the reservoir by the mean flux into and out of it. For rivers unaffected by human interventions, the mean residential time of water is about two and a half weeks (*1*). In contrast, the recharge rate of some groundwater aquifers is very slow, and the mean residential time is considered to be hundreds or even thousands of years. When water is extracted from such an aquifer, it will take a very long time, measured on a human time scale, to return to the original volume stored; in practice, that water is exhausted once it has been used. Because it took so long to accumulate, the groundwater in such aquifers is sometimes called fossil water.

How Much Renewable Fresh Water Is Available?

Can human demand for water be fully met by using only circulating renewable freshwater resources (RFWR)? The answer is both yes and no. Even though RFWR is naturally recycled, the circulation rate is determined by the climate system, and there is an upper limit to the amount of RFWR available to human society. On the global scale, current withdrawals are well below this limit, and if the water cycle is managed wisely, RFWR can cover human demand far into the future. Appropriate water management is a crucial point.

Conventional engineers of water resources consider the water withdrawn from surface and groundwater as water resources and evapotranspiration as a loss of water from the precipitated water. In that sense, precipitation minus evapotranspiration over land is a measure of the maximum available RFWR. The major part of this available RFWR is surface water, particularly river discharge. However, some part of the water, approximately 10% of total river discharge (*6*), infiltrates to deep underground and will never appear as surface water but discharge into the ocean directly from groundwater.

In contrast to the conventional view, it has been noted that evapotranspiration from nonirrigated cropland also is a water resource that is beneficial to society (*7*). To distinguish between this kind of resource and conventional resources, evapotranspiration flow has been named green water, and conventional withdrawal from rivers and groundwater has been named blue water (*7*).

About 3800 km^3/year of RFWR (blue water) is currently withdrawn by human beings, and that accounts for less than 10% of the maximum available RFWR in the world (Fig. 1). Evapotranspiration is estimated to be 7600 km^3/year from cropland and 14,400 km^3/year from permanent grazing land. Cropland and grazing land account for about one-third of the total terrestrial evapotranspiration.

Can We Use All the RFWR?

Why should we be concerned about water scarcity when presently only 10% of maximum available blue water and 30% of green water resources are used? The reason is the high variability of water resource availability in time and space (*8*). For example, the monthly mean discharge at the Obidos station in the Amazon River differs by a factor of 2 between the highest and the lowest months, even for climatologically averaged values. River discharge is more variable in smaller river basins in general, and daily river discharge is, of course, more variable than monthly river discharge. Because of this temporal variability, it is impractical to use 100% of the available RFWR for human society. Flow during floods and wet seasons cannot be used during the low flow seasons unless storage systems are in place. That is why there are millions of artificial reservoirs, lakes, and ponds in the world and why most of the major rivers are regulated (*9*). Total capacity of this artificial storage is estimated to 7200 km^3 (*10*), about twice the annual water withdrawal.

Another reason that RFWR can be insufficient is its uneven spatial distribution. Annual runoff (Fig. 2A) can be considered as the maximum available RFWR if water from upstream cannot be reused downstream because of consumptive

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use or water pollution (*11*). Runoff is accumulated through river channels and forms river discharge (Fig. 2B). River discharge can be considered as the potentially maximum available RFWR if all the water from upstream can be used. Both runoff and river discharge are concentrated in limited areas, and the amounts range from nearly zero in desert areas through more than 2000 mm/year of runoff in the tropics and more than 200,000 m^3/s of discharge on average near the river mouth of the Amazon. Furthermore, the water demands for ecosystems and navigation should also be met, and all the RFWR cannot be used only for human beings.

How Are the World Water Resources Assessed?

In the late 1960s, the International Hydrological Decade promoted studies on world water balances, and pioneering estimates were published in the 1970s (*5*, *12*, *13*). Shiklomanov (*4*) assembled country statistics on water withdrawals in the past and present and made future projections. Recent advances in information technologies have enabled global water-balance estimations at finer spatial resolution (*11*, *14*, *15*). Water withdrawals now can be distributed into grid boxes, using the distributions of population and the irrigation area as proxies, and compared with the available RFWR in each grid box (*11*, *14*, *15*).

The water scarcity index is defined as $Rws = (W - S)/Q$, where W, S, and Q are the annual water withdrawal by all the sectors, the water use from desalinated water, and the annual RFWR, respectively. A region is usually considered highly water stressed if Rws is higher than 0.4 (*7*, *11*, *14*, *15*). It is considered to be a reasonable, although not definitive, threshold value because not all the RFWR can be used by human society. Data with shorter time scales will enable more detailed assessments considering the effects of temporal variability in the hydrological cycles.

In the era of the "Anthropocene" (*16*), where human impacts on natural processes are large and widespread, it no longer makes sense to study only natural hydrological cycles. For this reason, some studies have started to consider the impact of human interventions on the hydrological cycles, thereby simulating more realistically the hydrological cycles on a global scale. In such studies, human withdrawals are subtracted from the river flow (*15*), and the regulation of flow regime by major reservoirs is incorporated (*17*).

The distribution of the water scarcity index Rws (*11*), recalculated with the latest multimodel ensemble estimates (*3*), is shown in Fig. 2C. Rws is high in Northern China, in the area on the border between India and Pakistan, in the Middle East, and in the middle and western areas of the United States. Based on this assessment, approximately 2.4 billion people are currently living in highly water-stressed areas (*18*).

Can the "Virtual Water Trade" Alone Save the Water-Stressed Regions?

Transporting water over long distances, from regions where water is abundant to dry regions under water stress, is only feasible when gravity can be used. The demand for high-quality drinking water is limited to a few liters per person per day and can be met through international trade or by desalination. However, other demands for water for households, industry, and agriculture require up to one metric ton of water per day per

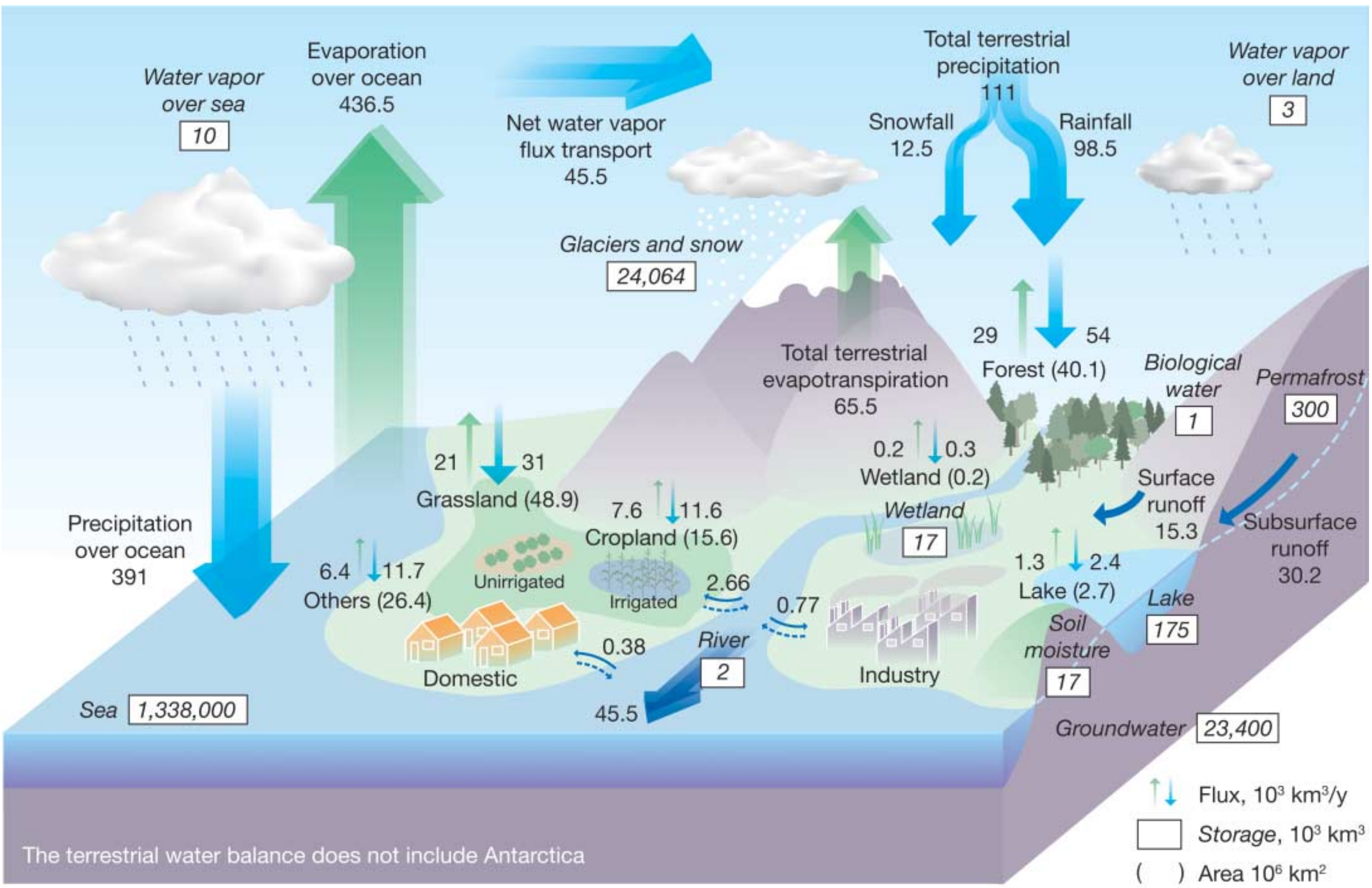

Fig. 1. Global hydrological fluxes (1000 km^3/year) and storages (1000 km^3) with natural and anthropogenic cycles are synthesized from various sources (*1*, *3*–*5*). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km^3/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km^3/year) presented by small vertical arrows; parentheses indicate area (million km^2). The direct groundwater discharge, which is estimated to be about 10% of total river discharge globally (*6*), is included in river discharge.

person in developing countries and considerably more in developed countries. Therefore, the supply for these sectors must be inexpensive, which means that transporting water by tanker or other high energy–consuming means is generally not realistic (*8*).

On the other hand, water demand for food and industrial production in dry regions can be offset by importing food or industrial goods. Such trade is called "virtual water trade" (*19*–*21*). The weight of traded goods is normally just a small fraction, such as $\frac{1}{100}$ to $\frac{1}{1000}$, of the weight of the water required to produce that goods, so transporting goods is considerably easier than transporting the water itself. Total international "virtual water trade" is estimated to be about 1000 km^3/year (*20*, *21*), although only a part of that "virtual water trade" is done to compensate for water shortage (*22*).

Problems of water, food, health, and poverty are interlinked in many developing countries, particularly in the regions where freshwater resources are scarce, the local economy is too weak to allow import of food from outside on a large scale, and desalination plants are impractical to implement.

On the contrary, once water supply is secured by appropriate infrastructure investments and improved management, public health conditions improve, food supply stabilizes, the potential for industrial development increases, and the time that was earlier devoted to acquiring water can be used for more productive work or educational opportunities. This is the reason that the target "Reduce by half the proportion of people without sustainable access to safe drinking water" (*23*) is one of the Millennium Development Goals of the United Nations.

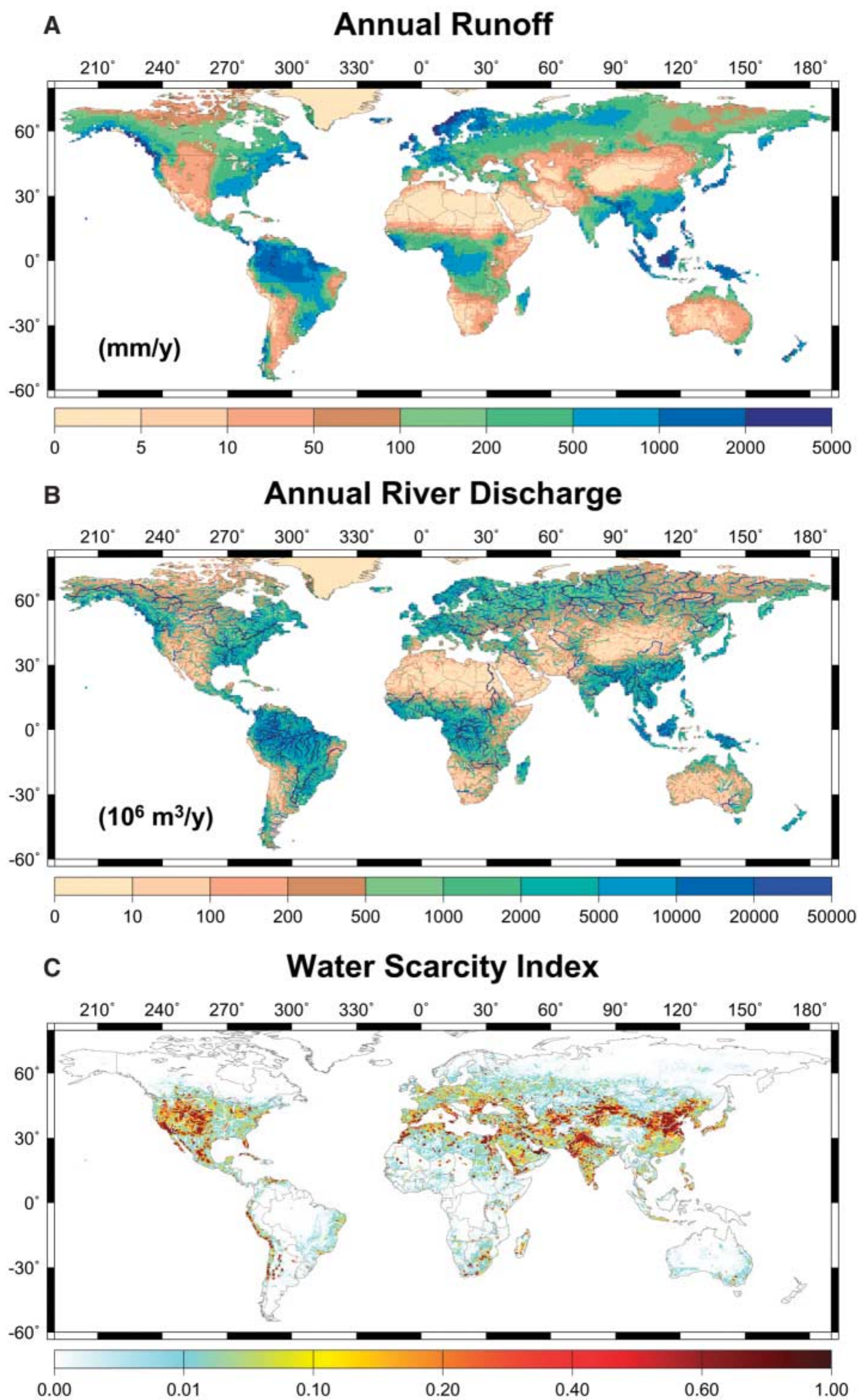

Fig. 2. Global distribution of (**A**) mean annual runoff (mm/year), (**B**) mean annual discharge (million m^3/year), and (**C**) water scarcity index *Rws* (*3*, *11*). Water stress is higher for regions with larger *Rws*.

How Will Water Use Change in the Future?

The global population will certainly grow, at least for several decades, and water demand will increase as a result. Water demand per person will most likely also increase due to economic growth. For example, an expected growth of meat consumption will increase the water demand for fodder production.

The ultimate objectives of future-oriented world water resource assessments are to show the international community what will happen if we continue to manage our water resources as we do today and to indicate what actions may be needed to prevent undesirable outcomes. In that sense, studies of future world water resources are successful if their predictions based on business-as-usual are proven wrong. In line with this, plausible scenarios informed by past experiences and current trends are built for future projections of the demand side.

In the agricultural sector, which is estimated to withdraw two-thirds of world water withdrawals and which accounts for 90% of total water consumption in the world (*4*), in the period from 1961 to 2004, crop yield per area increased by a factor of 2.3, more than the rate of population growth (2.0), and the total crop yield increased by a factor of 2.4, even though the area of cropland increased by only 10% and harvested area increased less than that (*24*). This phenomenal growth was to a large extent due to a doubling of the irrigation area and the corresponding increase of water withdrawal for irrigation in addition to the increased usage of fertilizer. Domestic per capita water use has increased with gross domestic product (GDP) growth, but in many developed countries this increase seems to have come to an end; in some countries, domestic per capita water use is now decreasing. Such trend shifts should be considered in predictions of future water use. Industrial water use has also increased along with GDP, but recycling technology has reduced the net intake of water for factories. For example, nearly 80% of water used in the industrial sectors in Japan is currently recycled (*25*).

There are concerns that in the decades ahead, water withdrawals for irrigation cannot be increased as required and that the lack of water will impede necessary growth of food production. However, *Rws* in developing countries is generally low, which means that they should have a potential to increase their water withdrawals. A key challenge for these countries should be how to implement soft measures (such as legislation, policies, and market mechanisms) in addition to technical ones to simultaneously increase the supply and manage the demand wisely (*26*).

What Effects Will Climate Change Have on RFWR?

The effect of global climate change on hydrological cycles is still uncertain, but higher temperatures will turn some part of snowfall into rainfall, the snowmelt season will be earlier, and, as a result, the timing and volume of spring flood will change substantially (*27*). Nearly half of the world's population depends on groundwater sources for drinking water supply and for other uses (*28*). Sea level rise will cause saline water intrusion into groundwater aquifers near the coasts and will decrease the available groundwater resources. On the water demand side, changes in the seasonal pattern have not been estimated globally, and a comprehensive description of groundwater withdrawal in the world is largely lacking.

Lack of seasonal details in existing assessments is the reason that crude annual average measures such as the water scarcity index *Rws* and the Falkenmark's indicator or the "water crowding indicator" $Aw = Q/C$ (*4*), where *C* is population size, are still being used. Of course, there have been advances in world water resource assessments; projections on the demand side now are based on the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios, making them consistent with future climate projections (*18*, *29*, *30*), and uncertainties in the projections of future hydrological cycles are reduced by the use of multimodel ensemble technique (*18*, *31*, *32*).

Figure 3 compares three assessments of the number of people who will live in regions with high water stress until the end of the 21st century (*11*, *18*, *29*, *30*). Even though the projections vary by scenario, their estimates correspond fairly well. Notably, climate change is expected to accelerate the global hydrological cycles, and precipitation will increase on average. Evapotranspiration will not increase as much as precipitation globally because elevated CO_2 concentration induces stomata closure and reduces transpiration (*33*), and river discharge will increase on global scale because of the increased precipitation and the reduced transpiration (*31*, *32*). As a result, the available RFWR is expected to increase at a higher rate than water demand, calculated from population and economic growth. Because of this, the water scarcity index *Rws* and the water crowding indicator *Aw*, both based on annual RFWR, show that water stress will be reduced on a macro scale, except for the A2 scenario, which represents a very heterogeneous world with high population growth. However, the decrease in the number of people under water stress is only marginal and the results should not be viewed too optimistically because they are based on estimates of annual RFWR. Other anticipated impacts of climate change on water resources, such as modification of seasonal variation of available RFWR, degradation of water quality, and associated changes in water resource management, are not taken into account. Furthermore, precipitation will become more intense and intermittent, and the risks of floods and droughts will increase, sometimes in the same region of the world (*34*). These changes in risks are not well considered in current global assessments on future water resource management.

Nevertheless, it is certain that there are people who are already suffering from water shortage today and that any change in the hydrological cycle will demand changes in water resource management, whether the change is caused by global warming or cooling, or by anthropogenic or natural factors. If society is not well prepared for such changes and fails to monitor variations in the hydrological cycle, large numbers of people run the risk of living under water stress or seeing their livelihoods devastated by water-related hazards such as floods.

How Can Hydrological Science Help Solve World Water Issues?

Detailed knowledge of global water resources certainly has been enriched over the 40 years that have passed since the International Hydrological Decade. Water cycles on Earth can now be measured and simulated on finer temporal and spatial scales with detailed models of each hydrological process, and the current and future status of the global water system can be illustrated (Figs. 1 to 3). In contrast to these achievements in studies of the natural hydrological cycles, data about the social aspects of water use are not easily available.

Finally, the future development of hydrology requires improved communication between scientists and policy-makers to ensure that hydrological expertise is translated into actions

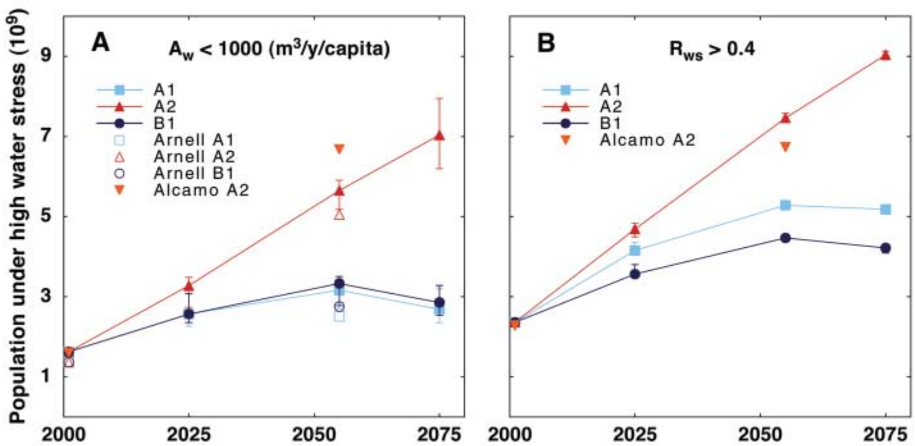

Fig. 3. Current and future projections of population under high water stress under three business-as-usual scenarios of the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios. Threshold values are set to be (**A**) the water-crowding indicator $Aw = Q/C < 1000$ m^3/year per capita and (**B**) the water scarcity index $Rws = (W - S)/Q > 0.4$, where *Q*, *C*, *W*, and *S* are renewable freshwater resources (RFWR), population, water withdrawal, and water generated by desalination, respectively. Error bars indicate the maximum and minimum population under high water stress corresponding to the RFWR projected by six climate models. Climatic conditions averaged for 30 years are used for the plots at 2025 (averaged for 2010 to 2039), 2055 (averaged for 2040 to 2069), and 2075 (averaged for 2060 to 2089).

that address water challenges (*35*) and to make sure that scientists understand what kinds of knowledge are required by policy-makers and by society at large.

References and Notes

1. T. Oki, in *Encyclopedia of Hydrological Sciences*, M.G. Anderson, J. McDonnell, Eds. (Wiley, New York, 2005), vol. 1, pp. 13–22.
2. M. W. Rosegrant, C. Ximing, S. A. Cline, *Environment* **45**, 24 (2003).
3. P. A. Dirmeyer *et al.*, *Bull. Am. Meteorol. Soc.,* in press.
4. I. A. Shiklomanov, Ed., *Assessment of Water Resources and Water Availability in the World* (World Meteorological Organization/Stockholm Environment Institute, Geneva, Switzerland, 1997).
5. V. I. Korzun, *World Water Balance and Water Resources of the Earth*, vol. 25 of *Studies and Reports in Hydrology* (UNESCO, Paris, 1978).
6. T. M. Church, *Nature* **380**, 579 (1996).
7. M. Falkenmark, J. Rockstrom, *Balancing Water for Humans and Nature* (Earthscan, London, 2004).
8. S. L. Postel, G. C. Daily, P. R. Ehrlich, *Science* **271**, 785 (1996).
9. C. Nilsson, C. A. Reidy, M. Dynesius, C. Revenga, *Science* **308**, 405 (2005).
10. *World Register of Dams* (International Commission on Large Dams, Paris, 1998).
11. T. Oki *et al.*, *Hydrol. Sci. J.* **46**, 983 (2001).
12. M. I. Lvovitch, *Trans. Am. Geophys. Union* **54**, 28 (1973).
13. F. Baumgartner, E. Reichel, *The World Water Balance: Mean Annual Global, Continental and Maritime Precipitation, Evaporation and Runoff* (Ordenbourg, München, Germany, 1975).
14. C. J. Vörösmarty, P. Green, J. Salisbury, R. B. Lammers, *Science* **289**, 284 (2000).
15. J. Alcamo *et al.*, *Hydrol. Sci. J.* **48**, 339 (2003).
16. P. J. Crutzen, *Nature* **415**, 23 (2002).
17. N. Hanasaki, S. Kanae, T. Oki, *J. Hydrol.* **327**, 22 (2006).
18. N. Utsumi, thesis, The University of Tokyo (2006).
19. J. A. Allan, *Yale Univ. For. Environ. Studies Bull.* **103**, 141 (1998).
20. T. Oki *et al.*, in *Value of Water Research Report Series No. 12*, A. Y. Hoekstra, Ed. (UNESCO-IHE, Delft, Netherlands, 2003), pp. 221–235.
21. A. K. Chapagain, A. Y. Hoekstra, *Value of Water Research Report Series No. 13* (UNESCO-IHE, Delft, Netherlands, 2003).
22. H. Yang, P. Eichert, K. C. Abbaspour, A. B. Zehnder, *Environ. Sci. Technol.* **37**, 3048 (2003).
23. UN Millennium Development Goals (www.un.org/millenniumgoals/index.html).
24. FAOSTAT (http://faostat.fao.org/).
25. *Water Resources in Japan* (Ministry of Land, Infrastructure, and Transport, Tokyo, 2005).
26. P. Gleick, *Science* **302**, 1524 (2003).
27. Intergovermental Panel on Climate Change, *Climate Change, 2001: The Science Basis* (Cambridge Univ. Press, Cambridge, UK, 2001).
28. World Water Day (www.worldwaterday.org/wwday/1998/).
29. J. Alcamo *et al.*, personal communication.
30. N. W. Arnell, *Glob. Environ. Change* **14**, 31 (2004).
31. D. Nohara, A. Kitoh, M. Hosaka, T. Oki, *J. Hydromet.*, in press.
32. P. C. D. Milly, K. A. Dunne, A. V. Vecchia, *Nature* **438**, 347 (2005).
33. N. Gedney *et al.*, *Nature* **439**, 835 (2006).
34. Y. Hirabayashi *et al.*, in preparation.
35. T. Oki, C. Valeo, K. Heal, Eds., *Hydrology 2020: An Integrating Science to Meet World Water Challenges, IAHS Publication 300* (IAHS, Wallingford, UK, 2005).

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REVIEW

The Challenge of Micropollutants in Aquatic Systems

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The increasing worldwide contamination of freshwater systems with thousands of industrial and natural chemical compounds is one of the key environmental problems facing humanity. Although most of these compounds are present at low concentrations, many of them raise considerable toxicological concerns, particularly when present as components of complex mixtures. Here we review three scientific challenges in addressing water-quality problems caused by such micropollutants. First, tools to assess the impact of these pollutants on aquatic life and human health must be further developed and refined. Second, cost-effective and appropriate remediation and water-treatment technologies must be explored and implemented. Third, usage and disposal strategies, coupled with the search for environmentally more benign products and processes, should aim to minimize introduction of critical pollutants into the aquatic environment.

About one-fifth of the world's population does not have access to safe water, and two-fifths suffer the consequences of unacceptable sanitary conditions (*1*). Pathogens in water cause more than 2 million deaths annually; most are children under the age of 5. The increasing chemical pollution of surface and groundwaters, with largely unknown long-term effects on aquatic life and on human health, could easily lead to a problem of similar or even greater magnitude. More than one-third of the Earth's accessible renewable freshwater is used for agricultural, industrial, and domestic purposes, and most of these activities lead to water contamination with numerous synthetic and geogenic compounds (Table 1). It therefore comes as no surprise that chemical pollution of natural waters has already become a major public concern in almost all parts of the world.

Industry and municipalities use about 10% of the globally accessible runoff and generate a stream of wastewater, which flows or seeps into rivers, lakes, groundwater, or the coastal seas (*1*). These wastewaters contain numerous chemical compounds in varying concentrations. About 300 million tons of synthetic compounds annually used in industrial and consumer products partially find their way into natural waters (Table 1). Additional pollution comes from diffuse sources from agriculture, where 140 million tons of fertilizers and several million tons of pesticides are applied each year (*2*). In the European Union, for instance, there are more than 100,000 registered chemicals, of which 30,000 to 70,000 are in daily use (EINECS, European Inventory of Existing Chemical Substances). The input of 0.4 million tons of oil and gasoline components through accidental spills represents yet another important source of water pollution. Other notable sources of contamination are the intrusion of salty water into groundwater due to overexploitation of aquifers; the human-driven mobilization of naturally occurring geogenic toxic chemicals, including heavy metals and metalloids (Table 1); and the biological production of toxins and malodorous compounds.

To date, an effective and sustainable global strategy against this insidious and mostly unseen contamination of aquatic environments barely exists. Source controls and technical systems, such as wastewater treatment plants, function as partial barriers, particularly in highly industrialized countries, but major challenges remain. The source, behavior, and treatment of the relatively small number of macropollutants (*3*) such as acids, salts, nutrients, and natural organic matter, occurring at μg/liter to mg/liter concentrations, are relatively well understood: High nutrient loads can lead to increased primary production,

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AUSTRALIA

River Basin Management Plan Secures Water for the Environment

MELBOURNE, AUSTRALIA—In the scramble to secure water for drinking and agriculture, the environment often gets overlooked. Australia is aiming to set an example of how to balance all three needs in its agricultural heartland. The Murray-Darling basin plan, adopted by the government on 22 November, "is historic," says Richard Kingsford, a conservation biologist at the University of New South Wales in Sydney. South Australian River Murray Minister Paul Caica praised the expected environmental gains: "It will help floodplains support healthy red gum forests, waterbird and fish breeding habitats. … It will keep water levels high enough to prevent acidification in the lower lakes … and reduce the risk of the Murray [m]outh needing to be dredged."

Water managers worldwide "see it as a model" for the use of technical advice and involvement of government at all levels, says water policy expert Sharon Megdal of the University of Arizona in Tucson. The plan's deft balancing of societal and ecological needs, adds Clifford Dahm, an aquatic ecologist at the University of New Mexico, Albuquerque, "gives us some useful ideas for science, planning, and the political tightrope that such decisionmaking requires."

The 1-million-square-kilometer Murray-Darling basin stretches across four states that have been brawling over water for more than a century. Rising from tributaries in Queensland and New South Wales, the Darling River flows southwest, joining the Murray River at the Victorian border, and finally enters the sea near Adelaide. Although the two rivers and their tributaries account for less than 7% of the nation's stream flow, the basin, which draws most of its water from the Murray, produces about 40% of the food grown in Australia. Its ecological treasures include Chowilla wetlands, Macquarie marshes, and, near the mouth of the Murray, the iconic Coorong with its 140-kilometer-long lagoon that provides sanctuary for a cornucopia of waterbirds.

Beginning in the 1950s, dams and irrigation channels transformed the free-flowing waterways into a highly managed system. Prior to the arrival of Europeans in the 1800s, more than 40% of rainwater entering the system annually, or 12,200 billion liters, made it to the sea, according to a 2008 study by the Commonwealth Scientific and Industrial Research Organisation. By 2008, even with normal rainfall, flow in the rivers' lower reaches had dwindled to nearly one-third of historical levels, about 4700 billion liters. The decadelong Millennium Drought starting in the late 1990s exacerbated the water shortage. Along the lower Murray, three-quarters of once-extensive red gum forests withered and died. The Goolwa wetlands dried up, oxidizing sulfates in the soil to sulfuric acid, which acidified the wetlands and adjacent farms once the waters returned and spread it. The Coorong was cut off from the Murray for 3 years. Its salinity jumped to five to seven times that of seawater, turning half of the estuary into a dead sea. "Paleoecological evidence indicates it was unusual even for the last 7000 years," Rebecca Lester, an environmental scientist at Deakin University in Melbourne, penned on *The Conversation*, a research news Web site.

Upstream, nutrients accumulating in the Murray and Darling rivers fueled toxic algal blooms, setting a world record in 1991 for a bloom that extended 1000 kilometers along the Darling River. Residents of Adelaide, the city last in line to draw water from the river system, had to contend with some of the world's saltiest drinking water. In 2009, experts raised the alarm with some predicting that within the year, the city would have to turn to bottled water.


Free-flowing. Balancing competing demands will keep water flowing through the Murray-Darling river system.

The Millennium Drought led to a number of measures, including the establishment in 2008 of the Murray-Darling Basin Authority (MDBA), which is an independent federal agency charged with finding the right balance between agricultural, social, and environmental values. Restoring river and wetlands health meant primarily removing less water for irrigation. "How much to take back is open for lots of debate," says Tony Minns, director of the Goyder Institute for Water Research in Adelaide. MDBA planners also called for fixing leaky irrigation systems to retain more water in rivers and proposed that flows could be bolstered by pumping in groundwater.

In June 2010, the Wentworth Group of Concerned Scientists, an independent conservation organization, called for water flows to be returned to two-thirds of historical levels, a target that won broad though not universal support among environmentalists. MDBA issued a preliminary plan in November 2010 that

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looked at three water recovery scenarios—none of which pleased farmers, who tossed it into bonfires. A final plan issued a year later improved modeling to assess how different scenarios would affect 18 key indicators of environmental health. One indicator is to keep salinity in the Coorong below 60 grams per liter—a safe level for seagrasses that fish and birds depend on. (Pre-European salinity was 24 grams per liter; by 2009 it had risen to 62 grams per liter.) Returning 3200 billion liters to the Murray-Darling system would satisfy 17 of 18 indicators and come close to the Wentworth target of two-thirds of historical flows. But it poses another problem: Infrastructure along the rivers' lower reaches built to suit reduced flows would be swamped. To accommodate more flow, the government earmarked $1.85 billion in October to raise bridges, build levees, and compensate landowners. Much of that water will come from buying water rights from farmers; better irrigation infrastructure will spread it further. The basin plan is expected to be fully implemented by 2024.

The plan still faces hurdles. "There are many ways the states could frustrate the deal," says Rhondda Dickson, MDBA chief executive. For instance, states still own the water and could cap the amount of irrigation rights MDBA can purchase, as New South Wales has threatened to do. "To make it work," Dickson says, "the government needs the states' support, however grudging." The environment ministry is working on an implementation agreement with the states.

Ecological recovery could take decades. MDBA's water purchases and infrastructure upgrades so far have returned 1327 billion liters to the rivers, rejuvenating parched wetland systems, Kingsford says. The numbers of nesting waterfowl species have bounced back, but *Ruppia tuberosa*, a key seagrass species that fish and waterfowl feed on, has disappeared. Soil acidification still affects wetlands and farm fields. "It's not clear whether these changes are permanent," Minns says, referring to both biodiversity loss and acidification.

The basin's future will depend not just on the volume of water flowing through the system, but how it's added. "We have to develop ecological watering plans [to decide] how much, how often and when [to release water] to achieve the environmental outcomes," Minns says. One goal is to restore natural flow variability. "Ecologically, occasional flooding is important for these river systems," Kingsford says. Now that MDBA is getting the water it needs, it will have to learn how to best manage it. As Minns says, "The real work starts now."

–ELIZABETH FINKEL AND DENNIS NORMILE

U.S. SCIENCE POLICY

White House Panel Urges Agencies to Take More Risks

Be bolder.

A new report by a presidential advisory panel urges U.S. research agencies to make a bigger commitment to supporting high-risk, interdisciplinary research by investigators with a strong track record. Current efforts by the National Institutes of Health (NIH) and the National Science Foundation (NSF) to do so are "a drop in the bucket of total agency funding," says a report released last week by the President's Council of Advisors on Science and Technology (PCAST).

The new PCAST report, entitled *Transformation and Opportunity: The Future of the U.S. Research Enterprise*, offers 17 recommendations to shore up the $450-billion-a-year U.S. research enterprise, both public and private, and increase its eventual economic payoff. Most of the ideas—including the need to ease the regulatory burden on universities, strengthen ties with industry, improve science and math education, and ensure a steady, predictable rate of growth for federal spending on science—will sound familiar to readers of other recent reports by equally prestigious panels. "The majority of these recommendations have been made by other groups," admits University of Texas, Austin, computer scientist William Press, who co-chaired the working group that produced the report. (Press is also president of AAAS, which publishes *Science*.) In fact, PCAST's suggestions to boost overall research spending to 3% of the nation's gross domestic product, make permanent a research tax credit for industry, and help foreign scientists remain in the United States after graduation have already been embraced by its intended audience: President Barack Obama. But advocates for the research community say that it never hurts to remind the administration that such proposed policy changes are important—especially when the White House and Congress are engaged in tense negotiations to avoid heading over the so-called fiscal cliff next month.

Presidential prodding. William Press led the PCAST panel that wants changes in U.S. research practices.

CREDIT: SARA PRESS

One area where the PCAST report breaks from the pack is its call for research agencies to adopt "revolutionary … interdisciplinary ... and people-based awards." Too much of federal spending—which amounts to about one-third of the nation's total investment in research—backs incremental advances, according to the report. And one of the culprits is a conservative merit review process that rewards safe bets.

NIH is taking small steps away from that approach with its Pioneer, New Innovator, and Early Independence awards from the director's office, the report notes. Likewise, the report praises NSF's Rapid Response Research grants and its planned expansion of programs to reward "creative … transformative interdisciplinary ventures." But Press says "the funding agencies have been slower than we would like to see in moving in these directions." And the report documents those baby steps: This year, it notes, NIH will make 50 awards in the three director's categories out of a total of 35,944 research grants. "While this plethora of initiatives, each worthy in its own way, gives an illusion of significant progress," the report notes, "in truth the sum of all these programs is tiny, almost invisible, in comparison to each agency's dominant" form of research support.

The report also urges Congress and the executive branch to find a way to provide research agencies with multiyear budgets, or at least funding guarantees for individual projects. Other countries operate on 5-year budgets, notes NSF Director Subra Suresh. But Suresh says "it's very difficult to carry out long-term planning with our sister agencies" under the current U.S. system of annual appropriations.

–JEFFREY MERVIS