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 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 km³, much less than the annual water withdrawal of 3800 km³/year (Fig. 1). Clearly, a more adequate measure of water availability is the 45,500 km³/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 non-irrigated 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 km³/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 km³/year from cropland and 14,400 km³/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 km³ (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 m³/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
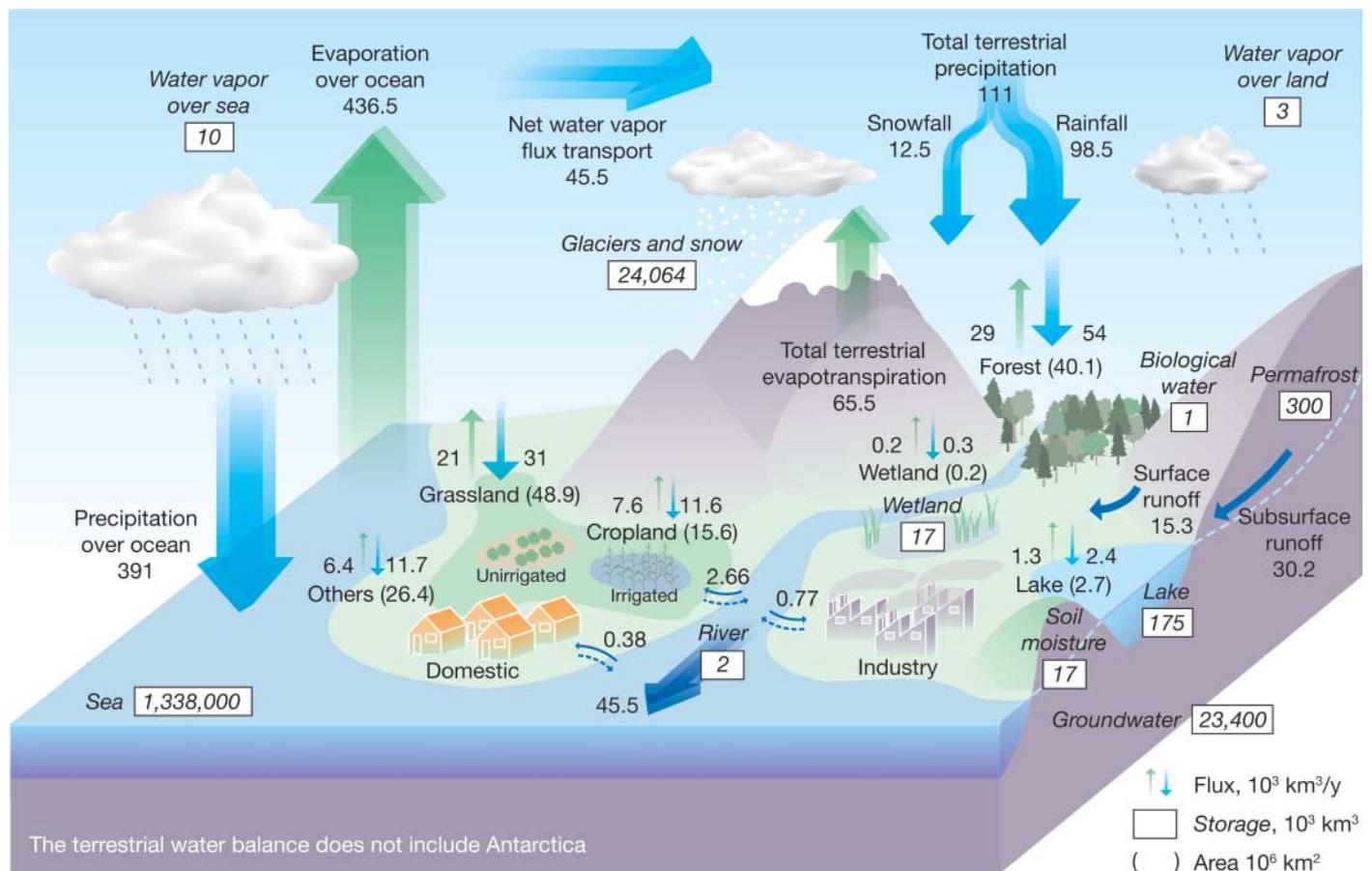

Fig. 1. Global hydrological fluxes (1000 km³/year) and storages (1000 km³) with natural and anthropogenic cycles are synthesized from various sources (*1*, *3–5*). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km³/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km³/year) presented by small vertical arrows; parentheses indicate area (million km²). 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 km³/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.

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
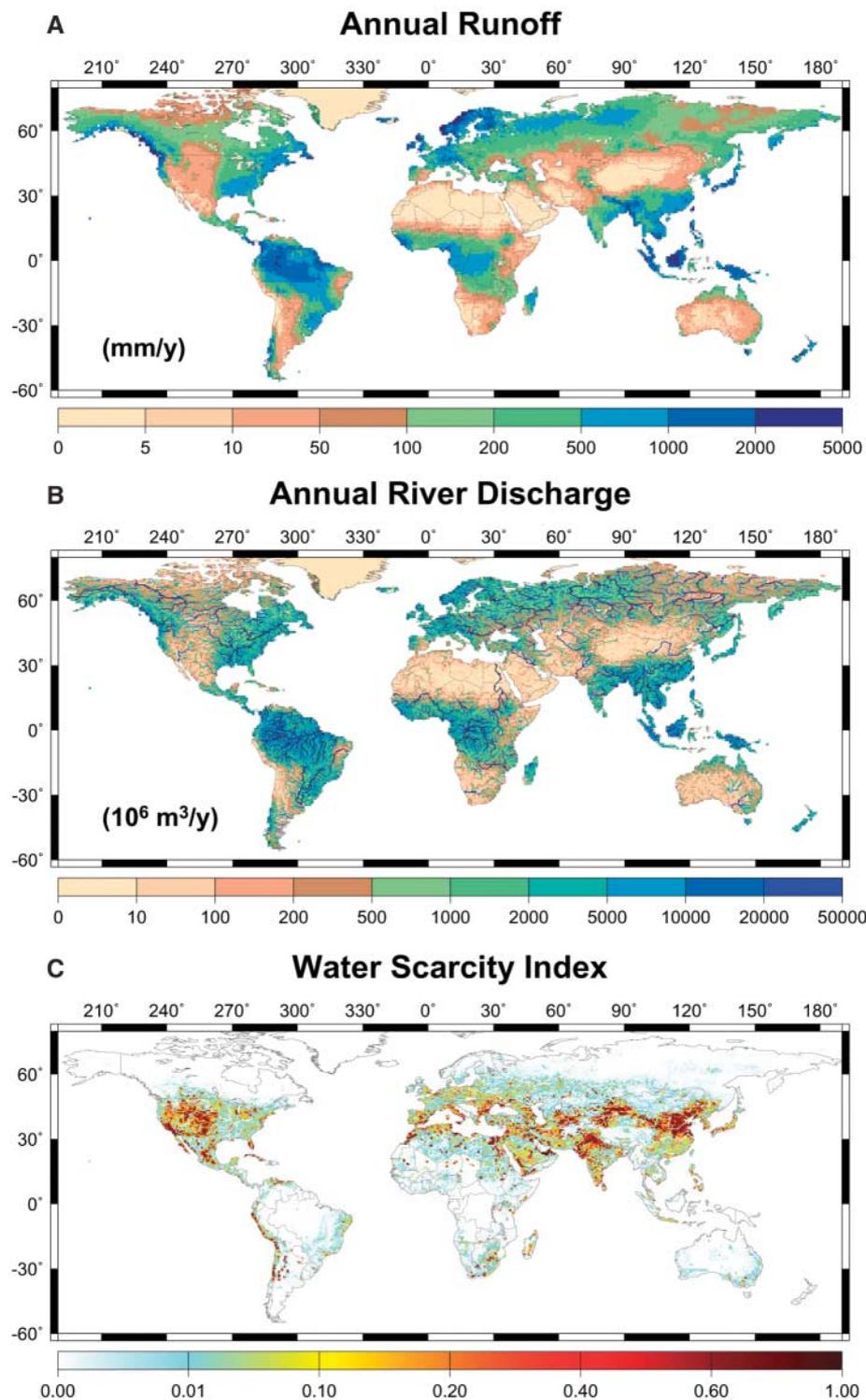

Fig. 2. Global distribution of (**A**) mean annual runoff (mm/year), (**B**) mean annual discharge (million m³/year), and (**C**) water scarcity index *Rws* (*3, 11*). Water stress is higher for regions with larger *Rws*.

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, R_{ws} 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 R_{ws} and the Falkenmark's indicator or the "water crowding indicator" $A_w = Q/C$ (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 R_{ws} and the water crowding indicator A_w, 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
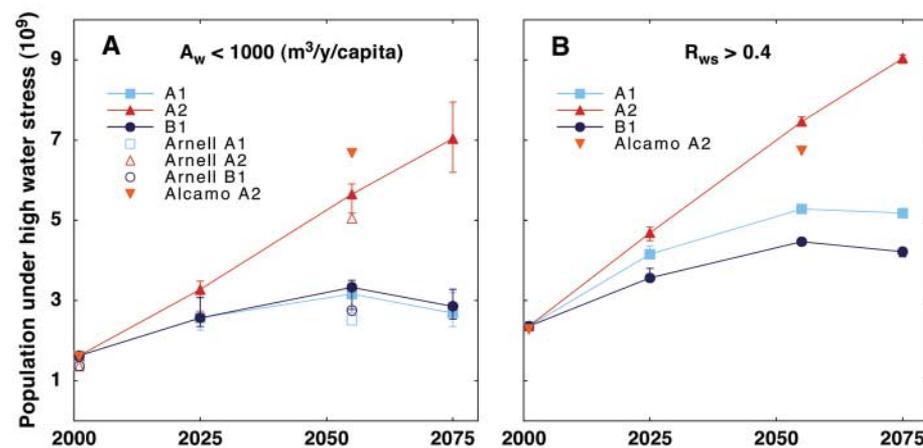

Fig. 3. Current and future projections of population under high water stress under three business-as-usual scenarios of the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios. Threshold values are set to be (**A**) the water-crowding indicator $A_w = Q/C < 1000$ m³/year per capita and (**B**) the water scarcity index $R_{ws} = (W - S)/Q > 0.4$, 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.

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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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