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RESEARCH ARTICLE

Managing water for life

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Abstract Water is essential for life. In spite of the entire engineering infrastructure devoted to the treatment, regulation and beneficial uses of water, occasionally sufficient quantities and qualities of water become scarce. When this happens, just how do we decide how much less water to allocate to all of us and the activities we engage in to sustain and enhance our quality of life? This paper addresses some of the complexities of answering such a question, especially as society increasingly recognizes the need to provide flow regimes that will maintain healthy aquatic and floodplain ecosystems that also impact the economic, physical and even the spiritual quality of our lives. For we depend on these ecosystems to sustain our wellbeing. We are indeed a part of our ecosystems. We depend upon on aquatic ecosystems to moderate river flow qualities and quantities, reduce the extremes of floods and droughts, reduce erosion, detoxify and decompose water-borne wastes, generate and preserve flood plain soils and renew their fertility, regulate disease carrying organisms, and to enhance recreational benefits of river systems. This question of deciding just how much water to allocate to each water user and for the maintenance of viable aquatic ecosystems, especially when there is not enough, is a complex, and largely political, issue. This issue is likely to become even more complex and political and contentious in the future as populations grow and as water quantities and their qualities become even more variable and uncertain.

Keywords water stress, aquatic ecosystems, sustainable water resource allocations, ecosystem water requirements

1 Introduction

We all know water is essential for life. We also know that many people are not getting enough of it, both quantity and quality, that allow them to live healthy lives. And for many of the world’s poor, access to clean water too costly. For some countries, the percentage of people lacking adequate water supplies exceeds well over half of their total populations. As a result, many, especially the very young, die. Others are constantly sick, and hence cannot achieve their full productive potential [1,2]. So, the question is just how can we “optimize water for life” especially in situations where there is not enough to satisfy even life’s basic needs? How do we make decisions on how much water to allocate to each of the many beneficial uses of water in times of water stress?

In addition to drinking water, people need food and clothing, and the production of the world’s food and fiber requires water. There is nothing we eat or wear that doesn’t depend on water. The production of energy, either thermal (including nuclear) or hydropower, requires water. The materials in the buildings we live and work in, and their contents, require water for their manufacture. Water also serves as an inexpensive means of transporting cargo and water-borne wastes. And very importantly, we need water to maintain viable and diverse ecosystems. We depend upon our environment and ecosystems to sustain the quality of our lives, and indeed life itself [3,4].

In the past decade, progress has been made in providing more people with access to clean drinking water and basic sanitation [2]. But a major effort is still required to extend these essential conditions to those still without them, the vast majority of who are poor and cannot pay the costs of these basic services. In addition, we are increasingly recognizing that we humans will not easily survive in the long run unless we pay attention to maintaining a quality environment and life-supporting ecosystems [5]. Again, water is needed to do this, and in times of drought determining the ‘optimal’ allocations of water to sustain our lives, our economic activities, and our ecosystems is indeed a challenging economic and social endeavor [6].

Balancing water demand allocations, especially when

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the demands exceed supplies, is a complex, and largely political, problem. It is not just an economic benefit-cost issue where all one has to do is allocate water in ways that will equate the present values of all marginal net benefits, unless otherwise constrained, to all water users. Some water use benefits, especially environmental and ecosystem benefits, and most non-use benefits, cannot be expressed adequately in terms of money. This is in spite of many such attempts by many highly respected individuals [6–9] and in spite of the desire for such simplified analyses by planners and politicians. The water allocation problem is likely to become even more complex and political and contentious in the future as populations grow and as water quantities and their qualities become even more variable and uncertain. But at least the political process of making allocations should be informed by predictions of the likely impacts of alternative allocation decisions [10,11].

How can one allocate scarce water supplies optimally among all demands that impact on the quality of, or even the existence of, life – both human and ecosystem life – in times of critical scarcity? A general precise answer that fits all circumstances is never clear, but what is certain is that both humans and ecosystems should be kept alive and healthy! If the latter is not, it is unlikely the former will either in the long run [12].

2 How much water do we need?

Just how much water does society need, now and into the future, to be sustainable? By 2025, an estimated 3.4 billion people will be living in countries defined as water-scarce. Many in those countries seem to be able to survive on as little as 3 L per day per person. However, it takes about 3000 L of water to produce a daily ration of food, about 1000 times what we minimally need for dietary purposes. A substantial portion of our food comes from irrigated lands. On average over 70% of total freshwater use in the world is devoted to irrigation. Over the next 30 years, about 70% of gains used in cereal production are expected to come from irrigated land [2].

Water is needed for energy as well. Hydropower provides a substantial portion of the energy consumed in some regions where water stored in reservoirs is available, but even thermal power plants require water. Thermal energy production converts heat into steam to drive turbines, and water is often used for cooling as well. But the biggest consumer of water for energy production today is that used for the production and processing of crops used for biofuels. The demand for water in the production of biofuels is a growing concern. For example, in the US, about 40% of all water withdrawals in the Midwest are for biofuel production. Given current subsidies that encourage biofuel production, this demand is expected to increase by 80% in the next 30 years. In Europe, where the issue is only beginning to be recognized, water consumption for energy production is expected to be equivalent to the daily water needs of 90 million people by 2030 [13,14].

Water also transports cargo and assimilates much of our domestic and industrial wastes. In developing countries, more than 90% of sewage and 70% of industrial wastewater is dumped untreated into surface water [15].

Freshwater is vital to human life and societal well-being. Water use for energy production, domestic and industrial consumption, crop irrigation, and ship transport has long been considered a key factor in economic development and consequently human welfare. These direct human and economic uses or purposes have traditionally taken precedence over other commodities and services provided by freshwater.

Historically humans have withdrawn freshwater from rivers, lakes, groundwater, and wetlands for many different urban, agricultural, and industrial activities, but in doing so have often overlooked its on-site value in supporting ecosystems. In more recent years there has been a growing recognition that aquatic and floodplain ecosystems provide many economically valuable services and long-term use and non-use benefits to society [16]. Long-term benefits include the sustained provision of those goods and services, as well as a more resilient and adaptive capacity of ecosystems to respond to future environmental alterations, such as global warming and its impact on the hydrologic cycle. Clearly, the maintenance of the processes and properties that support freshwater ecosystem integrity should be included in debates over sustainable water resource allocations, especially in times of water shortages [17–19].

The physical evidence of increasing periods of water scarcity can be found almost everywhere in the world. Water scarcity (Fig. 1) affects rich and poor countries alike. Nearly three billion people live in water scarce conditions (over 40% of the world's population), and this situation could worsen if current population growth trends continue, and if the melting of some of the major sources of water – the glaciers – continues. The manifestations of pervasive water poverty include millions of deaths every year due to malnourishment and water-related disease, political conflict over scarce water resources, extinction of freshwater species, and degradation of aquatic ecosystems. Roughly half of all the world's wetlands have already been lost and dams have seriously altered the flow of roughly 60 percent of the world's major river basins [20].

The situation only worsens with time. Figure 2 projects available water supplies per person per year by 2025 [21]. It shows the regions under stress whose available supplies in 2025 will be less than 1700 m^3 per year per person.

The UN estimates that about a sixth of today's world population has inadequate access to safe drinking water, and twice as many do not have adequate sanitation facilities [1,2]. Over a third of the world's population is water stressed. If we assume "business-as-usual" forecasts,

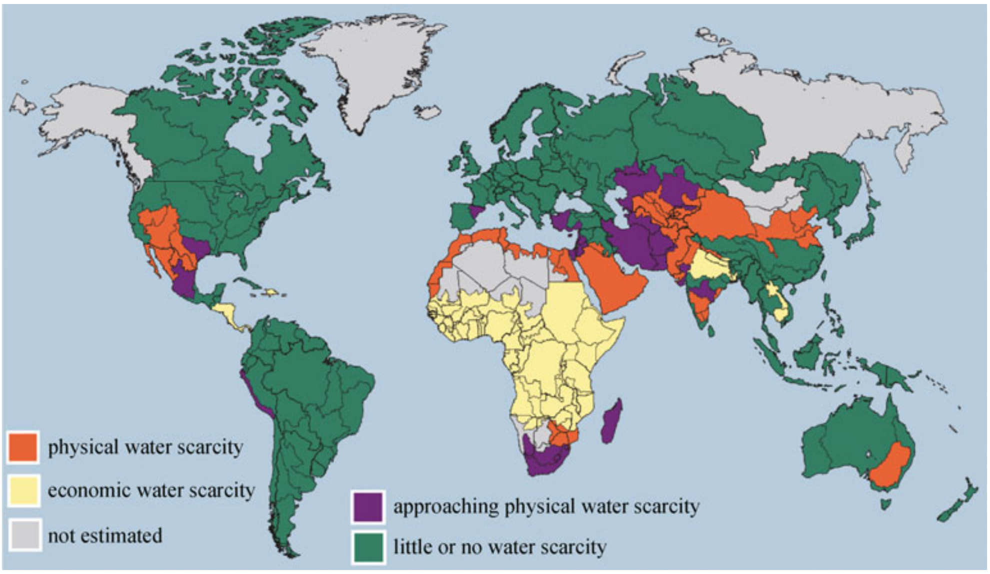

Fig. 1 Water scarce regions of the world [20]
Note: Physically water scarce regions are those in which the withdrawal and consumptive use of water exceeds 75% of the supply. Economically water scarce regions have sufficient supplies to meet demands, but potential users lack the means to access that water (http://earthtrends.wri.org)

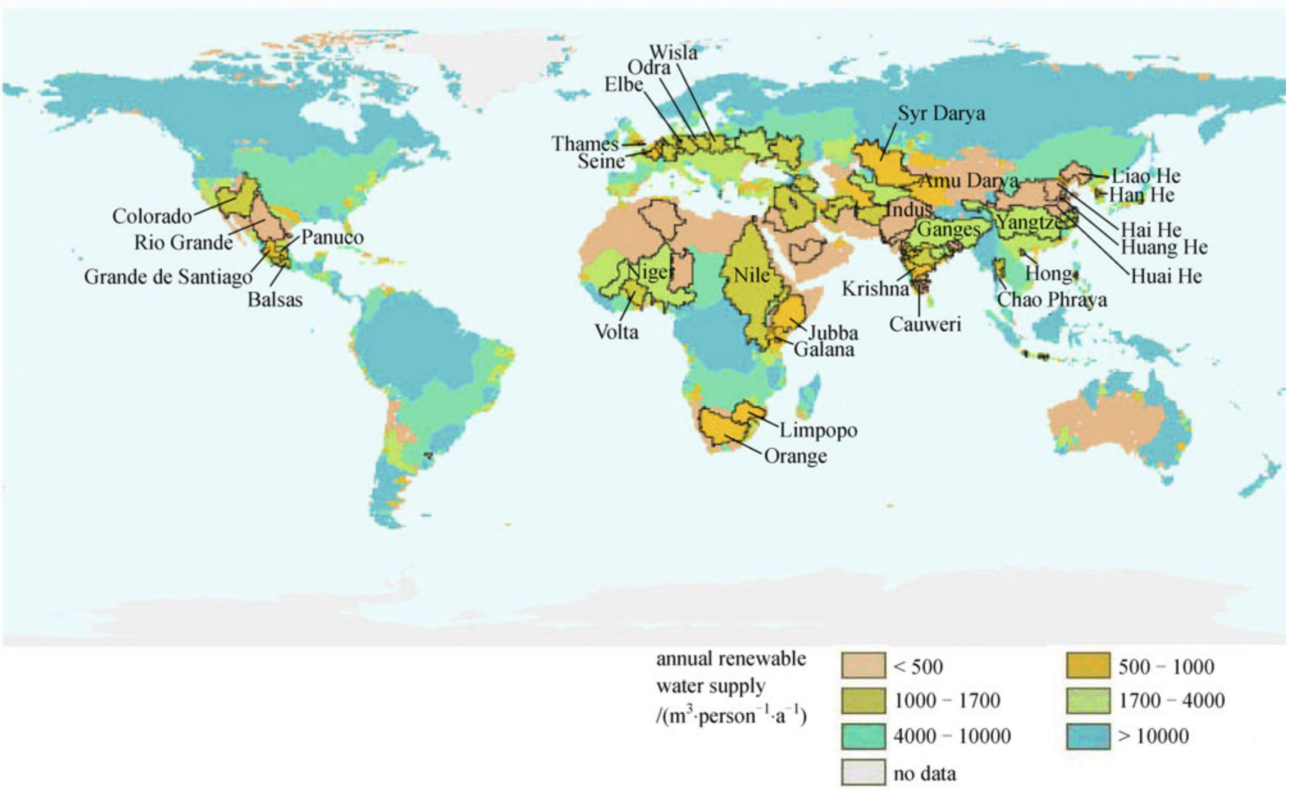

Fig. 2 Projected annual renewable water supply per person by River Basin, 2025 (http://earthtrends.wri.org/updates/node/179)

by 2050 about 40% of the projected global population of 9.4 billion is expected to be facing water stress or scarcity, as shown in Fig. 3 [22]. With increasing variability being predicted by global climate models, we may have more people without adequate water more of the time, even in water richer regions.

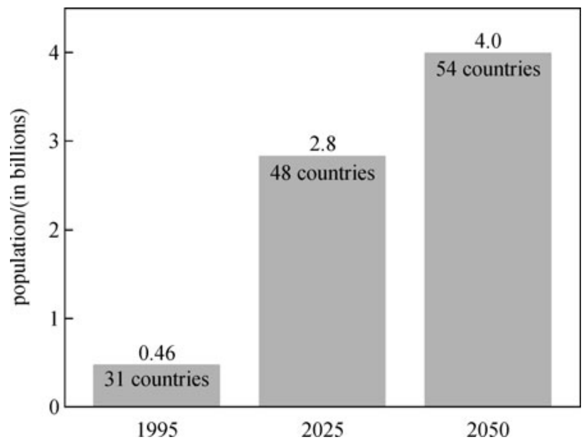

Fig. 3 Populations in water stressed countries from 1995 to 2050 (http://www.infoforhealth.org/pr/m14/m14print.shtml)

3 Where is the water will we need?

Most of that freshwater we now use comes from surface water in various river basins and groundwater in different aquifers, as shown in Figs. 4 and 5. Figure 4 locates 26 of the world's major river basins. River basins form a hydrological mosaic, with an estimated 263 international river basins covering 45.3% of the land surface area of the earth, excluding Antarctica [23].

As illustrated in Fig. 5, about 35% of the area of the continents (excluding the Antarctic) is underlain by relatively homogeneous aquifers (blue) and 18% is endowed with groundwater in geologically complex regions (green). Most of the remaining continental area contains generally minor occurrences of groundwater that are restricted to the near-surface unconsolidated rocks (brown) [24].

In spite of a continual increase in the use of desalinated saltwater, Rivers and aquifers will continue to be the major sources of our freshwater in the foreseeable future.

4 Where is there not enough water?

As Figs. 1 through 3 suggest, over time an increasing number of places will not have adequate water supplies to meet all water demands, all of the time. Such regions are under water stress. And climate change may be causing less freshwater runoff in major regions of the world [25], as shown in Fig. 6.

Source: United Nations Environment Programme (UNEP): World Conservation Monitoring Centre (WCMC): World Resources Institute (WRI): American Association for the Advancement of Science (AAAS): *Asias of Poputation and Environment.* 2001.

Fig. 4 Major river basins in the world (http://maps.grida.no/go/graphic/major_river_basins_of_the_world)

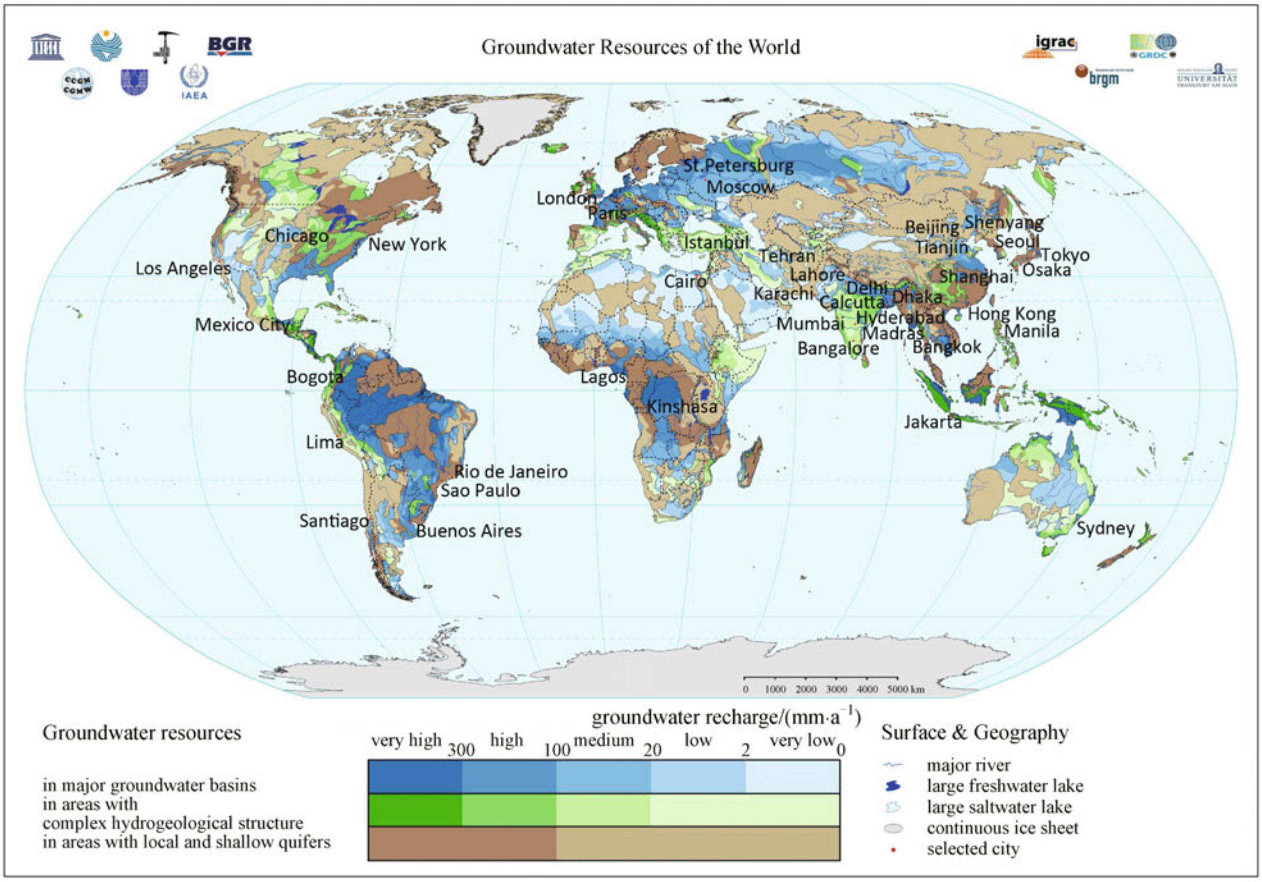

Fig. 5 Major groundwater aquifers in the world (http://www.bgr.bund.de/cln_109/nn_324520/EN/Themen/Wasser/Bilder/Was_wasser_startseite_gw_erde_g_en.html)

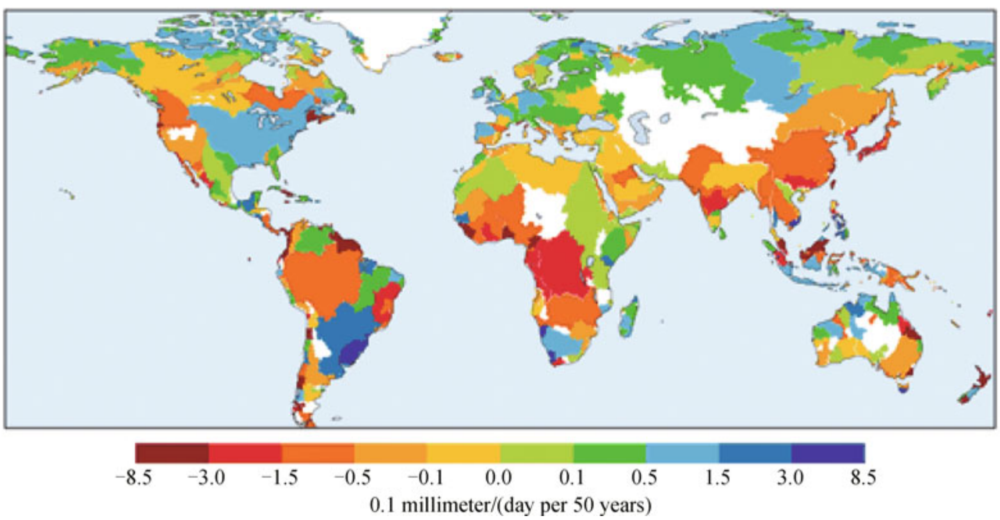

Fig. 6 Change in run-off inferred from streamflow records worldwide between 1948 and 2004, with bluish colors indicating more streamflow and reddish colors less (http://www.ucar.edu/news/releases/2009/flow.jsp)

During the 1948–2004 period there was considerable year-to-year variation in the flow of many rivers, but the overall trend showed annual freshwater discharge decreasing. Rivers showing declines in flow include the Yellow River, the Ganges, the Niger, the Colorado, the Amazon, the Congo, the Changjiang (Yangtze), the Mekong, the Irrawaddy, the Amur, the Mackenzie, the Xijiang, and the Columbia. Many of these serve large populations.

The countries of the Near East and North Africa face the greatest water stress (see Fig. 1). The Near East is the most water-short region in the world. The entire Near East uses more water from rivers and aquifers every year than is being replenished. Over the next two decades population increase alone — not to mention growing demands per capita — is projected to push all of the Near East into water scarcity. Many Near East countries are mining fossil groundwater to meet their water needs. Water is one of the major political issues confronting the region's leaders. Since virtually all rivers and most aquifers in the Near East are shared by several nations, current tensions over water rights could escalate into outright conflicts, driven by population growth and rising demand for an increasingly scarce resource [26].

Four Gulf states — Bahrain, Kuwait, Saudi Arabia, and the United Arab Emirates — have so little freshwater available that they resort to desalinization of sea water. Without desalinization, the Gulf States would be unable to support their current populations. Desalinization is too expensive and impractical for most water-short countries, not to mention land-locked countries, either today or in the foreseeable future.

Much of sub-Saharan Africa is facing serious water constraints. Rapid population growth will make this problem worse. By 2025 some 230 million people will be living in African countries where water is scarce [2].

Parts of many large countries, such as China, India, and the United States, face water stress or water scarcity as well. India as a whole is expected to enter the water-stress category by 2025. Both India and China are considering substantial, and expensive, water transfers from water richer to water poorer regions to reduce some of that water stress. And if the glaciers of the Himalayan mountains and Tibetan plateau continue to retreat this will have a substantial impact on hundreds of millions of the world's population that depend on that water flowing in rivers such as the Indus, Sutlej, Ganges, Brahmaputra and the Yangtze, Salween, Mekong and Huang He (Yellow River) [27].

China has over 20% of the world's population but only about 7% of the world's freshwater runoff. Water pollution, over-exploitation of underground water and low efficiency of water usage along with water shortages have continuously deepened the imbalance between water supply and demand in China [28]. China's freshwater supplies have been estimated to be capable of adequately supplying only half of the country's current population. Despite periodic flooding in the south, along the Yangtze River, China faces chronic freshwater shortages in the northern part of the country. Two thirds of China's major cities, including Beijing, face critical water shortages each year. The water table under Beijing has been dropping by roughly two meters per year [29].

In the US, groundwater reserves are being depleted in many areas. Overall, groundwater is being used at a rate 25% greater than its replenishment rate. In some areas of the western part of the country, groundwater aquifers are being depleted at even faster rates. In particular, the Ogallala aquifer, which underlies parts of eight states (shown in light blue in Fig. 5 and totaling 173000 square miles), provides irrigation and drinking water for one of the major agricultural regions in the world. Withdrawals from the aquifer amount to about 30% of the nation's ground water used for irrigation. Additionally, the aquifer provides drinking water to 82% of the people who live within the aquifer boundaries. In some regions of Texas and Kansas half of its available water has been withdrawn [30].

5 Competition for scarce water supplies

Where and when water is scarce, competition among water users increases, and hence so does the potential for conflict. A number of developed water-short countries currently face tensions over water, including Belgium, the UK, Poland, Singapore, and the US. In southern Britain, for instance, urban demand for water is outpacing the capacity of rivers and aquifers to meet that demand during the drier summer months. In the western US, farmers who want more irrigation water for their crops are in conflict with growing urban areas that demand more water for households and other municipal uses.

India's states have disputes over water rights and over dams that might provide more water for one state but at the expense of another. Water disputes, if not attended to, could become a major cause of instability in India.

China already is practicing what some call the "zero sum game of water management". The zero sum game — when authorities increase water supply to one user by taking it away from another — is played both between competing areas of the country and between competing types of use, as when cities compete with farmers. China's Yellow River is so oversubscribed that, for an average of 70 days a year for the past decade, its waters have dried up before reaching the coast. In 1995 the dry period lasted for 122 days. To meet urban needs, the government of China is constructing an aqueduct that will carry water from the Danjiangkou Reservoir in Hubei Province to Beijing, across 1300 km of heavily farmed land — land that also needs the water for food production [31,32].

In nearly all water-short areas the threat of regional conflicts over limited water supplies is emerging as a serious issue. In Africa, for example, about 50 rivers are shared by two or more countries. In particular, access to water from the Nile, Zambezi, Niger, and Volta river basins has the potential to create conflicts.

In Central Asia, the Aral Sea Basin is beset by international conflicts over water. Turkmenistan, Uzbekistan, Kazakhstan, Kyrgyzstan, and Tajikistan all depend for their survival on the waters of the Amu Darya and Syr Darya rivers. The flows of both rivers have been almost wholly diverted to feed water-intensive crops such as cotton and rice. Very little if any water reaches the Aral Sea. As demand for this water grows, the countries are increasingly at odds over its division, with all five Central Asian republics demanding a greater share. Disputes are growing between Kyrgyz and Uzbeks over water and land in the fertile Fergana Valley; between Kyrgyz and Tajiks over the allocation of irrigation water from the Syr Darya; and between Turkmens and Uzbeks over the distribution of irrigation water from the Amu Darya.

The south-eastern Anatolia Project in Turkey, known as GAP after its Turkish title (Guneydogu Anadolu Projesi) comprising a network of 22 dams and 19 power plants has significantly reduced the downstream flow of the river Euphrates (and to a lesser extent the Tigris), causing increased salinity and seriously affecting agriculture. The GAP project poses a real threat to future water supplies in Syria and Iraq and hence is a potential source of conflict in a region already in conflict. Reduced releases of Tigris and Euphrates River waters due to GAP can only inhibit the restoration of some former marsh areas in southern Iraq. But this will not be the only reason for less than complete restoration success. Rapid reestablishment, high productivity, and reproduction of native flora and fauna in reflooded former marsh areas indicate a high probability for successful restoration, provided the restored wetlands are hydraulically designed to allow sufficient flow of non-contaminated water and flushing of salts through the ecosystem. To avoid conflict over water, cooperation among all riparian countries will be necessary [33].

In the US, the Colorado River, which flows through the south-western part of the country, has fed irrigated agriculture and enabled the rapid growth of desert cities. Now, however, demands on the river's water supply for irrigation and urban use have become so great that the river flow no longer reaches its mouth in Mexico's Gulf of California. Instead, it trickles out somewhere in the desert south of the US-Mexican border. The premature disappearance of the river's flow has been a source of irritation between the US and Mexico [18,22,34,35].

In light of all these potential serious conflicts, and need for water to drink, to produce energy, to serve industry and to irrigate crops, just how easy is it going to be to allocate some of what is needed for these other uses to environmental flows?

6 Estimating ecosystem water requirements

Economics teaches us that to achieve maximum net benefits, the allocation of any scarce resource to multiple uses over space and time should be such that the present value of the marginal net benefits derived from each use, unless otherwise constrained, are all equal. That advice is useful, perhaps, if net benefit functions can be defined for all uses and if everyone agrees that maximizing the present value of total net benefits is a reasonable goal for water management. Even if everyone agrees that this goal is worth pursuing, defining net benefit functions is very difficult when it comes to water needs to sustain life. So, the question is what criteria should be used to determine just how much should be allocated to maintain healthy humans and their ecosystems [3].

Different ecosystems in different regions have adapted to different flow regimes. But in any region, the fundamental requirement for maintaining aquatic ecosystem health is to maintain critical components of the natural flow regime. Natural freshwater ecosystems have adapted to and depend on natural hydrologic variability. The structure and function of freshwater ecosystems are also linked to the watershed, or catchment, of which they are a part. Aquatic ecosystems are the recipients of materials generated from the land, and hence they are greatly influenced by terrestrial processes, including human modifications of land use and cover. The environmental drivers that influence freshwater ecosystem structure and function include not only the flow regimes, but also the accompanying sediment, organic matter, nutrients and various pollutants, the thermal and light characteristics, and the interactions among the mix of species making up the ecosystem and in turn, their combined interactions with the water and land [36,37].

The water stress indicator (WSI) map shown in Fig. 7 applies to environmental water needs — the amount of water needed to keep freshwater ecosystems in a fair condition [38]. It was developed using global models of hydrology and water use. Red areas show where environmental water needs are not being satisfied because too much water is already being withdrawn for other uses.

Estimating just how much water should be allocated to instream environmental flows, particularly in data-poor arid areas, can be challenging. Those deciding on what water allocations to recommend or make can benefit from having models that can predict ecosystem and geomorphologic responses to flow changes, and the impacts of such changes on other users of the rivers. Generally these predictions depend on several characteristics associated with the flow regime. These include base flow, annual or frequent floods, rare and extreme flood events, and annual variability. Flow regimes and hydroperiods also influence

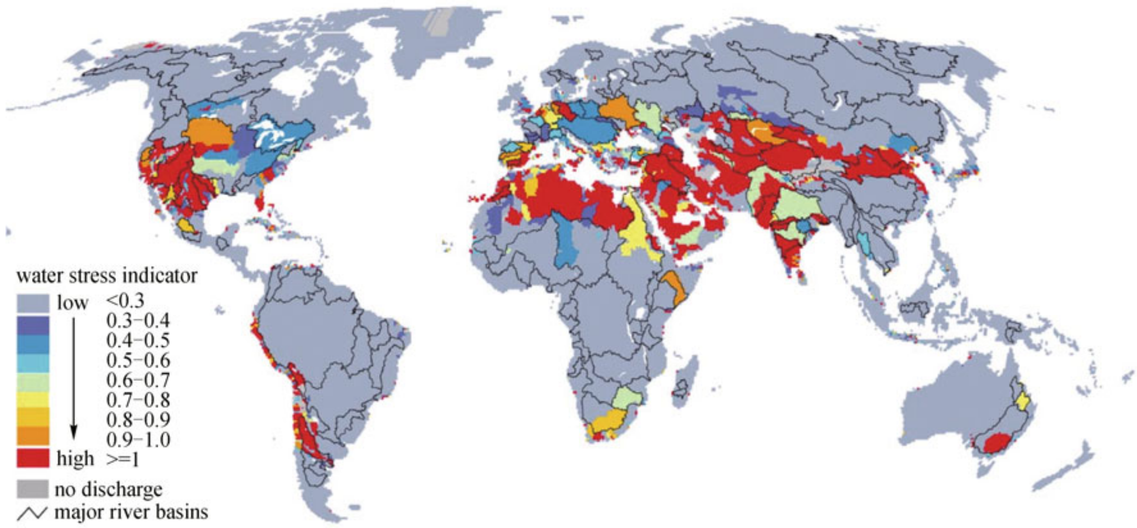

Fig. 7 A current water stress indicator map that shows regions where environmental flow needs are not being met (http://www.cgiar.org/enews/june2007/story_12.html)

the circulation patterns, renewal rates, and types and amounts of aquatic plants in lakes and wetlands. So it is not just a minimum required flow that is needed, it is a regime of varying flow conditions. This adds to the complexity of ‘allocating’ flows to the environment during periods of water supply stress.

7 Quantifying ecological responses to water management policies

One approach to quantifying the relationships between water regimes and ecosystem responses is to link hydrologic attributes (that can be managed) to the quality of the habitat of key species indicators. The use of these habitat suitability index methods tends to be concentrated in the northern hemisphere and in developing countries influenced by the work of ecologists in the United States and Europe. More holistic approaches are being applied in the southern hemisphere, especially in South Africa and Australia [39].

Environmental flow assessment (EFA) methods are termed holistic if they address the management of all non-pristine river ecosystems, all major abiotic and biotic components of the ecosystem, and the full spectrum of flows and their temporal and spatial variability [11]. This typically requires the use of various models or modules of a larger ecosystem response model, such as:

1) A biophysical module designed to maximize understanding of an aquatic ecosystem and predict the effects of flow change on the stream, wetland, lake or river;

2) A social module designed to maximize understanding of how people use the water resources and to predict how they would be affected by changing flows and qualities;

3) A module used to compile scenarios of hydrologic changes and the impact on people; and

4) An economic module in which the costs as well as the benefits of development scenarios can be identified and evaluated.

The EFA approach makes the condition of the water body a priority management issue while still considering economic benefits. It is designed to identify the trade-off between economic development benefits and the maintenance of sustainable ecosystems. EFA implementation is not an issue for managers alone; scientists need to work side by side with managers to ensure its success and usefulness [40].

8 Management actions and challenges

Human society is served in the long-term by ecosystem sustainability. We must develop policies that more equitably allocates water resources between natural ecosystem function and societal needs. Our welfare depends on it.

How can society extract the water resources it needs while not diminishing the important natural complexity and adaptive capacity of freshwater ecosystems? The requirements of freshwater ecosystems are often at odds with human activity, although this need not always be the case. Our present state of ecological understanding of how freshwater ecosystems function allows us to elaborate the requirements of freshwater ecosystems regarding adequate quantity, quality, and timing of water flows. Effective and timely communication of these requirements to a broad community is a critical step for including freshwater ecosystem needs in future water allocation decisions. Stakeholders must be involved in decision making if any restoration policies are to be sustainable. And that is a major challenge to the water resources management profession [41,42].

For scientific knowledge to be implemented science must be connected to the political decision making process. Scientists must explicitly identify and incorporate aquatic ecosystem needs in national and regional water management plans and policies. They must include watersheds as well as water in those plans and policies so that water resource allocation decisions are viewed within a landscape, or systems context. Scientists must educate and communicate across disciplines, especially among engineers, hydrologists, economists, and ecologists to facilitate an integrated view of water resource management. Regional environmental managers must include restoration efforts and protect the remaining freshwater ecosystems using well-grounded ecological principles as guidelines. All stakeholders must recognize and acknowledge the dependence of human welfare on naturally functioning ecosystems. All must assist in the development of coherent policies that equitably allocate water to maintain functioning natural ecosystems as well as meeting other societal needs [22]. Clearly more research is needed to help identify just how this can best be done in specific situations in the face of non-commensurate quantitative and qualitative performance measures.

9 Conclusions and perspective

Ecological processes are often viewed as occurring in remote and exotic places, not as essential to our daily lives, or strongly influenced by our actions. Actually, ecosystem sustainability requires that human society recognize, internalize, and act upon the interdependence of people and the environment. This will require broad recognition of the sources and uses of water for human health, societal and ecological needs. It will also require taking a much longer time view of water resource management and its associated infrastructure.

Water delivery systems, including dams, are developed with lifespans of decades, and some operate over a century. However, aquatic ecosystems have evolved over much longer periods of time, and their sustainability must be considered for a long period to come. Governmental policies, mass media, and market-driven economies all tend to focus more on perceived short-term benefits. Local watershed groups interested in protecting their natural resources provide a first step toward long-term stewardship. They need to be matched by state and national policies that recognize that fundamental human needs for water will continue on forever (or certainly into the distant future) and can only be sustained through decisions that preserve the life-support systems in the long-term.

Water uses, as critical or desired as they are, that have negative impacts on the environment cannot be sustained. Especially in times of water scarcity, the environment may have to suffer some because of higher priority uses, but it cannot suffer for long. By satisfying the need for naturally varying flow regimes, and reduced pollutant and nutrient inputs, natural aquatic ecosystems can be maintained or restored to a sustainable state that will continue to provide the amenities and services society requires and has come to expect. Managers are challenged, especially in times of water stress, to meet both humans and ecosystem needs, now and in the future. And with increasing population pressures and climate change impacts, periods of water stress will likely increase in duration and intensity.

It is indeed time to focus our attention on how best to allocate our increasingly variable and uncertain water supplies to meet increasing demands in a way that optimizes water for all life, for the sake of our own and that of our descendents.

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