The Future of Global Water Scarcity: Policy and Management Challenges and Opportunities

by J.C. Padowski and J.W. Jawitz

Water is a ubiquitous natural resource covering approximately three-quarters of the Earth's surface. However, almost all of the water on the planet (over 97 percent) is saline ocean water, unusable by most terrestrial organisms. Of the remaining three percent, more than two-thirds is sequestered as ice and snow at high elevations or latitudes and is functionally unavailable, leaving less than one percent of global water as both fresh and potentially available for meeting human needs (Figure 1).[1] While this fraction of available fresh water is small compared to the overall volume of water on the planet, this supply has been sufficient to meet historic needs. During the past century, water availability has become a prominent global concern, particularly as demands for fresh water have grown beyond our capacity to meet them.

Inefficient or non-existent water management regulations and policies, often combined with a lack of financial capital and a poor understanding of how local systems function, have perpetuated unsustainable water management practices. As a result, over-allocation and inefficient use of local water resources have significantly diminished supplies in many areas.[2] Groundwater mining—where water resources are removed at rates exceeding that at which they are recharged—has led to dramatic drops in water table levels in India, the United States, China, and Mexico threatening water supplies, the health of local ecosystems, and future food security.[3] Water quality degradation exacerbates these problems as pollution, poor sanitation, industrial waste, and salinization render available water sources unusable.

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In response to these problems, more governments are discarding old water management practices that ignore the socio-economic and environmental aspects of water use,

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and instead are adopting a new management framework that re-envisions water from a more holistic perspective. This paradigm shift on water resource use and development is designed to promote sustainability by accounting for the full range of water needs (social, economic, environmental) across sectors (agriculture, urban, industrial, ecosystem) through institutional coordination (local, regional, national, international). While the new framework seeks to integrate multiple facets of water resource development, this additional complexity makes implementation more difficult. This commentary highlights the extensive differences between the new framework and past management practices, and argues that future policies must actively support sustainable water management practices in order for these practices to succeed.

Defining Water Scarcity

Water scarcity is determined to occur when there is not enough clean water to meet human needs; however, more complex assessments may take into consideration environmental needs, individuals' capacity to access local resources, and multiple spatial or temporal scales.[4,5] Since there is no universal standard for how water scarcity should be analyzed, several measures currently exist for assessing global water scarcity. The Falkenmark Water Stress Index (1989) is one of the earliest assessments and measures water availability as a function of population, accounting for differences between "genuine" water scarcity—a lack of water due to climate or drought, and "human-induced" water scarcity—a reduction in water availability due to poor management or overpopulation.[6] Based on this definition, "degrees of scarcity" ranging from "limited water stress" (>1,700 m^3/person/year) to "absolute water scarcity" (<500 m^3/person/year) were developed based on a per capita minimum of 100 liters per day. While scientists have used this simple measure frequently over the past two decades to assess global water scarcity, others have developed alternative indices and assessments of varying complexity. Rijsberman[4] provides a useful review of the most commonly referenced global water scarcity indexes, including the Water Poverty Index and the Water Scarcity Index. The Water Poverty Index calculates scarcity by utilizing a set of qualitative and quantitative measures to determine the needs of both humans and ecosystems.[7] The International Water Management Institute's (IWMI) Water Scarcity Index breaks down water scarcity into "physical water scarcity," in which there are not sufficient water resources to meet agricultural, domestic, industrial and environmental needs, and "economic water scarcity," in which there are sufficient water resources, but access to them requires additional financial and infrastructural development.[8]

The rapid and unprecedented growth in water demand has outpaced the ability of many ecosystems and the human management thereof to supply clean water to every individual.

While the definition of water scarcity remains vague, the problem is real. The global human population has more than doubled since the 1950s from approximately three to six and a half billion people, and is predicted to reach nine billion by 2050.[9] Meanwhile, historic trends have shown water use to be increasing at approximately twice the rate of population growth as more fresh water is required not only for basic drinking needs, but for food production, industry, and improving human health.[10] This rapid and unprecedented growth in water demand has outpaced the ability of many ecosystems and the human management thereof to supply clean water to every individual. According to the water scarcity assessment issued by IWMI in 2006, water scarcity issues are a major problem for sub-Saharan Africa, the Middle East, and parts of Asia and North America (Figure 2).[11] As of 2000, the United Nations reported that approximately one billion people lacked access to safe drinking water and almost two and a half billion lack adequate sanitation.[12]

In addition to basic drinking water needs, growing needs for food have increased water demands for agricultural production. According to current global monitoring assessments of water withdrawn for human purposes, agriculture is by far the largest user of water, appropriating an estimated 70 percent of total water withdrawals.[13] On a national scale, water use generally depends on the level of economic development. Low income, developing nations tend to have smaller per capita water withdrawals, however, the majority of the water extracted is used for agricultural, rather than domestic or industrial, purposes (Figure 3). In general, withdrawals for agricultural irrigation purposes have grown rapidly since the 1930s, resulting in a five-fold increase in the global area of irrigated lands, and generally high and stable yields of crops throughout the growing season, independent of meteorological conditions.[13]

Today, there are a multitude of international organizations focused on water and water scarcity issues at the global level; the United Nations alone has twenty-six sub-organizations to deal with such issues. The complexity of the current efforts to evaluate and manage these issues speaks to the even greater complexity of the water cycle itself. Our accessible fresh water resources consist of water in aquifers, lakes, rivers, soil and the atmosphere. The majority of these resources are constantly renewed through a hydrologic cycle of condensation, precipitation, infiltration, runoff, and evaporation. Water is dynamic, not only in this cyclical sense, but varies significantly on both spatial and temporal scales. Weather patterns, topography, and geography dictate where and when precipitation will occur, and how much water an area will receive. Depending on the location, rainfall amounts can vary by orders of magnitude, from approximately 0.1 cm/yr to over 1300 cm/yr.[14] This rainfall, however, is often unevenly spaced throughout the year. Temporal variations, due to seasonality or extreme weather events such as floods and droughts, can have severe local or regional short-term impacts, but may not be detectable over averaged, long-term assessments. The effects of human management further compound the difficulties associated with assessing the status of water resources.

The shifting water management paradigm

Prior to the Industrial Revolution, methods used by humans to withdraw water from the natural hydrologic cycle relied on passive gravity-driven techniques or low-energy human and animal power. Limits on the amount of extractable water were dictated less by human aspirations than by the level of technology or the natural laws controlling the physical system. Today, however, there is growing evidence that this natural hydrologic balance has been disrupted. As we have little control over our meteorological conditions, water management frameworks are being scrutinized for their role in both solving and causing water scarcity.

Traditional management and the "technological fix"

The water management framework of the industrial era developed as a means for reducing natural water scarcity as growing human demands put increasing pressure on locally available water resources. This management framework was deeply rooted in technological innovation as a means for controlling and redistributing water and had two primary goals: to support economic development, and to increase the availability of fresh water in anticipation of growing needs.[15] To meet these goals, water managers typically increased the use of fossil fuel-driven technology and large infrastructure to implement supply-side solutions by controlling, extracting, and storing more water from the natural hydrologic cycle.[16,17] As a result, societies have been commandeering water resources at rates previously unimaginable, largely keeping pace with population growth, and providing water and food to millions who would otherwise go without. Today, at least 14 percent of countries monitored by the Water Resources Institute have reached the local limits of this trend, withdrawing more water than is produced within their borders.[18] These countries are mostly in arid regions and rely heavily on either trans-boundary sources or purchase water from other nations. As demands continue to grow; however, the external supplies these nations have come to depend on may no longer be available as upstream users require more water to keep up with population growth (Figure 4).

In an effort to reduce humanity's susceptibility to water scarcity, traditional management has implemented an unprecedented number of new engineering projects that have brought water to millions in need, however, these solutions have also created a new set of problems. In addition to the substantial financial cost of these extensive modifications to the land- and waterscapes, other unforeseen costs have been incurred in the form of ecosystem degradation, disruption to natural processes, and the displacement of millions of people.[19]

Assessing our current water problems from a technological perspective allows us a better understanding how traditional water management has affected our relationship with this resource. Inexpensive energy, either from hydropower or fossil fuels, and the widespread use of motorized water pumps for agricultural irrigation has made it possible to grow and produce foods in regions that were previously inarable or produced poor yields, expanding the total area in which humans can thrive. Advances in low-cost power and pumping technology have also given millions of people access to previously unavailable groundwater reserves. India alone has between 15 and 17 million motorized dug and tubewells, which are used to pump groundwater, irrigating approximately 70 percent of the nation's agricultural lands.[20] As a result, the overexploitation of aquifers is a now common problem around the world as more water is removed from underground reservoirs than is recharged. Groundwater mining is permanently removing approximately 10 km^3 of water on the North China Plain per year, and about 5 km^3 per year in Mexican aquifers.[21] In some cases, the continual removal of groundwater has led to dramatic declines in water table levels and instances of regional land subsidence, where aquifer collapse has led to substantial drops in aquifer yield capacity and land elevation in places such as California's Central Valley (9m), Shanghai (2.6m) and Mexico City (9m).[22]

The expanded use of large water control structures, like the proliferation of pumping wells, has been increasingly scrutinized and criticized. Dams, levees and canals have been used for centuries to manage water resources; however, recent technological advances have allowed these structures to be scaled to colossal proportions. Large dams now represent some of the most sizable man-made structures and are seen by many as symbols of technological progress in the form of flood protection, secure water provision, and power generation.[23] Today, tens of thousands of dams (Figure 5) protect millions of people from floods and droughts, as well as provide reliable water supplies for irrigation, domestic needs, and electricity through hydropower.[24] In the developed world, dam construction has all but halted as appropriate sites have dwindled; dams have already been built on almost every major river network. In contrast, construction continues in the developing world as large dams are sought for the technological and economic benefits they provide. Yet, relative to previous decades, the pace of construction has slowed considerably due to increased awareness of the effects of hydrologic modifications on both natural systems and downstream users. Natural fluctuations in water levels on many dammed rivers have all but ceased, reducing flood events, but also impacting riparian ecosystems. Upstream diversion of river flows significantly diminishes downstream flows, interfering with not only the reproduction and success of many aquatic species but also destroying the livelihoods of those who depend on both the water and those aquatic resources.[25]

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From natural to human-induced water scarcity

While traditional water management has eliminated many instances of "natural" water scarcity by reducing our vulnerability to meteorological variability, it has created opportunities for "artificial" or "human-induced" water scarcity. As the hydrologic cycle has been brought under human control, new water conflicts have arisen, often manifesting as juxtaposition between those who have plenty, and those who have little. This type of scarcity is commonly observed in the urban areas of developing countries where the costs of water provision create divisions between those who have access to water and those who do not. Urban areas typically rely on water utilities to supply water, a method requiring significant financial investments to not only obtain and clean the water supply, but to create, expand, and maintain the piping network and other infrastructure necessary to deliver water to the user endpoints. The financial costs associated with the creation and operation of a water utility are generally expected to be recovered through a customer's payment for services rendered. Extending services to those who cannot afford the payments can make cost recovery and the survivability of the utility impossible. Therefore, utilities only provide coverage and infrastructure to those who can afford it unless other mechanisms are put in place to subsidize the costs of supplying water to the poor.[26]

In other cases, this human-induced water scarcity is ironically the product of the same technology originally designed to relieve water stress. Water control structures such as dams give some users control over water sources, essentially granting them the power to decide when and how much water other users receive downstream. Many instances of this type of human-induced water scarcity have occurred over the past century; dams on the Euphrates river system have spawned conflict between Turkey, Iraq and Syria.[27] Disagreements over allocation and the timing of delivery have arisen between upstream and downstream users in the Colorado and Apalachicola-Chattahoochee-Flint river basins within the United States,[28,29] the Nile river basin in Africa[30], as well as in the Yellow River basin in China.[31]

Motorized water pumps have mobilized millions of users into the business of groundwater removal upsetting the natural balance between water recharge and water withdrawal. Water scarcity issues are particularly prominent in India, where several regions have seen steep declines in groundwater levels due to extractions for both irrigation and water farming—the business of pumping and selling groundwater. For example, landholders in Tirupur are selling their groundwater to the industrial sector in lieu of growing crops.[32] Groundwater exploitation has become increasingly important to sustain global food production; approximately 36 percent of global agricultural yields are from irrigated lands.[33] The United States, China, India, and Pakistan account for more than 50 percent of the world's irrigated land, most of which relies on water from diminishing aquifer supplies.[34,35] Thus, groundwater mining, while seemingly beneficial in the short-term, has serious long-term implications.

Integrated Water Resource Management- the new face of water management

While the traditional management framework has undeniably allowed modern society to flourish, the long-term environmental and human implications associated with this framework have become increasingly unacceptable to society. Many managers have expressed a renewed commitment to providing basic water services to all individuals through demand management, a solution that emphasizes improvements in efficiency and conservation rather than acquiring additional supplies.[36] In addition, formal institutional recognition of the importance of "ecosystem services," or those natural functions provided by ecosystems that directly or indirectly benefit humans (e.g., waste assimilation, water purification, nutrient recycling), for promoting sustainability and reducing economic expenses have convinced many that allocating water for the environment can be a worthwhile investment.[37] As a result of these changes, a new era of water management began in the 1970s with what is widely regarded as a "profound paradigm shift" in water resources management.[38,39] Today, this paradigm shift describes the transition from a traditional supply-oriented, infrastructure-based water management framework to one that places a growing emphasis on meeting both basic human and environmental needs for water in an equitable and sustainable manner.[40]

This new management framework, often referred to as "Integrated Water Resources Management" (IWRM), is fundamentally different from traditional management in that it embraces a more holistic view of the socio-economic-natural linkages that connect water users and resources.[41] One of the major differences between IWRM and traditional management is the use of participatory planning and stakeholder involvement at the watershed scale in support of policies that benefit all water users. Key tenets of IWRM are the management of demand (rather than supply) by increasing technological and financial efficiency, and the decentralization of water management to regional and local authorities.[42]

Major global organizations such as the United Nations, USAID, and the International Water Management Institute support IWRM, providing information and support to nations interested in reorganizing and reprioritizing how they use their water resources. To date, dozens of countries have implemented IWRM for a wide variety of water-related issues, with some of the most publicized cases related to international water conflicts. For instance, IWRM has helped mediate disagreements over the water and resources of both the Mekong and Nile rivers.[43, 44]

Today's challenges for water management- Addressing water scarcity

While the IWRM framework is designed to promote social, economic, and environmental sustainability, actual implementation of these principles has provided a host of new challenges. Now, water managers must not only meet growing human demands, but ideally must be responsible for short- and long-term environmental and social impacts of their management decisions as well. These new responsibilities pose a daunting new set of social, environmental, and economic policy concerns, which can only be addressed through the thoughtful re-examination of our current water institutions.

Water Institutions

Water scarcity is a complicated problem that spans multiple scales and affects a myriad of users in different ways. To best manage a resource of this complexity, it is advantageous to pool the collective knowledge, previous experiences, and value judgments of users into one framework from which managers draw when making decisions about how best to use the resource. This "codified knowledge" is the basis of any institution, and serves as a proxy for understanding systems with high degrees of complexity and uncertainty. In water resources management, different groups can use this shared information to coordinate interactions, provide structure, and define rules about humanity's role in the hydrologic cycle.[45]

For institutions to be successful, different stakeholder groups, such as politicians, lawyers, scientists and citizens must be able to effectively produce and implement meaningful policies at all governmental levels.[46] However, major disconnects, both between and within groups, exist in the current institutional framework. Many countries have unclear or poorly designed laws for regulating the use of water resources, limiting the effectiveness of even well-intentioned policies.[47] Disconnects also emerge when management is compartmentalized into specific topics such as "water quality" or "water allocation"; as focusing on only one aspect ignores the intrinsic and complex connection between all water resource problems.[48] Separating these issues across a variety of agencies creates gaps and doubles standards in the regulations and rules, making it difficult for managers to determine fair allocations, both between and across the range of environmental and human needs.[49,50] Finally, disconnects are present when traditional and/or political barriers exclude certain groups or when there is poor communication between stakeholders. Inefficient or poor communication can reduce the quality and quantity of information exchanged, as well as the degree to which groups coordinate and cooperate to manage water resources.[51,52] This communication disconnect is perhaps the most important, as acquiring and applying knowledge is one of the primary mechanisms though which institutions and management operate.

New outlooks, new solutions

The process of deconstructing and reconstructing water management during this "paradigm shift" has not only led to new knowledge and strategies for meeting human and environmental needs, but has laid a framework from which fresh ideas about humanity's role in the hydrologic cycle have evolved. This new understanding has profoundly changed the way we think about water scarcity For example, the concept of "virtual water," introduced by Allen in 1998 to quantify water consumption in agricultural practices, evaluates how much water humans move across basins, which countries are experiencing net water losses, and which are experiencing net gains. [53] While not developed directly for assessing water scarcity, this method is now frequently used to predict the future water supplies of nations.[54, 55] The assessment by Islam et al. was one of the first attempts to predict future water availability by directly linking the impacts of virtual water imports and exports on a nation's susceptibility to water stress as measured with the Falkenmark Index.[56] Using different scenarios, these authors predicted best- and worst-case estimates of water scarcity based on extent of virtual water trading and water availability (Figure 6).

Water scarcity problems are often related to land use practices, and therefore careful consideration should be given to these factors when performing regional planning assessments. Foley et al. reviewed recent research that details the effects agricultural and urban water consumption and disposal have on fresh water quality and quantity.[57] Kendy et al. further illustrated the direct relationship between land use and water availability by examining irrigation practices and water scarcity issues in the agricultural areas on the North China Plain.[58] Through this work, Kendy et al. identified evapotranspiration from crops as the major driver of groundwater depletion in the area, suggesting that no improvements to the irrigation methods, even the highly efficient drip irrigation system, would halt water table declines in the area. Rather, the evaporative water loss due to the high-intensity production of such water-intensive crops cannot be supported sustainably in the area. This study has major implications for the agricultural sector, as the results suggest that water availability should dictate land use, and not vice versa.

Concern over water scarcity has not only brought water issues to the forefront of international policy, but has spurred some fruitful discussion on how this issue may be resolved. By better understanding our role in the hydrologic cycle, we can identify why scarcity is occurring and what options are available for relieving this stress. How countries choose to do this (whether it is by importing/exporting water, changing policies about where people and agriculture can exist, or reconstructing their current management framework) depends on each unique situation. While those placed to make policy decisions have a daunting task ahead of them, the new knowledge produced through the recent paradigm shift in water resources management has provided many opportunities to develop a sustainable future. Therefore, while rainfall, climate, and geography will still impose physical limits on the resources available for human use, and many governments are still struggling to overcome socio-economic barriers to implement new programs, policies, and infrastructure, these new goals appear more realistic as the transition from traditional management practices to integrated water resource management continues through institutional reform and international cooperation. Success will depend on the level of resources and effort stakeholders and policy makers are willing to invest in sustainable water development, and the degree to which cooperation and coordination occurs both on a national and international level.

FIGURES AND TABLES

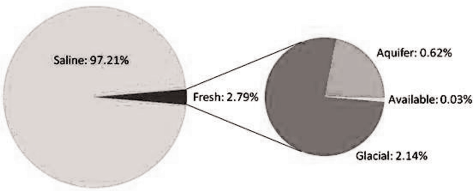


Figure 1. Compartmentalization of global water resources, with fresh water resources available for human use representing approximately 0.03 percent of all water on Earth.

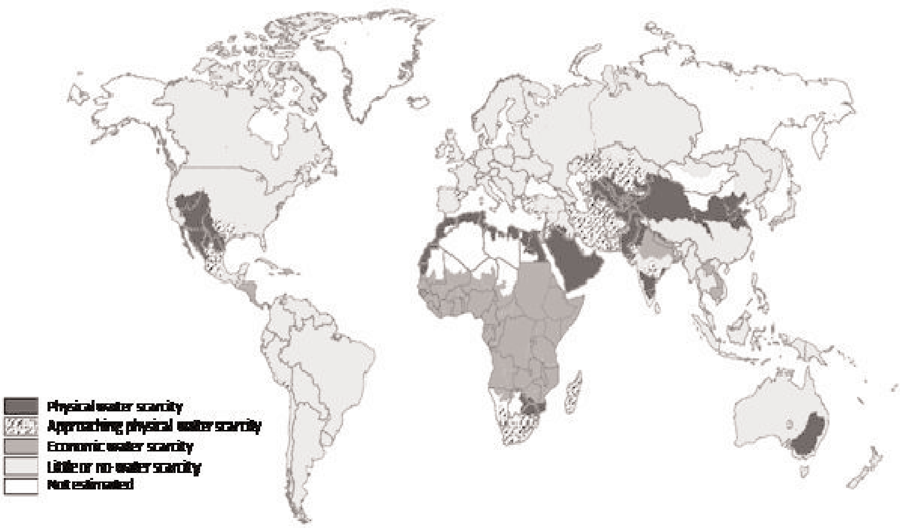


Figure 2. Current assessment of global water scarcity (Adapted from IWMI, 2006). Economic water scarcity was found to be a major stressor in sub-Saharan Africa, and physical water scarcity is predicted to grow in the lower latitudes of North America and throughout the Middle East and central Asia.

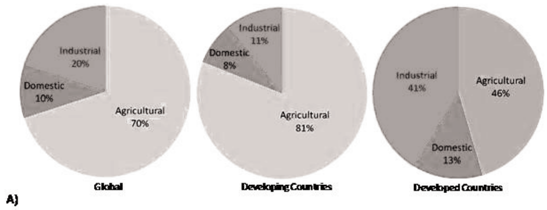
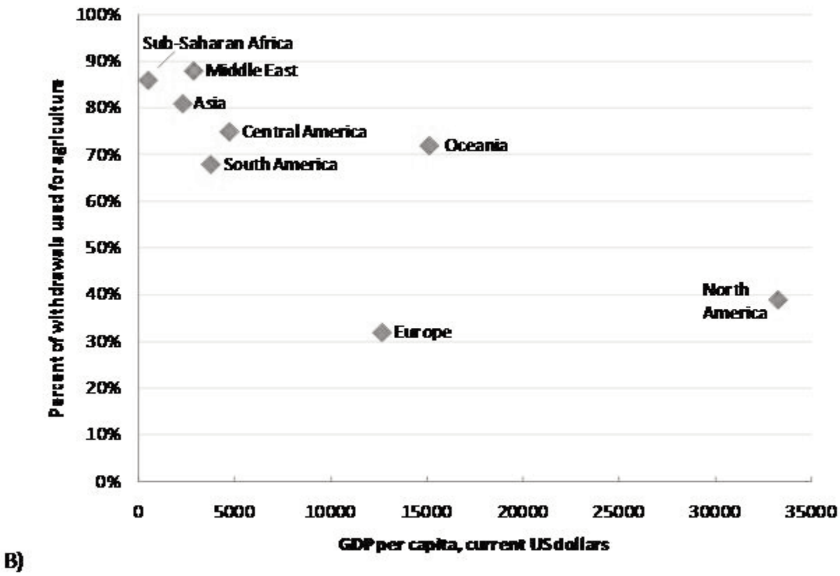


Figure 3. Global water withdrawals for 2000 A) by sector and B) as a function of gross domestic product (GDP).



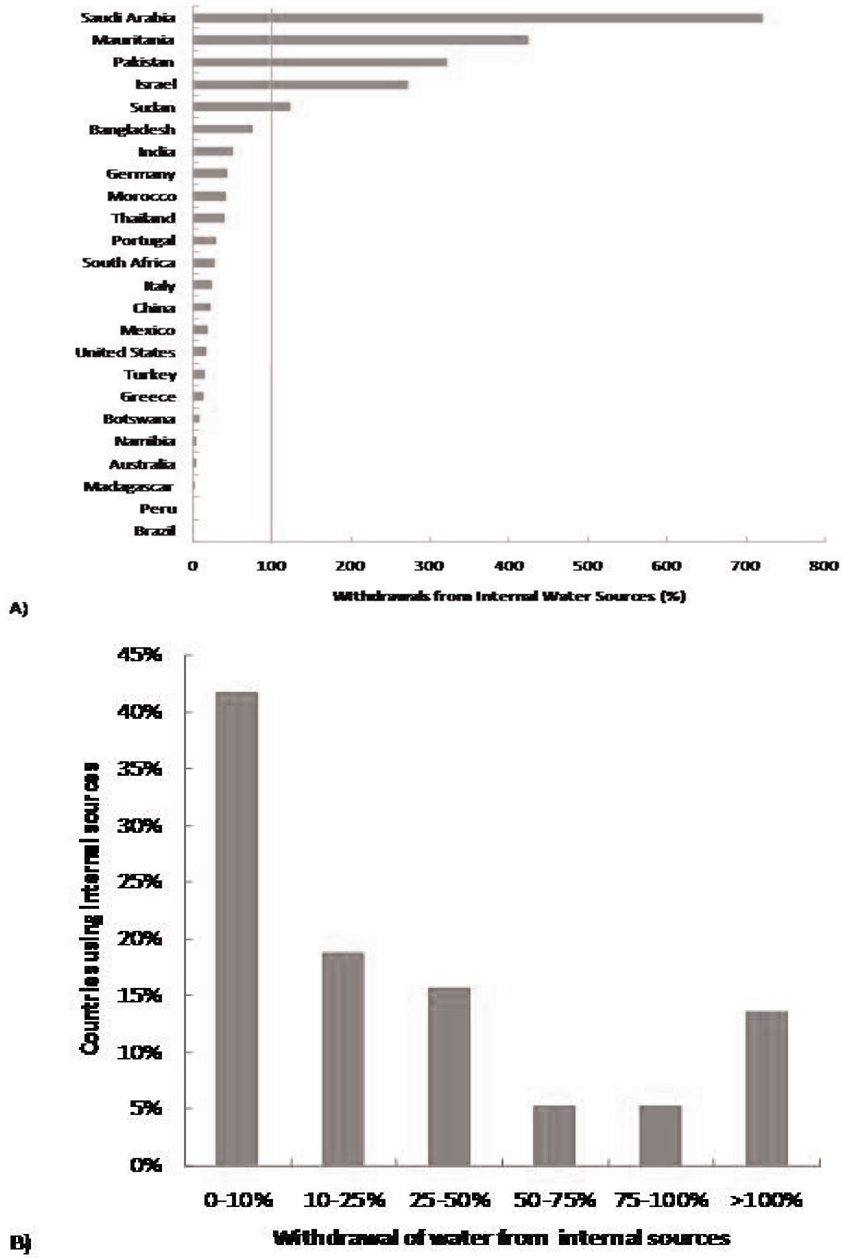


Figure 4 Annual water withdrawals as a percent of water produced internally A) within a selected sample of individual countries and B) as a percentage of the total number of countries monitored. (Data source: EarthTrends: Environmental Information. World Resources Institute).

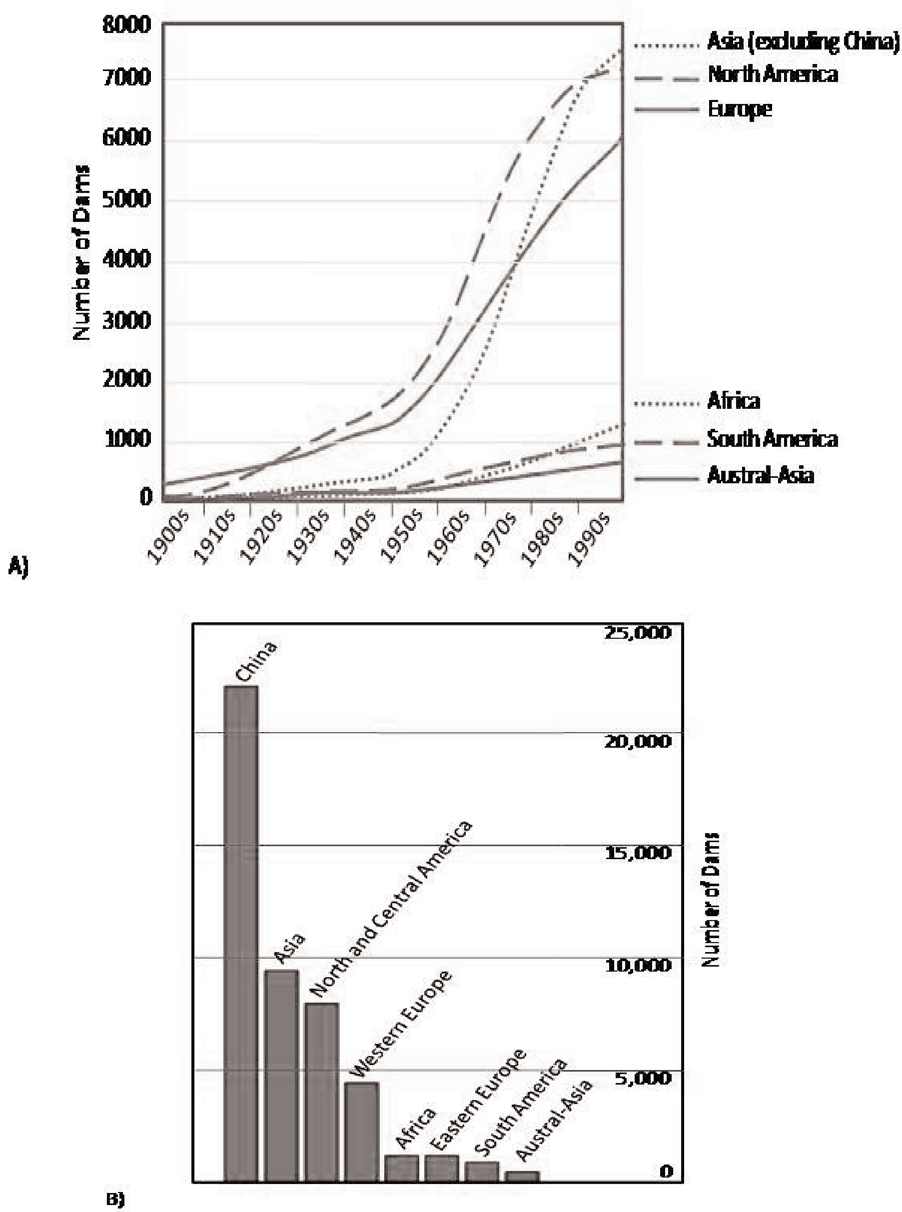
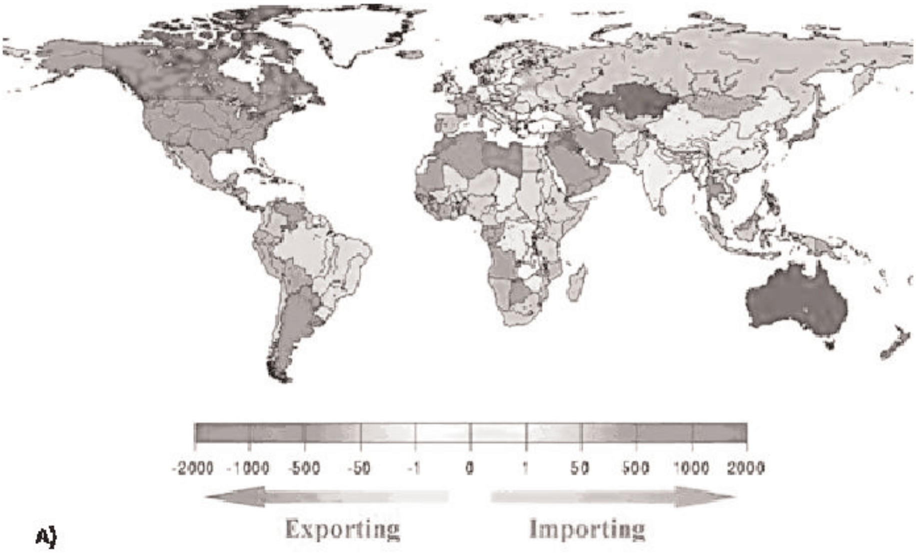
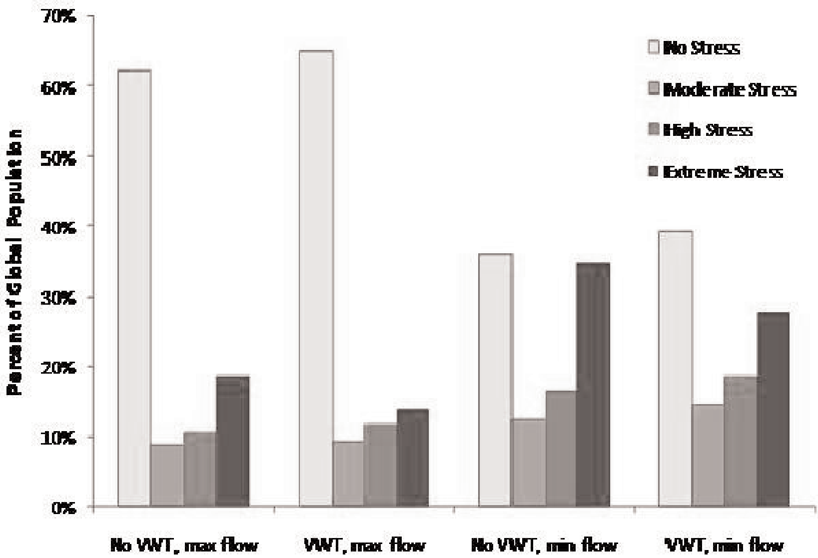


Figure 5. Regional distribution of dams A) over time and B) at the end of the 21st century. Both adapted from Dams and Development- A New Framework for Decision-Making. World Commission on Dams 45.



A)



B)

Figure 6. Global water scarcity assessment accounting for virtual water trading. A. Current net trading of virtual water (m^3/c/yr) (Source: Islam et al. 2007). B. Predicted future water scarcity depending on the use of virtual water trading (VWT) and the amount of upstream flow available to downstream users. (Data adapted from Islam et al. 2007).

Notes

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