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Rethinking Water Scarcity: The Role of Storage

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Water scarcity, in its simplest sense, can be defined as a shortage in the availability of freshwater relative to demand. Freshwater shortages directly affect food security, access to safe drinking water, hygiene and public health, and environmental well-being. Water scarcity can also retard economic development and promote civil strife. Robust measures of water scarcity are therefore required to inform water policy and help allocate resources to mitigate these effects.

The importance of such measures will increase dramatically over the next few decades as population growth and climate change shape the relationship between freshwater availability and demand in many regions of the world. According to current assessments, the number of people living under conditions of water scarcity is projected to double or triple within the next 40 years to between 3 and 7 billion [*Alcamo et al.,* 2003; *Arnell,* 2004; *Oki and Kanae,* 2006]. However, the exclusion of freshwater storage (e.g., groundwater, soil moisture, glaciers) from these projections critically undermines their ability to adequately represent water scarcity and profoundly constrains scientists' understanding of the global water crisis. Thus, new methods to assess water scarcity are critically needed.

Effects of Climate Change on Freshwater Storage

Current analyses of the impact of population growth and climate change on water scarcity use two widely adopted measures. The first holds that conditions of water scarcity exist when the per capita availability of renewable (annual) freshwater resources drops below 1000 cubic meters per person per year [*Falkenmark et al.,* 1989]. The second holds that water scarcity occurs when the ratio of estimated annual freshwater demand to availability exceeds 0.4 [*Vörösmarty et al.,* 2005]. In both of these measures, freshwater availability derives solely from observations and numerical simulations of mean annual river runoff (MARR). The use of MARR as a measure of freshwater availability supposes that river runoff represents the difference between precipitation and evapotranspiration, equivalent to the net annual contribution to land of water from the atmosphere. Changes in storage are assumed to be either negligible or unimportant.

The validity of this assumption is questionable, particularly because increases in global mean air temperature over the twentieth century have resulted in an intensification of the hydrological system [*Zhang et al.,* 2007]. This intensification has involved not only a net transfer of water out of long-term storage (e.g., glaciers) to more dynamic reservoirs but also higher saturation pressures—warmer air is able to hold more moisture. Projected warming over the 21st century will amplify these trends [*Wentz et al.,* 2007]. Indeed, the assumption that hydrological systems operate within an unchanging envelope of variability wherein net changes in storage can be considered negligible has recently been rejected by *Milly et al.* [2008], who assert "stationarity is dead." Although it is improbable that stationarity in hydrological systems was ever "alive," the assumption of unchanging storage remains central to the calibration of hydrological models used to estimate water scarcity.

Current Problems With Calculating Water Scarcity

Notwithstanding concerns over climate change, several problems exist with the calculation of water scarcity based on MARR. First, MARR does not represent the proportions of river flow that derive from base flow and stormflow; the former consists of discharges from basin stores such as groundwater and alpine glaciers whereas the latter comprises overland flow and interflow (i.e., subsurface runoff). As a result, current estimates of freshwater availability do not indicate the fraction of freshwater that is well distributed as groundwater with long

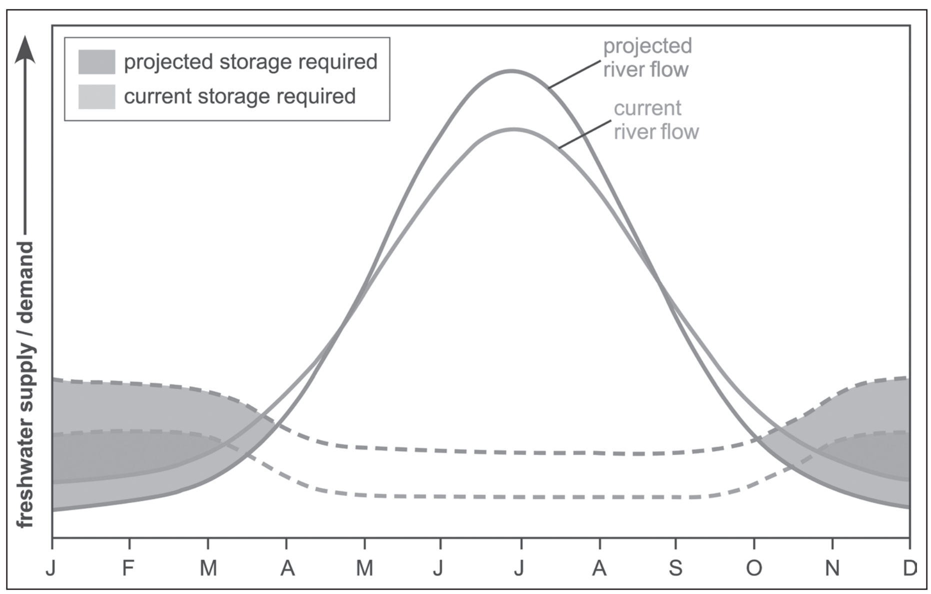

*Fig. 1. Conceptual representation of the dynamic nature of intra-annual freshwater supply (solid curves) and demand (dashed curves) for a basin characterized by marked (unimodal) seasonality and dry-season irrigation. Projected changes in freshwater supply (river flow) assume a basin response to an increased frequency of high-precipitation events and deceased frequency of low- and medium-precipitation events as a result of global warming [*Trenberth et al., *2003]. Projected changes in freshwater demand are assumed to result from rising population and related irrigation. Shaded areas represent the current and projected storage required to meet intra-annual freshwater demand. Original color image appears at the back of this volume.*

By R. Taylor

residence times (i.e., years to decades or longer) or that which is relatively ephemeral and concentrated in river channels (i.e., flood discharges). The range of these fractions throughout the world can be substantial. For example, according to recent estimates [*Döll and Fiedler,* 2008], groundwater constitutes just 25% of renewable freshwater resources in Asia whereas in Africa this fraction is 51%.

Second, freshwater availability defined by MARR excludes water stored as soil moisture. As noted by *Falkenmark and Rockström* [2004], failure to account for soil water underestimates available freshwater resources. For example, in sub-Saharan Africa where <5% of the arable land is under irrigation [*Giordano,* 2006], soil water sustains almost all food production. The fixed per capita demand for freshwater that is central to current measures of water scarcity assumes annual withdrawals for irrigated agriculture and industry that are 20 times that required for domestic water use. As a result, current assessments of water scarcity that rely solely on MARR [*Alcamo et al.,* 2003; *Arnell,* 2004; *Oki and Kanae,* 2006] provide grossly pessimistic and erroneous representations of the annual imbalance between freshwater demand and availability in sub-Saharan Africa.

Third, exclusion of basin storage from current estimates of freshwater resources is spurious because adaptive responses to intermittent or sustained shortages in the availability of freshwater commonly involve efforts to withdraw more freshwater from accessible storage, commonly groundwater, or to store more water (e.g., dam construction, rainwater harvesting, aquifer storage and recovery). For example, falling groundwater levels in the North China Plain [*Konikow and Kendy,* 2005], the United States' High Plains aquifer [*McGuire,* 2007], and several states in India [*Keller et al.,* 2000] clearly highlight imbalances between freshwater demand (i.e., groundwater-fed irrigation) and availability. Further, shrinking glacial stores of freshwater in the Andes and Himalayas represent a critical reduction in freshwater availability, particularly during dry periods, to downstream communities as a result of reduced glacial meltwater flows [*Singh and Bengtsson,* 2004; *Bradley et al.,* 2006]. Indeed, water scarcity is perhaps most acutely observed through reductions in freshwater storage.

Technical Challenges

The inclusion of freshwater stores (i.e., groundwater, soil, ice, and snow) in the assessment of water scarcity poses substantial technical challenges. Unlike the central availability and widespread coverage of records of runoff (see http://www.rivdis.sr.unh.edu/), data pertaining to freshwater stores are often highly localized, limited in their coverage, and in the case of groundwater and soil moisture, difficult to access. As a result, it is not presently possible to constrain transient hydrological models that explicitly consider time-variant contributions of freshwater stores to freshwater availability at national or basin scales across the globe.

Despite the promise of spaceborne measurements of freshwater stores in the hydrosphere, problems of scale and detection remain. Measurements of soil moisture by microwave remote sensing are confined to the most shallow soil layer and areas free of dense vegetation [*de Jeu et al.,* 2008]. Detection of recent changes in total freshwater storage via the Gravity Recovery and Climate Experiment (GRACE) begun in 2003 has been well demonstrated at continental scales [*Ramillien et al.,* 2008] and for large basins (>200,000 square kilometers) such as the Mississippi River [*Rodell et al.,* 2007]. However, despite recent advances [*Zaitchik et al.,* 2008], major technical challenges remain in using GRACE data to resolve water storage from groundwater, soil moisture, snow, and ice at scales that are able to assist water managers and policy makers. The gridded ($0.5° \times 0.5°$) global recharge model of *Döll and Fiedler* [2008] can help, providing a rough first approximation of potential diffuse (i.e., supplied by precipitation) recharge and thus the fraction of renewable freshwater derived from groundwater. Nonetheless, scientists have few reliable measurements of available groundwater storage for most regions of the world, making it difficult to test and validate this model.

Moving Beyond MARR

A new approach to measuring water scarcity that moves beyond MARR and is informed by available freshwater storage is required. Intra-annual analyses of freshwater availability would mark an important step forward in this regard because they would reveal the magnitude of freshwater storage required to meet intra-annual demand (Figure 1). Recent use of monthly river flow by *McMahon et al.* [2007] to estimate hypothetical reservoir capacities required to meet a target draft (water demand) is an example of such an approach. Critically, analyses of intra-annual water scarcity would inform adaptation because interventions seeking to increase or draw from freshwater storage could be directly compared against those to reduce freshwater demand, such as changing crop patterns [*Challinor et al.,* 2007] and trading in virtual water [*Allan,* 2003], the latter of which involves importing food and other products embedded with water.

If assessments continue to disregard storage, understanding the magnitude and spatial dimensions of the current global water crisis and projecting who may be affected by freshwater shortages as a result of rapid development and climate change will remain profoundly limited. Concerted action by the global hydrological community in collaboration with water users and policy makers is urgently required to improve both the coverage and frequency of measurements of freshwater stores, to facilitate access to data pertaining to freshwater stores, and to represent and validate freshwater storage in hydrological models. The incorporation of freshwater available from storage will substantially improve the accuracy and utility of current analyses of water scarcity. These can, in turn, inform more targeted strategies to address water scarcity now and in the uncertain future.

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Economic Cost of an Algae Bloom Cleanup in China's 2008 Olympic Sailing Venue

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In the summer of 2008, an algae bloom struck the coast of Qingdao, China, where the 2008 Olympic sailing events were to be held. The bloom was caused by the drift and proliferation of the green algae *Enteromorpha* (see http://precedings.nature.com/documents/2352/version/1). It lasted for more than 1 month and covered nearly the entire sailing venue. The *Enteromorpha* bloom was so intense that national and local governments invested a tremendous amount of labor and resources in a cleanup effort in order to achieve Olympic Games standards [*Hu and He,* 2008].

Because of the emergency nature of the cleanup operation, no cost analysis has been conducted and published to date. However, using data reported by the media and the Internet, estimates can be generated of the direct economic loss caused by the *Enteromorpha* cleanup operation.

The Algae Bloom and Extent Through Time

According to reports in local news media, the green algae appeared in the sailing waters near Qingdao on 31 May and disappeared on about 15 July, lasting for 46 days (see http://shui.shejis.com/zxzx/xygc/200807/article_7460.html).

On 14 June, extensive patches of floating algae appeared in coastal waters off Qingdao. According to ocean color data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite, the green algae were transported from the central Yellow Sea, where they covered about 400 square kilometers. The green algae drifted toward Qingdao at a speed of 17 kilometers per day (0.2 meters per second) from 30 June to 3 July (http://shui.shejis.com/ztwz/200807/article_7949.html). At its height, on 28–29 June, the densest area of the bloom covered about 160 square kilometers offshore Qingdao and Laoshan.

Within the Olympic sailing area, the algae covered 15.86 square kilometers by 28 June, prompting Qingdao's city government to initiate an emergency plan to collect the floating algae. By 14 July, the sailing area occupied by the green algae was reduced to 0.01 square kilometer (http://shui.shejis.com/zxzx/hyxw/200807/article_7866.html), and by 15 July the Olympic standard for sailing events, which requires 50 square kilometers of clear waters, was met.

The Cleanup Operation

An average of 5000 citizens and defense personnel, 200 trucks, and 1185 fishing boats per day were involved in the cleanup operation since the onset of the algae bloom on 31 May. Before the emergency plan was initiated, on 28 June, the cleanup operation was small; however, after 28 June the operation was scaled up, with sometimes more than 20,000 people per day involved.

Cleanup crews tackled both the open waters and the beach; the basic cleaning method involved laborers manually skimming the algae off the water, using fishing boats and nets, and picking them up onshore using shovels and machinery. The algae were then loaded onto trucks and transported inland. To receive the latest information on the developing trends of the algae bloom, a monitoring network consisting of surveillance vessels and airplanes was established as part of the emergency plan.

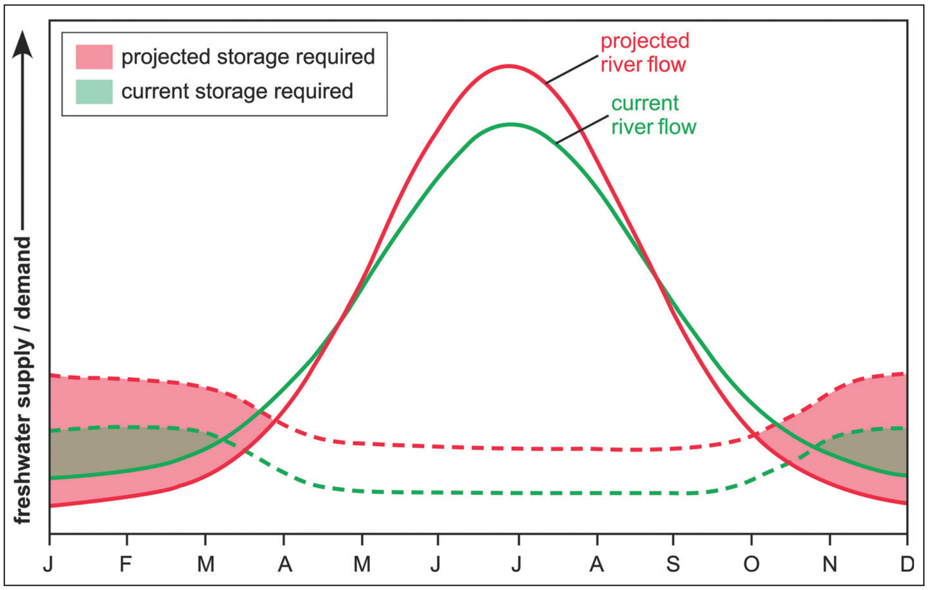
During the emergency operation, many people were employed to maintain and repair the boats that helped workers harvest the algae at sea and vehicles that transported the algae inland. Workers also provided services such as feeding and hydrating the harvesting workers. About 1000 personnel from surrounding regions participated in the cleanup. The trucks and fishing boats were loaned from neighboring provinces to aid the cleanup effort. The Qingdao local government also received donations including food and money from surrounding communities.

By 10 July, a total of 670,000 tons of green algae had been harvested offshore Qingdao, and by 14 July a further 80,000 tons had been removed. Also by 14 July, 24.7 kilometers of containment booms and 36.6 kilometers of nets had been deployed to contain the algae (see http://news.xinhuanet.com/environment/2008-07/14/content_8543484_3.htm and http://shui.shejis.com/zxzx/hyxw/

Table 1. Direct Economic Cost Borne by Local, Provincial, and National Governments, as Well as by Residents, for the Green Algae Cleanup Offshore of Qingdao in Summer 2008[a]

Expenditure Type	Item	Daily Quantity	Number of Days	Total Quantity	Unit Cost (CNY)[b]	Total Cost (Millions of CNY)
Containment boom	boom			24.7 km	80 per meter	1.976
	net			36.6 km	10 per meter	0.366
Cleanup	personnel	5,000	46	230,000 person days	100 per person per day	23
	fishing boat	1,185	46	54,500 days	10,000 per day	545
	truck	200	46	5,500 days	2,000 per truck	11
Monitoring	vessel	3	46	143 days	5,000 per day	0.715
	airplane	4	46	199 hours	19,392 per hour	3.859
Logistical support and donations	personnel, food, and other infrastructure donation					6.741
Total						**592.657**

[a]Data compiled from articles published by China's Shejis and Xinghua news services.
[b]Cost is in Chinese yuan (CNY).



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