On Adapting to Global Groundwater Crisis

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Introduction

Groundwater storage is dynamic in that recharge-discharge relationships function on various timescales from years and decades in the short term to centuries and millennia in the long term. Unconfined aquifers and associated confined aquifers experience short-term storage variations that are directly relevant to sustainable water management. This "renewable storage" is amenable to coordinated management with surface water storage that directly responds to rainfall variations. Groundwater storage changes on timescales of centuries or more are effectively "nonrenewable" and cannot be relied on for continued, stable water supplies. They are of value in a limited sense of one-time availability. The global groundwater crisis centers on withdrawals notably exceeding short-term renewable storage, and having adopted agricultural, industrial, and other uses that rely on nonrenewable groundwater. Such persistent use will lead to societal conflict as the nonrenewable sources inevitably dwindle. Stress will be exacerbated by water quality degradation due to human activities and multiyear droughts that are likely within the timescale of human generations. The hydrological cycle places definite limits on quantities of surface water and groundwater that can be diverted for human use. To ensure stable water supplies, societal water needs have to conform to water availability, and water management has to be based on coordinated use of groundwater storage with surface water storage, water quality protection, and water conservation. This article examines the global groundwater crisis within the framework of the hydrological cycle and offers perspectives on science and human challenges of adaptation.

Hydrological Cycle and Water Availability

Perhaps, the most important hydrology lesson of the past half century is that all human needs for water must be obtained from surface water and groundwater left over from precipitation after evapotranspiration. According to the available estimates (Shiklomanov 1997; Brutsaert 2005), average evapotranspirative returns to the atmosphere over land areas vary from 60% to 66% of annual rainfall. For purposes of first-order water budget development over large watersheds, or over land areas that comprise many watersheds with negligible inflows and outflows across boundaries, one may reasonably assume that 35% to 40% of annual precipitation may be available for diversion for human use. However, ecosystems, flora,

Table 1
Water Budget Estimates for California (Water Volumes in Cubic Kilometers)

	Water Year (% of Normal Precipitation)		
	1998 (171%)	2000 (97%)	2001 (72%)
Precipitation	407	232	172
Inflows across state borders	9.01	8.64	7.77
Total inflow	416	241	180
Water use	41.8	51.6	50.7
Change in storage (surface water + groundwater)	7.2	−7.2	−17.6
Water use attributable to total inflow	41.8	44.4	33.1
Water use as % of total inflow	10.0	18.4	18.4

Note: Kenny et al. (2009) provide estimates for water use in the United States during 2005. For the contiguous 48 states, the data indicate daily fresh water extraction of 347,368 million gallons, amounting to 480 km^3 over the year. Based on annual rainfall by states (National Climatic Data Center 2009), the weighted average annual rainfall for the conterminous United States for 1931 to 2000 is 746 mm. Combined with a land area of 7.83 million km^2, this amounts to about 5840 km^3 of water. Thus, the 2005 water use constitutes about 8.2% of annual precipitation.
Source: Department of Water Resources (2009a).

and fauna also depend on this water. This recognition, combined with technological limits to water transfer, restricts the portion of annual precipitation that can be extracted for human use. To comprehend what this portion might be, California and the contiguous United States provide examples.

For California, water budget estimates are available for normal, above-normal, and below-normal rainfall years (Table 1). California diverts about 18% of its total inflows for human use with the help of its extraordinary hydraulic structures and water conveyance systems. Currently, California is seriously reconsidering its water future, and significant reduction in water use is contemplated.

Accounting for imprecision and uncertainty associated with the aforesaid estimates, it seems reasonable to infer that 10% to 15% of annual precipitation may be available for human use over continental areas.

Groundwater Crisis and Renewable Storage

Within constraints imposed by the hydrological cycle, surface water and groundwater need to be conjunctively managed to meet societal needs. This task is rendered difficult by unpredictable climate variability, especially the possibility that subnormal rainfall may occasionally persist for successive years. Critical to water management is space available for water storage, including on-the-surface and below ground. Groundwater storage plays a unique role because unlike surface water storage, whose capacity is directly coupled with fluctuations in seasonal rainfall, groundwater storage occurs on different timescales. Thus, groundwater storage provides a buffer to smooth surface water storage fluctuations.

Groundwater storage is dynamic in that its recharge-discharge relationships occur over timescales varying from less than a year to thousands of years or more. In general, groundwater storage in shallow unconfined systems and immediately underlying confined systems is likely to change on a timescale of a year to decades. Deeper aquifer systems experience storage changes on timescales of centuries or longer. Actual timescale depends on climatic, physiographical, and geological attributes of particular groundwater systems of interest. It is reasonable to assume that for purposes of conjunctive water management, groundwater systems that experience storage changes on timescales of years to decades may be considered renewable. Systems functioning on scales of a century or longer may be considered effectively nonrenewable.

The current global groundwater crisis reflects the fact that over the past century, groundwater withdrawal has grown to exceed natural renewable groundwater storage. This overdraft has occurred worldwide. Perhaps the single most important cause was the invention of the deep-well turbine pump in the United States, first deployed for agriculture in California in 1907 (Freeman 1968). This device made it possible to lift large quantities of water from depths of tens of meters in wells, limited only by the availability of adequate energy. Initially a blessing, over the decades unintended consequences of groundwater depletion became manifest.

Observational Evidence

Thanks to the U.S. Geological Survey, we now have a century-long observational record on groundwater depletion in some major aquifer systems in the United States, including McGuire et al. (2003). Narasimhan (2009) summarized storage depletion information from five large groundwater basins, covering an area of about 675,000 km^2. Three of these, the Dakota Aquifer System, the Atlantic Coastal Plains System, and California's San Joaquin Valley System, are deep, confined systems, while the other two, the South Central Arizona System and the Ogallala Aquifer System, are unconfined. The three confined systems have experienced total withdrawals of about 24 km^3 over an area of 225,000 km^2, of which 80% has been irretrievably lost due to nonrecoverable compaction. How much of the remaining 20% can be renewed on a timescale of decades is unclear. The two unconfined systems have experienced a total withdrawal of about 323 km^3 over an area of about 450,000 km^2, accompanied by tens of meters of permanent water declines with no prospects of recovery in the foreseeable future. Groundwater mined from these systems has satisfied a one-time need.

Groundwater development in India presents another example of overdraft. Peninsular India is largely occupied by hard rocks, which occupies nearly half of India's area (Narasimhan 2006). In these areas, shallow groundwater occurs in weathered zones and saprolite and is directly coupled with the atmosphere. The introduction of turbine pumps during the 1960s to enhance agricultural production greatly succeeded in its goals, but it also led to severe declines in water levels and alarming depletion of groundwater storage over many parts of peninsular India. Further north, in the east-west trending Indo-Gangetic valley, new evidence of overdraft is emerging. Tiwari et al. (2009) and Rodell et al. (2009) report, based on analysis of satellite gravimetry, that groundwater storage is being depleted at an annual rate of about 54 km^3 from an area of about 2.7 million km extending from Punjab on the west to Bangladesh on the east. It is unclear what portion of the depletions may be considered nonrenewable.

Challenges to Adaptation

The hydrological cycle, in combination with local physiographical and geological conditions, places definite limits on the quantity of water that can be extracted from surface and groundwater sources for stable water supplies. Optimal use of finite groundwater supplies through coordinated use of surface water and groundwater storage is emerging to be central to water management. This further entails cooperation and coordination among scientists and water policy makers.

In water management, the goal of science is to continually assess the quantity of renewable water that can be diverted in a sustainable way for human use, identify appropriate conjunctive management strategies, and devise ways of protecting long-term resource integrity. This has to be achieved on a basin scale, duly considering geological and physiographic factors and climatic uncertainties. That such conjunctive management over watersheds is feasible has been established over small drainage basins. An example is Santa Clara Valley, California, popularly known as the Silicon Valley. This well-defined watershed covers an area of about 3000 km^2 and empties into the San Francisco Bay. Starting from the 1930s, an integrated system of surface water reservoirs, artificial recharge structures, regulated groundwater extraction procedures, and waste water treatment has been developed to optimally use the Valley's water resources. However, the Valley's water needs far exceed the capacity of the indigenous resources of the watershed itself, even with efficient integrated management. A little over half of the total annual water needs of about 475 million m^3 are met by imports from the Central Valley Project, the State Water Project, and the Hetch Hetchy Aqueduct. Using well-designed artificial recharge structures, surplus water during wet years is stored underground. Groundwater extraction, normally restricted, is increased as needed during dry years. For the future, plans are afoot for improved water efficiency, reuse, and conservation, while yet improving ecosystem health (Santa Clara Valley Water District 2009).

Water management experience within Santa Clara Valley is limited to municipal and industrial use, with fairly low per capita consumption. Extending this experience to large watersheds with higher per capita consumption arising from agricultural and other uses is a challenging task that has yet to be successfully addressed.

Although current scientific knowledge augmented by future research activities can help in sustainable groundwater management over long periods, our ability to successfully combat a global groundwater crisis vitally depends on human attitudes to natural resources in general and groundwater in particular. In the post-WWII world, economic and social thinking are dominated by visions of steady economic growth over the foreseeable future to eradicate poverty and facilitate prosperity for all. In turn, steady economic growth requires a continual increase in water availability, which is not realistic. Clearly, expectations of growth have to be decreased to conform to sustained water availability.

As pointed out by von Engelhardt et al. (1976), transition to a slow growth rate does not pose insurmountable technological problems. Rather, transition is confronted by inertia of human attitudes. Due to lack of water literacy and/or economic-political considerations, groundwater is generally treated as private property, to be abstracted for profit, without regulation. Even where water management is subject to public trust, it is applied to surface water and not groundwater. Whereas science unequivocally requires surface water and groundwater to be treated as a single unified resource, societal attitudes have hitherto tended to discourage or thwart unification. The badly needed change in attitudes is slow in coming.

Although the feasibility of integrated water management has been established over small basins, many challenges remain to extend such management to large watersheds. Intrinsically, large watersheds are to be treated as continuously evolving systems with complex internal structures, driven by time-variant boundary conditions. To comprehend their evolving behavior, a network of monitoring stations will have to be maintained and the resultant data consistently evaluated and used. Meeting this monitoring need will not be easy, considering that historically there has been little incentive to maintain or expand monitoring programs. A societal commitment to integrated, sustainable water resources management will lead to new approaches to funding water management, bolstering or establishing suitable institutions, research, training, and education.

Encouraging Signs

It is encouraging that the groundwater profession is strongly advocating sustainable groundwater management. In areas of proven unsustainable groundwater development characterized by disappearance of phreatophytes, drying-up of perennial streams, sea water intrusion, land subsidence, and other unacceptable consequences, groundwater is being gradually brought under scrutiny and regulation.

As evidence of this encouraging sign in the United States, the following examples are worth noting. At the national level, the Water Information Coordination Program (WICP 2009) is a collaborative program among federal agencies to improve water information for decision making about natural resources management. As part of this program, the Advisory Committee on Water Information represents the interests of water information users and the profession in advising the government. A groundwater subcommittee of this committee has been actively engaged since 2007 in developing a nationwide long-term groundwater quantity and quality monitoring framework that would provide information necessary for the planning, management, and development of groundwater supplies to meet current and future needs and ecosystem requirements.

Recently, California passed a comprehensive water legislation package involving four bills and a 11.4 billion dollar bond issue (Department of Water Resources 2009b). Of the four bills, Senate Bill No. 6 is devoted exclusively to groundwater monitoring, with the goal of long-term monitoring of groundwater basins through well-designed monitoring programs. Financial and technical support to local agencies is intrinsic to the overall goal. In addition to California, many other western states are devoting serious attention to long-term groundwater monitoring as a necessary adjunct to sustainable water management. For example, in Kansas all wells, excepting domestic wells, are metered (Sophocleous 2009).

Despite these encouraging signs, one cannot foresee, with any degree of confidence, the future of global groundwater crisis. This is because human attitudes are widely variable among the nations of the world. In the United States, the efforts of many institutions, governmental and nongovernmental, to further public education about water are having a slow but steady impact. Society is in a slow but steady transition toward adapting to constraints imposed by the hydrological cycle. The transition is characterized by vigorous debate among various segments of society concerning how finite resources can be shared within the context of rights to prosperity assured by democratic self-governance. One may reasonably expect that conjunctive water resources management will eventually occur out of sheer necessity.

References

Brutsaert, W. 2005. *Hydrology: An Introduction*. New York: Cambridge University Press.

Department of Water Resources, State of California. 2009a. *California Water Plan Update 2009, Bulletin 160-09*. Sacramento, California: DWR.

Department of Water Resources, State of California. 2009b. *2009 Comprehensive Water Package. Special Session Policy Bills and Bond Summary*. Sacramento, California: DWR.

Freeman, V.M. 1968. *People-Land-Water: Santa Clara Valley and Oxnard Plain, Ventura County*. Los Angeles, California: L.L. Morrison.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin. 2009. Estimated use of water in the United States in 2005. USGS Circular No. 1344.

McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten. 2003. Water in storage and approaches to ground-water management, High Plains aquifer, 2000. USGS Circular 1243.

Narasimhan, T.N. 2006. Groundwater in hard rock areas of peninsular India. *Ground Water* 44, 130–133.

Narasimhan, T.N. 2009. Groundwater: From mystery to management. *Environmental Research Letters* 4, 035002, DOI: 10.1088/1748-9326/4/3/035002

National Climatic Data Center. 2009. *State, Regional, and National Monthly Precipitation, Historical Climatography Series No. 4-2*. Asheville, North Carolina: National Oceanic and Atmospheric Administration. http://cdo.ncdc.noaa.gov/climatenormals/hcs/HCS_42.pdf (accessed November 15, 2009).

Rodell, M., I. Velicogna, and J.S. Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460, no. 7258: 999–1002.

Santa Clara Valley Water District. 2009. *On the Protection and Augmentation of Water Supplies. Water Utility Enterprise Report*. Santa Clara, California: SCVWD.

Shiklomanov, I.A. 1997. *Comprehensive Assessment of the Freshwater Resources of the World*. Geneva: World Meteorological Organization.

Sophocleous, M. 2009. Personal Communication. December 14, 2009.

Tiwari, V.M., J. Wahr, and S. Swenson. 2009. Dwindling groundwater resources in northern India from satellite gravity observations. *Geophysical Research Letters*, 36: L18401, doi: 10.1029/2009GL039401.

von Engelhardt, W., J. Goguel, M.K. Hubbert, J.E. Prentice, R.A. Price, and R. Trümpy. 1975. Earth resources, time, and man—A geoscience perspective. *Environmental Geology* 1, 193–206.

WICP. 2009. http://acwi.gov/wpinfo.html (accessed December 2009).