

Anthropogenic Disturbance of the Terrestrial Water Cycle



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The terrestrial water cycle plays a central role in the climate, ecology, and biogeochemistry of the planet. Mounting historical evidence for the influence of greenhouse warming on recent climate, and modeling projections into the future, highlight changes to the land-based water cycle as a major global change issue (Houghton et al. 1995, Watson et al. 1996, SGCN 1999). Disturbance of the hydrologic cycle has received significant attention with respect to land-atmosphere exchanges, plant physiology, net primary production, and the cycling of major nutrients (Foley et al. 1996, Sellers et al. 1996, McGuire et al. 1997). Changes in land use are also recognized as critical factors governing the future availability of fresh water (Chase et al. 2000).

Another important but seldom articulated global change issue is direct alteration of the continental water cycle for irrigation, hydroelectricity, and other human needs. Although the scope and magnitude of water engineering today are colossal in comparison with preindustrial times, most of the very same activities—irrigation, navigation enhancement, reservoir creation—can be traced back several thousand years in the Middle East and China. Stabilization of water supply has remained a fundamental preoccupation of human society and is a key security concern for most nations. Reducing flood hazard, enhancing food security, and redirecting runoff from water-rich to water-poor areas continue to provide a major challenge to our engineering infrastructure.

In this article we address three issues. First, we document the nature and magnitude of direct human alteration of the terrestrial water cycle, specifically through construction of engineering works for water resource management. We focus on the redistribution of freshwater among major storage pools and the corresponding changes to continental runoff. Second, we explore some of the impacts of this disturbance on drainage basins, river systems, and land-to-ocean linkages. Finally, we review key uncertainties regarding our current understanding of human-water interactions at the global scale and make suggestions on potentially useful avenues for future research.

RECENT ANALYSIS DEMONSTRATES THAT
HYDRAULIC ENGINEERING HAS PRODUCED
GLOBAL-SCALE IMPACTS ON THE
TERRESTRIAL WATER CYCLE

Evidence for global-scale human impacts on the terrestrial water cycle

Although an exact inventory of global water withdrawal has been difficult to assemble, the general features of anthropogenic water use are more or less known. Reviews of the recent literature (Shiklomanov 1996, Gleick 2000) show a range in estimated global water withdrawals for the year 2000 between approximately 4000 and 5000 km³/yr. Despite reductions in the annual rate of increase in withdrawals from 1970 (Shiklomanov 1996, 2000, Gleick 1998a), global water use has grown more or less exponentially with human population and economic development over the industrial era. By one account (L'vovich and White 1990), there was a 15-fold increase in aggregate

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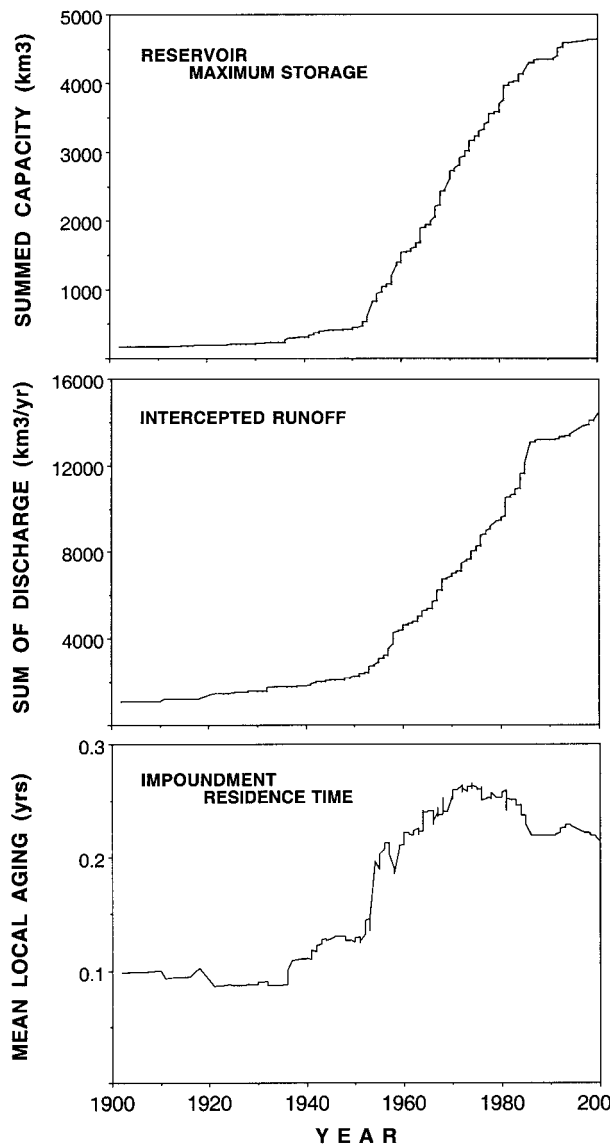


Figure 1. Global time series of (a) accumulated potential volume storage, (b) intercepted continental runoff, and (c) mean age of impounded river discharge calculated locally at reservoirs. We present here results for a subset of approximately 600 large reservoirs. At its endpoint, the maximum storage time series likely represents approximately 60% of the global storage of fresh water behind registered dams. (Data from Tilsley 1983, ICOLD 1984, 1988, USBR 1988, IWPDC 1989, 1994, Vörösmarty et al. 1997a.)

water use between 1800 and 1980, when the global population increased by a factor of four (Haub 1994). Aggregate irretrievable water losses (consumption), driven mainly by evaporation from irrigated land, increased 13-fold during this period. Global consumption for 1995 has been estimated at approximately 2300 km³/yr, or 60% of total water withdrawal (Shiklomanov 1996).

a

b

c

To place such water use into perspective, it is necessary to consider the global supply of renewable water. Using recent estimates of long-term average runoff from the continents totaling approximately 40,000 km³/yr (Fekete et al. 1999, Shiklomanov 2000) and an estimated withdrawal of 4000–5000 km³/yr, humans exploit from 10% to 15% of current water supply. It therefore might appear that water withdrawal over the entire globe is but a small fraction of continental runoff and that water poses no major limitation to human development. However, of the 31% of global runoff that is spatially and temporally accessible to society, more than half is withdrawn (35%) or maintained for instream uses (19%; Postel et al. 1996). And, by the early 1990s, several arid zone countries showed relative use rates much larger than the global average (e.g., Azerbaijan, Egypt, and Libya, which were already using 55%, 110%, and 770% of their respective sustainable water supplies; WRI 1998). Contemporary society is thus highly dependent on, and in many places limited by, the terrestrial water cycle defined by contemporary climate.

This dependency is likely to intensify as a consequence of population growth and economic development. From 1950 to 1998, water availability had already decreased from 16,000 to 6700 m³/yr per capita (WRI 1998, Fekete et al. 1999). If we assume no appreciable change in global runoff over the next several decades, a projected increase in global population by 2025 to approximately 8 billion people (WRI 1998) means that per capita supplies will continue to decline to approximately 5000 m³/yr (WRI 1998). Tabulating these statistics from the standpoint of accessible water, per capita availability would be reduced to approximately 1500 m³/yr. Given an estimate of mean global water use of 625 m³/yr per capita for 2025 (Shiklomanov 1996, 1997), withdrawals could therefore exceed 40% of the accessible global water resource even with presumed increases in use efficiency. This has obvious implications for human society and natural ecosystems, both of which are highly dependent on renewable supplies of water.

The primary application of water is to irrigate cropland in the many regions of the world where rain-fed agriculture is limited or where specific crops such as paddy rice typically are inundated during growth. Irrigation produces more than 40% of global food and agricultural commodity output (Shiklomanov 1996, 1997, UN 1997) on but 15–20% of all agricultural land worldwide. Recently, the extent of irrigated land is placed at approximately 2.5 million km², with a more than 50% rise between 1970 and 1995 (Gleick 1998a). For 1990, estimates of global irrigation withdrawals range from approximately 2300 to 2700 km³/yr or approximately 60–75% of all water withdrawals (Shiklomanov 1996, 1997). By some accounts (L'vovich and White 1990, Shiklomanov 1996, 1997), irretrievable losses of water total 60–70% of all water withdrawn for all purposes, and irrigation alone accounts for 85–90% of this consumption. Providing adequate irrigation water to a growing population constitutes a major

international security concern well into the future (UN 1997).

Major classes of water engineering

The expansion of global water use requires the stabilization of continental runoff and diversion of water from one part of the hydrologic cycle to another. These changes can be translated into particular storage changes as well as reductions or increases in natural hydrological fluxes. We provide here a synopsis of the major agents of anthropogenic change and their potential impacts on the terrestrial water system.

Aquifer mining. In most arid and semi-arid regions, where surface water is insufficient, mined fossil groundwater is the main water resource for irrigation and other uses. Natural rates of water recharge to the aquifer are very

low. Therefore, when water is extracted from such groundwater pools, and in particular when it is used for irrigation, most will be translocated from the aquifer to the atmosphere. This transfer represents both a depletion of continental storage and at least a temporary increase in atmospheric water vapor through the enhanced evaporative flux.

Surface water diversion and changes in internally draining lake volumes. Diversion of surface waters for irrigation in the internally draining basins of arid and other regions results in increased evaporation and a net loss of continental water. The shrinking Aral and Caspian Seas are striking examples of this effect, whereas Lake Chad has acted in the opposite direction but with much smaller magnitude. As in the case of aquifer mining, net loss of water from such lakes leads to a net decrease in con-

Table 1.^a Various anthropogenic mechanisms for altering continental water storage.

Human activity	Storage reservoir	Total volume removable ($\times 10^3 \text{ km}^3$)	Sea level equivalent (cm)	Twentieth century extraction rate (km^3/yr)	Sea level rise rate (mm/yr)
Aquifer mining	High Plains	4	1.1	12	0.03
	Southwest US	3	0.83	10	0.03
	California	10	2.7	13	0.04
	Sahara	600	167	10	0.03
	Arabia	500	140	16	0.04
Surface water diversion and volume changes of inland lakes	Aral (lake)				
	1960	1.1	0.3	27	0.08
	1990	0.3	0.08		
	Aral (groundwater)	2.2	0.6	37	0.1
	Caspian (lake)	56	15.4	7.7	0.02
	Caspian (groundwater)	220	61.2	4.7	0.01
	Chad (lake)	-0.04	-0.01	-2.5	-0.007
	Chad (groundwater)	-0.08	-0.02	-3.5	-0.01
Desertification	Sahel (soil water)	0.1	0.03	3.4	0.01
Wetland drainage	Waterlogged soils	8.6	2.4	2	0.006
Soil erosion in agriculture	Soil moisture	NA ^f	NA	8	0.02
Deforestation	Biomass and soil water	3.3	0.9	49	0.14
Dam building	Artificial Impoundments	-8.4	-2.4	-172	-0.48
	Total (without dams)	1408.5	392.5	193.8	0.54
	Total (with dams)	1401.1	390.1	21.8	0.06

^aTable modified from Sahagian et al. (1994).

^bTotal volume removable is the amount of water that can potentially be economically withdrawn from each storage type with current technology. The vast majority of this total is represented by groundwater. Methods of volume estimation vary from one storage type to another, so these figures should be considered as rough approximations.

^cSea level equivalent is the level that eustatic sea level would rise if the total volume removable were added to the oceans, which have an area of $3.6 \times 10^8 \text{ km}^2$.

^dTwentieth century extraction rates are derived from various publications. Note that in some cases extraction rate is negative (increase in reservoir storage).

^eSea level rise rate is based on the extraction rate spread over the entire area of the world's oceans.

^fNA, Not available.

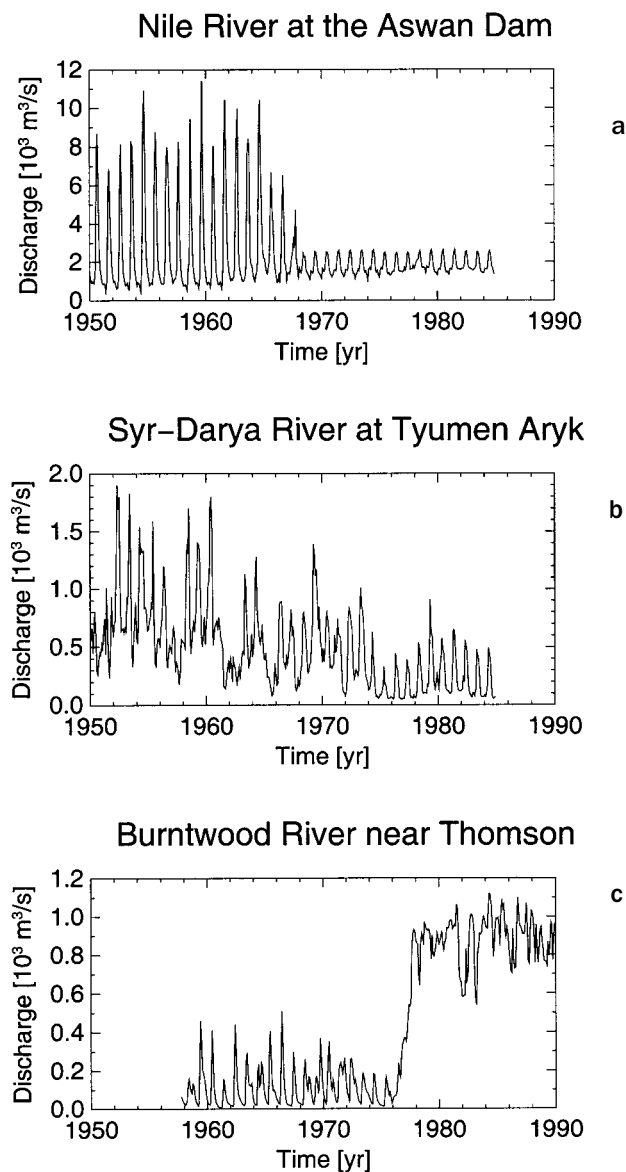


Figure 2. History of flow distortion by water engineering works in three heavily regulated rivers. (a) Nile River discharge is recorded just below the Aswan High Dam. The stabilization of flow is apparent and it is not difficult to identify the time at which the dam was constructed and Lake Nasser reservoir filled. The postimpoundment Nile shows reduced overall discharge, substantially truncated peak flows, higher low flows, and a many month shift in the timing of the natural hydrograph. (b) Sustained decreases in flow for the Syr-Darya River are associated with expanding water use for irrigation and the well-known, corresponding contraction of the Aral Sea. (c) Dramatic increases in discharge for the Burntwood River in Manitoba exemplify interbasin transfer schemes, here between the Churchill and Nelson Rivers, which empty into Hudson Bay. Monthly data from Vörösmarty et al. (1996, 1999), Lammers et al. (in press); see www.watsys.sr.unh.edu.

tinental water storage and enhancement of the land-to-atmosphere flux.

Desertification. Drying of marginal soils due to overgrazing and other intensive land use on semi-arid soils leads to a net loss of soil water storage, reduced evaporation, and increased storm runoff. This has potentially long-term consequences for the sustainability of local agriculture and hence the associated water balance.

Wetland drainage. Wetlands contain standing water, soil moisture, and water in plants. When wetlands are drained, much of this water storage will be lost from the system. In addition, drained wetlands will evapotranspire at lower rates than their natural counterparts and yield more variable discharge hydrographs.

Soil erosion in agricultural regions. Disturbance of agricultural soils by tillage and other cropping practices makes them highly susceptible to erosion. From a water storage standpoint, the most important effect is the change in the relation between surface topography and the groundwater table. Change in relief through erosion of uplands and deposition in valley bottoms can produce changes in hydraulic gradients, which in turn determine the rates of base flow and net water storage. Soils whose quality has been compromised through excessive erosion are likely to be less productive, evaporate less, and show increased storm runoff.

Deforestation. Forests store water in both living tissue and soils. When a forest is cut or burned, the vascular water is released and the biomass reverts to water and carbon dioxide. Soil water in the shallower root zone following disturbance is also reduced, leading to substantial release of water from the continental storage system. All other factors being equal, deforested sites will yield lower evapotranspiration and increased runoff, and may elevate groundwater tables depending on the condition of the soil. Widespread deforestation is believed to lead to a reduction in the recycling rate of water between plant canopies and the atmosphere, and thereby affect the climate system.

Dam building. Dams are constructed for a variety of purposes, but they all result in the trapping of freshwater runoff on the continental land mass. There is an additional, but poorly quantified, loss of surface runoff to groundwaters associated with impoundment, which results in an increase in the storage of continental water. Furthermore, substantial amounts of river flow can be transformed instead into evaporation from reservoirs, thus altering the overall water budget of drainage basins. The timing of river discharge and hence continental runoff to the oceans can also be substantially modified.

Impacts of human control of the terrestrial water cycle

Anthropogenic activities have resulted in the partitioning of water between that stored on the continents and in the ocean, leading to changes in sea level. The impoundment

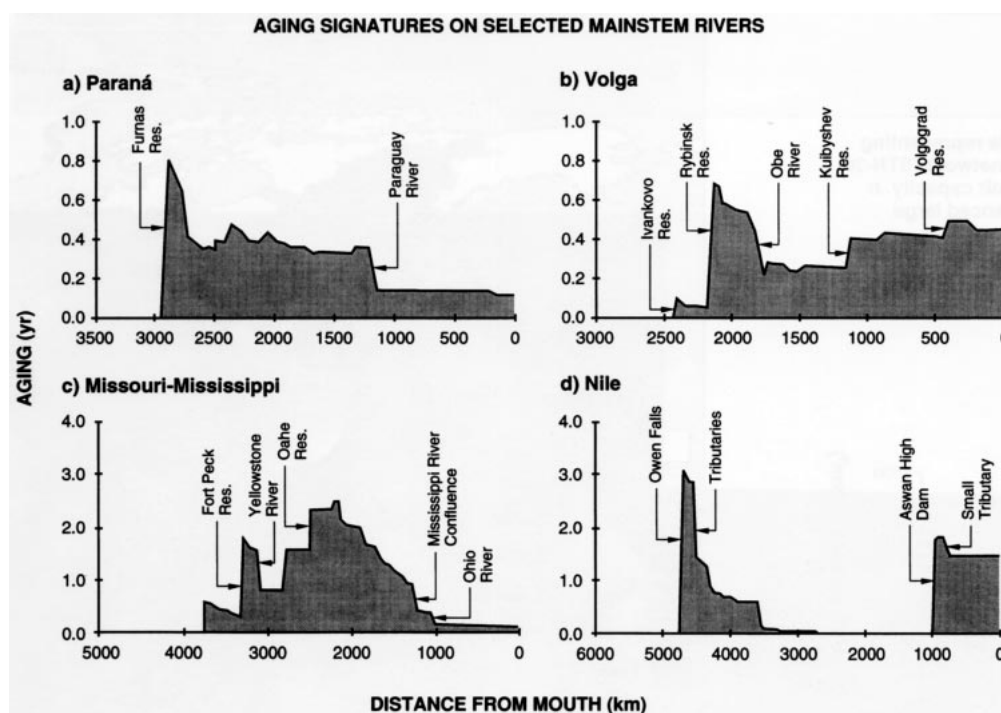


Figure 3. Computed runoff aging signatures for several mainstem rivers as a consequence of impoundment. For each river, local residence time change for individual reservoirs was computed, cascaded along simulated river networks, diluted by less regulated tributaries, and concentrated by additional downstream reservoirs or more heavily impounded tributaries. The mouths of several of the world's largest drainage basins have aging in excess of several months. Figure from Vörösmarty et al. (1997a). Reproduced with permission from Ambio.

of water in continental reservoirs also affects water quality and the time it takes for runoff to reach the ocean. We will explore some of these effects on the terrestrial water cycle.

Changes in water storage and sea level rise. Many human activities (e.g., aquifer depletion, wetland drainage) serve to divert water to the ocean that would otherwise have been stored on the continents. Dam building, on the other hand, impounds continental runoff that would otherwise have been transported to and stored in the ocean. The balance between these positive and negative alterations can be used as a measure of net anthropogenic disturbance to the global hydrologic cycle. However, a net of zero does not mean that the specific alterations are inconsequential, as anthropogenic alterations of hydrology can have a major impact on ecosystems, agriculture, and other biogeochemical systems.

Recent analysis (Sahagian et al. 1994) indicates that engineered alteration of freshwater storage has produced a quantitatively important impact on apparent sea level rise (Table 1). The calculations include only the largest and best-documented water sources for each of the categories of disturbance considered above. For example, we did not consider many small aquifers or any of the large Australian aquifers that are currently mined at very low rates. Thus, the totals in Table 1 should be considered minimum estimates. Because both anthropogenic sea level rise mechanisms and the counteracting dam-building activities are

underestimated, it is not clear at this point what the magnitude or even direction of net human influence has been on sea level (Gornitz et al. 1997). Tide gauge measurements, after application of appropriate postglacial rebound filters (e.g., Peltier 1999), indicate a rate of sea level rise of approximately 1.5–2.0 mm/yr in the twentieth century. As such, the rate of water loss from natural continental storage pools and consequent addition to the ocean (0.54 mm/yr) is sufficient to represent a significant fraction (approximately 30%) of the measured twentieth-century sea level rise (Sahagian et al. 1994, Sahagian in press). The construction of dams and consequent impoundment of water in artificial reservoirs has largely counteracted the effects of other human activities during the twentieth century, and the net effect is near zero if the underestimates in impounded water and other anthropogenic effects are roughly equivalent.

There is every indication that aquifer mining and the other human activities listed in Table 1 will continue into the future. However, it is unlikely that the twentieth century rate of impoundment will continue in the twenty-first century (Figure 1a), for a variety of technical, socioeconomic, and environmental reasons (Gleick 1998a). It is important to note that only filling of newly dammed reservoirs contributes to the flux between continents and oceans. Standing stock of water in old reservoirs has no effect unless there is a change in the volume. Thus, it is the

Table 2. Aggregate discharge, discharge-weighted runoff aging, and suspended sediment trapping due to large reservoirs. Composite values are determined from tabulations made at individual river mouths. Data from Vörösmarty et al. (1997a, 1997b).

Continent ^a	Discharge (km ³ yr ⁻¹)		Basin-wide $\Delta\tau_R$ (year) regulated basins ^c	Mean % suspended sediment retention regulated basins ^c	Mean % potential sediment retention all basins ^d
	Unregulated basins ^b	Regulated basins ^b			
Africa	3320 (n = 476)	870 (n = 25)	0.70	42	9
Asia					
Endorheic	200 (195)	140 (8)	0.48	26	10
North ^e	450 (313)	1560 (4)	0.24	23	18
South	6270 (1009)	4300 (64)	0.13	33	13
Australia/Oceania	690 (339)	70 (10)	0.45	41	4
Europe ^f	1490 (657)	1300 (45)	0.22	50 (23)	
North America	3290 (1362)	2600 (52)	0.31	43	19
South America	2110 (376)	9180 (28)	0.03	21	17
Total	17,820 (4727)	20,020 (236)	Avg. 0.16	30	16

^aDefined by river mouths within a digitized river network at 30-minute (latitude × longitude) spatial resolution from Vörösmarty et al. (2000a).

^bn refers to the number of distinct drainage basins.

^cDischarge-weighted and accounting for dilution by unregulated sub-basins. Retention specifically refers to that from impoundment.

^dDischarge-weighted and assuming that unregulated basins convey no anthropogenic sediment trapping potential.

^eDrainage into Arctic Ocean.

^fArea west of the Ural Mountains.

rate of new dam construction and reservoir filling, and not the total present volume of impounded water, that is relevant to sea level rise.

This issue has profound implications if the rate of dam building in the future will be less than it has been during the twentieth century (Gleick 1998b, Rosenberg et al. 2000), because we would then expect an acceleration in the rate of sea level rise. As a consequence, the full effect of other human activities will increasingly be felt and the rate of sea level rise will increase by an amount equivalent to the rate of twentieth-century water impoundment, namely approximately 0.5–1.0 mm/yr, depending on the extent of underestimation of the impoundment figures in Table 1. When this effect is added to mechanisms of sea level rise associated with increases in thermal expansion of the marine mixed layer and meltback of alpine glaciers, the satellite observations of sea level that will dominate the twenty-first century record are likely to measure significant increases in the rate of sea level rise, with concomitant socioeconomic impacts on coastal regions.

Distortion of continental runoff. Large reservoir systems, interbasin transfers, and consumptive water uses such as irrigation are capable of significant and easily identifiable restructuring of natural river flow regimes. There can be substantial changes in long-term net runoff (i.e., precipitation minus evaporation) as well as in the timing and magnitude of downstream peak and low flows (Figure 2).

Relative to unregulated rivers, artificial reservoirs have high evaporative losses that reduce net basin runoff. Such losses convey important effects on the water balance, especially in arid and semi-arid areas where freshwater resources are already severely strained. Dry-region impoundments lose significant amounts of water. Lake Nasser on the Nile, with a surface area of 6500 km², annually releases 7% of its total capacity and 13% of its inflow to evaporation and seepage (Said 1993). Lake Kariba on the Zambezi River (surface area 5200 km²) loses approximately 20% of its inflow (Vörösmarty and Moore 1991) as does the much smaller Tiga Reservoir (178 km²) in Nigeria, which evaporates 26% of its upstream inputs (Oye-bande 1995).

Large impoundments also change the character of natural hydrographs. Discharge time series of pre- and postregulated rivers unequivocally show this effect, even with relatively modest local residence time change. Figure 2a shows a 35-year time series of river discharge for the Nile River below the Aswan High Dam. The maximum-to-minimum discharge ratio decreased from a natural condition of 12:1 to 2:1 after construction of the dam, and the occurrence of high and low flows was shifted by several months. Similar levels of distortion are reflected in hydrographs from basins with significant irrigation water loss and interbasin transfers (Figures 2b and 2c).

In addition to the obvious difficulties such hydrographic changes create for studying progressive changes to the

terrestrial water cycle, including those arising from the greenhouse effect, they also produce direct environmental impacts on whole river systems. Water engineering works fragment otherwise free-flowing rivers with substantial loss of natural habitat and interference with the migration patterns of higher organisms (Dynesius and Nilsson 1994, Revenga et al. 2000). Flow stabilization below dams also reduces floodplain size and flooded extent. The effects of this reduction include diminished evaporation and disruption to riparian ecosystems whose biogeochemistry, trophic structure, and diversity are all highly adapted to periodic inundation and the associated input of sediment and nutrients (Petts 1984, UNEP/UNESCO 1986, ICOLD 1994, Sparks 1995).

Aging of continental runoff. Runoff retained in artificially impounded river basins can experience considerable delays in its passage from upstream source areas to river mouths, resulting in a series of local and downstream changes to river systems. An aggregate index of this “aging” of runoff over individual river segments, subcatchments, and entire drainage basins can be calculated as the ratio of effective water storage in reservoirs to mean annual discharge. Such calculations have been made globally for large reservoirs (maximum storage capacity more than 0.5 km³) from the combination of geographically referenced water balance models, observed and interpolated hydrographs, digitized river networks, and a global digital database of large reservoir statistics (Vörösmarty et al. 1997a, 1997b).

A large worldwide effect of this aging can be demonstrated. Figure 1 depicts three measures of interaction of large impoundments with the global water cycle over the twentieth century. Both maximum storage and locally intercepted discharge rose dramatically between 1940 and 1980, and mean runoff age within reservoirs more than doubled to over 3 months. Since 1980, the flattening of the maximum storage time series has contributed to the stabilization and recent reduction in local aging, but the global mean residence time is still substantial. These results must also be viewed from a drainage basin perspective. Individual rivers show unique signatures reflecting local reservoir aging and the mixing of tributary inputs that can dilute or concentrate the apparent runoff age (Figure 3). Mouths of several large rivers show a reservoir-induced aging of continental runoff exceeding 3 months (Figure 4). The average residence time for continental runoff in free-running river channels likely varies between 16 days (Covich 1993) and 26 days (Vörösmarty et al. 2000a). By contrast, at the mouths of the 236 drainage basins with large impoundments, the discharge-weighted global mean rises by nearly 60 days (0.16 years; Table 2). Thus, the mean age of river water is two to four times greater by the time it reaches the coastal zone after passing through contemporary regulated basins. Even when we include river basins that are unregulated by large reservoirs, the mean age of continental runoff has likely doubled or tripled to well over 1 month worldwide.

Increased aging generally reflects increased disturbance to the natural physical, chemical, and biological conditions of the river systems in which the impoundments reside (see Dudgeon 2000, Ittekkot et al. 2000, Nilsson and Berggren 2000, Pringle et al. 2000, Rosenberg et al. 2000, St. Louis et al. 2000). Among the physical changes, the increased evaporative losses and hydrograph distortion described above can be shown to correlate broadly with increases in residence time (i.e., runoff age in channel; Vörösmarty et al. 1997a). Aggregate increase in residence time in impounded US waterways is also associated with a net increase in reaeration capacity, although this finding should not obscure the important fact that a typical parcel of reservoir water is relatively inefficient at processing organic wastes (Vörösmarty et al. 1997a). Water quality problems—including eutrophication, reduced dissolved oxygen, and hydrogen sulfide toxicity—therefore emerge within reservoirs and downstream of dams (Lowe-McConnell 1966, Walker 1979, Kimmel et al. 1990, ICOLD 1994).

Another important physical effect is the interception and subsequent deposition of riverborne sediment within an impoundment. The sediment trapping efficiency, or proportion of inflowing sediment retained by a reservoir, can be simulated as a saturating function of local residence time change within that impoundment. In an earlier study (Vörösmarty et al. 1997a, 1997b), we found that approximately 70% of the discharge flowing into large reservoirs worldwide encounters a local residence time in excess of 3 days, sufficient to trap 50% or more of incident sediment flux. When these tabulations are placed into a drainage basin context, the mean aggregate trapping efficiency inside regulated basins for individual continents ranges from 21% to 50%, with a global total of 30% (Table 2). When the effects of impoundment are considered for all river systems across the continents, the range is from 4% to 23%, with a total retention of 16%. We anticipate that the impact of including smaller reservoir systems and farm ponds will increase the actual global sediment retention by reservoirs to more than 25% of the global flux transported by all rivers.

Reservoir sedimentation also can convey a direct and negative impact on river and coastal zone biogeochemistry. A key example has been documented for the Danube River (Humborg et al. 1997; see also Ittekkot et al. 2000). A two-thirds reduction in natural dissolved silicate loads has resulted from a net sink apparent behind the Iron Gates Dam, approximately 1000 km from the mouth of the river. The loss of silicate translates into an important shift in the nutrient stoichiometry in runoff delivered to the Black Sea, most importantly a silicon limitation. The relative shortage of silicon, in turn, discourages diatom blooms and favors nuisance and toxic phytoplankton (Justic et al. 1995a, 1995b), which may compromise the integrity of coastal food webs. Reservoir interception of riverine carbon flux was recently postulated to contribute substantially to a set of

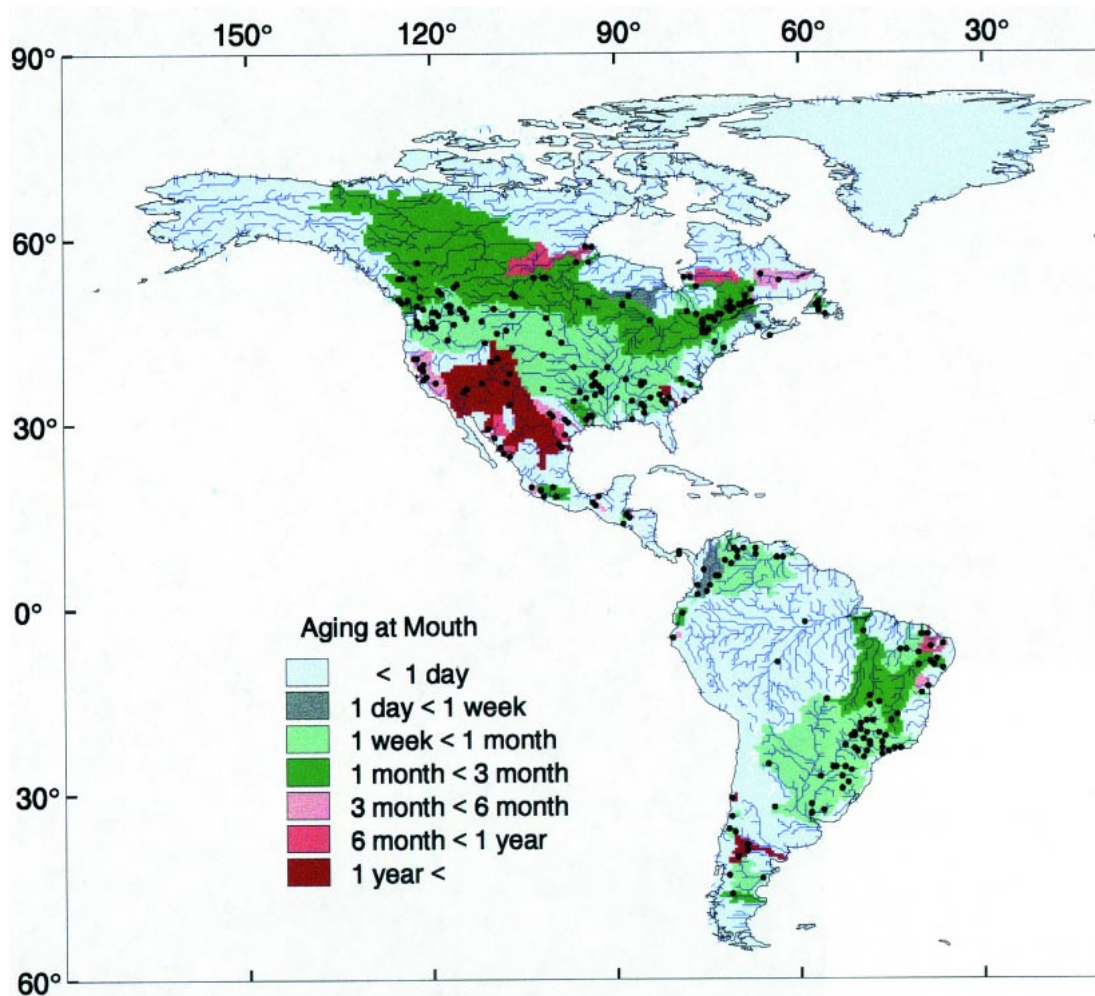


Figure 4. Computed aging of continental runoff in response to large reservoir impoundment tabulated at the mouths of 236 regulated basins. Also shown are the locations of 633 large reservoir systems used in the analysis. For comparison, it has been estimated (Vörösmarty et al. 2000a) that mean natural residence time for channel water held by the 50 largest rivers to be on the order of 60 days; for the remaining river systems it is approximately 3 days. (From Vörösmarty et al. 1997a, 1997b.)

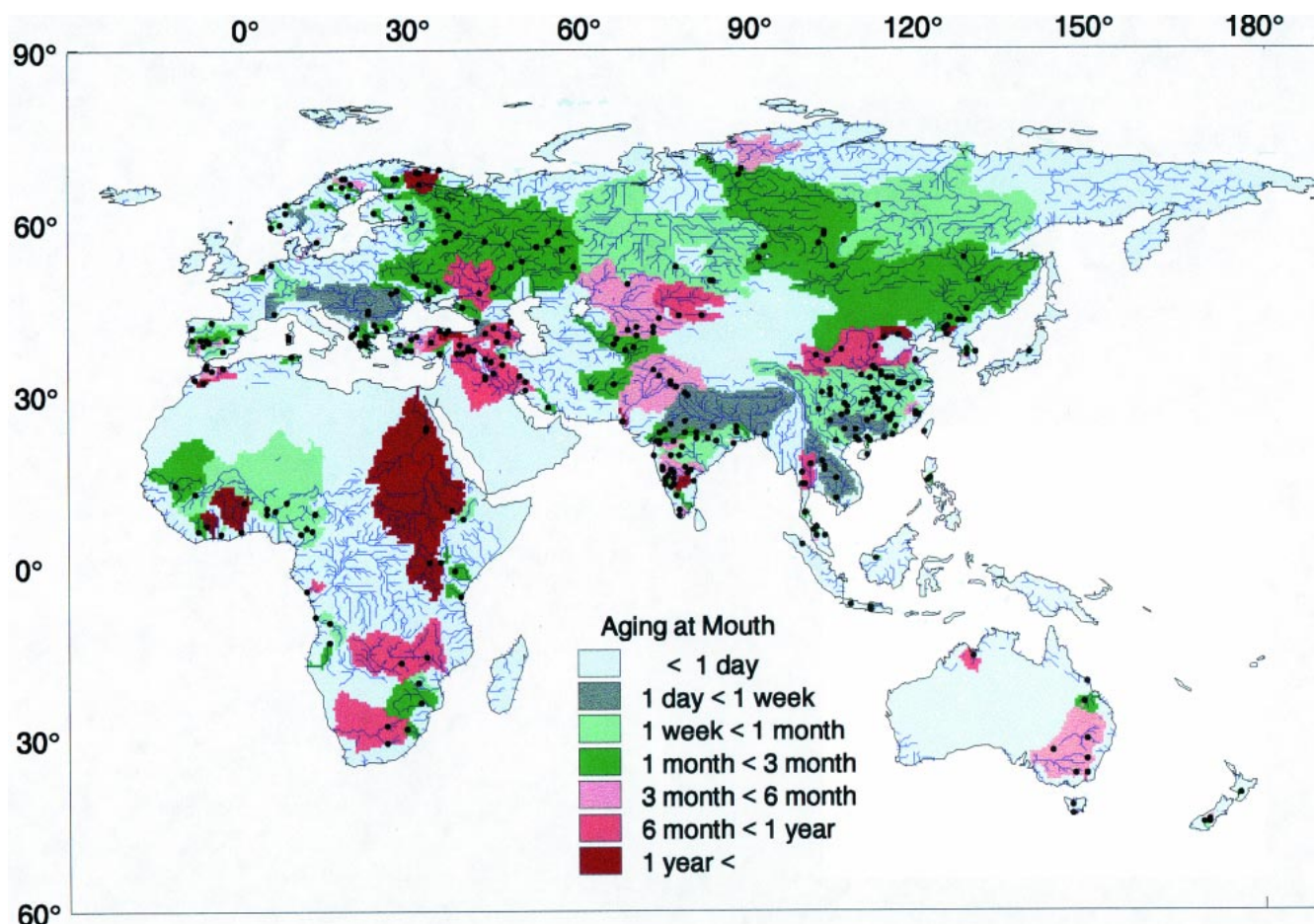
terrestrial sinks for “missing” atmospheric carbon in the Northern Hemisphere (Stallard 1998).

Future global water assessments: Limits and opportunities

The impact of hydraulic engineering on the terrestrial water cycle is evident even when using data sources that are limited in conceptual, geographic, and temporal scope. Several critical unknowns need to be addressed before a truly comprehensive analysis of global water resources can be secured.

Global water supply. Assessment of the global water supply has been an imprecise science. If we consider the renewable resource base to equal long-term mean runoff and river discharge, we can find estimates that vary between 33,500 and 47,000 km³/yr (Korzoun et al. 1978, L’vovich and White 1990, Gleick 1993, Shiklomanov 1996, Fekete et al. 1999). Monitoring of discharge at individual recording stations can provide what is arguably the least error-prone measurement of fluxes through the land-based water cycle (Dingman 1994). Nonetheless, at the precise moment when we need the clearest picture of

impending global change, we find an increasing number of obstacles to the acquisition of continental and global-scale hydrographic data. These impediments arise from the combined forces of commercialization, monitoring network atrophy, and intellectual property legislation (Wahl et al. 1995, Kanciruk 1997, Liedes 1997, Webster 1997). The number of stations reporting to the World Meteorological Organization’s (WMO) Global Runoff Data Center (GRDC; Koblenz, Germany) peaked in the mid-1980s and then fell sharply (Fekete et al. 1999). The decline has been marked in Africa, where a recent analysis shows that the number of gauging stations in most countries is well below WMO guidelines (Rodda 1998). Although several international initiatives (e.g., World Hydrological Cycle Observing System, GRDC) have sought to compile and publish hydrological data, they ultimately depend on the quality of the national networks. Even in the United States, the hydrological monitoring network has degraded. The US Geological Survey has been monitoring river flow for over a century. The network coverage expanded throughout the 1960s and 1970s, but contracted during the 1990s (USGS 1999). More than 100 riv-



er gauges with long-term (more than 30-year) records, the single most important class of stations for environmental monitoring and design engineering, are being lost each year (Lanfear and Hirsch 2000).

We know of no integrated body of literature describing the distribution, characteristics, and sustainable yields of groundwater at the global scale and but one forthcoming 1:10 M scale map (Dzhamalov and Zekster 1999). Noteworthy exceptions exist for regional aquifers (e.g. High Plains in United States; Gutentag et al. 1984), suggesting the feasibility of providing such information when suitable financial and technical resources are made available.

Global water use statistics. Global water demand information is still typically reported at the country level (WRI 1998) and for some countries dates to the 1970s. Furthermore, a key driver of water demand is human population. Yet the geography of human population is still incompletely documented, and the few digital data sets currently available are tied to administrative units that are of irregular geometry and of generally coarse scale (e.g., Tobler et al. 1995, Li et al. 1996). When relative water demand (i.e., the ratio of withdrawal to long-term discharge) is tabulated at the country scale, fewer than 0.5 billion people live under conditions of severe scarcity (more than 0.4), whereas the use of 30' resolution (latitude × lon-

gitude) grids yields well over 1.5 billion (Vörösmarty et al. 2000b). The uneven spatial distribution of water supply as well as economic and population-driven water demands will require development of geographically explicit water resource assessments linked to land surface hydrology and atmospheric models. Studies of alternative water use scenarios (Alcamo et al. 2000, Strzepek et al. 2000) appear promising but will become most valuable when coordinated with interactive socioeconomic analysis.

Incomplete registers of water engineering works.

Our analysis necessarily relied on existing inventories of water facilities, many of which are highly incomplete. The registers from the International Commission on Large Dams (ICOLD) and International Water Power and Dam Construction (IWPDC), for example, are predominantly for dams at least 15 m high; for China, Japan, India, and the United States, individual data entries are for dams greater than 30 m high, and even these listings are incomplete. In addition, 2000–3000 reservoirs in the former Soviet Union, some possibly with large storage capacities, have not been included. In contrast, US inventories of dams are much more comprehensive, with a total of 68,000 entries depicting dams as small as 1.83 m high (Stallard 1998).

Problems with geolocation. The disturbances listed in Table 1 are for major hydrologic alterations. Some of

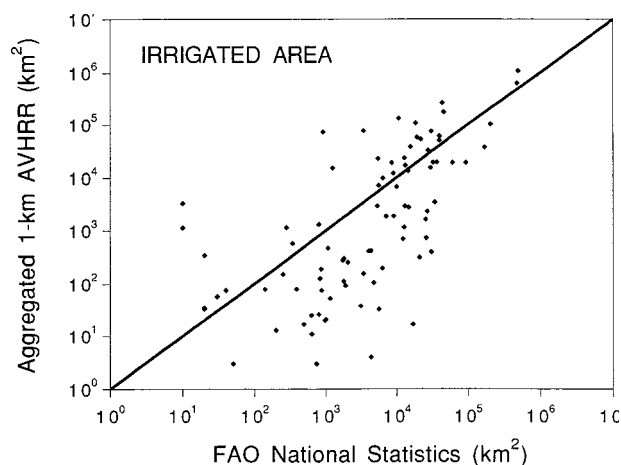


Figure 5. Comparison of two major compilations of irrigation area, showing country-level totals reported to the UN Food and Agricultural Organization (WRI 1996) and an aggregation to the national level of 1-km land cover (Olson 1994a, 1994b, USGS-EDC 1998) based on satellite remote sensing (National Oceanographic and Atmospheric Administration-Advanced Very High Resolution Radiometer).

these are easy to identify (e.g., Lake Chad, High Plains aquifer), whereas others are virtually impossible to locate with any precision (e.g., farm ponds, erosion, wetland destruction). A major uncertainty surrounds the geography of irrigable lands (Figure 5) and their influence on surface runoff and groundwater. Informal, unregistered irrigated areas surrounding Kumasi, Ghana, for example, constitute nearly twice the official irrigated cropland extent reported to the UN Food and Agriculture Organization for the entire country (Cornish 2000). The total extent of wetlands and the rate of loss of wetlands through drainage for agriculture is not well established because wetland inventories and histories are very incomplete (Sahagian and Melack 1998). The geography of reservoirs also presents a major challenge. The global data bank of large impoundments used in our analysis was restricted to approximately 750 entries drawn from a series of established world dam registers. Less than 650 of these could be geographically coregistered to our simulated river network (Figure 4). The current ICOLD and IWPDC databases provide no geographic coordinates for any of the listed dams, necessitating a tedious process of interpreting the ICOLD/IWPDC entries, which give only dam/impoundment name, river, country, state/district, and nearest city. The simple provision of longitude/latitude for each dam/reservoir would materially improve our current ability to place these structures within an appropriate hydrographic context.

Absence of biophysical data. Ironically, global analysis of water engineering works is limited by a paucity of hydrographic information. In the work on reservoir aging

reported here, we relied on modeling and reach-by-reach interpolations drawn from a digital archive of monitoring station records (Vörösmarty et al. 1996, 1999) and, when necessary, interpolated these values to specific dam sites along river networks. The dam registries we consulted give no information on river discharge, either into or out of the impoundments. They also fail to give complete information on storage volumes and area (see also St. Louis et al. 2000). Hypsometric relationships linking stage to area and volume are not supplied, yet such information is essential for computing accurate impoundment residence times and predicting hydrograph distortion (Takeuchi 1997, 1998). The volume of impounded groundwater is also not documented, even for the largest reservoirs, and the hydrology of millions of small impoundments such as farm ponds and rice paddies has been totally ignored.

Lack of operational data. There are no globally useful data banks describing the operation of water engineering facilities. For example, subannual fluctuations in reservoir height and storage are an important integrator of the variations in water input, area-dependent evaporation, and dam releases, and thus critical to the determination of water budgets on individual reservoirs. Comprehensive documentation on time-varying reservoir levels is simply not available at the global scale, although the use of satellite-borne altimetry does show promise (Birkett 1998). Our current research therefore has been limited to quantitative statements based on mean annual conditions. In addition, seasonal or episodic water stock depletion occurs in aquifer mining for irrigation, and a global analysis of growing season withdrawals together with a mapping of vulnerable groundwater stocks would make an important contribution. Efficiencies for irrigation can reach 95% in carefully managed industrial agriculture; however, the overall global efficiency of agricultural water use is possibly quite low, perhaps 40% (Postel 1997), so there is a wide spectrum of irrigation operations that needs to be monitored. Deforestation and regrowth has both a positive and negative impact on terrestrial water storage, and continued work on global land-cover dynamics (Turner et al. 1995), with a direct linkage to water storage changes, is also required.

A basic commitment to establish a coherent set of global water supply and engineering statistics will be critical to future progress in articulating the direct role of humans in the terrestrial water cycle. Correcting the deficiencies of existing data registers would be a good starting point toward gaining a more accurate view of the overall issue. However, such a data collection initiative will be worth little if it cannot also be integrated with state-of-the-art water budget, hydrology, land use, and climate models. This effort would necessarily have to address the question in a geographically specific manner to account for differences in the spatial distribution of human population, agriculture, climate, and potential climate change (Vörösmarty et al. 2000b).

Conclusions

Our review article reports on findings from a growing number of global-scale studies that show a clear influence of humans on the continental water cycle through the construction and operation of water engineering facilities. The changes we document are global and significant. As an example, the 8400 km³ of water estimated in Vörösmarty et al. (1997a) to be stored behind the global population of registered dams represents a sevenfold increase in the standing stock of natural river water and a manyfold increase in the natural residence time of channel waters. Furthermore, a 25–30% interception of global sediment discharge by artificial reservoirs appears likely. Because most of the large engineering works have been constructed over the last 50 years, our findings reflect a significant anthropogenic influence by virtually any measure of global change over a similar time span. In comparison, emissions of CO₂ from fossil fuels have increased four- to fivefold since 1950 (Marland et al. 1994); global population has increased more than twofold over the same period (WRI 1998); and global nitrogen fixation has doubled since preindustrial times (Galloway et al. 1995). From a global change perspective, engineering-based control of drainage basins represents a significant and virtually instantaneous alteration of the quantity and seasonal patterns of continental runoff.

An adequate supply of water will always be of critical concern to human society, and water engineering will continue to play an important role in providing this resource to a growing and economically developing population. This reality is of more than simple academic interest. Continued growth in human population, urbanization, and economic expansion will produce increased demands on global water resources. A significant fraction of the world's population already lacks sufficient fresh water and will undoubtedly experience water shortages through the coming decades (UN 1997). Mounting pressure to construct water engineering works that regulate continental runoff has the potential to create serious water conflict in the more than 250 transboundary river basins (Wolf et al. 1999), and may constitute the single most important threat to international security during the next century (Homer-Dixon 1994).

The traditional emphasis within the global change research community on the greenhouse effect and its impact on land surface hydrology per se has virtually ignored the direct impacts of hydraulic engineering. Approximately \$85 million—less than 5% of the \$1.8 billion US Global Change Research Program FY 2000 budget—is devoted explicitly to human dimension programs, while the vast majority of support goes to climate research (SGCR 1999). The current research agenda, in turn, has contributed to the striking limits of our knowledge concerning this additional yet important facet of the larger global change question. Modern anthropogenic water use is a significant factor that must now be considered an inte-

gral part of the global hydrologic cycle. An expanded view of global change, one that explicitly recognizes the dimensions and implications of direct human control of fresh water, will be essential to future progress in scientific understanding and policy formulation.

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