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Human Appropriation of Renewable Fresh Water

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Humanity now uses 26 percent of total terrestrial evapotranspiration and 54 percent of runoff that is geographically and temporally accessible. Increased use of evapotranspiration will confer minimal benefits globally because most land suitable for rain-fed agriculture is already in production. New dam construction could increase accessible runoff by about 10 percent over the next 30 years, whereas population is projected to increase by more than 45 percent during that period.

Unlike other important commodities such as oil, copper, or wheat, fresh water has no substitutes for most of its uses. It is also impractical to transport the large quantities of water needed in agriculture and industry more than several hundred kilometers (*1*). Fresh water is now scarce in many regions of the world, resulting in severe ecological degradation, limits on agricultural and industrial production, threats to human health, and increased potential for international conflict (*2, 3*).

In this report, we estimate how much of Earth's renewable fresh water is realistically accessible to humanity; what portion of this accessible supply humanity now uses directly, diverts into human-dominated systems, or appropriates; and by how much human access to fresh water is likely to expand over the next 30 years. On that basis, we derive an indicator of Earth's carrying capacity, as well as a measure of the sustainability of current water trends.

Fresh water constitutes only ~2.5% of the total volume of water on Earth, and two-thirds of this fresh water is locked in glaciers and ice caps (*4*). Just 0.77% of all water (~10,665,000 km^3) is held in aquifers, soil pores, lakes, swamps, rivers, plant life, and the atmosphere (*4*).

Only fresh water flowing through the solar-powered hydrological cycle is renewable (Fig. 1). Nonreplenishable (fossil) ground water can be tapped, but such extraction depletes reserves in much the same way as extractions from oil wells do. The terrestrial renewable fresh water supply ($RFWS_{land}$) equals precipitation on land (P_{land}), which then subdivides into two major segments: evapotranspiration from the land (ET_{land}) and runoff to the sea (R). Because ground water and surface water are often hydraulically connected, we include soil infiltration and ground-water replenishment as part of this runoff component. Thus, $RFWS_{land} = P_{land} = ET_{land} + R$.

Global water balance estimates are derived from interpolation of climatic, vegetation, and soil information for different geographic zones. The methods are inherently imprecise; estimates of annual runoff range from 33,500 km^3 to 47,000 km^3 (*5*). We use the estimates of L'Vovich *et al.* (*6*), which yield runoff values near the middle of this range (Fig. 2).

Transpiration is the uptake of moisture by plants and its release back into the atmosphere. On a large scale, it is difficult to estimate transpiration separately from evaporation; hence the joint term. Evapotranspiration represents the water supply for all nonirrigated vegetation, including forests and woodlands, grasslands, and rain-fed crops. Runoff is the source for all human diversions or withdrawals of water for irrigated agriculture, industry, and municipalities, as well as for a wide variety of instream water uses, including the maintenance of aquatic life (for example, fisheries), navigation, the dilution of pollutants, and the generation of hydroelectric power.

To estimate the share of ET appropriated by human activity, we started with the Vitousek *et al.* (*7*) calculation of the fraction of terrestrial net primary production (NPP) that humanity now co-opts. Co-opted NPP is material used directly by humans or used in human-dominated ecosystems by communities of organisms that are different from those in corresponding natural ecosystems. It includes, for example, cropland, grazing land, and trees harvested for fuelwood and timber. Vitousek *et al.* estimate that co-opted terrestrial NPP is 40.6 billion metric tons, or more than 30% of total NPP (Table 1).

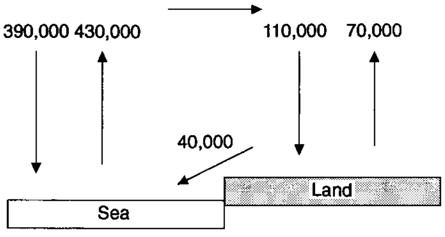

Fig. 1. A simplified depiction of the global hydrological cycle, adapted from Gleick (*5*). Flows are approximate, fall within ranges of estimates in (*5*), and are in cubic kilometers per year. Downward arrows signify precipitation; upward arrows signify evapotranspiration. The horizontal arrow represents the transfer of atmospheric moisture from sea to land and the arrow below it represents runoff from land to sea.

To arrive at a global estimate of the average volume of ET required to produce a unit of biomass, we divided total terrestrial NPP of 132 billion metric tons per year (*8*) by the global terrestrial annual ET estimate above, yielding 1.9 kg of biomass per ton of ET, or about 2 g of biomass per kilogram (or liter) of water (*9*). We then applied this global average to the calculated co-opted NPP (Table 1), making two adjustments. Approximately 16% of the world's cropland is irrigated to supplement in situ rainfall (*10*). To avoid double counting, we subtracted from our estimate of ET on cultivated land (Table 1) the share provided by irrigation water, ~2000 km^3/year. We also assume that half of the ET associated with lawns, parks, and other human-occupied areas is supplied by irrigation; thus the total ET co-opted is ~18,200 km^3. This represents 26% (18,200 km^3/69,600 km^3) of total terrestrial ET. The remaining 74% must meet the water needs of all other land-based species and natural communities.

We adjusted total runoff (40,700 km^3) for geographic and temporal inaccessibility to estimate the portion that is realistically available for human use; we call this accessible runoff (AR). The distribution of global runoff among the continents is highly uneven and corresponds poorly to the distribution of world population (Table 2). Asia, with 60% of world population, contains 36% of global runoff. South America, with ~5% of world population, contains 25% of runoff. Moreover, much of the runoff in the tropics and high northern latitudes is virtually inaccessible to the human economy and is likely to remain so for the foreseeable future.

Table 1. Estimates of ET appropriated for human-dominated land uses. A total of 26.2% of terrestrial ET is appropriated (18,200 km^3/69,600 km^3).

Land type	NPP co-opted* (10^9 metric tons)	ET co-opted† (km^3)
Cultivated land	15.0	5,500‡
Grazing land	11.6	5,800
Forest land	13.6	6,800
Human-occupied areas (lawns, parks, golf courses, and so forth)	0.4	100‡
Total appropriated	40.6	18,200

*NPP from intermediate calculation of Vitousek *et al.* (*7*). †Assumes 2 g of biomass produced for each liter of water evapotranspired. ‡Adjusts for share of ET requirement met through irrigation.

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The Amazon River accounts for 15% of global runoff (*11*). It is currently accessible, however, to ~25 million people (*12*)—0.4% of world population—and no massive expansion of irrigation is likely that would warrant major diversions from it. We thus consider 95% of its flow inaccessible. The Zaire-Congo ranks second in global runoff (3.5% of the total) (*11*) and supports ~1.3% of world population (*12*). We judge half of its flow to be inaccessible for purposes of irrigation and industrial and municipal use over the next 30 years.

The final subtraction is for the remote rivers of North America and Eurasia, 55 of which have no dams on their main channels (*13*). Most of this river flow is in tundra and taiga biomes that are remote from population centers. The combined average annual flow of these northern untapped rivers is 1815 km^3/year, and we subtract 95% of it.

Together, the inaccessible remote flows of the Amazon, Zaire-Congo, and northern-tier undeveloped rivers amount to 7774 km^3 per year (Table 3), or 19% of total annual runoff. This leaves ~32,900 km^3 geographically accessible. Our estimate is conservative because we made no subtractions for many (particularly northern) rivers that have very large flows relative to the human population size and water needs of their geographic areas (*14*).

We next adjusted for temporal inaccessibility. Irrigated agriculture, industry, and households require that water be supplied when and where it is needed. This degree of control over runoff is not easy to achieve. Approximately 11,100 km^3 of global runoff (~27% of the total) is renewable ground water and base river flow (*6*). As long as extraction does not exceed replenishment, these sources can provide a reliable renewable supply. The remaining runoff, ~29,600 km^3, is much harder to capture, because most of it is flood water. In Asia, for instance, 80% of runoff occurs from May to October (*4*, *15*). Capturing flood runoff generally requires the construction of dams. The present storage capacity of large dams collectively totals 5500 km^3, of which 3500 km^3 is actively used in the regulation of river runoff (*6*, *16*).

Adding together the base flow and the surface runoff controlled by dams gives an estimate of the total stable flow. Assuming that the geographically accessible runoff is divided between base and flood flow in the same proportion that total runoff is, we then reduced the estimate of total base flow by the share of it contained in the remote rivers, 2100 km^3 (0.27 × 7774 km^3), leading to an accessible base flow of 9000 km^3 (11,100 − 2100). Addition to this of the estimated 3500 km^3 of runoff regulated by existing reservoirs yields an estimate of present total AR of 12,500 km^3/year.

We next estimated what portion of AR humanity now uses. Three categories of water use are (i) withdrawals or abstractions, which represent water removed from rivers, lakes, and aquifers for human activities (also known as water demand or water use); (ii) consumption, which refers to withdrawals that are not available for a second or third use; and (iii) human instream flow needs. Together, withdrawals and instream uses provide a measure of human appropriation of runoff, and we estimate them separately here.

Agriculture uses by far the most AR worldwide. We estimated agricultural water withdrawals by multiplying an average water application rate of 12,000 m^3/ha (*17*) by the 1990 estimate of 240 million hectares of world irrigated area (*10*). This yields a total agricultural water demand of ~2880 km^3 (Table 4). The ratio of consumption to withdrawals varies with climatic factors, the crops grown, and irrigation efficiency, and typically ranges between 50 and 80% (*4*). We assume that ~65% of agricultural water withdrawals are consumed, for a global total of 1870 km^3.

Industrial water use has leveled off or declined in many wealthier countries, but is growing rapidly in much of the developing world (*2*). Shiklomanov (*4*) estimated that industrial use is ~975 km^3 globally, including the thermoelectric power industry. In contrast to agriculture, only a small share of water used in industry is consumed; most of it is discharged back to the environment,

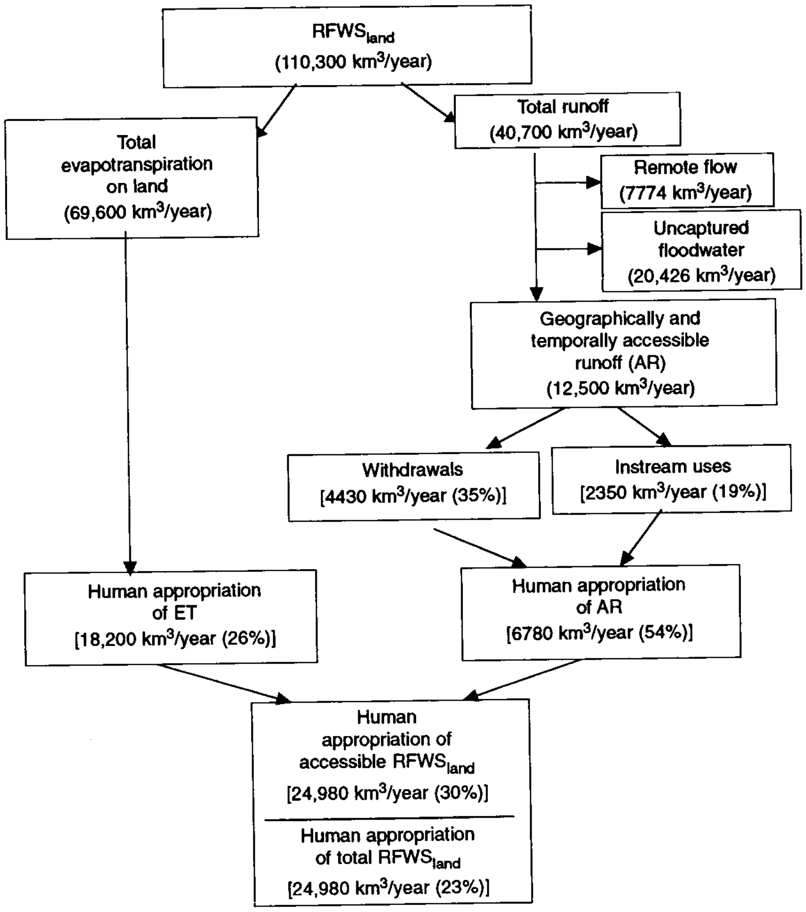

Fig. 2. Flow diagram of analysis of human appropriation of RFWS$_{land}$. The final box shows human appropriation of estimated accessible RFWS$_{land}$ to be 30% (24,980 km^3/82,100 km^3) and human appropriation of total RFWS$_{land}$ to be 23% (24,980 km^3/110,300 km^3).

Table 2. Share of global runoff and population by continent.

Region	Total river runoff* (km^3/year)	Share of global river runoff (%)	Share of global population† (%)
Europe	3,240	8.0	13.0
Asia	14,550	35.8	60.5
Africa	4,320	10.6	12.5
North and Central America	6,200	15.2	8.0
South America	10,420	25.6	5.5
Australia and Oceania	1,970	4.8	0.5
Totals	40,700	100.0	100.0

*Runoff estimates from (*6*). †Population estimates from (*32*).

Table 3. Estimates of inaccessible runoff of selected remote rivers.

River basin or region	Remote flow (km^3/year)
Amazon* (95% of total flow)	5387
Zaire-Congo* (50% of total)	662
Remote undammed northern rivers† (95% of totals)	
North America	979
Eurasia	746
Total inaccessible remote runoff	7774

*Amazon and Zaire-Congo runoff from (11). †Northern rivers from (13).

although it is often polluted. Some 9%—or ~90 km^3—of industrial water withdrawals are consumed.

Municipal use varies greatly among countries and regions. Shiklomanov (4) accounted separately for urban and rural inhabitants, using country-level data on demographic characteristics and water use. His estimated worldwide municipal use is 300 km^3 per year, of which ~50 km^3 (or ~17%) is consumed.

In certain geographic regions, reservoir losses to evaporation constitute a substantial share of total runoff (18). We assume that an average of 5% of the gross storage capacity of reservoirs worldwide (5500 km^3) is lost to evaporation, or 275 km^3/year.

Instream flow uses include maintenance of navigation paths, water quality, river deltas, fisheries, wildlife, riparian vegetation, other aquatic biodiversity, and recreational opportunities. Because instream requirements vary geographically and seasonally, we used pollution dilution as a global proxy and assumed that the dilution requirement is sufficient to meet other instream needs as well. An often used dilution factor for assessing waste absorption capacity is 28.3 liters per second per 1000 population (19). Applying this rate to the 1990 population yields a dilution requirement of ~4700 km^3. If 50% of municipal and industrial waste globally receives at least secondary treatment before discharge (20), then the instream flow requirement is 2350 km^3/year. In actuality, some dilution is accomplished by flood flows rather than by AR, and some additional pollution comes from dispersed (such as agricultural) sources, but because we are using the dilution requirement as a proxy for instream uses generally, we made no adjustments for these (21).

Table 4. Estimated global water use and consumption, by sector, ca. 1990.

Sector	Use (km^3/year)	Consumption (km^3/year)
Agriculture*	2880	1870
Industry†	975	90
Municipalities†	300	50
Reservoir losses‡	275	275
Subtotal	4430	2285
Instream flow needs	2350	0
Total	6780	2285
Total as a percent of AR (12,500 km^3)	54%	18%

*Assumes average applied water use of 12,000 m^3/ha and consumption equal to ~65% of withdrawals. †Estimates are from (4). ‡Assumes evaporation loss equal to 5% of gross reservoir storage capacity.

Overall, we estimate that ~18% of AR (2285 km^3/12,500 km^3) is now consumed directly for human purposes. Withdrawals from rivers, streams, and aquifers combined with instream flow requirements total 6780 km^3, which suggests that an additional 36%—for a total of 54% of AR (6780 km^3/12,500 km^3—is currently appropriated for human purposes. We estimate that human use of ET and runoff constitutes 30% of the total accessible RFWS [(18,200 km^3 + 6780 km^3)/(69,600 km^3 + 12,500 km^3)]. This is conservative, because it assumes that all ET is accessible (22). Comparison of human use with the total unadjusted RFWS indicates that *Homo sapiens* is co-opting ~23% of this life-support resource (18,200 km^3 + 6780 km^3/110,300 km^3).

How much can AR be expected to increase during the next three decades? The principal means of expanding AR is to capture and store more flood runoff or to desalinate seawater. Exotic options, such as towing icebergs, are unlikely to yield appreciable quantities of water on a global basis in the next 30 years.

Desalination, which supplies ~0.1% of world water use (23), is an expensive option, largely because it is energy-intensive. The theoretical minimum energy requirement to remove salt from water is 2.8 million joules per cubic meter, but even the best desalination plants now operating use 30 times this amount (24). Technological improvements might reduce energy needs to 10 times the theoretical minimum (24), but this is still a substantial energy requirement. For the foreseeable future, desalination is likely to continue to be used primarily to meet drinking water needs in water-scarce, energy-rich nations.

The creation of new reservoirs will continue to expand AR but at a slower rate. Worldwide, an average of 885 large dams (those at least 15 m high) were constructed per year between 1950 and the mid-1980s (25). At present, no more than ~500 large dams are being completed each year (26, 27), and we would expect this to drop further because of rising economic, social, and environmental costs (2). We assumed an average of 350 new dams per year for the next 30 years. If average reservoir capacity per dam remains the same as in the period from 1950 to 1985, as well as the proportion that is dead storage or otherwise unavailable for water supply, ~1200 km^3 would be added to the accessible supply circa (ca.) 2025 (28). Addition of this to existing active storage capacity of 3500 km^3 yields a total of 4700 km^3 ca. 2025. Combining this with the accessible base flow (9000 km^3) gives an AR ca. 2025 of 13,700 km^3/year (29).

If average per capita water demand remains the same in 2025 as at present [which is conservative, because withdrawals per capita increased nearly 50% between 1950 and 1990 (2)], global water demand ca. 2025 would total ~6400 km^3/year. Further, if instream flow needs for pollution dilution increase in direct proportion to population, these would total ~3430 km^3/year ca. 2025, for a total human appropriation ca. 2025 of ~9830 km^3/year, or >70% of estimated AR ca. 2025.

We ignore the possibility that, during the next few decades, runoff patterns might be altered substantially by temperature increases and precipitation shifts associated with the buildup of greenhouse gases (30). This, in turn, could alter dam requirements and reservoir storage and thus AR. Given the possible nonlinearities in the climatic system, our ca. 2025 AR estimate may be optimistic.

The aquatic environment is already showing signs of degradation and decline, particularly because of dam construction, river diversions, heavy pollution loads, and other habitat changes (27, 31). Substantially higher levels of human appropriation of AR could result in a severe faltering of aquatic ecosystem services, including broad decimation of fish populations and the extinction of numerous beneficial species. Greater investments in pollution prevention would free up AR to meet rising human water needs while safeguarding ecological functions. Likewise, greater efficiency of water use, changes in agricultural cropping patterns, and the removal of marginal lands from irrigation could help slow the growth of human appropriation of AR.

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6. M. I. L'Vovich *et al.*, in *The Earth as Transformed by Human Action*, B. L. Turner *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1990), pp. 235–252.
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9. Our global estimate conforms well to values derived from small-scale field studies with crops [B. A. Stewart, J. T. Musick, D. A. Dusek, *Agron. J.* **75**, 629 (1983); *Yield Response to Water* (U.N. Food and Agriculture Organization, Rome, 1979); Z. Zixi, B. A. Stewart, F. Xiangjun, *Field Crops Res.* **36**, 175 (1994)].
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14. We do not include in our estimate of remote northern river flows a large number of rivers that have one or two dams (typically for hydropower) on their main channels but have flows vastly in excess of water supply needs in the region, including, for example, the Ob and Lena rivers of Siberian Russia, with a combined flow of 935 km^3. The ambitious Soviet scheme to divert water from the Ob to the Aral Sea basin would initially have involved 25 km^3/year, just 6% of the Ob's annual average flow. Likewise, a proposal to ship water via undersea pipeline from southeast Alaska to California involved 5 km^3 annually, just under 5% of the combined average annual flow of the Copper and Stikine rivers, leaving 95% of their flow still remote [*Alaskan Water for California? The Subsea Pipeline Option—Background Paper* (U.S. Office of Technology Assessment, Washington, DC, 1992)].
15. Uncaptured flood runoff provides a variety of human benefits, including support of flood-recession farming, fisheries, and generation of hydroelectricity; however, in these capacities, its use is either insignificant globally or does not involve actual appropriation.
16. Theoretically, a reservoir could be filled and emptied more than once a year, creating a greater effective capacity to regulate runoff than the storage capacity alone would indicate. We know of no estimates of this effective storage capacity other than the statement by K. Mahmood [*Reservoir Sedimentation: Impact, Extent, and Mitigation* (The World Bank, Washington, DC, 1987)] that the usable reservoir storage capacity "is nearly used once every year." We therefore make no adjustments to the estimated 3500 km^3 of capacity usable for runoff storage on an average annual basis.
17. This is a somewhat higher rate than is implied by Shiklomanov's estimates (*4*), which suggest rates of 10,700 to 11,000 m^3/ha. We arrived at our figure after examining data for California that suggest an average water application rate on that state's irrigated area of $\sim$10,300 m^3 ha [*California Water Plan Update* (California Department of Water Resources, Sacramento, CA, 1994), vol. 1]. Because the average irrigation efficiency in California is reported to be 70%, which is substantially higher than the worldwide average [S. Postel, in (*5*), pp. 56–66], we believe that 12,000 m^3/ha is closer to the actual global average application rate. Moreover, the California figures account only for on-farm water applications and do not include the portion of diversions lost to seepage or evaporation between reservoirs and farmers' fields.
18. Evaporative losses from Lake Nassar, for example, have averaged 10 km^3/year, which is equal to 12% of the Nile's average annual flow [J. A. Allan, in *The Nile: Sharing A Scarce Resource*, P. P. Howell and J. A. Allan, Eds. (Cambridge Univ. Press, Cambridge, 1994), pp. 313–320].
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20. Even in the countries of the Organization for Economic Cooperation and Development, domestic wastewater treatment is estimated to cover only $\sim$60% of the population [A. K. Biswas, *Water Int.* **17**, 68 (February 1992)]. Information for developing countries is sparse, but treatment coverage is certainly far lower. Moreover, few regions control for farm runoff and other dispersed pollution sources that add substantial quantities of sediment, pesticides, and fertilizers to water bodies.
21. Even if wastewater treatment coverage should become nearly universal, substantial instream flows would still be required to maintain fisheries, support recreational demands, and satisfy other instream needs. For example, California's instream environmental water requirements (after omission of the north coast hydrologic region, which contains several wild and scenic rivers and thus may not be indicative of instream needs more narrowly defined) equal 22% of average annual runoff [*California Water Plan Update* (California Department of Water Resources, Sacramento, CA, 1994).
22. We did not consider it feasible to estimate accessible ET in a manner comparable to our estimate of AR. To be conservative, we therefore assumed all terrestrial ET to be accessible.
23. Wangnick Consulting, *1990 IDA Worldwide Desalting Plants Inventory* (International Desalination Association, Englewood, NJ, 1990).
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25. J. A. Veltrop, in *Water for Sustainable Development in the Twenty-first Century*, A. K. Biswas, M. Jellali, G. E. Stout, Eds. (Oxford Univ. Press, Oxford, 1992), pp. 102–115.
26. *Status of Dam Construction, 1991* (International Commission on Large Dams, Paris, 1992), suggests that $\sim$300 dams are now commissioned each year, but these data include only 64 countries.
27. A. P. Covich [in (*5*), pp. 40–55] indicates that large dams are currently being completed at an average rate of 500 per year, or 56% of the rate of the period from 1950 to 1986.
28. Because $\sim$85% of existing large dams were built since mid-century (*25*), this calculation assumes that 85% of total existing storage capacity was constructed since then, or 4675 km^3 (5500 km^3 $\times$ 0.85). With the assumption that 40% as many dams would be constructed between 1990 and 2025 as between 1950 and 1985, and that capacity per dam remains constant, 1870 km^3 (4675 km^3 $\times$ 0.40) of capacity would be added by ca. 2025, of which 1190 km^3 would be live storage for water supply.
29. Even as dam construction is adding to the total stable runoff, other human activities are reducing it. Deforestation and the paving over of aquifer recharge areas often reduce rainwater infiltration, thereby reducing base flow and increasing surface flood runoff. More important globally, many reservoirs are losing active storage capacity faster than originally estimated because of rapid siltation from deforestation, soil erosion, and generally poor watershed management. The Nizamsagar reservoir in India, for instance, lost more than 60% of its capacity over 40 years [M. Newson, *Land, Water and Development: River Basin Systems and Their Sustainable Management* (Routledge, London, 1992]. Lacking global estimates, we make no subtraction for these losses.
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33. We gratefully acknowledge comments from W. Falcon, P. Gleick, R. Naylor, A. Vickers, P. Vitousek, and two anonymous reviewers. Supported by a grant from Charles and Nancy Munger, the Winslow and Heinz foundations, and an anonymous donor.

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Rapid Collapse of Northern Larsen Ice Shelf, Antarctica

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In January 1995, 4200 square kilometers of the northern Larsen Ice Shelf, Antarctic Peninsula, broke away. Radar images from the ERS-1 satellite, complemented by field observations, showed that the two northernmost sections of the ice shelf fractured and disintegrated almost completely within a few days. This breakup followed a period of steady retreat that coincided with a regional trend of atmospheric warming. The observations imply that after an ice shelf retreats beyond a critical limit, it may collapse rapidly as a result of perturbated mass balance.

Ice shelves cover 11% of the total area of Antarctica (*1*) and play an important role in the mass budget and dynamics of the Antarctic Ice Sheet. Most of the ice that has accumulated over the grounded parts of Antarctica is discharged to ice shelves, where it is lost as icebergs along the seaward edges as well as by basal melting (*2*). Because ice shelves are exposed to both atmosphere and ocean, they are sensitive to changes in the temperature and circulation of either (*3*). The 0°C summer isotherm has been taken as the climatic limit for the existence of ice shelves along the west coast of the Antarctic Peninsula (*4*). Between 1966 and 1989, the Wordie Ice Shelf (Fig. 1) decreased from $\sim$2000 to 700 km^2, probably as a result of regional atmospheric warming (*5*). Here, we report on the recent disintegration of the northern Larsen Ice Shelf (LIS).

The LIS extends along the eastern side of the Antarctic Peninsula from latitude 64° to 74°S (Fig. 1). The part of the LIS north of Robertson Island has retreated slowly but constantly since the 1940s (*6, 7*). The retreat accelerated after 1975 (*8*), and

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