Annu. Rev. Environ. Resour. 2003. 28:275–314
doi: 10.1146/annurev.energy.28.040202.122849

WATER USE

Peter H. Gleick
Pacific Institute, 654 13th Street, Oakland, California 94612;
email: pgleick@pipeline.com

Key Words water consumption, withdrawal, scenarios, freshwater, conservation, water-use efficiency, water productivity

■ **Abstract** Water managers and planners are slowly beginning to change their perspective and perceptions about how best to meet human needs for water; they are shifting from a focus on building supply infrastructure to improving their understanding of how water is used and how those uses can best be met. This review discusses definitions of water use, explores the history of water use around the world and in characteristic regions, identifies problems with collecting and analyzing water data, and addresses the question of improving water-use efficiency and productivity in different regions and economic sectors. There is growing interest on the part of water managers around the world to implement these approaches to lessen pressures on increasingly scarce water resources, reduce the adverse ecological effects of human withdrawals of water, and improve long-term sustainable water use.

CONTENTS

INTRODUCTION

The history of human civilization is entangled with the history of the ways humans have learned to manipulate and use fresh water. The earliest agricultural communities depended on the vagaries of natural rainfall and runoff. Engineering advances came with simple dams and irrigation canals that permitted greater crop production and longer growing seasons. The expansion of urban areas eventually required the development of sophisticated piping and aqueducts, to bring water to users, and of innovative systems to remove wastes, some of which were put in place thousands of years ago (1, 2).

During the industrial revolution and population explosion of the nineteenth and twentieth centuries, the demand for water rose dramatically. Unprecedented construction of tens of thousands of monumental engineering projects designed to control floods, protect clean water supplies, and provide water for irrigation or hydropower brought great benefits to hundreds of millions of people. Thanks to improved sewer systems, water-related diseases such as cholera and typhoid, once endemic throughout the world, have largely been conquered in the more industrialized nations. Huge cities survive on water brought from hundreds and even thousands of kilometers away. Food production to meet the needs of more than six billion people is now largely dependent on artificial irrigation systems. Nearly one fifth of all of the electricity generated worldwide is produced by hydroelectric turbines. Even today, $30 to $40 billion are spent annually on new dams (3).

A wide variety of forces, however, are driving a shift away from the construction of new water infrastructure. Most important is the improved understanding of the true economic, social, and environmental costs of that infrastructure. As a result, water planners and managers are on the verge of a fundamental change in thinking about water—a change from a focus on new construction to a focus on evaluating how best to meet human needs and desires. New water facilities are still needed in many parts of the world, and the existing infrastructure must be maintained in order to keep the flow of benefits coming. But those responsible for water are now beginning to pay far more attention to the other side of the equation—how society uses water.

Most water planners throughout the world are not trained to think about water use in a systematic way. Definitions are used inconsistently and incorrectly. Forecasts of water use are made with inappropriate and irregular assumptions. And both water experts and policy makers often misunderstand the role of water use in water policy. New approaches to water planning and management are beginning to address issues of use directly, which lead to changes in management and to improvements in long-term sustainable water use. This review discusses definitions of water use, explores the history of water use around the world and in characteristic regions, identifies problems with collecting and analyzing water data, and addresses the question of improving the efficiency and productivity of water use in different regions and economic sectors.

Needs Versus Wants for Water

A shift in emphasis is underway away from evaluating broad demands for water to a better understanding of water needs and uses. Discussion of the differences between needs and wants has recently appeared in the resource literature (4). People need only basic amounts of water for drinking, cooking, cleaning, and hygiene to maintain human well-being (5). Rather, people seek water for goods and services, such as the production of food and industrial items, transportation, communications, and the elimination of wastes. In addition, people want goods and services beyond their basic needs; some of the wanted items are recreation, leisure, and luxury goods. Providing these needs and wants can be accomplished in many ways, which depend on technology, prices, cultural traditions, and other factors, often with radically different implications for water.

Traditional approaches to meeting water needs have focused on how to design, fund, and build water-supply systems; these range from dams and aqueducts to water treatment and distribution facilities. Water-supply systems have brought great benefits to water users by improving the reliability of supply, reducing water-related diseases associated with poor water quality, and buffering the impacts of extreme hydrologic events such as floods and droughts. They have also brought great costs, which include ecological and environmental degradation, social disruption associated with infrastructure construction, and economic problems.

An alternative approach, dubbed the “soft” path, also relies on centralized infrastructure but complements it with investment in decentralized facilities, efficient technologies, and human capital (6–8). It strives to improve the overall productivity of water use rather than seek endless sources of new supply. It delivers diverse water services matched to the users’ needs and works with water users at local and community scales.

A good example of the difference between needs and wants can be seen in approaches for disposing of human wastes. Waste disposal does not require any water, although using some amount of water for this purpose may be appropriate or culturally preferred. In many parts of the world, human wastes are disposed of safely without any water at all (except for modest amounts for hygiene and washing). In industrial nations, however, we have grown accustomed to flush toilets. Indeed, toilet flushing is usually the largest indoor residential use of water in richer nations. Yet even here, substantial improvements in technology in the past two decades have led to a 75% decrease in water used by toilets in the United States, and even greater improvements are achieved in toilets used widely in Australia, Japan, and Europe. All toilets manufactured in Australia are now dual-flush systems using either six liters or three liters per flush (9).

Many traditional approaches can also be used to manage human wastes without any water, and new technology can do this even in wealthier countries accustomed to traditional flush systems. At the high end, electrically mixed, heated, and ventilated composting toilets, which have no odors or insect problems, are available (10). These devices safely and effectively biodegrade human wastes into water, carbon dioxide, and a soil-like residue that can be used as compost. Although they can use substantial amounts of electricity, they can displace an equal or greater amount of electricity currently used to deliver water and treat wastewater.

Similarly, farmers do not want to use water, per se; they want to grow crops profitably and sustainably. Manufacturers are not interested in using water but in producing goods. Soft-path water planners would therefore argue that farmers and manufacturers are likely to implement any water-conserving technologies that make practical, economic, and social sense while permitting them to meet their needs. Comparable examples of technologies and practices that permit us to meet our needs and wants with less and less water can be found in every sector of society (11).

Definitions of Water Use, Conservation, and Efficiency

There is considerable confusion in the water literature about the terms use, need, withdrawal, demand, consumption, and consumptive use. Great care should be used when interpreting or comparing different studies or assumptions about water use. The term *water use*, while common, can mean many different things, referring at times to consumptive use and at times to withdrawals of water.

Withdrawal usually refers to water removed from a source and used for human needs. Some of this water may be returned to the original source with changes in the quantity and quality of the water, but some may be used consumptively. The term *consumptive use* or *consumption* typically refers to water withdrawn from a source and made unavailable for reuse in the same basin, such as through conversion to steam, losses to evaporation, seepage to a saline sink, or contamination. Consumptive use is sometimes referred to as irretrievable or irrecoverable loss (12). Thus a power plant may withdraw substantial amounts of water for cooling from a river but use that water in a way that permits it to be returned directly to the river, perhaps a bit warmer, for use by the next downstream user. A farmer may withdraw the same amount of water for irrigation, but the vast majority of it may be used consumptively by plants and become unavailable for any other activity.

Need for water is also a subjective term, but typically it refers to the minimum amount of water required to satisfy a particular purpose or requirement. It also sometimes refers to the desire for water on the part of a water user. *Demand* for water is an economic concept often used to describe the amount of water requested or required by a user (13). The level of demand for water may have no relationship to the minimum amount of water required to satisfy a particular requirement. Water demand to flush a toilet can range from six gallons in an old, inefficient U.S. toilet, to 1.6 gallons in a model that meets current U.S. standards, to zero gallons in an efficient composting toilet. What is actually being demanded is not a specific amount of water but the service of reliably and safely removing wastes.

A considerable number of other confusing terms have appeared in the water literature in the past few years. Among them are terms used to describe the kinds of water that might be saved by changes in technology and water policies, including real water, paper water, and new water. Some of these distinctions have been valuable in identifying where and when conservation is most beneficial and have allowed planners to focus on the improvements in water-use efficiency that are the most appropriate and valuable (14–17). Some of these distinctions, however, have been misleading or have misrepresented the value of efficiency improvements.

As noted above, consumptive uses of water prevent water from being reused in a watershed or system. Efforts to reduce consumptive uses clearly save real, physical water that can be made available to other users. But some planners are confused about the value of nonconsumptive uses of water: uses that permit later reuse.

The California Department of Water Resources (CDWR), for example, miscalculated the value of water-use efficiency efforts to reduce nonconsumptive uses in water plans prepared in the 1990s. The CDWR argued that upstream reductions in nonconsumptive use are *paper* water, i.e., they do not produce *new* water (by which they mean additions to supply), and hence do not help satisfy water demands (18, 19). Under this line of thought, Sacramento, an inland city, would not benefit from efforts to install residential water meters or retrofit houses with low-flow showerheads or efficient toilets because water used inefficiently (but nonconsumptively) in Sacramento is already being used by downstream users.

While no new water would be produced in this case, the water savings from efficiency improvements in Sacramento would nevertheless be a real reduction in demand that displaces the need for new supplies, because they would permit new customers and new demands in Sacramento to be satisfied without expanding capacity or infrastructure. Moreover, such reductions in demand would reduce the need to take water out of local rivers and aquifers, improve water quality and environmental values downstream of Sacramento, and provide enhanced recreation, fishing, tourism, and other benefits. This misunderstanding led state water planners to ignore or underemphasize improvements in urban water-use efficiency in inland regions. That, in turn, led to a potential overestimate of future increases in urban demand in California in 2020 by more than a billion cubic meters, which could in turn lead policy makers to commit major financial resources to unnecessary new supply projects (19). As will be described later, water forecasts leading to overestimates of future water needs are common.

Similarly, water accounts for the Nile River indicate that only 20%–30% of irrigation water diverted from the Nile is evaporated or transpired by crops (15). The remainder is return water typically reused downstream. Some have claimed that upstream reductions in nonconsumptive use are relatively unimportant because water loss is not the same as water waste (20). Of course this is strictly correct: Irrigation return flows are not wasted if they are used downstream. But upstream conservation efforts have other benefits: They would allow a larger upstream area to be irrigated, improve the navigability of the Nile, or as in the California example, improve water quality for downstream natural systems or users.

Related to problems of defining water use is the challenge of defining how to improve that use. The terms conservation, efficiency, and productivity are often used interchangeably to get across the idea of doing more with less. Used most generally, the term *water conservation* simply refers to reducing water use by any amount or any means, which may include applying new technology, improving old technology, and instituting behavioral changes.

Baumann et al. more explicitly defined *water conservation* as any socially beneficial reduction in water use or water loss. This definition suggests that efficiency measures should, in addition to reducing water use per unit of activity, make sense economically and socially (21). This leads to economically efficient outcomes, taking into account all costs, by pushing forward with conservation up to the point where the incremental cost of demand reduction is the same as the incremental cost of supply augmentation. The advantage of this definition is that it focuses on comprehensive demand and supply management with the goal of increasing overall well-being per unit of water used.

Water-use efficiency is a more precise measure of water conservation: how much water is actually used for a specific purpose compared to the minimum amount necessary to satisfy that purpose. Under this definition, the theoretical maximum water-use efficiency occurs when society actually uses the minimum amount of water necessary to do something. In reality, however, this theoretical maximum efficiency is rarely, if ever, achieved because the technology is not available or commercialized, because the economic cost is too high, or because societal or cultural preferences rule out particular approaches.

Finally, the concept of water productivity is useful in discussions about water use. *Water productivity* usually refers to the amount of measurable output per unit of water that is used. The units of output can be physical (e.g., tons of wheat) or economic (e.g., the dollar value of the good or service produced). Hence, the term water productivity is a comprehensive way to combine the ideas of doing more with less water.

HOW IS WATER USED?

Water is used for many different purposes throughout our economies and natural ecosystems. Agriculture is the largest consumer of water used by humans worldwide. Most observers put total consumptive use of water worldwide for irrigated agriculture at nearly 85% of total human consumptive use. This water is vital for the production of food. In 2000, around 270 million hectares of land were irrigated worldwide, which is 18% of total cropland (22). Around 40% of all agricultural production comes from these irrigated areas. As a result, evaluations of water use must pay particular attention to this sector.

Water is used by agriculture for a number of critical services. Water is necessary for growing biota, for maintaining temperature balances within plants, for leaching salts and other minerals away from the root zone, and more. Water diverted for agriculture is depleted by transpiration of the plants, by evaporation from soil and free water surfaces, and by deep percolation to groundwater. Some of this water can be considered to be used beneficially while a portion is lost to nonbeneficial uses.

In urban or residential settings, water is used for a wide range of daily activities, which include cooking, cleaning and bathing, small-scale irrigation for gardens or municipal landscapes, waste disposal, and commercial and industrial activities. Almost all forms of production of goods and services require water. Sometimes water is actually embodied in the production of a good, such as water used to can fruits and vegetables or to make beverages. Other times, water is simply used to clean, cool, or operate machinery. A substantial fraction of total water withdrawals in some industrialized nations is used for the production of energy, either directly in hydroelectric plants or indirectly for power plant cooling. Most of this water is not used consumptively. In the United States, 47% of total water withdrawals went to power plant cooling. In Europe, 32% went for these purposes (23–25).

Finally, there is a whole series of water uses by natural ecosystems that are almost always ignored in surveys or assessments of water use. Many of these environmental uses of water are not directly human uses, although they nonetheless contribute to maintaining the ability of natural ecosystems to provide certain kinds of goods and services critical for human well-being. While there are no satisfactory standards for how to account for this kind of water use, it is receiving growing attention in the water-use field. Indeed, the government of South Africa has formally acknowledged, the need to maintain basic water flows for the environment in its post-apartheid water laws (26).

Data Problems

Compounding problems with definitions of water use are serious problems with data. Data on water use are collected around the world to support scientific research, facilitate the operation of water-supply systems, and improve water-policy decisions. The types of data collected, the frequency and accuracy of collection, and the availability vary widely from place to place. Compared with data on the hydrologic cycle, such as rainfall, runoff, and temperature, data on water use are inadequate and incomplete, and pressures are growing to cut back collection for financial reasons (27, 28). Several serious problems hinder water-use analyses:

SYSTEMATIC COLLECTION OF WATER-USE DATA IS RARE Far fewer data are collected on water use than on water supply and availability. Domestic water use is often not measured directly, and details on how that water is used are rarely collected. Data on surface water are collected more frequently than data on the use or condition of groundwater. Data on urban water uses are more readily available than data on rural and agricultural uses, but even details of industrial and commercial water uses are inventoried infrequently or not at all. Even when water-use data are collected, information on changing water-use patterns over time is often not available; this makes analysis of trends difficult.

SOME WATER USES OR NEEDS ARE UNQUANTIFIED OR UNQUANTIFIABLE Some water uses and needs have never been adequately catalogued; others are unlikely ever to be accurately determined. For example, ecological needs, recreational uses, water for hydropower production or navigation, and reservoir losses to seepage or evaporation are often difficult to calculate with any accuracy. Information on total withdrawals is reported more frequently than information on consumptive uses. But water may be withdrawn once and then used several times in a process; so data on withdrawals may be an inadequate measure of overall use or need. These kinds of water-use distinctions and activities must be measured if effective water management is to be done.

THERE ARE SERIOUS GLOBAL AND REGIONAL DISPARITIES IN COLLECTION Although water-use data are usually more reliably and consistently collected in the industrialized nations, some regions have few or no programs in place to survey water uses. There are also regional disparities in the scope and quality of water-use data collection within countries, and even in wealthier countries, programs to evaluate water use are often the first victims of budget cuts during fiscal crises.

MANY DATA ARE INACCURATE Even when data are collected, inaccurate measurement and reporting are common. As mentioned above, confusion over definitions of withdrawals, consumption, and reuse make some comparisons difficult. It is difficult to determine water use when no meters or measuring devices are in place. And determining specific uses often requires estimates based on indirect factors, such as climate, typical crop characteristics, or assumptions about the performance of water-use technology. For example, showerheads that are designed to flow at a rate of 2.5 gallons per minute (the current U.S. standard) may actually flow at rates above or below this standard because of local differences in pipe pressure. Crops estimated to evapotranspire a certain amount of water may use more or less than that because of differing soil conditions, temperatures, or even local wind regimes.

ESTIMATES OF CURRENT WATER USE

As described above, collecting and reporting water-use data entail enormous challenges due to problems with the quality of data and differing definitions and standards for measurement. Because of these difficulties, estimates of current water use at the national or global level must only be considered approximations, even in the best of circumstances. Nevertheless, a number of comprehensive assessments have been done in an effort to get a broader picture of critical water concerns. Most global studies typically consist of separate regional or sectoral evaluations conflated to provide a global view. In this section, several global and regional water-use estimates are reviewed, and an overview of water use by major sectors is presented.

Global Water Use

Many factors determine water-use levels around the world: the extent and form of socioeconomic development, population size, climatic conditions, and the physical nature of a region. Various assessments have been made of global water use, typically by combining regional analyses that take these different factors into account. Shiklomanov and a group of researchers at the State Hydrologic Institute (SHI) of St. Petersburg have produced one of the most comprehensive and recent assessments. In this analysis, total water withdrawals and consumption were estimated for urban needs (domestic water consumption), industrial use (including power generation), irrigated agriculture, and evaporation losses from reservoir surfaces. Estimates were made for various periods, including 1900, 1940, 1950, 1960, 1970, 1980, 1990, and 1995 (12, 29).

The SHI estimated water use for approximately 150 countries, and the data were then generalized for larger economic regions and summed by continents. Preference was given to using actual reported data from individual countries or groups of countries, but when actual data were not available, estimates were derived by using information on reported economic activity using assumptions about the water implications of different activities or by drawing analogies with countries with similar physiographic and economic conditions.

Table 1 shows Shiklomanov's (29) estimates of both water withdrawals and consumption (reported as irrecoverable losses) by continental regions for decades from 1900 to the mid-1990s. As might be expected, water uses around the world are very uneven, both spatially and temporally. The data also indicate the quite strong and dramatic increases in total fresh water withdrawals and consumption in the twentieth century, which led to the widespread construction of large water systems. According to these estimates, water withdrawals in 1995 totaled 3765 cubic

TABLE 1 Water withdrawal and consumption estimates and projections in cubic kilometers (29)

	Historical estimates of use								**Forecasted use**		
Continent	**1900**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2010**	**2025**
Europe	37.5[a]	71	93.8	185	294	445	491	511	534	578	619
	17.6[b]	*29.8*	*38.4*	*53.9*	*81.8*	*158*	*183*	*187*	*191*	*202*	*217*
North America	70	221	286	410	555	677	652	685	705	744	786
	29.2	*83.8*	*104*	*138*	*181*	*221*	*221*	*238*	*243*	*255*	*269*
Africa	41.0	49.0	56.0	86.0	116	168	199	215	230	270	331
	34.0	*39.0*	*44.0*	*66.0*	*88.0*	*129*	*151*	*160*	*169*	*190*	*216*
Asia	414	689	860	1222	1499	1784	2067	2157	2245	2483	3104
	322	*528*	*654*	*932*	*1116*	*1324*	*1529*	*1565*	*1603*	*1721*	*1971*
South America	15.2	27.7	59.4	68.5	85.2	111	152	166	180	213	257
	11.3	*20.6*	*41.7*	*44.4*	*57.8*	*71.0*	*91.4*	*97.7*	*104*	*112*	*122*
Australia & Oceania	1.6	6.8	10.3	17.4	23.3	29.4	28.5	30.5	32.6	35.6	39.6
	0.6	*3.4*	*5.1*	*9.0*	*11.9*	*14.6*	*16.4*	*17.6*	*18.9*	*21*	*23.1*
Total (rounded)[c]	579	1065	1366	1989	2573	3214	3590	3765	3927	4324	5137
	415	*704*	*887*	*1243*	*1536*	*1918*	*2192*	*2265*	*2329*	*2501*	*2818*

[a] Underlined numbers show water withdrawal.

[b] Italic numbers show water consumption.

[c] Includes about 270 cubic kilometers in water losses from reservoirs for 2025.

kilometers annually, compared with 579 cubic kilometers in 1900. Consumptive uses in 1995 were estimated at 2265 cubic kilometers, up from 415 km^3 in 1900. Use in North America and Europe accounted for 19% of total estimated withdrawals at the beginning of the twentieth century. By 1995, withdrawals in North America and Europe had increased to 30% of the total, which reflects increased industrialization.

From a practical point of view, however, absolute measures of water use are sometimes less valuable than comparing water use with water availability, which can give a better sense of how close a region may be to stress or scarcity. For example, total water withdrawals at the end of the twentieth century comprised as much as 15% to 17% of total renewable water availability in Europe and Asia, but only 1% to 2% of availability in South America and Oceania. On an even finer regional scale, current water withdrawals are already as much as 24% to 30% of total supply in parts of southern and central Europe; at the same time in the northern part of the continent, there are regions where these values never exceed 3%. In Canada, water withdrawals are only about 1% of total water resources. Just to the south, the United States uses as much as 28% of total availability, and there are watersheds in the United States where water use approaches or even occasionally exceeds total regional water availability (due to unsustainable overdraft of local groundwater resources to supplement renewable supplies).

A slightly different approach to estimating water use at the global scale was taken by Postel et al. (30). In their analysis, they estimate the portion of the Earth's renewable water resources accessible to humans and the portion of this supply now being used. They use the estimates of Shiklomanov to calculate municipal uses and add water required for agricultural production and instream flows for human needs such as waste dilution, navigation, recreation, and environmental uses. Overall, Postel et al. (30) estimate that withdrawals from rivers, streams, and aquifers combined with instream flow requirements already total 6780 cubic kilometers per year and that these uses account for 54% of total accessible runoff.

Regional Water Use: National Water-Use Estimates

Data on water use by countries and by different economic sectors are among the most sought-after and unreliable in the water resources area. In recent years, more concerted and consistent efforts to collect and report national water-use estimates have been made by national water agencies and by the United Nations Food and Agriculture Organization (FAO) (31–34). The recent FAO reports cover most countries of Africa, the Near East, the former Soviet Union, Asia, Latin America, and the Caribbean. New, consistent estimates on use have yet to be done for Europe and North America, though national estimates from these regions are done on a more regular basis by those countries themselves. Within each of the continental reports, some of the national water-use data are still incomplete or grossly outdated. For Africa, for example, some of the data are more than 30 years old.

The most up-to-date national data on water use are reviewed and summarized every two years in the biennial book *The World's Water*. These data are reproduced here from the most recent volume (see Table 2) (35). This table shows total

TABLE 2 Freshwater withdrawal, by country and sector[a]

Region and country	Year	Total freshwater withdrawal (km^3/yr)	Per capita withdrawal (m^3/p/yr)[b]	Domestic use (%)	Industrial use (%)	Agricultural use (%)
Africa						
Algeria	1990	4.50	142	25	15	60
Angola	1987	0.48	38	14	10	76
Benin	1994	0.15	23	23	10	67
Botswana	1992	0.11	70	32	20	48
Burkina Faso	1992	0.38	31	19	0	81
Burundi	1987	0.10	14	36	0	64
Cameroon	1987	0.40	26	46	19	35
Cape Verde	1990	0.03	59	10	19	88
Central African Republic	1987	0.07	19	21	5	74
Chad	1987	0.18	25	16	2	82
Comoros	1987	0.01	14	48	5	47
Congo	1987	0.04	13	62	27	11
Congo, Democratic Republic of (formerly Zaire)	1990	0.36	7	61	16	23
Cote D’Ivoire	1987	0.71	47	22	11	67
Djibouti	1985	0.01	11	13	0	87
Egypt	1993	55.10	809	6	8	86
Equatorial Guinea	1987	0.01	22	81	13	6
Ethiopia (and Eritrea)	1987	2.20	31	11	3	86
Gabon	1987	0.06	49	72	22	6
Gambia	1982	0.02	16	7	2	91
Ghana	1970	0.30	15	35	13	52
Guinea	1987	0.74	94	10	3	87
Guinea-Bissau	1991	0.02	14	60	4	36
Kenya	1990	2.05	68	20	4	76
Lesotho	1987	0.05	22	22	22	56
Liberia	1987	0.13	40	27	13	60
Libya	1994	4.60	720	11	2	87
Madagascar	1984	16.30	937	1	0	99
Malawi	1994	0.94	85	10	3	86
Mali	1987	1.36	108	2	1	97
Mauritania	1985	1.63	632	6	2	92
Mauritius	1995	0.62	522	18	8	75
Morocco	1991	11.05	381	5	3	92
Mozambique	1992	0.61	31	9	2	89
Namibia	1991	0.249	144	29	3	68
Niger	1988	0.50	46	16	2	82

(*Continued*)

TABLE 2 (*Continued*)

Region and country	Year	Total freshwater withdrawal (km^3/yr)	Per capita withdrawal ($m^3/p/yr$)[b]	Domestic use (%)	Industrial use (%)	Agricultural use (%)
Nigeria	1987	3.63	28	31	15	54
Rwanda	1993	0.77	100	5	2	94
Senegal	1987	1.36	143	5	3	92
Sierra Leone	1987	0.37	76	7	4	89
Somalia	1987	0.81	70	3	0	97
South Africa	1990	13.31	288	17	11	72
Sudan	1995	17.80	597	4	1	94
Swaziland	1980	0.66	667	2	2	96
Tanzania	1994	1.17	35	9	2	89
Togo	1987	0.09	19	62	13	26
Tunisia	1990	3.08	313	9	3	89
Uganda	1970	0.20	9	32	8	60
Zambia	1994	1.71	187	16	7	77
Zimbabwe	1987	1.22	98	14	7	79
North and Central America						
Antigua and Barbuda	1990	0.005	75	60	20	20
Barbados	1996	0.08	312	77	0	23
Belize	1993	0.095	396	12	88	0
Canada	1990	43.89	1431	11	80	8
Costa Rica	1997	5.77	1520	13	7	80
Cuba	1995	5.21	465	49	0	51
Dominica	1996	0.02	239	0	0	100
Dominican Republic	1994	8.34	982	11	0	89
El Salvador	1992	0.73	115	34	20	46
Guatemala	1992	1.16	95	9	17	74
Haiti	1991	0.98	125	5	1	94
Honduras	1992	1.52	234	4	5	91
Jamaica	1993	0.90	348	15	7	77
Mexico	1998	77.81	787	17	5	78
Nicaragua	1998	1.29	274	14	2	84
Panama	1990	1.64	575	28	2	70
St. Lucia	1997	0.01	89	100	0	0
St. Vincent and the Grenadines	1995	0.01	88	100	0	0
Trinidad and Tobago	1997	0.30	221	68	26	6
United States of America	1995	469.00	1688	12	46	42

(*Continued*)

TABLE 2 (*Continued*)

Region and country	Year	Total freshwater withdrawal (km^3/yr)	Per capita withdrawal ($m^3/p/yr$)[b]	Domestic use (%)	Industrial use (%)	Agricultural use (%)
South America						
Argentina	1995	28.58	772	16	9	75
Bolivia	1987	1.21	145	10	3	87
Brazil	1992	54.87	324	21	18	61
Chile	1987	20.29	1334	5	11	84
Colombia	1996	8.94	230	59	4	37
Ecuador	1997	16.99	1343	12	6	82
Guyana	1992	1.46	1670	1	0	99
Paraguay	1987	0.43	78	15	7	78
Peru	1992	18.97	739	7	7	86
Suriname	1987	0.46	1018	6	5	89
Uruguay	1965	0.65	199	6	3	91
Venezuela	1970	4.10	170	44	10	46
Asia						
Afghanistan	1991	26.11	1020	1	0	99
Bahrain	1991	0.24	387	39	4	56
Bangladesh	1990	14.64	114	12	2	86
Bhutan	1987	0.02	10	36	10	54
Brunei	1994	0.92	2788	—	—	—
Cambodia	1987	0.52	46	5	1	94
China	2000	549.76	431	11	21	69
Cyprus	1993	0.21	267	7	2	91
India	1990	500.00	497	5	3	92
Indonesia	1990	74.35	350	6	1	93
Iran	1993	70.03	916	6	2	92
Iraq	1990	42.80	1852	3	5	92
Israel	1990	1.70	280	16	5	79
Japan	1992	91.40	723	19	17	64
Jordan	1993	0.98	155	22	3	75
Korea, Democratic People's Republic	1987	14.16	592	11	16	73
Korea Republic	1994	23.67	505	26	11	63
Kuwait	1994	0.54	274	37	2	60
Laos	1987	0.99	174	8	10	82
Lebanon	1994	1.29	393	28	4	68
Malaysia	1995	12.73	571	10	13	77
Maldives	1987	0.003	10	98	2	0
Mongolia	1993	0.43	157	20	27	53
Myanmar	1987	3.96	80	7	3	90
Nepal	1994	28.95	1189	1	0	99
Oman	1991	1.22	450	5	2	94

(*Continued*)

TABLE 2 (*Continued*)

Region and country	Year	Total freshwater withdrawal (km^3/yr)	Per capita withdrawal (m^3/p/yr)[b]	Domestic use (%)	Industrial use (%)	Agricultural use (%)
Pakistan	1991	155.60	997	2	2	97
Philippines	1995	55.42	739	8	4	88
Qatar	1994	0.28	476	23	3	74
Saudi Arabia	1992	17.02	786	9	1	90
Singapore	1975	0.19	53	45	51	4
Sri Lanka	1990	9.77	519	2	2	96
Syria	1993	14.41	894	4	2	94
Thailand	1990	33.13	548	5	4	91
Turkey	1992	31.60	481	16	11	72
United Arab Emirates	1995	2.11	863	24	9	67
Vietnam	1990	54.33	674	4	10	86
Yemen	1990	2.93	162	7	1	92
Europe						
Albania	1970	0.20	57	6	18	76
Austria	1991	2.52	304	19	73	8
Belgium	1990	9.00	877	11	85	4
Bulgaria	1988	13.90	1673	3	75	22
Czech Republic	1991	2.74	269	23	68	9
Denmark	1995	1.00	190	30	27	43
Finland	1994	2.43	469	12	85	3
France	1994	34.88	591	16	69	15
Germany	1990	58.85	712	14	68	18
Greece	1990	6.00	566	8	29	63
Hungary	1991	6.81	694	9	55	36
Iceland	1994	0.16	567	31	63	6
Ireland	1990	1.20	336	16	74	10
Italy	1990	56.20	983	14	27	59
Luxembourg	1994	0.06	133	42	45	13
Malta	1995	0.06	147	87	1	12
Netherlands	1991	7.80	491	5	61	34
Norway	1985	2.03	461	20	72	8
Poland	1991	12.28	317	16	60	24
Portugal	1990	7.29	745	15	37	48
Romania	1994	26.00	1155	8	33	59
Slovak Republic	1991	1.78	331	—	—	—
Spain	1994	33.30	837	12	26	62
Sweden	1994	2.96	333	36	55	9
Switzerland	1994	2.60	351	23	73	4
United Kingdom	1994	11.75	201	20	77	3
Yugoslavia[c]	1980	8.77	368	16	72	12

(*Continued*)

TABLE 2 (*Continued*)

Region and country	Year	Total freshwater withdrawal (km^3/yr)	Per capita withdrawal (m^3/p/yr)[b]	Domestic use (%)	Industrial use (%)	Agricultural use (%)
Former Soviet Union						
Armenia	1994	2.93	800	30	4	66
Azerbaijan	1995	16.53	2112	5	25	70
Belarus	1990	2.73	265	22	43	35
Estonia	1995	0.16	113	56	39	5
Georgia	1990	3.47	640	21	20	59
Kazakhstan	1993	33.67	1989	2	17	81
Kyrgyz Republic	1994	10.09	2221	3	3	94
Latvia	1994	0.29	121	55	32	13
Lithuania	1995	0.25	68	81	16	3
Moldova	1992	2.96	664	9	65	26
Russian Federation	1994	77.10	527	19	62	20
Tajikistan	1994	11.87	1855	3	4	92
Turkmenistan	1994	23.78	5309	1	1	98
Ukraine	1992	25.99	512	18	52	30
Uzbekistan	1994	58.05	2320	4	2	94
Oceania						
Australia	1995	17.80	945	15	10	75
Fiji	1987	0.03	35	20	20	60
New Zealand	1991	2.00	532	46	10	44
Papua New Guinea	1987	0.10	21	29	22	49
Solomon Islands	1987	—	—	40	20	40

[a] See (35) for details on original data. Figures may not add to totals due to independent rounding.

[b] Per capita figures calculated using 2000 population numbers: medium UN variant.

[c] Includes Bosnia and Herzegovina, Macedonia, Croatia.

freshwater withdrawals by country in cubic kilometers per year and cubic meters per person per year, using estimated water withdrawals for the year noted and the United Nations population estimates (medium variant) by country for the year 2000. The table also gives the reported breakdown of that water use for the domestic, agricultural, and industrial sectors, in percent of total water use. The independent data sources are identified in the original table [see (35)]. The domestic sector typically includes household and municipal uses as well as commercial and governmental water use. The industrial sector typically includes water used for power plant cooling and industrial production. The agricultural sector includes water for irrigation and livestock.

Extreme care should be used when applying these data; as noted earlier, they are often the least reliable and most inconsistent of all water-resources information. Despite the efforts of FAO to standardize reporting, the data still come from a wide variety of sources and are collected using different approaches, with few formal standards. As a result, this table includes data that are measured, estimated, and modeled using different assumptions or derived from other data. The data also come from different years, which makes direct comparisons difficult. As examples of some of the inconsistencies and gaps, separate data are not available for the former states of Yugoslavia; industrial withdrawals for Panama, St. Lucia, St. Vincent, and the Grenadines are included in the domestic category; and none of the national data include the use of rainfall in agriculture. Many countries use a significant fraction of the rain falling on their territory for agricultural production, but this category of water use is neither accurately measured nor reported.

Despite these data constraints, Table 2 offers dramatic insights into differences in water use around the world, especially when normalized for population. In Africa, for example, reported water uses range from approximately 600 to 800 cubic meters per person per year (m^3/p/yr) in Egypt, Libya, the Sudan and a handful of other countries to under 20 cubic meters per person per year in the poorest countries of the continent. For many countries of Africa, as much as 90% or more of reported withdrawals go to agricultural uses.

In contrast, almost no country in Europe reports per capita withdrawals of less than several hundred m^3/p/yr (estimates of 50 m^3/p/yr from Albania are more than 30 years old and highly suspect), and several exceed 800 m^3/p/yr, even with almost no irrigated agriculture. Another major difference between the two continents is the far higher proportion of total water use reported in the industrial sector in Europe, where industry commonly accounts for 60% or more of total withdrawals.

Experience from the United States

Few regions or countries have better long-term information on water use than the United States. Beginning in 1951, the U.S. Geological Survey published a series of comprehensive reports on water use in the United States at approximately five-year intervals (36–39). These water-use studies include compilations and estimates of surface and groundwater water use for all states and for various use categories by state and by major hydrologic region. The initial study estimated water use for all withdrawals, which included municipal, rural domestic and livestock, irrigation, industrial use, and hydroelectric power. Water for instream flows such as navigation, recreation, and fish and wildlife were also addressed, though only qualitatively. Consumptive use of water began to be estimated in the 1960 report, and estimates were also made of water use in the early decades of the century, beginning in 1900 (37, 40, 41).

Differences among the states in types of water use, methods of data collection, reliability of reporting, and funding priorities have resulted in unevenness in the breadth and depth of available information (42). As a result, the U.S. National Research Council (43) has recommended a series of improvements in the U.S. National Water-Use Information Program to help provide more comprehensive and

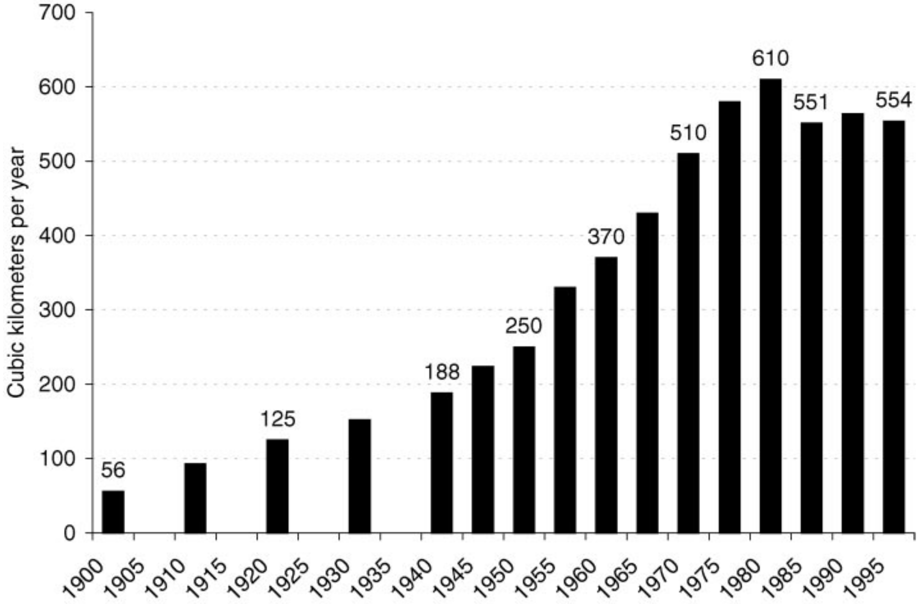

Figure 1 Total U.S. water withdrawals 1900 to 1995. The peak of withdrawals occurred in the 1980s and was followed by a decline as the efficiency of water use nationwide improved and as the economy shifted to less water-intensive uses.

accurate water-use data. Despite these problems, this series of water-use studies has proven to be extremely valuable for researchers and policy makers.

One of the most important findings from the long-term data provided by these reports has been an unexpected change in the trend of water use in the country. Figure 1 graphs total U.S. water withdrawals from 1900 to 1995 and shows rapid growth up until the mid- to late-1980s. Water withdrawals then began to level off and even decline, a change not noted or recognized by water managers or policy makers until the 1990s. This decline, however, has persisted; indeed, it is even more apparent when per capita use is measured. Figure 2 shows per capita water withdrawals (fresh and saline) from 1900 to 1995 together with U.S. population. Since 1980, per capita withdrawals have decreased 20% and now are at levels comparable to those of the mid-1960s. Yet U.S. population has grown from approximately 175 million in 1960 to over 270 million in 1995.

The implications of these trends for water planning and policy, and hence the value of consistency in collecting and reporting water-use data, are dramatic. In particular, they challenge the assumption of planners that economic and population growth lead inevitably to growth in water withdrawals and necessary expansion of supply. And they support the idea that improvements in water-use efficiency and shifts in economic structure can reduce resource use, even in an expanding economy (44).

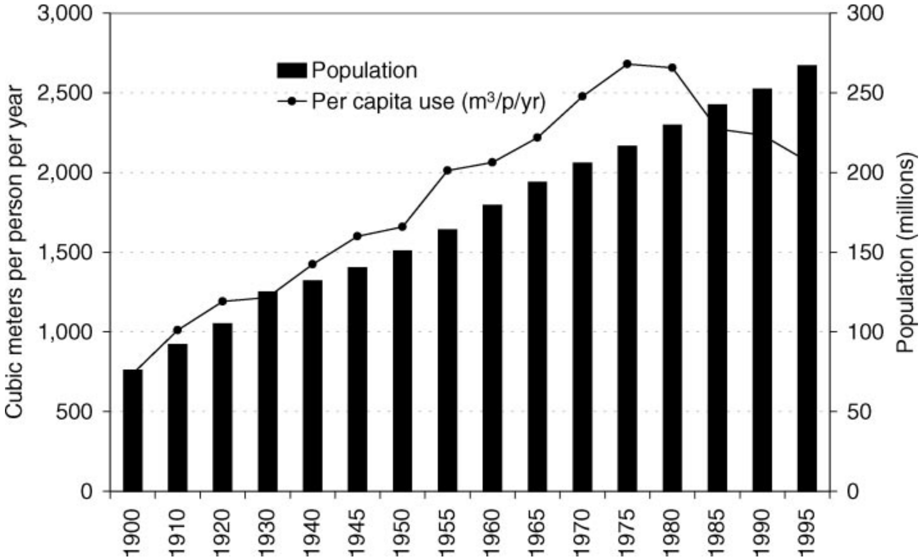

Figure 2 U.S. population and per capita water withdrawals (fresh and saline) from 1900 to 1995 (36–40, 93).

Despite the value and importance of regular reports on water use, financial and institutional pressures are forcing many water agencies to cut back, rather than expand, data collection. In the United States, fiscal policies are leading to reductions in data collection, analysis, and presentation on water use. The 2000 U.S. Geological Survey national water-use report (scheduled to be released in 2003), for example, will cut back on collection and presentation of data for several categories; these include mining, livestock, and aquaculture. Data will only be compiled for states where water uses in these categories are large. Withdrawals from major groundwater aquifers are only being reported for public supply, irrigation, and industry. Data on commercial water use, wastewater treatment, reservoir evaporation, and hydroelectric power are no longer being collected nor is information on consumptive use, reclaimed wastewater, return flows, or deliveries from public suppliers (41). These cutbacks in data collection will seriously imperil the long-term value of the U.S. time series on water use.

FORECASTING WATER USE

Humans have always thought about possible futures, explored plausible paths, and tried to identify risks and benefits associated with different choices. In recent years, this has led to a growing interest in scenarios, forecasting, and "future" studies [see, for example, Schwartz (45)]. Scenario planning has more than academic implications. Water planners are among the few natural resource managers to think more than a few years into the future. Designing and building major water infrastructure can take years, and dams, reservoirs, aqueducts, and pipelines may last for decades or even centuries, which requires planners to take a relatively long view.

In the water sector, expectations about future water use drive huge financial expenditures for water-supply projects. These projects, in turn, have significant human and ecological impacts. At the same time, not making necessary investments can lead to the failure to meet fundamental human water needs. The challenge facing water planners is to balance the risks and benefits of these kinds of efforts.

What will future water uses be? How can they be predicted, given all the uncertainties involved in looking into the future? At the global level, various projections and estimates of future freshwater demands have been made over the past half century; some extended out as much as 60 or 70 years. Reviewing the major studies that have been done reveals two noteworthy trends: Overestimating future water demand, often substantially, is the norm, not the exception; and as tools and methods for making forecasts improve, forecasts of future water needs drop.

Figure 3 and Table 3 show more than 25 different water projections made before 2000 for various points during the twenty-first century, along with an estimates

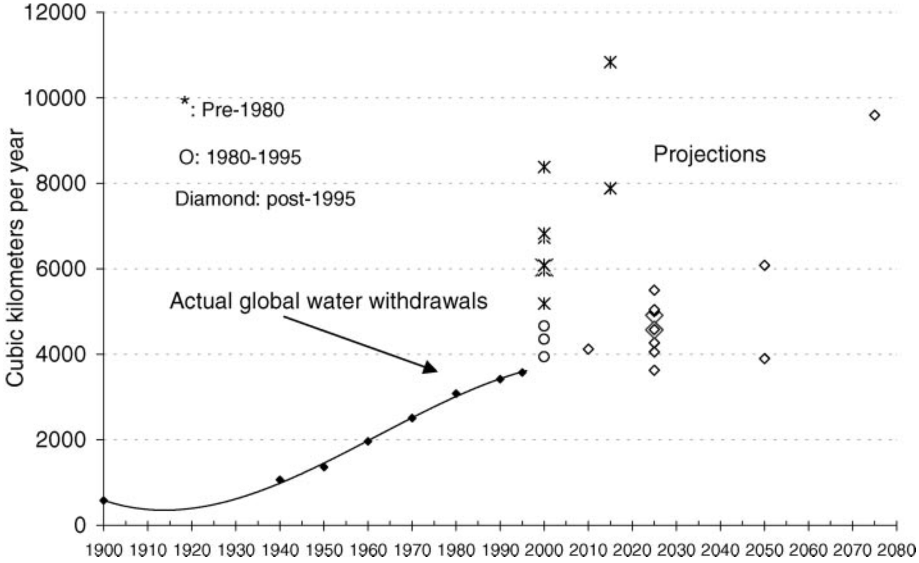

Figure 3 Various projections of global water use over time, together with an estimate of actual water withdrawals (29). Projections made in the 1960s and 1970s greatly overestimated water use in 2000. Even more recent projections tend to overestimate future use because of simplistic assumptions of the relation between population, economic growth, and water.

TABLE 3 Summary of various global water forecasts

Author	Scenario	Publication year	Forecast year	Estimated withdrawal (km^3/yr)
Nikitopoulos		1967	2000	6,730
L'vovich	Rational use	1974	2000	6,325[a]
L'vovich	Conventional	1974	2000	12,270[a]
Kalinin & Shiklomanov		1974	2000	5,970
Falkenmark & Lindh		1974	2000	6,030
Falkenmark & Lindh		1974	2000	8,380
Falkenmark & Lindh		1974	2015	10,840
Falkenmark & Lindh		1974	2015	7,885
De Mare		1976	2000	5,605[a]
Belyaev		1990	2000	4,350
World Resources Institute		1990	2000	4,660
Shiklomanov & Markova		1987	2000	4,976[a]
Shiklomanov		1998	2000	3,717[a,b]
Shiklomanov		1998	2010	4,089[a]
Shiklomanov		1998	2025	4,867[a]
Raskin et al.	Low	1997	2025	4,500
Raskin et al.	Mid	1997	2025	5,000
Raskin et al.	High	1997	2025	5,500
Gleick	Sustainable vision	1997	2025	4,270[a]
Alcamo et al.	Medium 2025	1997	2025	4,580
Alcamo et al.	Medium 2075	1997	2075	9,496
Raskin et al.	Reference 2025	1998	2025	5,044
Raskin et al.	Reference 2050	1998	2050	6,081
Raskin et al.	Policy reform 2025	1998	2025	4,054
Raskin et al.	Policy reform 2050	1998	2050	3,899
Seckler et al.	Business as usual	1998	2025	4,569
Seckler et al.	High irrigation efficiency	1998	2025	3,625

[a] These studies included estimates for water lost from reservoir evaporation. In order to make more consistent comparisons here with those studies that failed to estimate reservoir evaporative losses, those estimates are subtracted from total withdrawals. The numbers here thus represent withdrawals without reservoir evaporation. See Gleick (94) for specific assumptions underlying each projection and for full citations.

[b] Actual 1995 water withdrawals were estimated to be 3,765 km^3 by Shiklomanov (29).

of actual water use up to 2000. As the figure shows, every one of the projections made before 1995 greatly overestimated future water demands by assuming that use would continue to grow at, or even above, historical growth rates. Actual global water withdrawals in the late 1990s were only around half of what they were expected to be by most forecasts 30 years earlier. The inaccuracy of these past projections highlights the importance of developing better methods for making projections of future needs.

The earliest projections routinely, and significantly, overestimated future water demands because of their dependence on relatively simplistic extrapolation of existing trends. Most of the earliest projections used variants on the same methodology: Future water use was based on population projections; simple assumptions of industrial, commercial, and residential water-use intensity (e.g., water per unit population or income); and basic estimates of future crop production as a function of irrigated area and crop yield. Early scenarios were typically single, business-as-usual projections with no variants. Most scenarios ignored water requirements for instream ecological needs, navigation, hydropower production, and recreation. And almost all of these forecasts showed dramatic increases in demand over time, sometimes to implausible levels that led many observers to worry about water shortfalls and shortages. In some areas of the world, such shortages and shortfalls are already manifest, and new problem areas are likely to emerge in coming years. But it is also important to note that every one of the early global water projections estimated far greater demands for water, many of them by a substantial margin, than have actually materialized. This suggests that the traditional methods used by water-scenario developers are missing some critically important real-world dynamics.

One of the earliest and most comprehensive assessments was prepared in 1974 by L’vovich (46). Detailed assumptions were made for a variety of human uses to the year 2000; these included domestic and industrial water use, irrigated and nonirrigated agricultural water demands, and hydropower, navigation, and fishery water requirements. In his business-as-usual scenario, L’vovich assumed that domestic per capita withdrawals would continue to increase, that water consumption for energy production would grow by a factor of 20, while water consumption per unit energy would be cut in half, gross industrial water use would increase by a factor of 15, and agricultural water-use efficiency would increase slightly while total demands doubled with population. All together, he projected water demands in 2000 of more than 12,000 cubic kilometers, a fourfold increase over 1974. The work of L’vovich served as the basis for many later projections, which may have used different assumptions, baseline data, and details, but all approached the idea of water-use projections in the same way (47–49).

The methods and tools used for forecasting and scenario analysis have been getting more and more sophisticated and permit a better understanding of the driving factors behind changes in demands for water. New projections are taking advantage of advances in computer capabilities, the availability of better water data, and new concepts of scenario development. These estimates have begun to include reassessments of actual water needs and water-use efficiencies, dietary requirements, cropping patterns and types, and ecosystem functions (50, 51). Large-scale water-use projections have also become increasingly sophisticated due to the growing capability of easily accessible computers to handle significant numbers of calculations and the growing availability of water-use data. Assessments that were conducted for continental areas or on a national basis are now being done for watersheds on smaller and smaller temporal and spatial scales (52, 53).

THE CONNECTION BETWEEN WATER USE AND HUMAN WELL-BEING

The common assumption that growing populations and economic development will inevitably lead to greater human uses of water drove most of the projections described previously. This assumption, however, deserves closer scrutiny, especially if the idea of a soft path requires us to reconsider the distinction between water use and water needs (6–8). And when a closer look is taken, there are important examples for which, and reasons why, the assumption that increases in human well-being require ever larger uses of water breaks down.

Figure 4 shows the relationship between per capita GDP (a well-understood, albeit imperfect, measure of well-being) and per capita water use for a wide range of countries. As this graph suggests, there is no clear connection between these two variables. Several high water–using nations have very low per capita GDP, and several of the wealthiest nations have very low per capita water use.

A far more important determinant of water use is the extent to which countries commit their water resources to the production of food, especially irrigated agriculture. Large grain-producing countries, such as Canada, the United States, Argentina, and Australia, all have significantly higher per capita water use than average. Figure 5 shows per capita grain production and per capita water withdrawals for the world's major grain producers. The countries in the top right of the graph are those that produce large amounts of grain and serve as the world's leading grain exporters. As this graph suggests, a commitment to this level of agricultural production requires a commitment of a substantial amount of water.

This evidence also suggests that countries can have quite high standards of living (as measured by GDP) at modest per capita levels of water withdrawals, as long as someone is producing and exporting sufficient food to satisfy all needs. Indeed, the trade in grain has recently been acknowledged to be a trade in water as well—the water embodied in trade goods has been dubbed "virtual" water (54).

Many water planners still believe that using less water somehow means a loss of prosperity. The traditional assumption, repeated over and over in water plans and discussions about the risk of future water shortages, is that continued increases in population and improvements in well-being require continued increases in water use. This might be true in the absence of improvements in technology or water

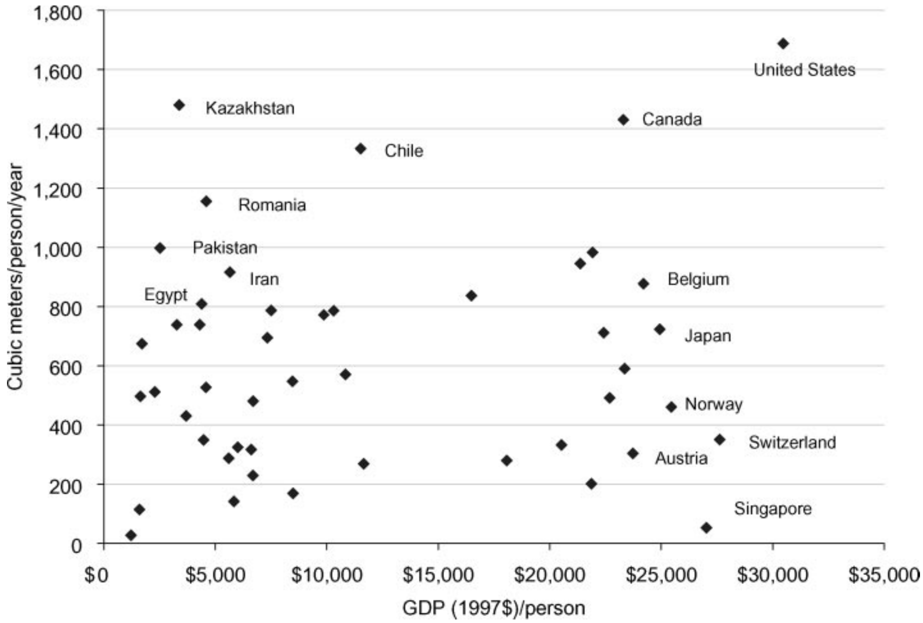

Figure 4 Per capita gross domestic product (GDP) plotted against per capita water withdrawals for a wide range of countries. No clear relationship can be seen from this graph, which suggests that the relationship between GDP and water use is not a simple one.

management, but with such improvements, there is enormous room for economic growth without growth in water use. For example, producing a ton of steel before World War II required 100 to 200 tons of water (55, 56). Today, each ton of steel can be produced with less than four tons of water: a vast improvement in water productivity (57). Furthermore, because a ton of aluminum can be produced using only one and a half tons of water, replacing the use of steel with aluminum, as has been happening for many years in the automobile industry, can further lower water use without reducing economic activity (6).

The links between water use, population, and economic well-being are not immutable. They can be modified and even broken, as has already happened in the United States, China, and elsewhere. For example, Japan used nearly 50 million liters of water to produce a million dollars of commercial output in 1965; by 1989 this had dropped to 14 million liters per million constant (inflation-adjusted) dollars of commercial output, which quadrupled water productivity (58).

The evidence for the changing connections between economic well-being and total water use can be seen by graphically comparing long-term data on water use, population, and gross domestic product for different regions. Serious data constraints limit the comparisons that can be made, especially constraints on the availability of reliable long-term water-use data. Nevertheless, data from a variety

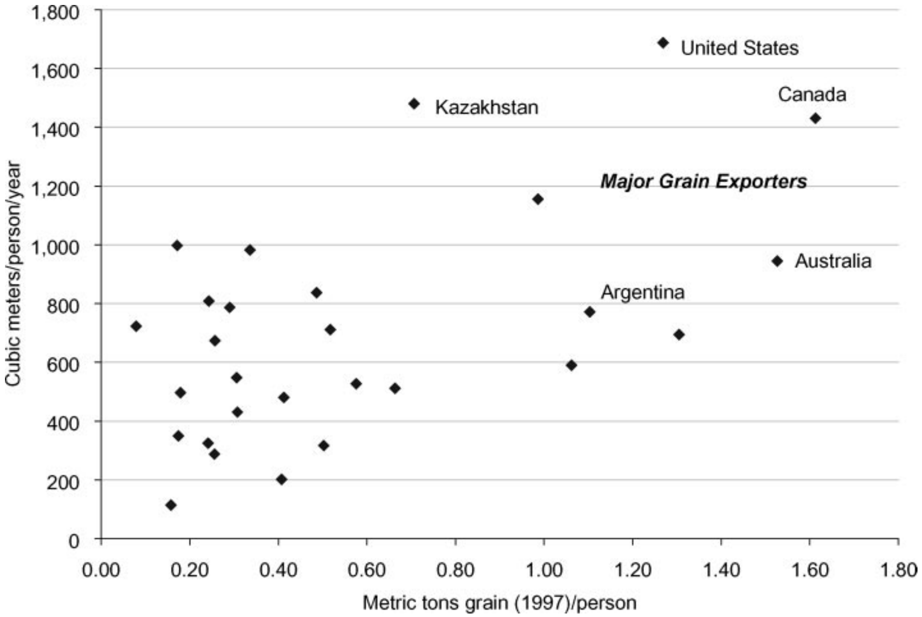

Figure 5 Per capita grain production plotted against per capita water withdrawals for a wide range of countries. Countries with major grain production also have major water use because of the need to supply substantial irrigation water.

of regions show the traditional increases in water use associated with increases in population and GDP, up to a point, followed by a divergence between these factors as countries begin to shift from a focus on supply and water development to one focused on water use and efficiency.

Figures 6, 7, 8, 9, 10, and 11 show estimates of total water use over time for a number of countries or regions plotted against GDP or population. The challenge for water managers in coming years is how to make the transition from the false assumption that growing populations and growing economies require ever increasing amounts of water.

CHANGING WATER-USE PATTERNS: THE POTENTIAL FOR IMPROVING WATER-USE EFFICIENCY

The relationship between water use and well-being is changing for two major reasons. First, improvements in technology and management approaches are permitting needs to be met with less water, and second, the nature of economies is shifting away from water-intensive goods and services toward lower water-using, higher-valued production. These changes permit nonstructural solutions to be considered as useful and practical tools for meeting future expectations about water demand.

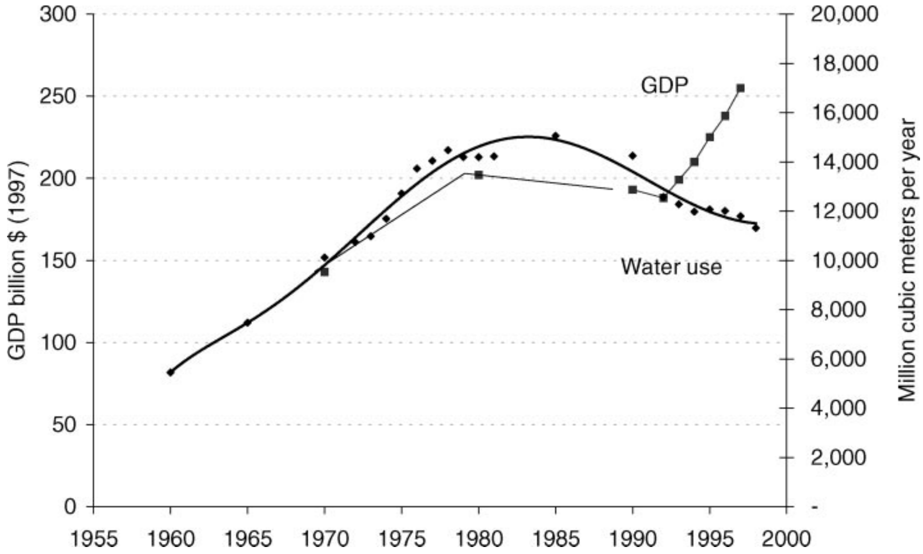

Figure 6 Polish GDP in U.S. dollars (*squares*) and total water withdrawals in Poland (*diamonds*). After democratization in Poland, economic productivity soared, and water use (represented as the trend line) decreased as industries rapidly improved overall efficiency.

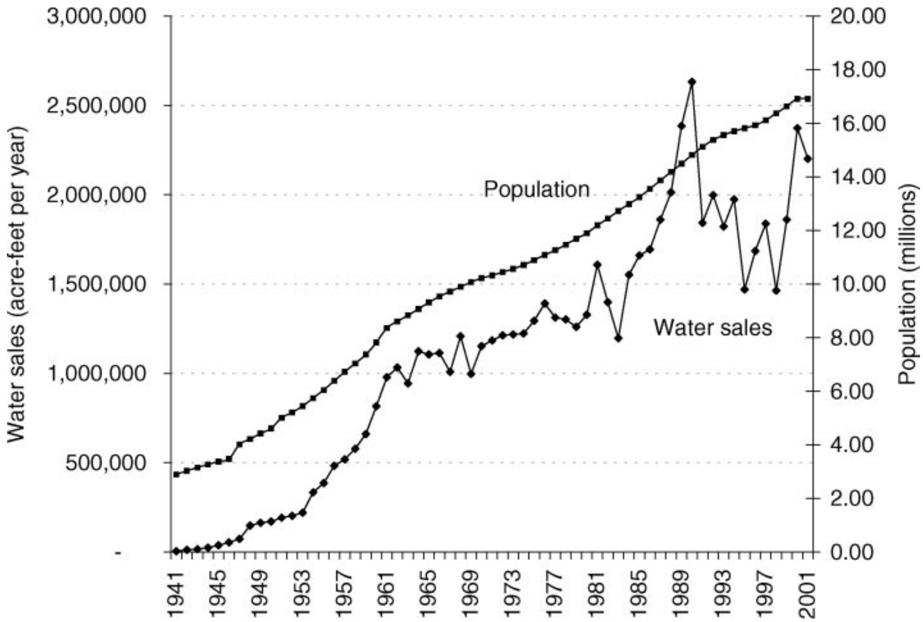

Figure 7 Water sales and population for the Metropolitan Water District of Southern California, which serves 17 million people. Water conservation and efficiency programs have led to a leveling off of demand, despite growing populations.

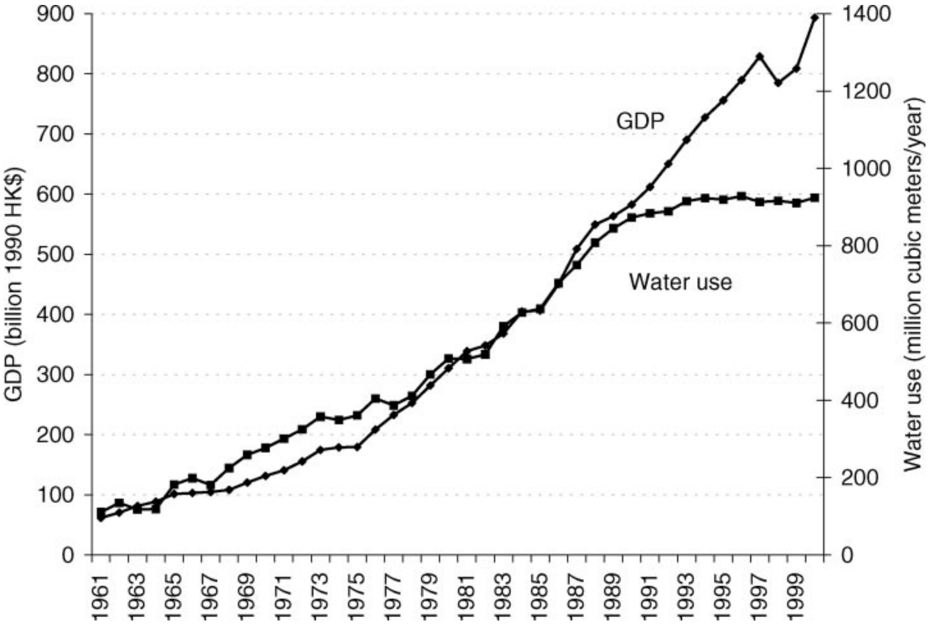

Figure 8 Hong Kong GDP and total water withdrawals. The curves appear to follow the water use in most classic industrialized countries, with a break between rising GDP in constant 1990 Hong Kong dollars and water use, which in this case occurred around 1990 (D. Chen, Chinese University of Hong Kong, personal communication).

The concept of integrating nonstructural water-management approaches into water planning goes back many decades. In 1950, the Water Resources Policy Commission of the United States published *A Water Policy for the American People,* which noted that

> We can no longer be wasteful and careless in our attitude towards our water resources. Not only in the West, where the crucial value of water has long been recognized, but in every part of the country, we must manage and conserve water if we are to make the best use of it for future development (59).

In the early 1960s, White called for broadening the range of alternatives examined by water managers who had previously only focused on structural solutions to water problems (60). Under White's approach, managers should consider both structural and nonstructural alternatives, including zoning, land-use planning, and changing water-use patterns. Unfortunately, traditional water management has, in general, continued to concentrate heavily on the construction of physical infrastructure.

Wherever fresh water was abundant historically, end-use technologies were simple. Washbasins, with or without running water, or pipes located at the proper height over well-drained surfaces were adequate for drinking, cooking, bathing,

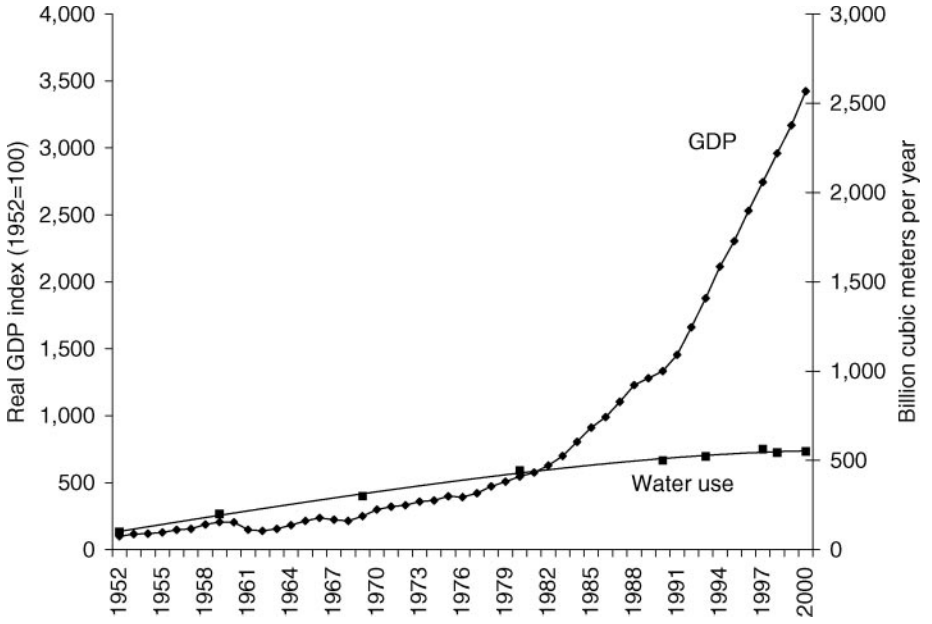

Figure 9 China's GDP index (1952 = 100) and total water withdrawals.

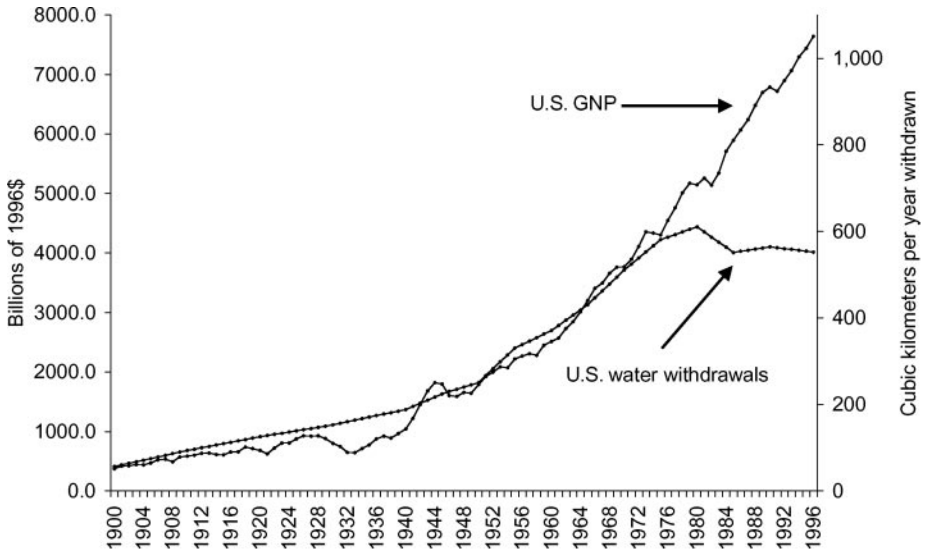

Figure 10 U.S. GNP (1996 dollars) and total water withdrawals in the United States. U.S. water use rose consistently with GDP up until the 1980s when the two curves split apart. Total water use in the United States is now actually well below its peak level, because the economic productivity of water use in the United States has improved.

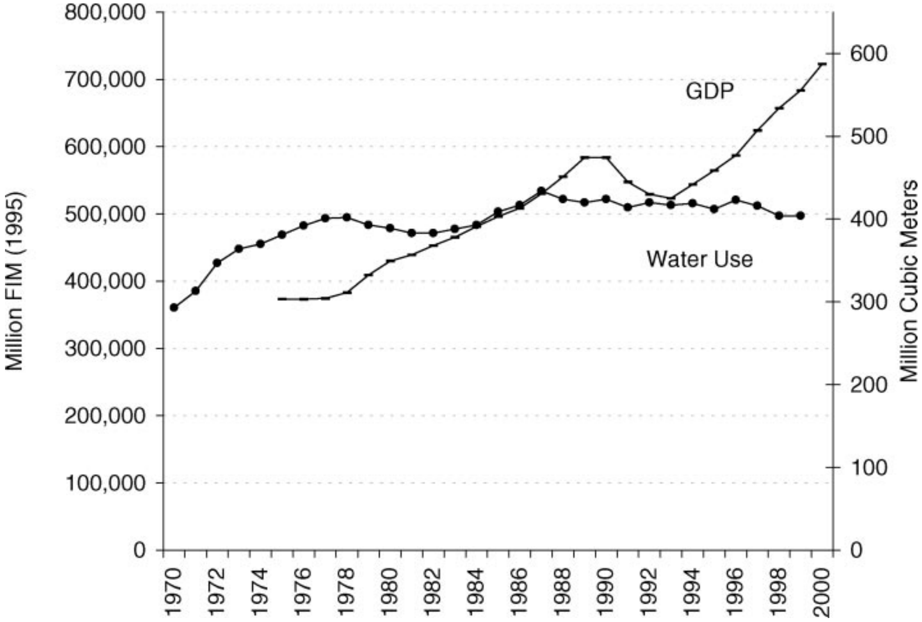

Figure 11 Total Finish GDP (1995 FIM) and water withdrawals in Finland.

and clothes washing. Machinery that used water, such as electrically powered clothes washers, were designed much later to replace human labor, not to use water more efficiently. Sophisticated and technically efficient water measurement and use devices, a key component of soft path water systems, were not necessary and did not develop as rapidly as did water collection and distribution technologies.

Where water was scarce, more efficient technologies and patterns of use were developed. The choice of crops is a good example: People need nutritional food but can choose among a variety of crops to meet that need. Olives are an important part of Middle Eastern and Mediterranean cultures because they are well adapted to semiarid regions. Rice was grown in wetter regions of the world and did not appear in arid regions prior to the availability of inexpensive energy and irrigation water. Such crop choices are examples of appropriate decisions when water is scarce.

Most water managers have a background in engineering with a focus on building structures to capture and deliver water and water services (61). Thus the idea that rice can be grown in water-scarce regions seems like a simple problem of figuring out how to move water from elsewhere. Efficiency improvements, however, depend on the behavior of water users, rather than water agency or company personnel, and on the application of technologies at the end-use level. Capturing these improvements requires different professional skills and training than are traditionally taught in water management schools. As the water-use efficiency and management field matures, however, water utilities will increasingly demand training in people management, the application of small-scale technology, and water-use assessment. Indeed, growing numbers of water agencies now have water conservation departments, and professional societies, such as the American Water Works Association and the International Water Resources Association, are promoting efficiency discussions and adding water-use experts and groups (62, 62a).

To compound the problem of training and the need for new professional skills, the economics of efficiency improvements have been poorly understood and inaccurately estimated by traditional methods. As a result, estimates of the potential for improving water-use efficiency are almost always lower than the true potential, as the inaccurate projections described earlier suggest. In places where an effort has been made to identify and capture improvements in water-use efficiency, water demands have been cut by 20%, 30%, 40% or more (11, 58, 63).

Cost-Effectiveness of Efficiency Improvements

Centralized water facilities were historically lower in cost, within a narrow accounting methodology, than decentralized investments in efficiency. This may still be the case in some circumstances. But the belief that efficiency improvements are more expensive than new or expanded centralized water supply is incorrect in most circumstances (64, 65). In addition, it is increasingly apparent that most cost projections of new large, centralized systems are routinely and often substantially underestimated, even without accounting for hard-to-measure environmental and social costs. Although this is a problem common to many large capital projects, it has received considerable attention around the construction of dams and reservoirs, which often end up costing much more than originally projected (66). World Bank statistics on dam construction projects suggest that construction cost overruns averaged 30% on the 70 hydropower projects funded by the Bank since the 1960s (67). Other World Bank studies found that three quarters of the 80 hydro projects completed in the 1970s and 1980s had costs in excess of their budgets, and almost one third of the projects studied had actual costs that exceeded estimates by 50% or more (68).

There are many reasons for cost overruns; these include delays, design errors, poor quality construction, or corruption of project advocates and managers. For example, the Chixoy Dam in Guatemala was delayed for nine years by the collapse of poorly designed tunnels, social opposition, and corruption. Its final cost of $1.2 billion was more than five times its initial cost estimate, and some studies suggest the final cost may have been as high as $2.5 billion (69). The Yacyreta Dam on the Parana River between Argentina and Paraguay became known as a “monument to corruption” as the cost of the project increased to $8 billion from an original estimate of $1.6 billion (67). Cost overruns are not restricted to projects in less developed countries. In 2000, an economist at the U.S. Army Corps of Engineers blew the whistle on biased cost-benefit studies for projects along the Missouri and Mississippi rivers, which led to calls for reform of the cost estimating and evaluation (70).

In contrast, the cost of efficiency improvements seems to be decreasing over time as technologies and conservation programs mature and as rate designs begin to account for the true costs of water supply (71, 72). In the United States, the best low-flow toilets cost no more on average than inadequate low-flow models or older wasteful models, especially over the lifetime of the product (11). As water suppliers have learned which models reliably save water, and provided this information to their customers, the cost of conserving water via low-flow toilet installation has fallen. This trend will continue as the technology for pressure-flush toilets (around 0.6 gallons per flush) and waterless toilets and urinals improves.

Another reason for the belief that efficiency improvements are too expensive is that traditional water planners usually estimate the cost of efficiency improvements without accounting for secondary benefits. Such secondary benefits, such as energy savings, can be substantial. In the residential sector in California, without accounting for the avoided energy expense for water heating, for example, only efficient toilets and showerheads are cost-effective compared with new water supply projects at any water price exceeding $0.05 per cubic meter. After accounting for energy benefits, efficient clothes- and dishwashers would be highly cost-effective, even if new water supply could be obtained for free (7, 73)

There are other secondary benefits to be gained as well that are rarely calculated. Among these are

- Reductions in peak water system loads. Peak loads determine the size of capital facilities required, hence capital costs. Lower peak loads mean that existing capital facilities can serve more customers and avoid or reduce the expense of these facilities.
- Reductions in peak energy demands. Energy and water supply networks are similar in many ways. Reduction of peak energy demands that result from efficiency improvements and a decrease in water pumping, treatment, or heating needs will similarly allow energy utilities to serve more customers with existing capital facilities and avoid or reduce capital expenses that are ultimately paid by energy purchasers.
- Reductions in wastewater treatment expenses, both operational expenses and costs for expanding sewers or treatment facilities.
- Reductions in environmental damage from water withdrawals or wastewater discharges in environmentally sensitive locations.
- Increases in employment, for example, by increasing the rate at which appliances or irrigation systems are monitored, serviced, or replaced. Investments in large, centralized capital facilities increase employment during construction but use relatively little labor once construction is complete (73, 74).

The belief that efficiency improvements are not economically competitive with expansion of centralized supplies is slowly being overcome. Water planners are beginning to realize that the cost escalation, construction delays, and interest charges that so often plague large capital-intensive water projects rarely occur in conservation programs. This has been seen over and over again. For example, in Santa Barbara, California, a severe drought in the late 1970s stimulated local residents to support the construction of a large desalination plant, as well as a pipeline to connect to the centralized state water project. When the very high economic costs of those facilities were passed on to consumers, conservation and efficiency improvements reduced demand so fast that the need for the new facilities disappeared (75). The desalination plant was never put into routine operation and is mothballed (partially decommissioned). If effective pricing programs, education, and community planning had been done first, the expense of these facilities could have been long delayed and perhaps completely avoided.

A number of municipal water suppliers around the world have implemented aggressive water conservation programs. Municipal conservation programs that are fully integrated have shown impressive successes. Postel (63) includes an excellent summary of successful municipal programs in Jerusalem, Israel; Mexico City, Mexico; Los Angeles, California; Beijing, China; Singapore; Boston, Massachusetts; Waterloo, Canada; Bogor, Indonesia; and Melbourne, Australia. Reductions in water demand varied from 10%–30%. Vickers (11, 76) updates the results from the Massachusetts Water Resources Authority, which serves the Boston area, and presents data for the City of Albuquerque, New Mexico, and many other communities. Several municipalities have reported reductions of 25% or more. Owens-Viani (77) presents results from the Marin Municipal Water District in Northern California, where a conservation management plan led to a reduction in demand of about 15% in the first 10 years of implementation, despite a 7.5% increase in the district's population. This is only about half of their 20-year target of up to a 32% reduction in absolute demand despite increases in population. After adjusting for population growth, this 20-year target, already half achieved, amounts to a reduction in water use of approximately 45% per capita.

There are many opportunities for improving the efficiency of commercial, industrial, and institutional water uses. Pike (78) evaluated opportunities for various commercial and institutional water users in the United States and found that average potential savings vary from 9% to 31% within 18 categories of users (e.g., eating and drinking places, vehicle dealers, and services). Gleick et al. (73) found that overall savings potential in California's commercial and industrial sector was nearly 40% with existing technology. Similar statistics are provided by Vickers (11), who includes examples from outside the United States where potential reductions in industrial water use are often larger when combined with aggressive leak detection and repair. In many developing countries, 20% to 40%, or even more, of the water put into a system never reaches consumers because of leaks. Table 4 from Gleick (17) summarizes information on "unaccounted for water" from cities and countries around the world.

Most of these opportunities are cost effective and widely applicable. For industrial savings, one analysis found typical reductions of 30%–40% with estimated payback periods of less than one year (79). The report concluded: "The cost

TABLE 4 Unaccounted for water (17). See original for details on sources

Location	**Period/year**	**Percent**
Africa (large city average)	1990s	39
Algiers, Algeria	1990s	51
Amman, Jordan	1990s	52
Asia (large city average)	1990s	35 to 42
Bahrain	1993	36
Bahrain	2000	24
Barbados	1996	43
Buenos Aires, Argentina	1993	43
Buenos Aires, Argentina	1996	31
Canada (average)	1990s	15
Casablanca, Morocco	1990s	34
Damascus, Syria	1995	64
Dubai, United Arab Emirates	1990s	15
Gaza	1995	47
Gaza	1999	31
Haiphong, Vietnam	1998	70
Hanoi, Vietnam	1995	63
Hebron	1990s	48
Johor Bahru, Malaysia	1995	21
Kansas, United States (average)	1997	15
Kansas, United States (range)	1997	3 to 65
Lae, Papua New Guinea	1995	61
Latin America/Caribbean (large city average)	1990s	42
Lebanon	1990s	40
Male, Maldives	1995	10
Mandalay, Myanmar	1995	60
Mexico City, Mexico	1997	37
Mexico City, Mexico	1999	32
Nairobi, Kenya	2000	50
Nicosia, Cyprus	1990s	16
North America (large city average)	1990s	15
Oran, Algeria	1990s	42
Penang, Malaysia	1995	20
Phnom Penh, Vietnam	1995	61

(*Continued*)

TABLE 4 (*Continued*)

Location	Period/year	Percent
Poland (medium utility range)	1990s	19 to 51
Rabat, Morocco	1990s	18
Ramallah	1990s	25
Rarotonga, Cook Islands	1995	70
Sana’a, Yemen	1990s	50
Seoul, South Korea	1996	35
Singapore	1990s	11
Singapore	1995	6
Sydney, Australia	1990s	13.4
Tamir, Yemen	1990s	28
Teheran, Iran	1990s	35
Tunisia (large utility range)	1990s	8 to 21
United Kingdom (small utility range)	1990s	14 to 30
United States (average)	1990s	12
Vietnam (average)	1998	50
Washington, DC area suppliers	1999	10 to 28

effective water conservation measures successfully used at the case study facilities can readily be adopted by other facilities and other industries.”

Major efficiency improvements are possible in the agricultural sector as well, and because this sector consumes such a large fraction of total human water use, it is deserving of special attention (80–82). Traditional irrigation methods are very inefficient. Furrow or flood irrigation is the simplest form of irrigation, with water delivered to rows of crops from a ditch or pipeline. As water moves into each row, it infiltrates the soil. For ideal irrigation, the amount of water infiltrated is just adequate to replace depleted soil water. In actuality, however, soils at the top end of rows receive more water than necessary to ensure that water reaches the end of each furrow, even if land is leveled to permit full coverage. These systems are among the most inefficient available, though experienced irrigators and careful tuning can somewhat reduce losses.

More efficient sprinkler systems that can apply water more accurately and carefully than flood systems are available. Sprinklers can be fixed or moving and require pumps to provide pressure necessary to distribute water through pipes. Fixed sprinklers require sufficient pipes and sprinkler heads to cover an entire field. To irrigate the field, sprinklers need only to be turned on and off. Moving sprinkler systems permit a small system to cover larger areas and can include periodically moved systems or constantly moved systems. Center-pivot and lateral-move systems are the most common, with a lateral pipeline that moves continuously in a direction perpendicular to the lateral or is fixed at one end to irrigate a large circular area. A modification of these moving systems is the low-energy, precision application (LEPA) system that discharges water just above the soil surface and reduces unproductive evaporative losses (83, 84).

Water productivity improvements can also be gained from techniques such as furrow diking, land leveling, direct seeding, drip irrigation, micro sprinklers, careful scheduling of irrigation, water recycling, and careful water accounting (85). For example, micro-irrigation systems (primarily drip and micro sprinklers) often achieve efficiencies in excess of 95% as compared with flood irrigation efficiencies of 60% or less (11, 86). As of 2000, however, the area under micro irrigation is around 2.8 million ha, only about 1% of all irrigated land (87). In China, vast quantities of the water used in agriculture are used inefficiently. In 2000, 97% of all Chinese irrigation used furrow/flood irrigation; 3% of the irrigated area was watered with sprinklers and drip systems (88). Even in California, a small fraction of all cropland was irrigated with drip systems in the mid-1990s (6).

Another example is laser leveling of fields, which permits water to be distributed more uniformly. This reduces the water required to ensure that all parts of the field are irrigated adequately. Recent experience growing wheat, alfalfa, and cotton in the Welton-Mohawk Valley of Arizona found that water use declined between 20%–32% as a result of laser leveling, and yields increased from 12%–22% (11). This practice requires that land be leveled every two to five years, at a relatively modest cost, ~$100 per hectare.

Precision irrigation remains expensive, which makes it suitable only for higher-value crops. Extending more efficient irrigation systems to the vast numbers of small farmers is critical if significant new improvements in agricultural water use are to be captured. Most of the world's 1.1 billion farmers live in developing countries and cultivate plots smaller than two hectares (89). These farmers cannot afford sophisticated and costly precision irrigation systems, yet they would benefit from access to better equipment. In recent years, new low-cost drip techniques have begun to emerge and open up vast potential for the poor small farmers of developing countries. International Development Enterprises has helped push the development of simple but functional low-cost solutions using cloth filtration, a bucket as a container, and inexpensive drip lines. These systems can reduce the capital costs from $2500 to $250 per hectare, reduce water use by 50%, and increase yields (90–92). Widespread expansion of such low-cost drip systems has the potential to boost farmer incomes, raise yields and crop productivity, and ameliorate persistent hunger, while reducing overall water use in agriculture. It remains to be seen if the barriers to widespread application of inexpensive efficiency systems, such as higher production and maintenance expenses, the need for local production of equipment, and farmer reluctance to adopt unfamiliar technology, can be overcome.

Urban Improvements: The Example of California

California has begun to explore the potential for improving the efficiency of water use in every sector because of growing constraints on new supply. New studies suggest that the future potential for improving urban water-use efficiency is large even in regions and sectors that have already conserved a considerable amount of water (73). Figure 12 shows indoor residential water use in California under a business as usual scenario through 2020 and an estimate of total indoor residential use if currently cost-effective technologies and policies are implemented. The upper line in this figure indicates the level of water use statewide without implementing efficiency measures and would require the state to develop new water supplies to meet this projected need. The lower line in the figure is the maximum practical savings from implementing the current best practical technologies.

The two curves show that a traditional water policy would require about a 45% increase (over 1.1 billion cubic meters per year from current levels) in water supply for indoor residential purposes by the year 2020, but an efficient path actually reduces total indoor residential demand by about 25% (over 600 million

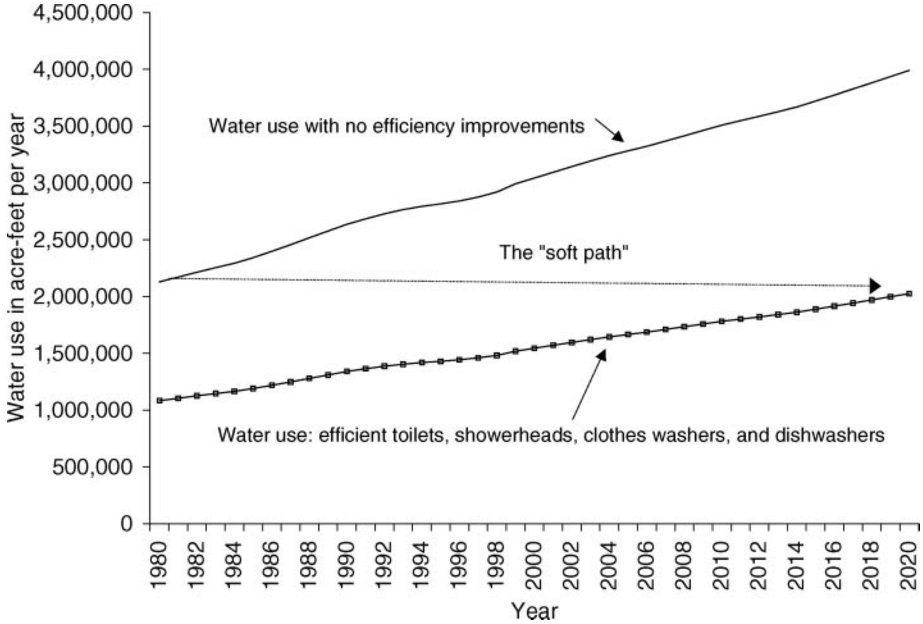

Figure 12 Expected California indoor residential water use from 1998 to 2020 assuming no improvements in efficiency (*top curve*) and assuming that all cost-effective improvements using existing technology are implemented (*bottom curve*). If all efficiency improvements are implemented, total indoor residential water use in 2020 could be below the level of actual water use in 1980, despite a 50% increase in population.

cubic meters) despite population growth. This means that the soft path for indoor residential use can cost-effectively conserve about 1.7 billion cubic meters of water by the year 2020 (73). This simple example, for a single sector of California water use, shows the dramatic gains possible by putting more effort into demand-management of water.

CONCLUSIONS

The focus of water planning and management is slowly shifting from the development of water-supply systems to more integrated analysis of how and why humans use water. By better understanding water needs, improvements in the overall productivity of human activities can be identified and achieved, which will reduce water use and the adverse implications of that use.

Water use is still poorly understood and inadequately measured and reported. Problems with definitions and data collection hinder efforts to improve water-use efficiency. Inappropriate water planning still results from simplistic assumptions about how water uses will change in the future. Nevertheless, a substantial shift in thinking has occurred in recent years as the social, political, economic, and environmental costs of traditional water developments have become apparent. There is growing evidence and experience that shows how improvements in water-use efficiency can offer the fastest and cleanest sources of new supply by reducing overall demands for water in every sector. In some countries, water use is even beginning to level off or decline despite growing populations and economies and offers the hope that smart management will be an effective tool in sustainable water systems.

The *Annual Review of Environment and Resources* is online at http://environ.annualreviews.org

LITERATURE CITED

1. Crouch DP. 1993. *Water Management in Ancient Greek Cities*. New York: Oxford Univ. Press
2. Landels JG. 2000. *Engineering in the Ancient World*. Berkeley, CA: Univ. Calif. Press
3. World Comm. Dams. 2000. *Dams and Development: A New Framework for Decision-Making*. London: Earthscan
4. Douglas M, Gasper D, Ney S, Thompson M. 1998. Human needs and wants. In *Human Choices and Climate Change*, Vol. 1, ed. S Rayner, E Malone, pp. 195–263. Columbus, OH: Battelle
5. Gleick PH. 1996. Basic water requirements for human activities: meeting basic needs. *Water Int.* 21:83–92
6. Gleick PH. 2002. Soft water paths. *Nature* 418:373
7. Wolff G, Gleick PH. 2002. The soft path for water. In *The World's Water 2002–2003*, ed. PH Gleick, WCG Burns, EL Chalecki, M Cohen, KK Cushing, et al., pp. 1–32. Washington, DC: Island
8. Brooks D. 2003. *Another path not taken: a methodological exploration of water soft paths for Canada and elsewhere*. Friends of the Earth Can. Rep. (March) pp. 67
9. White S. 1999. Integrated resource

planning in the Australian water industry. *Proc. CONSERV99, Am. Water Works Assoc., Monterey, CA*, Feb.

10. Del Porto D, Steinfeld C. 1999. *The Composting System Toilet Book*. Concord, MA: Cent. Ecol. Pollut. Prev.
11. Vickers AL. 2001. *Handbook of Water Use and Conservation*. Amherst, MA: WaterPlow. 439 pp.
12. Shiklomanov IA. 1993. World fresh water resources. In *Water in Crisis: A Guide to the World's Fresh Water Resources*, ed. PH Gleick, pp. 13–24. New York: Oxford Univ. Press
13. Boland JJ, Dziegielewski B, Bauman DD, Opitz EM. 1984. *Influence of Price and Rate Structures on Minimum and Maximum Water Use*. Carbondale, IL: Plan. Manag. Consult.
14. Keller A, Keller J. 1995. *Effective efficiency: A water use efficiency concept for allocating freshwater resources*. Water Resour. Irrig. Div. Discuss. Pap. 22. Cent. Econ. Policy Stud. Arlington, VA
15. Molden D. 1997. *Accounting for water use and productivity. System-wide initiative on water management (SWIM). Rep. 1*. Int. Irrig. Manag. Inst., Colombo, Sri Lanka
16. Seckler D. 1996. *The new era of water resources management: from dry to wet water savings*. *Res. Rep. 1*. Int. Irrig. Manag. Inst., Colombo, Sri Lanka
17. Gleick PH. 2002. *The World's Water 2002–2003*. Washington, DC: Island
18. Calif. Dep. Water Resour. 1998. *The California Water Plan Update.* Bull. 160–98, Sacramento, CA
19. Gleick PH, Haasz D. 1998. *Review of the CalFed water-use efficiency component technical appendix*. *Rep*. Pac. Inst. Stud. Dev., Environ., Secur. Oakland, CA
20. Palacios-Velez E. 1994. Water use efficiency in irrigation districts. In *Efficient Water Use*, ed. H Garduno, F Arreguin-Cortes. Montevideo: UN Educ. Sci. Cult. Organ./Reg. Off. Sci. Technol. Lat. Am. Caribb.
21. Baumann DD, Boland JJ, Sims JH. 1980. *The problem of defining water conservation*. Cornett Pap., Univ. Victoria, Vic., BC, Can. pp. 125–34
22. UN Food Agric. Organ. 2002. FAOSTAT AQUASTAT database. www.fao.org
23. Solley WB, Pierce RR, Perlman HA. 1998. *Estimated Use of Water in the United States*. US Geol. Surv. Circ. 1200. Denver, CO
24. Eurostat Year B. 1997. *Statistics of the European Union*. EC/C/61 Ser.26GT. Luxembourg
25. Eur. Environ. Agency. 1999. *Sustainable Water Use in Europe*. Copenhagen, Den.: EEA
26. Gov. S. Afr. 1998. *National Water Act 36 of 1998*. Pretoria: Gov. S. Afr.
27. Schultz GA. 2000. Potential of modern data types for future water resources management. *Water Int.* 25(1):89–109
28. Simonovic SP. 2000. Tools for water management: one view of the future. *Water Int.* 25(1):76–88
29. Shiklomanov IA. 1998. *Assessment of water resources and water availability in the world. UN Rep. Compr. Assess. Freshw. Resour. World*, Data arch. CD-ROM State Hydrol. Inst., St. Petersburg, Russia
30. Postel SL, Daily GC, Ehrlich PR. 1996. Human appropriation of renewable fresh water. *Science* 271:785–88
31. UN Food Agric. Organ. 1995. *Irrigation in Africa in figures*. Water Rep. 7. Rome, Italy
32. UN Food Agric. Organ. 1997. *Irrigation in the Near East region in figures*. Water Rep. 9. Rome, Italy
33. UN Food Agric. Organ. 1997. *Irrigation in the former Soviet Union in figures*. Water Report No. 15. Rome, Italy
34. UN Food Agric. Organ. 2000. *Irrigation in Latin America in figures*. Water Rep. 20. Rome, Italy
35. Gleick PH, Burns WCG, Chalecki EL, Cohen M, Cushing KK, et al. *The World's Water 2002–2003, Table 2*, pp. 243–51. Washington, DC: Island

36. MacKichan KA. 1951. *Estimated Water Use in the United States, 1950*: US Geol. Surv. Circ. 115. Reston, VA. 13 pp.
37. MacKichan KA. 1957. *Estimated Water Use in the United States, 1955*: U.S. Geol. Surv. Circ. 398. Reston, VA. 18 pp.
38. MacKichan KA, Kammerer JC. 1961. *Estimated Use of Water in the United States, 1960*: U.S. Geol. Surv. Circ. 456. Reston, VA. 26 pp.
39. Solley WB, Pierce RR, Perlman HA. 1998. *Estimated Use of Water in the United States*. U.S. Geol. Surv. Circ. 1200. Denver, CO
40. Natl. Res. Counc. 2002. *Estimating Water Use in the United States: A New Paradigm for the National Water-Use Information Program*. Washington, DC: Natl. Acad.
41. Counc. Environ. Qual. 1991. *Environmental Quality: 21st Annu. Rep.*, Washington, DC
42. US Dep. Inter. 2002. *Rep. Cong. Concepts for National Assessment of Water Availability and Use*. Circ. 1223, US Geol. Surv. Reston, VA
43. Natl. Res. Counc. 2002. *Estimating Water Use in the United States: A New Paradigm for the National Water-Use Information Program*. Washington, DC: Natl. Acad.
44. Cole MA. 2003. Economic growth and water use. *Appl. Econ. Lett.* 10: In press
45. Schwartz P. 1991. *The Art of the Long View*. New York: Currency/Doubleday
46. L'vovich MI. 1974. *World Water Resources and Their Future*. Transl. R Nace, 1979, Washington, DC: Am. Geophys. Union 415 pp.
47. De Mare L. 1976. *Resources—Needs—Problems: An assessment of the World Water Situation by 2000*. Lund, Swed.: Inst. Technol./Univ. Lund
48. Falkenmark M, Lindh G. 1974. How can we cope with the water resources situation by the year 2050? *Ambio* 3(3–4):114–22
49. Kalinin GP, Shiklomanov IA. 1974. *USSR: World Water Balance and Water Resources of the Earth*. USSR Natl. Comm. IHD, Leningrad (In Russian)
50. Raskin P, Gleick PH, Kirshen P, Pontius G, Strzepek K. 1997. *Water Futures: Assessment of Long-range Patterns and Problems.* Backgr. Doc. Chapter 3 Compr. Assess. Freshw. Resour. World. Stock. Environ. Inst. Boston, MA. 77 pp.
51. Seckler D, Amarasinghe U, Molden D, de Silva R, Barker R. 1998. *World water demand and supply, 1990 to 2025: scenarios and issues*. Res. Rep. 19, Int. Water Manag. Inst., Colombo, Sri Lanka
52. Gleick PH. 1997. *Water 2050: Moving Toward A Sustainable Vision for the Earth's Fresh Water*. *Rep.* Pac. Inst. Stud. Dev., Environ., Secur., Oakland, CA
53. Alcamo J, Döll P, Kaspar F, Siebert S. 1997. *Global change and global scenarios of water use and availability: An application of Water GAP 1.0*. *Rep.* Wiss. Zent. Für Umweltsystemforschung, Univ. Gesamthochsch. Kassel, Ger.
54. Allan T. 1997. *'Virtual water': a long term solution for water short Middle Eastern* economies? Presented at Br. Assoc. Festiv. Sci.,Univ. Leeds,UK. Sept. 9. http://www2.soas.ac.uk/Geography/WaterIssues/OccasionalPapers/AcrobatFiles/OCC03.PDF
55. Natl. Assoc. Manufact. 1950. *Water in industry*. *Rep.* Econ. Policy Div. Ser. 36, Append. C. Washington, DC
56. Kollar KL, MacAuley P. 1980. Water requirements for industrial development. *J. Am. Water Works Assoc.* 72 (1):2–9
57. Posco Steel. 2002. *Environmental Progress Report: Environmentally Sound and Sustainable Development*. Pohang, Korea. http://www.posco.co.kr/en/sustain/environment04_01.html
58. Gleick PH. 2001. Making Every Drop Count. *Sci. Am.* Feb.:28–33
59. Water Resour. Policy Comm. 1950. *A Water Policy for the American People, The Report of the President's Water Resources Policy Commission, Vol. 1*. Washington, DC: US GPO. 445 pp.

60. White GF. 1961. The choices of use in resource management. *Nat. Resour. J.* 1:23–40
61. Schultz GA. 1998. A change of paradigm in water sciences at the turn of the century? *Water Int.* 23(1):37–44
62. Am. Water Works Assoc. *Water Conservation Around the Home*. http://www.awwa.org/Advocacy/learn/conserve/
62a. Metrop. Water Dist. South. Calif. *Conservation and the Environment.* http://www.mwd.dst.ca.us/mwdh2o/pages/conserv/conserv01.html
63. Postel S. 1997. *Last Oasis: Facing Water Scarcity*. New York: Norton. 239 pp.
64. Macy P, Maddaus W. 1989. Cost-benefit analysis of conservation programs. *J. Am. Water Works Assoc.* 81:3–43
65. Maddaus WO. 1999. Realizing the benefits from water conservation. *Water Resour. Update* 114:8–17
66. World Comm. Dams. 2000. *Overview summary. Dams and development: a new framework for decision-making. Rep.* http://www.dams.org/report/wcd_overview.htm
67. McCully P. 1996. *Silenced Rivers: The Ecology and Politics of Large Dams*. London: Zed Books. 350 pp.
68. Morrow EW, Shangraw RF Jr. 1990. *Understanding the costs and schedules of World Bank supported hydroelectric projects*. *Rep.*, World Bank Ind. Energy Dep. July. Washington, DC
69. Chen C. 2000. *The Chixoy Dam Case Study*. World Comm. Dams. Submiss. soc073. http://www.dams.org/kbase/submissions/sublist.php
70. US Off. Spec. Counc. 2000. *Letter to the President, Dec. 6. USOSC File No. DI-00-0792.* Washington, DC
71. Goldstone J. 1986. Full-cost water pricing. *Am. Water Works Assoc. J.* 78(2):52–61
72. Chesnutt TW, Beecher JA, Mann PC, Clark DM, Hanemann WM, Raftelis GA. 1997. *Designing, Evaluating and Implementing Conservation Rate Structures: A Handbook*. Sacramento, CA: Calif. Urban Water Conserv. Counc.
73. Gleick PH, Haasz D, Henges-Jeck C, Srinivasan V, Wolff GH, Mann A. 2003. *Waste not, want not: the potential for urban water conservation and efficiency in California*. *Rep*. Pac. Inst. Stud. Dev., Environ., Secur. Oakland, CA. In press
74. Dziegielewski B. 1999. Management of water demand: unresolved issues. *Water Resour. Update* 114:1–7
75. Calif. Resour. Agency. 1997. *California's Ocean Resources: An Agenda for the Future*. Sacramento, CA http://resources.ca.gov/ocean/97Agenda/97Agenda.html
76. Vickers AL. 1999. The future of water conservation: challenges ahead. *Water Resour. Update* 114:49–51
77. Owens-Viani L. 1999. Marin Municipal Water District's innovative integrated resource management program. In *Sustainable Use of Water: California Success Stories*, ed. L Owens-Viani, AK Wong, PH Gleick, pp. 11–26. Oakland, CA: Pac. Inst. Stud. Dev., Environ., Secur.
78. Pike C. 1997. *Some implications of the 1997 California food processor survey.* Presented at 214th Am. Chem. Soc. Natl. Meet., Sept. 9. Las Vegas, NV
79. Brown & Caldwell, Inc. 1990. *Case studies of industrial water conservation in the San Jose area.* Brown & Caldwell, Pleasant Hill, CA
80. Molden D, Sakthivadivel R, Perry CJ, de Fraiture C, Kloezen WH. 1998. *Indicators for comparing performance of irrigated agricultural systems*. *Int. Water Manag. Inst. Res. Rep. 20*. Colombo, Sri Lanka
81. Natl. Res. Counc. 1996. *A New Era for Irrigation*. Washington, DC: Natl. Acad.
82. Counc. Agric. Sci. Technol. 1988. *Effective use of water in irrigated agriculture*. Task Force Rep. 113. Ames, IA
83. Schneider AD, Howell TA, Evett SR. 2001. *Comparison of SDI, LEPA, and spray irrigation efficiency*. Agric. Res. Serv. Pap. 012019 2001. Presented at ASAE Annu. Int. Meet., Sacramento, CA.

84. Fipps G, New LL. 1994. Improving the efficiency of center pivot irrigation with LEPA. In *Efficient Water Use*, ed. H Garduño, F Arreguín-Cortés. Montevideo, Urug: UN Educ. Sci. Cult. Organ./ Reg. Off. Sci. Technol. Lat. Am. Caribb. 379 pp.
85. Guerra LC, Bhuiyan SI, Tuong TP, Barker R. 1998. *Producing more rice with less water from irrigated systems*. Int. Water Manag. Inst. SWIM Pap. 5. Colombo, Sri Lanka
86. Keller J, Bliesner RD. 1990. *Sprinkle and Trickle Irrigation Design*. New York: Van Nostrand Reinhold
87. Postel S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: Norton. 313 pp.
88. Jin L, Young W. 2001. Water use in agriculture in China: importance, challenges, and implications for policy. *Water Policy* 3(3):215–28
89. Van Hofwegen P, Svendsen M. 2000. *A vision of water for food and rural development*. Presented at 2nd World Water Forum. The Hague, Neth.
90. Polak P, Nanes Adhikari D. 1997. A low-cost drip irrigation system for small farmers in developing countries. *J. Am. Water Resour. Assoc.* 33(1):119–24
91. Postel S, Polak P, Gonzales F, Keller J. 2001. Drip irrigation for small farmers: A new initiative to alleviate hunger and poverty. *Water Int.* 26(1):3–13
92. Int. Dev. Enterprises. 2002. *Low Cost Drip Irrigation Fact Sheet*. http://www.ideorg.org/html/gallery/drip.html
93. Gleick PH. 1998. The changing water paradigm. In *The World's Water 1998-1999*, ed. PH Gleick, pp. 5–37. Washington, DC: Island
94. Gleick PH. 2000. Pictures of the future: a review of global water resources projections. In *The World's Water 2000–2001*, ed. PH Gleick, pp. 39–61. Washington, DC: Island