WATER DEMAND, SUPPLY, AND QUALITY IN THE UNITED STATES: SUSTAINABILITY OF WATER USES

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ABSTRACT

The purpose of this paper is to develop, from a very wide variety of public data, a synthesis of the status of water supply, demand, and quality for the United States from 1985 to the present, in an effort to obtain a dynamic baseline for assessing the sustainability of multiple water uses. Although the United States has relatively ample supplies of water, it is likely that deficits will occur in areas with increasing population and economic development. Variations in population, industrial, and agricultural production are driven by internal and external factors among which water probably causes the largest disruptions because of the inability to adapt to those changes. Climate changes due to global and regional warming trends also have major impacts on water availability and quality, although they are less sudden than structural changes in the economy. To help frame a baseline from which those changes can be measured to assess its sustainability for the population of the United States, we summarize the most salient findings about the status of US water supply, demand, and quality at the level of the water resource regions, and states over a period of approximately 20 years. Our synthesis of the data collected by the US agencies indicates that water quality is improving and the supply of water for the United States is generally good. However, shortages of water predicted from linear extrapolations of past trends, appear principally to affect the western water resource regions. Using US Census Bureau 'high population' forecasts, water shortages may be felt earlier and in more water resource regions than previously expected. These conclusions implicitly take into account changes in the US economy during the mid-eighties but do not account for: regional-scale climate, legal low-flow requirements, or other non-routine occurrences.
Keywords: demand, supply, sustainability, water quality, water quality index, water uses.

1 INTRODUCTION

Water is an essential factor of production; it harbors and supports life. Yet, some of the life it harbors can cause illness or death; droughts and floods cause casualties, environmental and property damage, and dislocate the economy. Some changes, such as in the frequency and intensity of floods and droughts, can create a great variety of adverse impacts on society and the natural environment. When coupled to concomitant changes in population growth, these increase the vulnerability of those not previously at risk and exacerbate the vulnerability of those who already are at risk [1, 2].

The central purpose of this paper is to establish a historical, dynamic baseline for water supply, demand, and quality, beginning in 1985 and ending in 2002, for the United States. We study fresh and saline, surface and ground waters, but focus on fresh surface and ground water availability and the demands by such specific sectors of the economy as agriculture, livestock, thermoelectric power generation, industrial, public, and commercial users, as well as water quality at a relatively high level of resolution, but a level of detail that is consistent for the Nation as a whole. Water demands and allocations are affected by multiple and diverse factors and events. Adverse events can – and often do – occur at different points in time and space and be of very different duration. Those events, such as droughts or floods, may have diverse trends, cycles, and seasonalities. Even when demand is met efficiently, water policy must confront wasteful uses [3, 4]. Moreover, indirect changes, such as changes to the quantity of water embodied in foodstuff, affect sectoral water demands. The factors that affect water quality, availability, and use include legal requirements, such as low-flow requirements

and water use efficiency, socio-economic and health ones. Environmental events, such as toxic spills, also affect water demand, allocations, and quality and thus affect the social and economic well-being of either a community or a region.

In this paper we give a qualitative, unified synthesis and perspective on the quantities of water supplied and demanded at the level of detail of the water resource region, WRR, (a US Geological Survey definition of homogeneous water basins), and water quality summaries at the state level. We thus complement, augment, and corroborate several contributions from the literature and fill a gap in the information by providing an integrated view of water supply, demand, and quality that so far appears to have been missing. To our knowledge, this integration of water quality supply, demand, and quantity at this level of detail, namely the water resource region and state levels, and for several sectors of the economy, has not been reported elsewhere.

1.1 The Context

On average, from 1900 to 1990, the population of the Unites States increased by about 1.2% per year while water withdrawals increased at a faster rate, approximately 2.4% per year. Table 1 summarizes population projections for the United States as a whole [5, 6].

Americans withdrew, in 1900, 475 GPD (1,798 liters per day) (lpd); but that number has increased to approximately 1,350 GPD (5,110 lpd) in 1990. More recently, in 1995, the United States surface fresh water withdrawals were 324,000 million gallons per day (MGD) (12,264,734,243,215 lpd), total ground water withdrawals were 77,500 MGD (293,369,414,768 lpd) and the saline water uses were about 60,800 MGD (230,153,037,650 lpd) [7]. The largest water users were irrigation, which used most of the fresh water at 134,000 MGD (507,245,181,664 lpd), and thermal power generation, which used 190,000 MGD (507,245,181,664 lpd) (of which approximately 58,000 MGD (219,553,884,601 lpd) was saline water) [7]. There are remarkable differences in the fate of water withdrawals by different sectors. For instance, a large percentage of the water withdrawn for cooling thermal power plants is quickly returned to the source water body, albeit at a higher temperature and with perhaps added chemicals. In that same year, reclaimed wastewater use was approximately 1,000 MGD (3,785,411,803 lpd). The 1995 overall water withdrawals were 10% less than the 1980 withdrawals. The five sectors of the economy we use in this work (irrigation, thermoelectric power generation, industrial and commercial users, domestic and public users, and livestock) show a decline in water use from 1980 to 1995, ranging from 3 to 14%, although the US population increased by approximately 16% over this period. About 60 million US households are served by urban/storm water systems and about 10.5 million households have non-urban storm water systems [8].

Table 1: Population Projections (adapted from [5, 6]).

Year	Lowest series	Middle series	Highest series
2000	274,853,000	275,306,000	275,816,000
2010	291,413,000	299,862,000	310,910,000
2020	303,664,000	324,927,000	354,642,000
2030	311,656,000	351,070,000	409,604,000
2040	314,673,000	377,350,000	475,949,000
2050	313,546,000	403,687,000	552,757,000

The reasons for the changes in water demand include federal legislation (such as the Clean Water Act, 1972; the National Energy Policy Act, 1992, and other federal and state laws) as well as conservation, leak detection and repairs, and pricing policies. The structural changes reflected in past *aggregate* water projections were the result of the transitions from supply-side management of water to demand-side management and increased users' awareness of the importance and costs of water [9]. Federal laws controlling water pollution caused the technological changes in processes that use water as an input (including cooling towers) and the increased recycling of water. The agricultural sector improved its crop patterns and the delivery of water for irrigation; it also lessened its reliance on ground water because of increased costs of pumped water. At the same time, agricultural patterns shifted from the West of the United Sates to the East [4, 10]. The number of irrigated areas peaked in 1980, and has been steady from 1985 to 1995 (at about 58 million acres, million ac, or 23,472,278 hectares, ha). In the West, the irrigated acreage was 49 million ac (19,830,028 ha) in 1980, declining to about 45 million ac (18,211,251 ha), while the East has steadily increased from about 2 million ac (809,389 ha) in 1950 to about 12 million ac (4,856,333 ha) in 1995 [9]. Domestic water uses have been approximately constant from 1980 to 1995 [9].

The use of water by the five sectors of the economy we consider is characterized by complex and inter-dependent relationships that determine the temporal equilibrium between water supplied and demanded. An important macroeconomic aspect of what can happen to water supply and demand in the long-term is the effect of technological change. For example, from 1950 to 1980, the patterns of water use show a steady *increase* that, however, was reversed by a *decrease* from 1980 to 1985. A structural change in the US economy occurred between 1980 and 1985. After 1985, water uses have remained approximately steady [9] while, from 1950 to 1995, the US population increased at a relatively constant rate from 150 million to 250 million, and in 2006 it is approximately 300 million people. The *consumptive* use of water in 1995 was about 100 billion gallons per day, BGD (378,541,180,346 lpd), approximately 29% of the total water withdrawals [10]. Population changes in trend, composition, and location are a major reason for changing water demand and supply at the levels of detail that we have adopted. The relatively predictable demographic effects of an aging population can affect the supply of water in a number of ways including the potential for retirees to migrate between water districts. A less predictable, but nonetheless important, unknown is the effect of droughts on water supply and the social and economic dislocations that severe droughts can cause. Another important unknown involves societal and political attitudes regarding the management of ecological assets via minimum stream flow requirements for sustaining aquatic communities, in conditions of sustained water scarcity or shortages. When we look for physical factors affecting water supply and demand, little is known about cold and heat waves. Similarly, few studies provide information on the frost-free seasons, cold and warm days for the northeastern United States and trends in the exceedance of 0 degrees centigrade and 32.2 degrees centigrade thresholds for the United States [2]. Increased precipitation, as number of days in a year exceeding 50.8 mm and 101.6 mm., have been increasing since 1910 as have interval exceedences and their frequencies (1 to 7- day totals, 1:1 and 1:5 year return periods). Nonetheless, the droughts in the 1930s and 1950s still dominate long-term time series [2] thus adding uncertainty to the current projections.

No analysis of sustainability of water uses can be complete without accounting for water pollution. It results from many diverse sources. For example, point sources include industrial and sewage treatment discharges, underground storage tanks leaks and spills. Non-point sources include agriculture, silviculture, construction, mining, urban run-off, septic fields, and landfills. For some sources of water pollution, their classification as either point or non-point source can be somewhat arbitrary because it is a judgment based on the regulatory agency's administrative rules that limit discharge

of water to a receiving body, such as a bay or river. Natural erosion can decrease water storage and affect tourism by increasing turbidity and reducing water depth; it increases dredging and irrigation costs, and hinders natural water filtration, but knowledge about these, including pollution and risks generated by dredging, is incomplete [11].

Table 2 summarizes water use projections made by Brown [10, 12] and the 1995 data developed by Solley, Pierce, and Perlman [7], (the basis for the projections is a water budget in which withdrawals = consumption + return flows + recharges). These projections use the Census Bureau (1992) and Bureau of Economic Analysis (1992) data for states and counties, and income data from the Bureau of Economic Analysis (1992). The results are aggregated at the WRR level by Brown [10, 12] and others, which we summarize in Table 2.

Key aspects of US water quality are summarized in Tables 3–6. Table 3 describes the aggregate qualitative status of water quality – as the degree of support for specific uses – in 1988 and 1990; it is based on data from states and other jurisdictions reporting to the US EPA, under the Clean Water Act Section 305(b). The reporting jurisdictions *assessed* approximately 520,000 river miles (836,859 km) and 1,8000,000 stream miles (2,896,819 km), but the percentage of waters assessed by some jurisdictions were much lower than the percentage of water assessed by other jurisdictions; some jurisdictions sampled their waters, but others used models to predict water quality. In 1988, approximately 16 million ac (6,475,111 ha) of lakes, ponds, and streams were assessed with reporting issues similar to those for rivers and streams. Approximately 27,000 square miles (69,930 square km) of estuaries were assessed; the range of the assessed waters varying from 2 to over 90%, depending on the jurisdiction submitting the data. Approximately 4,500 miles (7,242 km) of the Great Lakes shorelines were assessed but the assessments are characterized by considerable differences in the reporting methods. There were approximately 3,800 miles (6,116 km) of assessed ocean coastal waters; however, approximately half of the reporting jurisdiction reported monitoring data, while the others were 'evaluative' assessments and the variability of the assessed water ranged from 4 to 100% assessed. The status and percentage of water uses supported at levels such as 'good' and 'fair' are shown in Table 3, from data that we summarize from the US EPA [13, 14].

Eight years later, in 1996, the quality of American waters, from information reported from states and other jurisdictions under Section 305(b), can be described more fully through a wider spectrum of uses [15, 16]. For that year, there are 54 reporting jurisdictions that *surveyed* approximately 700,000 miles (1,126,541 km) (19% of the total miles) of rivers and streams, out of a total of 3,600,000 miles (5,793,638 km). The quality of lakes, ponds, and reservoirs is reported by 45 jurisdictions that surveyed 16,800,000 acres (6,798,867 ha) (40% of the total 41,700,000 acres or 16,875,759 ha); different form of pollution (e.g. mercury, or other, such as eutrophication) affect these bodies of water. Approximately 94% of the Great lakes' 5,521 shore miles (8,885 km) have been surveyed (i.e. 5,186 miles or 8,346 km); of these, about 97% are characterized by fish consumption advisories. The quality of estuarine waters surveyed by 23 jurisdictions (28,819 miles or 46,380 km) is 72% of the total 39,839 miles (64,115 km). Finally, 10 jurisdictions surveyed their ocean coastlines, namely 3,651 miles or 5,876 km (6%), out of 27 jurisdictions: a total of 58,585 miles (94,283 km) (94%) remained to be surveyed. These results for 1998 are depicted in Table 4.

In 1998 there were 842,426 river miles (1,355,753 km) (23%) *assessed*, out of a total 3,662,255 miles (5,893,828 km). Approximately 17,390,000 acres (70,376,637 ha) (42%) of the lakes, reservoirs, and ponds were *assessed*, out of a total of approximately 41,378,000 acres (16,745,447 ha), from data provided by 45 jurisdictions that relied on monitoring, and other evaluations. For estuaries, for which 22 jurisdictions out of 27 have provided water quality information the situation was as follows: 28,687 square miles (74,299 square km) (32%) of the total 90,465 square miles

Table 2: Summary of the variability of US water uses, in 1995 & projection for 2040.

1995 Water use (BGD is billion gallons per day; GPCD is gallons per capita per day; lpd is liters per day)	Source of water	Year 2040 projections, as intervals if available, middle population forecast by US Census	Key predictors of water use
Livestock (≈ 5.5 BGD (20,819,764,919 lpd) by Solley, Pierce and Perlman; 21 GPCD (79 lpd/person))	Self-supplied	[5.5 BGD or 20,819,764,919 lpd) (1995) to 7.7 BGD or 29,147,670,886 lpd (2040)]; 21 GPCD (89 lpd/person).	Population; withdrawals/capita
Domestic and public (≈ 32 (121,133,177,711 lpd) or 43.6 BGD (165,043,954,631 lpd) by Solley, Pierce and Perlman; 121 GPCD (458 lpd/person)	Self- and public-supplied	[32 BGD (1995) (121,133,177,711 lpd) to 45 BGD (2040) (170,343,531,156 lpd)]; 121 GPCD (458 lpd/person).	Same
Industrial and commercial (≈36 BGD (136,274,824,925 lpd) or 23.6 BGD (89,335,718,562 lpd) by Solley, Pierce and Perlman)	Self- and public-supplied	[37 BGD (1995) (140,060,236,728 lpd) to 39 BGD (2040) (147,631,060,335 lpd); [7.4 GPCD (28 lpd/person)to 3.9 GPCD (15 lpc/person)]	Population; per capita income; withdrawals/ $ of income
Mining (2.6 BGD by Solley, Pierce and Perlman)	Self-supplied	NA	None stated
Thermoelectric (≈ 130 BGD (492,103,534,450 lpd) or 132 BGD (499,674,358,057 lpd) by Solley, Pierce and Perlman)	Self-supplied	[132 BGD (1995) (499,674,358,057 lpd) to 143 BGD (2040) (541,313,887,895]; [504 GPCD (1,946 lpd/person) to 389 GPCD (1,473 lpd/person)]	Population; kW-hrs/ capita; freshwater kW-hrs/total kW-hrs
Hydroelectric power (NA)	Self-supplied	NA	None stated
Agricultural irrigation (≈ 130 BGD (492,103,534,450 lpd) or 134 BGD (507,245,181,664 lpd) by Solley, Pierce and Perlman)	Self-supplied	[134 BGD (1995) (507,245,181,664 lpd) to 130 BGD (2040) (492,103,534,450 lpd)]; [514 GPCD (1,946 lpd/person to 354 GPCD (1,340 lpd/person)].	Acres irrigated; withdrawals/acre

Notes: The minimum and maximum, within square brackets, show the empirical variability. NA = not available.
Source: Various tables and discussion in Brown [10, 12] and Table 3, p. 10, Solley *et al.* [7] who provide 1995 data.

Table 3: Status and percentage of uses supported in 1988, adapted from US EPA [14] (EPA 440-4-90-003).

	All uses	
	Good (%)	Fair (%)
Rivers and stream	70 (361,332 miles; 581,507 km)	20 (104,632 miles; 168,389 km)
Lakes, ponds and reservoirs	74 (12,021,044 ac; 4,864,850 ha)	17 (2,701,577 ac; 1,093,313 ha)
Estuaries	72 (19,110 mi^2; 49,495 km sq)	23 (6,078 mi^2; 15,742 km sq)
Great Lakes shorelines	8 (372 miles; 599 km)	18 (819 miles; 1318 km)
Ocean coastal waters	89 (3,324 miles; 5349 km)	8 (307 miles; 494 km)

Notes: Good is *fully supporting* and fair is *partially supporting*; all uses means designated uses: fisheries, contact recreation, and drinking water. Forty-eight jurisdictions reported data on water quality, but the information on rivers and streams from 10 jurisdictions were unusable for the purpose of the CWA§305(b) reporting. For estuaries, data were reported by 28 jurisdictions, with data from 7 jurisdictions being unusable. Of the 8 Great Lakes States, 6 provided data. Twelve jurisdictions reported the status of their coastal waters.
Source: US EPA [14], Figures 1-1, 2-1, 3-1 and 4-8.

Table 4: Status and percentage of uses supported in 1996, developed from US EPA [15] (EPA 841-S-97-001).

Water body	Full support all uses (Good) (%)	One or more uses threatened (Good) (%)	One or more uses impaired (Impaired) (%)	Not attainable (%)
Rivers and streams	56	8	36	<1
Lakes, ponds and reservoirs	51 (lakes only)	10 (lakes only)	39 (lakes only)	<1 (lakes only)
The Great Lakes	2	1	97	<1
Estuaries	58	4	38	<1
Ocean shoreline waters	79	9	13	0

Notes: Good, Impaired and Not attainable are short descriptions used by the US EPA to characterize the status in the columns' headings. Wetlands data are not reported in this table for brevity.
Source: Developed from Figures 3, 6, 9, 12 and 15, US EPA [15].

(234,303 square km) were assessed. Finally, approximately 3,130 miles (5,037 km) (5%) of ocean shorelines were *assessed,* out of 66,645 total miles (107,255 km), including Alaska's. As discussed for 1996, these data are developed from heterogeneous reporting methods: for example thirteen States rated swimming, six fish consumption, and eight shellfish consumption. The results for 1998 are shown in Table 5.

An indication of the progress in measuring the status of US waters in the percentages of the body of waters *assessed* in the last decade is depicted in Table 6,which is developed from the data US EPA [17] data.

Table 5: Status and percentage of uses supported in 1998, developed from US EPA [17] (EPA 841-R-00-001).

Water body	Fully supporting all uses (Good) (%)	One or more uses threatened (Good) (%)	One or more uses impaired (Impaired) (%)	Not supporting (Poor) (%)	Not attainable (%)
Rivers and streams	55	10	35	5	<0.02
Lakes, reservoirs, and ponds	46	9	45	5* (0, 67)[a]	<0.01
The Great Lakes	2	2	96	12*	0
Estuaries	47	>9	44	3[#]	0
Ocean shoreline	80	8	12	2[#]	<0.02

Notes: *Geometric average of the percentages for six uses (aquatic life, fish consumption, swimming, secondary contact, drinking water supply, and agriculture).
[a]The numbers in parenthesis are the minimum and the maximum of the six values used in calculating the geometric average.
[#]Geometric average of four reported uses (aquatic life support, fish consumption, swimming and secondary contact).
Source: EPA 841-R-00-001 [17]: Figures 3-2, p. 58, 4-2, p. 84, 5-1, p. 104, Tables 3-3, p. 60, 8-3, p. 203. Figures 3-3, p. 60, 4-3, p. 85, 5-7, p. 112. Figure 5-2, p. 105, and Figure 5-11, p. 117.

This data shows significant differences between the years, although some of the differences are due to the inclusion of Alaska and to the changes in the basis for the calculation of percentages. These overall results, discussed in more detail in the next section, do not permit inference to the nation's water because of their heterogeneity in reporting, types of sampling, evaluation criteria, and possibly different and incomplete modeling used for predictions in assessing the quality of water for specific uses. We concur with Vorosmaty *et al.* [18] that the vulnerability of water resources to climate change and the effect of population growth on demand require the joint analysis of water quality demanded, supplied, and quality. We provide some of the needed information in the next sections, which describe the water situation for the United States using WRR (for water supply and demand) and states (for water quality).

2 WATER SUPPLY AND DEMAND: BASELINE AND A VIEW ON THE FUTURE

US WRR (from WRR 1 to WRR 20) are used by Guldin [19] to develop water budgets from 1985 to 2040 and by Brown's [10] projections. Guldin's analyses have data gaps (the period 1985 to 2000) that can affect understanding potential changes in water supply and demand from 2000 to 2050. Solley, Pierce, and Perlman [7] for the year 1995 provide additional information needed to 'fill' gaps in the data and projections developed by Guldin[19]. (The basic water budget is the balance of the following factors, over the k years time horizon ($k = 55$ years for Guldin [19]); average annual precipitation, renewable water supply, groundwater overdrafts, imports or exports, net reservoir evapo-transpiration,

Table 6: Extent and percentages of *assessed* bodies of water 1992–1998, by type and year.

Water body	1992	1994	1996	1998
Rivers and streams	642,881 mi (1,034,617 km) (18%) of 3,551,247 mi (5,715,178 km)	615,806 mi (991,044 km) (17%) of 3,548,738 mi (5,711,140 km)[#]	693,905 mi (1,116,732 km) (19%) of 3,634,152 mi (5,848,601 km)	842,426 mi (1,355,753 km) (23%) of 3,662,255 mi (5,893,828 km)
Lakes, reservoirs, and ponds	18,300,000 ac (7,405,908 ha) (46%) of 39,920,000 ac (16,155,403 ha)	17,134,153 ac (6,934,097 ha) (42%) of 40,826,064 ac (16,522,082 ha)	16,819,769 ac (6,806,867 ha) (40%) of 41,684,902 ac (16,869,649 ha)	17,390,370 ac (7,037,786 ha) (42%) of 41,376,729 ac (16,744,933 ha)
Estuaries	27,227 mi^2 (70,518 km^2) (74%) of 36,890 mi^2 (95,545 km^2)	26,847 mi^2 (69,533 km^2) (78%) of 34,388 mi^2 (89,065 km^2)	28,819 mi^2 (74,641 km^2) (72%) of 39,839 mi^2 (103,183 km^2)	28,687 mi^2 (74,299 km^2) (32%) of 90,465 mi^2 (24,514 km^2) now including Alaska, Guam, and Comm. N. Mariana Is.
Great Lakes shorelines	5,319 mi (8,560 km) (99%) of 20,121 mi (32,382 km)	5,224 mi (8,407 km) (94%) of 5,559 mi (8,946 km)	5,186 mi (8,346 km) (94%) of 5,521 mi (8,885 km)	4,950 mi (7,966 km) (90%) of 5,521 mi (8,885 km)
Ocean shoreline waters	3,398 mi (5,469 km) (17%) of 20,121 mi (32,382 km)	5,208 mi (8,381 km) (9%) of 58,421 mi (94,019 km)*	3,651 mi (5,876 km) (6%) of 22,585 mi (36,347 km)	3,130 mi (5,037 km) (5%) of 66,645 mi (107,255 km)

Notes: *As reported in the 1994 Sect. 305(b) Report. #Numerical discrepancies due to reporting differences; mi = miles.
Source: US EPA [17] (EPA 841-R-00-001), pages 50, 81, 101, 103, 111, 116.

Table 7: Determinants of water use and trends up to 2040.

Water demand by user	Example of determinants of demand	Trends [12]
Livestock	Consumer taste, income, potential diseases.	5.5 BGD (20,819,764,919 lpd) in1995 to 7.7 BGD (29,147,670,887 lpd) in 2040 with possibly higher increases
Domestic and public	Housing stock, technological innovations and modernization, conservation. Water withdrawal rates to follow population growth rate	Historical rates of change: 1.5% in the 60s, 0.9% in the 70s, 0.8% in the 80s, 0.3% in the period 1990–95. Expected to *increase* from 32 BGD (121,133,177,711 lpd) to 45 BGD (170,343,531,156 lpd) in 2040 (42% increase)
Industrial and commercial (I&C)	Efficiency, consumer confidence, employment rates, changes in taxes Withdrawals predicted on the basis of GPD/$1000 personal income, income/caput, population.	2.5% in the 60s, 2.3% in the 70s, 6.1% in the 80s, 1%1990–95, and about 1.5% to 2040
Thermoelectricity generation	As for the I&C sectors, federal and state energy policy. Predictions based on total kW-hrs/person.	Historical rates of total energy (kW-hrs) uses: 6% in the 60s, 3% in the 70s, 1.1% in the 80s, 0.4% 1990–95, 0.6–0.14% 1990–95. Freshwater use per kW-hr to *decrease* from 1.3% in 1995 to 0.6% in 2040
Agriculture	Urban sprawl, energy costs, technological changes, taste, income, transportation, climate change, federal and state policy. Predictions based on withdrawals/acre.	*Western US:* annual rates *decreased* from 1% from 1980 to 1985, 0.1% from 1985 to 1995. Predicted to *decrease* 0.08 to 0.04 per year to 2040 *Eastern US:* predicted have *no* growth to 2040

BGD = billion gallons per day; kW-hr = kilowatt-hour.

non-agricultural off-stream consumptive uses, average stream outflows and instream flow requirements. The critical assumptions based on constant prices, constant institutional framework, are that the average is the optimal metric and that the instream flow requirements are optimal with respect to fish and wildlife habitats. Variability about the average precipitation is taken to be ± 20%. Some of the components of the water budget include additional factors such as self-supply.) The principal classes of water users developed by the USGS [10] are: livestock, domestic and public, industrial and commercial, thermoelectric, and irrigation. Table 7 contains a summary of the predictions of water demands (often stated as *withdrawals*) by these users and examples of the determinants of the demand for water.

From 1960 to 1985 the total water withdrawals of the United States increased by approximately 60%, consumptive use increased by 50%; thermoelectric consumptive use increased by more than 1,800%, irrigation by 40%, groundwater withdrawals by 80% and surface water withdrawals by 50%. By contrast, the more recent data – based on 1995 numbers – are as follows:

1. *Livestock (cattle, hog, sheep, and poultry) withdrawals.* The predictions are not based on the number of animals because this data is not available; the proxy used is meat consumption. On that basis, the daily water withdrawals per capita were slowly declining from about 10 GPD (38 lpd/person) in 1980 to about 8.5 GPD (32 lpd/person) in 1995 [12]. However, accounting for other animal stock raises the GPD withdrawals from about 2 GDP (8 lpd/person) in 1980, to about 22 GPD (83 lpd/person) in 1995, with a steady use at about 18 GPD (68 lpd/person) from 1985 to 1995. Solley, Pierce, and Perlman [7] state that 5.50 BGD (21 lpd/person) were used by this sector in 1995.

2. *Domestic and public use withdrawals.* Overall, from 1960 to 1995, water withdrawals, either in gallons per capita per day or in gallons per household per day, have been increasing but are essentially constant from 1990 to 1995. The per-capita withdrawals increased from approximately 86 GPD (326 lpd/person) in 1960 to 122 GPD (462 lpd/person) in 1990, but then decreased to 120 GPD (454 lpd/person) in 1995 [12], Solley, Pierce, and Perlman [7] calculate that 43.60 BGD (165,043,954,631 lpd) were used in 1995. Per-household data are valuable because they reflect the decline in the number of individuals per household due to changing social and economic factors.

3. *Industrial and commercial use.* Brown [10, 12] has used gallons/day/$1000 income to capture the essence of the past trend in water withdrawals by the industrial and commercial sectors. The trend, from a high of approximately 24 gallons/day/$1,000 in 1960 (90 lpd/$1,000), has steadily declined to about 7.5 gallons/day/$1000 (28 lpd/$1,000) in 1995. The reasons for the decrease include increased process efficiency and recycling. The 1995 water quantities developed by Solley, Pierce, and Perlman [7] are 23.60 BGD (89,335,718,561 lpd) of fresh water, with an additional 1.66 BGD (6,056,658,886 lpd) of saline water used by the industrial sector only.

4. *Thermoelectric use.* The pattern of water use from 1960 to 1995, measured in gallons/day, has been declining. The shape of the function is almost the same as that of the industrial and commercial use (roughly shaped as a negative exponential function), from a high of 60 gallons/ KW-hr (227 liter/ KWh-hr) to a low of about 23 gallons/ kW-hr (87 liter/ KW-hr). The production of electricity from 1960 to 1995 has increased from about 450 to 2150 10^9 kW-hr. The decrease in water usage per unit of energy produced is primarily due to re-use. Thermoelectric power generation water withdrawals for 1995 calculated by Solley, Pierce, and Perlman [7] are 132 BGD (499,674,358,057 lpd) of freshwater and 57.9 BGD (219,173,433,420 lpd) of saline water.

5. *Irrigation use.* The demand for water has shown a positive trend from 1960 to 1980, declining to approximately in 1995. A major reason for the decline in water withdrawals is the shift, over that period of time, from irrigated agriculture in the West (WRRs 10 through to 18) to the East (WRRs 1 through 9). The East requires less water per acre for irrigation than the West due to greater levels of rainfall. Other reasons suggest that there have been efficiency gains, which have taken into account plant evapo-transpiration, and the price of pumped water has increased. Solley, Pierce and Perlman [7] calculate irrigation withdrawals to be 134 BGD (507,245,181,663 lpd).

6. *Hydroelectric power.* The production of electric power has increased from approximately 150 × 10^9 kW-hr in 1960 to 310 × 10^9 kW-hr in 1975, becoming fairly stable from 1975 to 1995, at about 300 × 10^9 kW-hr. Water withdrawals have declined from a high of approximately 5,000 gallons/KW-hr (18,900 l/KW-hr) in 1960 to 3,800 gallons/KW-hr (14,400 l/KW-hr) in 1995.

However, water withdrawals have increased from approximately 2×10^{12} GPD (7,570,823,606, 923 lpd) in 1960 to 3×10^{12} GPD (1,1356,235,410,384 lpd) in 1975, remaining constant thereafter.

The 1995 magnitude of the withdrawals from surface and ground water sources is developed from Solley, Pierce, and Pearlman ([7]; definitions of each water region can be found in this reference) and is summarized in Table 8.

Domestic and public water, livestock and commercial and industrial water demands correlate as depicted in Fig. 1. This Figure suggests that there are a few outliers, but most of the data appears to be within the 95% confidence ellipse.

To gain additional insights, we depict clusters of WRRs within the WRR data. The dendrogram (estimations by Ward's method) of the domestic and public water demands (from Table 8) depicts their clustering (Fig. 2): the clusters suggest some of the potential relationships between WRRs and water demands by the public and domestic, livestock, and commercial and industrial sectors of the US economy. The graphs in Fig. 2 depict the dendogram and the scree diagram of the clusters.

The clusters are indicated by the dots '**.**', '**x**' and '**+**' codes in Fig. 2. The scree plot also suggests that there are three major clusters of WRRs: each change in the slope of the line slope indicates a clustering of WRRs. The cluster (**+**) consists of the N. Atl., S. Atl, G. Lakes, and Ohio WRRs. The cluster (x) consists of the L. Miss, Souris R, Pac NW, and CA WRRs. The third cluster (.) accounts for the remaining WRRs. The surface and ground water withdrawals at the WRR level by economic sector, in 1995, are summarized in Table 9.

The predictions of changes in water withdrawals from 1995 to 2040, by WRR, developed by Brown [10, 12] and Guldin [19], using the 1995 US Census Bureau Population Series Projections, are summarized in Table 10.

The clusters are indicated by the dots '**.**', '**x**' and '**+**' codes in Fig. 3. As for the previous analysis, there are three clusters. These are North Atlantic, Great Lakes and California (**x**), South Atlantic (**+**), and the rest of the WRRs forming the third cluster (**.**).

Table 11 depicts a plausible distribution of the per capita domestic and public water withdrawals up to 2040 [12].

2.1 Surface water surpluses and deficits

The sensitivity of the water demands can be assessed by using recent population projections made by the US Census Bureau [5] and adopting average water consumption as shown in Table 12.

These results are based on average daily demand held constant throughout the three periods of time (2000, 2040, and 2050), multiplied by the predicted population numbers provided by the US Census Bureau, and then converted to BGD. For example: 122 gallons per capita per day demand by domestic and private sources multiplied by 274,853,000 people in the United States in 2000 equals 3.3×10^{10} gallons per day or 33 BGD (125 bld). The population numbers are those provided in an earlier Table of this Report. The second assumption is that the unit water demands apply to the population as a whole. The daily water per capita demand is that given in Brown [12] (Table A1.7, p. 42). If we use the average sectoral consumption (that is 122, 106, 389 and 354 GPCD; 462, 405, 1,473 lpd/pers on) for 2040, and use the difference in the highest series population number in 2040 (475,949,000) and Guldin's 2040 population estimate for that year at 333,300,000 we obtain 142,550,000 people as the potential positive population gap in that year. The corresponding sectoral consumption gaps for 2040 become: domestic and public = 17.4 BGD (65.87 bld); industrial and commercial = 15.1 BGD (57.6 bld); thermoelectric = 55.5 BGD (210.09 bld); and agricultural = 50.5 BGD (191.16 bld). Clearly, population may increase at either a slower rate or at

Table 8: Sectoral total fresh water withdrawals in 1995 (developed from Solley *et al.* [7]), by WRR.

WRR (per capita withdrawals in GPD; lpd)	Population 1995 (10⁶ individuals)	Livestock (MGD; mld)	Domestic and public (MGD; mld)	I&C (MGD; mld)	Thermal (MGD; mld) saline omitted	Irrigation (MGD; mld)
N. Engl. (289; 1,094)	13.4 (12.8)	19; 71	1,609; 6,091	243; 920	1,670; 6,322	146; 553
M. Atlan. (509; 1,927)	42.4	134; 507	6,486; 24,552	1,713; 6,484	12,600; 47,696	293; 1,109
S. Atl.-G. (848; 3,210)	37.6 (27.8)	405; 1,533	7,189; 27,213	2,920; 11,053	17,600; 66,623	4,600; 17,413
G. Lakes (1,500; 5,678)	23.5 (21.8)	70; 265	4,775; 18,075	3,322; 12,575	22,800; 86,307	315; 1,192
Ohio (1,330; 5,035)	21.1 (22.6)	141; 534	3,008; 11,387	4,130; 15,634	22,600; 85,550	104; 394
Tenn. (2,140; 8,101)	4.3 (4.2)	205; 776	638; 2,415	1,118; 4,232	6,990; 26,460	48; 182
U. Miss. (1,050; 3,975)	22.8 (22.3)	255; 965	2,191; 8,294	1,196; 4,527	19,100; 72,301	484; 1,832
L. Miss. (2,720; 10,296)	7.3	1,010; 3,823	1,143; 4,327	2,926; 11,076	6,730; 25,476	8,130; 30,775
Souris- R. (693; 2,623)	0.7	20; 76	83; 314	22; 83	38; 144	88; 333
Missouri (3,380; 12,795)	10.3 (10.7)	426; 1,613	1,708; 6,465	186; 704	8,800; 33,312	24,600; 93,121
AK-W -R. (1,800; 6,814)	8.7 (8.9)	395; 1,495	1,655; 6,265	553; 2,093	4,170; 15,785	9,250; 35,015
TX-G. (1,050; 3,975)	15.9 (16.8)	208; 787	2,955; 11,186	1,102; 4,172	7,680; 29,072	5,530; 20,933
R. Grand. (2,600; 9,842)	3.1 (2.6)	35; 132	502; 1,900	29; 110	18; 68	6,020; 22,788
U. Col. (10,400; 39,368)	0.7	54; 204	153; 579	13; 49	146; 553	7,030; 26,611
L. Col. (1,500; 5,678)	5.3	40; 151	1,215; 4,599	77; 291	63; 238	6,410; 24,265
G. Basin (2,510; 9,501)	2.4	86; 326	619; 2,343	116; 439	24; 91	5,110; 19,343
Pac.NW (3,220; 12,189)	9.9	1,510; 5,716	2,170; 8,214	2,150; 8,140	385; 1,457	25,700; 97,285
CA (32,060; 123,404)	32.3 (32.0)	453; 1,715	5,734; 21,706	937; 3,547	205; 776	29,100; 110,155
Alaska (604; 2,286)	0.6	0.5; 1.9	90; 341	66; 250	31; 117	0.6; 2.23
Hawaii (1,187; 4,493)	1.2	10; 38	218; 825	65; 246	67; 254	652; 2,468
Caribbean (152; 575)	(3.9)	6; 23	450; 1,703	17; 64	2; 825	107; 405
US (1,280; 4,845)	(267)	5,490; 20,782	43,590; 165,006	23,590; 89,298	132,000; 499,674	134,000; 507,245

Notes: The population numbers by WRR of Brown [12], Table 3, p. 16 and Solley *et al*. [7], Table 1, p. 7 are shown without and with parentheses, respectively. Mining withdrawals are omitted (total MGD = 2,560; mld = 9,691) as are saline water withdrawals by thermoelectric sector (57,900 MGD; 219,175 mld).

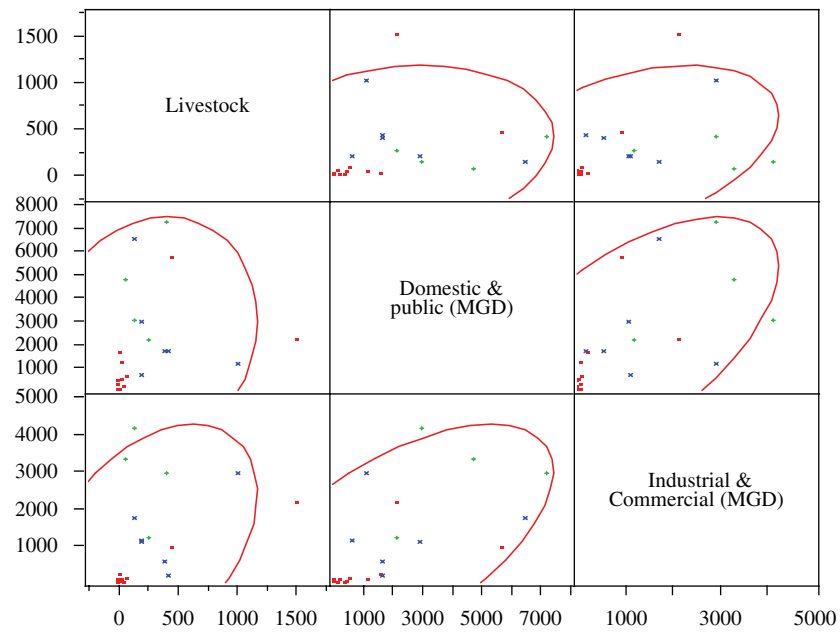*Source*: Developed from Table 1, p. 7, and Table 3, p. 10, Solley *et al*. [7].

Figure 1: 95% Confidence ellipse for domestic and public water, livestock, commercial, and industrial water demands in MGD (WRRs data for 1995, Table 8).
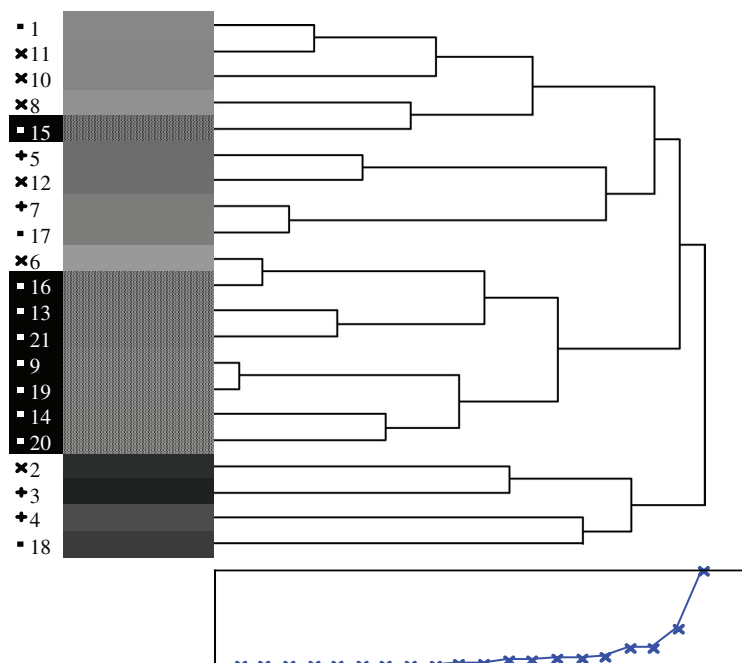

Figure 2: Clusters of WRRs (from Table 8 data.)

Table 9: Sectoral surface and ground water fresh water withdrawals in 1995 [Ground water], adapted from Solley *et al.* [7], by WRR (MGD; mld).

WRR (per capita withdrawals GPD; lpd)	Population in 1995 (10^6)	Livestock (MGD, mld)	Domestic and public (MGD, mld)	I&C (MGD, mld)	Thermal (MGD; mld)	Irrigation (MGD; mld)
N. Engl. (289; 1,094)	13.4 (12.8)	13; 49 [6.4; 24]	1,101; 4,168 [503; 1,904]	126; 477 [117; 443]	1,620; 6,132 [49; 185]	99; 375; [47; 178]
M. Atlan. (509; 1,927)	42.4	55; 208 [79; 299]	4,731 17,909 [1,756; 6,647]	1,156; 4,376 [561; 2,124]	12,600; 47,696 [11; 42]	165; 625 [128; 485]
S. Atl.-G. (848; 3,210)	37.6 (27.8)	217; 821 [188; 712]	2,710; 8,214 [3,479; 13,169]	2,026; 7669 [901; 3,411]	17,500; 66,245 [79; 299]	2,320; 8,782 [2,280; 8,630]
G. Lakes (1,500; 5,678)	23.5 (21.8)	20;76 [50; 189]	3,831; 14,502 [939; 3,555]	4,008; 15,172 [314; 1,189]	22,800; 86,307 [8; 30]	145; 549 [170; 644]
Ohio (1,330; 5,035)	21.1 (22.6)	81; 307 [60; 227]	1,805; 6,833 [1,203; 4,554]	3,390; 12,835 [470; 1,779]	22,600; 85,550 [70; 265]	43; 163 [61; 231]
Tenn. (2,140; 8,101)	4.3 (4.2)	187; 708 [19; 72]	449; 1,700 [189; 715]	1,048; 3,967 [39; 148]	6,990; 26,460 [0; 0]	39; 148 [9; 34]
U. Miss. (1,050; 3,975)	22.8 (22.3)	39; 148 [216; 818]	731; 2.767 [1,461; 5,530]	774; 2,930 [422; 1,673]	19,000; 71,923 [24; 91]	54; 204 [430; 1,628]
L. Miss. (2,720; 10,296)	7.3	272; 1,030 [740; 2,801]	330; 1,249 [814; 3,081]	2,301; 8,710 [626; 2,370]	6,670; 25,249 [69; 261]	1,200; 4,542 [6,930; 26,233]
Souris- R. (693; 2,623)	0.7	3; 11 [17; 64]	32; 121 [51; 193]	20; 76 [2; 8]	38; 144 [0; 0]	43; 163 [45; 170]
Missour. (3,380; 12,795)	10.3 (10.7)	173; 655 [253; 958]	927; 3,509 [780; 2,953]	65; 246 [111; 420; 1,590]	8,700; 32,933 [30; 114]	16,600; 62,838 [8,030; 30,397]
AK-W-R. (1,800; 6,814)	8.7 (8.9)	205; 776 [190; 719]	1,170; 4,429 [483; 1,828]	450; 1,703 [94; 356]	4,140; 15,671 [37; 140]	2,590; 9804 [6,660; 25,211]
TX-G (1,050; 3,975)	15.9 (16.8)	126; 477 [82; 310]	1,860; 7,041 [1,093; 4137]	854; 3,233 [248; 939]	7,630; 28,883 [50; 189]	1,170; 4,429 [4,370; 16,542]

(*Continued*)

Table 9: Continued.

WRR (per capita withdrawals GPD; lpd)	Population in 1995 (10^6)	Livestock (MGD, mld)	Domestic and public (MGD; mld)	I&C (MGD; mld)	Thermal (MGD; mld)	Irrigation (MGD; mld)
R. Grand. (2,600; 9,842)	3.1 (2.6)	9; 34 [27; 102]	131; 496 [381; 1,442]	2; 8 [27; 102]	2; 8 [16; 61]	4,600; 17,413 [1,420; 5,375]
U. Col. (10,400; 39,368)	0.7	50; 189 [4; 15]	106; 401 [46; 174]	5; 19 [8; 30]	146; 553 [0; 0]	6,990; 26,460 [38; 144]
L. Col. (1,500; 5,678)	5.3	7; 27 [33; 125]	698; 2,642 [520; 1,968]	13; 49 [64; 242]	17; 64 [45; 170]	4,200; 15,899 [2,210; 8,366]
G. Basin (2,510; 9,501)	2.4	77; 291 [9; 34]	256; 969 [363; 1,374]	46; 174 [70; 265]	21; 79 [3; 11]	4,020; 15,217 [1,090; 4,126]
Pac. NW (3,220; 12,189)	9.9	1,420; 5,375 [44; 167]	1,003; 3,797 [1,170; 4,429]	1,896; 7,177 [252; 954]	384; 1,454 [0.5; 1.9]	21,700; 82,143 [4,030; 15,255]
CA (32,060; 121,360)	32.3 (32.0)	222; 840 [231; 874]	2,892; 10,947 [2,842; 10,758]	338; 1,279 [599; 2,267]	202; 765 [4; 15]	18,200; 68,895 [10,900; 41,261]
Alaska (604; 2,286)	0.6	0.4; 1.5 [0.1; 0.4]	50; 189 [38; 144]	51; 193 [14; 53]	26; 98 [4; 15]	0.5; 1.9 [0.1; 0.4]
Hawaii (1,187; 4,493)	1.2	3; 11 [8; 30]	15; 57 [202; 765]	0.4; 1.5 [64; 242]	0; 0 [87; 329]	479; 1,813 [173; 655]
Caribbean (152; 575)	(3.9)	2; 8 [5; 19]	349; 1,321 [101; 382]	6; 23 [11; 42]	0; 0 [2; 8]	75; 284 [33; 125]
US (1,280; 4,845)	(267)	3,230; 12,227 [2,260; 8,550]	25,138; 95158 [18,450; 69,841]	18,650; 70,598 [5,029; 19,037]	131,000; 495,889 [565; 2,139]	84,700; 320,624 [49,000; 185,485]

Notes: Surface water mining withdrawals are omitted (total saline and freshwater MGD = 1,691; 6,401 mld) as are all saline water withdrawals; thermoelectric = 57,900 MGD; 291,175mld. Ground water mining withdrawals = 2,080 MGD; 7,874 mld.

Source: Developed from Tables 5 and 7, p. 12, 14, Solley *et al.* [7].

Table 10: Changes in withdrawals (in MGD; mld) of freshwater (1995–2040), using US Census Bureau 'middle population series' (adapted from Brown [12]).

WRRs	Population 1995 (10^6)	Livestock (MGD; mld)	Domestic and public (MGD; mld)	I&C (MGD; mld)	Thermal (MGD; mld)	Irrigation (MGD; mld)	Income 1995 ($ 10^3)	Percent change (1995–2040) in income
N. Engl.	13.4 (12.8)	7; 27	412; 1,560	−18; − 68	167; 632	−18; −68	22.9	34
M. Atlan.	42.4	39; 148	1,456; 5,512	−208; −787	140; 530	−5; 19	23	37
S. Atl.-G.	37.6 (27.8)	223; 844	2,521; 9,543	807; 3,055	3,936; 14,899	919; 3,479	17.6	42
G. Lakes	23.5 (21.8)	18; 68	866; 3,278	−481; −1,821	185; 700	79; 299	19.9	38
Ohio	21.1 (22.6)	43; 163	593; 2,245	−91; −344	381; 1,424	85; 322	17.0	42
Tenn.	4.3 (4.2)	86; 326	168; 636	87; 329	1,320; 4,997	23; 87	15.6	42
U. Miss.	22.8 (22.3)	84; 318	385; 1,457	−17; −64	742; 2,809	135; 511	18.9	41
L. Miss.	7.3	333; 1,261	298; 1,128	73; 276	262; 992	4,410; 16,694	15.0	45
Souris-R	0.7	5; 19	17; 64	−2; −8	2; 8	51; 193	15.8	42
Missour.	10.3 (10.7)	169; 640	524; 1,984	51; 193	1,100; 4,164	−783; −2,964	18.3	43
AK-W-R	8.7 (8.9)	147; 556	397; 1,502	85; 322	354; 1,340	1,751; 6,628	16.4	47
TX-G.	15.9 (16.8)	91; 344	1,157; 4,380	150; 568	914; 3,460	−1,290; −4,883	18.2	44
R. Grand.	3.1 (2.6)	17; 64	198; 750	23; 87	3; 11	−1,992; −7,541	12.5	45
U. Col.	0.7	31; 117	70; 265	13; 49	38; 143	2,068; 7,828	15.5	44
L. Col.	5.3	28; 106	641; 2,426	145; 549	27; 102	27; 102	17.2	41
G. Basin	2.4	65; 246	353; 1,336	123; 465	9; 34	7; 27	15.7	47
Pac.NW	9.9	804; 3,043	797; 3,017	389; 1,473	1,705; 6,454	−3,718; −14,074	18.2	40
CA	32.3 (32.0)	235; 890	2,306; 8,729	262; 992	100; 379	−1,956; −7,404	21.3	39
Alaska	0.6	0; 0	29; 110	12; 45	12; 45	0; 0	20.9	35
Hawaii	1.2	5; 19	88; 333	9; 34	14; 53	−69; −261	20.5	32
Caribbean	(3.9)	NR	NR	NR	NR	NR	NR	NR
US	(267)	2,430; 9,199	13,275; 50,251	1,411; 5,341	11,411; 43,195	−4,142; −15,679	19.3	39

Note: See Table 5, p. 28, for changes in withdrawals; Table 3, p. 16, for population and income numbers in Brown [12].
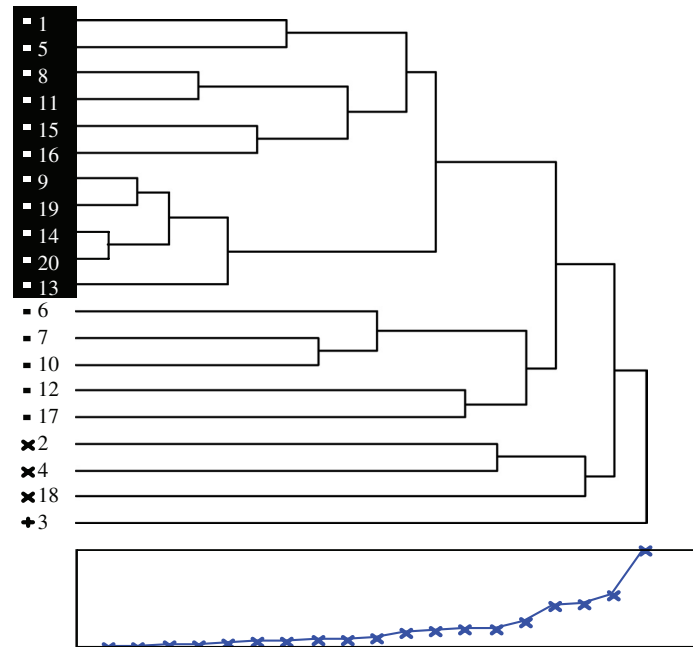
Figure 3: Cluster analysis (data from Table 10).

Table 11: Per capita domestic and public withdrawals, 1995 and projections for 2040.

Measures	Base year 1995	2040 Low	2040 Best guess	2040 High
Gallons per person/ day; lpd/person	121; 458	115; 453	122; 462	134; 507
Domestic and public (BGD; bld)	32; 121	42; 159	45; 170	49; 185
Total US (BGD; bld)	340; 1,287	361; 1,367	364; 1,378	368; 1,393

Source: Table 10, p. 32, Brown [12].

a faster rate, depending on immigration policies and other labor-related considerations. However, if the gap leads to local or regional shortages, infrastructure must be put in place to deal with it.

3 WATER QUALITY

We have selected the data sets that the states and other major jurisdictions provided to the US EPA, under section 305(b) of the Clean Water Act. This data set is homogeneous with respect to the protocols that the states and other jurisdictions have adopted and include the input from a number of stakeholders, such as Indian Tribes. Nevertheless, there are differences in the summaries developed by each jurisdiction and provided to the US EPA, due to changes in the monitoring networks, the number of stations recording from time to time, differences in the methods for assessment, and so on.

Table 12: Potential water withdrawal by sectors, using Lowest (L), Middle (M) and Highest (H) Population Series, US Census Bureau [5] for 2000, 2040, and 2050, in BGD and bld.

Sector (yearly GPCD used; lpd/person)	2000 L	2040 L	2050 L	2000 M	2040 M	2050 M	2000 H	2040 H	2050 H
D&P (122 GPD; 462 lpd)	34; 129	38; 144	38; 144	34; 129	46; 174	49; 185	34; 130	58; 220	67; 253
I&C (134, 106, 106 GPCD; 507, 405, 405 lpd/person)	37; 140	33; 125	33; 125	37; 140	40; 151	43; 163	37; 140	51; 193	59; 223
TE (486, 389, 389 GPCD; 1,840, 1,473, 1,473 lpd/person)	130; 492	120; 454	120; 454	130; 492	150; 568	160; 606	130; 492	190; 719	220; 833
Agri. (491, 354, 354 GPCD; 1,859, 1,340, 1,340 lpd/person)	130; 492	110; 416	110; 416	140; 530	130; 492	140; 530	140; 530	170; 643	200; 757

Notes: D&P = domestic and public; I&C = industrial and commercial; TE = thermoelectric; Agri. = agriculture.

3.1 Surface Water

Earlier results about the quality of US water are available for 1988 (US EPA [14], EPA 440-4-90-003). We limit the discussion to status: *good*, meaning *fully supporting* and *fair*, meaning partially supporting (from the sets of *fully supporting*, *threatened*, *partially supporting*, *not supporting*, and *not attainable* as used by the EPA), for brevity and because two uses (*fully supporting* and *partially supporting*) are often the largest, as percentages. The US EPA's 1988 assessment is based on about 520,000 assessed miles (836,859 km) of rivers (48 jurisdictions), 16,000,000 assessed lake-acres (64,750 km^2) (40 jurisdictions); and 26,700 miles^2 (69,153 km^2) of assessed estuaries (23 jurisdictions). In 1988, the major causes of river pollution were (rank ordered from highest percent of river-miles impacted): silt, nutrients, pathogens such as bacteria, organic matter, metals, pesticides, suspended solids, salinity, flow alterations, habitat modification, pH, and thermal discharges. Table 13 depicts the national aggregate *percentages of impaired waters* aggregated over major, moderate, and minor impacts (US EPA [14], EPA 440-4-90-003).

In 1990 approximately 42% of the assessed water of the United Sates were classified as *good* (*fully supporting*); in 1996 the percentage increased to 55% and, in 1998, the percentage was 70%. In some instances not all uses are given a percentage number in the original sources and, in 1988, data for the oceans shore miles were unavailable. Also, some percentage numbers for a year may have approximately an order or magnitude range (e.g. in 1988, 70% of the rivers and streams were classified as *good*, while only 8% of the shoreline-miles of the Great Lakes were *good*). Because of the variability, non-reported numbers, and other technical considerations relating to taking averages, these averages should be understood as being qualitative and aggregate descriptions only.

Table 13: Summary of percent of US impaired waters 1988 by cause of pollution (%).

	Waters		
	Rivers	Lakes	Estuaries
Silt	42	25	7
Nutrients	27	49	50
Bacteria	19	9	48
Organic enrichment	15	25	29
Metals	11	7	10
Pesticides	10	5	1
Suspended solids	6	8	NR
Salt/oil and grease	6	14	23
Flow	6	3	NR
Habitat modification	6	11	NR
pH	5	5	<1
Thermal/flow alteration	4	3[#]	[#]

Notes: [#]There is no thermal effect reported for lakes.
Percentages are calculated as the sum of the quantities (in miles or acres) of pollution-specific impaired miles or acres divided by the total impaired miles or acres, for all jurisdictions. Lakes are affected by priority organics (8%). Estuaries are affected by priority organics (4%), unknown toxicants (5%) and other inorganics (<1%). Percentages may not add up to 100%.
Source: Developed from EPA 440-4-90-003 [14], Tables A-1, 2-2, and 4-2.

According to the National Water Quality Inventory (1998), the majority of the water bodies in the United States are adversely affected by 'moderate to high levels of agricultural run-off'. Furthermore, about 1/3 of the US waters were characterized by fish advisories leading to no fish consumption; and about 1/5 of the country has high levels of wetland loss. The principal causes of water pollution are agriculture, hydrological changes, urban run-off, construction, resources extraction, and grazing. For 1998, the US EPA has ranked (1 being the highest) the five principal causes of water pollution (US EPA [15], Table 2, p. 9 and Table 4, p. 13; Figs 4, 7, and 13) and EPA [20] Figs 4, 7, 10, 13, and 16; EPA [17] Fig. 5-8, p. 113), as summarized in Table 14.

The situation, as reported towards the end of 1997, is that '16% of the watersheds had slight water quality problems, 36% had moderate water quality problems, 21% had more serious problems, and sufficient data was lacking to characterize the remaining 27%' (US EPA [16], p. 3). Specifically, the 1996 and 1998 results (US EPA [16] Fig. 1, p. 7 and US EPA [20] Fig. 1, p. 5) are shown in Table 15.

The status of the nation's waters, by water body and by selected water uses in 1996, is described in Table 16 (developed from data in US EPA [17, 20]).

Table 17 was developed from water quality data from the US EPA [20] to summarize the percent of water uses supported and the degree of support, for 1998.

In 1998 (US EPA [20], EPA 841-S-00-001), from the states' reporting of their rivers' water quality the results are that for the 23% of the rivers and stream assessed, 55% of those waters are rated *good*, 10% is rated *good but threatened*, and 35% is *impaired*. Of the 42% of the lakes, reservoirs and ponds assessed, 46% are *fully supporting all uses*, 9% are *fully supporting but threatened*, and 45% are *impaired*. Approximately 32% of the US estuaries have been assessed, and 47% are *fully supporting*, 9% are *fully supporting but are threatened* and 44% are *impaired*. The situation for the shores of the Great Lakes, 90% assessed, only 4% are fully supportive of all uses, and 96% is impaired.

The 1996 and 1998 water quality of estuaries of the nation as a whole appears to be relatively good, as depicted in Table 18.

The Great Lakes region of the United States was approximately fully surveyed (96% of about 5,500 miles). However, the geometric average of the fully supporting (*good*) water use (for six uses) is 35% (range 2–96%), the partially supporting (*fair*) is 6% (range <1–34%) and the not supporting (*poor*) status averages 22% (range 0–64%). (Data from US EPA [15], EPA 841-R-97-008, p. 312, Fig. 12-4, p. 316.) However, within these numbers, there are significant impairment: aquatic life support and fish consumption are poor (not supporting) in about 63% of the miles surveyed.

The latest nationwide data on water quality that are consistent with the data shown previously are those available for 2002 [21]. Consistent with the reporting used by the EPA in 2002, we use three descriptors: *Good*, *Impaired*, and *Threatened*. We summarize the results as distributions ($n = 47$ jurisdictions, mainly the states that have reported to the US EPA including Alaska under the Clean water Act, section 305(b), excluding territories, other jurisdictions, and North Carolina and Washington; we include the arithmetic mean and the standard deviation, SD) in Table 19.

The leading sources of water pollution affecting these assessments include atmospheric depositions, discontinued discharges from pipes, contaminated sediments, land disposal of waste, unspecified non-point sources, various point sources, urban runoff, and storm sewers. The major pollutants include priority toxic chemicals, organic chemicals, pesticides, non-priority organic chemicals, nutrients, metals, endocrine disruptors, and oxygen-depleting substances.

3.2 Ground water

Because of the differences an 'evaluation of ground water quality data is not possible' (US EPA [16], EPA 816-R-98-011, p. 24). Nevertheless a qualitative understanding of the ground water situation

Table 14: Ranking of principal sources of water pollution by cause.

Rank of causes of pollution	Rivers (% impaired)	Lakes (% impaired)	Estuaries (% impaired)	Ranking of major sources of pollution	Impaired Great Lakes shoreline miles (1998), leading pollutants (total miles = 4,950); major sources of pollution
1	Siltation (18%)	Nutrients (20%)	Nutrients (22%)	1. Agriculture	Priority toxic chemicals (28%), 1,391 miles; atmospheric deposition
2	Nutrients (14%)	Metals (20%)	Bacteria (16%)	2. Point and non-point sources	Pesticides (22%), 1,017 miles; discontinued discharges from pipes
3	Bacteria (12%)	Siltation (10%)	Priority toxic organic, chemicals (15%)	3. Municipal point sources	Nonpriority organic (22%), 1,017 miles; contaminated sediments
4	Oxygen-depleting substances (10%)	Oxygen-depleting substances (8%)	Oxygen-depleting substances (12%)	4. Upstream sources discharges	Nutrients (5%), 234 miles; industrial
5	Pesticides (7%)	Noxious aquatic plants (6%)	Oil and grease (8%)	5. Agriculture	Pathogens (4%), 186 miles; urban runoff

Note: EPA [17], Fig. 5-8, p. 113 indicates that 90% of the total 5,521 shoreline miles of the Great Lakes were assessed, of that 90% 96% were *impaired* and 4% *good.*

Table 15: Extent of US waters assessed and surveyed, 1996 and 1998 (reported in 1998 and 2000).

Rivers and streams	Total miles: 3,634,152; 5,848,6001 km	(1996) Miles surveyed: 693,505; 1,116,088 km	(1998) Miles assessed: 842,426; 1,355,753 km
Lakes, ponds, reservoirs	Total acres: 41,684, 902; 168,693 km^2	(1996) Acres surveyed: 16,819,769; 68,067 km^2	(1998) Acres assessed: 17,390,370; 70,376 km^2
Estuaries	Total mi^2 39,839; 103,183 km^2	(1996) mi^2 surveyed: 28, 819; 74,641 km^2	(1998) mi^2 assessed: 28,687; 74,300 km^2
Ocean shoreline waters	Total miles: 58,585; 94,283 km	(1996) Miles surveyed: 3,651; 5,876 km	(1998) Miles assessed: 3,130; 5,037 km
Great Lakes shorelines	Total miles: 5,521; 8,885 km	(1996) Miles surveyed: 5,186; 8,346 km	(1998) Miles assessed: 4,950; 7,966 km

Note: The EPA has used different terms (surveyed and assessed) in its reports.

Table 16: 1996 Percentage of individual uses supported by use (Developed from US EPA [15], EPA841-R-97-001).

Use supported	Rivers and stream Good (%)	Fair (%)	Lakes, ponds & reservoirs Good (%)	Fair (%)	Estuaries Good (%)	Fair (%)	Great Lakes Good (%)	Fair (%)	Ocean shorelines Good (%)	Fair (%)
Aquatic life	60	23	55	25	61	27	12	9	91	3
Fish consumption	84	14	60	32	75	22	2	34	91	5
Swimming	76	10	63	21	83	15	96	3	82	5
Secondary contact	78	16	62	23	76	22	96	4	93	5
Drinking water supply	79	19	81	7	NA	NA	98	<1	NA	NA
Shell-fishing	NA	NA	NA	NA	69	16	NA	NA	84	6
Agriculture	93	3	84	10	NA	NA	89	11	NA	NA

Note: Good is *fully supporting* and fair is *partially supporting*.
Source: US EPA [15], Tables 2-3, 3-3, 4-3, 4-8, and 12-4.

for 1996 (developed from US EPA [16], EPA 816-R-98-011, Table 1, p. 24, 25 and US EPA [17], EPA 841-R-00-001, Table 7-1, p. 170, 171), based on 162 aquifers and other hydrological units in 29 states (26 states in 1998, shown in parentheses) is depicted in Table 20.

Ground water quality is determined from finished water from public water supply wells, PWS wells, (61%), untreated water from PWS wells (24%), monitoring networks (52%), untreated water from private wells (36%), special studies (6%), and facility monitoring wells (EPA 816-R-98-011 [16], p. 34, 35, 36, 37, and Fig. 19, p. 32). The water quality parameters include nitrate, VOC, SVOC, bacteria, pesticides ionizing radiation, a number of metals, inorganic compounds, TDS, hardness,

Table 17: 1998 Percentage of individual water uses supported by use (Developed from US EPA [20], EPA 841-S-00-001).

Use supported	Rivers and stream		Lakes, ponds & reservoirs		Estuaries		Great Lakes		Ocean shorelines	
	Good (%)	Fair (%)	Good (%)	Fair (%)	Good (%)	Fair (%)	Good (%)	Fair (%)	Good (%)	Fair (%)
Aquatic life	58	20	58	23	54	29	36	12	87	4
Fish consumption	87	5	54	35	63	34	4	29	84	10
Swimming	69	11	69	15	88	5	97	2	80	8
Secondary contact	76	14	78	10	81	15	99	1	93	5
Drinking water supply	87	6	82	9	NA	NA	98	0	NA	NA
Shell-fishing	NA	NA	NA	NA	70	14	NA	NA	89	11
Agriculture	97	2	89	3	NA	NA	100	0	NA	NA

Note: Good is *fully supporting* and fair is *partially supporting*.
Source: US EPA [20], Figures 3, 6, 9 12, and 15.

Table 18: 1996 and 1998 percent of individual use support in US estuaries (developed from US EPA [15] EPA 841-R-97-008 and US EPA [17] EPA 841-R-00-001).

Use (mi^2 surveyed), 1996 and 1998	Good (full support) (%), 1996 and 1998	Fair (partial support) (%), 1996 and 1998	Poor (not supporting) (%), 1996 and 1998
Aquatic life support, 23,921 and 22,447	61 and 54	27 and 29	3 and 5
Fish consumption 15,821 and 15,260	75 and 63	22 and 34	2 and 1
Shell-fishing, 16,821 and 18,212	69 and 70	16 and 14	12 and 13
Swimming, 24,087 and 21,214	83 and 88	15 and 5	1 and 4
Secondary contact, 14,086 and 10,503	76 and 81	22 and 15	2 and 1
Geometric average	72 and 70	20 and 16	3 and 3

Note: The row percentages may not add to 100 because *good* (threatened) and *poor* (not attainable) are not included in this Table; mi^2 means square miles.
Sources: Adapted from EPA 841-R-97-008 [15], Fig. 4-3, p. 60 and EPA 841-R-00-001 [17] Fig. 5-2, p. 105.

Table 19: Aggregated water quality for the United States, 2000 (overall usability as a percent of *assessed* water, for 47 States).
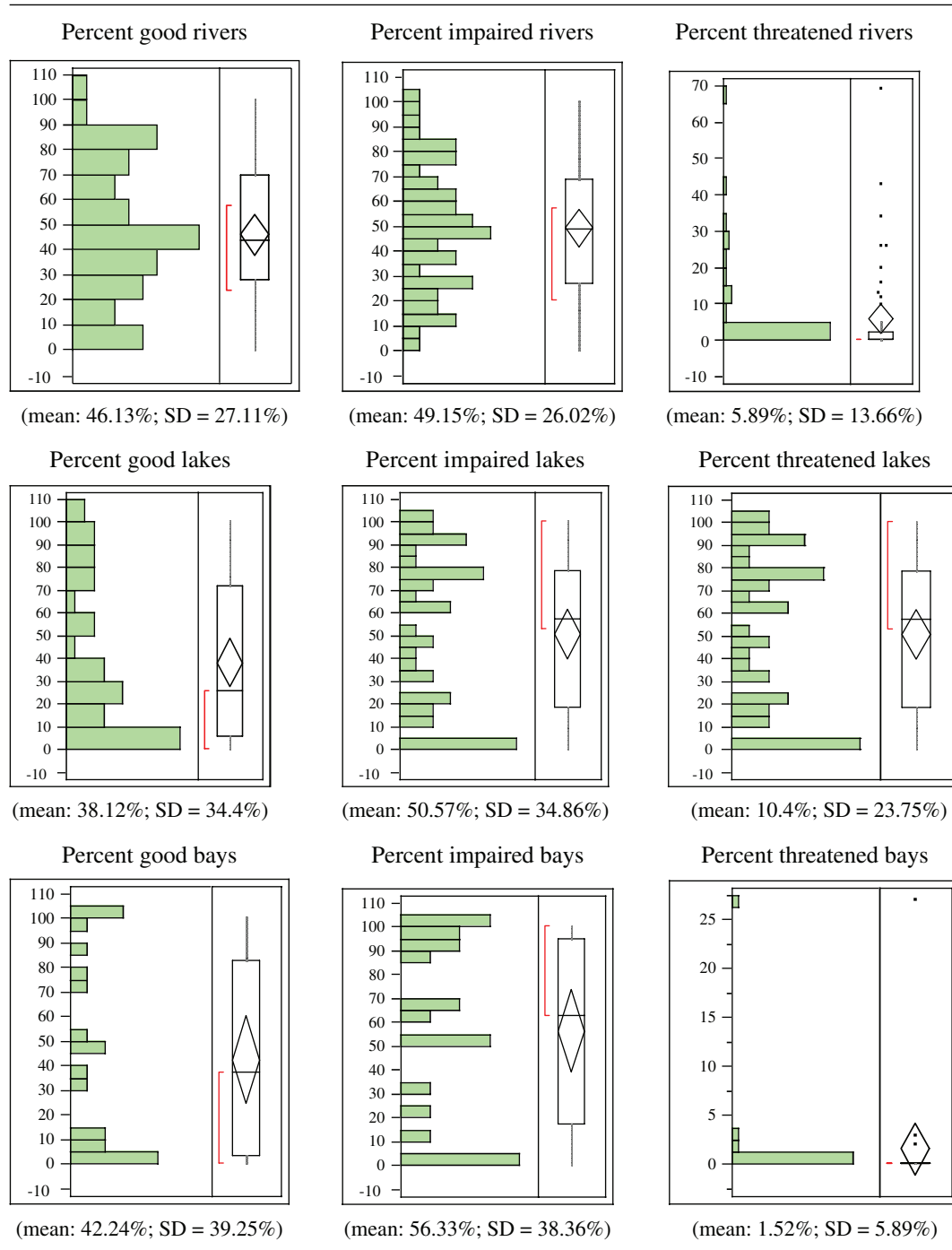

Percent good rivers
(mean: 46.13%; SD = 27.11%)

Percent impaired rivers
(mean: 49.15%; SD = 26.02%)

Percent threatened rivers
(mean: 5.89%; SD = 13.66%)

Percent good lakes
(mean: 38.12%; SD = 34.4%)

Percent impaired lakes
(mean: 50.57%; SD = 34.86%)

Percent threatened lakes
(mean: 10.4%; SD = 23.75%)

Percent good bays
(mean: 42.24%; SD = 39.25%)

Percent impaired bays
(mean: 56.33%; SD = 38.36%)

Percent threatened bays
(mean: 1.52%; SD = 5.89%)

Table 20: Number and Sources of Ground Water Contamination in the US, 1996 and (1998).

Sources of contamination	Number of sites	Sites listed and/or with confirmed releases	Sites with confirmed ground water contamination	Sites with completed cleanup
Leaking UST	100,921 (85,067)	40,363 (48,320)	17,827 (15,436)	19,379 (21,438)
UST sites (no releases found)	2,210 (NR)	NA (NR)	NA (NR)	NA (NR)
Septic systems	10,656 (NR)	10,594 (NR)	NA (NR)	NA (NR)
State sites	7,017 (12,202)	5,751 (6,199)	2,614 (3,139)	3,166 (3,242)
Underground injections	5,006 (31,480)	1,077 (1,313)	911 (172)	204 (425)
CERCLIS (CERCLA, non-NPL)	2,399(3,506)	1,332 (1,381)	645 (802)	49 (316)
RCRA corrective action	2,114 (2,696)	283 (538)	289 (267)	52 (67)
DOD and DOE	404 (8,705)	234 (4,470)	166 (286)	39 (1,937)
Miscellaneous	229 (NR)	905 (NR)	514 (NR)	32 (NR)
Non-point sources	171 (2,030)	190 (44)	62 (31)	36 (3)
National priority list	167 (307)	250 (275)	204 (249)	24 (33)
Landfills	149 (1,356)	78 (110)	74 (110)	0 (NA)
wastewater land application	116 (NR)	NA (NR)	24 (NR)	0 (NR)

CERCLIS = Comprehensive Environmental Response, Compensation, and Liability Information System; NA = not available; NR = not reported; RCRA = Resource Conservation and Recovery Act; UST = underground storage tanks.

specific conductivity, alkalinity, nutrients, and so on. Table 21 is a summary of water wells impacted and the rank-ordering of the most significant ground water pollutants, in 1998, at the national level, based on the reporting states.

3.3 Comment

Our analyses are at a higher level of detail than the analyses reported by Oki and Kanae [22]. In particular, we do not use hydrological indices, such as the water scarcity index, R_{ws}, in part because this index is limited by its components (namely, annual water withdrawals, desalinated water, and circulating renewable freshwater) and thus does not account for water quality and for sectoral water withdrawals. Although indices are essential for global comparisons, we believe that the summaries we present in this paper (as well as the more detailed assessments by Ricci and Ricci [23] and Roy *et al.* [24]) are of sufficient specificity to form a dynamic baseline for planning and for assessing sustainability of water uses in the future. A rough comparison of the results reported by Oki and Kanae [22] for US jurisdictions suggests that the R_{ws} for the West is between 0.2 and 1.0; for the East, it is between 0.01 and 0.2.

Table 21: Wells with number of MCL exceedances (number of states reporting exceedances/total number of states reporting) Rank-ordered by importance (I highest).

Monitoring type	I. Nitrates	II. VOCs	III. SVOCs	IV. Pesticides	V. Metals	VI. Bacteria
Networks	267 (8/15)	30 (7/10)	5 (3/7)	5 (2/8)	195 (7/11)	10 (1/3)
PWS untreated water	85 (5/7)	77 (5/6)	10 (3/4)	2 (1/2)	100 (2/2)	1 (1/1)
Private untreated water	2,233 (9/10)	96 (2/3)	4 (1/3)	101 (4/5)	113 (1/1)	0 (0/1)
PWS finished water	230 (11/18)	152 (6/17)	18 (3/14)	0 (0/1)	175 (4/6)	404 (3/3)
Special studies	309 (2/2)	19 (1/1)	0 (0/0)	0 (1/1)	0 (0/0)	101 (1/1)

Notes: The maximum concentration levels, MCLS, for individual constituents of VOCs, SVOCs, metals, pesticides and bacteria are omitted for brevity's sake. The MCL for nitrates is 10 mg/l of water.
Source: Tables 3 through to 8, EPA 816-R-98-011 [16], pages 34 though to 39.

By way of interpretation, a $R_{ws} > 0.47$ suggests 'highly water stressed' areas. Elsewhere [24] we have used two water indices with more dimensions than a purely hydrological index, and predicted water scarcity or shortages for the United States, at the county level, to approximately 2025, using the coefficient method. In that work, we did not use the IPCC projections, but relied on the US Census Bureau population predictions to assess future water uses. In this work, we focus on existing data, rather than on predictions as those predictions may be greatly affected by geopolitical factors and technologies that are difficult to account for explicitly. Additionally, the impact of climate change on the dynamic baseline we have developed is implicit in the numbers used and is least variable and uncertain relative to prediction for 2050 and 2075 (Oki and Kanae, [22], Fig. 3, Panels A and B). This is not to say that the effects of anthropogenically induced climatic changes are unimportant; quite the opposite: we think that because '[t]he effect of climate change on the hydrological cycles are still uncertain' [22], a semi-quantitative dynamic baseline is essential for water resources planning and management and to assist in meeting the desiderata of sustainability of water uses. In particular, we concur with these authors (p. 1071), who state that 'Climate change is expected to accelerate the global hydrological cycles, and precipitation will increase on average. Evapo-transpiration will not increase as much as precipitation globally because elevated CO_2 … reduces evapo-transpiration, and river discharge will increase'.

4 FACTORS AND FUNCTIONS RELATING TO WATER QUALITY AND QUANTITY
The *factors* that affect the predictions of water supply, demand, and quality include:

- Pollution
- Droughts, as increases in frequencies and magnitudes
- Floods, as increases in frequency and magnitude
- Excess water availability, restrictions to access to clean water
- Trans-boundary transfers of water
- Pollution control costs
- Water treatment, including desalination, and other infrastructure

- Investment costs and timing
- Ecosystems at special risk
- Rehabilitation/restoration of degraded areas
- Food-crop management
- Capacity building for energy supply
- Local, regional, and global climate changes
- Biotechnology applied to crops, livestock, and other uses of crops
- Use of low water consumption crops
- Population growth in urban areas
- Sanitation
- Irrigation changes and efficiencies
- Demand-side management and full pricing of water-related services
- Energy supply and cost

There also are *functions* that can affect the supply and demand of water; these include:

- Water use conflicts and their resolution
- International effects and implications of non-water-related events
- Policy changes and effects of immigration, employment, subsidies, taxes, or other policies, and
- Changes in the structure of the US economy *and* in its international partners or competitors

   Examples of factors and function, with the ability to reduce water demand and environmental impacts, include:

- Reduced water withdrawals to reduce impact on fish and wildlife, tourism, and navigation
- Reduced water consumption by applying electro-technologies to treat incoming water, reused water, and outgoing wastewater
- Reduced water consumption through operating practices (e.g. water pinch analysis) that streamline the water quality needs (e.g. temperature, chemistry) from one point in a water distribution system to another
- Reduced irrigation withdrawal making more water available to other sectors
- Adoption of economic instruments in the context of increasing water quality, and
- Recharging depleted groundwater aquifers with re-used water.

5 CONCLUSIONS

The water situation for the United States is dynamic and is affected by national and international trade, environmental treaties, and conventions (for example NAFTA, Climate Change Treaty, the Kyoto Convention), demographic factors, environmental and energy-related changes, as well as changes in technology, laws, and regulations. The data that we have developed suggests a complex mix of short- and long-term water variability and that structural changes in the (regional and national) economy and socio-economic shifts (such as ageing population) are linked in ways that probably cannot be meaningfully modeled, other than in semi-quantitative ways. The overall description that we have obtained is qualitative: it suggests a relatively good supply of water of good quality *from small deviations from the status quo*. For example high water prices will occur if the population increases at rates approximating the 'high' Census predictions and if, concomitantly, international demands for US agricultural products change. These increases can affect large segments of the population inequitably. We are also concerned by the potential regional impacts of long-term climate change on the total water picture for the United States. The picture may not be quite as optimistic as some of the predictions discussed suggest.

The difficulties we have encountered are principally data availability and methodological. We have not studied the national and international institutional, legal, and political aspects of water management, including using economic instruments to control water pollution and their contribution to optimal water resources pricing. Although these impacts are not included in the projections and water budgets reviewed and used in this work, we have developed an information base that can be augmented by these considerations. For example the international demand for agricultural and other US products that strongly depend on water quality and quantity are indirectly accounted for in the water budget and predictions; they should be further assessed relative to future economic changes in the international markets supply and demand. Thus, the agricultural sector is represented in the analyses; however, if the international markets were to deviate significantly from the baseline of the water predictions shown in this work, regional water budget will change accordingly. Understanding local or regional vulnerability of water supply requires a consistent and integrated effort based on empirical and theoretical work necessarily based on modeling. Because of the diversity of jurisdictions, methods used to determine water quality, and changes in both, no between-jurisdictions comparison should be made.

The water quality and quantity monitoring data available to provide the empirical basis for future analyses should be coupled with databases that describe socio-economic, land use, urbanization, ecosystem degradation, and demographic changes. Policy choices affecting water must be resilient to sudden changes and account for the adaptability of ecological systems and the potential for technological innovations, including the potential for unexpected events and outcomes, or responses by stressed systems. Whether or not the overall quality of US waters will approach the 100% *good* water quality is difficult to assess but, qualitatively, the overall indications are positive. However, optimisms must be tempered by at least three strong assumptions: (1) regional and global climatic changes will be coped with successfully, (2) the economy will have a rate of growth consistent with its population and productivity growth, and (3) no major catastrophic, either man-made or natural, events will occur in those years.

CONVERSION FACTORS

Gallons per day (GPD) = 3.785 liters per day
Million gallons per day (MGD) = 1.121 thousand acre-feet per year
1 million gallons (1 MG) = 3.07 acre-feet
1 acre-foot = 325,851 gallons
Thousand acre-feet per year = 0.8921 MGD
1 cubic foot = 7.48 gallons
1 inch of rain = 17.4 million gallons per square mile
1 inch of rain = 27,200 gallons per acre

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