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Dam nation: A geographic census of American dams and their large-scale hydrologic impacts

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Abstract. Newly available data indicate that dams fragment the fluvial system of the continental United States and that their impact on river discharge is several times greater than impacts deemed likely as a result of global climate change. The 75,000 dams in the continental United States are capable of storing a volume of water almost equaling one year's mean runoff, but there is considerable geographic variation in potential surface water impacts. In some western mountain and plains regions, dams can store more than 3 year's runoff, while in the Northeast and Northwest, storage is as little as 25% of the annual runoff. Dams partition watersheds; the drainage area per dam varies from 44 km^2 (17 $miles^2$) per dam in New England to 811 km^2 (313 $miles^2$) per dam in the Lower Colorado basin. Storage volumes, indicators of general hydrologic effects of dams, range from 26,200 m^3 km^{-2} (55 acre-feet $mile^{-2}$) in the Great Basin to 345,000 m^3 km^{-2} (725 acre-feet $mile^{-2}$) in the South Atlantic region. The greatest river flow impacts occur in the Great Plains, Rocky Mountains, and the arid Southwest, where storage is up to 3.8 times the mean annual runoff. The nation's dams store 5000 m^3 (4 acre-feet) of water per person. Water resource regions have experienced individualized histories of cumulative increases in reservoir storage (and thus of downstream hydrologic and ecologic impacts), but the most rapid increases in storage occurred between the late 1950s and the late 1970s. Since 1980, increases in storage have been relatively minor.

1. Introduction

Dams have segmented most rivers in the Northern Hemisphere with associated large-scale environmental disruption [*Dynesius and Nilsson*, 1994]. In the United States the interspacing of dammed, drowned, preserved, and restored reaches has fragmented every large river by disconnecting once integrated free-flowing systems [*Graf*, 1992]. Dams have provided valuable services such as irrigation capabilities, hydroelectric power, improved navigation, some flood protection, and expanded recreation opportunities. However, unexpected costs associated with dams, such as undesirable changes in downstream ecosystems, have become apparent [*Hunt*, 1988]. Some detailed, localized investigations have explored downstream impacts of dams, including investigations on the Colorado River [*Carothers and Brown*, 1991; *U.S. Bureau of Reclamation*, 1995], and the Trinity River of California [*U.S. Senate*, 1992; *Pitlick*, 1992]. Trade-offs between economic and environmental benefits and costs of dams have led to the retirement of many small structures and plans for the removal of some large ones [*Task Committee on Guidelines for Retirement of Dams*, 1997]. However, general statements about the fragmentation of rivers and the large-scale hydrologic consequences of dams at a national scale are not available. The purpose of this report is to provide perspective, background, and context for investigations and decision making for individual dams and rivers by using new data to answer the following questions. In the United States, how many dams are there and what is their size distribution? What is the geographical distribution of dams with respect to natural and human contexts? What are the magnitude and distribution of likely impacts of dams on the surface water component of the hydrologic cycle at the national scale?

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2. Data and Methods

Newly available data make it possible to address these questions from a quantitative perspective that heretofore has been impossible. In response to the federal Dam Safety Act of 1972 (PL 92-367) and the Water Resources Development Act of 1982 (PL 99-662), the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) collated location and other information to track engineering safety evaluations of all dams in the United States that meet certain criteria [*U.S. Army Corps of Engineers*, 1996]. The resulting database, the National Inventory of Dams, includes all dams of environmental consequence: those that are greater than 2 m (6 feet) high with more than 61,700 m^3 (50 acre-feet) of storage, those that are greater than 8 m (25 feet) high with more than 18,500 m^3 (15 acre-feet) of storage, and those of any size that pose a significant downstream threat to human lives or property. There are likely to be a substantial number of dams that are smaller than those included in the National Inventory of Dams, but they are not likely to store large amounts of water or sediment compared to the larger structures. Data presented below show that although small structures are numerous, their cumulative storage pales in comparison with the cumulative storage of large dams. In any case, there is no accurate accounting for dams that are smaller than those considered in this analysis.

Although USACE and FEMA collected the data for administrative purposes, the data are also useful for investigating the distribution of the structures and the potential large-scale effects they might have on the hydrologic environment. The

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database characterizes about 75,000 dams, but there are some errors and omissions in the data that limit their accuracy in geographic or hydrologic assessments. Review of individual records shows that any calculations using the data set are likely to contain errors of up to 4%. USACE and FEMA are continuing to update the database and improve its quality, with revisions planned within 2 years.

USACE and FEMA assembled the data for administration and legal purposes and organized the database by states, counties, and congressional districts. Evaluation of the hydrologic effects of the dams requires reassembly of the data into a watershed-based framework so that each dam may be seen as part of a naturally defined system. The most commonly used large-scale, watershed-based regions of the United States are water resource regions, 21 areas that are either large river basins or contiguous smaller basins with common characteristics [*Seaber et al*., 1987]. The investigations reported here pertain to the 18 regions that constitute the continental United States (Figure 1a; Table 1). This report does not include Alaska (97 dams), Puerto Rico (35 dams), Hawaii (132 dams), or island trust territories (2 dams) because these areas are not part of the continental American river system.

In the following report, the potential reservoir storage created by the dams is a measure of their hydrologic impact. Storage of surface water as part of the hydrologic cycle occurs naturally in lakes, but the imposition of artificial reservoirs changes the storage and through-put of surface flow, with additional changes resulting from evaporation and seepage losses. Larger numbers and sizes of reservoirs have potentially greater impacts. The precise measurement of these effects awaits further research, but, in general, the amount of reservoir storage in a given watershed provides a relative measure of the likely changes in flow regimes and associated downstream effects.

3. Dam Census

Using the congressionally mandated FEMA definition for dams, there are 75,187 such structures in the entire United States, 74,921 of which are in the continental United States. Dams are a ubiquitous feature of the American hydrologic system, and all watersheds in the nation larger than about 2000 km^2 (750 $miles^2$) have some dams. Although the Yampa River of Colorado, Virgin River of Utah, Upper Yellowstone of Montana and Wyoming, and Middle Fork of the Salmon are commonly cited as "undammed," their watersheds contain scores of small structures in tributaries. These small structures affect the hydrologic behavior of these systems to some degree and exert local influences on riparian environments of small streams by changing the natural regimes of tributary flows.

Most of the dams in the nation are small, but most of the storage is associated with a limited number of large structures (Figure 2). Those dams creating reservoirs of greater than 1.2×10^9 m^3 (1×10^6 acre-feet) account for only 3% of the total number of structures, but they account for 63% of the total storage. The large structures are therefore the ones most likely to have the greatest aggregate effects on downstream rivers and riparian ecosystems. Small dams are numerous, but their aggregate effect is likely to be small except in highly localized contexts. The numbers and storage potential of the very large dams include 12 structures in lowland Florida where storm protection works and transportation lines built on low berms create potential impoundments of more than 9.6×10^9 m^3 (8×10^6 acre-feet). Though perhaps not considered to be dams in the traditional sense, the hydrologic and ecologic functions of these structures are the same as dams. The data in this general accounting do not include the largest "reservoir" in the nation: storage of 11.6×10^{12} m^3 (9.7×10^9 acre-feet) potentially added to Lake Superior by the 5.3 m (17 feet) high Soo Compensating Works associated with the locks at Sault Ste. Marie, Michigan.

4. Geographic Distribution of Dams and Impacts

Initial review of the database by USACE and FEMA revealed that of the nation's 3043 counties, Worcester County, Massachusetts, has the greatest number of dams, 425. Of the 50 states, Texas has the greatest number of dams, 6801. Partitioning the data according to political jurisdiction meets the administrative needs of federal and state agencies, but it is not informative from a hydrologic standpoint. Assessment of the geography of dams according to water resource regions, river basins, or aggregates of similar basins provides more insight to the potential effects on natural processes. Within this watershed framework, the density of dams and the fragmentation they cause in the hydrologic system are decidedly unequal across the continental United States (Figure 1b; Table 1). The greatest density of dams occurs in east coast and southeastern areas. The New England Water Resource Region has the highest density, 0.015 dams km^{-2} (0.059 dams $mile^{-2}$), a legacy of the region's long history of mill dams. The structures partition New England watersheds into units averaging about 44 km^2 (17 $miles^2$).

The ratios of the storage capacities of dams to the areas of their watersheds are gross measures of the potential magnitude of potential change in rivers flows, and by implication the ratios measure potential for ecologic disruption (Figure 1c; Table 1). Those regions with high storage capacity/drainage area ratios experience the greatest changes. The highest ratios, and thus the greatest segmentation or fragmentation, occur in the California, Texas-Gulf, and South Atlantic-Gulf water resource regions. The highest ratio of storage to drainage area, 345,000 m^3 km^{-2} (725 acre-feet $mile^{-2}$), is in the South Atlantic-Gulf Region, partly because of numerous low structures in Florida where the National Inventory of Dams shows that many of the largest impoundments of the region potentially store large volumes of water in the low-relief landscape.

Another, perhaps more informative measure of the potential impact of dams on the nation's large-scale hydrologic processes is a within-basin comparison of the amount of reservoir storage to mean annual runoff. Although runoff varies from year to year, long-term averages provide a basis for general analysis [*van der Leeder et al*., 1990]. The national total storage capacity of about 1300 km^3 (10^9 acre-feet) is somewhat less than the mean annual runoff of about 1700 km^3 (1.4×10^9 acre-feet), but this aggregate value masks substantial regional variation (Figure 1d; Table 1). In the upper Midwest and Northeast, the ratios of storage to runoff range from 0.25 to 0.37 years; that is, storage is only about a quarter to a third of annual runoff. At the opposite extreme are the Rio Grande and Upper Colorado basins, where dams potentially store three to four times the mean annual runoff. The Great Plains, Rocky Mountains, and the arid Southwest have the highest ratios and are therefore most likely to experience the greatest changes in river discharges as a result of dams.

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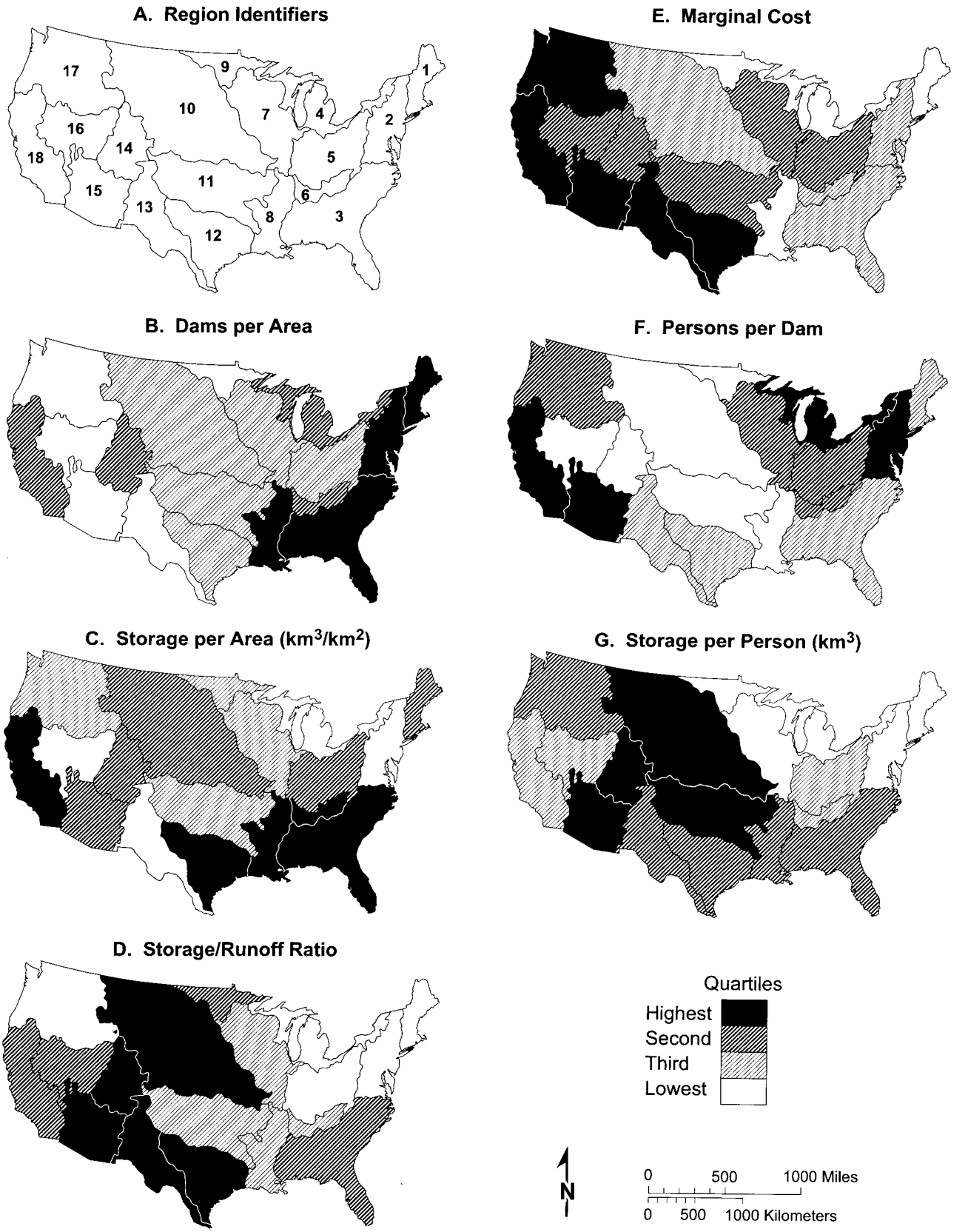

Figure 1. All distributions mapped as quartiles of the 18 water resource regions or 48 states of the continental United States; see Table 1 for specific values and notes: (a) water resource regions, essentially river basins or groups of basins, numbers for which are keyed to column 1 of Table 1, (b) dams per unit area (dams km^{-2}), (c) reservoir storage per unit area of the entire region (m^3 km^{-2}), (d) ratio of reservoir storage divided by mean annual runoff, (e) marginal cost of water (\$ m^{-3}), (f) number of persons per dam, and (g) reservoir storage capacity per person (km^3).

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Table 1. Regional Dam, Hydrologic, and Economic Data

		Area/Dam		Storage/Area			Marginal Cost[c]			Storage/Person	
	Dams[a]	km^2	mi^2	$10^3 \times$ m^3 km^{-2}	ac ft mi^{-2}	Storage/Runoff,[b] years	\$ m^{-3}	\$ (ac ft)$^{-1}$	Persons Dam,[d] persons	m^3 pr^{-1}	(ac ft) pr^{-1}
1. New England	3,789	43	17	201.5	423	0.26	0.003	4	3,391	2,579	2.09
2. Mid-Atlantic	4,709	61	24	83.3	175	0.25	0.020	25	9,007	566	0.46
3. South Atlantic-Gulf	13,705	53	20	345.8	725	0.92	0.010	12	2,761	6,592	5.34
4. Great Lakes[e]	2,075	223	86	66.3	139	0.35	0.006	7	10,523	1,402	1.14
5. Ohio	4,796	87	34	151.2	317	0.37	0.025	31	4,719	2,788	2.26
6. Tennessee	615	171	66	217.8	457	0.40	0.011	14	6,826	5,484	4.43
7. Upper Mississippi	4,318	110	42	111.5	234	0.59	0.024	30	5,157	2,377	1.93
8. Lower Mississippi[f]	3,813	71	27	223.7	469	0.90	0.006	8	1,921	8,227	6.67
9. Souris	398	393	152	112.6	236	2.06	0.025	1	1,741	25,381	20.57
10. Missouri	16,957	90	35	149.1	313	2.51	0.011	13	629	17,605	14.27
11. Arkansas	8,284	81	31	143.7	301	0.72	0.025	31	1,078	10,741	8.70
12. Texas-Gulf	5,434	90	35	256.2	538	2.28	0.052	64	3,083	7,367	5.97
13. Rio Grande	716	480	185	75.6	159	3.83	0.155	191	3,584	10,106	8.19
14. Upper Colorado	1,164	250	96	197.1	414	3.08	0.026	32	613	80,132	64.94
15. Lower Colorado[g]	446	810	313	165.7	348	2.55	0.099	122	11,924	11,225	9.10
16. Great Basin	803	452	174	26.3	55	1.17	0.031	38	2,995	3,068	2.49
17. Pacific Northwest	2,048	351	136	139.5	293	0.35	0.045	55	4,857	10,081	8.17
18. California	1,530	250	96	239.6	503	1.02	0.041	51	20,954	2,855	2.31
Weighted mean[h]		217	84	169	355	1.57	0.032	39	4,696	11,586	9.01

See Figure 1a for locations of regions; calculations made carrying all digits, reported in rounded form. Here, mi, miles; ac ft, acre-feet; \$, dollars; pr, person.

[a]Total for all regions in continental U.S. is 74,921; column sum contains 0.9% error as a result of data and processing errors.

[b]Mean annual runoff estimates by U.S. Geological Survey and Water Resources Council [*van der Leeder*, 1990, p. 70].

[c]Marginal cost calculations from Resources for the Future, Inc., data [*Frederick et al*., 1997].

[d]Population data from 1990 census, partitioned by *Solley et al*. [1998].

[e]Storage excludes elevated level of Lake Superior created by locks on St. Mary River, Sault Ste. Marie, Michigan.

[f]Does not include inflow from upper basin; no dams on the main stem of the Lower Mississippi River.

[g]Includes inflow from upper basin, includes dams on the main stem of the Lower Colorado River.

[h]Mean values weighted according to regional percentages of the sum of all 18 regions.

Because of their storage, dams change river discharges in the United States to a much greater degree than any adjustments anticipated from global climate change for the near future. While some predictions indicate that climatic adjustments may cause changes of 15–20% in annual water yield with modest changes in flood magnitude and frequency [*Waggoner*, 1990; *Tegart et al*., 1990; *Watson et al*., 1996], dams in many regions already have storage capacities greater than the regions' annual runoff, and reduce downstream flows by almost 100%. When dams release water, they often do so at times and rates that are different from natural rhythms. Water losses through evaporation and seepage, combined with larger losses through consumptive diversions, reduce the total amount of water released. In some rivers, dams have changed sediment throughput and radically reduced the frequency of floods or completely eliminated them, with the effects reaching hundreds (or in the case of the Mississippi system) thousands of kilometers downstream [*William and Wolman*, 1984; *Collier et al*., 1997]. Dams store much of the sediment that enters their reservoirs, disrupting the movement of these materials through previously integrated river systems [e.g., *Trimble and Bube*, 1990]. The exact hydrologic effects of global climate change remain speculative, but the effects of dams are real, measurable, and susceptible to management.

Dams and the water they store are intimately bound up with the economic fabric of the nation, but the marginal cost of water is variable across the country (Figure 1e; Table 1). Marginal cost is the cost of supplying an additional increment of water to consumers. It is a measure of economic efficiency reflecting the influences of hydroclimate and human infrastructure. Marginal costs are lowest in regions with abundant water: the northeastern tier of regions and the Lower Mississippi. Despite massive infrastructure investments and attendant environmental costs in the southwestern regions, areas continue to exhibit the highest marginal water costs.

The relationship between the nation's population and its dams also exhibits a distinct geographic pattern. Water resource regions with large populations compared to the number of dams are in the upper Midwest and Southwest (Figure 1f). These regions are either well watered and therefore do not require large numbers of dams (such as the upper Midwest) or simply have large populations (California) or very few dams (Arizona). The relationship between population and reservoir storage presents a very different distribution (Figure 1g). In total, American dams potentially store 5000 m^3 (4 acre-feet) of water per person, but regional volumes of storage per person are particularly high in states of the northern Great Plains, Rocky Mountains, and Southwest. In many cases the reservoirs in these regions are exceptionally large, sometimes storing water for export to other regions, or generating hydroelectric power for consumption elsewhere. The result is a form of hydrologic colonialism, whereby the plains, mountains, and southwestern areas export water or water-related services while retaining the environmental costs. The environmental costs of dams in the form of disrupted downstream hydrologic and biotic systems are likely to be greater in these regions than elsewhere.

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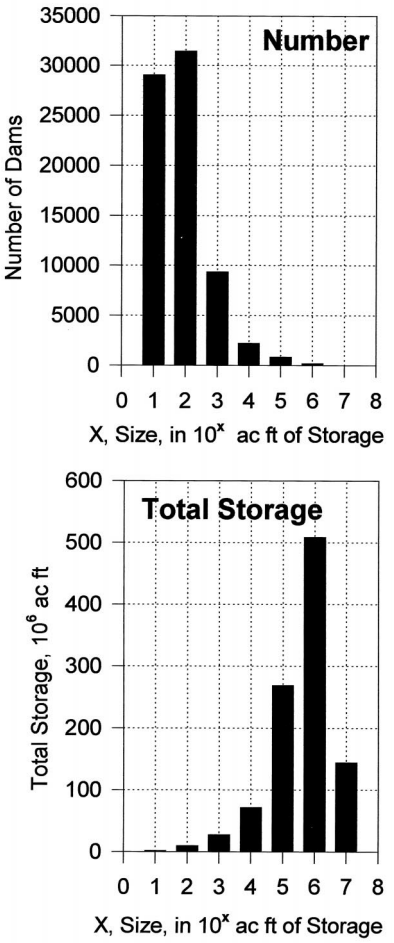

Figure 2. Number and storage capacity of dams and reservoirs in the continental United States. Data from *U.S. Army Corps of Engineers* [1996].

5. History of Dam Closures

Preliminary analysis of the database by USACE and FEMA revealed that the oldest surviving American dam is Mill Pond Dam, Connecticut, built in 1677. The decade of the 1960s saw the addition of 18,833 dams in the United States (including some of the largest), more than any other decade, with relatively few additions after the mid-1980s [*U.S. Army Corps of Engineers*, 1996]. A more detailed evaluation of the year-by-year increase of the total reservoir storage capacity of the nation as a whole shows that the greatest rate of increase was from the late 1950s to the late 1970s (Figure 3). The oft-heard colloquial wisdom that "the nation's dam building era is over" is born out by the relatively minor increases in storage after 1980. This general history explains why the downstream environmental costs of dams have only recently captured scientific attention. The maximum potential for the downstream hydrologic disruptions through reservoir storage has been in place for less than two decades, and the effects have only recently become obvious.

An extended analysis of the historical data partitioned by water resource region shows river basins did not all experience the same history of dam construction, and therefore they are likely to evidence different timing in downstream hydrologic and ecological responses. Although each region has its distinct history, there are two general historical patterns in cumulative reservoir storage: continual gradual increase and gradual increase with an accelerated increase (Figure 4). Regions with relatively gradual, continual increases in storage include the New England, mid-Atlantic, Great Lakes, Tennessee, Upper Mississippi, Souris, Rio Grande, and Great Basin. Regions with accelerated periods of dam construction include the South Atlantic-Gulf, Ohio, Lower Mississippi, Missouri, Arkansas, Texas, Pacific Northwest, and California. Two regions, the Upper and Lower Colorado, have hybrid histories whereby the closure of a single immense structure in each region has interrupted the overall gradual trend. Boulder (later renamed Hoover) Dam in the Lower Colorado and Glen Canyon Dam in the Upper Colorado imprinted large increases in storage on their basins in 1936 and 1963, respectively.

In eastern water resource regions and the Pacific Northwest, reservoir storage does not exceed mean annual runoff, but in several water resource regions, dams and their reservoirs are so numerous and large that they store more than the annual runoff. The date at which storage exceeded mean annual runoff gives an indication of the length of time that the downstream ecological effects of dams have had to develop in downstream areas. The regions with more storage than mean annual runoff and the dates when this exceedence occurred are the Souris (1909), California (1927), Rio Grande (1935), Lower Colorado (1936), Upper Colorado (1950), Missouri (1953), and Texas-Gulf (1962). These regions are most likely to now evidence the greatest downstream impacts from dams, all other factors being equal.

6. Conclusions

Dams segment the rivers and fragment the watersheds of the United States. Dams are a pervasive component of the nation's river system, but there is substantial geographic variation in their numbers, storage capacity, and economic value of the water they control. Dams are significant features of every river and watershed of the nation, but greatest surface water impacts are in the Rocky Mountains, Great Plains, and Southwest. While it is true that global climate change will be likely to have environmental effects on the nation's delicately balanced river and riparian systems [e.g., *Nash and Gleick*, 1993; *Ferguson*, 1997], the construction and operation of dams has already had greater hydrologic and ecologic impacts on American rivers than any changes that might reasonably be expected from global climate changes in the near future. The dam building era is over, but in many water resource regions, downstream hydrologic and ecologic effects of dams are now becoming apparent because the maximum reservoir storage has only

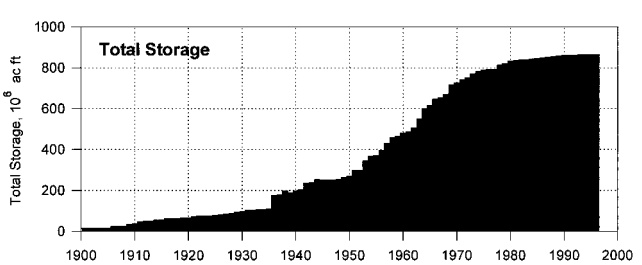

Figure 3. History of increasing total reservoir storage for the continental United States. Data from *U.S. Army Corps of Engineers* [1996].

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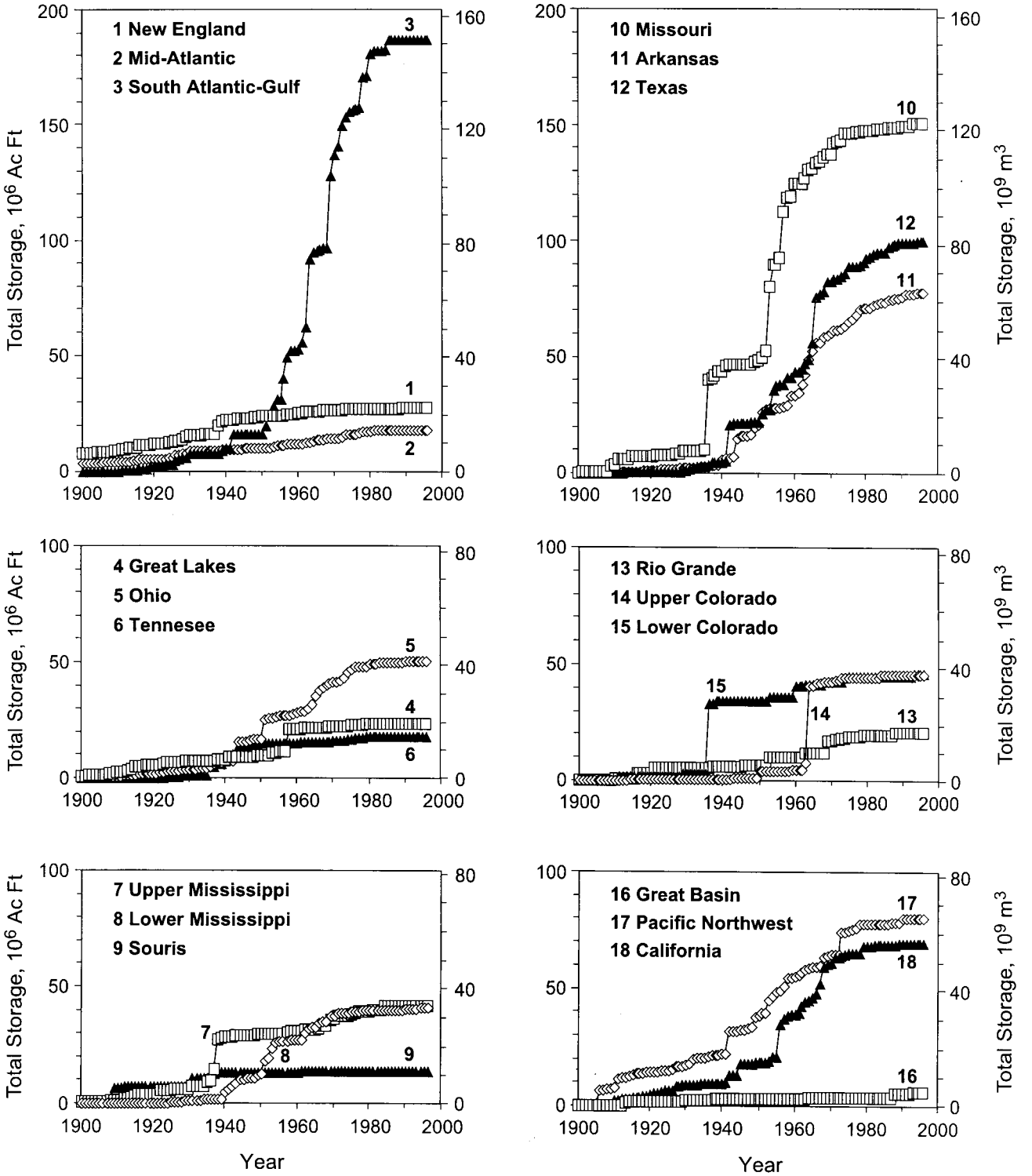

Figure 4. History of increasing total reservoir storage by water resource region. Data from *U.S. Army Corps of Engineers* [1996].

been in place two to three decades. The widespread and intensive nature of the effects of these structures suggests that they also offer means of mitigating some hydrologic impacts, if not through retirement of dams, through changes in their operating rules.

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