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General Technical
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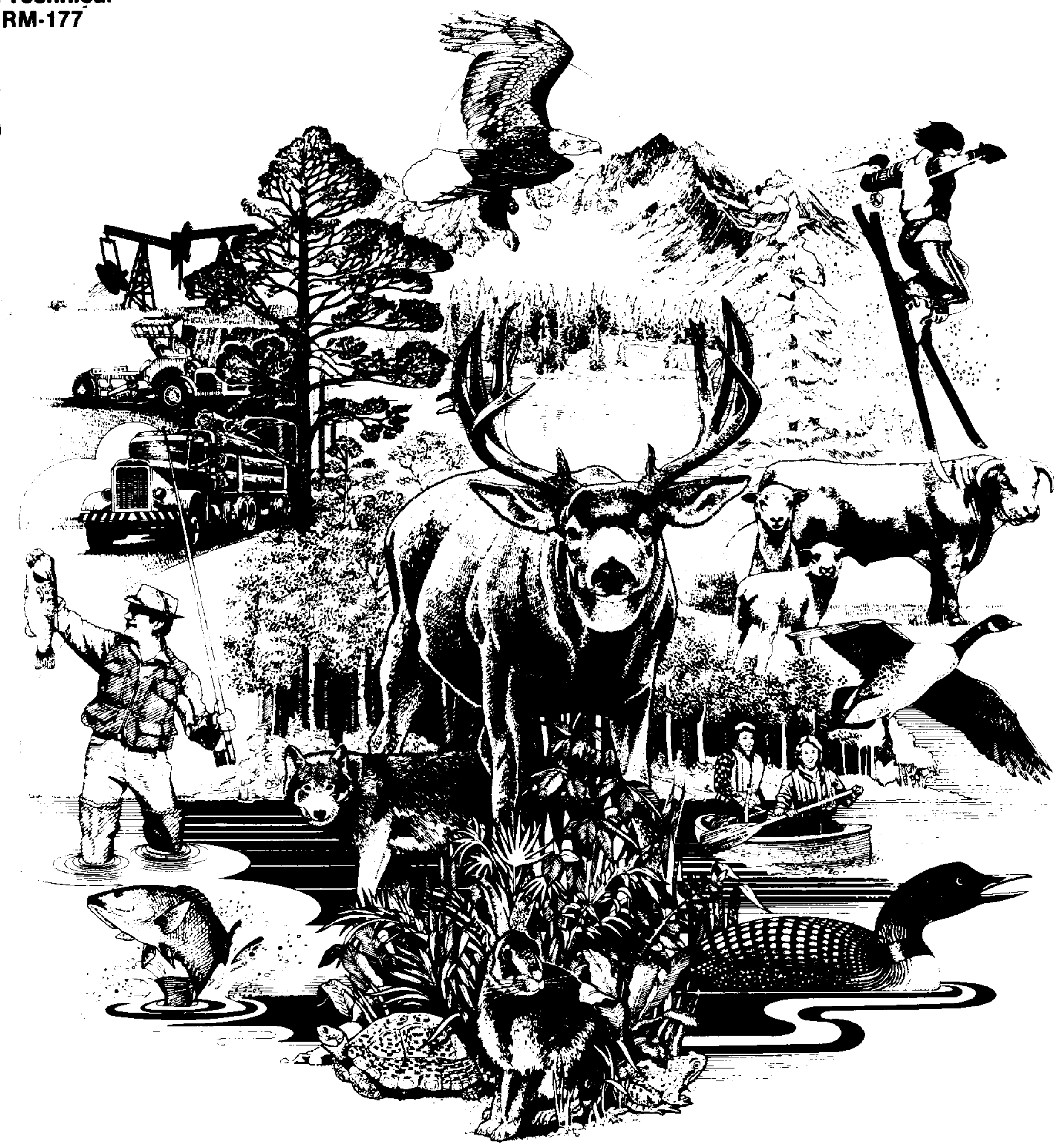
An Analysis of the Water Situation in the United States: 1989–2040

A Technical Document Supporting the
1989 USDA Forest Service RPA Assessment

Richard W. Guldin



Preface

The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA), P.L. 93-378, 88 Stat. 475, as amended, directed the Secretary of Agriculture to prepare a Renewable Resources Assessment by December 31, 1975, with an update in 1979 and each 10th year thereafter. This Assessment is to include "an analysis of present and anticipated uses, demand for, and supply of the renewable resources of forest, range, and other associated lands with consideration of the international resource situation, and an emphasis of pertinent supply, demand and price relationship trends" (Sec. 3.(a)).

The 1989 RPA Assessment is the third prepared in response to the RPA legislation. It is composed of 12 documents, including this one. The summary Assessment document presents an overview of analyses of the present situation and the outlook for the land base, outdoor recreation and wilderness, wildlife and fish, forest-range grazing, minerals, timber, and water. Complete analyses for each of these resources are contained in seven supporting technical documents. There are also technical documents presenting information on interactions among the various resources, the basic assumptions for the Assessment, a description of Forest Service programs, and the evolving use and management of the Nation's forests, grasslands, croplands, and related resources.

The Forest Service has been carrying out resource analyses in the United States for over a century. Congressional interest was first expressed in the Appropriations Act of August 15, 1876, which provided $2,000 for the employment of an expert to study and report on forest conditions. Between that time and 1974, Forest Service analysts prepared a number of assessments of the timber resource situation intermittently in response to emerging issues and perceived needs for better resource information. The 1974 RPA legislation established a periodic reporting requirement and broadened the resource coverage from timber to all renewable resources from forest and rangelands.

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USDA Forest Service

ACKNOWLEDGMENTS

A decade has passed since publication of *The Nation's Water Resources: 1975–2000* by the Water Resources Council. The 1979 RPA Assessment and the 1984 Assessment Update drew heavily upon that report. But because data for the former report are now 15 years old, new data and new projections were needed for this report. Water resource literature has expanded tremendously in the past 15 years, due largely to the proliferation of research and reports in response to the Clean Water Act. Susan Johnson reviewed more than 1000 abstracts and screened hundreds of publications for this report. Without her help, this report could not have been written.

Wayne Solley, Geological Survey, provided data that was essential for making projections of water withdrawals and consumption.

Several people reviewed part or all of the manuscript. These include Peter Avers, James Brown, Richard Cline, David Darr, Richard Domingue, Arthur Flickinger, Kenneth Frederick, Jack Frost, James Gregory, Thomas Hamilton, Warren Harper, Adrian Haught, Fred Kaiser, Kermit Larson, Robert Moulton, John Nordin, Dean Rasmuson, Gray Reynolds, Larry Schmidt, Rhey Solomon, Gordon Stuart, Benee Swindel, and Clive Walker. They helped prevent many errors of omission and commission.

In spite of all this assistance, perfection remains elusive. I alone am responsible for the errors that remain.

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Richard W. Guldin

CHAPTER 1: OVERVIEW

INTRODUCTION

Several Federal agencies have historically had responsibilities for conducting assessments of the Nation's water resources. The U.S. Geological Survey (USGS), U.S. Army Corps of Engineers, U.S. Department of Agriculture's Soil Conservation Service (SCS), and U.S. Environmental Protection Agency (EPA) and its predecessor agencies, among others, have conducted studies assessing the current situation and future prospects for water in particular regions of the country.

Responsibility for national water assessments was assigned to the U.S. Water Resources Council (WRC) by the Water Resources Planning Act of 1965. With the demise of the WRC in 1981, several member agencies have attempted to take over parts of the WRC role and improve their own analyses. USGS began to publish an annual National Water Summary in 1984. The first three annual reports, Water-Supply Papers 2250 (USGS 1984), 2275 (USGS 1985), and 2300 (USGS 1986), have been used extensively in the preparation of this Assessment. In some cases, extended portions of text have been lifted from those reports; in other cases, topics are presented in the same order. The 1986 Summary (USGS 1988) was published after preparation of this report was completed. Similarly, EPA publishes biennial reports to Congress on the National Water Quality Inventory. Information from these reports has also been extracted for this Assessment.

The Forests and Rangelands Renewable Resources Planning Act of 1974 (88 Stat. 476, as amended; 16 U.S.C. 1601–1614) (RPA) directs the Secretary of Agriculture to conduct an assessment of the Nation's forest and rangeland resource situation covering all renewable resources within the purview of the Forest Service. Water is one of the renewable resources. RPA legislation also directed the Forest Service to follow two principles in conducting assessments. First, assessments were to analyze the resource situation from a national perspective—including all ownerships, public and private. Second, the Forest Service was to use, to the extent practicable, information collected by other public agencies on the resources studied. This report faithfully follows that direction.

This report has nine chapters beginning with a broad overview of the current water resource situation in the United States. The extensive reference citations are a "road map" directing readers to more detailed discussions of individual topics in the reports of other agencies.

One requirement of the RPA legislation is an analysis, looking 50 years into the future, of prospective demands and supplies of each resource. Chapter 3 contains an analysis of historical trends in withdrawals and consumption and projections to 2040 based on data from USGS and SCS. In this report, withdrawals and consumption are treated as two different forms of demand for water. Both forms of demand are projected independently of supplies. Consumption is used in later chapters as the preferred definition of demand. Chapter 4 contains an analysis of historical trends in water supplies and projections to 2040 based upon generalized water budgets. The projections of demand and supply are the results of new analyses by the author. It is important to recognize that trends projected in these chapters are not in any sense "most likely." Rather, they portray what might occur if factors determining water resource management and use continue unchanged from those in effect since 1970. Obviously, projections of past trends will demonstrate conflicts between the level of consumptive use demanded and the level of supply projected to be available. A discussion of those conflicts is presented in Chapter 5 and the social, environmental, and economic implications of those conflicts is presented in Chapter 6. Chapters 5 and 6 also contain analyses of some alternative future scenarios for water resources having the potential to alter the demand and supply projections which were based upon recent trends.

Although projections of consumption demands and available supplies differ—creating either surpluses or shortages—these differences will not really occur. Rather, the economy will function and prices for water and other goods and services (such as water treatment) will change, thereby bringing supplies and demand into equilibrium. These adjustments, if not planned in advance, can lead to undesirable consequences. Water resource users and managers have opportunities to alter use and management practices inherent in the recent trends to achieve a more desirable future water resource situation. These opportunities are outlined in Chapter 7. Similarly, there are some obstacles—economic, social, environmental, institutional, and regulatory—to taking advantage of opportunities. These obstacles are discussed in Chapter 8. Chapter 9 discusses implications of these opportunities and obstacles on Forest Service resource management and research programs, providing guidance for agency strategic planning.

HIGHLIGHTS OF THE WATER RESOURCES SITUATION: 1989–2040

CURRENT WATER RESOURCE SITUATION

The United States has abundant supplies of fresh water. The renewable water supply of the coterminous United States amounts to about 1,400 billion gallons per day (bgd). Aggregate daily withdrawals amount to 343 bgd or 25% of renewable supply. Aggregate daily consumption amounts to 93 bgd or 7% of renewable supply.

The Nation's watersheds are generally in good condition. But special attention must be given to managing the soil and vegetation on more than 70% of our watersheds to maintain or improve the quality and quantity of water flowing from them. A survey of watersheds in the U.S. revealed that 28% are in prime condition; 50% require special consideration of soil and vegetation characteristics when resource management plans are prepared; and 22% require direct capital investments to restore watershed condition to a level consistent with resource management goals. Most watersheds in prime condition are in the West; most special emphasis watersheds are in the South and North; and most watersheds requiring direct capital investments are in the North and Rocky Mountains.

There are 90 million acres of wetlands remaining in the coterminous United States, less than one half the acreage that existed 200 years ago. Wetlands losses are continuing at an alarming rate estimated at 350,000 to 500,000 acres annually. The principal reason for the continued decline in wetlands is conversion to urban, suburban, and agricultural land uses.

Concerns about water shortages in the United States arise because water supplies are unevenly distributed in relation to the regional and seasonal distribution of water demands.

Water resource development has been the preferred way of increasing water availability but future large scale developments are unlikely due to economic and environmental costs. A total of 480 million acre-feet of storage exists in the 2,654 largest reservoirs and controlled natural lakes with capacities greater than 5000 acre-feet; fifty thousand smaller reservoirs exist and have capacities between 50 and 5000 acre-feet. In addition, there are 2 million smaller ponds.

Other methods of increasing water availability have been tried, such as weather modification, recycling wastewater, and reducing leaks, seepage, and evaporation. Recycling was touted in the mid-1970s as having great potential, but it is no more popular today than back then.

Acid deposition, erosion, and groundwater contamination are three important water related environmental problems. All three arise due to *externalities*—resource management actions that fail to take full account of potential disruption to ecosystems caused by pollutants.

A relative abundance of good quality surface water still exists; however, serious water-quality problems have developed in some stream reaches and some streams cannot support the full range of desired uses. Programs resulting from the 1972 Clean Water Act have made significant progress in cleaning up point-source pollution. For example, total biochemical oxygen demand declined for both municipal and industrial dischargers between 1972 and 1982 (46% and 71%, respectively). Monitoring studies have found widespread decreases in fecal coliform bacteria and lead concentrations. Phosphorus concentrations have also declined, but to a lesser extent.

Nonpoint-source pollution has become more prevalent and its importance better understood as point-source pollution has been cleaned up. Monitoring studies show widespread increases in nitrate, chloride, arsenic, and cadmium concentrations. Suspended sediment and nutrients from agricultural sources are the most damaging nonpoint-source pollutants nationally.

PROJECTED DEMANDS AND SUPPLIES

The rates of increase in demand experienced from the mid-1950s to the mid-1970s have slowed. Freshwater withdrawals in the South and Rocky Mountains increased (85 and 75% respectively) at twice the rate of increases in the North and Pacific Coast regions (42 and 37% respectively). Irrigation is both the largest withdrawal use and the largest consumptive use. Thermoelectric steam cooling withdrawals have been growing most rapidly in recent years and are now almost equivalent to irrigation, but consumption is much lower.

Shortages (the situation where demands exceed supplies) are projected by 2040 for the Lower and Upper Colorado River, Rio Grande, Great Basin, California, and Lower Mississippi River Valley. Offstream water users will find water unavailable or there will be insufficient instream flows remaining to provide good survival habitat for fish, wildlife, and other instream uses. Water surpluses exist, even in dry years, in most regions east of the Great Plains and in the Pacific Northwest.

Four common themes emerge from the analysis of projected surpluses and deficits:

1. The impetus to resolve deficits will come from a desire to mitigate adverse impacts on fish, wildlife, and recreation uses caused by low instream flows.
2. Irrigation is the predominant consumptive use in each region where deficits occur; consequently, eliminating deficits will require a reduction in projected rates of growth in irrigation water consumption.
3. Non-structural approaches, such as modifications in water rights institutions and freer functioning of water markets, will play a dominant role in solving water supply deficits.
4. Water yield augmentation by vegetation management, building snow-trapping structures, and weather

modification can help remedy small deficits. However, these techniques are unlikely to be employed as the dominant way of eliminating major regional deficits.

Water quality in 2040 will be somewhat better than current quality because nonpoint-source pollution abatement efforts are just beginning to bear fruit. But water quality will be somewhat poorer than the baseline levels for forests and rangelands because some sites will undergo short-term disturbances.

Alternative futures have been briefly analyzed. If demand for water grows faster than in recent years so that total demand is 20 percent higher than projected by 2040, deficits will emerge sooner and be more severe. If the rate of increase in demand is reduced so that total demand is 20 percent lower than projected by 2040, deficits emerge later and are not as severe. If global climate changes produce average annual temperatures 2°C warmer and precipitation is 10% lower, renewable supplies are projected to be from 5 to 40% lower, depending on the region. Deficits occur everywhere except in the Lake States and Northeast and are often severe, given projected future demands.

ENVIRONMENTAL, SOCIAL, AND ECONOMIC EFFECTS

If recent patterns of water and related land resource use continue to 2040, there will be significant adverse environmental, economic, and social implications for American society. Avoiding the adverse consequences of these implications creates an impetus for changing soil and water resource management in the near future. A continuation of recent trends will:

- Reduce fish and wildlife habitat and populations and other instream uses, such as recreation;
- Lead to increased salinity causing disruptions in local economies relying upon surface water resources for potable supplies; and those relying heavily on irrigated agriculture and the processing, sale, and transportation of irrigated crops and products;
- Lead to significant additional reductions in waterfowl populations and reduction in fishing, hunting, and other recreational benefits;
- Lead to expansion of urban and suburban areas at the expense of prime agricultural land and wetlands;
- Lead to water shortages that will cause major social impacts on local residents and their communities and increase the cost of food for humans and livestock; and
- Lead to intensive groundwater mining.

MANAGEMENT OPPORTUNITIES

Many opportunities exist for changing watershed management practices on all types and sizes of ownerships to help avoid environmental, social, and economic implications of water shortages. Only through the coordinated efforts of all landowners can the use of water and related resources reach their full potential.

Major opportunities to protect minimum instream flow levels exist through administrative controls and state water rights procedures.

Major opportunities for improving watershed condition exist through increasing emphasis on maintaining water quality through vegetation management; managing runoff timing through vegetation management, snow-trapping structures, and weather modification; increasing emphasis on improving riparian areas to keep pollutants out of streams and to provide cover for fish and wildlife; and increasing opportunities to enhance soil productivity through consideration of chemical and biological aspects of soils in addition to soil physical characteristics.

Nonstructural measures, such as zoning flood plains to restrict certain types of development, provide State and local officials with the biggest opportunity for flood damage reduction.

Silvicultural nonpoint-source pollution abatement practices are well-developed; however, many opportunities exist to educate landowners about these practices and to apply them more consistently. Opportunities include better pre-harvest planning; better planning, design, and construction of roads; less soil-disturbing techniques for harvesting, storage, and hauling procedures; closure and revegetation of temporary roads and landings not needed after harvest; and careful application of fertilizers and pesticides.

Legislative changes recently implemented in the Food Security Act of 1985 and expected increases in crop yields present major opportunities to reverse the trend in loss of wetlands.

OBSTACLES TO IMPROVING WATER RESOURCE MANAGEMENT

There is political resistance in some regions to free markets for water. Water institutions are giving high priorities to offstream uses to the detriment of instream uses such as fish and wildlife habitat and recreation.

Information that accurately assesses current watershed and stream channel conditions and capabilities on all ownerships has not been consolidated. Further, information available is often not displayed to managers in ways useful to evaluate management impacts or plan rehabilitation of watersheds in the poor condition.

Private landowners lack incentives to implement *Best Management Practices* to reduce nonpoint-source pollution.

Income and property tax laws and regulations encourage wetlands conversion. There are few incentives to encourage private landowners to manage wetlands for wildlife and recreation benefits to society.

Large-scale water yield augmentation entails significant environmental and social risks.

IMPLICATIONS FOR WATER RESOURCE MANAGEMENT

The challenge for forest and rangeland managers is to preserve the volume and *quality* of water for instream flows that promote fish and wildlife habitat and recreation and that will also satisfy emerging municipal needs in the next century.

The role of vegetation management, snow-trapping structures, and weather modification for increasing water supplies could be reconsidered. Although these practices have been extensively researched, social acceptability of implementing them over wide areas and their role in expanding regional supplies has not been clearly decided.

Institutional barriers have been erected in many areas that prevent a market for water from emerging, or where one has emerged, that constrain it from functioning efficiently. Freer functioning of water markets can help reduce shortages.

Recent gains in agricultural productivity are going to decrease the Nation's reliance on irrigation. In addition, society's preferences for water use are changing because demographic shifts are reducing the number of agricultural voters. Consequently, municipal supplies and adequate instream flows are becoming more important to society than increased irrigation usage.

Maintaining and improving water quality will become a top priority for land managers. Because municipalities prefer to pay the costs of transporting clean water long distances instead of the cost of cleansing nearby water to potable standards, municipalities outside the traditional bailiwick of the resource manager may become vitally interested in land and water management issues.

Private landowners need education and technical and financial assistance to help them make the most of their opportunities to improve water quality, to restore and protect riparian areas, and to reduce downstream flood damages.

Long-term data is an important tool for studying complex ecological problems such as acid deposition. Background information on how the ecosystem functioned before the problem emerged is also essential to determine true effects. A system of sites for long term ecological monitoring needs to be established and monitoring begun.

Additional research is needed on cumulative effects of changes in land ownership and land management objectives as applied temporally and across a watershed.

Additional research is needed on maintaining soil productivity. Work to predict vegetation growth and harvestable outputs as a function of site characteristics is in its infancy. The nutritional needs of agricultural crops and effects of nutrition on yields are much better understood. Similar kinds of information are needed for forest and rangeland species.

CHAPTER 2: THE CURRENT WATER RESOURCE SITUATION

PRECIPITATION PATTERNS[1]

The quantity of fresh water in rivers and streams is largely a function of the amount of precipitation. Nationwide, average precipitation is about 30 inches per year; however, precipitation patterns are quite variable. Average annual precipitation ranges from a few tenths of an inch in some southwestern desert areas to nearly 400 inches on some Hawaiian islands (fig. 1). East of the Great Plains, precipitation rates average 40 inches or more. In much of the West, however, precipitation rates are generally less than 20 inches annually.

After falling, precipitation moves in two general directions—directly back into the atmosphere or to streams. About two-thirds of the precipitation that falls either evaporates directly or is taken up by plants and transpired back to the atmosphere (when both are discussed together, the term used is *evapotranspiration*). Evapotranspiration rates are influenced significantly by temperature. The remaining third either runs over the soil surface to streams—perhaps causing erosion along the way—or percolates into the soil and moves through the soil profile to streams via groundwater flows. Underground geological formations containing water are called *aquifers*. Water withdrawn from streams, rivers, lakes, and reservoirs is called surface water withdrawal. Water withdrawn from aquifers via wells is called groundwater withdrawal.

RUNOFF-PRECIPITATION RELATIONSHIPS

The land area drained by a single stream is called a *watershed*. When talking about watersheds, all soil, vegetation, topographic and other factors that combine to make an integrated ecosystem are included.

It is important to understand the relationship between the amount of precipitation falling on a watershed and the amount of water in the stream flowing out of the watershed in order to measure the effect of land management activities. The relationship is usually expressed in per-acre terms comparing precipitation and runoff. The average annual runoff is computed as the average annual stream flow volume at the bottom of a watershed divided by the number of acres in the watershed.

Runoff rates are also highly variable across the United States (fig. 2). Part of the runoff variation is due to precipitation variability.[2] Other factors such as size, duration, and frequency of storms; climate, topography and geology of the watershed; and vegetation type and

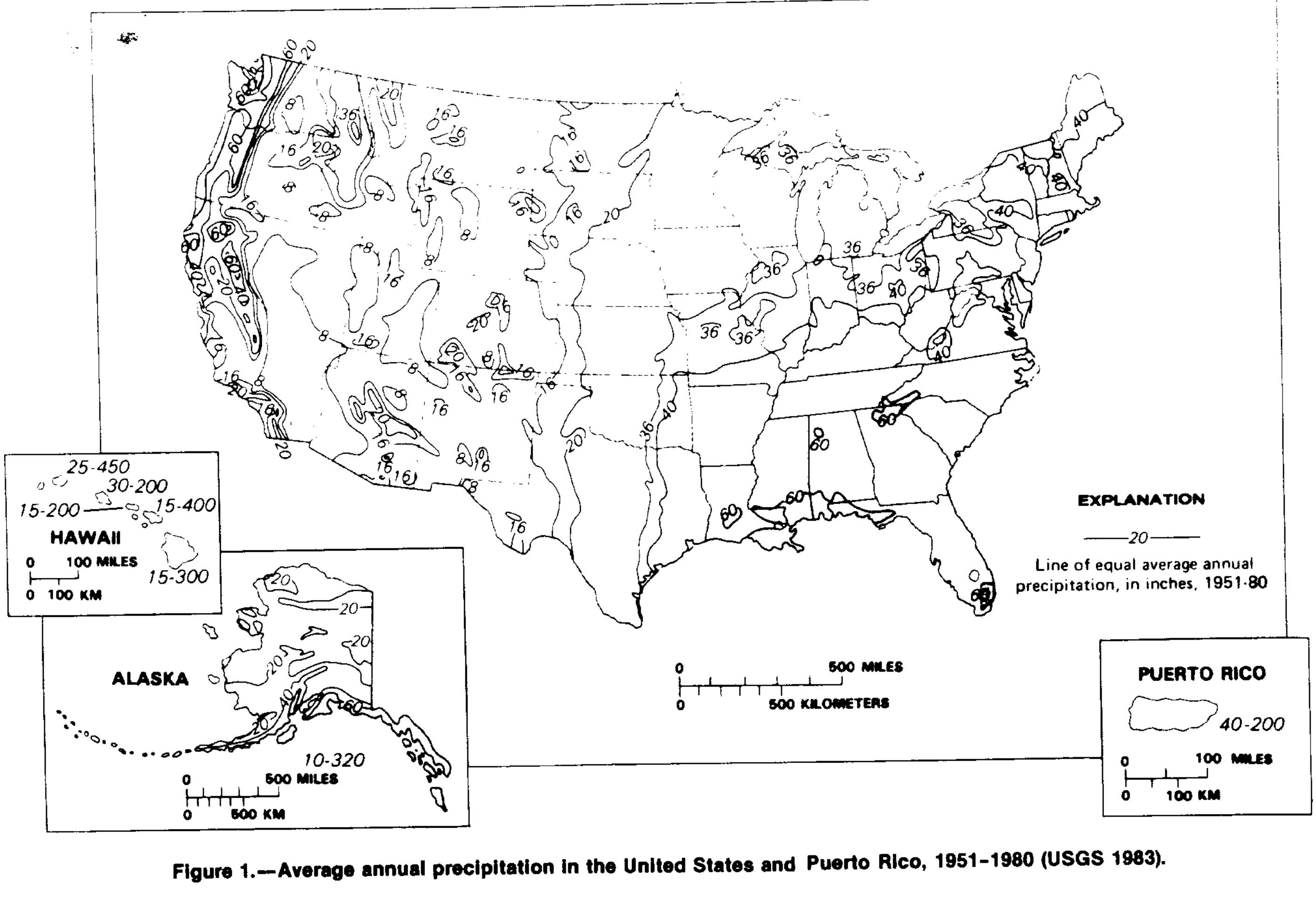


Figure 1.—Average annual precipitation in the United States and Puerto Rico, 1951-1980 (USGS 1983).

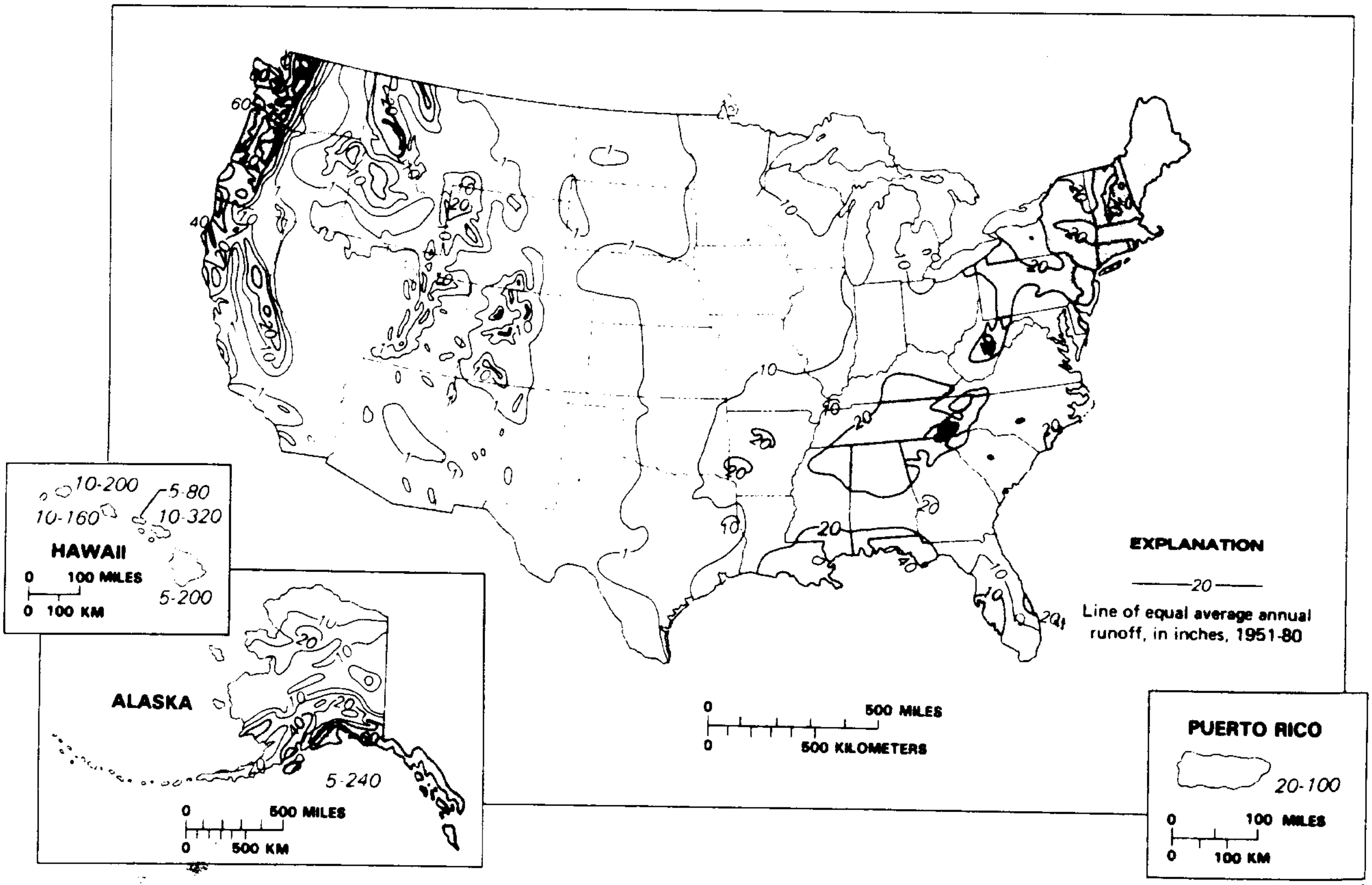


Figure 2.—Average annual runoff in the United States and Puerto Rico, 1951-1980 (USGS 1983).

distribution in the watershed also have a large bearing on runoff-precipitation relationships. The interrelationships among all these factors is what makes watershed management challenging.

Very high or very low runoff-to-precipitation relationships typically complicate managing forest and range ecosystems. High runoff-to-precipitation rates are typically associated with storms of high frequency and/or severe intensity, steep topography, and very fine or very coarse textured soils. Very low runoff-to-precipitation ratios are associated with infrequent storms or frequent ones with little rainfall per storm; storms that occur largely in summer when temperatures, evaporation, and transpiration rates are high; and with coarse textured soils or soils where high evaporation rates concentrate salts in plant root zones.

A comparison of figures 1 and 2 reveals a similarity in geographic patterns of precipitation and runoff. The highest annual runoff rates in the United States occur in Hawaii, typically exceeding 100 inches and occasionally reaching 320 inches. In southeastern Alaska and western Washington and Oregon, the annual runoff exceeds 60 inches in many watersheds. Runoff in the northern and central Rocky Mountains, the Adirondacks, and southern Appalachians exceeds 40 inches. Large areas west of the Great Plains, especially those on the east side of mountains, have runoffs of an inch or less.

Differences between precipitation and runoff are largely due to differences in evapotranspiration and groundwater recharge. Differences in evapotranspiration and recharge are due primarily to climate, topography, geology and cover.

The role of climate.—In semiarid and arid climates, most precipitation is lost to evaporation shortly after it falls. In some instances, rain can evaporate even before reaching the ground. Although potential evapotranspiration in semiarid areas may exceed 70 inches, actual evapotranspiration rates are much lower because precipitation is so scarce. Thus, actual evapotranspiration nearly equals precipitation and runoff is therefore very low. East of the Great Plains where the climate is more humid, precipitation is typically 15 to 20 inches greater than average evapotranspiration rates of between 20 to 40 inches and runoff volumes are greater.

Runoff amounts from equal annual precipitation rates vary depending on the nature of precipitation events. Given the same annual precipitation, more runoff comes from a few large storms than many small ones. Runoff is also affected by the timing of storms. Watersheds where storms are more common in summer will produce less runoff than watersheds where storms are more common in winter. The higher temperatures and more active vegetation respiration present in summer leads to more evapotranspiration than in winter.

The role of topography.—Watershed topography also affects the amount and character of runoff. A watershed with steep slopes at high elevation receiving the same precipitation as a watershed with gentler slopes at lower elevation will produce more runoff. Steeper slopes allow water to flow more rapidly through the watershed so less time exists for evapotranspiration. Higher elevations are also associated with lower temperatures, which also decrease the rate of evapotranspiration.

Watershed topography has a significant influence on runoff because it influences the amount of precipitation received. Precipitation is usually greater at higher elevations than lower ones. Further, location of mountains relative to prevailing storm paths is another topographic factor. As an air mass crosses a mountain range, most of the precipitation falls on the side from which the storm approached. In the United States, this windward side typically faces west. The leeward side is said to be in the *rain shadow*.

The role of geology.—Geology influences runoff largely through its effect on soil texture and permeability. Runoff patterns are a direct reflection of depth, storage capacity, and permeability of soil. Coarse-textured soils encourage rapid infiltration of precipitation and rapid percolation to aquifers. Groundwater flow in such situations is relatively rapid. Fine-textured soils impede infiltration and percolation, thereby encouraging overland flow to streams. Sedimentary rock, such as limestone, generally stores more water than igneous rock. Older rock formations tend to be more fractured than younger formations, thus they store more water than younger formations. Consequently, watersheds based on relatively new igneous formations will have more runoff than watersheds based on older, more sedimentary formations.

Groundwater storage quantity is largely a function of the porosity of rock formations. Groundwater is replenished, or "recharged," by percolation of precipitation and by seepage from stream channels. Where porous rock strata intersect stream channels, water can move back and forth between streams and groundwater. Whenever stream levels are higher than groundwater levels, streams recharge an aquifer in the porous strata. When stream levels drop lower than groundwater levels, groundwater seeps into streams and becomes part of streamflow. The ability of aquifers to store runoff is so great that groundwater seeping into streams may provide an average of 40% of the annual streamflow in some areas and nearly all the flow during periods of lowest flow when direct runoff from precipitation is nil.

The role of cover.—The type of cover and its pattern on a watershed strongly influence the quantity, velocity, and timing of runoff after precipitation falls. Cover can be natural vegetation (trees, grasses, forbs), manmade (asphalt or concrete), or absent (exposed bare soil). If a large percentage of precipitation becomes runoff, little precipitation is soaking into the soil to promote plant growth and recharge groundwater. If runoff velocity is high, the likelihood of soil erosion and its concomitant loss of site productivity increase because fast-flowing water has more energy to pick up and transport soil particles. Short durations between rainfall and runoff lead to reduced likelihood of infiltration and increased stress on aquatic ecosystems and the stream channel networks receiving runoff.

Precipitation falling on a vegetated area will experience a delay in movement between falling and runoff. The surface area of living vegetation and decaying litter on a site is immense and provides significant temporary detention of precipitation. By temporarily storing some precipitation, vegetation prolongs the period of time that water can infiltrate the soil. Once infiltrated, it becomes available for uptake by roots and percolation to groundwater. Vegetation (especially roots and litter) provide texture to soil surfaces and retard runoff.

Vegetation patterns can also influence precipitation detention. For example, contour plowing and stripcropping are excellent techniques for slowing runoff. "No-till" farming also helps conserve moisture. Manipulation of timber harvest patterns is another example. Cut areas can be designed to efficiently trap blowing snow and lengthen the period of snowmelt to allow for more infiltration and extend the period of runoff.

In contrast, precipitation falling on urban areas experiences rapid runoff from the impervious surfaces of parking lots and building roofs. Large peak flows due to extensive urbanization and rapid runoff can overwhelm stormwater conveyance systems and wastewater treatment facilities. These consequences can lead to discharge of partially treated wastewater to streams and subsequent declines in dissolved oxygen, which is harmful to fish. In estuarine systems, a massive dose of freshwater can temporarily upset the salinity balance. Nutrient cycling can also be disrupted.

Changes in land use patterns, particularly changes in cover types from forested or range to agriculture or urban uses, are an important factor in determining stream water volumes as well as the stability of aquatic ecosystems, their structure, and richness of their diversity.

Summary of roles.—Annual runoff from a watershed is the net result of all these natural influences interacting with the human influences of watershed use and management. For watersheds where natural influences predominate, the average runoff over a long period of years (to eliminate short-term climatic variations) is a reliable indicator of the long-term renewable supply of water. For watersheds where human influences predominate, mankind's effects are a much stronger determinant of the long-term renewable supply.

SEASONAL RUNOFF AND STREAMFLOW VARIATIONS

Within a given watershed, streamflows vary by season. A period of high flows is normally followed by a period of low flows. The timing of high and low flows differs by watershed location and is a function of seasonal distribution of precipitation and temperature.

Where temperatures are seldom below freezing for more than a few days at a time, the monthly distributions of runoff and streamflow volumes correspond closely to the monthly distribution of precipitation. For example, both precipitation and runoff are highest during winter in watersheds along the Pacific Coast.

Where temperatures are below freezing for extended periods, winter precipitation accumulates as snow and ice until temperatures climb above freezing and melting occurs. If snow and ice accumulate only in a limited area high in the watershed, the effect of melt water on streamflow will be minor. If only small amounts of snow and ice accumulate due to the occurrence of several freeze-thaw cycles during the winter, or if wintertime precipitation is low, little water will be stored as snow and ice, and runoff will have only a minor effect on streamflow. These are the normal situations in mountain watersheds across the United States at southerly latitudes. If wintertime precipitation is high and below-freezing temperatures occur for extended periods, then precipitation storage as snow and ice is large and the potential for a major increase in streamflow in the spring and summer is high.

The character of temperature warmup in spring after an extended period below freezing also affects streamflow variations. If the watershed is uniformly covered with snow and ice, streamflow will rise rapidly. Floods are likely in this situation. If warmup is gradual and mild, then snow and ice will melt slowly and streamflow will be higher for a longer period, albeit at a lower maximum daily flow. Flooding is less likely with this temperature scenario.

FLOW ANOMALIES

Annual variations in runoff from a watershed are caused by changes in weather patterns and precipitation. Runoff variations will be highest in arid and semiarid watersheds because a small change in precipitation has a large effect on runoff. In other watersheds, the varying intensity of storms has a large effect on streamflow. Hurricanes along the Gulf Coast can cause severe increases in streamflow.

Droughts

A drought is the prolonged and abnormal deficiency of moisture with concomitant decline in runoff to a level significantly lower than usual. The concept of moisture deficiency includes more than lack of precipitation. It also includes consideration of potential evapotranspiration, antecedent soil moisture conditions and factors influencing runoff. The effects of a drought are a function of the severity, duration, and geographic extent of the moisture deficiency; whether water supplies are drawn from streams, impoundments or aquifers; and the type and magnitude of water use.

In humid areas, a drought of a few weeks is quickly reflected in soil and vegetation moisture deficiencies. Dry-land (without irrigation) farming crop yields will decline if rain does not occur for a few consecutive weeks during the growing season. Municipal water supplies that depend on streamflow and have limited storage will not be adequate unless replenished by runoff every few weeks. Prolonged droughts rarely occur in humid areas. In more arid regions, the inhabitants protect themselves from short droughts by using stored ground or surface water. Only when these supplies run low does drought become critical in these areas. In semiarid watersheds, livestock often depend upon small reservoirs or stock ponds for water. If water users draw supplies from large rivers or major impoundments holding the equivalent of two or three years' annual flow, a critical drought is caused only by precipitation deficits that extend over several years or that are exceptionally widespread geographically. During droughts of this nature, usable water in both reservoirs and impoundments becomes progressively depleted until the usual rates of water withdrawals cannot be made.

Drought severity is often used to express the degree of adverse effects felt by vegetation, humans, and animals. Drought severity is normally expressed as a probability of a monthly low flow being attained. A streamflow drought is said to occur when streamflow for a 30-day period or longer is unusually deficient. An "80 percent" drought means that a monthly flow higher than that observed is expected every 8 of 10 years. In the water supply analysis of Chapter 3, the definition of a "dry year" is an 80% drought.

The effects of major multi-year droughts this century have been devastating. The "Dust Bowl" of the 1930s stemmed from a multi-year drought in the Great Plains. The effects of a decline in waterfowl habitat from that era are still being felt in current waterfowl populations. Other notable multi-year droughts occurred in the 1950s (Thomas et al. 1962, Nace and Pluhowski 1965) and 1970s (Matthai 1979). The years 1985–1988 have also been unusually dry in parts of the U.S.

Droughts are related to anomalous occurrences in the atmospheric circulation and solar phenomena. Droughts may occur in one part of the U.S. while another part of the country will be abnormally wet. There is as yet no agreement among meteorologists on how these abnormal atmospheric circulation patterns are generated. Some are convinced the climatic process is random. In this case, long-term accurate forecasting is impossible and the appropriate approach to the problem is through statistical probabilities. Others are convinced droughts are cyclical, so prediction involves extrapolation of historical trends to the future. In either instance, water shortages and droughts will continue to plague us. Strategies and techniques are available or are being developed that offer promise for reducing the adverse effects of droughts.

Floods

A flood is a streamflow so high that it overtops any part of a stream's natural or artificial (levee or dike) channel. Floods range from fairly common annual high flows that barely overtop natural stream banks to rare events that crest well above natural channels. Floods are usually compared according to the heights of their crest above some reference point or the probability that flows of a given size can be expected. For example, a "100-year flood" is a flow that has a one-in-one hundred chance of being exceeded in any given year.

Floods along the coast usually result from high tides and storm surges, such as expected with a hurricane. Floods along inland streams and rivers usually result from intense rains, rapid snowmelt, or a combination of the two. The largest floods usually are caused by intense rainfall occurring in several adjoining watersheds with the runoff peaks arriving simultaneously at the confluence of tributaries from the watersheds. Flood damages are often high in such cases because towns are often located at river confluences. The second most common cause of severe floods is the combination of rapid snowmelt and heavy rainfall. Such a situation occurred in the Colorado River basin in 1984 when abnormally heavy snowpack followed by unseasonably warm temperatures caused a near-record runoff that began about May 20, 1984. Heavy rains in part of the basin led to peak flows more than 1.5 times the estimated 100-year flood level on the Uncompahgre River at Delta, CO.

Floods can also be created or exacerbated by other watershed factors. These include mountain glaciers, unstable soil and rock formations, earthquakes, volcanic activity and the presence of impoundments in combination with the above. For example, the flood resulting from the June 5, 1976 collapse of Teton Dam in the Snake River drainage, Idaho, has been attributed to porous fractured rock formations used to anchor an abutment and that underlay the dam itself.[3] Mud flows resulting from the combination of glacier melt and volcanic explosion on Mount St. Helens in 1980 caused great damage—even obstructing the shipping channel in the Columbia River 70 miles from the volcano. Even after receding, the mud left along the Toutle and lower Cowlitz Rivers so constricted the channels that even the average annual high flow could have caused severe over-bank flooding (Foxworthy and Hill 1982).

About 6% of the land area in the lower 48 states is prone to flooding. Nearly 21,000 communities have flood problems. Floods cause about 10 times more deaths each year than any other natural hazard. During 1985, the economic loss due to flooding was about $500 million—the lowest amount since 1971. Despite these losses, floods do have beneficial effects. Because a large part of the annual runoff from some streams occurs during floods, such floods play a major role in replenishing reservoirs and are important elements in water supply management.

Intensive land use has drastically modified flood plains and streamflow characteristics from their natural condition 400 years ago. It is clearly established that virtually every change in land use alters, to some extent, the water quality and flow regime of a watershed. This is especially true of use changes in the floodplain. Development typically involves placing impervious surfaces (roofs, pavements, roads) over part of the area. Runoff from these surfaces is high and fast. Thus, development tends to increase flood peaks and shorten peak duration, thereby increasing flood damages. Because of the high cost of structural flood control and attendant undesirable side effects, emphasis in flood protection has shifted to non-structural measures. These include improving flood forecasts, installing community flood warning systems, zoning or limiting land uses in flood-prone areas, and publicizing flood hazards. The USGS, the U.S. Army Corps of Engineers, the Federal Emergency Management Agency (FEMA), the National Oceanic and Atmospheric Administration (NOAA), SCS, and various state agencies have cooperated to develop and implement flood control measures.

Despite non-structural measures, the long-term trend in flood damages is increasing. Much of the increase in economic losses can be attributed to continuing encroachment of development onto the floodplain. In spite of the risk, people continue to be attracted to floodplains by advantages such as flat land, desirability for transportation routes, access to water, and superior agricultural soils. Once floodplain uses are established, governments try to control flood damages by building dikes, levees, dams, and other flood control structures. Because these structures successfully reduce damages from small to moderate floods, additional incentives exist to develop the floodplain further. Thus, when a flood occurs that overwhelms flood control structures, resulting damages are often much greater than if development had been limited by periodic, small-scale flooding.

WATERSHED CONDITION

What happens to precipitation after it falls is affected by the intensity and duration of the rainfall as well as the climate. Short, light rains in arid climates evaporate nearly completely; long intense rains during a hurricane largely become runoff. The nature and condition of soils and vegetation where precipitation falls also play an important role in the amount of precipitation that evaporates, infiltrates the soil, or runs off the site. Dense vegetation intercepts precipitation and promotes evaporation and transpiration; scattered vegetation, perhaps due to recent disturbance by fire or management practices, intercepts less water so more is available for infiltration or runoff. Sandy soils and flat topography promote infiltration; clayey soils and steep topography promote runoff.

Human influences that modify soil and vegetative patterns in watersheds alter natural watershed responses to precipitation. For example, urban development paves and erects roofs over land making it impervious to rainfall; less infiltration and more runoff is the result. Removing forest cover or plowing prairie grasslands reduces evaporation and exposes soil to the erosive influences of runoff. Because the influence of mankind's use of the land and vegetation is pervasive in many watersheds, managing soil and vegetation on the watershed is a key factor in managing the quality and quantity of water draining out of the watershed.

National Forests were originally established "...to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of the citizens of the United

States..."[4]. The central idea was to manage the forested ecosystem to maintain favorable (in terms of both quantity and quality) water flows and to maintain soil productivity to produce vegetation such as forage and trees. These goals for forest and rangeland management are embodied in the concept of *watershed condition*. Watershed condition describes the relative health of a watershed. It reflects the stewardship role of the Forest Service and is measured against management objectives in terms of factors affecting favorable conditions of flow and soil capabilities.

Maintaining favorable conditions of flow refers to behavioral characteristics of a watershed described in terms of its ability to sustain water quality, quantity, and timing necessary to support water-dependent ecosystems, instream uses, and downstream withdrawals of water. Included in this concept are managing land uses affecting water quality and quantity as well as managing the natural and manmade stream channels carrying flows to users. Also included is managing water in streams, associated fauna and groundwater flows.

Maintaining soil capability refers to the inherent capacity of a soil to support growth of specific plants, plant communities, and sequences of plant communities. Included in the concept of plant communities and the succession of communities are the associated fauna.

The concept of watershed condition provides an excellent basis for assessing the resource situation for water and related land resources. The condition of watersheds nationwide has been evaluated for this report by analyzing watersheds (40,000 to 180,000 acres in size) in each Forest Service Region. Each watershed was placed in one of three watershed condition classes described below. A regional summary was prepared describing the percentage of watersheds in each part of the United States that are in each condition class (table 1).

CLASS I: REGIMEN ATTAINMENT

Watersheds in this class provide a robust basis for sustained production of goods and services. Watershed management is such that no long-term changes are occurring even when major precipitation events occur. These watersheds represent an attainable, desirable condition. They are in dynamic equilibrium as evidenced by a stable drainage network. Response of a watershed to use is accommodated by the current channel network density, size, and process.

Table 1.—Watersheds by watershed condition class, 1987

Region	Condition Class I	Condition Class II	Condition Class III
	------- *percent* -------		
North	15	60	25
South	20	67	13
Rocky Mountains	27	49	24
Pacific Coast	36	45	19
U.S. Total	28	50	22

In Class I watersheds, production of goods and services can be sustained with low risk of deterioration in watershed condition. These watersheds are most prevalent in the Pacific Coast and Rocky Mountain regions. Legislation and regulations governing use of land designated as wilderness have a major influence in keeping watersheds in Class I condition because they have proscribed many surface-disturbing uses such as off-road vehicle use and timber harvesting. Considerable roadless land not designated wilderness is in watersheds having such rugged terrain that land-disturbing activities can only occupy limited areas if they can occur at all.

CLASS II: SPECIAL EMPHASIS

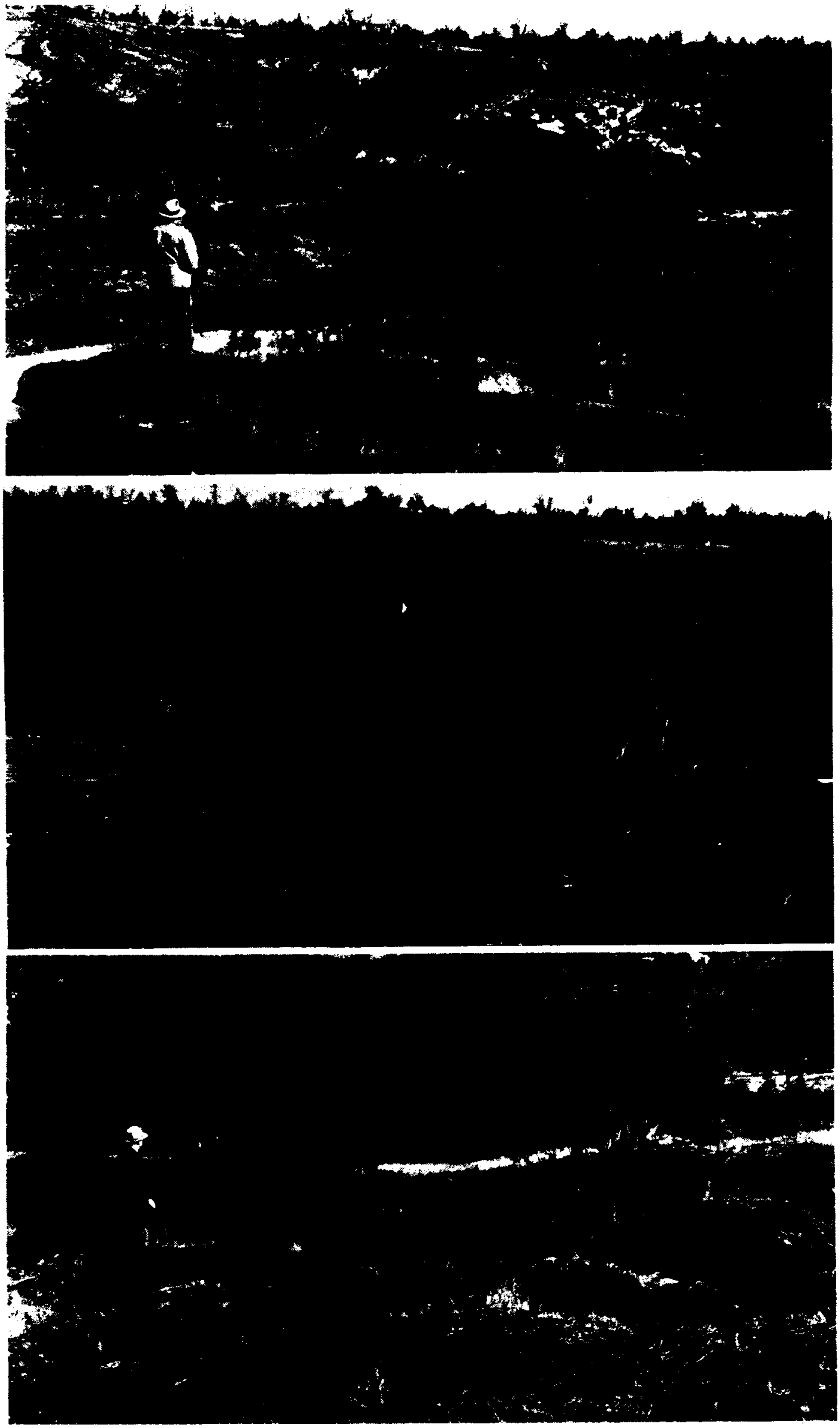
Watersheds in this class are not attaining Class I requirements but do not require capital investments to restore Class I watershed conditions.

One-half of watersheds surveyed are in Class II. Watersheds in this class require special consideration of soil and vegetation characteristics when resource management plans are prepared because soils in these watersheds have a high potential for erosion and significant risks to water quality exist. In short, improper or insensitive management may quickly lead to major soil or water problems and deterioration to Class III conditions.

Many Class II watersheds are currently performing to management objectives. There are four reasons why most watersheds are in Class II. Some are sensitive to specific land-disturbing activities such as mining, off-road vehicle driving, or timber harvesting. Other watersheds are sensitive to the cumulative effect of activities. Cumulative effects can result from activities having a light per-acre impact, but a total effect that has overwhelmed the watershed's ability to tolerate widespread use. Also in Class II are watersheds where use potential is inherently limited due to fragile soils and stream channels, and watersheds that have not reached a dynamic equilibrium in recovering from past abuses.

The South and North have the greatest number of watersheds in Class II primarily because of high water tables, severe erosion hazards, and a lower percentage of wilderness and other unroaded lands than in the Pacific Coast and Rocky Mountain regions. High water tables reduce trafficability. Lands with limited potential for maintaining favorable water flows are most common in the Rocky Mountain region; and comprise the bulk of Class II watersheds there. Watersheds in Class II in the Pacific Coast region are subject to landslide hazards, primarily in high rainfall areas. Because of steep terrain in the Rocky Mountains and Pacific Coast regions, watershed condition concerns often relate to location of transportation corridors and protection of riparian areas. Steep terrain also increases the risk to downstream areas of flooding because of rapid runoff. Therefore, any activities that disrupt infiltration and increase overland flow are of particular concern in Class II watersheds in these regions.

Factors affecting watershed condition and risks to sustaining condition vary greatly among and within a



The Yazoo-Little Tallahatchie Flood Prevention Project demonstrated how tree planting could help restore soil productivity in badly eroded watersheds. (a) Eroded field typical of many thousands of acres in northcentral Mississippi, 1948. (b) Loblolly pines were planted in 1949; four years later, the area is beginning to recover, 1953. (c) By 1957, rehabilitation of the site was well underway.

region. Because such a large proportion of watersheds are within Class II, opportunities to improve conditions through integrated resource management are greater than through direct capital investments. While both approaches cost time and money, the process of integrating resource management is often more affordable per acre. However, integrated resource management requires highly professional skills and creativity.

CLASS III: INVESTMENT EMPHASIS

Watersheds in this class require technologically and economically feasible capital investments to restore watershed conditions to a level consistent with resource management goals. Determination of feasibility must consider environmental, social, and economic desirability. Land treatments and structural measures are necessary to provide an improved watershed equilibrium, which will improve the watershed to Class II condition. In contrast, non-structural measures—integrated multiple-resource activities—are used to improve a Class II watershed to Class I status.

Nationwide, about 22% of all watersheds need capital investments to restore water quality, quantity, timing, or soil productivity to acceptable levels. This does not mean that 20% of the land area or channels are in Class III condition. A relatively small area can disrupt an entire watershed system by its contribution of sediment, mine waste, increased flow volume, or other impacts that influence soil productivity and favorable conditions of water flow.

The South has the fewest watersheds needing capital investments to restore watershed conditions to levels consistent with management goals. In other regions, between one-fifth and one-fourth of watersheds need capital investments. At the beginning of the 20th century, many watersheds across the South were badly deteriorated because of abusive farming practices in the 1800s. After agriculture was abandoned, many watersheds seeded naturally to southern pines. Reforestation restored the watershed condition to Class II in most cases.

A classic example of the kinds of capital investments necessary to restore Class II conditions is the Yazoo-Little Tallahatchie (Y-LT) Project in north-central Mississippi. Watersheds of the Yazoo and Little Tallahatchie Rivers contain highly erodible soils, many of loessal origins. By the 1930s, after being farmed for a century, soil capability to produce crops was exhausted. Due to a lack of vegetation to serve as ground cover, precipitation caused massive and widespread gully erosion. In 1946, the Forest Service and SCS began a joint rehabilitation program. The project area covered 4.2 million acres in 19 counties. Four major goals of the Y-LT Project were to reduce floodwater and sediment damages, to promote proper land use, to stabilize stream channels, and to improve the local economy in north-central Mississippi (Guttenberg and Pleasonton, 1961). In the early 1960s, it was the largest individual land and water management program in the United States.

Farm conservation plans based on land capabilities were developed with the assistance of SCS District personnel. Following approval of the conservation plans, financial assistance was provided to plug gullies and plant trees. On "critical" areas (exposed soil, slopes over 8%, gully erosion present, and downstream damage occurring), the entire cost was paid by the government. On other areas, free tree seedlings were provided and costs of planting and control of competing vegetation were shared between the government and landowner. Today, watersheds of the Yazoo and Little Tallahatchie Rivers support productive stands of southern pine with sufficient volumes to attract new wood processing industries to the north-central Mississippi town of Grenada. Some areas are currently being harvested, providing jobs and income to the local economy. Of course, harvesting must be done carefully to avoid creating new erosion and replanting is essential.

The Y-LT Project is an example of how direct capital investments can be used to rehabilitate Class III watersheds and move them to Class II conditions. Its success has been the impetus for more recent watershed rehabilitation and improvement programs, such as the Soil Bank Program of the 1950s and 1960s, and the Conservation Reserve Program of the 1980s.

SUMMARY

Watershed condition strongly influences the quantity and quality of water available for use. Current status of the Nation's watersheds is less than ideal—one-fifth need capital investments and one-half need especially careful management to attain long-term land and water resource management goals. Consequently, the quantity and quality of water currently available for use is also less than ideal.

The current situation for water use from a quantity perspective is examined next. Following that, the Nation's water quality situation is reviewed along with the wetlands situation. These discussions of rainfall and runoff volumes, watershed condition, quantity and quality of water currently used, and wetlands condition provide the necessary background to assess future demands and supplies of water as outlined in Chapters 3 and 4.

QUANTITY OF WATER AVAILABLE FOR USE

The renewable water supply of the coterminous United States amounts to about 1.4 trillion gallons per day. Even though total offstream withdrawals of surface water nearly doubled from 1960 to 1985, withdrawals still remained only 21% of the renewable supply in 1985. Despite major droughts, such as the one in the eastern United States in 1985 and 1988, and despite chronic water shortages in some localities, the nation is not "running out" of water. Periods of drought will be followed by periods of above-normal precipitation and runoff as in the past. Most concerns about water shortages arise because of uneven water distribution in relation to the regional and seasonal distribution of water demands. Concerns also arise because of increasing demand for existing supplies and related difficulties in distribution. In some situations, changes in engineering, management, or institutional procedures can improve the situation.

Although the available supply appears unlikely to change appreciably in the near future, estimates of that supply may not be very accurate because there is no objective way of selecting a representative period of record that includes the full range of possible variations. Moreover, even if the long-term average supply could be closely estimated, the actual supply over a specific future period probably will deviate from that average. One problem facing water resource planners is the inability to define accurately the amount of water available. This uncertainty should be considered in developing and allocating water resources.

INSTREAM VERSUS OFFSTREAM USES

Water has value both instream and offstream. Instream uses of water include navigation, fish and wildlife habitat, hydropower generation, recreation activities, and dilution of wastes. Instream uses usually require some minimum flow rate, thus they compete directly with offstream uses which reduce instream flows. For example, instream flows must not fall below some minimum rate if navigation is to continue. Some instream uses can tolerate reductions below the minimum essential level for a short period of time with little or no long-term adverse effect. For example, navigation can be suspended for several weeks during exceptionally low flows and start up when sufficient water is available without incurring a significant long-term reduction in navigation benefits. Wildlife and fish habitat, on the other hand, can suffer devastating long-term losses from several weeks of abnormally low flows. Of the instream uses mentioned above, fish and wildlife habitat is the most sensitive because long-term damage results from low flows.

Offstream uses are also called diversions or withdrawals because water is withdrawn or diverted from the stream channel or pumped from the ground and transported to the point of use. Offstream uses include cooling power generators (thermoelectric steam cooling in USGS parlance), irrigation, industrial and commercial use, and potable use. For all uses except irrigation, most water is returned to the stream following use, usually with some aspect of its quality (temperature, dissolved solids, other chemical constituents, sediment load) changed. That part of the water withdrawn from the stream and not returned is "consumed", principally by vegetation which subsequently transpires it back to the atmosphere or by evaporation during use. In Chapter 3, the trends in demand for water will be discussed in terms of withdrawals and consumption by six main uses.

In parts of the country, large flows are withdrawn from watersheds and transferred by pipes or aqueducts to other watersheds where demands for withdrawals exceed available flows. For example, water from streams in central and northern California and from the Colorado River are currently transferred to southern California. Such interbasin transfers of water are equivalent to a 100% consumptive use from the perspective of the watersheds where the water originates.

Pumping groundwater is also considered an offstream withdrawal of water. Where a porous stratum containing groundwater intersects a stream bed, pumping water from the aquifer can not only intercept water that would otherwise seep into the stream channel, but if sufficiently intensive, can induce water to flow from the stream into the aquifer. Reductions in instream flows occur some time after the onset of pumping, and unless the wells are very near the stream, usually do not coincide with the times of peak withdrawals from the streams.

GROUNDWATER DEVELOPMENT[5]

The volume of groundwater in storage in the upper half-mile of the Earth's crust within the coterminous United States has been estimated to be about 50,000 cubic miles (55,000 trillion gallons). Some water is highly saline and unsuitable for most uses. The recharge, or the rate of flow through the groundwater system, is estimated to be near 1 trillion gallons per day. A large percentage of this flow moves through very shallow aquifers which discharge to streams without reaching major aquifers. Only a portion of this shallow recirculation could be recovered by wells.

The pumping rate of fresh groundwater in the United States in 1985 was approximately 83 billion gallons per day (bgd), or about 8% of the estimated daily flow through the Nation's groundwater systems. From a national perspective, the groundwater resource is not overdeveloped. However, problems do exist in many localities.

The total groundwater withdrawn in 1985 represented about 24% of the total freshwater withdrawals in the United States. The largest single use is for irrigation—slightly more than 56 bgd. Although irrigation is the largest withdrawal, roughly half the population in the United States relies upon groundwater for potable supplies. About two-thirds of the groundwater withdrawals in 1980 were concentrated in eight states: California (21 bgd); Texas (8 bgd); Nebraska (7.2 bgd); Idaho (6.3 bgd); Kansas (5.6 bgd); Arizona (4.2 bgd); Arkansas (4 bgd); and Florida (3.8 bgd). Nine states use more groundwater than surface water—Arizona, Delaware, Florida, Hawaii, Kansas, Mississippi, Nebraska, Oklahoma, and Texas.

The pumping rate for groundwater increased steadily from 1960 to 1980 (fig. 3). Some factors responsible for the increase include: 1) a significant expansion of irrigation in the humid East as well as the West, particularly through the use of center-pivot irrigation systems; 2) water supply requirements of growing urban areas, particularly in the South and Southwest; 3) water demands associated with energy production; 4) a desire to establish drought-resistant supplies; 5) objections to the construction of surface reservoirs; and 6) objections to exporting water from one watershed to another. The quantity of groundwater withdrawals in 1985 represents the first reduction in withdrawals reported in the past 3 decades. The 10% reduction is more than a data anomaly—it reflects some changes in factors contributing to the increase since 1960.

Aquifer Declines

Aquifer declines have occurred in many areas since development began. But not all declines are of major concern. In most areas, declines occurred at depths substantially deeper than the water table. But because of artesian processes involved, declines do not represent the loss of large quantities of water from storage.

In some areas, however, declines are serious. For the High Plains region of Kansas, New Mexico, Oklahoma, and Texas, and for the alluvial watersheds of southern Arizona, aquifer declines resulted in a significant lowering of the water table. In these areas, very large volumes of water have been withdrawn, and continue to be withdrawn from storage. In some parts of central California, substantial withdrawals of groundwater in local areas have largely dewatered porous strata, leading to compaction of the strata and surface land subsidence. A description follows of the situation's severity in the four areas most heavily affected.

The High Plains

The High Plains encompass 174,000 square miles in northwestern Texas, the Oklahoma panhandle, western Kansas, Nebraska, and the eastern fringes of Wyoming, Colorado, and New Mexico. A rapid expansion in groundwater withdrawals for irrigation began in the southern High Plains in the early 1940s. Irrigation spread to the middle High Plains in the 1950s and to the northern High Plains in the 1960s. As irrigation spread, so did groundwater withdrawals. In 1949, about 2 million acres in the High Plains were irrigated by 1,303 billion gallons.

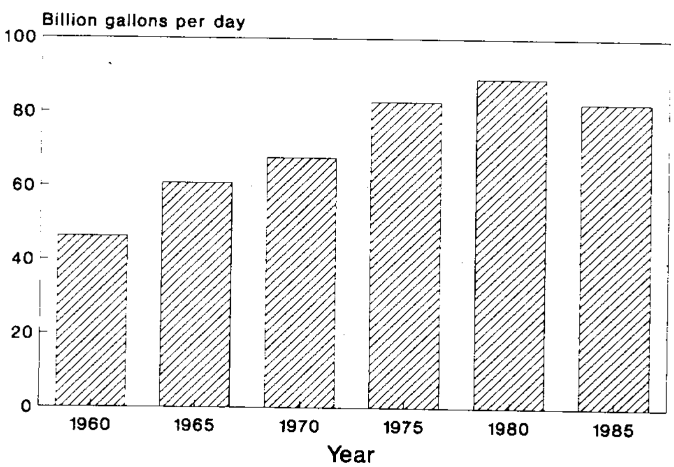


Figure 3.—Trends in groundwater withdrawals in the United States, 1960–1985.

By 1980, 5,865 billion gallons were pumped to irrigate 13 million acres.

Between 1940 and 1980, 68.4 trillion gallons of groundwater were withdrawn for irrigation in the southern High Plains. It is estimated that 43% of this volume was water from storage, 45% was recycled irrigation water percolating back to groundwater, and the remaining 12% was groundwater diverted from two sources as water tables dropped. The sources were groundwater that would otherwise have drained into streams and additional groundwater entering aquifers from streams. Floods in the early 1970s contributed significantly to recharge.

Between 1950 and 1980, 31.3 trillion gallons of groundwater were withdrawn for irrigation in the central High Plains. Withdrawals from storage were 57%, recycled irrigation water 39% and groundwater diversions/recharge 4%. The 1970 floods provided little recharge here.

Between 1960 and 1980, 34.2 trillion gallons of groundwater were withdrawn for irrigation in the northern High Plains. About 14% was withdrawn from storage, 36% by recycled irrigation water, and 50% from diversions/recharge.

Several factors contribute to the differences between the northern High Plains and the other High Plains areas. In the northern High Plains, more surface-water irrigation occurs. Groundwater recharge rates before irrigation development began were also higher in this area. Land use changes have also had an effect. As more land was brought under cultivation, increased infiltration of rainfall led to more recharge. Because rainfall is more prevalent in the northern High Plains, more recharge occurs. Finally, irrigation in the northern High Plains requires a much lower rate of pumping per square mile than in the southern High Plains.

In the southern and central High Plains, withdrawals from storage have been so great that the aquifer has been dewatered by more than 50% in over 3,500 square miles. This decline affected irrigation in two ways. First, increased energy costs are required because water is pumped from a greater depth. Second, as the saturated thickness of the strata declined, yields of individual wells also declined, so additional wells must be drilled to provide the same water volume. These economic impacts led to the beginning of a gradual decline in the use of groundwater in the High Plains—withdrawals in the southern High Plains declined 11% since 1964. Growers are taking other approaches such as installing more efficient irrigation hardware and shifting to crops and varieties that require less water.

Central Valley of California

The Central Valley of California is the most heavily pumped contiguous area in the United States. The watershed encompasses 20,000 square miles. Prior to development, total groundwater circulation through the aquifer system was 650 billion gallons per year. From 1961 to 1978, about 7.2 trillion gallons per year were used for irrigation in the Central Valley—about half from groundwater. During this period, groundwater recharge was about 90% of withdrawals; however, 82% of the recharge water came from irrigation water percolating back to the aquifers. Consequently, 261 billion gallons per year were withdrawn from groundwater storage. About half this amount lowered the water table and about half came from dewatering sediments that compacted and led to surface subsidence.

Since 1978, generally wet conditions in the Central Valley stimulated recharge to the point where groundwater withdrawals from storage ceased and some additions to storage occurred. Given the wet weather and current equilibrium in groundwater withdrawals and recharge, Central Valley water managers believe that subsidence can be controlled. The key appears to be limiting withdrawals to keep the water level above its historical low point in subsidence-prone areas.

Southeastern and Atlantic Coastal Plain

Two regional aquifers provide water over a wide area along the Atlantic Coast. One underlies Florida, southern and eastern Georgia, and adjacent areas of South Carolina and Alabama. The second underlies the Atlantic Coast between South Carolina and Long Island. Both have been extensively developed for agricultural, industrial, and municipal supplies. The former aquifer exists primarily in limestone and dolomite rock formations; the latter in unconsolidated sands and gravels of the coastal plain. In both, recharge is excellent due to humid climate and plentiful precipitation.

Extensive development in both aquifers led to declines in water levels. In both aquifers, the effective lower boundary is the transition from circulating freshwater to underlying saline water which moves much slower, if at all. Transition layer location is deepest where recharge is greatest and rises toward the coastlines in the general direction of streamflow. In some parts of coastal Florida, especially the area south of Lake Okeechobee, brackish or saline water extends to the top of the aquifer. Here, and also along the Atlantic Coast, development of the groundwater resource is encouraging saltwater intrusion.

In addition to saltwater intrusion, heavy pumping in these coastal plain aquifers results in a reduction in instream flows. Both the limestone formations beneath the Southeastern Coastal Plain and the unconsolidated sands and gravels beneath the Atlantic Coastal Plain have many intersections with streambeds. Part of the reason that recharge is excellent for these aquifers is due to the ease with which streamflow can be diverted into the rock, sands, and gravels. Because heavy pumping induces a recharge response from all directions, intensive development of these coastal aquifers draws saline water from the oceans and drains freshwater from streams. In some aquifers, such as the Castle Hayne in eastern North Carolina and Virginia, heavy withdrawals for municipal and industrial uses created several large zones of depression that are merging regionally.[6] The long-term consequences of both situations are unfavorable.

Arizona Lowlands

The semiarid lowlands of Arizona cover 50,000 square miles and are the most heavily pumped region in the state. Irrigation is the largest use of water with two-thirds drawn from groundwater. In recent years, competition has been growing between irrigators and municipalities. Tucson is entirely dependent upon groundwater and more than half of Phoenix's supply comes from groundwater.

Vast quantities of groundwater are stored in sediments beneath the basin. Because potential evapotranspiration greatly exceeds precipitation, only limited amounts of water are available for natural recharge to the groundwater. Thus, extensive withdrawals of groundwater from storage resulted. In 1981, about 1.7 trillion gallons of groundwater were pumped, of which 1.4 trillion gallons were used for irrigation. The current annual depletion of groundwater in the area is estimated at 650 billion gallons, or roughly 40% of withdrawals.

A number of hydrologic changes resulted from intensive withdrawals of this magnitude. Groundwater levels declined as much as 400 feet in some places since the 1940s and rates of water-level decline been as great as 8 feet per year. In many areas, water-level declines altered natural flow patterns that existed prior to development, creating a series of small, self-contained individual flow systems near each pumping center. In some areas of extensive water-level decline, the land surface subsided as much as 12 feet and earth fissures caused damage to public and private property. Concerns over land subsidence together with the self-limiting factors inherent in groundwater storage depletion—declining well yields and rising energy costs for pumping—are acting to reduce withdrawal rates.

Groundwater Summary

Patterns of water development in the nation have varied between two general conditions. In water deficient areas, such as southern Arizona and the southern High Plains, long-term withdrawal of groundwater from storage (groundwater mining) has supplied agricultural and municipal needs for many decades. These withdrawals cannot be sustained indefinitely. Decreases in withdrawals are taking place as falling water levels cause well yields to decrease and pumping costs to rise. In humid areas such as the Southeastern and Atlantic Coastal Plains, groundwater development has redistributed the natural flow pattern so that water which originally discharged to streams, to the sea, or to evapotranspiration, is now diverted to well fields. In these areas, the groundwater system conveys water from source areas to points of use and provides short-term storage during drought. The net depletion of groundwater in storage has been small since the aquifers were first developed. In the Central Valley of California, groundwater development has followed a course somewhat between these two conditions. Substantial withdrawals occurred, but the system now appears to be in equilibrium between withdrawals and recharge. Coordinating the use of both surface and groundwater withdrawals, in which short-term depletions of groundwater are used to make up deficiencies in surface supplies during droughts, and recharging aquifers when surface supplies become more plentiful, should be possible on a sustained basis.

INSTREAM USE

Instream uses include fish and wildlife propagation, recreational activities, maintenance of estuary salinity balances, hydropower generation, navigation, and waste dilution and transportation. In the past, waste dilution and transport was considered the primary use of instream flows. Findings by Wollman and Bonem (1971) ignored water flows needed for navigation and fish habitat, assuming that if sufficient water was available for waste dilution, those needs would also be met. They calculated flows needed for waste dilution at different wastewater treatment rates. They concluded that if municipalities removed 70% of the waste delivered to them and private treatment facilities (generally industrial plants) removed 50% of the waste delivered, then instream flows needed to preserve instream water quality would vary from 1,423 bgd in 1985 to 5,569 bgd in 2020. If 90% of the waste was removed by both public and private facilities, the instream flow needs would be reduced to 231 and 740 bgd in 1985 and 2020 respectively. The maximum volume of instream flows reported by Wollman and Bonem was 956 bgd. Thus, it was clear that with the assumption of 70% and 50% treatment levels, instream water quality would seriously deteriorate.

These findings served as a major impetus for passage of Public Law 92–500, the Federal Water Pollution Control Act Amendments of 1972, also known as the Clean Water Act. This law revised national policy toward instream water quality and wastewater treatment by limiting use of instream flows for additional waste dilution and setting goals for attaining "fishable-swimmable" water quality in most streams through use of "best practicable" and "best attainable" wastewater treatment technologies.

Instream flows for hydropower electricity generation are typically provided by dams. Instream flows typically do not have the required "head" to generate power without some sort of storage and/or diversion structure. These uses will be reviewed below in the surface water development section.

Freshwater stream flows are essential to keep the proper salinity balance in estuaries. Estuaries are often very fertile interfaces between saline ocean waters and freshwater from streams. The resulting brackish waters support extensive commercial and sport fisheries. For example, along the Gulf Coast, brackish water serves as vital breeding habitat for brown and white shrimp, blue crabs, redfish, and speckled trout. Black bass will come down freshwater streams to feed on grass shrimp produced in the brackish water. Thus, maintaining the proper salinity balance with instream freshwater flows becomes critical to sustaining fisheries. Too much freshwater during floods or too little freshwater during droughts are both equally harmful to fisheries depending on brackish water.

Instream flows are also essential for maintaining wetlands and swamps. These ecosystems are also the source of wildlife and fish habitat.

Navigation and recreation activities, such as water skiing and swimming, generally do not suffer benefit losses over a long-term if low instream flows occur. Wildlife and fish populations, on the other hand, do suffer long-term effects from low flows—effects from which they may take years to recover. Recreational and commercial activities associated with wildlife and fish will also suffer long-term losses in benefits if low flows destroy habitat or breeding populations. This Assessment defines necessary instream flow levels based upon wildlife and fish needs.

Generalized Water Budgets

Generalized water budgets have been used by resource planners and managers to evaluate water resource allocations (USGS 1984, Foxworthy and Moody 1986, and Flickinger 1987). Updated water budgets for water resource regions were developed for this Assessment and reflect the latest information (water use data for 1985 from USGS). The first portion of the water budget is presented here, with the final part in Chapter 4, where water supply projections are developed. The objective of the first portion of the budget is to account for groundwater depletion rates and instream flows necessary for optimum wildlife and fish habitat. The balance of instream flows are then available for additional consumption by offstream uses.

Average annual stream outflows at the downstream end of major water resource regions were estimated by Graczyk et al. (1986) (table 2). Average annual stream outflows come from gauging stations and reflect current consumptive use and net reservoir evaporation levels in the basins. For this table, outflows, consumptive use and evaporation are regarded as fixed. When the annual depletion of groundwater storage (from Foxworthy and Moody 1986) is deducted under the assumption it will cease, the balance is the average annual net streamflow available for instream and additional offstream withdrawal uses. Net reservoir evaporation was estimated by Foxworthy and Moody (1986). The instream flows necessary for optimal fish and wildlife habitat were defined by Flickinger (1987). The amount of water available for additional offstream uses is the net amount remaining after instream flow requirements are deducted from average annual net streamflow. Put another way, the remainder is the limit on volume of surface water available for growth in consumption in each water resource region. The analysis shows that instream flows in the Rio Grande, Upper Colorado, and Lower Colorado water resource regions are insufficient to meet current needs for wildlife and fish habitat, much less allow any additional offstream use.

Table 2.—Average annual net streamflow (billion gallons per day), by water resource region, 1985

Water resource region	Area (1000 sq. miles)	Average annual stream outflows[1]	Annual depletion of ground-water storage	Average annual net streamflow	Instream flow requirement[2]	Net flow available for additional offstream uses
New England	69	76.4	0.0	76.4	69.0	7.4
Mid-Atlantic	103	93.8	0.0	93.8	68.8	25.0
South Atlantic-Gulf	271	207.2	0.0	207.2	188.7	18.5
Great Lakes	134	73.0	0.0	73.0	64.0	9.0
Ohio[3]	160	137.4	0.0	137.4	122.0	15.4
Tennessee	43	42.9	0.0	42.9	38.5	4.4
Upper Mississippi[4]	181	79.5	0.0	79.5	69.7	9.8
Lower Mississippi[5]	106	382.9	5.8	377.1	359.0	18.1
Souris-Red-Rainy	55	7.2	0.0	7.2	3.7	3.5
Missouri	511	55.8	2.2	53.6	34.0	19.5
Arkansas-White-Red	244	61.5	3.6	57.9	46.2	11.7
Texas-Gulf	178	34.2	3.1	31.1	22.9	8.2
Rio Grande	137	2.1	0.0	2.1	2.3	-0.2[6]
Upper Colorado	103	7.6	0.0	7.6	8.0	-0.4[6]
Lower Colorado	155	1.4	2.1	-0.7	6.9	-7.6[6]
Great Basin	139	4.5	0.0	4.5	3.4	1.1
Pacific Northwest	271	277.6	0.0	277.6	214.0	63.6
California	165	71.8	1.4	70.4	32.6	37.8
Alaska[7]	586	921.0	0.0	921.0	---	---
Hawaii[7]	6	13.6	0.0	13.6	---	---
Caribbean[7]	4	4.8	0.0	4.8	---	---

[1]*Gauging station outflows, which include current consumptive use, imports/exports, and net reservoir evaporation.*

[2]*Instream flow requirements were taken from Flickinger (1987). They represent the optimal flows for fish and wildlife habitat—the most critical of instream uses—in average flow years.*

[3]*Excluding outflows from the Tennessee region.*

[4]*Excluding outflows from the Missouri region.*

[5]*Land area for the Lower Mississippi region alone. Flows include inflows from the entire Mississippi River basin, including the Ohio, Tennessee, Upper Mississippi, Missouri, and Arkansas-White-Red regions.*

[6]*Negative numbers indicate that insufficient water currently exists to maintain optimal instream flow conditions and also avoid groundwater depletions.*

[7]*No information on instream flow requirements was available for Alaska, Hawaii, and the Caribbean in Flickinger (1987).*

There are two implications of this current resource situation. The first is that groundwater withdrawals are essential in these regions to maintain current levels of consumptive use. The second is that if growth in offstream uses exceeds the net amount shown or that occurs in the Rio Grande, or Upper or Lower Colorado regions, then either groundwater mining is occurring in excess of current depletion estimates or fish and wildlife habitat is sub-optimal and other instream uses may be curtailed at certain times of the year. In addition to providing habitat, instream flows are essential for maintaining wetlands and swamp ecosystems and for maintaining salinity balances in brackish water ecosystems.

SURFACE WATER DEVELOPMENT[7]

The nation's total endowment of surface water is more than adequate to meet current demands. The real issue is that water is not always available when and where needed. Besides groundwater depletion, the other major reason for water scarcity in an area is increasing competition for what is essentially a fixed supply. For example, from 1960 to 1985, total withdrawals from surface water increased 55% while population increased 32%. This means that surface withdrawals per capita per day have risen from 937 gallons to 1,086 gallons—an increase of 16%.

Water use is analyzed from two perspectives—withdrawals and consumption. Withdrawals are water withdrawn or diverted from a source for use. Consumption is water no longer available for use because it has been evaporated, transpired, incorporated into products or crops; consumed by humans or livestock; or otherwise removed from the water environment. Water withdrawn from a stream is either consumed or returned to the stream, usually after treatment. Water returned is then available for withdrawal and consumption downstream.

Surface water development issues in a particular reach of stream are often most concerned with withdrawals. But from a regional perspective, consumption is the more important measure of use. It is not unusual for withdrawals in a basin to be a multiple of runoff volume because much of the water withdrawn is returned to streams following waste treatment. But total annual consumption cannot exceed total annual runoff at the foot of the basin unless water is withdrawn from groundwater or surface storage. Consequently, water budgets focus on consumption. Surface water structures such as dams, pipes, and canals focus on withdrawals.

In 1985, total freshwater withdrawals in the United States were 343 bgd—83 billion from groundwater, 260 billion from surface water, and 0.6 billion from wastewater. Consumption in 1985 totaled 94 bgd—27% of withdrawals. Irrigation is the use that has the highest ratio of consumption to withdrawals—51% (73.8 bgd consumed of 142.5 bgd withdrawn). Thermoelectric steam cooling has the lowest consumption ratio, 3% (4.8 bgd consumed of 130.9 bgd withdrawn). These are the two uses with the largest withdrawals. Domestic self-supplied and livestock watering have consumption ratios approaching the ratio of irrigation (47% and 45% respectively), but their combined withdrawals in 1985 only totaled 8.3 bgd. Municipal and industrial self-supplied uses fall in the middle, with consumption ratios of 16% and 22% respectively, and withdrawals of 36.7 and 24.5 bgd respectively. Further information on withdrawal and consumption trends is presented in Chapter 3.

The annual consumption rate of 93 bgd is directly comparable with the "net flow available for offstream uses" column in table 2. Because irrigation consumes 10 times the water of any other use and more than 3 times the total consumed by all other uses, obtaining more water for irrigation was the prime water development problem in the U.S. earlier this century. In recent years, however, increasing population and development of diversified commercial and industrial economies in water resource regions where irrigation was historically the dominant water use have increased the competition for water. Emergence of competing uses for water, both in the short-term during droughts and in the long-term to stimulate development, has heightened concern over the adequacy of water supplies and likelihood of water scarcities that hinder growth of both agricultural and nonagricultural economies.

Four approaches have been used to resolve problems of surface water availability: (1) developing structures to store water when it is plentiful and convey it to the area where and when needed; (2) reducing or preventing certain water losses or uses deemed not beneficial; (3) attempts to increase the amount of precipitation; and (4) changing the nature and efficiency of water uses and treatment processes so water of lower quality can be used. Only the second approach deals with altering demand, the other three all seek to modify timing or amount of the available supply.

Structural Surface Water Developments

Of the four approaches available for dealing with surface water scarcity, society invested the most in building storage and conveyance structures. Unregulated flow of many of the Nation's rivers is highly variable throughout the year. For example, the rate of flow during floods is many times greater than during droughts. Some streams are called "intermittent" because they cease flowing during parts of the year. Most withdrawals, on the other hand, show much less variability—many being nearly constant on a weekly basis. When the rate of withdrawals approaches the average daily flow rate of a river, there are many days during the year when the desired amount of water is unavailable. Thus, reliance upon surface water as a source of supply usually requires damming to create a reservoir to store water from wet periods for use during dry periods. If the reservoir is located upstream from where water is used, water stored behind the dam may be released during dry periods to flow downstream to the point of use. In some cases, stored water is withdrawn directly from the reservoir and carried by pipe or canals to the point of use. In either situation, there are usually minimum instream flows that must be maintained below the dam or the point of diversion.

There are 2,654 reservoirs and controlled natural lakes with capacities of 5,000 acre-feet or more in the United States and Puerto Rico. These have a combined normal storage capacity of 480 million acre-feet. The 574 largest reservoirs account for almost 90% of total storage. In addition, there are at least 50,000 smaller reservoirs with capacities in the range of 50 to 5,000 acre-feet and about 2 million smaller farm ponds used for storage, table 3 (U.S. Army Corps of Engineers, 1981). Distribution of reservoir capacity in the water resource regions of the Nation, expressed as the sum of the normal capacities of all reservoirs larger than 5,000 acre-feet, is shown in table 4 (U.S. Army Corps of Engineers 1981). Normal capacity—the capacity exceeded only during floods—represents a desired storage level for the reservoir and averages about two-thirds of maximum capacity.

Reservoirs are often described as having a "safe yield" which is the amount of water that can be withdrawn or released on an ongoing basis with an acceptable risk of a supply interruption. If the desired safe yield is small in comparison to the average flow rate of the river (say 10% of average flow), then the dry period for which the reservoir stores water may be a few weeks or months of the year's driest part. For a safe yield approaching the average annual river flow (between 50% and 90% of average flow), the dry period for which the reservoir stores water may span several years. The required size of a reservoir to satisfy a given demand is determined by the volume of water necessary to carry users through

Table 3.—Summary of reservoir storage capacity, including controlled natural lakes, in the United States and Puerto Rico, 1981

Reservoir size[1] (acre-feet)	Number of reservoirs	Total reservoir storage: Capacity (1,000 acre-feet)	Percent of total
Greater than 10,000,000	5	107,655	22.4
100,000 to 10,000,000	569	322,852	67.3
50,000 to 100,000	295	20,557	4.3
25,000 to 50,000	374	13,092	2.7
5,000 to 25,000	1,411	5,632	3.3
Total[2]	2,654	479,788	100.0

[1]*Reservoir size is expressed as normal capacity of storage, which is the total storage space in a reservoir below the normal water retention level. Normal capacity includes dead storage and inactive storage but excludes any flood-control or surcharge storage.*

[2]*In addition, there are perhaps at least 50,000 reservoirs with capacities ranging from 50 to 5,000 acre-feet, and about 2 million smaller farm ponds used for storage.*

Source: U.S. Army Corps of Engineers (1981), cited in Anon. (1984)

Table 4.—Distribution of reservoir storage by water resource region, 1981

Water resource region	Area in region 1000 mi²	Average renewable supply, bgd	Normal reservoir capacity: Million acre-ft	Acre-ft per square mile	Percentage of renew. supply
New England	69	77.3	13.0	188	15.0
Mid-Atlantic	103	96.5	10.3	100	9.5
South Atlantic-Gulf	271	213.0	38.7	143	16.0
Great Lakes	134	76.8	6.9	51	7.9
Ohio[1]	160	140.0	19.6	123	12.0
Tennessee	43	43.3	11.2	260	23.0
Upper Mississippi[2]	181	79.7	12.2	67	14.0
Lower Mississippi[3]	160	76.0	5.7	36	6.7
Souris-Red-Rainy	55	7.7	8.0	145	93.0
Missouri	511	67.3	84.3	165	112.0
Arkansas-White-Red	244	63.7	31.8	130	45.0
Texas-Gulf	178	35.9	24.7	139	61.0
Rio Grande	137	5.0	10.4	76	189.0
Upper Colorado	103	12.3	37.7	366	261.0
Lower Colorado[4]	155	-1.1[5]	32.7	211	299.0
Great Basin	139	8.3	3.3	24	35.0
Pacific Northwest	271	291.0	60.9	225	19.0
California	165	86.9	38.8	235	42.0
Alaska	586	921.0	1.5	3	0.1
Hawaii	6	14.3	0.0	2	0.0
Caribbean	4	5.1	0.3	90	5.2

[1]Exclusive of outflows from the Tennessee water resource region
[2]Exclusive of outflows from the Missouri water resource region
[3]Exclusive of outflows from the Ohio, Tennessee, Upper Mississippi, Missouri, and Arkansas-White-Red water resource regions.
[4]Represents conditions in the Upper and Lower Colorado water resource regions.
[5]The annual renewable supply of the combined Upper and Lower Colorado water resource regions is 11.2 bgd. The supply for the Upper Colorado was reported as 12.3; the estimate for the Lower Colorado was computed.

U.S. Army Corps of Engineers (1981), cited in Anon. (1984)

the dry period. This volume is the product of flow deficiency (demand minus flow) and duration of the dry period.

As is the case with pumping groundwater, the law of diminishing returns applies. Each successive increment in safe yield requires more storage than the preceding increment. For example, doubling safe yield would require more than doubling storage capacity, which, in turn, requires more than doubling construction costs. Hardison (1972) found that, for all water resource regions in the continental U.S., the point at which safe yield reaches its maximum is when storage is in the range of 160 to 460% of average renewable supply of the region. The variation depends, in part, upon the use or variety of uses (such as water supply, flood control, power generation) served by the stored water.

Another index of reservoir capacity is normal reservoir capacity in the region per unit area of the region. If Alaska and Hawaii are excluded, the range in intensity of development among regions is considerable—ranging from 24 acre-feet per square mile in the Great Basin to 366 acre-feet per square mile in the Upper Colorado. Factors influencing the intensity of development include availability of precipitation and groundwater to help satisfy water demands, magnitude of the surface flows available for development, existence of suitable reservoir sites, and political and institutional factors governing reservoir development. The upper limits on development of suitable sites among regions appear to range from about 250 to about 500 acre-feet per square mile (Langbein 1982).

Historical trends in reservoir development show an average growth rate in capacity of major reservoirs in the United States of about 80% per decade from 1920 to the early 1960s. Since then, reservoir capacity increased at a much slower rate. The current status of reservoir development is about 450 million acre-feet. Based on a number of intensive surveys, there remain about 750 million acre-feet of potential storage in the continental U.S. where building dams is feasible from an engineering perspective. Because most cost-effective sites have been developed, adding a significant portion of the potential storage to the current level of development will entail very high investments—so high as to be nearly prohibitive. If so, the Nation's current reservoir capacity may be near the limit of development.

There are, however, other means for coping with providing water to meet future demands. Most of these are non-structural measures that require changing management guidelines or regulations. Such changes, of course, often have costs of their own—social and environmental as well as economic. For example, there are a large number of multiple-purpose reservoirs where withdrawals are not now the primary purpose of management. A shift in water allocation could make additional capacity available to meet future water supply shortages in time of drought. Better management has the potential for increasing safe yields, up to a limit, without increasing storage (Toebes 1981).

An example of better reservoir management is found in the Washington, DC metropolitan area (Sheer 1983). The area's water supply comes from three rivers and four reservoirs: the Potomac, with one reservoir 200 miles upstream; the Patuxent in Maryland, with Tridelphia and Rocky Gorge Reservoirs; and the Occoquan, with Occoquan Reservoir. The sum of safe yields of these three sources is 513 million gallons per day, but demand for water is expected to reach 750 million gallons per day by the year 2000. Through analyses of the complete system—intentionally ignoring certain institutional constraints of three separate water supply agencies—it was found that existing structures could reliably supply water until the year 2030. After recognizing the large gains that could be achieved through flexible and integrated operations, those involved forged the necessary legal and financial agreements to make this possible. The savings are in excess of $200 million. These savings were achieved through systems analysis techniques such as linear programming, synthetic hydrology, statistical analysis, hydrologic modeling, long-range probabilistic forecasting, and computer simulation.

The trend towards using nonstructural measures to solve problems instead of building more dams places greater dependence upon management skill, understanding the nature of river behavior, and better river forecasting. At some point, potentials for conservation and better management may become less cost effective than building additional storage.

Controlling Losses and Low-Priority Uses

A number of options are available for eliminating or curtailing water losses and uses judged not beneficial, given current supplies. One is to reduce water leaks from pipes and ditches delivering water to municipal and irrigation users. Stopping leaks does not make more water available in a region because leakage returns to aquifers. But it is a way of increasing the usable supply at low cost because leakage water has been diverted, treated and transported—often at high cost—yet is never available for use. Moyer et al. (1983) and Pilzer (1981) analyzed leak detection programs.

Implementing voluntary or mandatory rationing schemes is the quickest way to curtail low priority water uses. Mandatory actions such as restricting lawn watering to one day in three or prohibiting automobile washing during a drought period were employed during recent droughts in the East. Some citizens adapted to such restrictions by using rinse water from laundry to water vegetable gardens or wash vehicles—a form of household recycling. Other forms of voluntary household conservation include installing a showerhead that emits fewer gallons per minute and bending the float arm in toilet tanks to reduce the volume of water per flush.

Voluntary or mandatory rationing schemes are but one type of institutional modification that can reduce demand and stretch available supplies. Experience with such institutional changes demonstrates that there are few absolute water requirements. Most offstream water users have considerable flexibility in selecting rates of water intake and recycling. Water use may change, for example, in response to changes in water prices or waste treatment charges (Foster and Beattie, 1979; Strudler and Strand, 1983; and Young et al., 1983). Installation of water meters has led to reductions in water use in some areas; a contributing factor is often the switch from flat rate to variable rate structures. Industrial users may change water use practices in response to energy prices and waste treatment regulations (Babin et al., 1980). Irrigators are moving to more efficient irrigation hardware and management methods. The Federal Interagency Task Force on Irrigation Efficiencies (1979) estimated that $5 billion in public and private expenditures on water conservation by 2010 could reduce withdrawals by 13 to 18 bgd and thereby make 1.7 to 4.5 billion gallons available for new consumptive uses. In some western states, the appropriation doctrine of water rights limits user flexibility to sell water not currently needed, often placing users in a "use it or lose it" situation. Modifications in the water-rights institution can help shift water from users who have more senior rights to those with junior rights. Ideally, such changes could be temporary so the owner of senior rights does not lose them permanently or through markets enabling junior users to bid for rights.

A detailed discussion of the many forces influencing water use and of various demand management practices and policies is beyond the scope of this Assessment. Kelso et al. (1973) examined some of these problems in a case study of Arizona. Hirshleifer et al. (1969) and Baumol and Oates (1979) provide a more general discussion of these topics.

Increasing Precipitation

Weather modification is another approach to enhancing water supplies. Serious scientific attention to techniques for artificially increasing precipitation began around 1946. There have been more than a dozen major research projects dealing with this subject in the United States. Findings of these studies are the subject of controversy in scientific literature. See, for example, Hess (1974), Tukey et al. (1978) and Braham (1979).

Ski areas in California and Colorado are practicing weather modification on a commercial basis. However, serious impacts on stream channels can occur where snow accumulates in excess of what stream channels can handle during snowmelt. Reservoir capacity must be available to store increased snowmelt if this runoff is to contribute to increased regional water supplies.

Using Low Quality Water

Using water of lower quality, such as recycling treated wastewater, has not become as popular as some forecast when Congress debated the Federal Water Pollution Control Act Amendments of 1972. Wastewater use today is 5% lower than in 1960. Between then and now, use peaked 10% higher than present and dropped 20% below present. A decided trend in wastewater use is not evident, except it has not increased nearly as much as expected. Wastewater reuse is not new. Bethlehem Steel in Baltimore, MD has used over 100 million gallons per day of Baltimore's treated wastewater since 1942.

Saline water use has increased seven-fold from 1950 to 1980 (Solley et al., 1983), mostly for industrial cooling purposes. Saline water use represents an enhancement of supply, but presents problems for industry. The rate of increase in saline use, however, demonstrates that solving those problems has proven less costly than acquiring additional supplies of freshwater.

QUALITY OF WATER AVAILABLE FOR USE[8]

Water-quality degradation is widely publicized but has not become a major limitation on water availability or use nationwide. A relative abundance of good quality surface water still exists, even though serious water-quality problems have developed in some stream reaches and some streams cannot support the full range of desired uses.

There are six major categories of pollutants:

1. Disease-causing organisms—Fecal coliform bacteria are used as indicators of the presence of other infectious agents including bacteria, fungi, and viruses.
2. Nutrients—These stimulate aquatic plant growth, and can result in altered aquatic communities, fish kills, excess weed growth, unpleasant odors and tastes, and impaired recreational uses.
3. Silts and suspended solids—These modify aquatic communities through habitat alteration, impair fish respiration and reproduction, and reduce plant productivity by reducing sunlight penetration and photosynthesis. Silts and solids, known as turbidity, may reduce aesthetic appeal and recreational uses.
4. Biochemical oxygen demand (BOD)—These materials reduce availability of dissolved oxygen crucial to respiration of fish and aquatic invertebrates.
5. Salinity and total dissolved solids—These materials impair the use of water for drinking and crop irrigation and adversely affect aquatic ecosystems.
6. Toxics—These substances can cause death, mutation, or reproductive failure in fish and wildlife and may pose carcinogenic or other health threats to humans.

Water pollution is usually attributed to one of two sources—point or nonpoint—depending upon how water enters the aquatic environment. Point sources discharge a flow to the aquatic environment through a pipe, ditch, or other mode of conveyance. Nonpoint sources discharge a flow to the aquatic environment as runoff, not collected or concentrated by a conveyance structure.

During the 1960s, growing environmental awareness of water quality issues led to passage of several laws pertaining to water quality. The Clean Water Act of 1972 (amended in 1977 and 1981) and the Safe Drinking Water Act of 1974 (Public Law 93–523) were two of the most prominent. These laws motivated both the public and private sectors to spend billions on different types of pollution abatement programs, designed mainly to reduce point-source pollution and improve instream quality. For example, more than $100 billion was spent for pollution control between 1974 and 1981 (U.S. Environmental Protection Agency 1984). From 1972 to 1982, total biochemical oxygen demand (BOD) load from municipal waste treatment plants decreased an estimated 46% and industrial load decreased at least 71% (ASIWPCA 1984). These gains in waste treatment occurred simultaneously with increases in population and real Gross National Product (GNP) of 10% and 27% respectively.

Significant improvements have been reported by the National Stream Quality Accounting Network (NASQUAN) stations operated by USGS and the National Stream Quality Surveillance System (NWQSS) operated by EPA. Between October 1974 and October 1984, widespread decreases in fecal coliform bacteria, lead concentrations, and phosphorus concentrations have been monitored downstream of major point-source dischargers (Smith et al., 1986 and 1987). These trends provide some evidence of benefits of improved wastewater treatment for point-source discharges and benefits from the switch to unleaded gasoline. The same studies, however, have also shown widespread increases in nitrate, chloride, arsenic, and cadmium concentrations. Recorded increases in nitrogen fertilizer applications and use of salt on highways along with regionally variable trends in coal production and combustion are reflected in increasing nonpoint-source pollution loads.

Every two years, EPA summarizes water-quality reports submitted by the States and other jurisdictions in accordance with Section 305(b) of the Clean Water Act, as amended. The 1986 Report (EPA, 1987) marked the first time that all states and jurisdictions submitted data.[9] These data show that three-fourths of the Nation's rivers, lakes, and streams are fully supporting their designated uses (table 5).

States were asked to rank pollution sources impairing the ability of surface and groundwater to fulfill desired uses. Nonpoint sources are responsible for impairing water quality much more frequently than point-source pollution. Of assessed waters with impaired uses, nonpoint sources of pollution were responsible in 76% of lake acres, 65% of stream miles, and 45% of estuarine square miles. Point sources were responsible in 34% of estuarine square miles, 27% of stream miles, and 9% of lake acres.

In 1986 reports under Section 305(b) of the Clean Water Act, States were asked to provide individual discussions of issues found to be of either current or emerging special concern (EPA 1987). Surface water concerns most often discussed by States included mine drainage, nonpoint-source pollution, toxics and public health, acid deposition, groundwater protection, and wetlands loss.[10]

Table 5.—Degree of designated use supported by the Nation's waters, 1986

	Rivers (miles)	Lakes (acres)	Estuaries[1] (sq. miles)
Total in U.S.	1,800,000	39,400,000	32,000
Total Assessed	370,544	12,531,846	17,606
(% of total in U.S.)	(21%)	(32%)	(55%)
Fully supporting uses	274,537	9,202,752	13,154
(% of total assessed)	(74%)	(73%)	(75%)
Uses are impaired			
Partially supporting uses	70,196	2,181,331	3,224
(% of total assessed)	(19%)	(17%)	(18%)
Not supporting uses	22,974	859,080	1,177
(% of total assessed)	(6%)	(7%)	(7%)
Unknown support of uses	2,127	288,684	51
(% of total assessed)	(1%)	(2%)	(0.3%)

[1]*Total U.S. estuarine square miles exclude Alaska*

Source: EPA (1987)

In the mid-1970s, experts believed that point-source pollution was the more significant source. Accordingly, efforts to improve water quality were focused upon point sources discharging more than 5 million gallons per day. The effect was to target grant and enforcement programs on roughly a fifth of the dischargers, who in total, created nearly four-fifths of the total volume discharged. Obtaining compliance by this group required substantial public and private investments and water quality has improved. Obtaining similar compliance by the remaining large number of small point-source dischargers will be more difficult and not nearly as cost-effective. Further, as the large point-source discharges were brought into compliance, it became more and more evident that nonpoint sources (which are even more difficult to track and costly to control than small point sources) were also a major cause of water quality problems.

POINT-SOURCE POLLUTION

There are three major types of point-source dischargers—municipal sewage treatment plants, industrial facilities, and combined sewer overflows. Municipal sewage treatment plants commonly discharge BOD, bacteria, nutrients, ammonia, and toxics. Industrial facilities commonly discharge BOD. There are a wide variety of other substances discharged by industries, depending upon their manufacturing processes. Chief concerns center around toxics. Combined sewer overflows occur where urban stormwater runoff flows into catch basins that empty into the same sewer pipes as residential and industrial wasteflows. If the runoff volume exceeds the short-term conveyance capacity of sewers, excess water causes sewers to overflow and dump a mixture of stormwater runoff and untreated residential and industrial waste into nearby surface waters. The most common pollutants in combined sewer overflows are BOD, bacteria, turbidity, total dissolved solids, ammonia, and toxics.

Biochemical Oxygen Demand

In the decade after passage of the Clean Water Act, municipal loads of BOD decreased 46% and industrial BOD loads decreased 71% nationally. Industrial sources currently contribute about one-third of the total point-source BOD load nationwide. Most industrial BOD load reduction occurred in the mid-1970s shortly after the law was passed. Municipal reductions occurred later, in the early 1980s. Federal expenditures for upgrading municipal facilities under the Construction Grants Program reached a maximum in 1980 and totaled $35 billion from 1972 to 1982. Smith et al. (1987) outlined results of statistical analyses of BOD reductions and changes in dissolved oxygen deficits. They reported little statistical support for concluding that construction expenditures reducing BOD loads had a significant effect on reducing dissolved oxygen deficits. This finding is contrary to surveys of state and local pollution control personnel (ASIWPCA 1985) which reported increased instream dissolved oxygen concentrations.

Bacteria

Decreases in fecal coliform and fecal streptococcal bacteria were widespread from 1972 to 1982. Decreases in fecal streptococcal bacteria were especially common in parts of the Gulf Coast, central Mississippi, and the Columbia basins. Decreases in both forms of bacteria were common in the Arkansas-White-Red basin and along the Atlantic Coast. A major emphasis of the Construction Grants Program was installation of secondary treatment as the minimum treatment level. This led to construction of centralized waste collection and treatment facilities for the first time in many communities. Whenever new collection sewers were installed, they were kept separate from stormwater collection sewers. In many cases, new residential and industrial sewers were constructed to segregate residential and industrial wastes from stormwater.

Another major source of fecal bacteria is runoff from animal feedlots, a nonpoint source of bacteria. Several lines of evidence suggest that the widespread decreases in fecal bacteria are due to improved municipal waste treatment and not to any concerted effort to reduce feedlot runoff. Where fecal bacteria increases have been measured in recent years, they are positively associated with cattle population density and feedlot activity in the watershed (Smith et al. 1987).

Mine Drainage

When thinking of industrial facilities, manufacturing plants more often come to mind than resource extraction facilities. But water pollution from resource extraction operations was recognized as a major problem as far back as the 1800s. Although most resource extraction operations create nonpoint-source pollution, mines create both point- and nonpoint-source pollution.

In spite of tremendous strides that the mining industry has made to clean up abandoned mines and control discharges from active ones, mine drainage was still reported as one of the major point-source concerns by nine States in their 305(b) reports (EPA 1987) (fig. 4). In addition, mining activities were widely reported by states as a cause of use impairment across the Nation.

Mine-related sources cause a variety of impacts to rivers and lakes. Acid mine drainage occurs when sulfur-bearing minerals are exposed to water and air in the mining process and join to form sulfuric acid. Contaminated water draining or seeping from mines can create acidic conditions in receiving streams. This may dissolve metals from geologic formations and carry these into waterways and, when entering a pH-neutral stream, may form iron compounds that "settle out" and smother bottom-dwelling aquatic organisms, thus creating havoc with aquatic ecosystems (EPA 1987). These factors can devastate streams for miles downstream of mining activity. Cleanup and control, always a complex issue, is complicated further because many of the worst problems come from mines operated and abandoned long before water quality impacts were a consideration.

Metal mines, such as silver, lead, and copper, most widely found in the western U.S., can directly contribute metal-laden runoff through tailings piles and mine seepage. Sedimentation, erosion, and habitat destruction resulting from earthmoving activities are also significant problems associated with mining.

Point-source discharges from active mines are regulated by EPA and state National Pollutant Discharge Elimination System permits. Many states also use Best Management Practices (BMPs) to regulate nonpoint emissions from mines. Pollution from abandoned mines is addressed in the Federal Surface Mining Control and Reclamation Act of 1977 (Public Law 95–87). Programs to control runoff from abandoned mines include treating wastes; reclaiming land through refilling, regrading, and replanting; and sealing mine openings.

NONPOINT-SOURCE POLLUTION

There are seven major types of nonpoint-source pollution dealing with some form of runoff. Categories and the types of pollutants commonly found include:

1. Agricultural runoff—Nutrients, turbidity, total dissolved solids, toxics, and bacteria;
2. Urban runoff—Same pollutant categories as agricultural runoff, but in different concentrations;
3. Silvicultural runoff—Nutrients, turbidity, toxics;
4. Construction runoff—Same pollutant categories as silvicultural runoff, but in different concentrations;
5. Mining runoff—Turbidity, acids, toxics, total dissolved solids;
6. Landfills/spills—Toxics, miscellaneous substances;
7. Septic systems—Bacteria, nutrients.

Bacteria, nutrients (principally nitrates, ammonia, phosphorus), and turbidity (suspended sediments) are the key nonpoint-source pollutants.

Thomas (1985) suggested that nonpoint-source pollution may prevent achievement of national water-quality goals even after complete implementation of planned point-source controls. Sixteen states identified nonpoint-source pollution as an issue of special concern in their 305(b) reports (fig. 5). Suspended sediment and nutrients

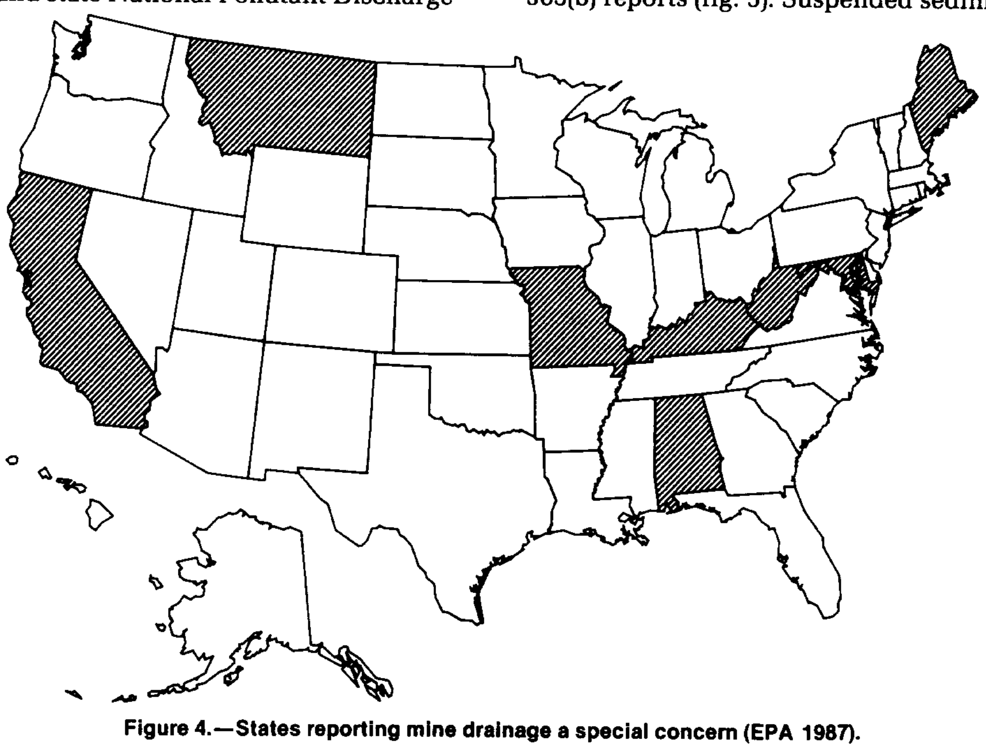


Figure 4.—States reporting mine drainage a special concern (EPA 1987).

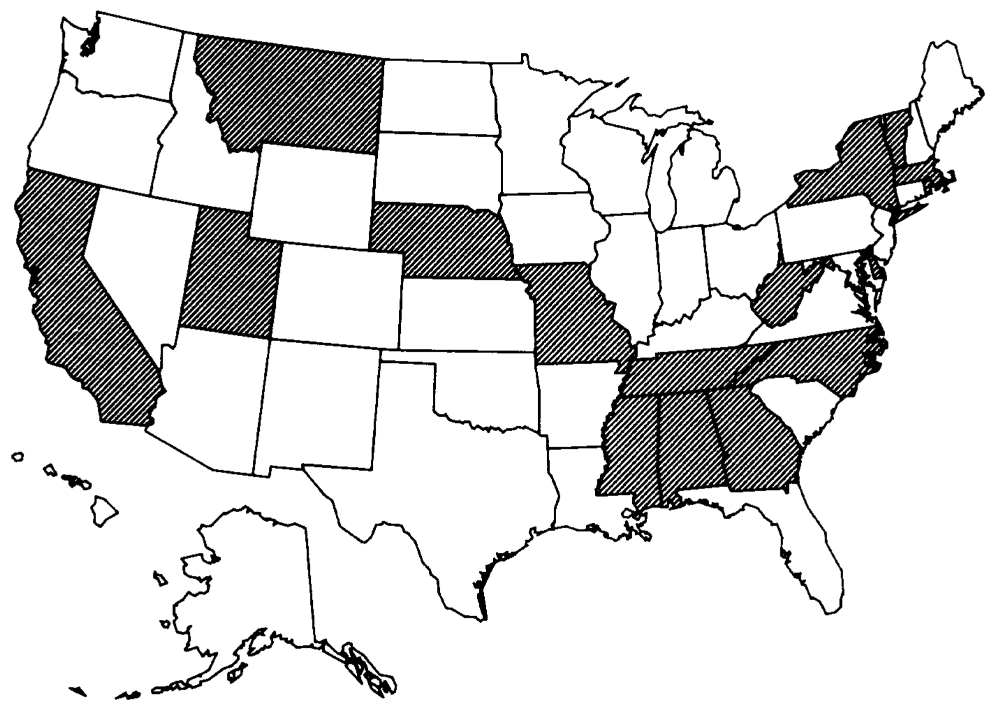


Figure 5.—States reporting nonpoint-source pollution as a special concern (EPA 1987).

from agricultural sources are cited as the most damaging nonpoint-source pollutants nationally. The cost of the hydrologic impacts of soil erosion and related nutrients on aquatic ecosystems has been estimated at $3.5 billion annually (Clark et al. 1985). In spite of wide recognition of nonpoint-source pollution problems, little information is available on long-term trends of nonpoint-source pollution.

Farm activity increased significantly between 1972 and 1982. Fertilizer application rates increased 68% between 1970 and 1981 as farm production increased rapidly (Smith et al. 1987). The extent to which these and other changes in land management practices, primarily agricultural, are reflected in trends in suspended solids, nitrogen, and phosphorus concentrations in streams has largely been a matter of guesswork because no systematic long-term studies are available (Smith et al. 1987).

Suspended Sediment

Nationwide trends from 1974 to 1980 in suspended sediment concentrations were mixed, reflecting both increases and decreases. Increases in suspended sediment concentrations occurred in watersheds where the predominant forms of land use have historically been associated with high rates of soil erosion. An example is logging in the Columbia basin. Smith et al. (1987) tested the association between suspended sediment trends in streams and erosion rates for specific land use categories by using the USDA National Resources Inventory from 1982. They found that trends in suspended sediments were not significantly associated with estimates of total watershed soils erosion. Increases in suspended sediments, however, were significantly related to soil erosion contributed by cropland in the watershed. In contrast to these results, suspended sediment concentrations were *not* associated with erosion rates on forest land, pasture, or range.

Factors other than soil erosion have played an important part in suspended sediment concentrations in streams in some watersheds. For example, some streams in the Columbia basin carried increased sediment loads in 1980 and 1981 after the eruption of Mount St. Helens. Declining concentrations have been reported at several locations in the Missouri River basin and have been clearly traced to the effects of reservoir construction throughout that basin in the 1950s and 1960s (Williams and Wolman 1986).

Phosphorus and Nitrates

Trends in total phosphorus concentrations followed a pattern similar to that of suspended sediments with the exception that decreases in total phosphorus were prevalent in the Great Lakes and Upper Mississippi basins. Decreases in the Great Lakes region resulted partly from point-source reductions in the late 1970s. Increases in the Great Lakes region resulted largely from nonpoint sources. As with sediments, phosphorus increases are significantly associated with various measures of agricultural land use including fertilized acreage and cattle population density. Additional evidence is provided by the close relationship between changes in phosphorus concentrations and changes in suspended sediment concentrations which have already been shown closely linked to agricultural land use changes.

In contrast to suspended sediments and total phosphorus, increasing trends in total nitrate concentrations were common and widespread. Increasing trends were most prevalent in the North and South. Increases in total nitrates were strongly associated with several measures of agricultural activity including fertilized acreage as a percentage of watershed areas, livestock population density, and feedlot activity.

In addition to agricultural runoff, atmospheric deposition became a major source of nitrate in surface waters, especially in forested watersheds of the North. Few nitrate deposition records exist for the years before 1980, but those that do (National Academy of Sciences, 1983; Galloway et al., 1982), together with emission estimates for nitrous oxides (Gschwandtner et al., 1985) show a general pattern of increasing rates during the 1974-to-1981 period. Consistent with this trend, total nitrate increases at monitoring stations were strongly associated with high levels of atmospheric nitrate deposition, particularly in the Ohio, Mid-Atlantic, Great Lakes, and Upper Mississippi water resource regions.

Point-source nitrogen loads declined in many watersheds during the late 1970s as a result of improvements in municipal wastewater treatment facilities. But improvements in point-source nitrate loads had no statistically significant effect upon nitrate concentrations instream (Smith et al. 1987). Consequently, total nitrate trends appear more related to nonpoint sources than to point sources. In particular, atmospheric deposition of nitrates may have played a large role in the frequent occurrence of total nitrate increases in midwestern and eastern watersheds.

Given the large increases in fertilizer application rates that occurred in the 1970s and early 1980s, it is not surprising that trends in both total phosphorus and total nitrates show strong associations with measures of agricultural activity. Despite the importance of agricultural sources, however, distinct differences exist in trend patterns for phosphorus and nitrates. Increasing trends in phosphorus and suspended sediment concentrations occurred with only moderate frequency and were largely confined to major mid-continent watersheds. In comparison, increasing trends in nitrate concentrations occurred with high frequency and were widely distributed from the Great Plains eastward. The differences in pollution patterns appear to result from three factors. First, atmospheric deposition seems to have played a large role in the high frequency of increasing trends in nitrate concentrations, especially among forested watersheds in the Lake States, Central States, and East. Second, low frequency increasing trends in, and strong association between, phosphorus and suspended sediment concentrations suggest that anticipated increases in phosphorus concentrations resulting from increases in agricultural activity in the 1970s were moderated or delayed by temporary storage of phosphorus in the soil and sediments in stream channels. Ellis (1973) and Hook et al. (1973) described mechanisms whereby phosphorus applied to forest and agricultural soils in wastewater was either adsorbed by soil colloids and sediments or precipitated from soil solution. Both mechanisms functioned most effectively in the top 6 to 12 inches of the soil. These findings support the moderation or delay findings of Smith et al. (1987). Third, point-source control efforts during the late 1970s and early 1980s focused much more heavily upon phosphorus than nitrates because phosphorus was considered more limiting to eutrophication in freshwater ecosystems. Results of this policy difference are observable both in the greater ratio of phosphorus-decreasing trends to increasing trends and in the stronger association of phosphorus-decreasing trends with point-source load concentrations.

Perhaps the greatest consequence of differences in the nitrogen and phosphorus concentration trend patterns is seen in recent changes in volumes of nutrients delivered to coastal freshwater and marine estuaries. Nitrate loads to Atlantic Coast estuaries, the Great Lakes, and the Gulf of Mexico increased between 25% and 45% between 1974 and 1981 while phosphorus concentrations declined as much as 20%. The exception to this phosphorus finding is the South Atlantic Coast and Gulf Coast where increases in sediment deliveries have also brought increases in phosphorus. There is increasing concern over the problem of eutrophication in estuaries and debate has arisen over the need for nutrient controls in tributary basins (Thomas 1985). Increased deliveries of nitrate to estuaries are a major concern because of the tendency of nitrogen to be the limiting factor for eutrophication in many estuarine environments. For example, emerging problems due to excessive nutrients in the Chesapeake Bay resulted in the Governors of Maryland, Pennsylvania, and Virginia and the Mayor of the District of Columbia creating the Chesapeake Bay Agreement of 1983. Since signing the agreement, interagency networks were developed to deliver educational, technical and financial assistance to dischargers and landowners. Grants to install BMPs for control of nonpoint-source pollution reduced runoff and erosion from 61,120 agricultural acres by 364,000 tons of sediment and provided controls for 830,000 tons of animal waste. EPA (1987) contains additional case studies where reductions in nutrient and sediment deliveries to estuaries, lakes, and streams were recently accomplished.

Total Dissolved Solids (Salinity)

Increasing trends in concentrations of chloride, sulfate, and sodium in streams have occurred since the mid-1970s. The magnitude of the increase—averaging 30%—and the wide distribution of these trends represents a significant increase in salinity in the Nation's waters.

Several factors appear responsible for the general pattern of salinity increases. First, chloride trends were moderately correlated with population changes from 1974 to 1981. Because human wastes are a major source of chloride in many populated basins, increasing trends are not unexpected. Second, salt use on highways increased nationally by a factor of 12 between 1950 and 1980. This trend stands out as a likely cause for sodium and chloride trends in watersheds where a significant portion of annual precipitation falls in the winter months. Increasing sodium and chloride concentrations were significantly associated with high rates and large increases in highway salt use, especially in the Ohio, Tennessee, lower Missouri, and Arkansas-White-Red water resource regions. Although irrigated agriculture has a large influence on salinity in certain western rivers, chloride trends were not significantly correlated with changes in irrigated acreages nationally (Smith et al. 1987).

Increases in sulfates were especially frequent in the Missouri, Arkansas-White-Red, and Tennessee water resource regions and were highly correlated with changes in open-pit coal production. Sulfate trends were not significantly correlated with underground coal mining in the same water resource regions.

In contrast to most of the nation, the Upper and Lower Colorado water resource regions showed significant decreases in salinity between 1974 and 1981. Decreases in chloride concentrations in these watersheds are noteworthy in view of the history of salt problems there. Decreases were traced to salinity control efforts and temporary effects of reservoir filling in the early 1970s.

Toxics

Although many chemicals have toxic effects if present in sufficient amounts (e.g. table salt) a number of chemicals appear to have adverse and long-term effects at extremely low concentrations. These are commonly referred to as toxics. They may be either naturally occurring, such as heavy metals, or synthetic, such as some pesticides. They may be persistent or dissipate quickly. The key is that effects result from very low dosages and often are cumulative so that consequences do not emerge until some time after exposure.

In 1986, 16 states reported that toxic substances or some aspect of toxic substance control is an issue of special concern (fig. 6).

The problem of controlling toxics is particularly troublesome because of the Nation's dependence upon products that may contain hazardous substances or lead to the creation of hazardous substances. Over 60,000 commercial chemical substances are currently in use in the U.S. More than 50,000 pesticide products have been registered since 1947. About 3.5 billion pounds of formulated pesticide products are used each year. Benefits created by using these products in everyday life is substantial, so a wholesale retreat from their use is unlikely. Therefore, the key is to prevent misuse of these products and avoid actions resulting in environmental degradation and health risks. There is also a need to clean up those sites and waters that are contaminated.

Recent advances in monitoring and analytical precision have allowed a much more detailed description of trace elements in surface waters than was available a decade ago. Although no long-term records exist, short-term records frequently show increasing trends in the dissolved forms of two potentially toxic heavy metals—arsenic and cadmium. The dissolved forms are of particular concern because they can enter potable water supplies more readily than suspended materials. Increasing trends in arsenic and cadmium concentrations occurred with greatest frequency in watersheds in the Lake States and northern Great Plains. Evidence suggests that increased atmospheric deposition of fossil-fuel combustion byproducts was the predominant cause of increases in both elements (Smith et al. 1987). Runoff from

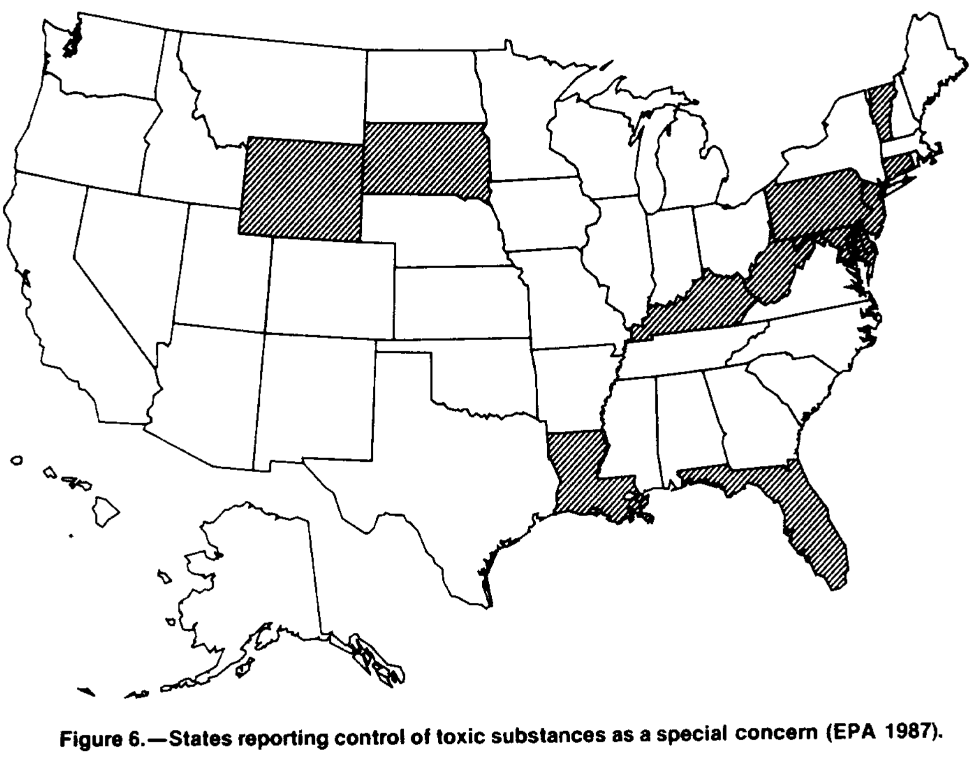


Figure 6.—States reporting control of toxic substances as a special concern (EPA 1987).

fly-ash storage areas near power plants and nonferrous smelters is the other typical way that combustion byproducts enter surface waters. Other sources of arsenic and cadmium entering waste streams include primary metals manufacturing and plating, pesticides, herbicides, and phosphate-bearing commodities such as detergents and fertilizers.

In contrast to arsenic and cadmium, concentrations of dissolved lead have decreased across the Nation. Principal areas of decrease are heavily populated areas of the East and West coasts and along the Missouri and Mississippi Rivers. The decline is due to a shift from leaded to unleaded gasoline. Consumption of leaded gasoline declined 67% between 1975 and 1981. In addition, lead concentrations in leaded gasoline also declined in the same period. Declines in airborne lead have been reported for many U.S. cities. Exceptions to the observed decline of lead in streams and air are the Ohio and Great Lakes water resource regions. Although leaded gasoline consumption declined in these regions, lead concentrations in streams did not. Unknown factors related to the solubility and transport of lead have influenced lead concentrations in streams in these regions.

Urban stormwater runoff is a major source of heavy metals entering surface waters. Concentrations of some heavy metals can be significantly higher in street sweepings than in naturally-occurring soils, rocks, and sediments (table 6). Shale was selected as the rock for comparison because it is a sedimentary rock and represents naturally occurring concentrations in the absence of human influences. All metals in the table are used in common industrial processes or in domestic materials.

Pesticides, including insecticides and herbicides, are applied extensively to crop, pasture, and forest land throughout the Nation. In urban areas they are used on lawns, gardens, and to exterminate pests in buildings and homes. Pesticides in runoff from cropland have been investigated, but little work was done on pesticide residues and other organic substances in urban runoff, although significant concentrations of many of these substances have been measured in urban runoff.

Because of the wide variety of pesticides in use, diversity of application from place to place, and complexity of processes which control amounts of these substances washing from agricultural land, studies attempting to quantify pesticide concentrations in streams from particular land uses or land applications have proven fruitless (Anon. 1984). However, some broad patterns have been recognized in relationships between application methods, chemical properties of certain common pesticides, and losses from the soil (Wauchope 1978).

The greatest release of pesticides has been on farms (Eichers et al. 1978), of which about 98% was applied to crops and 2% to livestock. Corn, cotton, wheat, sorghum, rice, other grains, soybeans, tobacco, peanuts, alfalfa, other hay and forage, and pasture and rangeland accounted for 85% of pesticides used on crops. Nationally, the total volume of insecticides used annually is shrinking; largely because new products are more potent and thus applied at lower rates. For example, since 1976, fenvalerate and permethrin use on cotton at very low application rates largely replaced toxaphene and methyl parathion which were applied at much higher dosage rates to obtain equivalent protection. Less than 100 million pounds of insecticides are currently applied annually to crop, pasture, range, and forest land. Nationally, the total volume of herbicides applied to crop, pasture, range, and forest land increased from 100 million pounds in 1966 to 500 million pounds in 1982. These poundages do not include quantities applied in urban and suburban areas, primarily by homeowners.

Organochlorine insecticides, such as DDT, chlordane, and dieldrin, are strongly adsorbed by soil particles and enter surface waters as a result of soil erosion. Use of these products has been largely banned but, because they are so resistent to decay, they continue to be found in stream sediments. From 1975 to 1980, the Pesticide Monitoring Network (Gilliom 1985) found traces of organochlorine pesticides in more than 50% of streambed sediments sampled, but in less than 5% of water samples. Historically, toxaphene, methoxychlor, DDT, and aldrin were most heavily used; consequently, they should show up in samples most frequently. However, available tests for toxaphene and methoxychlor are the least sensitive of the tests for all organochlorine pesticides so they are seldom found. DDT and aldrin break down rapidly, so are rarely detected. Byproducts of their degradation, however, are found frequently. In contrast to these more heavily used compounds, lindane has been used relatively little, but was the most frequently detected organochlorine in water because of lindane's relatively high solubility, high persistence, and easy detection. Lindane is one of the products recommended for use in control of the southern pine beetle and, given its properties just cited, care is needed to keep lindane out of surface waters. Chlordane was one of the most common termiticides used to treat building foundations. From a quantity standpoint, it was about as popular as lindane. Because chlordane is only one-third as soluble as lindane, it is almost never found in water samples. Yet, it is prevalent in stream sediments. Thus, the patterns of detection that would be expected from use data alone do not occur because of varying chemical properties and analytical capabilities.

Table 6.—Average concentrations (parts per million) of heavy metals in street sweepings compared to shale.

Heavy metal	Street sweepings[1]	Shale[2]
Cadmium	3.4	0.3
Chromium	211	100
Copper	104	57
Iron	22,000	47,000
Lead	1,810	20
Manganese	418	850
Nickel	35	95
Zinc	370	80

[1]*Bradford (1977)*
[2]*Krauskopf (1967)*

Organophosphate insecticides are highly soluble in water and usually last only days or weeks before degrading. Although they do not accumulate in organisms, they are more acutely toxic than organochlorine insecticides. Examples of these pesticides, also known as carbamates, are malathion and diazinon. Because they are so soluble in water, they are able to dissolve readily and move off the land surface as runoff or infiltrate the soil surface and move to groundwater if precipitation occurs while they are still active. Also, because of their high solubility and short life, they were very rarely detected in stream sediments, although they were detected in 5% of stream samples taken between 1975 and 1980. Of the organophosphates, only diazinon use is increasing. Methyl parathion was used in the largest quantities, mainly on cotton. No trends are evident in pollution by organophosphate insecticides on a national scale.

Chlorophenoxy and triazine herbicides account for the third major pesticide category. Atrazine and 2,4-D are responsible for most of the five-fold increase in herbicide use in the past 25 years. By 1980, however, use was shifting from atrazine and 2,4-D to newer products that are used in much smaller dosages. Data from the Pesticide Monitoring Network show virtually no detections of herbicides in streambed sediments and, except for atrazine, few detections in water samples. Atrazine was found in roughly 5% of water samples and chlorophenoxys in 0.2% of samples or less (Gilliom 1985). Atrazine is widely used on corn; most samples where atrazine was found were downstream of major corn-production areas. 2,4-D alone, and in combination with related products, is widely used in granular and liquid formulations for turf management in residential and recreational settings (such as golf courses and parks).

In the 1950s and 1960s, chlorophenoxy herbicides were very popular for forestry applications. In the 1970s and early 1980s, new products were introduced that are more selective, have modes of activity that are less toxic to animals, and are available in formulations that are less likely to drift or drain out of the target area. Triazine derivatives and 2,4-D are still popular but new families of herbicides, such as the sulfonated ureas, have become quite popular. When applied according to registrations and label directions, the latter have a very low probability of contaminating streams and aquifers.

Other toxic organic chemicals not used in land management have also entered the aquatic environment. The most significant of these are polychlorinated biphenyls (PCBs). PCBs typify compounds used in production of goods and services that are then disposed of when usefulness is exhausted. Among other things, PCBs are used to cool electrical transformers. EPA (1987) reviews some cases where PCB contamination of stream sediments has led to moratoria in 15 states on consumption of fish caught in streams below points of known PCB discharges.

Because many toxics are long-lived, disposal of wastes and sediments contaminated by toxics is a major problem. Hazardous waste in groundwater was mentioned as a problem by 39 States and in surface water by 16 States (Anon. 1984). Groundwater contamination by toxics is regarded as a more serious threat than surface water contamination because groundwater pollution is much more difficult to treat. Consequently, preventing toxics from entering groundwater is the major emphasis of toxic waste disposal.

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980, referred to as the "Superfund" legislation, established procedures for EPA to identify abandoned hazardous waste sites in need of remedial cleanup action. By 1982, EPA had selected more than 400 sites for action and initiated cleanup measures. The list is updated regularly with sites added and deleted as appropriate. The Resource Conservation and Recovery Act of 1976 gave EPA the authority to regulate disposal of newly generated hazardous materials. As part of this process, the agency has identified 14,000 hazardous-waste disposal sites across the nation. These sites are carefully tracked as potential point sources of pollution.

RESOURCE MANAGEMENT EXTERNALITIES AFFECT WATER RESOURCES

When pollutants generated at one place move off-site and affect stream ecosystems or downstream water users, the off-site effects are called *externalities*. Although externalities may create benefits free of charge, the more likely scenario is that externalities create uncompensated costs. The key to creating externalities is that off-site effects to others do not enter the initial resource management decision. For example, where soils are saline, irrigators periodically apply extra water to dissolve the salt and flush it out of the crop rooting zone. Salt-laden irrigation return flows move downstream where other irrigators reusing the water must either use more water to avoid salt accumulations in their fields or suffer crop damage from the salt. Using more water costs money and so does crop damage; neither cost is borne by the upstream water user who put the salt into the water.

The standard solution to an externality problem is to find a way to make the party creating the damage bear the full costs of that damage. One characteristic of externalities is that it is not usually possible to assign responsibility to a particular action or landowner. Rather, the best that can be done is assign responsibility to a certain class of actions or group of landowners. This characteristic complicates solving the externality; it means that some level of government must regulate activities causing off-site damages.

This section outlines three major water resource problems and illustrates how externalities contribute to them. The first is acid deposition. Emissions of certain byproducts of combustion processes to the atmosphere create externalities when those airborne emissions undergo chemical reactions and are subsequently deposited on downwind sites. When sites receiving deposits are at high elevations and ecosystems are fragile, externalities pose significant environmental problems for water resources. The second case is erosion. When sediments and related materials, such as nutrients, pesticides, and organic acids, flow off a site and into streams, there are adverse impacts on stream ecology and downstream water users. The third case is groundwater contamination from land management. Contamination most commonly arises from improper water management although it can arise from many different and normal land management activities. Municipal, industrial, and livestock waste disposal each have the potential to alter chemical composition of groundwater. All three of these problems stem from externalities that are forms of nonpoint-source pollution. Yet each presents special problems for regulators because of the nature of the pollution and its effects on other water users.

ACID DEPOSITION[11]

Acid deposition is a comprehensive term incorporating precipitation of acids in rain and snow; contact of acidic clouds, dew, and fog with the land and vegetation; and dry deposition of solid and gaseous acid precursors. The major acids involved are sulfuric and nitric. Neither of these acids is emitted directly into the atmosphere in significant quantities. Rather, they are formed in the atmosphere by the oxidation of sulfur dioxide, nitrogen oxides, and a variety of volatile organic compounds by a number of atmospheric oxidants.

Sulfur dioxide is emitted primarily by combustion of coal and heating oil containing high amounts of sulfur and by metal smelters. Coal-fired electric generators are the largest source of sulfur dioxide in the East and the second largest source in the West. The Ohio water resource region contains a high percentage of older powerplants that have historically used high-sulfur coal. In the West, metal smelting is the largest source and accounts for one-half of all sulfur dioxide emissions (Roth et al. 1985). Denton (1987) reported that, according to Canadian authorities, the Inco smelting facility in Canada was responsible for 3% of the total North American emission of sulfur dioxide on an annual basis. According to EPA in 1977, stationary fuel combustion was responsible for the largest share of sulfur dioxides (20%) and nitrogen oxides (13%).

Few argue about the need to reduce sulfur dioxide emissions. But few can agree on who should pay or how much. The decision on how to reduce emissions will affect jobs, electricity rates, and the environment throughout the East. For example, a low-cost way to reduce sulfur dioxide emissions is to switch to low-sulfur coal. But there are 30,000 jobs mining high-sulfur coal and two to three times that number in related industries such as railway transportation of coal. A switch to low-sulfur coal could halve the existing market for high-sulfur coal with devastating economic results for many small towns in Appalachia. Alternatively, new technology could be installed on power plants burning high-sulfur coal to remove sulfur from emissions, thereby protecting mining and related jobs. If costs of the new technology were passed to consumers, electricity rates would increase 5% to 25%. New emissions technology is most expensive for small power plants and those whose fuel is predominantly high-sulfur coal. Consumers may seek federal assistance for utilities hardest hit, thereby spreading the cost to taxpayers across the nation. In total, reducing sulfur dioxide emissions by 10 million tons annually (40%)—considered by many to be a politically and economically realistic goal—would cost the nation from $3 – $6 billion annually for the foreseeable future (Davis 1988). Who should pay to clean up future emissions and how much has not yet been decided. The reality of the situation is that the environment is forced to pay the total cost.

Nitrogen oxides are emitted primarily by motor vehicles and, to a lesser extent, electric utilities. In the West, motor vehicles contribute half of all the anthropogenic nitrogen oxide emissions.

Volatile organic compounds are released during petroleum refining, chemical manufacturing, paint and solvent use, and transportation. Industrial processes emitted the largest share of volatile organic compounds (10%) and also contributed the biggest share of suspended particulate (5%). Transportation was responsible for 85% of the carbon monoxide emissions.

The chemical transformations of sulfur dioxide and nitrogen oxides into acids can occur in clear air or in clouds, near or far from the point of emission. Eventual deposition is influenced both by prevailing meteorological conditions and surface characteristics. Chemical transformations of sulfur dioxide and nitrogen oxides into acids requires intervention of oxidants in the atmosphere. Oxidants, in turn, are the result of an interaction of volatile organic compounds with nitrogen oxides in the presence of sunlight. A most important recent finding in atmospheric chemistry is that oxidant availability may limit the production of sulfuric acid, at least during some portions of the year.

Thirteen states cited acid deposition as an issue of special concern in their 1986 Section 305(b) reports (fig. 7). In general, states cite lowered pH of rainfall as evidence of potential problems even though effects of acid deposition remain uncertain and unquantified. Nonetheless, factors other than rainfall pH must be considered when evaluating impacts of acid deposition. Perhaps the most significant other factor is the geology of the area. Some soils and rock formations have a few natural carbonates to neutralize acidity ("buffering capacity"), while other soils and rock formations are generally well buffered.

The government conducted a review of knowledge about acid precipitation in the 1970s. That review resulted in passage of the Acid Precipitation Act of 1980 (Title VII of the Energy Security Act of 1980, Public Law 96–294) and establishment of the National Acid Precipitation Assessment Program (NAPAP). NAPAP is an interagency effort with the objective of conducting a ten-year research program crucial to understanding processes involved in acid deposition and assessing their quantitative impacts on ecosystems.

In cooperation with the states, NAPAP has constructed a detailed inventory of anthropogenic emissions for 1980 (and is currently developing an inventory for 1985). This inventory concluded that natural emissions of sulfur are small relative to man-made ones. Dampier (1982) noted

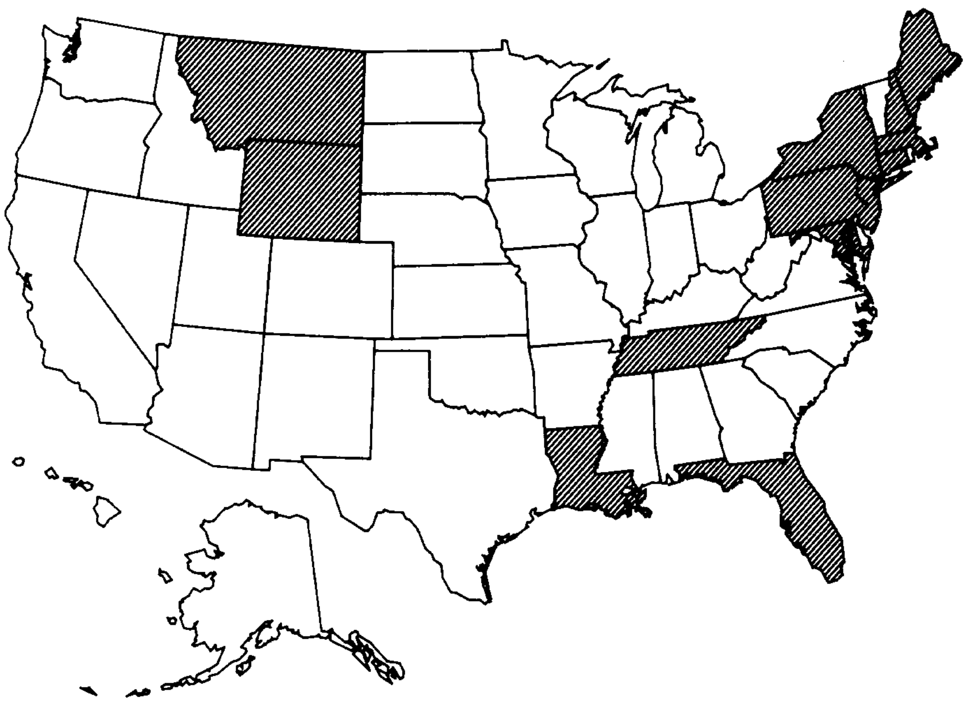


Figure 7.—States reporting acid deposition as a special concern (EPA 1987).

that sulfur dioxide emissions are much higher in the northern hemisphere than southern hemisphere (145.5 million tons per year versus 5.5 million tons, respectively), and are steadily increasing at the rate of 5% annually. Considerable uncertainty exists regarding the relative importance of natural versus man-made nitrogen sources. Some estimates of natural emissions range from 8% to 30% of man-made levels. Natural volatile organic compounds emissions are believed large relative to man-made emissions.

The general geographic pattern of precipitation acidity has changed very little since extensive monitoring began in 1978. Rain and snow acidity for 1985 was highest in the northeastern U.S. The highest acidities, below pH 4.2, were found in the upper Ohio River Valley of eastern Ohio and western Pennsylvania and extended across the Canadian border into southcentral Ontario. Precipitation monitored at remote sites generally has a pH between 5.0 and 5.5 (Roth et al. 1985). Precipitation pH below 5.0 is generally taken as indicative of anthropogenic influences. Roth et al. (1985) note that the amount of deposition measured in precipitation is typically doubled to account for all the different types of deposition when estimating total deposition load. But it is not known whether this rule of thumb is adequate for more arid western locales where most precipitation falls as winter snow.

Linkages to Other Air Quality Problems

It is important to note that while acid deposition is normally viewed as an independent issue, chemical changes occurring in the atmosphere are inextricably related to one another. Problems of ozone depletion, visual impairment, "greenhouse warming," and acid deposition are all interconnected to some degree and all are associated with changes in atmospheric composition. For example, gases which are predicted to modify the distribution of stratospheric ozone (i.e. carbon monoxide, methane, nitrous oxide, and chlorofluorocarbons) are the same gases which are infrared active (greenhouse gases) and are predicted to warm the planet. In addition, increasing concentrations of methane are also predicted to increase ozone in the troposphere and may be responsible for some forest damage that is occurring. Increased atmospheric levels of sulfur may possibly influence climate through enhanced levels of sulfate aerosols. Oxides of nitrogen strongly influence the production of ozone in the troposphere. Many of these chemicals and byproducts of chemical reactions are responsible for gases and aerosols that create visual impairment.

Implications for Aquatic Ecosystems

Lake and stream acidification, which can damage aquatic organisms, may result from natural or man-made causes. Surface water chemistry can change either over the long term or during short episodes such as spring snow melt. Budiansky (1981) noted that the greatest pH shock to lakes occurs when snow melts and runs off. Soil type, hardness of the winter freeze, and amount of dry deposition, together with type and amount of snow and ice, all determine the amount of acidic material that has accumulated over winter and the portion likely to be absorbed by the soil, given its buffering capability. The larger the portion of annual precipitation that falls as snow and the lower the soil buffering capability, the greater the potential for damage due to a pulse of acidity entering a waterbody during snowmelt. Roth et al. (1985) note that springtime acid pulses from snowmelt can severely harm sensitive aquatic ecosystems even if the ecosystems do not permanently acidify.

Middleton and Rhodes (1984) concluded that acid deposition has the potential to contribute to drinking water toxicity. Raw drinking water that is acidic can free toxic metals such as aluminum from the chemical bonds normally immobilizing them to soil colloids. If not adequately neutralized as part of water treatment, acid remaining in water can dissolve toxic metals such as lead from water distribution pipes. Because of the number of areas in the northeastern U.S. using surface water sources for drinking water supplies, the impact could be considerable. Water treatment processes exist for dealing with acidity in raw water and for removing toxic metals during water treatment; however, they are more costly than conventional treatments.

Analysis of historical records by the National Academy of Sciences shows no net acidification of lakes in the past 50 to 60 years in either Wisconsin or New Hampshire, although a few high elevation lakes in the Adirondack region of New York may have suffered some increased acidification. The study noted that quantifying the amount of acidification was not possible at this time. Our understanding of how acid deposition interacts with individual biological, geological, and chemical processes in watersheds and surface waters is considerable. However, major uncertainties exist regarding how individual processes work together over broader areas to result in observed surface water chemistry, according to the Council on Environmental Quality (1987).

New York and Canada allege a much greater impact on high elevation lakes than determined by the National Academy of Sciences. New York considers damage to some 500 lakes in the 6 million-acre Adirondack Forest Preserve to be catastrophic (USDA 1987). About 2 million acres in the Catskill area are also reported to be affected to a lesser extent. By Canada's count, 13 salmon-bearing lakes and 14,000 other lakes in eastern Canada are incapable of supporting fish life (Denton 1987). Studies cited by Roth et al. (1985) report that between the 1930s and 1970s, the percentage of lakes in the Adirondacks with pH less than 5.0 increased from 8% to 48% and the percentage with no fish increased from 10% to 52%. In New England, a study of 95 lakes for which there are historical pH data showed an average alkalinity decrease of 100 milliequivalents per liter between the 1930s and 1960s.[12] Likens (1976) found a clear correlation between geographic areas where precipitation is particularly acidic and areas where lake acidification has occurred. Evidence that other mechanisms could have caused acidification is less convincing.

Roth et al. (1985) summarized the prevailing hypotheses about how lakes and streams subject to acid deposition lose fish populations. Chemical reactions that are dependent upon low pH and that mobilize aluminum, found in most watershed soils, are identified as the primary culprit. Laboratory studies show that fish are injured directly by low pH and indirectly when concentrations of toxic metals result. Both combine to cause reproductive failure in fish and also in organisms in the fish's food chain. Low pH and metal concentrations are thought to be more damaging to aquatic organisms in the spring when many are in early developmental stages. This coincides with onset of snowmelt. Roth et al. (1985) report that the effects of partial acidification due to presence of some natural alkalinity are less well understood.

Implications for Forests

Observations of diminished growth in southern softwoods at low elevations and of visually apparent deterioration of spruce-fir forests at high elevations have heightened concern over the causal factors and the possible role played by air pollution generally, and acid deposition in particular. Budiansky (1981) said that the real question is how the entire forest responds when perturbed by pollution. He noted that the major problem facing vegetation in the Northeast may be ozone, not acid precipitation or sulfur dioxide. Williams et al. (1977) found widespread damage to ponderosa pine, apparently from ozone, in dry regions downwind of Los Angeles and Central Valley. The injury suggested that trees growing in a relatively dry habitat on sensitive soil may be subject to direct damage from air pollution, possibly including acidic deposition interacting with ozone and other pollutants (Roth et al. 1985). Weisskopf (1988), reporting results of a recently released study by World Resources Institute, identified ground-based ozone as the primary cause of death or damage to 87% of the Jeffrey and ponderosa pine on the San Bernardino National Forest near Los Angeles, to white pines in the East, and to major crops in the Midwest and Southeast, including corn, soybeans, wheat, peanuts, barley, and hay. Annual crop losses caused chiefly by ozone are estimated at $5 billion (Weisskopf 1988).

Scientists are not yet able to show that changes in acid deposition will result in changes in forest growth or other measures of forest vigor. The problem is a complex one involving related chemical, physical, and biological systems and requiring a comprehensive, interdisciplinary approach. Current research involves efforts to explain observed forest changes by systematically testing a long list of hypotheses including natural cycles, climate change, pests and disease, forest stand history effects (e.g. exhaustion of residual fertilizer nutrients from previous agricultural use of the land), land management practice effects, and air pollution and acid deposition. A diversity of views exist currently about the impact of acid deposition on forested ecosystems and tree growth, as illustrated by the three sources cited below.

Woods (1987) noted that long-term effects of acid deposition on soils include making elements normally bound by soil particles (such as aluminum ions) more available for plant uptake. Aluminum ions can be concentrated in plant roots to toxic levels. Aluminum ions also reduce the availability of calcium. These changes lead to nutrient imbalances in plants which can cause reductions in productivity well before toxicity causes death. Small changes in the physiology of trees can cause losses in forest growth. Trees are vulnerable because of long growth cycles. Conifers are especially vulnerable because needles persist for two to four years and are exposed longer to atmospheric deposition.

Brown (1987) noted that the amount of acidity generated by natural sources in the eastern U.S. is much greater than for acid rain. Animal waste and decaying vegetation are responsible for many soil acids. Heavy rains wash these acids into rivers and streams before they can be neutralized by deeper soil layers. Unusual damage to forests is more likely to stem from the combination of natural stresses, such as droughts, frosts, insects, and pathogens coupled with the impact of various air pollutants. Ozone may be a contributor to the problem.

Johnson and Siccama (1983) noted that available evidence does not show a clear cause and effect relationship between acid deposition and forest decline and dieback in the U.S. Given the lack of other causal agents and characteristics of observed dieback, it appears that mortality is probably related to some environmental stress or combination of stresses. Mortality was only significantly correlated with elevation. Several stress factors are related to elevation; it is not currently possible to determine which factors are relevant. Wind speed, exposure to cloud moisture, hydrogen ion concentration, and heavy-metal content of soil all increase with elevation. Drought stress, in combination with predisposing factors related to site conditions, has triggered forest declines in the past. Growth reductions in red spruce during the mid-1960s represent initiation of dieback and decline in these trees. The early and mid-1960s were a period of drought in the Northeast. Available information does not suggest that either sulfur dioxide or ozone plays a major role in spruce decline. Other studies cited by Johnson and Siccama support drought as a prominent factor in observed forest diebacks in North America and Europe.

EROSION

The off-site impacts of sediment were identified in USDA (1987) (the Appraisal) as one of the most significant impacts created by agricultural land management practices on non-federal lands. Erosion reduction is the major focus of the *National Conservation Plan* currently being developed by the SCS in response to the Appraisal. It is also one of the primary water-related impacts of forest and rangeland management on federal lands.

Clark et al. (1985) focused specifically on the off-farm impacts of erosion measured largely by the effects of sediment on water use. The study examined problems caused by sediment and other contaminants carried off by storm water after leaving eroding fields. They found that sediment causes a variety of instream and offstream damages influenced by a complex set of hydrological, physical, chemical, and biological interactions. Christensen and Ribaudo (1987) estimate that sediment in water causes $7.1 billion in damages annually, of which cropland's share is $2.6 billion.

Instream damages are caused by sediment, nutrients and other erosion-related contaminants in streams and lakes and affect aquatic organisms, water-based recreation, water storage facilities, and navigation. Offstream damages occur before sediments reach a waterway, during floods, or after water is diverted from a waterway for use.

Erosion Impacts

Biological impacts of erosion.—Aquatic ecosystems are affected in a variety of ways generally related either to reproduction or respiration. Sediment destroys spawning areas, food sources, and habitat and causes damage to fish, crustaceans, and other aquatic wildlife. Algal growth stimulated by nutrients blocks sunlight while algae are alive; when dead, algal decomposition strips dissolved oxygen from the water rendering respiration impossible. Pesticides and other contaminants from agricultural lands can be directly toxic to fish and to organisms lower in the food chain. Clark et al. (1985) identified agricultural runoff as chronically affecting fish communities in 30% of the nation's waters. Fish kill reports identified such runoff as a major cause of acute episodes.

Although some of these biological impacts are reflected in damage estimates to recreational and commercial fishing, the overall magnitude of impacts cannot be measured because methodology is not available. This is not to say that damages are small or nonexistent.

Recreational impacts of erosion.—All types of water-based recreational activities are adversely affected by erosion-related pollutants. The value of freshwater fishing is reduced because of the demise of valued species and reductions in fish populations. Fishing is also less successful in turbid water because fish have difficulty seeing lures. Many of the same problems affect marine recreational fishing. Many marine species reproduce in estuaries and rivers. As the deterioration of Chesapeake Bay fisheries amply demonstrates, eroded sediments and excess nutrients can lead to severe reductions in fin and shellfish populations.

Boating and swimming are affected because weed growth and siltation physically interfere with recreational activities. Hunting is also affected because many waterfowl depend upon aquatic vegetation and other affected aquatic wildlife for food. Total economic cost of these recreational damages was estimated by Christensen and Ribaudo (1987) at $1.9 billion per year and $544 million for marine fishing.

Erosion damages to water storage.—Damage to reservoirs from sediment is measured by the increasing cost of building and maintaining water-storage capacity. An estimated 1.4 to 1.5 million acre-feet of reservoir and lake capacity is permanently filled each year with sediment. Recent construction of new storage capacity averages 1 million acre-feet annually at a cost of $300 to $700 per acre-foot. Not only is the nation failing to keep up with the rate of sedimentation, but costs of providing additional storage are increasing because low-cost dam sites have already been utilized.

Erosion not only creates major problems on sites where it occurs, annual off-site damages caused by transported sediments exceed $7 billion.

Sediment and nutrients affect the rate of evaporation and transpiration from water bodies. Evaporation is a particularly serious problem in arid regions because more than an acre-foot of storage has to be constructed to provide an acre-foot of yield. Here, suspended sediments and algae may provide a benefit because they reflect much of the solar energy that would otherwise warm the water and enhance evaporation. However, sediments and nutrients are a two-edged sword because they also increase the transpiration rate by stimulating growth of water-consuming vegetation in shallow lake areas.

Lake cleanup is a final cost related to water storage. Lakes are the only water bodies that have suffered a net decline in water quality since 1975. All levels of government are spending substantial amounts for weed control and other cleanup activities. The total annual cost of all these impacts on water-storage facilities is estimated to be $1.1 billion (Christensen and Ribaudo 1987).

Impacts of erosion on navigation.—Sedimentation affects navigation in diverse ways. The major economic cost is maintenance dredging of harbors and waterways. The major environmental cost is disposal of dredged spoil. Prior to the 1950s, spoil was typically disposed of by filling wetlands for further urban development. This practice has largely ceased. Coastal dredged spoil was often barged to sea and disposed offshore. In either case, the dredging process causes temporary turbidity plumes downstream. If these coincide with critical reproduction times, the effects can be just as severe as longer term turbidity. Other costs include accidents and shipping delays. The total annual cost to navigation is estimated to be $680 million annually (Christensen and Ribaudo 1987).

Other instream impacts of erosion.—Soil erosion damages commercial fisheries in much the same way that it affects recreational fisheries. The total cost of other instream impacts of erosion on commercial fishing was estimated to be $409 million (Christensen and Ribaudo 1987).

Soil erosion can also reduce preservation/option/bequest values—the benefits people place upon clean water even though they may never make direct use of the water body. Some studies have shown these values to be even higher than the costs borne by recreational and other uses. Damage to preservation/option/bequest values is not currently estimable with the same accuracy as the other damages. Comparing Clark et al. (1985) and Christensen and Ribaudo (1987), perhaps up to $600 million in damages to these values occurs annually.

Other offstream impacts of erosion.—Water often contains sediment or agricultural byproducts such as dissolved salts in concentrations that are too small to justify treatment. Yet these constituents in water cause increased operation and maintenance costs and more frequent replacement of irrigation equipment. Salt and alkali buildups in pipes can lead to added maintenance and replacement costs. Irrigators using turbid water experience increased costs and reduced yields if fine silt causes a crust to form on the soil surface, impeding water infiltration and seed germination. Christensen and Ribaudo (1987) estimated that the net cost of all these other offstream impacts at $135 million annually.

Flood damages of erosion.—Sediment contributes to flood damages in three ways. First, by settling out in streambeds and clogging waterways, it increases frequency and depth of flooding. Second, because suspended sediment is carried by flood water, the volume of the water/soil mixture is increased, thus raising flood crests. Third, many flood damages are caused by sediment, not by the water itself. There may be long-term damages to agricultural land if floods leave infertile silt behind. The total of all these damages was estimated by Christensen and Ribaudo (1987) to be $888 million per year.

Water-conveyance impacts of erosion.—Some sediment settles out in drainage ditches before water reaches streams. Clark et al. (1985) cited estimates from Illinois that highway department crews annually remove from drainage ditches an amount of sediment equal to 1.4% of the total erosion occurring in the state. The annual cost of controlling weeds and removing sediment from the 110,000 miles of irrigation canals in the U.S. accounts for 15% to 35% of annual canal maintenance costs. Total cost of these damages is estimated to amount to $214 million per year (Christensen and Ribaudo 1987).

Water-treatment costs of erosion.—The cost of treating water before municipal or industrial use increases when raw water is turbid. Sedimentation basins must be built and periodically cleaned out, chemical coagulants must be added, filters must be cleaned more frequently, and special treatment apparatus installed to handle nutrients and other contaminants. For example, nutrients and algae may clog heat exchanger tubes in steam boilers or cooling towers and necessitate increased maintenance costs. Christensen and Ribaudo (1987) estimated that these procedures cost $1.2 billion annually.

Summary

The total estimate of erosion-related damages is $6.1 billion annually of which $2.2 billion is attributable to cropland. If sediment damages are isolated from nutrient, pesticide, and other erosion-related damages, the totals are $3.5 billion of which $1.2 billion is attributable to cropland.

Erosion-related damages not attributable to cropland fall into two categories. The first is erosion from other land management practices. Examples are construction, forestry, grazing, and mining operations. Forestry activities with high erosion potential include road building, timber harvesting operations, and wildfire.

Overgrazing is the primary source of erosion from rangelands. The Appraisal found that at present, 20% of rangeland has erosion exceeding T.[13] The Appraisal concluded that erosion on rangeland is a potential problem on 61% of non-federal range. The assumption made when evaluating this potential was that all range in less than good condition is susceptible to damage. The watershed condition class discussion earlier in this chapter pointed out that 72% of watersheds are either in the Special Emphasis class and need careful management to avoid problems, or in the Investment Emphasis class and need technological and economically feasible investments to restore watershed conditions to a level consistent with watershed management goals. The most significant factor placing these forests and rangelands at risk is the potential for erosion and movement of sediment off-site.

The second category of erosion-related damages not attributable to cropland comes from sediment deposits currently in streams. In some areas where erosion was a major problem such as the abandoned cropland in some parts of the South, streams no longer carry the fresh sediment loads they did at the turn of the century. As sediments were prevented from entering streams either by conversion of the land to forests or more enlightened land management, water energy formerly used to carry sediments has begun scouring old sediment deposits from stream channels and is carrying these previously-deposited sediments downstream. This water action has confounded many studies seeking to demonstrate that land management activities had direct effect on reducing instream sediment concentrations because little reduction in sediment in the water was observed. In some streams, long-buried bridges and other historical artifacts reemerging from silt are offering historians fresh opportunities for studying pioneer and plantation life of the 1700s and 1800s. It may take another 50 to 100 years for these entrained sediments in stream channels to be scoured out and streams returned to the channel configurations they enjoyed before development began.[14]

Clark et al. (1985) concluded that developing an effective, efficient program to control off-farm impacts of eroded materials will be difficult. They called for new regulatory programs that were more accurately targeted at erodible soils and land management practices insensitive to erosion. A key element identified was taking the most seriously eroding lands out of row-crop production or out of production altogether. The Food Security Act of 1985 contained a section dealing with soil conservation measures having several provisions that respond quite closely to the conclusions reached by Clark et al. (1985). Four notable provisions to reduce cropping of erodible land and the environmental implications of land management were (1) creation of the Conservation Reserve Program (CRP), (2) the Conservation Compliance provision, (3) the "Sodbuster" provision, and (4) the "Swampbuster" provision. These provisions only apply to lands with the potential to erode more than eight times faster than new soil can be regenerated. There are 118 million acres of such soils in the U.S., 35 million of which are being managed to prevent erosion in excess of the rate of regeneration (Reichelderfer 1987). It is estimated that 40 to 45 million acres will be enrolled in the CRP by 1990.

The conservation compliance provision is designed to keep erosion low on 35 million acres of erodible lands currently being farmed. Failure to do so causes the farmer to forfeit the right to participate in other farm programs offered by USDA.

The sodbuster provision denies eligibility for USDA programs to farmers who newly cultivate highly erodible land without using an approved conservation system. The swampbuster provision denies eligibility to farmers to convert wetlands to production of agricultural commodities.

The latter two provisions are designed to discourage conversion of grasslands and river bottomlands which are predominately forest to crop production.

GROUNDWATER CONTAMINATION

Most groundwater supplies in the U.S. are of good quality. In some localities, however, contamination has caused well closures, public health concerns, and economic losses. These problems could spread. The challenge is to prevent localized problems from becoming local crises or regional problems.

The Conservation Foundation (1987) concluded that groundwater protection efforts have been limited at best. Regulatory programs put in place often have failed to exercise much of the statutory authority available. Because many laws were written at different times and for different purposes, they often add up to a program of groundwater protection that is neither coherent nor consistent even if those laws are implemented to the limits of enacted authority.

Groundwater can be contaminated in a variety of ways. EPA (1987) summarized major sources of groundwater contamination reported by states. More than 40 states reported septic tanks, underground storage tanks, and agricultural activities as major sources of contaminants. More than 30 states reported landfills, lagoons, and abandoned waste sites as major sources of groundwater contamination.

Underground storage tanks.—Underground storage tanks were listed as the primary source of groundwater contamination by 11 states. These are Alabama, Alaska, Florida, Michigan, Montana, New Jersey, New York, North Carolina, Pennsylvania, South Dakota, and Virginia. The Conservation Foundation (1987) provides additional detail on the magnitude of problems associated with underground tanks by citing a recent Congressional Research Service report. That report estimated there are between 5 and 10 million underground tanks of all kinds (EPA's estimate is 3 to 5 million), of which 1.5 million tanks contain petroleum or hazardous substances (1.4 million by EPA's estimate). Most existing tanks are made of carbon steel, unprotected from corrosion, and range in size from 10,000 to 50,000 gallons. Some fiberglass tanks are also used, but they tend to be smaller, averaging 10,000 gallons. The Congressional Research Service estimated that 25% to 30% of tanks containing petroleum products may be leaking (a limited EPA survey in 1986 found 35% leaking). Vehicle filling stations accounted for the majority of leak locations. Other studies found that the majority of leaks occur from operating tanks and not abandoned ones. Leaks of solvents are proportionately more prevalent than leaks from petroleum tanks. Corrosion of tanks and associated pipes and fittings accounts for 90% of the leaks according to the Conservation Foundation (1987).

Septic tanks.—Failure of septic systems was reported as the primary cause of groundwater contamination by nine states, including Arkansas, Delaware, Illinois, Kentucky, Maine, Maryland, Nevada, Ohio, and Tennessee. Contamination from this source is not a new problem; however, shifts in housing patterns and land use, particularly increasing housing densities in suburbs, have made septic system discharges a more prevalent problem. About one-fourth of American homes (20 million homes) use on-site sewage disposal; most of these are east of the Great Plains.

Septic systems are far more popular than cesspools or pit privies. A 1980 study cited by Conservation Foundation (1987) reported that up to one-third of the systems were operating improperly. Groundwater pollution by nitrates, phosphates, heavy metals, other inorganics, and toxic organics often used as system cleaners, result when systems are not operating properly. The efficiency of a septic tank decreases over time, even with proper maintenance (periodic removal of sludge), because of a buildup of film on the outside of drains or clogging of the drainage bed material. One study reported by the Conservation Foundation (1987) found that 75% of septic system failures can be attributed to overloading the drain field with sludge. The cleaning and sludge removal process often uses chemicals such as trichloroethane, benzene, or methyl chloride, to dissolve sludge in tanks and drain fields—chemicals that should not come in contact with groundwater. Widespread use of these chemicals on Long Island in 1979 (an estimated 400,000 gallons total, many applied by homeowners themselves) resulted in closure of many public and private wells (Conservation Foundation 1987). Careful location, construction, and maintenance provides some measure of protection against groundwater contamination.

Agricultural activities.—Agricultural activities were cited as the primary source of groundwater contamination by 6 states including Arizona, Arkansas, California, Connecticut, Hawaii, and Iowa. The primary contaminants are nutrients from fertilizers, livestock waste disposal, and pesticides.

Fertilizer use in the U.S. has grown drastically, rising 300% between 1960 and 1980. Nitrogen fertilizer applications have quadrupled over the same period. In addition to the large increases in fertilizer applications to cropland, large amounts are also applied in urban areas to turf and gardens. The Conservation Foundation (1987) recounts results of several studies in Wisconsin, Nebraska, and Iowa linking increases in nitrate concentrations in well water to heavy usage of nitrogenous fertilizers.

Animal wastes are another source of nutrients and bacteria. Feedlots are often viewed as major sources of contamination but manure disposal on individual farms can also cause problems. Southeastern Pennsylvania is one of the most concentrated areas of dairy farms in the nation. The volume of manure created and the small size of the typical dairy farm combine to create manure disposal problems. Application rates exceeding 2 tons per acre per year are not uncommon; at a 5% nitrogen content, this equates to more than 200 pounds of nitrogen per acre annually. Runoff from fields contaminates surface waters and leachate percolates to groundwater. Because of the limestone geology of Southeastern Pennsylvania, there are many channels and solution cavities providing speedy access of percolate to aquifers which exacerbates manure disposal problems. The Conservation Foundation (1987) recites manure disposal problems associated with beef production in Colorado and poultry production in Delaware. Methods of solving nutrient contamination problems from agricultural operations include matching fertilizer requirements and timing of applications more closely with actual crop needs and collecting, storing, and treating livestock and poultry wastes before applying them to fields.

Pesticide applications were the second concern related to agricultural operations. The Conservation Foundation (1987) reported that herbicide use has grown by 200% between 1966 and 1981 as chemicals replaced mechanical cultivation for controlling weeds. In 1982, 91% of all U.S. cropland farmed was planted with row crops and 44% of those acres had herbicides applied. However, 85% of the herbicides and 70% of the insecticides were applied to only four crops—corn, cotton, soybeans, and wheat. The two most heavily used substances are the herbicides alachlor and atrazine; accounting for 25% of the total national usage. The two states using the largest quantities are Iowa and Illinois, which account for 21% of total usage. Soluble formulations of pesticides and those products designed to kill soil pests have the greatest potential for contaminating groundwater. Problems with groundwater contamination can be minimized by using formulations that do not migrate through the ground, by taking greater care in where, when, and how pesticides are applied, and by combining pesticide usage with other non-chemical techniques in a program of integrated pest management.

Landfills.—Five states identified landfills as the primary source of groundwater contamination. It is estimated that between 15,000 and 20,000 municipal dumps and sanitary landfills exist in the U.S. An exhaustive list is not available; the actual number could be as high as 40,000. Four out of five facilities are small, handling less than 100 tons of waste daily. Two hundred seventy five million tons of municipal solid wastes are disposed of in landfills annually. Older landfills and open dumps were often uncovered, unlined, and located with no consideration of their potential for contaminating groundwater. In addition, many landfills were located on marshlands, abandoned gravel pits, and old strip mines. Such sites are susceptible to groundwater contamination if infiltration flowing through the disposal site is a source of groundwater recharge and if underlying soils are sufficiently permeable to allow leachate to enter the groundwater system. Percolation of leachate from landfills is inevitable unless the site is completely sealed on all sides. Few are. Groundwater contamination from landfills can be minimized by improved design, construction, operation and maintenance. Design considerations should always include hydrogeology of the landfill location, area to be served, and types of wastes. The use of liners and covers, as well as collection and treatment of leachate, further reduce the potential for groundwater contamination (Conservation Foundation 1987).

Hazardous wastes.—Hazardous wastes, while a major cause of concern by 29 states, were a primary concern of only three states. About 5,000 sites in the U.S. are treating, storing, and disposing of hazardous wastes. The largest number of sites are in the Great Lakes region followed by the Southeast and Southwest. As of June 1986, 888 abandoned hazardous waste sites were listed or proposed for listing on the National Priorities List and thus targeted for federally-funded cleanup under the Superfund. Seventy-five percent of the sites on the National Priorities List have documented groundwater contamination problems. The most commonly found substances include trichloroethane, lead, toluene, benzene, PCBs, chloroform, phenol, arsenic, cadmium, and chromium.

The potential for contaminating groundwater can be reduced in several ways. Careful siting and operation of treatment, storage, and disposal facilities can minimize the potential for unforeseen problems. Liners and leak detection systems can be installed to reduce the possibility that contaminants can escape unnoticed. Enclosing more hazardous substances in concrete, glass, or ceramic vessels reduces potential for leakage. Alternative disposal techniques such as incineration or waste solidification may have less environmental hazard than burial. Finally, reducing the generation of hazardous wastes through modifying plant processes, recycling, detoxifying, drying, or substituting nonhazardous materials should also be examined. These steps provide the most attractive long-term methods for reducing the problem (Conservation Foundation 1987).

A Groundwater Protection Strategy

The 1987 National Groundwater Policy Forum (Conservation Foundation 1987) concluded that the nation must adopt a much more aggressive policy of groundwater management if the resource is to be adequately protected for current and future users. Because the problem is complex, a highly coordinated attack is required with participants from all levels of government and industry. Partnerships must be forged to achieve the common goal of protecting the groundwater resource. Four principles should guide the development of a protection strategy: (1) active management is required to meet human and ecological needs; (2) contamination should be prevented wherever possible because of the technical difficulties and costs of cleanup; (3) degradation of the most valuable aquifers and critical water supplies must be prevented; and (4) the strategy must recognize the wide variation across the country in the nature, vulnerability, and use of groundwater, and in state and local governments' ability to manage it.

The Policy Forum recommended a new environmental partnership to avoid creation of a new and burdensome bureaucracy. Partners should include federal, state, and local governments, private industry, and public interest groups. The Forum recommended that the partnership be structured so that a clear national mandate is set forth while ensuring that states, assigned the lead role, have ample room to operate. Two key aspects from the states' perspective are (1) consolidating groundwater laws and programs under the jurisdiction of a single state agency to facilitate a coordinated approach to problem prevention and solution; and (2) having substantial flexibility to design programs that respond to specific local needs. The federal government's role was envisioned as balancing national consistency with the reality of geographic differences. Ten components of a prototype state groundwater protection program were identified:

1. Comprehensive mapping of aquifer systems and their associate recharge and discharge areas;
2. Anticipatory classification of aquifers;
3. Ambient groundwater standards;
4. Authorities for imposing controls on all significant sources of potential contamination;
5. Programs for monitoring, data collection, and data analysis;
6. Effective enforcement provisions;
7. Surface-use restrictions to protect groundwater quality;
8. Programs to control groundwater withdrawals to protect groundwater quality;
9. Coordination of groundwater and surface-water management; and
10. Coordination of groundwater programs with other relevant natural resource protection programs.

Other institutional arrangements to implement the prototype program are discussed by the Conservation Foundation (1987).

SUMMARY

The three major water-related environmental problems identified in this Assessment are acid deposition, erosion, and groundwater contamination. All stem from externalities—resource management actions that fail to take full account of the potential disruption to ecosystems caused by pollutants. Pollutants are nothing more than resources out of place. When removed from their proper place, these resources cause ecosystems to change in ways not desirable to society.

There are several steps in solving problems created by resources out of place. The first is deciding how we want ecosystems to function. This step involves deciding how much ecological change society deems acceptable. "No change" is rarely a viable option because resource use invariably changes ecosystems in one way or another. The second step is identifying mechanisms by which unacceptable ecosystem changes are occurring. With erosion, this step has been answered more fully than for acid deposition or groundwater contamination. The third step is devising a way to alter mechanisms causing unacceptable ecosystem changes.

Tools to help solve problems include market-oriented processes and institutional processes, such as regulations or legislation. Today's society appears to prefer using market forces instead of institutional processes. But if market pressures are demonstrated to be ineffective, society has no qualms about insisting on using institutional processes. Dickering over ways, means, and costs via the political system is the way our society achieves consensus on attacking problems.

This section of Chapter 2 focused specifically on the second step in a general process outlined above. The major causes of acid deposition, erosion, and groundwater contamination have been reviewed with the objective of describing the sources and scope of the problems. The abbreviated discussions of acid deposition, erosion, and groundwater contamination presented are only abstracts of the highlights from literature cited in this chapter. Interested readers should consult the literature cited as they contain a wealth of more detailed information on the subjects.

CONDITION AND DISTRIBUTION OF THE NATION'S WETLANDS

PRESENT DISTRIBUTION OF WETLANDS BY SIZE AND REGION

There are 90 million acres of wetlands in the lower 48 states or about 5% of the total land area. Of all wetlands, 95% are inland freshwater wetlands and 5% are of the coastal saltwater type.

Wetland ecosystems are especially prevalent in Alaska. That state alone has approximately 200 million acres of wetlands (60% of its land area); over twice the total of the lower 48 states. Outside of Alaska, the largest concentrations of wetlands are found in the North and South. Those located in the South are primarily caused by sedimentation where soil is eroded from seacoasts or riverbanks and deposited behind barrier islands or onto alluvial plains. Wetlands caused by glaciation are found in the North and scattered throughout the West.

Glaciers form wetlands in three ways: large blocks of ice melt to form depressions; rivers are dammed by glacial debris; and lake beds are formed by scouring action. Other causes of wetlands are beaver dams, human activity, wind erosion, geologic movement such as sinkholes, and freezing/thawing. Alaska's wetlands are caused by the last category—soils near one surface thaw on a seasonal basis but their moisture is prevented by permafrost from entering the water table. Wetlands are especially prevalent in the upper Midwest, the lower Mississippi River valley, and along the Atlantic Ocean and Gulf of Mexico (fig. 8 and table 7).

Throughout history, wetlands have been considered wastelands that could only be put to productive use if they were drained or filled. Within the last 200 years, over 50% of the wetlands in the lower 48 States have been converted to other uses such as agriculture, mining, forestry, oil and gas production and urbanization. Wetland losses are continuing today at an alarming rate, estimated at 350,000 to 500,000 acres annually.

The most extensive inland wetlands losses have occurred in Louisiana, Mississippi, Arkansas, North

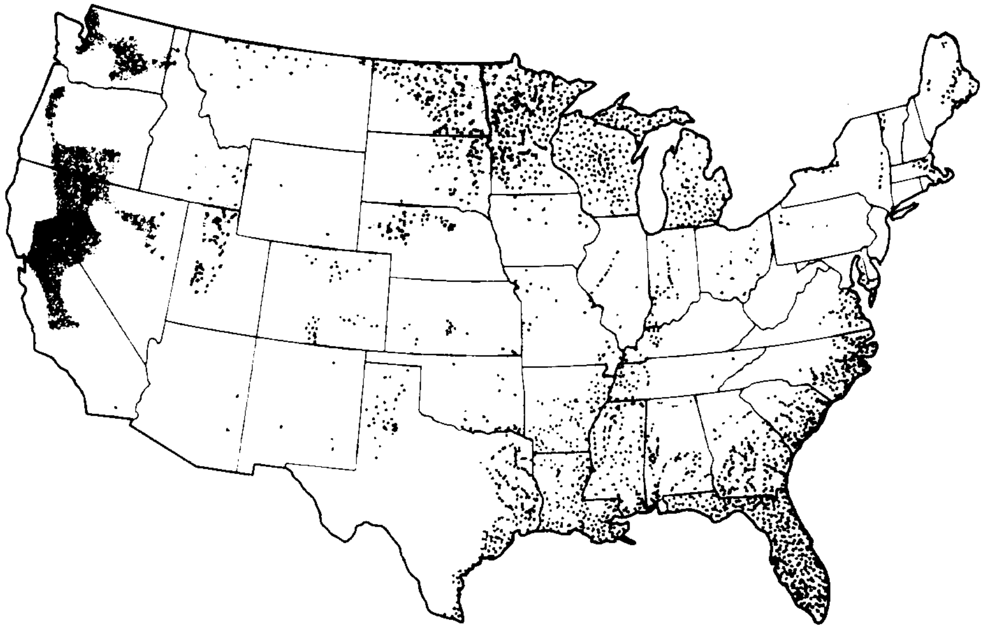


Figure 8.—Distribution of wetlands (OTA 1984).

Table 7.—Geographic distribution of wetlands, by type

Wetland type	Water resource region
Inland freshwater marsh	South Atlantic-Gulf Souris-Red-Rainy Texas-Gulf
Inland saline marsh	Lower Colorado Great Basin Pacific Northwest California
Bogs	South Atlantic-Gulf Great Lakes Ohio Upper Mississippi Lower Mississippi
Tundra	Alaska
Shrub and wooded swamps	South Atlantic-Gulf Great Lakes Ohio Upper Mississippi Lower Mississippi Texas-Gulf
Bottomland hardwoods	South Atlantic-Gulf Lower Mississippi Texas-Gulf
Coastal salt marshes	New England Mid-Atlantic South Atlantic-Gulf Texas-Gulf Pacific Northwest California
Mangrove swamps	South Atlantic-Gulf Texas-Gulf
Tidal freshwater wetlands	Mid-Atlantic South Atlantic-Gulf Texas-Gulf

Source: After OTA (1984)

Carolina, the Dakotas, Nebraska, Florida, and Texas. Estuarine wetlands losses have been greatest in California, Florida, Louisiana, New Jersey and Texas.

Results of these wetlands losses have been devastating. In many coastal areas where estuarine wetlands losses are high, urbanization and increased ground-water withdrawals have resulted in saltwater contaminating public water supplies. In Chesapeake Bay—the largest estuary in the U.S.—sea grass, wild celery beds, and tidal wetlands have been declining since the 1960s. In the upper Bay, they have almost disappeared. Canvasback ducks that thrived on the wild celery beds at the turn of the century are rarely found in the upper Bay and their population in the lower Bay is down significantly.

In North Carolina, forestry and agriculture have played an important role in the loss of considerable evergreen forested and scrub-shrub wetlands known as *pocosins*. Most of these areas were transferred to large-scale agriculture even though difficult to drain. In addition to extensive land clearing and ditching, large quantities of fertilizers and lime must be added to these wetlands to keep them fertile and productive. Runoff carries nutrients which degrade the water quality of adjacent estuaries. Development of pocosins for intensive softwood silviculture changes their character but the lands remain wetlands. In EPA (1987), 11 States reported that wetlands were a special concern (fig. 9).

INFLUENCE OF WETLANDS ON REDUCING PEAK FLOW RATES

Some wetlands have been used to help reduce flood damages to developed areas. Because wetland hydrology is extremely complex and variable by wetland type, not all such areas can provide temporary detention of runoff or a time lag between entering and exiting a wetland.

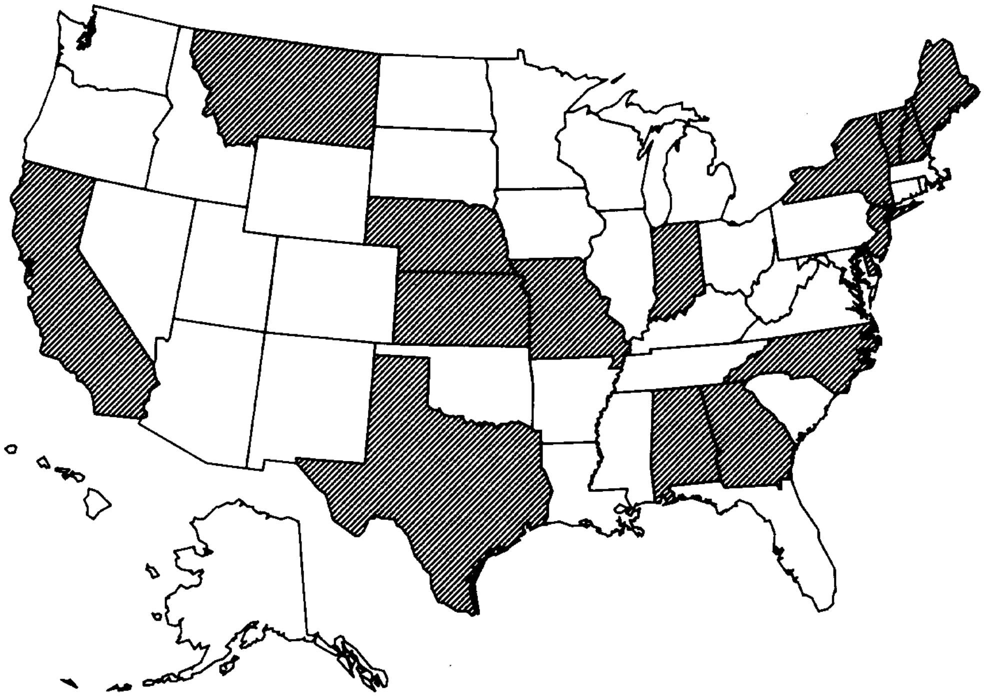


Figure 9.—States reporting wetlands loss as a special concern (EPA 1987).

When wetlands can provide temporary detention and a lag in runoff timing, they help reduce flood damages by lowering the peak flow rate of flood waters. A high peak flow for a short period of time tends to cause more damage to developments than a lower peak flow rate over a longer period of time. A second way that wetlands can help reduce flood damages is by slowing flood water velocities. When the velocity drops, flood waters experience a reduction in their ability to carry debris and sediment. Debris such as tree limbs, shopping carts, and sediment are responsible for a significant portion of flood damages both by crashing into objects and breaking them, as well as by being deposited in developed areas necessitating expenditures for cleanup. A third way that wetlands can help reduce flood damages is by helping to siphon off floodwaters and carry them around or away from developed areas. The classic example of how wetlands help in this way is found in southern Louisiana. When the lower Mississippi River reaches a certain flood stage, the U.S. Army Corps of Engineers diverts a portion of the Mississippi River around Baton Rouge and New Orleans through the Atchafalaya Swamp to the Gulf of Mexico. Also, the Bonnie Carrie Spillway above New Orleans can be opened to divert more of the river's flow across several miles of marshland to Lake Pontchartrain and through the Lake's outlet to the Gulf. A fourth way that wetlands can help reduce flood damages applies specifically to coastal wetlands. They help absorb the energy of the tidal surge accompanying hurricanes.

When development encroaches on coastal wetlands, periodic major storms can cause extensive damages. An example from southern Louisiana illustrates the point. The Pearl River is the border between eastern Louisiana and southern Mississippi. The lower 15 miles are a classic freshwater bottomland hardwood and cypress swamp, nearly 5 miles wide at points. Interstate 10 cuts across the lower part of the swamp forming a 5 mile-long dike punctured by 5 bridges and several culverts. In recent years, major floods on the Pearl have backed up behind the I-10 roadway causing damage to residential areas rimming the swamp, flowing over the roadway closing I-10, and threatening to wash out the roadbed.

INFLUENCE OF WETLANDS ON MAINTAINING WATER QUALITY

Richardson (1988) concluded that some wetlands are valuable from an ecological perspective because of their ability to transform, store, and recycle nutrients and sediments. By temporarily or permanently retaining pollutants such as toxic chemicals and disease-causing micro-organisms, wetlands can improve the quality of water that flows over and through them. Some pollutants that are trapped in wetlands may be converted by biochemical processes to less harmful forms. Some pollutants may remain buried; others may be taken up by wetland plants and either recycled within the wetland or transported from it. By temporarily delaying the release of nutrients until the fall when marsh vegetation dies back, wetlands can prevent excessive algal growth in open-water areas in the spring and summer. This characteristic led some communities in coastal areas to move their wastewater effluent pipes from rivers and offshore areas to wetlands where marsh vegetation can remove the nutrients. Not all types of wetlands have these characteristics.

REGULATIONS INFLUENCING WETLANDS CONVERSIONS

Section 404 of the Clean Water Act gives the U.S. Army Corps of Engineers authority to issue permits for the discharge of dredged or fill material into the navigable waters at specified disposal sites. This program is discussed in more detail in Chapter 8.

Inland freshwater wetlands comprise 95% of the remaining wetlands resource in the U.S. and more than 90% of the estimated 300,000 acres of freshwater wetlands lost each year to development. Many of the losses involve drainage without a discharge which is not regulated by the 404 Program. The swamp buster provision of the 1985 Farm Bill should help mitigate this problem by discontinuing subsidies to farmers who drain and plant wetlands.

Approximately 11,000 permit applications under Section 404 are processed by the Corps of Engineers each year. The EPA , the Fish and Wildlife Service (FWS), and the National Marine Fisheries Service all have a role in the permit review process as do states and other interested parties. One role of EPA is to determine if the proposed use will have "an unacceptable adverse effect on municipal water supplies, shellfish beds and fishery areas (including spawning and breeding areas, wildlife, or recreational areas)." If so, they can prohibit or restrict proposed site use.

As a result of this process, the Corps of Engineers annually denies about 3% of permit applications. About one-third of the permits are significantly modified from their original application and about 14% of permit applications submitted each year are withdrawn by the applicants. The Office of Technology Assessment (OTA 1984) estimated that these denials, modifications, and application withdrawals save 50,000 acres of wetlands every year.

NOTES

1. The material in this section is drawn largely from Foxworthy and Moody (1986).

2. Precipitation variability is even more extreme than depicted in figure 1 because of gauging station locations. Gauging stations are typically located at or near settlements to facilitate daily reading of the instruments. In mountainous areas, settlements are nearly always situated in valley bottoms where precipitation is often much lower than on the slopes or tops of the nearby mountains.

3. See the discussion by Reisner (1986).

4. Organic Administration Act of June 4, 1897 (Ch. 2, 30 Stat. 11, as amended; 16 U.S.C. 475).

5. The information in this section is drawn largely from "Water Availability Issues" in USGS (1984; p. 36–45).

6. Dr. James B. Gregory, Associate Professor of Forest Hydrology at North Carolina State University, brought this example to my attention.

7. The discussion is drawn largely from Foxworthy and Moody (1986).

8. Information in this section is drawn largely from three sources: Anon. (1984) provided an overview; Smith et al. (1987) reports trends based upon information data from two stream sampling networks operated by USGS; and EPA (1987), a biennial report to Congress.

9. The discussion that follows was drawn largely from EPA (1987).

10. Funding needs for waste treatment was also listed as a concern by 10 states. The funding concerns reflect expectations of additional funding cutbacks; because they have not yet occurred, the funding cutbacks were not analyzed in this report.

11. The discussion in this section is drawn largely from Council on Environmental Quality (1987), unless information is otherwise cited.

12. Alkalinity is a measure of the acid neutralizing capability of a waterbody. When a strong acid, such as sulfuric, enters the water, the natural alkalinity in the water buffers the acid added by chemically neutralizing it. In so doing, some of the alkalinity is consumed. So, a decline in alkalinity shows that acid entered the waterbody and was neutralized.

13. T is a measure of the erosion potential of the soil and its associated vegetative cover. Its use to evaluate land condition is explained more fully in USDA (1987).

14. Personal conversation with Wayne Swank, Forest Service Research Hydrologist, during the review of the water aspects of the *South's Fourth Forest* (USDA Forest Service 1988).

HISTORICAL OVERVIEW OF DEMAND FOR WATER

The emergence and growth of the United States as an industrialized nation has been closely tied to water use. Settlement along the Atlantic Coast was initially tied to use of water for transportation—settlements quickly sprung up at good harbors. Commercial fishing and trade were early water-based stimulants to local economies. Inland waterways became transportation corridors for trade in both raw materials and finished goods. In the West, Spanish settlers and missionaries established modest irrigation works in the 17th century. By the early 1800s, settlements were well established at many locations where favorable conditions of flow and topography permitted waterpower to be harnessed for milling products such as grain, logs, and wool. Development of the steam engine in the early 1800s suddenly freed industries from having to locate on stream banks to secure waterpower and the Industrial Revolution was underway. Mormon settlers began irrigation in 1847. Ranchers and miners in the West were also diverting water in the mid-1800s.

After being a constraint on growth for 200 years, water was much less so for the rest of the 19th century. Instead, fuel for the steam engine became the primary constraint. Wood and coal instead of waterpower fueled industrial expansion into the early 1900s. Also during this period, railroads rose to prominence as a method of transportation, thus making the country much less reliant on boats and barges and navigable streams and harbors. Water for drinking and water for waste disposal were the two uses that increased most rapidly to the beginning of the 20th century.

By the beginning of the 20th century, civilization had tainted most coastal waters and many inland streams. Rapid population growth of cities and increasing concentrations of industry combined to overtax the ability of the nation's water resources to meet all needs. Typhoid epidemics erupted in a number of cities along the East Coast around the turn of the century. The cause was finally determined to be contaminated drinking water. Practical methods of chlorinating drinking water had not yet been discovered. Rural and urban developments in the floodplain of major streams such as the Mississippi, Missouri, and Ohio Rivers, both contributed to the cause of flooding and incurred damages due to flooding. Flood control structures—dams and levees—were fragmentary. In the Midwest and West, many areas could not sustain settlement because insufficient water was available for crops or animal husbandry. Securing the coal and wood needed to fuel the economic engine of the U.S. led to resource extraction practices that fouled waters with sediment and acid. Land reclamation and forest regeneration practices had not yet been developed.

By the middle of the 20th century, the country had begun to remedy many water and related land resource problems. Local, state, and federal agencies led an assault

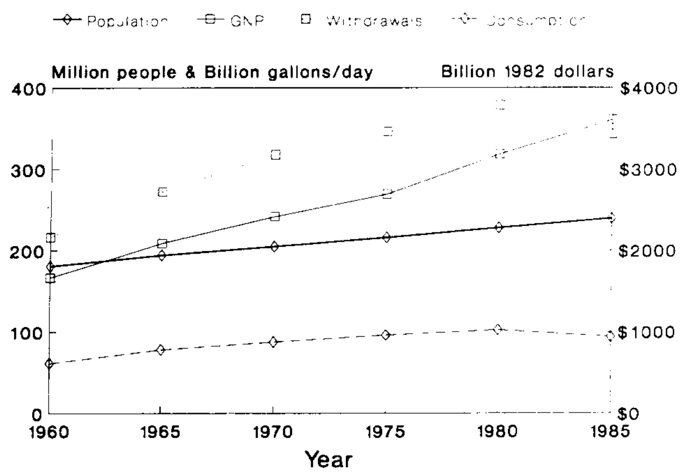


Figure 10.—Rates of increase in GNP, population, and water withdrawals, 1960-1985.

on the problems. Structural approaches to solving water resource problems were favored. The Army Corps of Engineers improved navigation and controlled flooding with locks, dams, dredging, levees, and other works. The Bureau of Reclamation built dams and irrigation structures to water the West. The Forest Service and SCS developed and installed land management practices to keep soil in place, thereby preserving clean water. The Tennessee Valley Authority began economic redevelopment of the southern Appalachians—a massive demonstration of how water resources could be better harnessed for economic development. Local and state governments installed water and waste treatment facilities to render potable supplies safe and remove suspended solids from waste flows.

The demands for water today stem largely from this history of developing water resources. The inertia created by using water resource development to drive economic development continues to affect demand for water today and will for years to come. Trends in water withdrawals and consumption through the 1960s and 1970s show an inexorable climb in total use, marching lockstep with increases in gross national product (GNP) and population (fig. 10).

But by the early 1970s it became clear that while prior developments had, to a great extent, solved problems of water flow volumes, much remained to be done about problems of water quality. Public Law 92–500 and subsequent amendments and related water quality legislation provided the added momentum needed to preserve pristine water quality where it existed and to clean up fouled water to fishable and swimmable levels. The legislation provided a major shift in the long-run trend of ever-increasing withdrawals and consumption. The added cost of waste treatment imposed by the legislation made water conservation and recycling much more cost-effective than it had been in the past. Recent water withdrawals and consumption information (Solley et al. 1988) shows that water quality legislation has also had a significant effect in retarding growth in demand for withdrawals and consumption (fig. 10).

This chapter reviews historical trends in water demand and projects those trends into the future. Water withdrawals and consumptive use are both referred to as "demand" in this chapter. In later chapters, demand analyses will use consumption because it is the more limiting form of water use.

Historical data on water withdrawals and consumption is summarized from USGS (MacKichan and Kammerer 1961, Murray 1968, Murray and Reeves 1972 and 1977, Solley et al. 1983, and Solley et al. 1988). Projections of withdrawals and consumption are presented for the years 2000 to 2040 based on USGS data from 1960 to 1985. Water demand projections made in other studies published since 1960 are reviewed and comparisons of data recently collected with previous projections are made.

HISTORICAL DATA ON WATER WITHDRAWALS AND CONSUMPTION

National trends in withdrawals and consumption.—The USGS reported estimates of water use in the United States at five-year intervals since 1950 (MacKichan 1951). The most recent data available is 1985 (Solley et al. 1988). Withdrawals in 1960 totaled 216 bgd and consumption was 61 bgd.[1] By 1985, withdrawals totaled 343 bgd and consumption 93 bgd, reflecting increases of 59% and 52% respectively (fig. 11).

National trends by water use.—Increases in total withdrawals and total consumption obscure interesting trends in the six major categories of water use and over time. Water uses examined in this report include thermoelectric steam cooling, irrigation, municipal central supplies, industrial self-supplies, domestic self-supplies, and livestock watering. Trends in freshwater withdrawals vary by use. Withdrawals for municipal central supplies rose 78% from 1960 to 1985 while withdrawals for industrial self-supplies dropped 21% (table 8).

Consumption trends also vary by use. Consumption by thermoelectric steam cooling rose 1840% from 1960

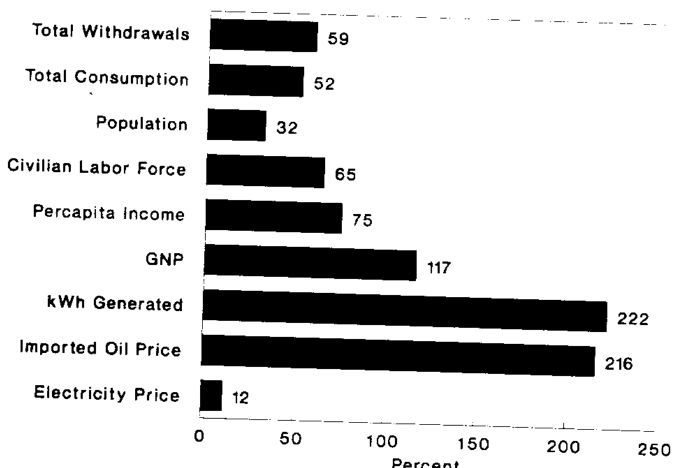


Figure 11.—Increases in withdrawals, consumption, and related variables from 1960 to 1985.

to 1985 while consumption by irrigation only rose 42% (table 9). Detailed tables of withdrawals and consumption by type of use are presented in Appendix A. Detailed discussion of trends by use category are presented later in this chapter when projections are discussed.

National trends by water source.—Withdrawal and consumption trends vary by source of water. From 1960 to 1985, groundwater withdrawals rose 81% and surface water withdrawals rose 53%; however, wastewater withdrawals declined 5%. The latter figure is particularly noteworthy because in the early 1970s, wastewater reuse was strongly encouraged. The reduction apparently only counts water withdrawn from conveyance structures after municipal wastewater treatment. One policy implemented by regulations arising from the Clean Water Act was to charge industries the full cost of treating industrial waste flows sent to municipal treatment plants. It now appears that industrial users adopted internal recycling strategies to reduce their waste flows and thus municipal waste treatment fees. Data showing industrial self-supplied withdrawals dropping 21% and consumption rising 39% are consistent with significant increases in internal recycling.

Regional trends in withdrawals and consumption.—Trends in freshwater withdrawals between 1960 and 1985 also varied among geographic regions (table 10). Withdrawals in the South and Rocky Mountains rose 89% and 75% respectively. This doubled the increases in the North and Pacific Coast, which were 40% and 32% respectively. Over this period, Censuses of Population and Manufacturing both reported population and industrial growth in the South and West and declines in the North. Water withdrawals were similarly affected. The lower percentage increase in withdrawals along the Pacific Coast reflects the fact that major increases in population and industry occurred in a water-short area (e.g. in Southern California) relying heavily on imports from other hydrologic basins.

Consumption trends by region show a different story. Consumption in the North increased 132%, far eclipsing increases in the South (68%), Pacific Coast (49%) and Rocky Mountains (37%). Because the North is more heavily industrialized than other parts of the United States, it shows a larger increase in consumption than the other regions. Irrigation is the primary component of consumption in the other three regions. There have been smaller percentage increases in consumption in irrigation than in the industrial sector.

PROJECTED DEMANDS FOR WATER

The projections from 2000 to 2040 presented here are the result of Forest Service analyses conducted especially for this Assessment. Projections *are not* the Forest Service interpretation of a "most likely" scenario. The projections *are* a statement of demand levels in 2040 if recent trends in demand for water continue. Projections of withdrawals and consumption are intended to suggest future demands if water resource management continues as it has from 1960 to 1987. However, some demand pro-

Table 8.—Total freshwater withdrawals (million gallons per day) in the United States for 1960 to 1985, by water use and source, with projections of demand to 2040

Water use and source	1960	1965	1970	1975	1980	1985	Projections 2000	2010	2020	2030	2040
Thermoelectric steam cooling											
Groundwater	920	1100	1400	1400	1600	610	700	700	690	680	680
Surface water	73100	90500	118300	129600	146800	129800	156700	174500	192200	209900	227600
Total Thermoelectric	74000	91600	119800	131000	148400	130400	157400	175200	192900	210600	228300
Irrigation											
Groundwater	30400	41600	45250	57100	61200	56300	55600	58300	60900	62650	64200
Surface water	54000	74400	81700	85000	90400	85800	86600	92900	99100	104210	109100
Wastewater	560	500	370	370	280	450	290	260	200	200	200
Total Irrigation	84900	116500	127300	142500	151900	142500	142500	151500	160200	167100	173400
Municipal central supplies											
Groundwater	6300	8100	9500	10800	11700	14600	20100	24100	28200	31600	33700
Surface water	14200	15700	17900	18800	22300	21900	30500	34600	38500	41640	43500
Total Municipal	20500	23800	27400	29600	34000	36500	50600	58700	66700	72300	77100
Industrial self-supplies											
Groundwater	6000	6800	8000	9700	10300	6100	5600	6400	7340	8310	9340
Surface water	27200	29700	31200	28600	28700	20200	21700	23600	25420	27220	28960
Wastewater	70	140	150	170	190	150	300	400	420	470	500
Total Industrial	33300	36600	39300	38500	39200	26450	27600	30400	33200	36000	38800
Domestic self-supplies											
Groundwater	1840	2200	2500	2670	3260	3250	4300	4800	5250	5600	5800
Surface water	160	120	120	130	180	60	80	60	40	30	30
Total Domestic	2000	2320	2620	2800	3340	3320	4380	4860	5290	5630	5830
Livestock watering											
Groundwater	825	1000	1070	1250	1200	3020	1500	1600	1690	1750	1780
Surface water	675	740	800	900	970	1450	1180	1260	1330	1380	1410
Total Livestock	1500	1740	1870	2150	2170	4470	2680	2860	3020	3130	3190
Total groundwater withdrawal	46285	60800	67720	82920	89260	83880	87800	95900	104070	110590	115500
Total surface water withdrawal	169335	211160	250020	263030	289350	259210	296760	326920	356590	384380	410600
Total wastewater withdrawal	630	640	520	540	470	600	590	660	620	670	700
U.S. Total Withdrawals	216200	272400	318300	346600	379000	343700	385200	423600	461300	494800	526600

NOTE—The sum of totals by use and by water source differ because of independent rounding of intermediate sums.

Source: Data for 1960 through 1985 from U.S. Geological Survey Circulars, except for 1985 irrigation numbers. These are from the Soil Conservation Service, modified by additional non-agricultural irrigation use. Data for 2000 through 2040 are Forest Service estimates based upon trends in the historical data.

jections lead to environmental, social, and economic implications at odds with the nation's goals. Consequently, these demand projections are a description of what planners call the "without" condition; the basis for evaluating the impacts of possible changes in water resource management to better achieve environmental, social, and economic goals for the future.

In the course of analyzing demand data, it became clear that simple linear extrapolation of data from 1960 to 1985 did not fit as well as semi-logarithmic or logarithmic curve forms. Linear trends usually had the 1985 datum well beneath the trend line and the 1980 datum on or slightly beneath the line. The Water Resources Council (1978) projected that the *rate of increase in demand* from most uses would decline drastically by the year 2000 as a consequence of the Clean Water Act. They believed that water conservation and internal recycling would combine to hold demands in the year 2000 at about 90% of the 1975 level. The 1980 data were close enough to the 1975 data that one could not be certain whether the rate of increase in demand had begun to decline or if the 1980 data were but a momentary pause in the rate of increase. The 1985 data provide conclusive evidence that demand was strongly affected by legislation and regulations of the 1970s—in fact, there was about a decade's lag between changing national policy and the effects of the policy change becoming apparent. Because structural changes in waste treatment and water conservation required planning, design, and securing of funding after regulations were written and before construction could begin, a 10-year lag between the law's passage and the first clear evidence of changes in water use is reasonable.

Semi-logarithmic and logarithmic curve forms provided a better fit to the historical data than linear trends. The curves imply that conservation and recycling will continue to occur at levels mandated by 1970s legislation. Additional increments of waste treatment and

Table 9.—Total freshwater consumption (million gallons per day) in the United States for 1960 to 1985, by geographic area and use, with projections of consumption to 2040

Water use	1960	1965	1970	1975	1980	1985	Projections 2000	2010	2020	2030	2040
North											
Domestic self-supplies	427	517	513	356	594	595	482	494	504	511	515
Industrial self-supplies	1045	1351	1187	1177	1247	1656	2790	3155	3523	3891	4262
Irrigation	233	398	460	613	1278	1187	1417	1481	1543	1592	1637
Livestock watering	603	628	614	689	623	650	643	680	711	733	746
Municipal central supplies	1329	1735	1881	1749	1615	1618	2335	2575	2783	2931	3016
Thermoelectric steam cooling	53	87	106	630	1294	2865	5457	6539	7379	8483	9829
Total North	3691	4717	4762	5215	6651	8571	13124	14924	16443	18142	20005
South											
Domestic self-supplies	519	798	721	661	842	843	732	750	766	777	783
Industrial self-supplies	1524	1581	2220	2075	2781	1702	2378	2690	3003	3317	3633
Irrigation	9143	14913	12646	17564	16356	14701	17550	18349	19116	19717	20278
Livestock watering	416	472	540	680	769	992	925	977	1022	1054	1073
Municipal central supplies	1139	1301	1612	2323	2172	2176	3140	3464	3742	3942	4056
Thermoelectric steam cooling	96	228	568	1061	1536	1089	1739	2083	2351	2703	3132
Total South	12837	19294	18307	24364	24455	21503	26464	28312	29999	31509	32954
Rocky Mountains											
Domestic self-supplies	120	136	161	188	293	293	211	216	221	224	226
Industrial self-supplies	157	248	378	601	625	376	503	569	635	701	768
Irrigation	24073	30491	34755	34999	36242	31689	37836	39558	41212	42508	43717
Livestock watering	315	439	476	498	430	524	533	563	589	607	618
Municipal central supplies	495	584	756	857	1303	1305	1883	2077	2244	2364	2432
Thermoelectric steam cooling	48	83	126	207	369	303	482	578	652	750	869
Total Rocky Mountains	25208	31981	36651	37350	39260	34494	41449	43561	45553	47154	48631
Pacific Coast											
Domestic self-supplies	151	117	261	244	253	253	249	255	261	264	267
Industrial self-supplies	249	181	306	332	364	409	1044	1180	1318	1456	1594
Irrigation	18576	20095	25608	26745	29243	26211	30695	32091	33433	34484	35465
Livestock watering	103	82	82	84	80	207	211	223	233	240	244
Municipal central supplies	508	1517	1675	1737	2006	2010	2901	3199	3457	3641	3746
Thermoelectric steam cooling	27	18	24	40	42	96	86	103	117	134	155
Total Pacific Coast	19614	22010	27957	29182	31987	29186	35185	37052	38817	40220	41472
U.S. Total Consumption	61350	78002	87677	96111	102353	93755	116222	123850	130812	137025	143062

Source: Data for 1960 through 1985 from U.S. Geological Survey Circulars. Data for 2000 through 2040 are Forest Service estimates based upon trends in the historical data.

recycling beyond that mandated by existing legislation are not assumed to occur in the future. Comparisons of projections in 2040 between linear and the two curve forms showed that, on average, demands are 15% to 20% lower for the curve forms than the linear form. The analyses suggest that is a reasonable expected gain from conservation and recycling.

The 1987 release of BMDP Statistical Software (Dixon et al. 1985) for personal computers was used to analyze data and perform projections. Standard BMDP diagnostics were used to evaluate statistical fit and significance. Projection equations and goodness-of-fit statistics are listed in Appendix B. The data consisted of historical water withdrawal and consumption information from USGS reports and demographic information forming the basic assumptions for this Assessment (table 11).

Projections were made by water use category at the national level. The projections were then disaggregated to water resource regions and Forest Service Regions based on the shares each region had of the 1985 total withdrawals and consumption. Where historical data suggested that regional shares were changing, a continuation of the rate of change was factored into the disaggregation process. Results are displayed in tables 8–10 and in Appendix A.

THERMOELECTRIC STEAM COOLING

Thermoelectric power is electricity generated using either fossil-fuel (coal, oil, or natural gas), renewable (wood or geothermal), or nuclear energy. No matter what the energy source, the principal method of generating electricity is to convert water into steam and then use steam pressure to propel the generator's turbine. Spent steam recondenses into hot water which must then be dealt with in some way. In nuclear reactors, the steam generation and recondensation process is typically a closed-loop process where the recondensed water is recycled back to the boiler. Cooling water is used to assist the recondensation process.

Table 10.—Total freshwater withdrawals (million gallons per day) in the United States from 1960 to 1985, by geographic area and water source, with projections of demand to 2040

Region and water source	**1960**	**1965**	**1970**	**1975**	**1980**	**1985**	**Projections 2000**	**2010**	**2020**	**2030**	**2040**
North											
Groundwater	5625	7130	8750	8920	9930	9395	12060	13840	15670	17225	18365
Surface water	70735	92000	107355	106975	110050	97785	117110	130450	143600	156350	168450
Wastewater	80	125	130	155	190	105	250	310	325	375	415
Total North	76440	99255	116235	116050	120170	107285	129420	144600	159595	173950	187230
South											
Groundwater	15570	21820	19165	23650	24040	24520	25795	28280	30790	32830	34390
Surface water	34635	42765	57415	68265	83295	70460	82360	91450	100400	109050	117300
Wastewater	30	5	20	65	70	175	100	110	100	105	105
Total South	50235	64590	76600	91980	107405	95155	108255	119840	131290	141985	151795
Rocky Mountains											
Groundwater	12690	15920	18675	27920	31140	29190	27515	29220	30890	32125	33120
Surface water	36420	47420	52740	53380	59745	57520	61475	66320	71075	75100	78850
Wastewater	90	125	170	155	35	55	70	75	65	60	60
Total Rocky Mountains	49200	63465	71585	81454	90920	86765	89060	95615	102030	107285	112030
Pacific Coast											
Groundwater	13400	15930	21130	22430	24150	20790	22430	24560	26720	28410	29625
Surface water	27545	28975	32510	34410	36260	33450	35815	38700	41525	43880	46000
Wastewater	430	385	200	170	175	260	165	165	135	130	120
Total Pacific Coast	41375	45290	53840	57010	60585	54500	58410	63425	68380	72420	75745
Total groundwater	46285	60800	67720	82920	89260	83800	87800	95900	104070	110590	115500
Total surface water	169335	211160	250020	263030	289350	259210	296760	326920	356590	384380	410600
Total wastewater	630	640	520	540	470	600	590	660	620	670	700
U.S. Total Withdrawals	216200	272400	318300	346600	379000	343700	385200	423600	461300	494800	526600

NOTE—The sum of totals by region and by water source differ because of independent rounding of intermediate sums.

Source: Data for 1960 through 1985 from U.S. Geological Survey Circulars, except for 1985 irrigation numbers. These are from the Soil Conservation Service, modified by additional non-agricultural irrigation use. Data for 2000 through 2040 are Forest Service estimates based upon trends in the historical data.

Table 11.—Data used to project withdrawals and consumption

Variable	**1955**	**1960**	**1965**	**1970**	**1975**	**1980**	**1985**	**2000**	**2010**	**2020**	**2030**	**2040**
Population[1]	165.9	180.7	194.3	205.1	216.0	227.8	239.3	274.9	294.3	312.1	325.5	333.4
Civilian labor force[2]	65.02	69.63	74.45	82.77	93.77	106.94	115.46	142.54	159.16	175.09	192.26	211.86
Disposable income[3]	5.71	6.06	7.03	8.13	8.94	9.72	10.62	13.92	16.73	19.66	23.53	28.79
Gross national product[4]	1,494.9	1,665.3	2,087.6	2,416.2	2,695.0	3,187.1	3,607.5	5,402.0	7,031.3	9,166.1	11,956.7	15,626.0
Billion kWh generated[5]	-----	557.	791.	1,143.	1,318.	1,612.	1,794.	2,311.	2,765.	3,285.	3,760.	4,265.
Imported oil price[6]	-----	7.67	7.35	7.05	23.49	39.54	24.21	32.08	51.10	69.85	88.86	107.88
Electricity price[7]	-----	16.10	14.20	12.50	15.00	17.50	18.00	19.00	19.50	20.00	20.50	21.00

Notes:

[1]*Million people*
[2]*Million people*
[3]*Thousand 1982 constant dollars per capita*
[4]*Billion 1982 constant dollars*
[5]*Generation by fossil-fueled powerplants. Historical information from Energy Information Administration, projections based upon the historical linkage between GNP and electricity demand described in Department of Energy documents.*
[6]*Constant 1982 dollars per barrel, F.O.B. domestic refinery.*
[7]*Constant 1984 dollars per million BTUs*

Source: Darr (1989)

In fossil-fuel and geothermal power plants, the process is not always a closed loop. "Once-through" cooling was the norm until the early 1970s. Legislation then recognized that putting excess heat back into the aquatic environment was as damaging as putting excess nutrients or allowing suspended sediments into the streams. Excess heat is called *thermal pollution*. Today, power generation facilities use a variety of ways to get rid of waste heat to the atmosphere before piping cooled water back to the stream. Some plants use cooling towers or cooling ponds, relying upon evaporation to cool the water. These are often effective enough that the cooled water can be recycled through the plant. As recycling increases, the amount of water consumed through evaporation will increase.

Electricity generation in the United States has set a new record every year since the early 1940s except for 1982. In 1985, a new record of 2.47 trillion kiloWatt-hours (kWh) was set. Electricity generation from petroleum, natural gas, and hydroelectric power has continued to decline, while generation using coal, nuclear, and renewable resources has continued to rise (fig. 12) (Energy Information Administration 1986a). These changes continue the shifts in mix of fossil fuels that have been underway since the 1950s. The share of electricity generated by natural gas and petroleum has fallen from 37% in 1972 to only 16% in 1985. Generation using petroleum products peaked at 365 billion kWh in 1978 and declined to 100 billion kWh in 1985. Generation using natural gas peaked at 376 billion kWh in 1973 and has dropped to 292 billion kWh since then. The share generated by coal and nuclear fuel has risen over the same period from 47% to 72%. Generation using coal has increased more than 100% since 1970 and stood at 1,401 billion kWh in 1985. Nuclear power generated 384 billion kWh in 1985, a 1000% increase since 1971. The share of electricity generated by hydropower is also on the decline. Although outputs have remained essentially constant, subject to vagaries of the weather, the share has fallen because total generation increased. Hydroelectric power peaked at 332 billion kWh in 1982 but dry weather in recent years resulted in a decline to 282 billion kWh in 1985.

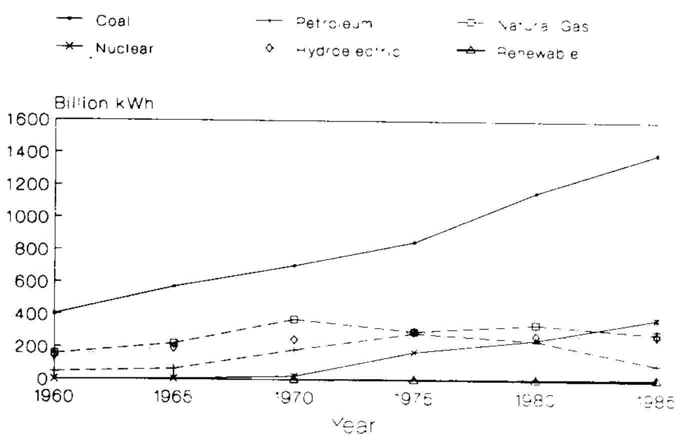


Figure 12.—Electricity net generation by fuel source, 1960-1985 (Energy Information Administration 1986a).

Choice of fuels varies across regions due to availability and transportation costs. The Northeast relies primarily upon nuclear and oil-fired units; the Pacific Coast on natural gas and hydropower. All other regions—especially those in the South and Southwest experiencing the largest rates of population and industrial growth—depend primarily on coal (Energy Information Administration 1986b).

A recent examination of electricity demand between 1953 and 1983 determined that a structural change did occur in 1973 following the Arab oil embargo (Energy Information Administration 1985). A more recent study (Cornett 1985) analyzed changes in demand in the early 1980s following the structural change. This analysis demonstrated that changes in demand were uneven across sectors of the economy and areas of the country. Less rapid growth in electricity use in the residential and commercial sectors can be explained mainly by conservation measures in response to higher electricity prices. Average growth of about 2.0% per year in residential electricity demand between 1980 and 1984 compares with average annual GNP growth of 2.7% for the same period. Average growth in commercial demand exceeded 4%. Industrial growth in electricity demand was down sharply during the last recession. Average annual growth in demand was only 0.8% per year—less than one-third the growth rate in GNP. If growth in residential and commercial demand for electricity remains moderate (as a result of slow growth in housing and commercial sectors) and growth in industrial output remains low, then the ratio of electricity-to-GNP growth rates could remain below 1.0—barely one-half the 1.8 average ratio for the 1953–1984 period. Cornett (1985) found that most of the change in residential and commercial demand for electricity in the early 1980s can be attributed to changes in real income. The change in industrial demand for electricity is attributed largely to changes in output associated with the recession. Cornett concluded that if recent sluggish output trends in housing construction, food, paper, chemicals, and primary metals sectors (the five biggest industrial users of electricity) continue, and if gains in energy efficiency continue because prices remain high, future electricity/GNP growth ratios will continue to remain below 1.0.

Cornett's outlook for electricity demand was amplified in the National Energy Policy Plan (Department of Energy 1985). Energy productivity (GNP per unit of energy consumed) rose 28% between 1974 and 1985—14% between 1981 and 1985, the greatest improvement in efficiency since World War II. This progress is continuing for all types of energy including electricity. Energy conservation has made a bigger contribution to reducing the need for new or imported energy resources than any change in fuels has accomplished (e.g. substituting coal for petroleum). The plan proclaimed coal as the fuel for America's future. It has become the main fuel for electric utilities. Modern coal-fired powerplants are cleaner than most older oil-fired plants. New technologies to burn coal are being developed that promise even higher efficiencies and environmental performance. The increased demand for coal will lead to more mining which has implications for mine-related water impacts.

Nuclear energy is now the second-largest source of electricity and provides 15% of the nation's needs. This is expected to rise to 20% by the turn of the century. Renewable energy resources (now primarily wood and water) contribute about 9% of the country's domestic energy production. This could rise to nearly 13% by the end of the century and to 15% by 2010 as more economical renewable energy technologies (e.g. wood, geothermal, solar, or wind) develop.

Future trends in energy consumption, particularly electricity consumption, suggest that efficiency increases will continue. The National Energy Policy Plan projects that it could take 20 to 30 years to gain full advantage of all the opportunities for efficiency that have been recognized in the industrial sector. The residential sector has shown a 40% drop in energy use per household since 1973 due largely to improved insulation, improved appliance efficiency, and changes in household behavior. Further, the average efficiency increase in energy-using capital goods will increase over time by an additional 20% to 50% through normal turnover of stock and implementation of more efficient technologies.

Given the assumptions of energy conservation outlined above, the nation will need between 100 and 300 gigawatts of new electrical generation capacity between now and the year 2000; over and above the 70 gigawatts under construction in late 1985. This new capacity will be needed to replace obsolete units as well as satisfy growth in electricity demand. The nation currently has some excess electrical generation capacity. Utilities are trying to stretch their capacity by improving operation and maintenance. They hope to boost utilization factors of generating units by 10% to 25%. More intensive use of existing capital will help postpone new construction but does not significantly reduce cooling water needs.

Another way of meeting power demands is to import energy. Power imports from Canada (principally hydropower) have grown six-fold since 1970. They are expected to double from the current 40 billion kWh level (2% of domestic demand) to 80 billion kWh by the year 2000 (3% of domestic demand). Between excess capacity and improving utilization, conservation, interconnection of power distribution networks, and imports from Canada, public utilities are attempting to stave off the need for construction of new powerplants.[2] However, by the turn of the century, significant expansions in construction programs of many utilities will inevitably occur to meet rising demand.

Current projections by the Department of Energy show demand for electricity growing in rough proportion to growth in the nation's economy for the foreseeable future. The question pertinent to this Assessment is the nature of the relationship because cooling water withdrawals are made in direct proportion to the number of kWh generated by fossil-fuel, nuclear, and wood-burning powerplants. All conclusions by the Department of Energy (1985) suggest that the historic tie between rate of growth in GNP and electricity demand has undergone a major structural change since the mid-1970s and that the ratio of growth in electricity generated to growth in GNP is likely to stay below 1.0 well into the next century. Efficiency gains reported and expected mean that the nation will use less electricity to produce increments of GNP in the future than in 1950s and 1960s. Consequently, this Assessment adopts the 0.8 ratio determined by the Department of Energy for the early 1980s and projects kWh as a linear function of the growth in GNP.

Water use and trends.—Thermoelectric powerplants furnish practically all of their own water; less than 1% is obtained from public supplies. In 1985, total water withdrawals for thermoelectric steam cooling totaled 187 bgd—a decrease of 11% from 1980. This total includes 130.4 bgd of freshwater and 56 bgd of saline water (saline water withdrawals and consumption are not studied in this Assessment). The 1985 freshwater withdrawal level is 12% less than the 1980 level and the same as withdrawals in 1975 even though the kWh generated have increased 36% since then (figs. 13–16; tables A.1, A.7, and A.13; figs. A.3 and A.4).

About 99% of withdrawals are used for condenser and reactor cooling of generators. About 4% of freshwater withdrawn is consumed, up from 2% in 1980, 1% in 1975 and 0.5% in 1970.

Thermoelectric steam cooling is the second largest withdrawal use next to irrigation. It has been the fastest growing use in recent years. Assumptions made about the continued increase in demand for electricity lead to projections of withdrawals that make it the largest use of water by 2040. Most of the increase in water use comes after 2000 when a large number of new power plants begin generation.

One of the largest withdrawal uses—thermoelectric steam cooling—is one of the smallest consumptive uses. Consumption has been rising rapidly, but from an extremely small base. Consumption is projected to double by 2010 and triple by 2040. However, even by 2040, consumption is still projected to be only 6% of withdrawals.

Potential for changes in the projections.—Because electrical demands are tied so closely to GNP increases, and because GNP growth rates show long-term increases, it would take a major economic disturbance to significantly alter these long-run withdrawal and consumption projections. The Arab oil embargo of the early 1970s was just such a disturbance and resulted in a structural change in the electricity/GNP long-term trend. Other potential events that could significantly alter withdrawals and consumption include additional major water quality legislation directed at thermal pollution, which would boost consumption and cut withdrawals, and the advent of practical uses for recently invented superconductor materials, which would reduce withdrawals.

IRRIGATION

Irrigation is the act of applying water to land to promote vegetation growth or obtain other benefits. In arid and semi-arid parts of the Rocky Mountains and Pacific Coast, irrigation is needed to raise most non-native

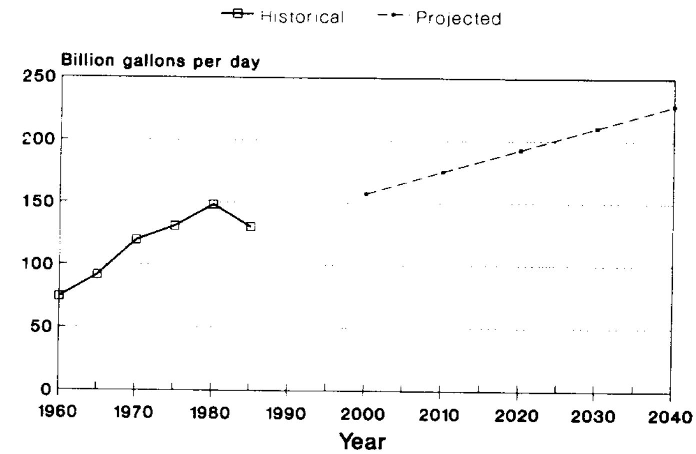


Figure 13.—Thermoelectric stream cooling, total freshwater withdrawals.

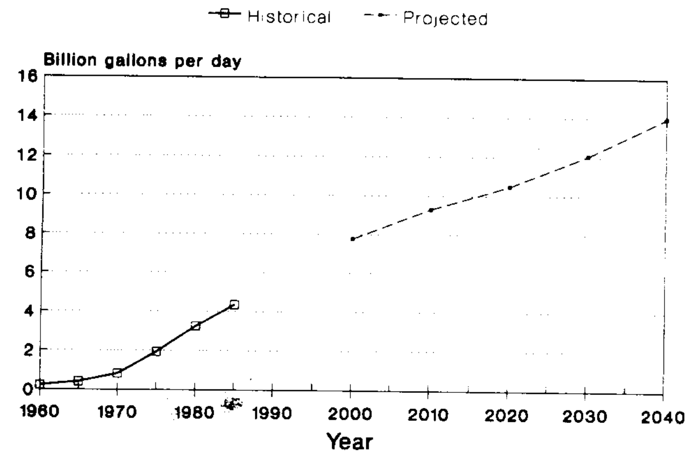


Figure 14.—Thermoelectric steam cooling, total freshwater consumption.

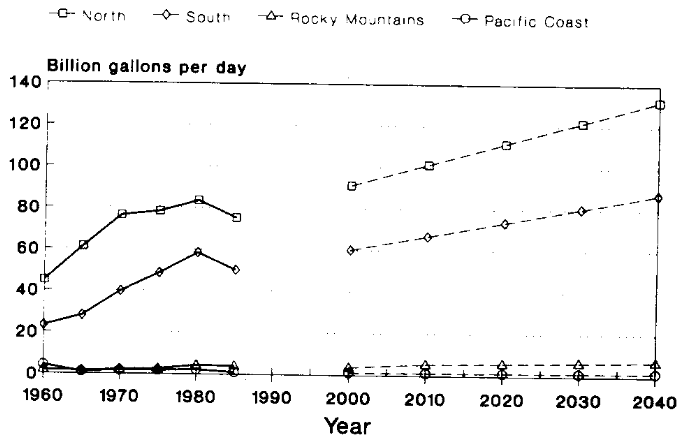


Figure 15.—Thermoelectric steam cooling, freshwater withdrawals by region.

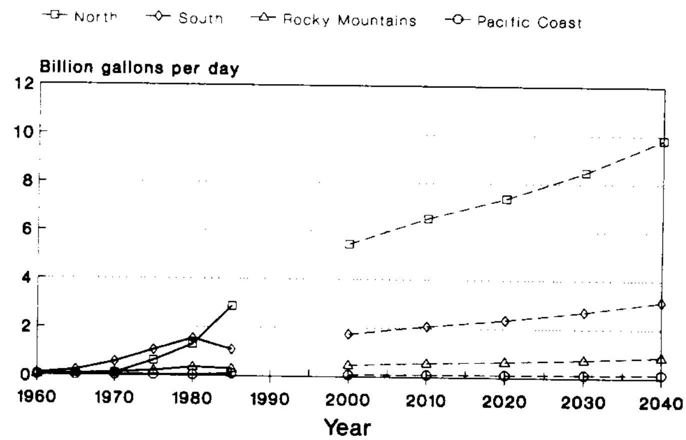


Figure 16.—Thermoelectric steam cooling, freshwater consumption by region.

vegetation. Agricultural, horticultural, and viticultural activities depend on regular applications of water at frequent intervals. In many Western areas, home, business, roadside, and recreation settings, turf and landscape plantings require irrigation too. Irrigation also promotes beautification in residential and business settings and helps keep buildings cooler.

Irrigation is often essential to recreation activities such as managing turf on golf courses and making snow for downhill skiing. In rural areas, irrigation of roadside plantings and property perimeters can assist in wildfire control by establishing a buffer of less-combustible vegetation. In the more humid North and South, irrigation also provides an increase in the number of plantings per year, yield per crop, and reduces the risk of losses during drought periods. High-valued crops such as fruits and vegetables are irrigated to maintain quality standards and some canners and processors will not buy non-irrigated produce. Irrigation is also used to reduce nursery and fruit losses to late spring and early fall frosts. Estimates of withdrawals and consumption of water for irrigation purposes vary greatly because of the many factors involved.

Most irrigation involves crops. If acres in crop production and water application rates can be determined, then some reliable estimates of withdrawals for irrigation can be made. Additional information about evapotranspiration must be known to reliably estimate consumption. This data is scarce. Different sources of irrigation information gather data in different ways, thus complicating the process of estimating acreage irrigated. For example, the Census of Agriculture conducted by the Department of Commerce reports land as irrigated only if irrigated in the year of the census. The Natural Resources Inventory conducted by the SCS every 5 years records land as irrigated if irrigated in the year of the survey or in two or more of the preceding four years. Irrigation trade associations publish statistics based upon other criteria. An extensive analysis of irrigation water requirements for croplands was conducted by Flickinger (1987) for the Appraisal.

Day and Horner (1987) present data on the history of irrigated agriculture. In 1889, 3.6 million acres (0.6%) of the 623 million acres of farmland in the U.S. were irrigated. All irrigated land was located in the arid and semi-arid West, principally California (1 million acres) and Colorado (0.9 million acres). In 1889, 54,000 farms were irrigating an average of 67 acres and each producing $11.50 per acre in crop value. Today, about 45 million acres of farmland are irrigated, an average of 210 acres per farm and producing about $530 per acre. Irrigated land area has grown continuously, except for several years during the Great Depression and during 1978–1984. The growth rate declined since the mid-1950s except for a brief increase from 1969 to 1978. The proportion of irrigated to non-irrigated farmland reached a record high of 5% in 1978 with approximately 50 million acres irrigated. Since then, irrigated acreage of farmland declined by about 11%. During the recession of 1982–1984, irrigated acreage declined 4.3 million acres.

A major factor behind the rapid expansion of western irrigation during 1880 to 1900 was the need for winter feed to sustain the growing cattle industry. Simple low-head dams and stream diversion structures were constructed to flood meadows and irrigate hay and other feed crops. Without winter feed, it is likely that millions of acres of rangeland would have been underused and the feed grain-livestock economy of the Great Plains might never have developed. Today, 60% of irrigated farmland is used to produce forage, roughage, and feed grain crops (corn, barley, oats, sorghum, hay, pasture, and silage) for livestock.

Wheat and rice production—food grains for humans—slowly gained importance as a component of irrigated farmland, rising from a 10% share in 1889 to a 17% share by 1982. As agricultural technology and transportation systems improved and as consumer demand for a wider variety of crops increased, irrigated land increasingly was devoted to what were initially known as "specialty crops". Today, this list includes cotton, sugarcane, peanuts, tobacco, soybeans, vegetables, and orchards. Twenty percent of farmland irrigated is used to grow these crops (Day and Horner 1987).

Day and Horner (1987) document how irrigation use differs among regions. The Pacific Coast and Rocky Mountain regions account for 85% of irrigated farmland in the U.S. About 12% of southern farmland is irrigated, principally the river delta areas in Arkansas, Louisiana, and Mississippi, where rice, cotton, and sugarcane are grown extensively, and in Florida where citrus and vegetables are widely grown. The rapid growth of irrigated farmland in the South is largely due to expansion in Georgia, now the eighth largest state for irrigated corn production (Bajwa et al. 1987). Irrigation is much less prevalent in the North, but supplemental irrigation is expanding rapidly in the Lake States and Corn Belt (Iowa, Missouri, Illinois, Indiana, and Ohio) as farmers learn how to augment rainfall to improve planting schedules and reduce weather risks. About 4% of the farmland in the North is irrigated.

The federal government played a large role in the development of irrigation in the western states. The Reclamation Act of 1902 established the Bureau of Reclamation in the Department of the Interior to facilitate settlement of the western States by developing irrigation water supplies. Since then, the Bureau has carried out an extensive program of dam and water distribution system construction and operation. In 1982, 10.9 million acres of land were irrigated with water from Bureau of Reclamation projects. This acreage produced about $7.3 billion in gross revenues. These figures represented about 20% of all irrigated farmland in the contiguous U.S. and about 30% of the value of all irrigated farmland outputs (Day and Horner 1987).

U.S. farmers use two basic types of irrigation water application systems—gravity and sprinkler. Gravity systems apply water using gated pipes, ditches with siphon tubes, overland flooding, and underground porous pipes (subirrigation). Gravity systems were used on 27.5 million acres of farmland in 1984 (Day and Horner 1987). Bajwa et al. (1987) reported that the farmland acreage irrigated by gravity systems dropped 12% between 1979 and 1984.

Sprinkler systems are the more modern of the two application systems and also more expensive. Sprinklers include different types of equipment delivering water under pressure. Hardware includes center pivot systems, side-roll units moved either mechanically or by hand, permanent sprinklers, moveable and permanently mounted guns, and drip systems. Sprinkler systems were used on 18.3 million acres of farmland in 1984 (Day and Horner 1987). Bajwa et al. (1987) reported that farmland acreage irrigated with sprinklers dropped 8% between 1979 and 1984.

A relatively new pressurized method currently included in the sprinkler figures is drip or trickle irrigation. This technique is very popular in orchards. Its use expanded by 161% between 1979 and 1984, but the total acreage irrigated with this method in 1984 was still less than 1 million acres. The major virtue of drip or trickle systems is less water use than conventional sprinkler systems. Major disadvantages of drip systems are they cannot be used to flush salts from saline soils and they are expensive.

Water use and trends.—Irrigation water withdrawals in 1985 totaled 142.5 bgd, a decline of 6% since 1980 (fig. 17). The 1985 level of withdrawals is equivalent to the 1975 level. Irrigation withdrawals in 1985 were larger than for any category of water use. Irrigation is by far the largest consumptive user. Consumption totaled 73.8 bgd in 1985, or 78% of the total consumption by all uses (fig. 18). It is this aspect of irrigation water use that has the most significance for current and projected future water use and development. Regional breakdowns of irrigation water withdrawals and consumption are shown in figures 19 and 20 and tables A.2, A.8, and A.14; and by source in figures A.5–A.7.

Irrigation water comes from wells, on-site surface sources, and surface sources provided by off-site suppliers such as irrigation districts and ditch companies. The principal source is from wells—56.3 bgd, or 68% of total groundwater withdrawals. Surface withdrawals amounted to 85.8 bgd in 1985, which is 33% of total national withdrawals. Bajwa et al. (1987) report that 3 of every 4 gallons from surface sources are provided by off-site suppliers. As discussed in Chapter 2, irrigators in the Great Plains rely heavily on groundwater withdrawals while irrigators in other parts of the Rocky Mountain and Pacific Coast regions rely heavily on off-farm suppliers.

Because both wells and on-farm surface water sources must be pumped to deliver water to crops, energy expenses of irrigating farmland can be quite high. Total energy expenses for irrigation pumping reached $1 billion in 1984. Average expenditures per acre grew by 60% from $20 per acre in 1979 to $32 per acre in 1984. This growth in energy costs occurred during the same period that farmland acreage irrigated fell by 11%. Viewed in this context, the rise in energy costs is even more dramatic. Five sources of energy are used to pump irrigation water—electricity, natural gas, liquid propane (LP) gas, diesel oil, and gasoline. Electricity dominates at 58%, natural gas is 19%, and diesel oil 17% of the irrigation pumping energy market. Since 1979, electricity usage grew in importance, natural gas declined, and diesel oil held steady (Bajwa et al. 1987).

Flickinger (1987) reported that water withdrawals by farmers for irrigating crops in 1982 was 129.6 bgd—about 87% of total irrigation withdrawals for that year. The fundamental difference between Flickinger and USGS estimates is that Flickinger carefully estimated withdrawals and consumption *only* for agricultural uses. USGS estimates include withdrawals for non-agricultural uses. In some water resource regions, Flickinger's estimates were larger than the 1982 estimate interpolated from USGS numbers. This Assessment concurs with

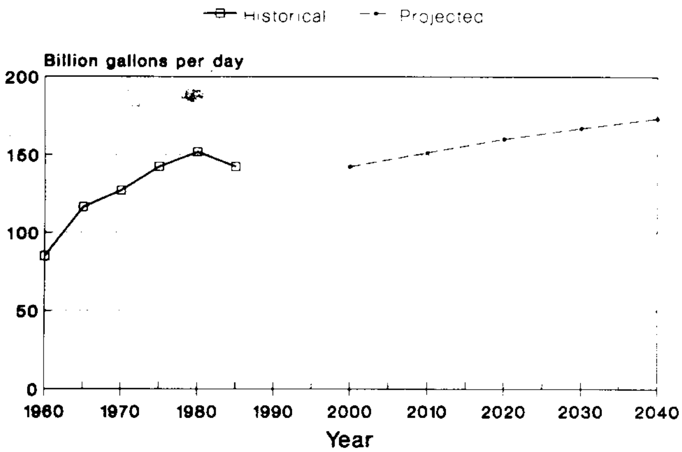


Figure 17.—Irrigation, total freshwater withdrawals.

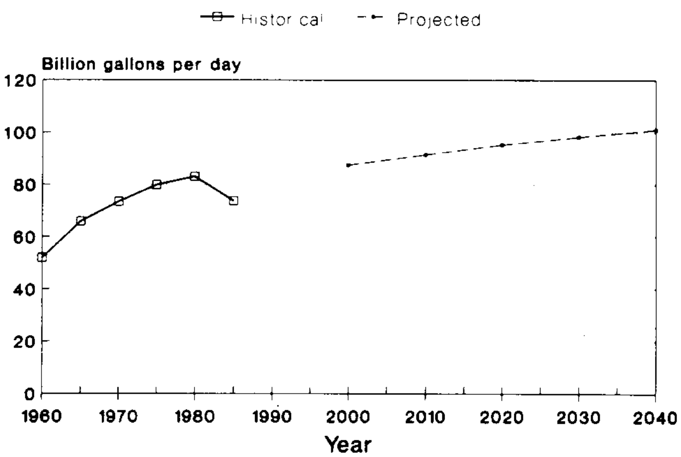


Figure 18.—Irrigation, total freshwater consumption.

Flickinger's estimates for agriculture and uses them as a base. In water resource regions where USGS estimates are larger than Flickinger's, USGS numbers are used to account for non-agricultural irrigation. The pattern of water resource regions where USGS estimates were higher fit the expectation of regions having significant non-agricultural irrigation. Thus, irrigation withdrawals and consumption numbers in this Assessment are somewhat larger than the irrigation estimates for 1985 by Solley et al. (1988).

Bajwa et al. (1987) contains detailed information on the farmland irrigation situation in each state including methods, sources, and expenses of irrigation and comparisons of the average value of farm capital for farms using irrigation compared to dryland production practices.

Potential for changes in the projections.—Irrigation water usage is projected to grow at a much slower rate over the next 50 years than over the previous 25 years. From 1960 to 1985, the average annual growth increase was 2.1%. From 2000 to 2040, the projected growth rate is 0.5%. A major reason is the continuing increase in pumping costs. Energy cost increases and aquifer declines increase pumping costs. Increased pumping costs reduce net return per acre, thus narrowing the advantage enjoyed by irrigated crop production over dryland crop production. The point has been reached in parts of the Southern Great Plains where net returns from irrigated crop production are lower than for dryland crop production. As soon as irrigation equipment is depreciated and paid for, many farmers stop irrigating. If crop prices rise, additional income may restore the cost advantage of using irrigation.

Bureau of Reclamation water pricing policies have come under scrutiny recently by interests seeking to reduce crop production subsidies. Irrigators are charged for water obtained from Bureau projects, but prices are user-favorable. If prices increase, then irrigation water use is expected to decline below projected levels. Also, a shift from irrigating low-valued crops such as alfalfa, hay, and pasturage would likely occur.

Technological advances in irrigation are expected to continue because of expected cost increases in pumping water. Chief among new technologies to be implemented soon are drip and trickle irrigation systems. These enable the farmer to control water applications much more precisely and have much lower losses to evaporation and excess runoff. It has been shown that evaporation loss from sprinklers is an exponential function of wind velocity and that in the southern plains, an average of 17% of the water passing through a standard sprinkler nozzle evaporates before reaching the target (Clark and Finley 1975). Other management practices could be employed to reduce energy and related irrigation costs (Gilley 1983). To the extent that such practices are adopted, projected withdrawal and consumption projections could reflect even less than a 0.5% growth per year, perhaps even an absolute reduction. The recent downturn in use (figs. 17–20) may be the beginning of a downward trend, but the 1990 water use estimates are needed for confirmation.