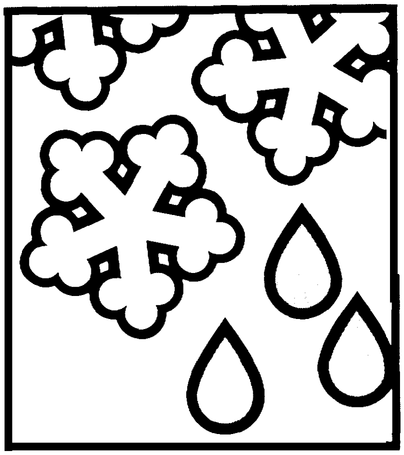

Water Supply and Use in the Western United States

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Chapter III

Water Supply and Use in the western United States

The existing relationship between water supply and use in the Western United States determines both the extent of the supply / use problem and the potential of any individual technology to alleviate current or anticipated problems. Regional water-use patterns, that have evolved as a result of the spatial and temporal variability of water supplies, are linked in a complex fashion by the hydrologic cycle. The understanding of the hydrologic cycle and of current or potential water problems is inextricably tied to the way in which relevant data are coIlected and analyzed.

This chapter provides an overview of the existing water resources and current water uses in the Western United States. It is the foundation for assessing water-related technologies in succeeding chapters. The purpose of this chapter is: 1) to outline the major components of the hydrologic cycle, their interrelationships, and their variability as they are altered naturally or technologically; 2) to discuss the adequacy of data available on the quantities of water in various components of the cycle and problems of water-data acquisition and analysis; and 3) to evaluate, in the context of available data, the nature of the supply and demand relationships of the major river systems of the Western United States. The chapter begins with a review of the major Federal agencies dealing with water.

SURVEY OF FEDERAL AGENCIES INVOLVED IN WATER

Various agencies within the Federal Government have been involved in water and water-resources management since the United States was formed. Generally, these activities have been oriented toward supporting the specific mission and program of each agency.

Discontinued Federal Efforts

Water Resources Council: Established by the Water Resources Planning Act of 1965 (Public Law 89-90); produced a first National Water Assessment in 1968, based mainly on data compiled and analyzed by major Federal agencies; produced second National Water Assessment in 1978 which updated information on the Nation's water resources and which attempted to determine the adequacy of water supplies for future use; agency functions essentially abolished in 1981 with termination of funding.

National Water Commission: Established by Act of Congress (Public Law 90-515) for a fixed term; produced in 1973 a report to the President, *Water Policies for the Future,* that considered the Nation's water-resource supplies and uses and outlined several alternative futures and possible actions for water-resource development to the year 2020; Commission terminated with production of report.

Office of Water Research and Technology: Established within the Department of the Interior; sponsored State programs of research, development, and demonstration in the fields of water and water-related resources generally through State water research institutes; abolished by Reagan administration in early 1980's.

Ongoing Federal Efforts

Currently, Federal responsibility for water-data acquisition, *planning,* and management of particular relevance to this assessment includes the Departments of Agriculture (USDA), Commerce (DOC), Defense (DOD), and Interior

(DOI) and the Environmental Protection Agency (EPA). The key mission and water-related activities of the principal agencies within each Department are summarized below from Plans *for Water Data Acquisition by Federal Agencies Through Fiscal Year 1983 (11),*

Agricultural Research Service (USDA): Conducts research on water-use technologies for agriculture, analyzes data on agricultural water use, and develops practices involving use of soil, water, and air resources for agriculture.

Forest Service (USDA): Maintains responsibility for water resources that are derived from Forest Service lands, protects tributary waters, and conducts water-resource research relevant to the long-term productivity of forests and rangelands.

Soil Conservation Service (USDA): Collects water-related data, including snow data, for downstream agricultural users and undertakes soil, water, and related resource projects with farmers, ranchers, and groups of individuals to improve production and protect the resource base.

National Oceanic and Atmospheric Administration (DOC): Includes the National Weather Service; provides water data in support of basic hydrographic surveys, research, water regulations, specialized users, and safe navigation; conducts some weather modification work.

U.S. Army Corps of Engineers (DOD): Plans, designs, constructs, and operates water-resource projects throughout the United States; performs similar analyses for nonstructural projects.

Bureau of Land Management (DOI): Manages water resources on the public lands administered by the Bureau and conducts inventories and analyses of quality and quantity of surface- and ground-water resources on public lands.

Bureau of Reclamation (DOI): Plans and constructs water projects in the 17 Western States to provide flood control, water for irrigated agriculture, municipal and industrial water supplies, and hydroelectric generation; involved in some weather modification work.

Fish and Wildlife Service (DOI): Responsible for overseeing national interests in the conservation of fish and wildlife and their habitat; provides ecological expertise to water-resource planning, development, and management activities.

U.S. Geological Survey (DOI): Collects and analyzes water data, operates the National Water Data Exchange (NAWDEX) program, and provides hydrologic information for the use and management of the Nation's water resources.

U.S. Environmental Protection Agency: Conducts research and demonstration projects on water quality, monitors water quality, establishes and enforces water-quality standards, and defines water pollution controls.

WATER SUPPLY: THE HYDROL0GIC CYCLE

present agricultural practices in the arid and semiarid portions of the Western United States are the result of complex interactions involving both the biophysical environment and human modification of and adaptation to that environment. Water is one of the primary limiting factors in this environment, and it is generally only where this limitation has been overcome by rangeland, dryland, and irrigation technologies that agricultural production has been feasible.

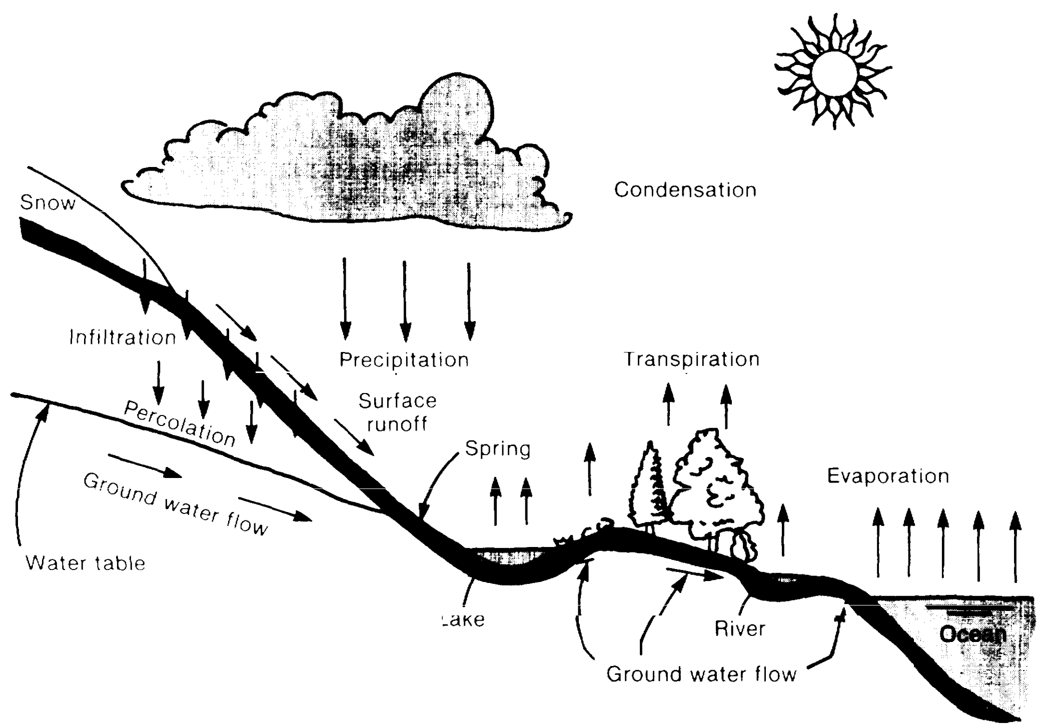
In arid and semiarid areas, both temporal and spatial inequities in the distribution of water lead to shortages. These shortages may be chronic for certain areas, such as the deserts of the Southwest, or seasonal in areas that derive the bulk of their water supply from the annual spring snowmelt and runoff. Water-related problems are site-specific to some extent. This geographical aspect of the problem varies with agricultural practices and depends, to some extent, on which water processes are involved.

The fundamental, unifying concept in the study and understanding of water is the hydrologic cycle (fig. 8). The cycle is the conceptual model that relates the interdependence and continuous movement of all forms of water through the vapor, liquid, and solid phases. It may be considered the central concept in hydrology.

The components of the hydrologic cycle are:

- *precipitation:* Water added to the surface of the Earth from the atmosphere. It may be either liquid (e.g., rain and dew) or solid (e.g., snow, frost, and hail).
- *Evaporation:* The process by which a liquid is changed into a gas. In the context of the hydrologic cycle, the most important form of evaporation is probably that

Figure 8.—**The Hydrologic Cycle**



Water passes continuously through this cycle from evaporation from the oceans into the atmosphere through precpitation onto the continents and eventual runoff into the oceans Human use of water may modify this cycle at virtually every point

SOURCE H Hengeveld and C DeVocht *Urban Ecology 6(1-4)* 19, 1982 which takes place from the seas and oceans. This is the main source of water on land areas.

- *Transpiration:* The process by which water vapor passes through a living plant and enters the atmosphere.
- *Infiltration:* The process whereby water soaks into, or is absorbed by the surface soil layers.
- *Percolation:* The downward flow of water through soil and permeable rock formations to the water table.
- *Runoff:* The portion of precipitation that comprises the gravity movement of water in surface channels or depressions. It is a residual quantity, representing the excess of precipitation over evapotranspiration when allowance is made for storage on and beneath the ground surface.

All water is involved in continuous cyclical movement according to the hydrologic cycle. Some of the water vapor in the atmosphere gives rise to precipitation through complex processes of condensation and freezing. Not all precipitation reaches the surface of the Earth. Some evaporates while falling and, more importantly, some is intercepted by vegetation or artificial structures and is then returned to the atmosphere by subsequent evaporation.

The watershed, or river basin, is the fundamental geographic unit of hydrology. It is also the fundamental biophysical unit within which technologies to affect precipitation and runoff must be assessed. A watershed is a land area surrounded at its perimeter by highlands that cause precipitation falling within the watershed's bounds to flow generally toward its center to form rivers or streams. In 1970, the U.S. Water Resources Council divided the United States into geographic units based on the watershed, or river basin, for the collection and organization of hydrologic data (12) (fig. 9).

Water reaching the surface of the watershed follows one of three courses. First, it may remain on the surface as pools and surface moisture that eventually evaporates back into the atmosphere. Or it may be stored on the surface in the form of snow until air temperatures are high enough to allow melting and runoff. Storage as snow is a common occurrence during at least a portion of each year in much of the Western United States.

Second, precipitation reaching the ground may flow over the surface into depressions and channels to become surface runoff in the form of streams and lakes. It then moves by evaporation back into the atmosphere, or by infiltration into the soil and toward the ground water table, or by continued surface flow back into the seas.

Third, falling precipitation may infiltrate the surface and percolate to ground water. As ground water, it is stored for periods ranging from days to thousands of years. Ground water can be removed naturally by upward capillary movement to the soil surface and plant root zone, by ground water seepage, or by runout into surface streams, lakes, and oceans. Some of it is removed by pumping from wells, in which case it again arrives at the surface as artificial precipitation and follows one of the paths described above.

Generally acceptable estimates of the amounts of water passing annually through the various phases of the hydrologic cycle for the Western United States have not been found in the literature. Based on estimates for the United States as a whole, however, more than 1,500 million acre-ft of water are added to the Western United States each year as precipitation and the majority of this is consumed by evapotranspiration (12). Approximately 500 million acre-ft constitute the measured streamflow from the region (e.g., 4,12) and 50 million acre-ft of water are added annually to the ground water reserves of the region.

Runoff is not uniformly distributed throughout the Western United States. Streamflow to the Pacific Ocean, primarily from the Pacific Northwest region, is estimated to be over 335 million acre-ft annually, or nearly 70 percent of the total for the entire region. Almost all of the remaining surface runoff flows into the Mississippi River and ultimately into the Gulf of Mexico. In general, those areas with the low-

Figure 9.—The Water Resources Regions of the Western United States

The conterminous portion of the Western United States has been subdivided into 9 water resource regions, containing 52 subregions as defined by the water Resources Council (WRC) for the Second National Water Assessment. These are shown below. The water resource regions in the Western United States: (10) the Missouri region, (11) the Arkansas-White-Red region, (12) the Texas-Gulf region, (13) the Rio Grande region, (14) the Upper Colorado region, (15) the Lower Colorado region, (16) the Great Basin region, (17) the Pacific Northwest region, and (18) the California region.

The water resources regions consist of either the drainage area of a major river, such as the Missouri region, or the combined drainage areas of a series of rivers, such as the Texas-Gulf region. The second level of classification, the subregion, consists either of an area drained by a river closed basin(s), or a group of streams forming a coastal drainage area. Ail subregion boundaries are hydrologic (i.e., are located along watershed boundaries) except where discontinued at international boundaries The subregions were reorganized by WRC in 1974 and 1978. They do not correspond to those in use by the U.S. Geoogical Survey.

SOURCE U S Water Resources Council, The Nation's Water Resources 1975-2000 (Washington, DC.: U.S. Government printing Office, 1978)

Photo credit USDA So// Conservation Service

The most important source of renewable surface water supplies in the Western United States is the mountain snowpack. This photograph of a snowpack in the Teton Range has an average depth of some 5 ft. When Western snowpacks melt in the spring and summer they supply an estimated 70 to 100 percent (depending on location) of the total annual surface runoff for all river basins except the Texas-Gulf region

est annual precipitation contribute runoff to rivers only during sporadic summer thunderstorms. The bulk of the runoff in the region originates from the melting mountain snowpack each spring and summer. Following snowmelt, runoff enters the river system of the region, where it is often stored in surface reservoirs until the period of peak demand in late summer.

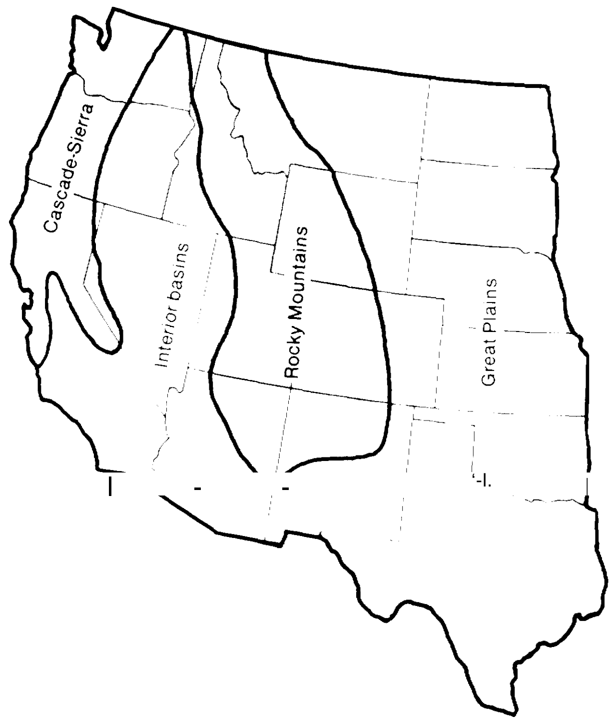
The Components

The Western United States has a wide range of hydrologic environments, both in terms of the absolute amount of water in the various hydrologic components and also in terms of the interrelationships among the components.

Precipitation

The primary factor determining the amount of precipitation that falls over the 17 Western States appears to be topography (fig. 10). The four broad north-south zones are generally more uniform within themselves than are any two adjacent east-west zones. These general hydrologic zones are: 1) the mountain ranges of the Pacific coast, consisting mainly of the Sierra and Cascade Mountain ranges; 2) the interior basins; 3) the Rocky Mountains; and fi-

Figure 10.—Major Landforms of the Western United States



The total amount of precipitation and the form in which it falls (snow or rain) are related more to the major landforms of the region — i.e., mountains or plains—than to any other factor

SOURCE Off Ice of Technology Assessment

nally 4) the Great Plains, which extend from the eastern side of the Rocky Mountains to the western edge of the more humid portions of the continent, at approximately the 100th meridian, or the Missouri River.

Air masses that carry atmospheric moisture over the region move generally onto the west coast of the continent and follow a west-to-east path. As these air masses cross the Western portion of the United States, they are forced upward to cross each of the two major mountain chains in their path. The forced, or orographic, rise produces a band of increased precipitation associated with each of the major mountain chains. The subsequent descent on the downwind sides of these chains produces the two belts of generally deficient rainfall.

Precipitation amounts in the region vary widely, depending largely on the geographical location of a particular site with respect to these mountain chains and on the location of the major storm tracks (fig. 11). The percentage of annual precipitation that falls as snow is highest in the mountain ranges (fig. 12). The snow/rain ratio is particularly important in understanding the role played by precipitation at a particular site. Snow represents a form of natural storage during months of generally low water demand and a natural release to surface runoff at a time approximately coincident with peak demand. Therefore, it is more important to agriculture than is an equivalent amount of rainfall received when demand is low or stored at high cost.

The greatest amount of precipitation in the Western United States occurs in the Pacific Northwest, on the Olympic Peninsula, and on the west slope of the Cascade Mountains where amounts total over 100 inches per year. At the opposite extreme, values of less than 5 inches per year are recorded in some of the southwestern deserts.

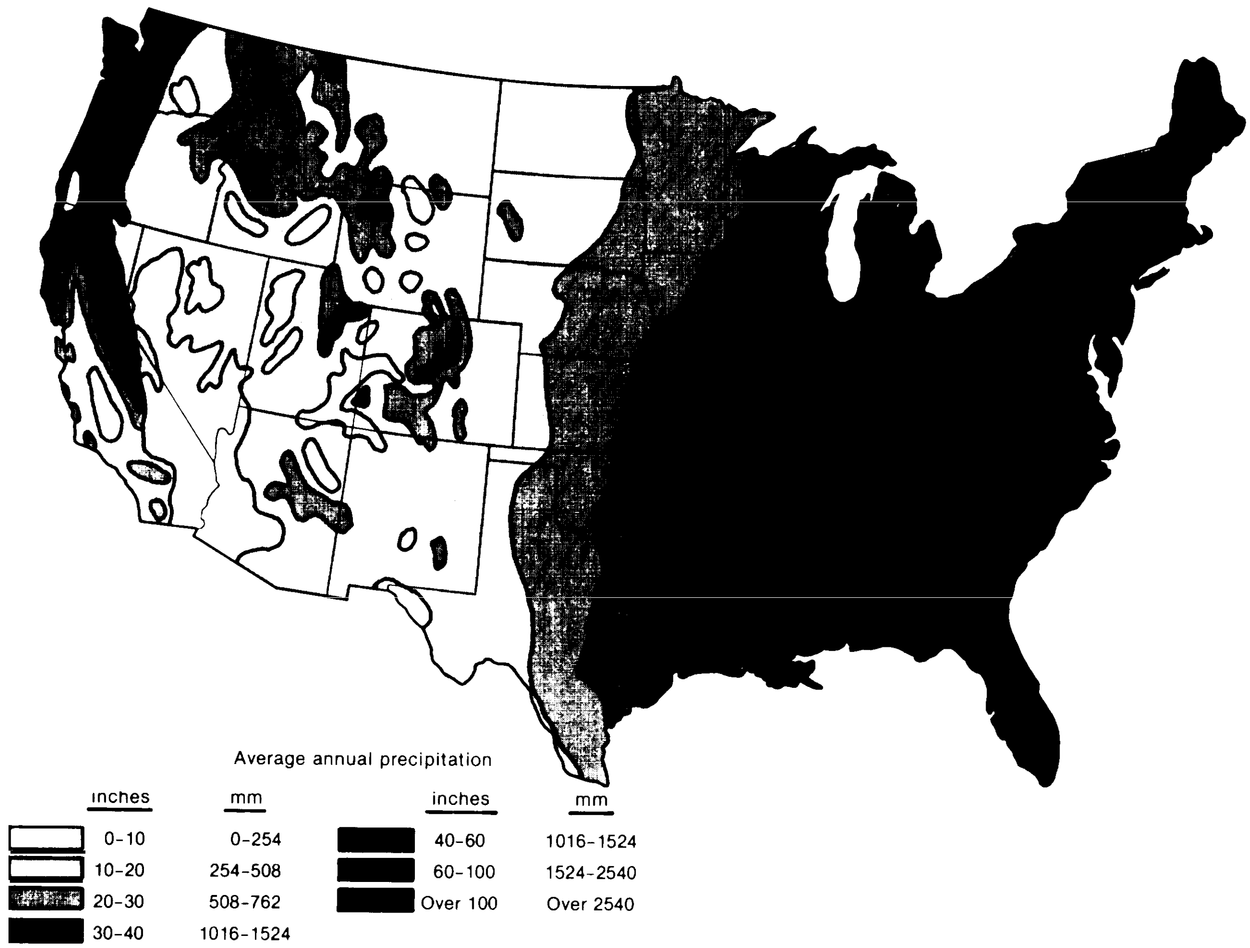
The annual regime of precipitation is highly variable from one part of the region to another. As much as half of the annual precipitation may fall during the growing season in much of the eastern portion. On the Pacific coast, the distribution is reversed, and virtually all of the total annual moisture falls during winter.

Evapotranspiration

Evaporation and transpiration are processes that return water to the atmosphere. These processes are controlled by the amount of energy available to convert liquid water to vapor and are limited also by the amount of available water. The term "evapotranspiration' is used to designate the loss of water from the soil by evaporation and from plants by transpiration.

Values of evapotranspiration are more difficult to evaluate than those of precipitation because in many areas of the West total evapo-

Figure 11.—Average Annual Precipitation of the United States



Precipitation patterns closely reflect a region's landforms, which are a primary factor in determining the amount of water available for use in any given area,

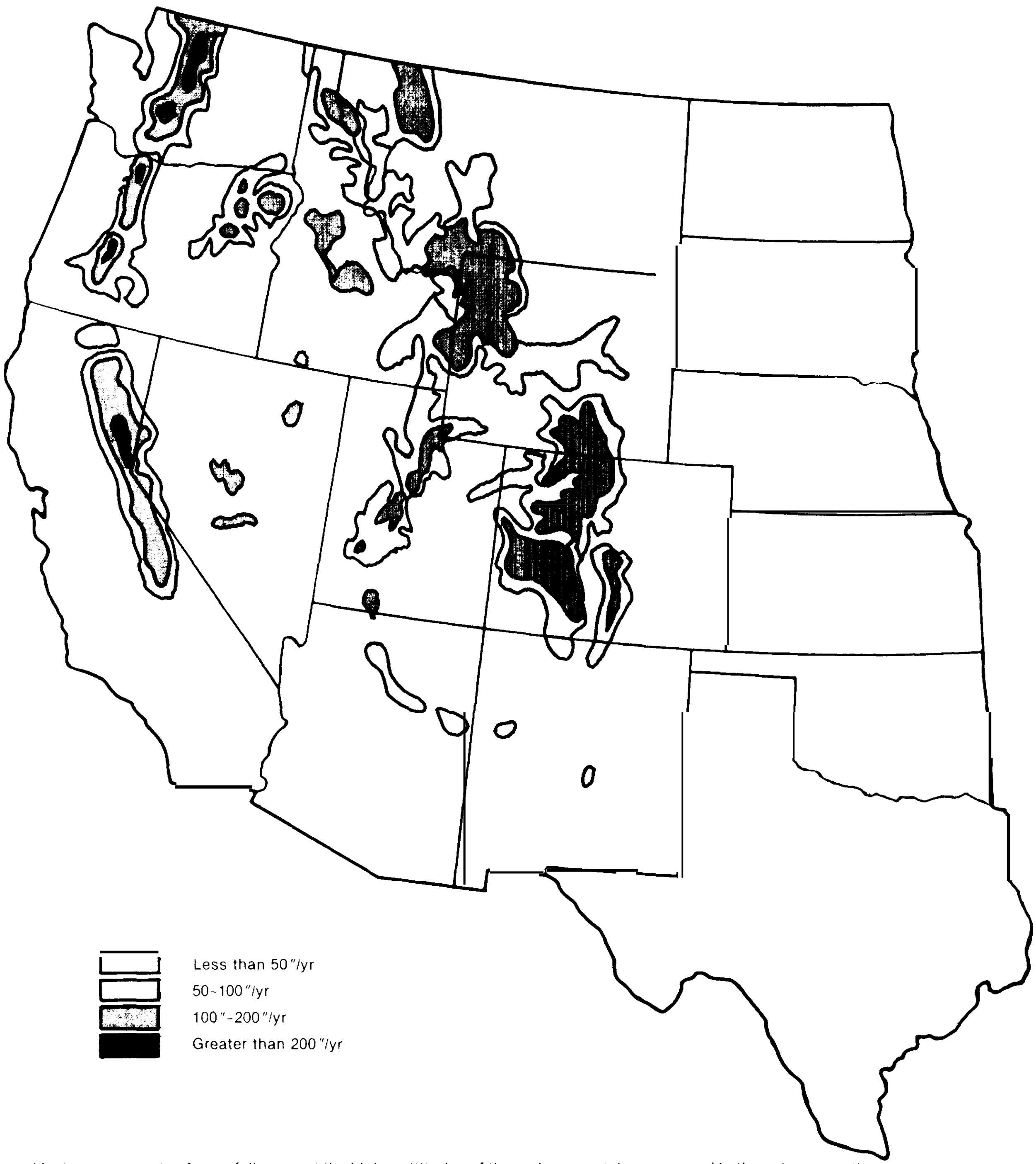
SOURCE: H. Anderson, M Hoover, and K Reinhart, *Forests* and *Water: Effects of Forest Management on Floods, Sedimentation and Water Suply,* USDA Forest Service General technical report PSW-18, 1976

transpiration is limited only by the available water supply. Potential evapotranspiration is the amount of water that would be lost if precipitation were unlimited. Throughout the interior basins, the desert southwest, and much of the southern portion of the Great Plains, actual evapotranspiration is a small fraction of potential evapotranspiration.

Actual evapotranspiration is determined in part by the seasonal distribution of precipitation and in part by air temperature regimes. If precipitation occurs largely during winter, as is the case in the mountain ranges of the Western United States and along the Pacific coast, much of this precipitation runs off or infiltrates the soil, For most of the region, however, precipitation occurs during the summer, when evapotranspiration is at a maximum, and much of it is returned to the atmosphere without affecting other components of the hydrologic cycle.

The timing of precipitation and evapotranspiration is important to agriculture in the Western United States because of its effect on available soil water and plant growth. Seasonal variations in soil water, as determined by the

Figure 12.—Average Annual Snowfall in the Western United States



Maximum amounts of snowfall occur at the higher altitudes of the major mountain ranges and in the extreme northern section of the country, a result of the increasing length of the winter season with altitude and latitude. This snowfall represents the primary form of natural water storage for the region

SOURCE U S Department of the Interior, Geological Survey, The *National Atlas of the United States of America* (Washington. D C U S Government Printing Office, 1970) balance existing between precipitation and evapotranspiration for several selected stations in the region, are shown in figure 13.

The average potential evapotranspiration in the Western United States ranges from an estimated low of 15 to 20 inches in the high mountains of the Pacific Northwest and northern Rocky Mountains to a high of more than 60 inches in small isolated areas in the deserts of Arizona and southern California (fig. 14). It is less than 20 inches along the Canadian border and more than 60 inches in southern Texas. Although potential evapotranspiration and precipitation are independent climatic elements, potential evapotranspiration in arid regions is greater because of the higher daytime temperatures resulting from the absence of clouds and rain. High values in the Colorado and Gila Deserts and in the lower Rio Grande Valley are examples. In the arid sections of the Columbia River Valley between Washington and Oregon, potential evapotranspiration is more than 30 inches, whereas it is only about 20 inches at the same latitude in the Eastern United States.

The variation of potential evapotranspiration through the year follows a uniform pattern in most of the region, It is negligible in the winter months as far south as the Gulf Coastal Plain. It rises to a maximum in July that ranges from 5 inches along the Canadian border to 7 inches on the gulf coast. In some mountainous areas and along portions of the Pacific coast, it does not reach 5 inches in any month,

Infiltration and Percolation

Precipitation that falls on a surface and that is not immediately returned to the atmosphere by evaporation may infiltrate into the surface soil layers. The amount of that which can infiltrate the surface layers is determined largely by the permeability of those layers (the ability to transmit water which is governed by the size and geometry of the spaces within the soil or rock layers) and the amount of water already present in those spaces. Infiltration rates are highest at the beginning of a rainstorm, gradually decreasing with time until some relatively constant value is reached. Some infiltrated water will be retained near the surface by capillary forces. Some will move by gravity flow either toward adjacent stream channels where it will appear as runoff or, more commonly, downward by percolation to the water table where it will enter into ground water storage,

All water that exists below the surface of the Earth in interconnected openings ("interstices") of soil or rock may be called "subsurface water, " That part of the subsurface water in interstices completely saturated with water is called "ground water. " The upper surface of the zone of ground water is known as the "water table. " Between the water table and the surface of the Earth is the "zone of aeration, ' where the interstices of the soil and rock may contain some varying amount of water, less than total saturation. The water table commonly rises and falls as the availability of water at the surface varies with time (e.g., as a result of climatic change) or as a result of groundwater extraction practices.

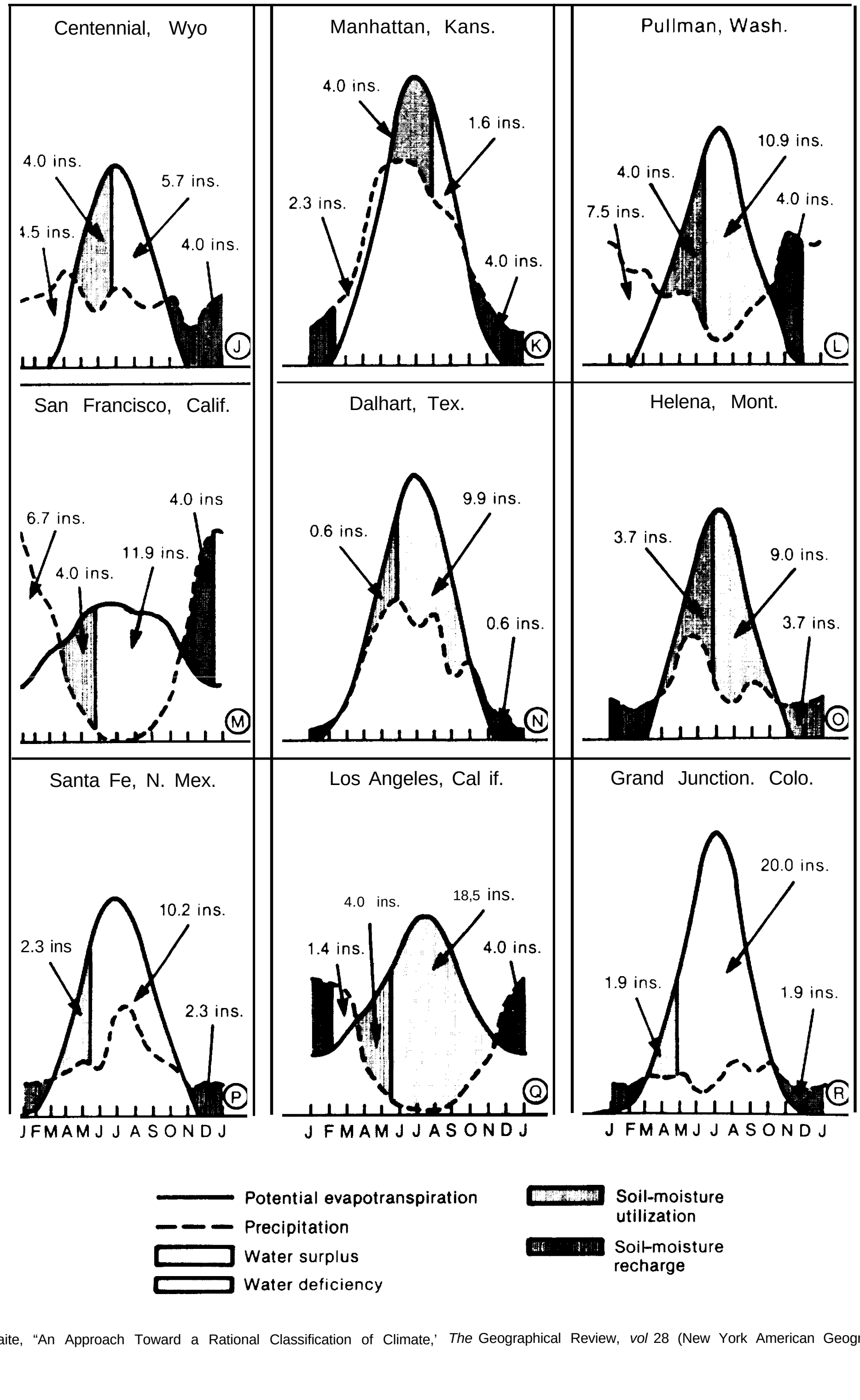
Ground water is not uniformly distributed throughout the West. The major producing aquifers are deposits of unconsolidated sands, gravels, and clays located on preexisting outwash plains or in former lake beds and in the basalts of the Pacific Northwest. In general, the thickness of these aquifers ranges from tens of feet to several thousand feet. Both the amount of water they produce and the quality of that water are extremely variable, even from well to well within the same aquifer. The general locations of the more important ground-water resource regions of the Western United States are shown in figure 15. A detailed discussion of the individual ground-water resource regions is contained in appendix B.

Surface Runoff

Surface runoff, as rivers or streams, generally occurs only after the requirements of evapotranspiration and soil- and ground-water recharge have been satisfied. Where the requirements of either, or both, processes are in excess of annual precipitation amounts, no runoff will take place, Water lost to evapotranspiration is completely lost to runoff. Water that infiltrates into the soil or percolates to ground

Figure 13.—The Relationship Between Precipitation and Potential Evapotranspiration

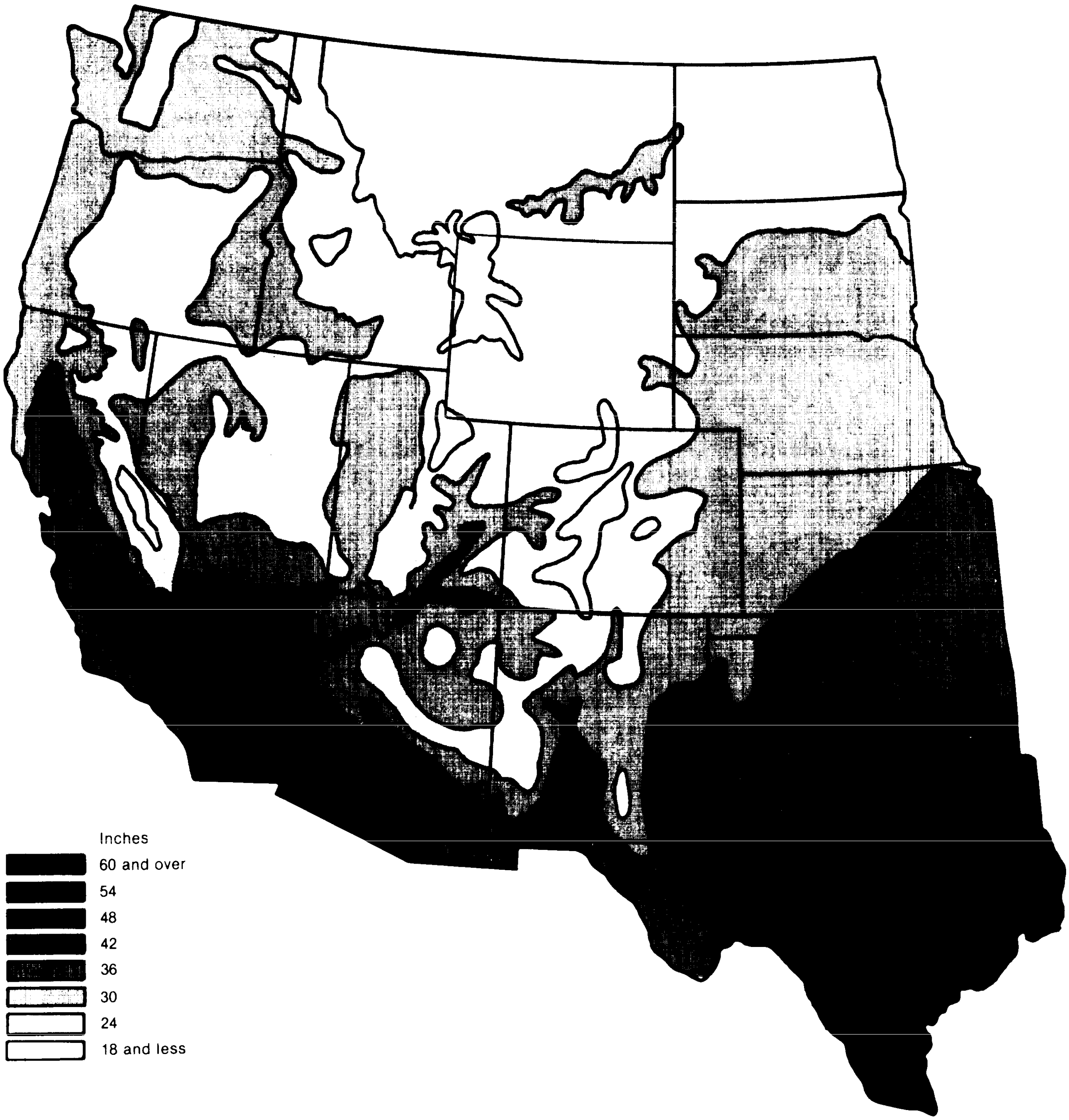
Monthly trends for selected stations in the Western United States show the effects of precipitation and potential evapotranspiration on soil-water conditions. For all stations, precipitation exceeds evapotranspiration only during the winter months. During the summer months, periods of soil-water deficits occur and may last up to 6 months.



SOURCE R Thornthwaite, "An Approach Toward a Rational Classification of Climate," *The* Geographical Review, *vol* 28 (New York American Geographical Society, 1948)

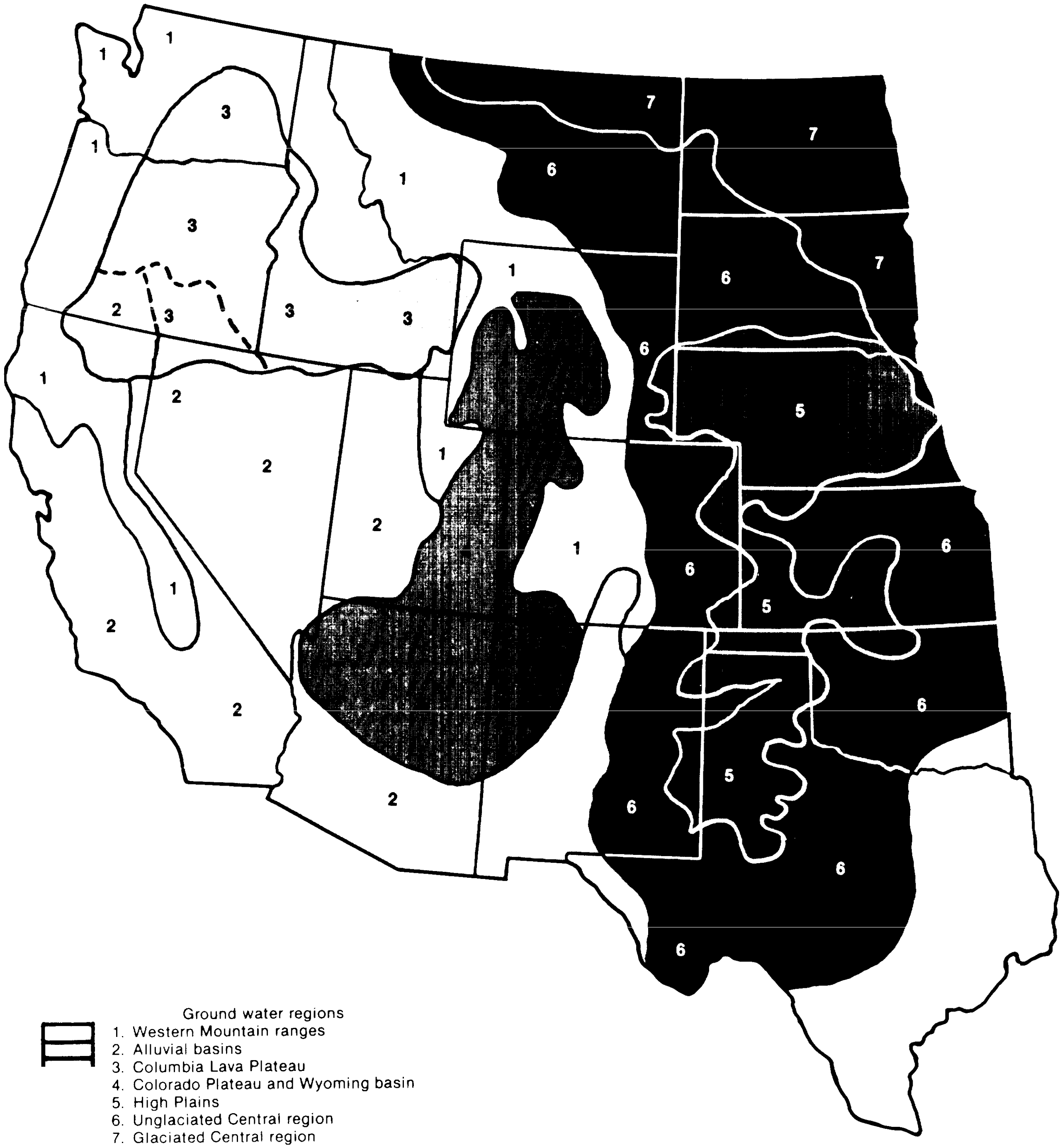
Figure 14.— Potential Evapotranspiration in the Western United States

The pattern of average annual potential evapotranspiration as calculated by Thornthwaite (1948). This figure is included to illustrate a general pattern rather than the actual values for evapotranspiration over the region. Various technologies have been developed to measure total potential evaporation. Actual values will depend on the method of measurement used.



SOURCE: R. Thornthwaite, "An Approach Toward a Rational Classification of Climate," *The Geographical Review, vol.* 28 (New York: American Geographical Society, 1948).

Figure 15.—Major Ground Water Resource Regions of the Western United States



SOURCE D Todd. Ground *Water Hydrology.* 2d ed (New York: John Wiley & Sons, Inc 1980) water may ultimately appear as surface runoff at some point distant from that at which it fell as precipitation, This will be determined by the amount of transpiration losses, which depletes soil water, and by the ability of the rock formations at a given location to transmit water.

Surface runoff in the Western United States is highly variable, both from one river basin to another and from one time of the year to another. In terms of total volume of annual discharge, the major river system of the region is the Columbia River, which has a mean annual flow in excess of 140 million acre-ft and represents nearly 36 percent of the total volume of surface water available for the entire region. The river system with the smallest annual discharge volume is that of the Rio Grande River, which has an estimated mean annual discharge between approximately 1.3 million acre-ft/yr (1.2 million gal/day] (4) and 6.0 million acre-ft/yr (5.4 million gal/day) (12).

All rivers of the Western United States, except those flowing through the Texas Gulf region, have their headwaters in the mountain ranges of the region or in Canada (fig. 16). The period of peak runoff coincides with the period of spring snowmelt and generally occurs during May or June. There are two exceptions to this general pattern. First, rivers flowing into the Pacific Ocean from the west side of the Sierra and Cascade Mountain ranges in Washington, Oregon, and northern California have

Figure 16.—Average Streamflow for Major U.S. Rivers, 1941-70

The rivers in the Western States originate in the mountains of Montana, Wyoming, and Colorado, with the exception of the Red River in northern Texas and the Columbia River, which flows into the United States from the Rocky Mountains in Canada. One cubic foot per second (cfs or ft^3/s) equals approximately 2 acre-feet per day

SOURCE J Bredehoeft Physical Limitations on Water Resources in the Arid West ' paper presented at a conference on Imnpacts of Limited Water *for Agriculture in the Arid* West, Asliomar, Calif. Sept. 28-Oct. 1, 1982 a peak discharge in January or February. Second, the lower reaches of the Missouri and Snake Rivers have a peak flow in March or April, reflecting the contribution of meltwater produced by the snow deposits of the plains.

The total amount of runoff contained in streams during the spring and summer months varies from over 90 percent of the annual total for some small streams totally dependent on the mountain snowpack to less than 15 percent for streams originating in the Cascade Range, where the contributions to flow are more uniformly balanced between winter rains and spring and summer snowmelt. Figure 17 shows the spatial pattern of the variations in areal contributions to surface runoff in the Western United States. These values are the depth of runoff produced annually and underscore the importance of the mountainous portions of the region in determining water supply,

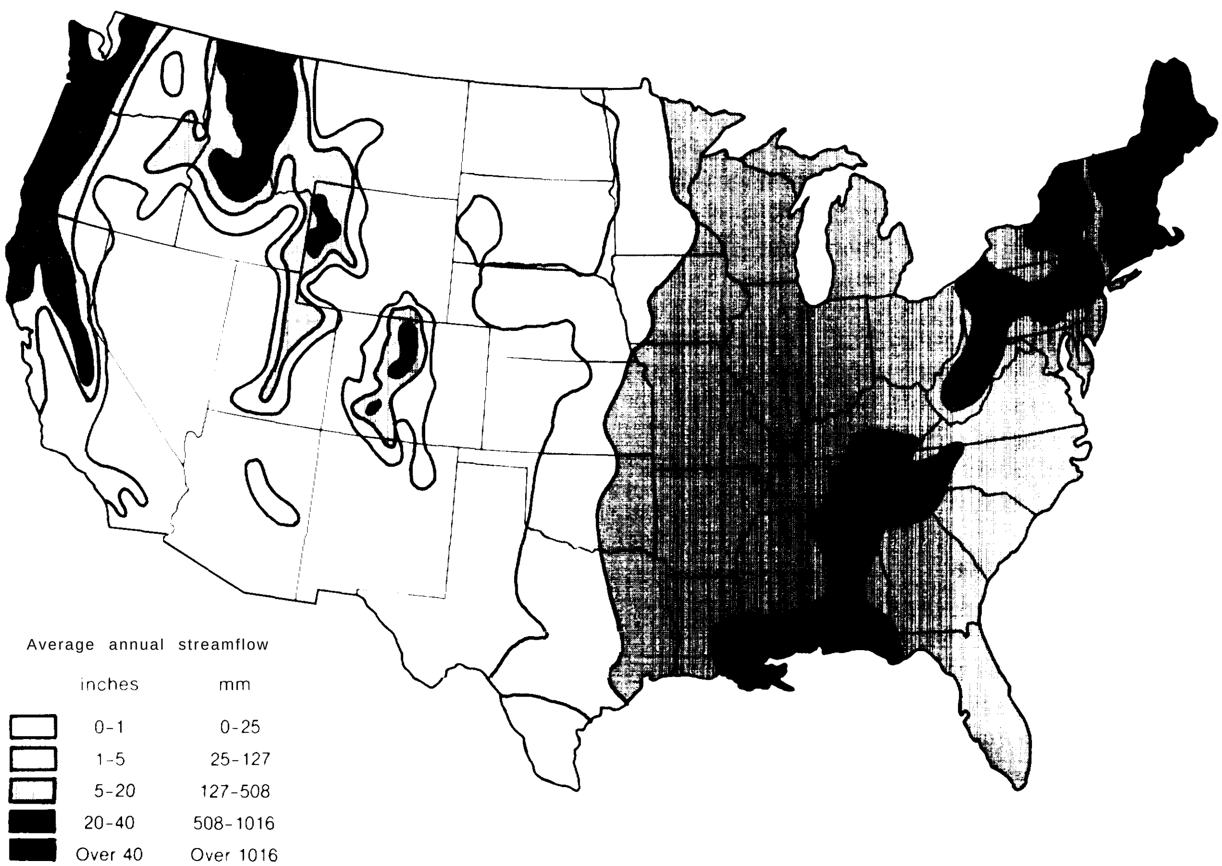
For the Western United States as a whole, surface runoff estimates vary, depending on the data source (4,6,12). The range of estimates is between 515 million and 550 million acre-ft/yr (460 billion to 490 billion gal/day) for the amount of surface runoff that passes through the major river systems of the region.

Variability in the Hydrologic Cycle

Both human-caused and natural variations in the hydrologic cycle affect the timing and

Figure 17.—The Spatial Pattern of Annual Streamflow

With the exception of the Rocky Mountains and the Cascade-Sierra Mountains, much of the Western United States averages less than 1 inch of runoff or streamflow annually



SOURCE: H. Anderson, M. Hoover, and K. Reinhart, *Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Suply*, USDA Forest Service General technical report PSW-18, 1976.

volume of available water in the Western United States. It is important to recognize that in the Western United States, very few areas remain where the hydrologic cycle operates naturally. Estimates of water availability in any particular component of the cycle must take into account human intervention at the specific site. The impacts of this intervention may vary from site to site. This is due partly to the particular nature of the human activity and partly to the natural hydrologic variability of the area. Thus, it is important to understand the natural variability of Western water resources as well as the variability when modified by humans,

Human Intervention

The primary approaches to accommodate natural variability of Western rivers have been: 1) construction of reservoirs to delay the surface runoff; 2) development of ground water resources; and 3) in limited cases, importation of water from adjacent basins with greater natural supplies. It is estimated that in a natural state the runoff from the 17 Western States would be approximately 590 million acre-ft/yr (12). Human modification of the river systems of the region through the construction of storage reservoirs and water diversions for offstream consumptive uses has reduced natural runoff by approximately 100 million acre-ft/yr. Other components of the hydrologic cycle have also been affected by technological intervention. Human withdrawals from ground water, estimated to be nearly 70 million acre-ft/yr, affect the amount of recharge required to maintain the natural equilibrium (12).

Natural Variability

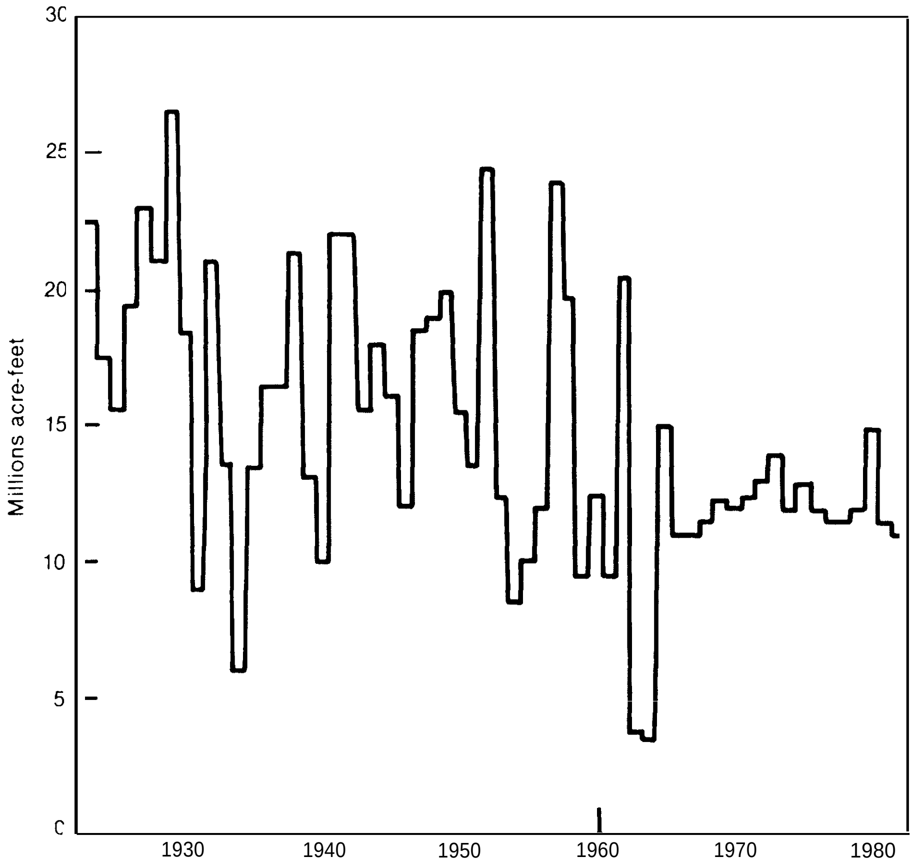
For any given watershed, "wet" and "dry" years are defined with respect to the long-term average streamflow for that watershed. The definitions are based on the percentage of time that given flow volumes occur, as determined by a statistical analysis of the available streamflow record. For the Second National Water Assessment (12), a "dry" year has been defined in terms of the streamflow that would occur, as indicated by a statistical analysis of the data, 20 years out of every century, or 1 year out of 5. The volume of streamflow, as determined in this way, would be much less for a subregion that has a normally low volume of streamflow than for one where this volume was high. Where natural year-to-year variability of streamflow is low, little difference in the flow volume will exist between a "dry" year and a "normal year." For those subregions with a high annual variability, the "dry" year may be a small fraction of the "normal" year flow volume.

It is generally recognized that the annual and seasonal variation in the flow of rivers in the Western United States is significant, often varying by as much as 10 times during a year or during 2 succeeding years. For example, figure 18 reflects the variability of the Upper Colorado River, a pattern typical of Western rivers. Because of such variability, the long-term average annual streamflow volume is not a particularly useful measure of the amount of water that will be available for any given year. Similarly, the monthly volume of flow fluctuates widely, with that occurring during the spring and summer months often representing as much as 90 percent of the total annual flow of many Western rivers (fig. 19). Because of the extreme variability associated with both the annual and monthly streamflow volumes, water-management approaches that are based on a long-term average annual flow will generally be unrealistic for shorter time periods, such as a single year or month during a given year.

In determining the adequacy of existing reservoir storage facilities to meet water demand for agriculture during a series of dry years, it is more useful to know the year-to-year fluctuation of flow and the number of years that this may be expected to drop below an acceptable level than to know only the average flow for some period of years. In determining the extent to which a river will meet seasonal needs of irrigated agriculture, it is more useful to understand the nature of the seasonal variability of streamflow than to know the annual flow volume. Most discussions of the adequacy of water supplies in the Western United States

Figure 18.—The Annual Variability of Steamflow Volume, Upper Colorado River, 1920-80

The year-to-year variability of most Western rivers is high, as typified by the Upper Colorado River. Where water is al located on the basis of some long-term mean-flow volume, there will be insufficient water to meet that al location during many years The decreased variability of the Colorado River shown on this fiqure beginning in the mid- 1960's results from the construction of dams and reservoirs



SOURCE Off Ice of Technology Assessment. compiled from National Water Data Exchange (NAWDEX), U S Geological Survey, 1983

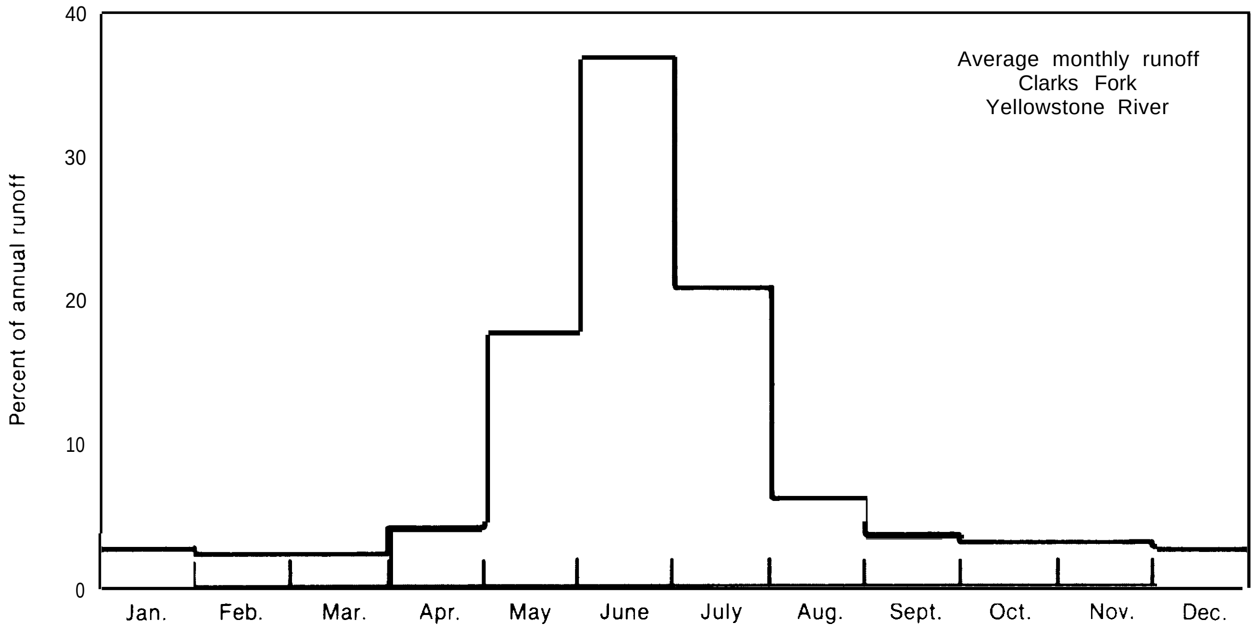
have been developed in terms of annual mean values [e. g., 4).

Estimates of future water availability, including that for all types of agriculture, must be based on some estimates of climatic trends. Climatic fluctuations affect all components of food-producing ecosystems, Changes in food production can be caused by the effects of weather on pests, pathogens, weeds, and crop plants and by altering water-supply and water-use patterns. Western agriculture has developed during a particularly warm period in recent climatic history (7). Climatic records show that climate has varied in the past, however, and significant fluctuations have occurred in recent history,

In addition to the natural variability of climate, there is growing speculation about human-induced climatic change. These include: 1) the decreasing pH (increasing acidity) of rainfall, which may be caused by emissions from burning fossil fuel; 2) the gradual increases in the atmospheric fraction of carbon dioxide (CO_2) and other infrared absorbing gases, also largely a result of increased burning of fossil fuels; and 3) the associated changes in water quality, quantity, and, specifically in the case of the infrared absorbing gases, air temperature increases.

Figure 19.— Average Monthly Runoff, Clarks Fork, Yellowstone River

Natural seasonal variability in the volume of flow of most Western rivers is large. In come cases, the spring and early summer snowmelt peak flow of Western rivers represents as much as 90 percent of the annual volume of flow of these rivers



SOURCE J Bredehoeft, "Physical Limitations on Water Resources in the And West," paper presented at a conference on: Impacts of *Limited* Water *for Agriculture in the Arid West,* Asilomar, Calif., Sept 28-Oct 1, 1982

Long-term agricultural planning and policy-making must be undertaken with the knowledge that some climatic change is inevitable. The geographic extent of any changes in climate will be related to the frequency of the change. Changes on the order of a few years to a few decades will be more localized geographically than will those that persist for decades. To the extent that the ability to predict climatic trends is limited, so too is the ability to determine continuing availability of water for agriculture in the Western United States. As stated in a National Research Council report (5), "Our knowledge of mechanisms of climate change is at least as fragmentary as our data. " An improvement in the existing data base, as discussed in the next section, should be a first step toward improving the ability to factor climatic trends into agricultural planning.

Measurement

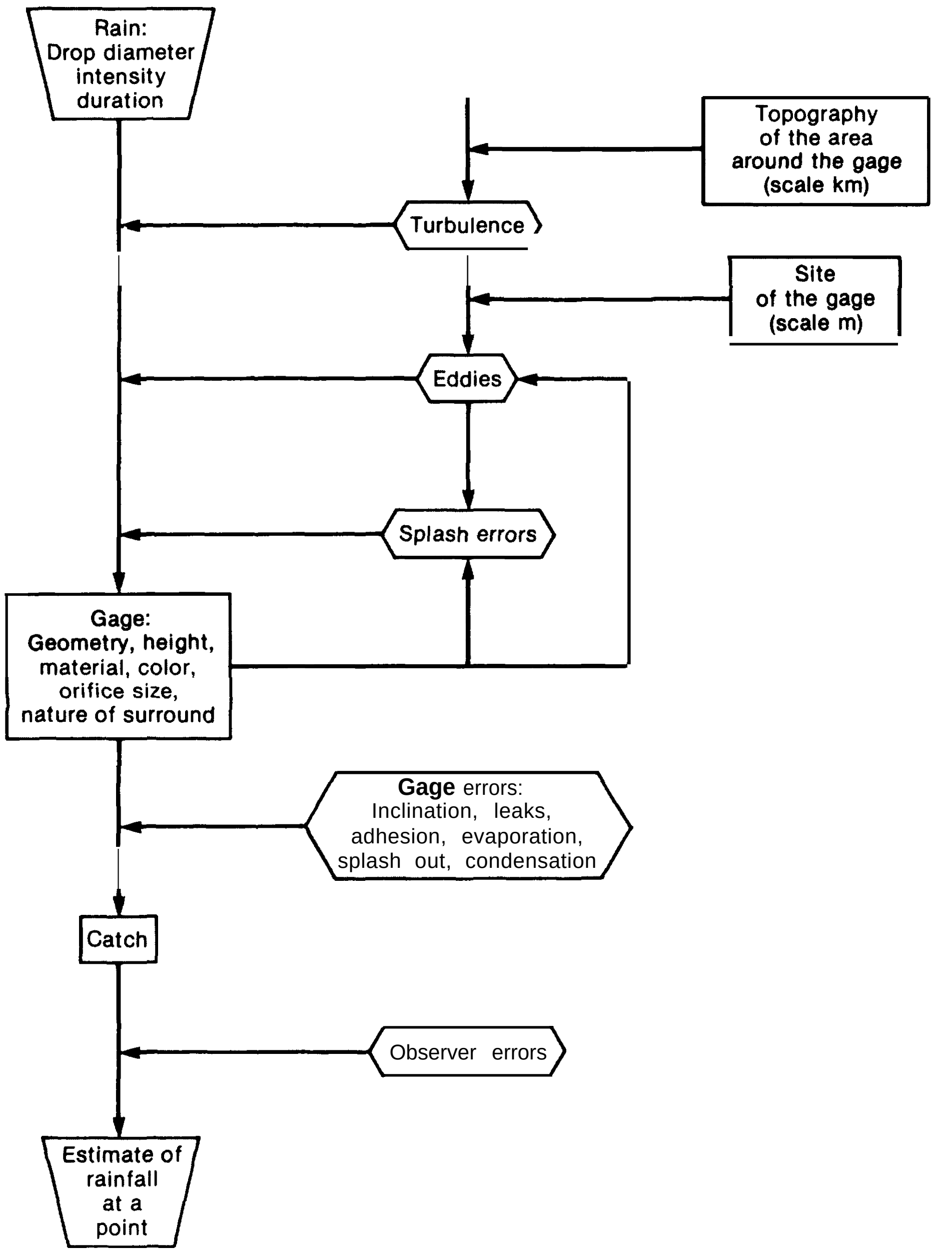
Water is in continuous movement through the hydrologic cycle. A variety of measurement techniques are required to monitor this movement. While all hydrologic processes take place over the surface area of a region, measurements of elements of the hydrologic cycle such as evapotranspiration or precipitation are made at discrete points within that region. In order to determine the volume of water involved in these transfer processes, it is necessary to combine the individual point measurements into a spatial pattern from which volume can be estimated.

Some of the problems inherent in all point measurements may be illustrated by those associated with determining the amount of rain that falls at a point, The uncertainties involved in even this apparently simple measurement are illustrated in figure 20. In developing average values representative of a particular place or time, the selection of the data to be included or excluded is critical.

Only surface runoff may be measured as an areal value, since all the surface runoff from a region must pass through a surface-gaging station. Thus, for surface water, the location selected for the placement of the gaging sta-

Figure 20.— Potential Errors in Water Measurements

Errors can occur in the measurement of any of the components of the hydrologic cycle and can affect the accuracy of the data.



SOURCE R Ward *Principles of Hydrology (New* York McGraw-Hill 1 975) tion is critical. In many cases, the proximity of a gaging station to the point of use determines the usefulness of the data obtained.

In addition to the uncertainties of point measurements for estimating spatial volumes, there are uncertainties in developing time trends from estimates of selected time periods. The amount of water in each of the solid, liquid, and vapor phases changes naturally with time. In order to reduce this continuous variation to terms meaningful for analysis, it is common to present data pertaining to elements of the hydrologic cycle as averages for selected time periods. Thus, concepts such as "mean annual precipitation" or "mean monthly streamflow" have been introduced to simplify data manipulation. Ultimately, this simplifying process has produced concepts such as "the average precipitation for Arizona" or the "average runoff of the Upper Colorado River. " In both cases, a large amount of spatial and temporal variation in the natural processes has been condensed in order to compare the environments of two or more hydrologic areas.

Also, as discussed above, various components of the hydrologic cycle are modified by human intervention. For example, as water is stored in reservoirs or removed from the surface or subsurface and applied to some use such as irrigation, the fundamental natural relationships are altered. Virtually all the technologies discussed in this assessment are designed to modify to some degree the distribution of water within the natural hydrologic cycle. The degree to which the hydrologic cycle has been modified varies widely among the river basins of the Western United States. This human-caused variability further complicates collecting, interpreting, and developing useful averages from existing data.

In developing average values, short- and long-term syntheses are prepared. Short-term syntheses relate to daily, monthly, or annual fluctuations and are referred to as "climate" or as the "hydrologic regime" of a region. Climate is the average course or condition of the weather at a place over a period of years, as exhibited by air temperature, wind velocity, and precipitation. Taken together, these simple measurements of complex processes of water and energy transfer estimate the disposition of water among the various phases of the hydrologic cycle. These short-term syntheses are important in making decisions concerning water availability and use from one year to the next or from one growing season to the next.

Long-term syntheses involve the concept of climate change over decades, centuries, or longer. This type of synthesis uses the average values developed from short-term data collected over a few decades. Long-term change is identified as the climate slowly becomes wetter or drier, warmer or cooler. An example of climate change that has been important for recent water planning involves the value for the average flow of the Colorado River used in the Colorado River Compact (discussed in ch. V). Runoff in this river during the period used to determine an "average" flow for allocating the waters of the Colorado River was higher than the average annual flow that now exists. A change in the climate of that river basin has gradually decreased the flow of the river below the value used in the allocation of water between the upper and lower basin States.

Decisions on water availability and use in the Western United States must reflect uncertainties associated with measurement. To some extent, all measurements of the elements of the hydrologic cycle are estimates, As concluded by another OTA assessment, estimates of water volume or time-trends from point estimates have varying degrees of reliability (8), The reliability of these estimates will be determined by: 1) the ability of an instrument to accurately measure the processes involved; 2) the extent to which the measurement site is representative of the area in which it has been established, and 3) where point-source data (e.g., precipitation measurements) are involved, the number of gages that are combined to develop the estimate, This reliability is also related to the length of record and the assumption of no climate change during the period of record.

WATER PLANNING, DATA COLLECTION, AND ANALYSES

Evolution of the Federal Role

The Federal Government has been involved in water-data collection and water-resources planning and analyses since the formation of the Nation. It intensified its activities with the passage of the 1902 Federal Reclamation Act. More than 20 major national studies or programs have been undertaken since then for the purpose of defining and guiding Federal activity in this complex and important area (13).

Some of the more publicized programs have occurred since the 1940's when a major focus was the development of multipurpose river basin plans and the analysis of river basin problems. One reason that the Federal Government became involved was that river basins and aquifers (basic water-planning units) almost always cover parts of more than one State and require a broad regional geographic perspective. In 1943, the Federal Inter-Agency River Basin Committee (FIARBC) was established as a coordinating body for agencies involved with preparing river basin surveys. After World War 11, FIARBC developed regional committees for some of the major river basins, including the Missouri and Columbia basins in the West. In 1959 Congress established a Senate Select Committee on Water Resources. The work of this committee was later translated into two major acts, the Water Resources Research Act of 1964 (Public Law 88-379) and the Water Resources Planning Act of 1965 (Public Law 89-90), which has provided the basis for much recent Federal involvement in water. The Water Resources Council (WRC) created under the latter act produced the first National Water Assessment in 1968,

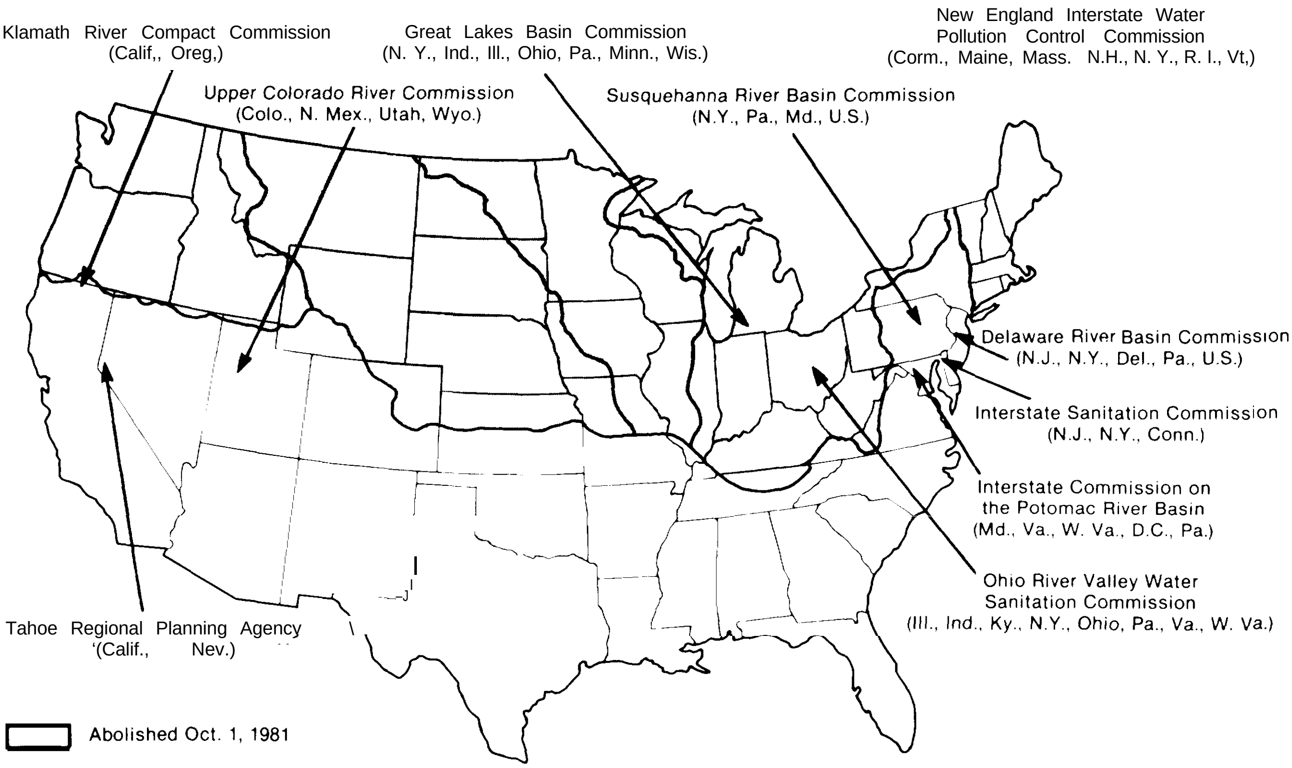
In the 1970's, attempts continued to better define a Federal role in water-resources planning. A National Water Commission, established by an Act of Congress (Public Law 90-515), produced a report to the President and to Congress in 1973, *Water Policies for the Future*. This report outlined several alternative futures and possible actions for water-resources development to 2020 in light of the Nation's water-resource supplies and needs, WRC produced a second national assessment in 1978 that compiled data on the Nation's water resources to determine the adequacy of water supplies for meeting anticipated future needs in the 21 major water-resources regions of the United States. Then, during the Carter administration, an intensive review of national water policy and several water-policy initiatives were begun, including increased attention to water conservation and environmental quality.

The early 1980's brought a major reversal in Federal water involvement from that which had developed over the past two decades, president Reagan removed Federal sponsorship of WRC, the river basin commissions (fig, 21), and the State water research institutes previously supported through DOI's Office of Water Research and Technology. This action effectively caused the demise of these institutions except in a few cases where States have attempted to assume full financial responsibility for operations.

These earlier broad-based Federal attempts to integrate water-resource research, policy, and planning have not been replaced. The Reagan administration created a small Office of Water Policy in DOI in 1982 to serve the Department Secretary. Then in March 1983, DOI announced that it would prepare annual National Water Summary reports in a simplified and condensed form for decisionmakers as an alternative to previous detailed national water assessments.

Currently, no additional funds are available for this activity. All costs for data collection and analysis are to be absorbed within existing budgets of the Department and of other agencies that will be expected to volunteer staff and equipment to respond to data requests. Also, these summaries will not project future trends. That function will be a responsibility of the individual States. According to the Department, this program is in furtherance of the present administration's policy "that responsibility for

Figure 21.— River Basin Commissions and Other Regional Water Agencies Abolished in 1981



SOURCE: K. C. Flynn, "Loss of River Basin Commissions Forces a Look at Alternatives, " Journal *WPCF,* vol. 54, No 1, January 1982, p. 9.

water resources management rests with the States" (9).

Data Collection and Analysis Responsibilities

A fundamental barrier to any institutional attempt to assess the nature and magnitude of potential water-related problems facing Western arid/semiarid lands is the nature and adequacy of the water-resources data base. Basic hydrologic processes are complex, and the data required to evaluate water available at a particular point in the process are often unavailable in the form needed.

Responsibilities for water-related data collection, analysis, dissemination of information based on those data, and planning are scattered widely among a number of Federal and State agencies. Most of the regionally useful data have traditionally been collected by agencies of the Federal Government (table 11). In recent years individual States have begun developing a data collection and interpretation capability to fulfill local needs.

Among Federal agencies, the lack of a single or coordinated mechanism for data collection and analyses has produced a number of data bases and interpretations with varying degrees of compatibility. * Beginning in 1973, a national confederation of water-oriented organizations was formed to improve access to water data (10). The resulting program, the National Water Data Exchange (NAWDEX), became operational in January 1976, with the U.S. Geological Survey (USGS) having lead-agency responsibility through its Office of Water Data Coordination. NAWDEX can provide data directly or a listing of those organizations responsible for the data, together with a description of the

*For an analysis of water models, see the OTA assessment (8).

Table 11.— Federal Water-Data Collection Agencies[a]

	Government agencies						Independent agencies			
In-house data programs	USDA	DOC	DOD	DOE	DOI	DOT	EPA	IBWC	NRC	TVA
Surface water	X	x	x	x	x	x	x	x	–	x
Ground water	X	—	x	x	x	x	x	x	–	x
Water quality	X	x	x	x	x	x	x	x	–	
Water use	X	x	x	x	x	–	–	–	–	I
Environmental impact	X	—	x	x	x	x	x	–	–	x
Ecology	X	–	x	x	x	x	x	–	—	x
Management effects	X	—	x	x	x	x	x	—	–	x
Basin studies	X	—	—	—	x	x	x	—	—	x
Real-time sensing	X	x	x	–	x	x	—	–		
Remote sensing	X	x	x	–	–	x	x	—	:	x
Data sensing	X	—	x	x	x	—	x	–	—	
Instream use	X	—	—	—	x	–	–	–	–	:
Water rights	X	—	—	—	x	—	–	–	—	_
Floods	—	x	–	–	x	x	–	—	—	x
Energy	—	—	—	x	x	–	–	–	x	—
Nuclear	—	—	—	x	x	–	x	–		
Precipitation quality	—	—	—	—	x	–	x	—	?	;

KEY USDA—U S Department of Agriculture, DOC—Department of Commerce, DOD—Department of Defense; DOE—Department of Energy, DOI—Department of the Interior, DOT— Department of Transportation, Independent agencies" EPA— Environmental protection Agency; IgwC—international Boundary & Water Commission, NRC—Nuclear Regulatory Commission, TVA—Tennessee Valley Authority.

aFor the 1981.82 fiscal year, 26 Federal *agencies,* representing six departments and four Independent agencies, collected water resource data These efforts have pro.-duced a diffuse data base, confused agency responsibilities for water measurements, and often introduced varying data collection techniques which produce data Incompatibility

SOURCE U S Department of the *Interior,* Geological Survey, Office of Water Data Collection. Plans for Water Data Acquisition by Federal Agencies *Through Fiscal Year* 1983 (Reston, Va 1982), p 7

characteristics of the data. Through NAWDEX, it is possible to obtain basic data from several data systems:

- the Water Data Storage and Retrieval (WATSTORE) System of USGS;
- the Storage and Retrieval (STORET) System of EPA;
- the Environmental Data and Information Service (EDIS) of the National Oceanic and Atmospheric Administration (NOAA);
- the Water Resources Scientific Information Center (WRSIC) of USGS; and
- various State agencies, such as the Texas Natural Resources Information System (TNRIS), the Nebraska Natural Resources Information System (NNRIS), and the Utah Division of Water Rights.

NAWDEX is a significant improvement over the previous method. It was formerly necessary to obtain the published lists of data from each responsible agency. However, it is still necessary to analyze any data obtained through the NAWDEX system, since the system mainly provides data storage and retrieval without extensive analytical capabilities,

For the purposes of this assessment, OTA has relied heavily on preexisting analyses, rather than on the data base itself. These analyses, consisting of reports by the National Water Commission (6), WRC (12), and USGS (e.g., 4) provide summaries of many pertinent aspects of the hydrologic regime of the Western United States.

There are, however, discrepancies among the summarized data contained in these reports (tables 12 and 13). For assessment purposes, it has been assumed that these discrepancies have arisen from the nature of the assumptions made in the analysis of basic data and from the use of different data bases rather than from faulty analytical procedures. It has not been possible to resolve these differences, and they can only be noted here, In some cases, these discrepancies are great enough to make it difficult or impossible to reach any firm conclusion about the total availability of water for

Table 12.—Estimates of Average Annual Runoff in the Western United States, 1975 (in billion gallons per **day [bgd] and million acre-feet [maf])**

Estimates of average annual runoff in the Western United States for 1975, show a wide range of data. Published estimates for individual regions varied by more than 400 percent. Until discrepancies such as these can be eliminated, it will be difficult to reach valid decisions on water resource management.

Region	WRC bgd	WRC maf	USGS bgd	USGS maf	% WRC
10 Missouri	44.1	49.4	54.0	*60.5*	122
11 Arkansas-White-Red	62,6	70.1	73.0	*81.8*	117
12 Texas-Gulf	28.3	31.7	32.0	*35.8*	113
13 Rio Grande	1.2	1.3	5.0	*5.6*	417
14 Upper Colorado	10.0	11.2	13.0	*14.6*	130
15 Lower Colorado	1.6	1.8	3.2	*3.6*	200
16 Great Basin	2.6	2.9	7.5	*8.4*	288
17 Pacific Northwest.	255.3	285.9	210.0	*235.2*	82
18 California	47.4	53.1	62.0	*69.4*	131
Regions 10-18	453.1	507.5	459.7	514.9	101

SOURCES: U.S. Water Resources Council, *The Nation's Water Resources* 1975-2000 (Washington, D C. U S Government Printing Office, 1978), vol. 3, table II-6.
C. Murray and E. Reeves, *Estimated Use of Water* in *the United States in 1975,* U.S. Geological Survey Circular 765, 1977, p. 18.

Table 13.—Estimates of Total Water Withdrawals in the Western United States, 1975 (in billion gallons per day [bgd] and million acre-feet [maf])

Estimates of total water withdrawals in the Western United States for 1975 were made by the Water Resources Council and U.S. Geological Survey. A wide range exists in the data, a result largely of data selection criteria and assumptions used in the interpretation of those data. Until these differences are resolved, it will be difficult to reach an agreement on the nature of the water problems in the area.

Region	WRC bgd	WRC maf	USGS bgd	USGS maf	% WRC
10 Missouri	38.0	42.6	35.0	39.2	92
11 Arkansas-White-Red	13.0	14.6	15.0	16.8	115
12 Texas-Gulf	26.0	29.1	22.0	24,6	84
13 Rio Grande	6.3	7.1	5.4	6.1	86
14 Upper Colorado	6.9	7.7	4.1	4.6	59
15 Lower Colorado	8.9	10.0	8.5	9.5	96
16 Great Basin	8.0	9.0	6.9	7.7	86
17 Pacific Northwest.	37,6	42.1	33.0	37.0	88
18 California	54.2	60.7	51.0	57.1	94
Regions 10-18	198.9	222.9	180.9	202.6	91

SOURCES: US Water Resources Council, The Nation's Water Resources 1975-2000 (Washington, D C U S Government Printing Office, 1976), *Summary,* vol 1, p. 25.
C Murray and E Reeves, *Estimated* Use of Water in the *United States in 1975,* US Geological Survey Circular 765, 1977, p. 19.

some water resource regions or about the regional usefulness of a given technology designed to increase water-use efficiency.

Some form of coordinating mechanism is essential for collecting and synthesizing available data and communicating results to a wide audience. The necessity for such an organization is doubly important inasmuch as water is an extremely dynamic resource. Because of this dynamism, both the data base and the assumptions applied to its interpretation must be continually tested if both are to remain relevant to the solution of emerging problems.

WATER USE IN THE WESTERN UNITED STATES

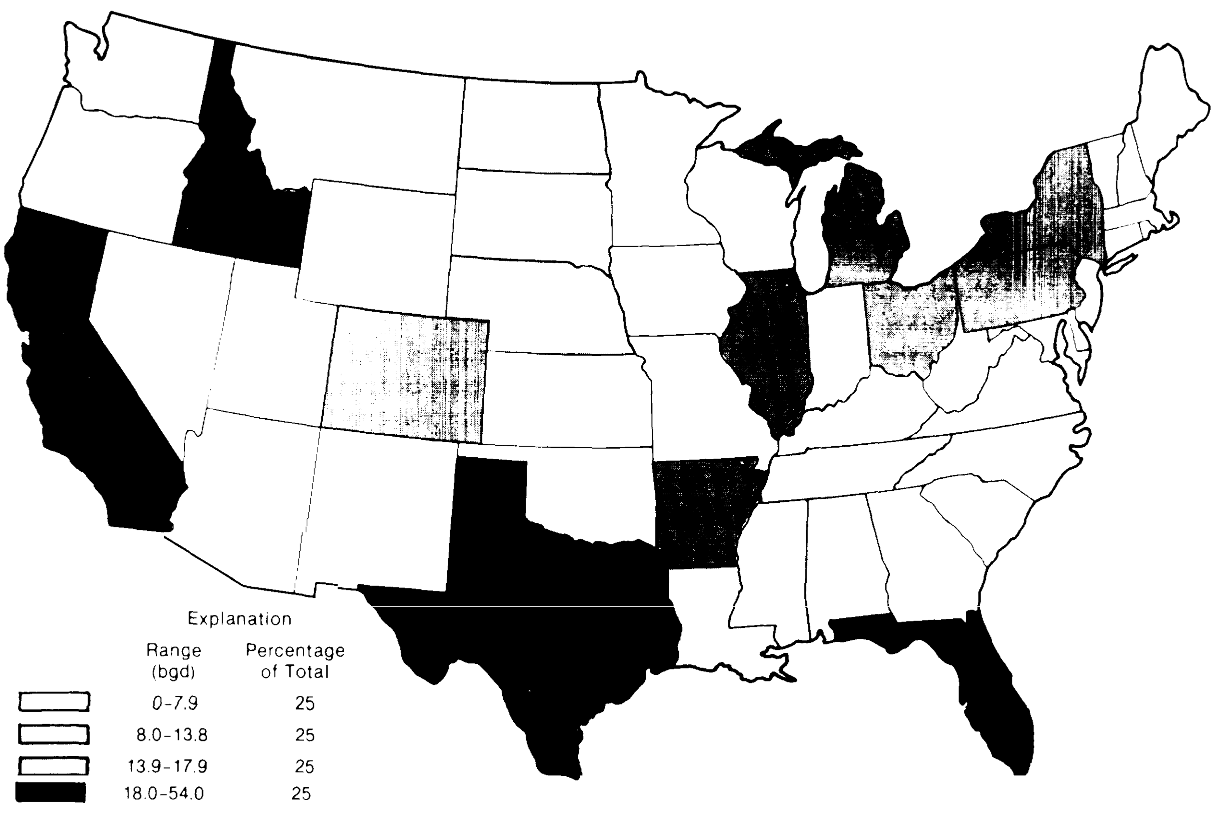
Relationship Between Supply and Demand

Depending on the areas, from 70 to 90 percent of the total annual surface runoff and ground-water recharge in the Western United States occurs during spring and summer. It is derived largely from the melting of the mountain snowpack of the region (e.g., 2). The contribution of snowmelt may be as low as 30 percent of the annual total flow in the mountains of western Washington State, where the precipitation peak occurs as a result of rainfall during the winter months, to as high as 90 percent along tributaries of the upper Missouri or Colorado Rivers.

Water is "consumed" when it is withdrawn and used in such a way that it is no longer available for additional uses. This means it has been either evaporated, transpired, incorporated into products or crops, consumed by livestock or humans, or otherwise removed from the water environment. Water is "used" but not consumed when it is withdrawn and returned to a river, as with irrigation return flows, hydroelectric energy generation, or maintenance of instream flow requirements,

According to USGS data, in 1975, water withdrawn from surface and ground water supplies in the Western United States averaged 3,000 gallons per person per day for a population of 50.8 million people. The total withdrawal was approximately 170.7 million acre-ft. A comparison of total water withdrawal, by State, is shown in figure 22. Water use in the Western and Eastern States is compared in table 14.

Figure 22.—Total Off stream Water Withdrawals, by States, 1980



SOURCE: W. Solley, E. Chase, and W. Mann, *Estimated Use of Water in the United States in 1980*, U.S. Geological Survey circular 1001, 1983.

Table 14.—Per Capita Water Use in the Eastern and Western United States

These figures represent both water withdrawals and consumptive uses.

	Contiguous United States water resources regions		
	Eastern (9 regions = 31 States)[a]	Western (9 regions = 17 States)[a]	United States (50 States, District of Columbia, Puerto Rico, and Virgin Islands)
Population, in millions:			
Total	155.7	69.1	229.6
Served by public supplies	123.5	58.1	186.1
Self supplied (rural)	32.2	11.0	43.5
Per **capita water use, In gallons per day:**			
Off stream use:			
Total withdrawals	1,600	2,900	2,000
Public supplies:			
All uses[c]	160	230	180
Domestic and public uses and losses[c]	100	150	120
Rural domestic use[d]	73	98	79
Irrigation[b]	82	2,000	660
Self-supplied industrial	1,300	660	1,100
Consumptive freshwater use[b]	120	1,200	450
Instream use:			
Hydroelectric power[b]	8,900	27,000	14,000
Total off stream and instream use[b]	10,000[e]	30,000[e]	16,000

qApproximate boundaries
Based on total population.
cBased on population by public supplies
'Based on rural population.
'Totals may not add due to rounding.
NOTE' All per capita data calculated from unrounded figures and rounded to two significant figures
SOURCE: W Solley, E Chase, and W. Mann, *Estimate Use of Water in the United States in 1980*, U S Geological Survey Circular 1001, 1983

Also according to USGS data, the per capita consumption of water in the Western United States averages 1,300 gallons per person per day, or approximately 145 million acre-ft. Eighty-five percent of the total withdrawals are for irrigated agriculture. The amount of this irrigation withdrawal that is consumed ranges from over 80 percent in the Texas-Gulf Water Resources Region to slightly more than **30** percent in the Pacific Northwest and Upper Colorado River Water Resources Regions. The average water consumed by irrigated agriculture for the nine western WRC regions is 56 percent of that withdrawn (4,12). Aspects of water supply, withdrawal, and consumption in the nine water-resource regions of the Western United States are given in table 15.

A variety of problems is encountered in defining the amount of water actually available for use in the Western United States. The most obvious one is determining the total volume of water that passes annually through the hydrologic cycle of the region. A second measure of water availability, that of determining the quantity of water that is used "consumptively," and thus made unavailable for any subsequent uses, is becoming a less certain indicator of water availability because, increasingly, nonconsumptive uses such as hydroelectric generation or instream flow requirements compete with consumptive uses such as irrigated agriculture. It is apparent that the same unit of water cannot generate electricity and concurrently be used for irrigation. Increasingly, decisions about the timing of storage and release of water from regional reservoirs will be made in the context of diverse and often conflicting uses.

Water Supply and Use Patterns

Annual Estimates of Supply

Attempts to estimate a "dependable" supply for the purposes of water planning and management are partially subjective, involving the relationship between supply and use at the time of use. Total annual streamflow is not a useful

Table 15.—Water Supply and Use, Including Off-Channel and Hydroelectric Generation, by Region

Water resources region	Area (000 ml^2)	Average runoff[a] Maf/yr	Average runoff[a] Inches/year	Normal reservoir storage[b] (maf)	Established dependable supply[a] (maf)	Withdrawals all sources[c] (maf)	Consumption[c] (maf)	Ground water withdrawn[c] (maf)	Hydroelectric generation (maf)
10	515	60.5	2.2	83.4	33.6	43.7	17.9	13.4	160,0
11	265	81.8	6.0	30.3	22.4	26.9	10.7	10.6	70.0
12	175	35.8	3.9	23.5	19.0	19.0	7.3	5.7	8.7
13	136	5.6	0.8	7.8	3.4	5.3	2.7	2.1	1.2
14	110	14.6	2.5	10.2	14.6	9.5	2.6	0.2	18.0
15	137	3.6	0.5	61.3	2.2	9.7	5.5	5.0	43.0
16	185	8.4	1,0	3.8	10.1	8.4	4.4	1.8	6.2
17	271	235.0	16.0	54.8	78.4	38.1	13.4	9.2	1,700,0
18	120	69.4	9.0	40.0	31.3	60.5	28.0	23.5	83.0
Total	1,914	514.9	4,7	315.0	215.0	221.1	97.5	71.6	2.090.1
Percent of conterminous Us.	630/o	380/o	560/o	70 "/0	37 "/0	44 "/0	57 "/0	73 "/0	560/o

NOTE Partial figures may not add because of independent rounding.
aC. Murray and E Reeves Estimated Use of Water in the *United States in 1975,* U S Geological Survey Circular 765, 1975
bUS Water Resources Council, The Nation's Water *Resources 1975-2000* (Washington, DC U.S Government Printing Office, 1978), vol 2, pt. IV, 1978, p 13
CW. Solley, E Chase, and W Mann, *Estimated Use of Water in the United States in 1980,* U S Geological Survey Circular 1001, 1983

indicator of water availability for most uses because a considerable amount of seasonal and year-to-year variation exists in the volume of flow of the rivers of the Western United States. Water supply at any point is a result of a complex interaction between withdrawal activities and return flows all along the system, involving some consumptive uses and some instream, nonconsumptive uses. Moreover, these use patterns are subject to change as the needs or desires of society change.

Analyses of the adequacy of water supplies are commonly based on the annual amounts of consumptive water use and streamflow. USGS has developed estimates of dependable annual supply for the water-resource regions *(14),* based on a statistical analysis of streamflow records and an evaluation of the degree to which reservoir storage assists streamflow in maintaining a satisfactory available supply. These estimates do not relate specifically to the needs of irrigated agriculture because they do not reflect the relationship between supply and use patterns during summer when demand for irrigation water is at a maximum. They do, however, serve as a useful first approximation of water availability in the West.

According to the USGS statistical analysis of streamflow and storage, the Missouri and Arkansas-White-Red regions have moderately large water supplies and favorable supply-to-demand relationships. In the Texas-Gulf region, withdrawals are greater than the estimated dependable supply and have exceeded the flow in 90 years out of 100, and excess demand is made up largely from ground water and water reuse, Consumption of water in the Rio Grande region is greater than dependable supply, while in the Upper Colorado region, supply exceeds demand. Both water withdrawals and consumption in the Lower Colorado region exceed the supply originating in that area. Excess demand is met by inflow of water from the Upper Colorado region, importation of surface water, repeated withdrawals of water, and ground water "mining." Large ground water withdrawals are characteristic of the Texas-Gulf, Rio Grande, Arkansas-White-Red, Lower Colorado, and California regions,

A slightly different approach to estimate water supply and demand has been used by another USGS scientist who defines a "relative water depletion" index as the total consumptive use plus any water exported from each basin, divided by the total supply (1). Ground water mining was excluded from this USGS calculation,

Bredehoeft found that for:

1. most of the lower Colorado River basin, southern California, and most of Nevada, depletion exceeds 100 percent of the annual surface supply;

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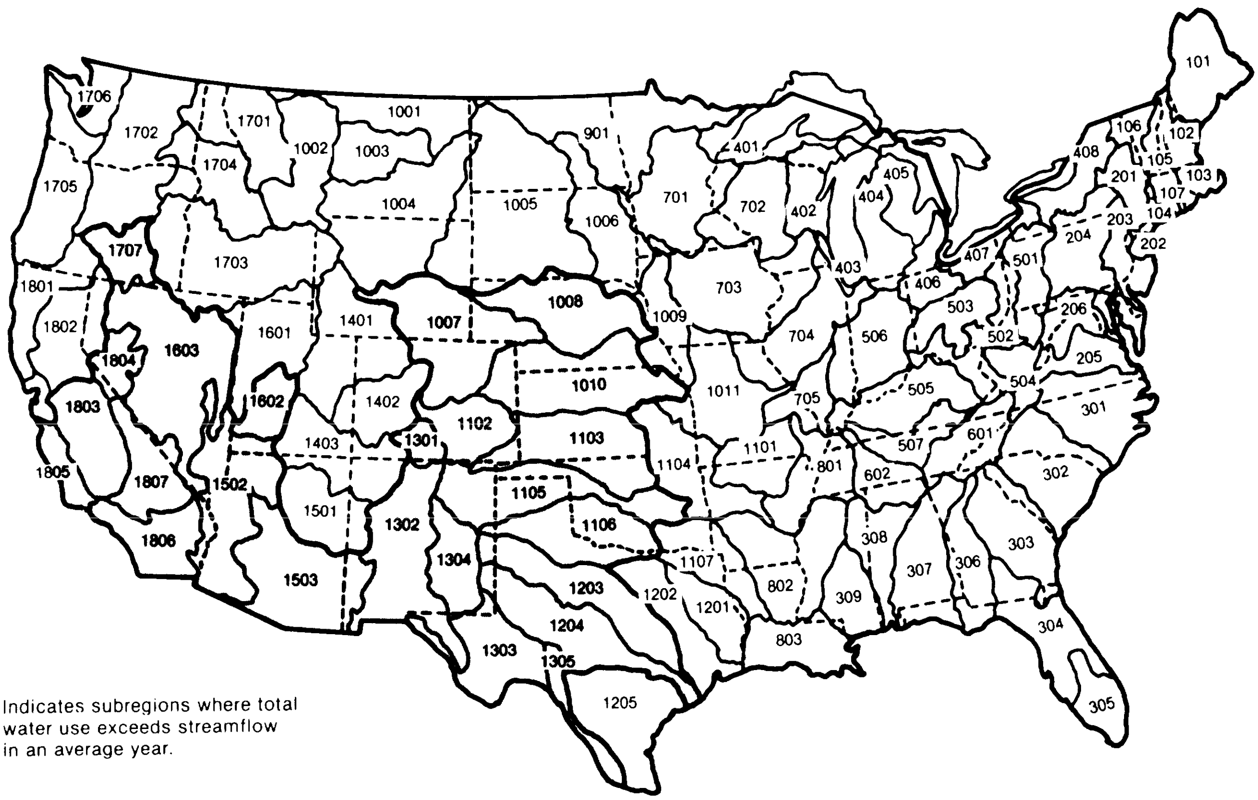
2. south-central California, including the San Joaquin and Owens Valleys, depletion exceeds 75 percent of the annual surface supply;
3. the High Plains of Colorado and west Texas, depletion exceeds 75 percent of annual surface supplies; and
4. much of New Mexico, depletion exceeds **75** percent of annual surface supplies.

A third comparison of water supply and use in the Western United States is contained in the Second National Water Assessment (12). This assessment presents both annual aggregate values of streamflow, total water use (including instream flow requirements), offstream consumption, and ground water mining for the 52 water-resources subregions of the West as well as monthly values for each. In the Second National Assessment, "use" is defined as the total of all offstream consumptive uses plus evaporation losses (from ponds and reservoirs) and net imports of water. "Supply" is defined as the streamflow volume that would occur at the outflow point of each subregion if consumption were eliminated, ground water overdrafting were discontinued, and current water transfer and reservoir practices were continued.

Based on the Second National Water Assessment data for average year conditions, total water use exceeds streamflow in 28 subregions, which account for about 66 percent of the West's irrigated land (fig. 23). In most of the other 24 subregions, there is little difference between streamflow and total water use. Total use is less than 75 percent of streamflow in one subregion, northern California, where there is limited agricultural potential,

In a year of below-average streamflow, the imbalance between supplies and estimated

Figure 23.—Water Resource Subregions Where Total Water Use Exceeds Streamflows in an Average Year



SOURCE: K. Frederick and J. Hanson, *Water for Western Agriculture* (Washington, D.C.: Resources for the Future, Inc., 1982). (Original source: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 2, pt. II, p. 4.)

total water use is more intense and widespread. Shortfalls are more likely not only because supplies are reduced but also because demand may be higher, especially for irrigation to compensate for reduced precipitation. In a dry year, total water use exceeds streamflow in 48 of the 52 subregions. Four of the exceptions are in the Pacific Northwest region, and the other is in the northernmost subregion of the California region. In eight of the subregions, use is more than twice the dry-year streamflow.

Monthly Estimates of Supply

The use of annual aggregates to determine the water-supply/use patterns of the Western United States often obscures the seasonal nature of many of the shortages that characterize the area. A more reasonable indicator of adequacy would relate water supplies to water needs of humans, animals, and plants during periods of maximum need. Currently, the shortest period for which data are readily available is *1* month. While this is longer than most living organisms can survive without water, it approximates more closely a realistic indicator of water-supply adequacy. An inspection of the Second National Water Assessment data suggests that there are at least three major water-supply/use patterns in the Western United States. These are subregions where: 1) streamflow exceeds offstream uses during every month of the year; 2) streamflow exceeds offstream uses during summer months only, when irrigation withdrawals reach their peak; and 3) streamflow is exceeded by offstream uses during every month of the year.

The Second National Water Assessment found that in *26* of the *52* water-resources subregions of the Western United States, offstream water use exceeded 90 percent of the average monthly supply during at least *1* month each summer (table *16).* These subregions are generally located in the areas also identified by USGS sources (1,4) as experiencing water-supply problems. Those areas experiencing at least *1* month of a water-supply deficit during each summer are southern California; the Great Basin; portions of Arizona, New Mexico, Colorado, Nebraska, Kansas, Texas; and the Snake River Plain in southern Idaho.

Consumptive Uses of Surface Water

Consumptive uses of water account for more than the amount being renewed on an annual basis in approximately *40* percent of the water-resources subregions of the Western United States during at least some portion of each year, For much of the Western United States, August is the month of maximum offstream consumptive use. In August, generally, streamflow volumes have diminished significantly from the peak flows of springtime snowmelt. Based on August values of offstream consumption and total streamflow taken from the Second National Water Assessment *(12),* figure *24* shows that for all of the water-resources regions of the West (excluding the Pacific Northwest), consumption of water is estimated to be about 90 percent of total streamflow during the month of August and goes as high as 395 percent of streamflow in the Brazes River subregion in Texas (12). * Water consumption of many of the subregions of the West actually exceeds 90 percent of streamflow during more than 1 month of each year (see table *16).* This suggests that there is currently no excess surface water during August in the Western United States, since even in the Pacific Northwest water that is not used off stream is required for instream hydroelectric generation. In some areas, no excess surface water exists during other months as well. A variable percentage of this water consumption is based on reuse of surface waters and ground water withdrawals depending on the water-resources region. If it is assumed that ground water withdrawal is not sustainable because of "mining" and rising energy costs, current patterns of Western water consumption and use are probably not sustainable.

The monthly patterns of water supply and offstream use for several selected subregions

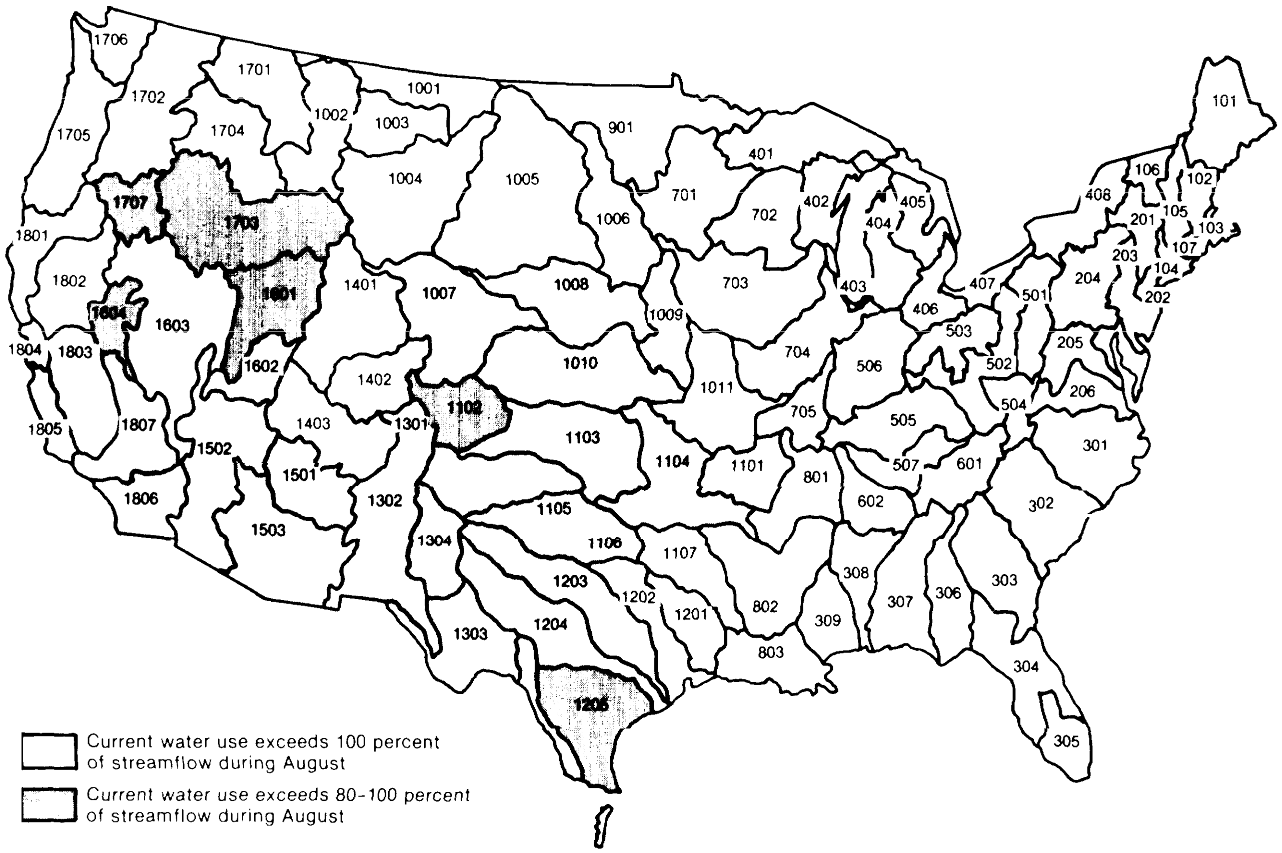
"Total streamflow is defined as a "computed flow that includes effects of consumption, water transfers and evaporation from manmade reservoirs, but not ground [i. ater overdraft.

Table 16.—Western Water Resource Subregions Where Off stream Use Exceeds Total Streamflow

Region number	Subregion number	Name	Months during which off stream use exceeds 90% of total streamflow
10		MISSOURI:	
	01	Missouri-Milk-Saskatchewan	—
	02	Missouri-Marias	—
	03	Missouri-Musselshell	—
	04	Yellowstone	—
	05	Western Dakotas	—
	06	Eastern Dakotas	—
	07	North and South Platte	June-September
	08	Niobrara-Platte-Loup	July-September
	09	Middle Missouri	—
	10	Kansas	July-August
	11	Lower Missouri	—
11		ARKANSAS-WHITE-RED:	
	01	Upper White	—
	02	Upper Arkansas	June-July
	03	Arkansas-Cimmaron	July-August
	04	Lower Arkansas	August
	05	Canadian	July-September
	06	Red-Washita	July-September
	07	Red-Sulphur	—
12		TEXAS-GULF:	
	01	Sabine-Neches	—
	02	Trinity-Galveston Bay	—
	03	Brazes	July-September
	04	Colorado (Texas)	June-September
	05	Nueces-Texas Coastal	—
13		RIO GRANDE:	
	01	Rio Grande Headwaters	July-August
	02	Middle Rio Grande	June-October
	03	Rio Grande-Pecos	March-September
	04	Upper Pecos	April-September
	05	Lower Rio Grande	March-August
14		UPPER COLORADO:	
	01	Green-White-Yampa	—
	02	Colorado-Gunnison	—
	03	Colorado-San Juan	—
15		LOWER COLORADO:	
	01	Little Colorado	—
	02	Lower Colorado Main Stem	March-October
	03	Gila	January-December
16		GREAT BASIN:	
	01	Bear-Great Salt Lake	July-August
	02	Sevier Lake	June-September
	03	Humboldt-Tonopah Desert	February-December
	04	Central Lahontan	August
17		COLUMBIA:	
	01	Clark Fork-Kootenai	—
	02	Upper/Middle Columbia	—
	03	Upper/Central Snake	—
	04	Lower Snake	—
	05	Coast-Lower Columbia	—
	06	Puget Sound	—
	07	Oregon Closed Basin	—
18		CALIFORNIA:	
	01	Klamath-North Coastal	—
	02	Sacramento-Lahontan	—
	03	San Joaquin-Tulare	June-October
	04	San Francisco Bay	July-August
	05	Central California Coast	June-September
	06	Southern California	April-November
	07	Lahontan-South	April, July-September

SOURCE' U S Water Resources Council, The Nation's Water Resources 1975-2000 (Washington, D.C U S Government Printing Office, 1978), vol 3, app Ill, table III-5.

Figure 24.—Ratio of Off stream Consumptive Use to Streamflow During August



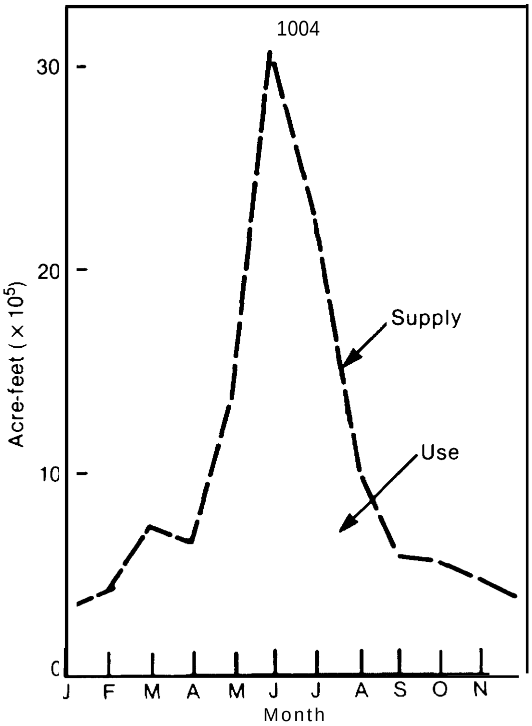
SOURCE U S Water Resources Council The Nation's Water *Resources* 1975-2000 (Washington, D.C. U.S. Government Printing Office 1978)

in the Western United States are shown in figure 25A, B, and C. These rivers are, respectively:

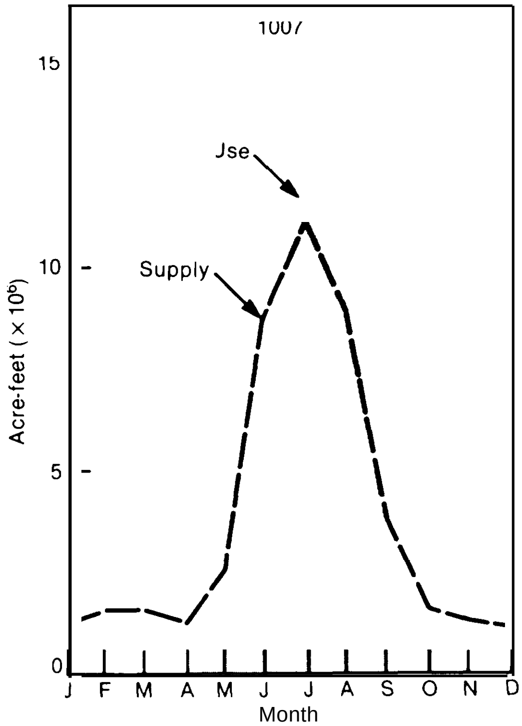
1. the Yellowstone, a tributary to the Missouri, which has its headwaters in the northern Rocky Mountains;
2. the North and South Platte Rivers, which originate in the Colorado Rocky Mountains and flow eastward through Nebraska to enter the Missouri River; and
3. the Gila River, which drains the southwestern portion of Arizona and includes the metropolitan areas of Tucson and Phoenix within its watershed.

The monthly supply/demand relationships for the Yellowstone River in southwestern Montana are typical of many of the rivers of the Pacific Northwest and northern Rocky Mountains, where water supplies normally exceed withdrawals during all months of the year. For the North and South Platte Rivers in Colorado, Wyoming, and Nebraska, supply exceeds withdrawal only during the winter months. During the irrigation season, from April through August, offstream demand exceeds the supply available from these rivers during each month. The deficit is made up by pumping ground water. This pattern is typical for a majority of the water-resources subregions of the Western United States. The most extreme imbalance between supply and offstream demand is represented by the Gila River, which is characteristic of those in the Southwestern tier of States. Here, offstremn demand exceeds supply during every month of the year, a situation made possible only by the reuse of surface water supplies and by extensive ground water "mining, "

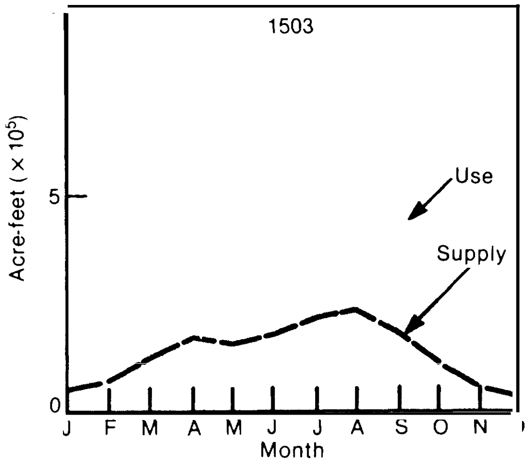
Figure 25.— Monthly Relationship Between Water Supply and Use for Three Western Rivers



A. The **Yellowstone** River, a tributary to the Missouri River. This pattern is typical of many in the northwestern portion of the Western United States.



B. The North and South Platte Rivers, tributaries to the Missouri River in the central portion of the Western United States. Use of water in this subregion exceeds supply during a portion of each year. This deficit is made up by pumping ground water.



C. The Gila River in Arizona. Water use exceeds the renewable supply during every month of the year in this river basin. This is made possible only by the extensive mining of ground water.

SOURCE Office of Technology Assessment, 1982, from U.S Water Resources Council, 1978

Offstream demand in excess of surface water supply in the southwestern United States has become a difficult social and economic problem. An extensive social infrastructure has developed in that region based largely on investments that depend on a reliable water supply. In these regions, surface supplies often do not meet demands and ground water must be tapped, From a hydrologic point of view, ground water use in excess of ground-water recharge cannot be sustained into the future, either because of declining volumes of water in the aquifers of the region or increasing pumping costs to extract the water. These factors are contributing to shifts in water-use patterns in the Southwestern United States. (See app. B for further graphics on variability among the water resource regions in spatial and temporal availability of water and in the use of that water.)

Nonconsumptive Uses of Surface Water

A number of nonconsumptive instream uses are as important as consumptive uses but are not often generally considered in determining the supply/use relationship for an area. These are instream requirements for habitat maintenance and waste assimilation, hydroelectric generation, recreation, and the maintenance of commercial fisheries.

Instream uses, " . . . that amount of water flowing through a natural stream channel needed to sustain the instream values at an acceptable level" (12), are particularly difficult to define or quantify. The first attempt to accomplish this was made by the Second National Water Assessment, largely based on minimum streamflow levels required for maintenance of fish and wildlife populations and for navigation, where applicable.

An example of the economic and social desirability of maintaining sufficient instream flow for the support of fish habitat involves the salmon fishing industry of the Pacific States of Washington, Oregon, and northern California. The anadromous (primarily salmon) fish runs of the rivers draining into the sea have national as well as regional importance because they support a commercial fishery, an extensive sports fishery, and an Indian fishery. Damage to this fishery, either by a diminution of instream flows or by undesirable water-quality changes, will have both serious economic and social effects.

Other instream uses also exist that have a direct impact on human activity. An important instream flow use involves waste assimilation and dilution. It is common practice to discharge municipal and industrial wastes into streams with less than complete, or tertiary, treatment (3). Approximately 50 percent of the water used in irrigation returns to the river degraded in quality. Without some minimum level of streamflow, the water quality of return flows will become, in effect, the water quality of the stream. While this will have an effect on fish and wildlife, it also will mean that the water will require extensive and expensive treatment before being suitable for human domestic use.

A third instream use in a number of the water-resources regions of the Western United States involves hydroelectric generation, This use requires that water be "spilled" from a reservoir. If this spillage is to be consistent with the energy demands of the region supplied, reservoir water levels cannot be allowed to fall below some minimum level. If an optimum reservoir level is to be maintained, the spillage must be approximately equal to the amount of water flowing into the upstream end of the reservoir. In the case of the Pacific Northwest Water Resources Region, for example, present patterns of hydroelectric generation require that a monthly average of 140 million acre-ft of water (1.7 billion acre-ft/yr, or more than 12 times the annual flow of the Columbia River) be discharged from the reservoirs of the region to generate the energy being produced there, Without cumulative inflows to these reservoirs of 140 million acre-ft/month, hydroelectric generation must decrease. Thus, this instream use requires a certain volume of water with relatively little room for equivocation. Other uses such as irrigated agriculture, which might require reservoir water, would be detrimental to the hydroelectric use at the point that agricultural demands cause reservoir drawdown and decreased power generation.

Fourth, outdoor recreation activities, while somewhat more difficult to quantify, are important instream uses. According to the Second National Water Assessment, in 1975 there were 592 million water-related outdoor recreation activity "occasions" * in the 17 Western States. On a per-capita basis, this is 11.8 occasions per capita in those States compared with a per capita average of 8.4 occasions in the Eastern United States. Most of the water-related recreational activities in the water-short Western United States center on reservoirs and the free-flowing streams of the region. In both cases, some minimum level of instream flow is required to maintain a reservoir pool level suitable for recreational purposes. A minimum instream flow is necessary specifically to maintain flows during late summer in unregulated streams and to maintain recreational activities below dams on regulated streams.

* Participation by a person 12 years or older in a specific activity without regard to the duration of the activity.

There are no simple measures of instream flow requirements. To a certain extent, these must reflect the current level of development within a given river basin or along a given stream reach. Water use has already exceeded average annual streamflow in the Southwestern and Great Plains subregions of the Western United States. For these areas, adding another use in the form of instream flow requirements is largely academic.

The issue of instream uses and their priority was raised but not resolved in the Second National Water Assessment. An acceptable definition and quantification of these important uses should be of the highest priority for economic, social, and environmental reasons, Because these uses have national as well as regional and local significance, this area needs national as well as regional and local attention (see also ch. V).

FUTURE ENERGY DEMANDS FOR WESTERN WATER

Water availability is commonly noted as one of the key factors for the successful development of Western energy resources. Some areas of the northern Great Plains and the Rocky Mountain region already are experiencing economic activity as the result of energy development. Surface waters from both the Upper Colorado River Basin and Upper Missouri River Basin, as well as ground waters in these areas, have been described in a number of studies for purposes of water availability for Western energy development. *

Water requirements of energy facilities vary considerably. For example, coal-fired electric power generation requires more water than synthetic fuel technologies and more water than slurry pipelines to produce an equivalent amount of energy. High-Btu coal gasification consumes more water than either coal liquefaction or in situ oil shale production, but less than some oil-shale conversion methods. Water requirements for shipping coal by slurry pipelines are less than for some conversion facilities.

*See previous OTA reports on: ***Increased Automobile Fuel Efficiency and Synthetic Fuels: Alternatives for Reducing Oil Imports, OTA-E-186,*** September 1982; ***An Assessment of Oil Shale Technologies, OTA-M-118,*** June 1980; ***The Direct Use of Coal: Prospects and Problems of Production and Combustion,*** OTA-E-86, April 1979; and ***A Technology Assessment of Coal Slurry Pipelines, OTA-E-60,*** March 1978. Also see Science and Public Policy Program, University of Oklahoma, ***Energy From the West: A Technology Assessment of Western Energy Resource Development,*** 1981, University of Oklahoma Press.

projections of actual water demand from Western energy development are difficult and depend on numerous assumptions about Western law, needs of existing users, economic value of the water to be used, the specific site and time of development, and the technology used. Studies on individual energy resources have concluded that sufficient quantities of suitable water may be physically available or could legally be made available for certain kinds of energy development. The quality of water required for some energy uses may be lower than that required for agriculture.

No definitive estimate of the cumulative effects of Western energy development for agriculture is available, however. The difficulty with providing such an estimate is due, in part, to complex and dynamic legal, institutional, political, and economic issues involved. Moreover, data on water availability, current uses, and future demands are incomplete. The impacts of water demand for energy hinge on the quality of water required and future local, State, and Federal roles in programs to make water available for energy development. International activities also will influence the Western energy industry. The energy-specific studies generally recognize that on a site-specific basis, some Western agricultural areas could experience significant impacts from increased water use for energy.

CONCLUSIONS

Both the spatial and temporal availability of water for agricultural uses in the Western United States are related to variations in the components of the hydrologic cycle. It should be recognized that the use of a technology to produce a change in any single component of the hydrologic cycle to create additional water or water savings will inevitably affect other components of the cycle. A detailed analysis of the existing hydrologic regime at the site of technological modification will help to determine the extent to which that modification will affect the desired change (e. g., in increased surface runoff, decreased evapotranspiration, and increased soil-water storage). It will also help to define possible adverse impacts on other components of the cycle.

Evaluating the potential of a given technology for either producing additional water or conserving supplies will be difficult unless the quantities of water now involved are defined more accurately. Both the reliability and availability of water-resources data present problems for site-specific hydrologic analysis. Estimates of annual streamflow volume now vary by as much as several hundred percent, depending on the river basin and the source of the estimate. Additional cooperation and coordination among the involved Federal and State agencies would help to resolve water-data problems and discrepancies. Consideration should be given to using a lead agency concept for various data-reIated activities.

It is inevitable that both short- and long-term fluctuations in climate affecting water availability in the Western United States will continue in the future. Short-term variations in water supply lasting a single season or year have traditionally been a factor in planning and management of the water resources of the region. Changes in the water supply associated with long-term changes in the climate are less commonly considered in either planning or management. The past several decades have been particularly favorable for agricultural development. It must be assumed that present levels of agricultural production are at least partly the result of this, Short-term fluctuations in water supply can be accommodated in management and planning schemes by a statistical analysis of trends in the recent past, However, because there is no reliable method for predicting the nature of long-term trends, water use and planning over the long-term should tend toward conservative estimates of future availability.

The most important source of renewable surface water supplies in the Western United States is the mountain snowpack. This snowpack accumulates during the winter months in both the mountains bordering the Pacific Ocean and the Rocky Mountains in the interior. When it melts in the spring and summer months, it supplies an estimated 70 to *100* percent (depending **on** location) of the total annual surface runoff for all river basins except the Texas-Gulf region. Traditionally, the approach to the study of water resources in the Western United States has been one that emphasized problems related to meeting demand rather than those associated with the sources of supply,

Relatively little research attention has been given to the snowpack, either **in** terms of the spatial and temporal variations of volume of water stored each year or the rate at which surface runoff is produced during the melt seasons. Technologies such as weather modification and streamflow forecasting to improve reservoir management would benefit considerably from an increased understanding of the snowpack as the dominant source of the renewable surface water supplies. The snow survey program of the USDA Soil Conservation Service has produced a valuable data base that would greatly facilitate this research.

Based on the available estimates of water supply and use, almost half of the Western United States is experiencing water-supply problems in relation to demand. In much of the Southwest and southern High Plains, the total available surface supply is used in some way annually, and ground water is being withdrawn faster than its recharge rate in order to sustain the levels of use that have developed. Ground water mining can only be considered a short-term solution to water-supply problems, since diminishing reserves and increasing energy costs may gradually make the pumping of ground water prohibitively expensive, Where water supply is not entirely consumed, competing nonconsumptive uses, such as instream flow requirements or hydroelectric generation, are increasingly creating scheduling conflicts for offstream uses. Water-quality problems may prove to be an even more critical factor affecting patterns of future Western water use.

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