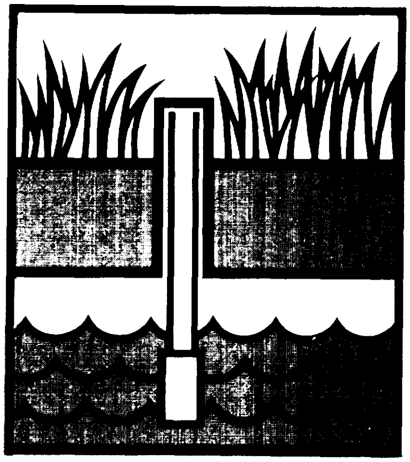


Technologies Affecting Ground Water

Contents

List of Tables

List of Figures

Chapter X

Technologies Affecting Ground Water

Ground water resources have become increasingly important to Western agriculture in the past decades, since increased use of ground water allows large new areas of land to be irrigated, Concerns exist that such use is not sustainable over the long term and that more careful decisions must be made to protect the valuable, finite water resource.

This chapter assesses ground water's role in agriculture and in other uses in the Western United States and evaluates technologies associated with its use. The chapter discusses ground water availability, water-quality degradation, and the interrelated character of ground and surface water, with emphasis on broad ground water principles applied to technologies and problems of the arid and semiarid West. Technologies designed to manipulate ground water quantity and quality are discussed separately to reflect the fact that, in general, water-supply technologies may involve active management, while water-quality technologies generally require a more passive approach. In practice, this separation seldom exists,

A wealth of information exists on ground water supplies and quality in the individual aquifers of the Western United States, but a regional synthesis was not found in the literature and may not exist. The recent trend toward sophisticated computer models has produced a competence for detail, but has exacerbated the problem of gaining an overview of this resource.

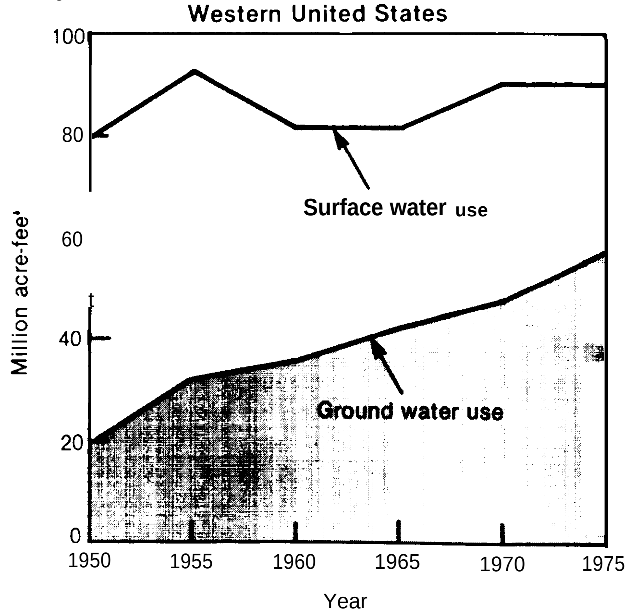
THE WATER SETTING

Ground Water Use in the Western United States

During the past three decades, ground water use in the Western United States has almost tripled, and the percentage of total withdrawals coming from ground water has nearly doubled, from 21 percent in 1950 to 39 percent in 1975 (fig. 62). Ninety-six percent of the ground water used in the entire United States occurs in the 17 Western States. Agriculture, including rural domestic water use, relies heavily on ground water (fig. 63), but the absolute and relative amounts involved vary greatly within the region (table 69),

Major Western aquifer areas in heavy use are the Ogallala (or "High Plains") aquifer, which stretches south from Nebraska to the Texas panhandle, the aquifers of the interior valleys of California, and those of the Snake River plain in Idaho. Each of these ground water areas supplies a significant percentage of the total irrigation and domestic water used in these areas. In other areas, however, the importance of an individual aquifer is more local.

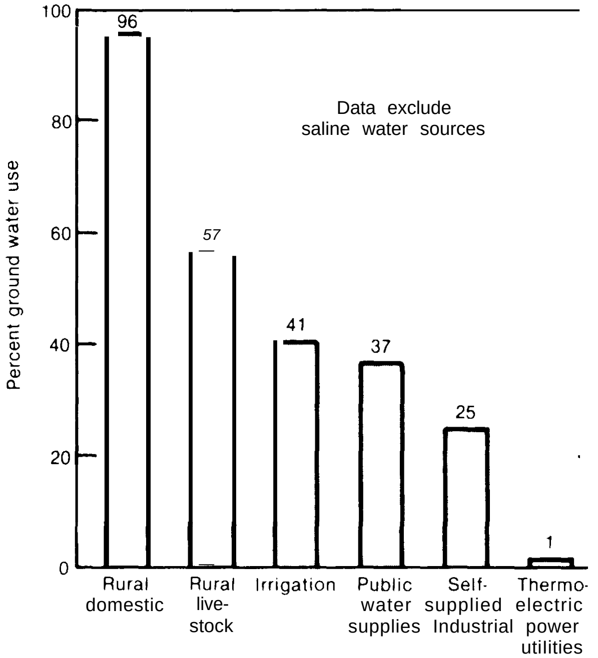
Figure 62.— Ground and Surface Water Use in the Western United States



Ground water withdrawals rose from 21 to 39 percent of total water withdrawals during the period from 1950 to 1975. These data include the nine water resource regions of the West; such trends cannot be sustained.

SOURCE Office of Technology Assessment, 1982 (Original source U S Geological Survey, *Estimated Use of* Water in the *United States,* published at 5-year intervals)

Figure 63.—Ground Water's Contribution to Various Water Uses, 1975



In 1975 approximately 96 percent of the water for rural domestic use came from ground water Rural livestock also derived a large share of their water from ground water supplies.

SOURCE: D Todd, *Ground* Wafer *Hydrology, 2d* ed. (New York' John Wiley & Sons, Inc., 1960). (Original source: C. Richard Murray 'and E. Bodette Reeves, Estimated Use of *Water in the U.S.* in **1975,** U.S. Geological Survey Circular 765, 1977.)

The extent of ground water withdrawals in excess of recharge, or "mining," is also a local problem. With the exception of a few areas (e.g., Texas and Arizona) where obvious declines in the regional water table are being noted, the relationship between recharge and pumping is quite speculative.

The perception that ground water is an inexhaustible resource has gradually changed during the last 30 years. Ground water is increasingly viewed as a finite resource that is being overdrafted. Both the National Water Commission (7) and the U.S. Water Resources Council (WRC) (15) discussed the sustainability of activities based on ground water extraction and concluded that much of the irrigated agriculture in areas such as Texas, Oklahoma, and Kansas which are heavily dependent on ground water (primarily the Ogallala aquifer), probably are not sustainable. Further study of this region by the High Plains Associates (5) outlined some of the effects of diminishing water and energy resources at the local, State, regional, and national level.

Ground water overuse and its effects on agriculture (i. e., abandonment of once productive farmland, higher pumping costs, and land subsidence) are only one element of the perceived problem, however. The deterioration of ground water quality, resulting from the infiltration of agricultural, industrial, and municipal pollutants may be of even greater significance for future ground water use in the Western United States. Most rural uses involve untreated water, and the quality of this water is therefore of great importance, especially to those users requiring high quality, such as domestic rural users (ch, IV).

Table 69.—The Importance of Ground Water in Different Western Regions, 1975

Region	Total withdrawal all sources	Total withdrawal ground water	Percent ground water of total withdrawal	Overdraft	
				Total (maf)	Percent (maf)
Missouri	42.6	11.7	27	2.9	24.6
Arkansas-White-Red	14,4	9.9	69	6.1	61.7
Texas-Gulf	19.0	8.1	43	6.3	77.2
Rio Grande	7.1	2.6	37	0.7	28.1
Upper Colorado	7.7	0.1	1.0	0	0
Lower Colorado	10.0	5.6	56	2.7	48,2
Great Basin	9.0	1.6	18	0.7	41.5
Pacific Northwest	42.0	8.2	20	0.7	8.5
California	44.4	21.5	48	2.5	11.5

Note: All volumetric data in million acre-feet (maf), conversion from million gallons per day (mgd) and rounded to nearest 0.1 maf.

SOURCE: US Water Resources Council, The *Nation's Water Resources* 1975.2000 (Washington, D. C.. U.S Government Printing Office, *Summary, vol. 1, 1978),* pp. 16-25.

Box W.—When the Well Runs Dry-The High Plains Study

In 1976, prompted by concern about the diminishing ground water supplies in the Ogallala aquifer and possible effects on irrigated agriculture in the six High Plains States (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas) underlain by the aquifer, Congress authorized and funded the High Plains study (Water Resources Development Act of 1976, Public Law 94- 587). Congress gave major responsibility to the U.S. Department of Commerce; the U.S. Army Corps of Engineers was assigned the task of planning and evaluating the potential for interbasin transfer of water to the High Plains.

Five major policy alternatives for the High Plains study were evaluated: 1) no change in public water policy; 2) increased education and research to improve water use efficiency; 3) new regulations restricting the amount of water pumped for irrigation; 4) intrastate surface water development; and 5) interstate surface water development. The effect of each policy was considered for total irrigated acres, crop-production volumes, total returns to land and management, number of acres shifting to dryland production, changes in ground water levels, water use, sales volumes by economic sector, employment, and population. Values were estimated for the years 1977,1985, 1990, 2000, and 2020.

According to the scenarios developed by the study, projections of future crop production do not indicate a significant change in the current mix of crops and relative size of their production volume to 2020. Instead, the problem of ground water depletion and disruption in irrigated crop production is localized within States. Education and research on water conservation and legal restrictions on pumping could slow depletion of the aquifer. Intrastate and interstate surface water development also could help slow ground water depletion but would require large economic investments and entail extensive environmental and social costs.

SOURCES: High Plains Associates,"'Six-State High Plains Ogallala Aquifer Regional Resources Study, Summary." A Report to the U.S. Department of Commerce and the High Plains Study Council, July 1982. Raymond J. Supalla, Robert R. Lansford, and Neal R. Gollehon, "'Is the Ogallala Going Dry?," J. *Soil and Water Cons. 37:310-314.*

Ground Water Characteristics

Ground water may result from a number of processes:

1. infiltration of precipitation;
2. seepage through the banks and beds of surface water bodies such as ditches, rivers, lakes, and oceans;
3. ground water leakage and inflow from adjacent aquifers; and
4. artificial recharge from irrigation, reservoirs, water spreading, and injection wells,

There is "misinformation, misunderstanding, and mysticism" (7) about ground water that credits it with occurrence in underground rivers, pools, and veins, and thus separating "percolating" underground water from "underground streams. " Ground water does not occur in pools or channels of the kinds commonly seen on the surface, with a few exceptions, such as in some limestone or basalt formations. Instead, it is found usually in small open spaces, or interstices, of subsurface geological formations of rock or unconsolidated sediment.

Ground water represents a vast and largely unmeasured natural storage reservoir. Although nearly all rocks contain some water, rocks that yield significant quantities of water are known as "aquifers." The subsurface layers of the earth, below the soil moisture zone, comprise a great reservoir through which water moves very slowly. Its journey underground may be extremely brief or very long. This reservoir acts as a vast natural regulator in the hydrologic cycle, comparable in its effects to the oceans. It absorbs some fraction of the rainfall and snowmelt that would otherwise reach streams and rivers very rapidly as surface runoff, and it maintains streamflow during dry periods when no surface runoff occurs.

Only a small proportion of the total subsurface zone saturated with ground water is composed of rocks that store and transmit significant amounts of water. A wide range of permeabilities exists, ranging from cavernous limestones that may transmit water in much the same fashion as surface rivers and streams, to semipermeable layers that transmit water imperceptibly and that are not important in moving water to a spring or well.

In all cases, the deeper levels of the ground water zone consist of interstices that are so few and small that further downward percolation of water is impossible. Generally, the amounts of water to be found below a depth of 2,000 to 3,000 ft below the surface are very small, except in exceptional circumstances.

If inflow to a ground water system exactly equals outflow from that system, storage remains constant and the ground water will be a renewable resource. Ground water that is used at a rate in excess of recharge, no matter what the total available volume may be, is being "mined," and its use is not renewable. Agricultural development based on such mining will ultimately be threatened. For example, irrigated agriculture in the High Plains region of Texas was based on ground water development. The ground water used for irrigation has been mined from the Ogallala aquifer in excess annual recharge to that aquifer. In a period of slightly more than 20 years, some irrigated acreage is reverting to nonagricultural uses or other types of agriculture (e. g., limited irrigation, rangeland agriculture, and dryland farming) as the ground water reserves of the Ogallala aquifer in that area have been depleted or energy costs of pumping have become prohibitive,

In arid and semiarid areas, ground water inflow from adjacent aquifers, particularly those found in higher level ground water basins, may be important in local ground water recharge. The actual effect of this at a particular site is difficult to determine without detailed studies of the meteorological and geological site characteristics. Attempts to recharge overdrafted aquifers artificially have increased in recent years, particularly in areas of water shortage and may be locally significant. *

Western Ground Water Regions

Ground-water resource regions are more difficult to define than are surface-water resource regions. While surface-water resource regions may be differentiated on the basis of topographic divides, ground-water resource regions must be separated on the basis of varying rock types and surface climate. Arbitrary decisions concerning the relative importance of these factors must be made in assigning an area to a given ground-water resource region. Thus, various experts may have slightly different opinions concerning the placement or definition of the controlling factors for a particular site. A given ground water region may be comprised of a number of surface water basins.

For purposes of this assessment the major ground-water resource regions of the Western United States are defined as:

1. Western Mountain Ranges,
2. Alluvial Basins,
3. Columbia Lava Plateau,
4. Colorado Plateaus and Wyoming Basin,
5. High Plains,
6. Unglaciated Central Region, and
7. Glaciated Central Region (fig, 64).

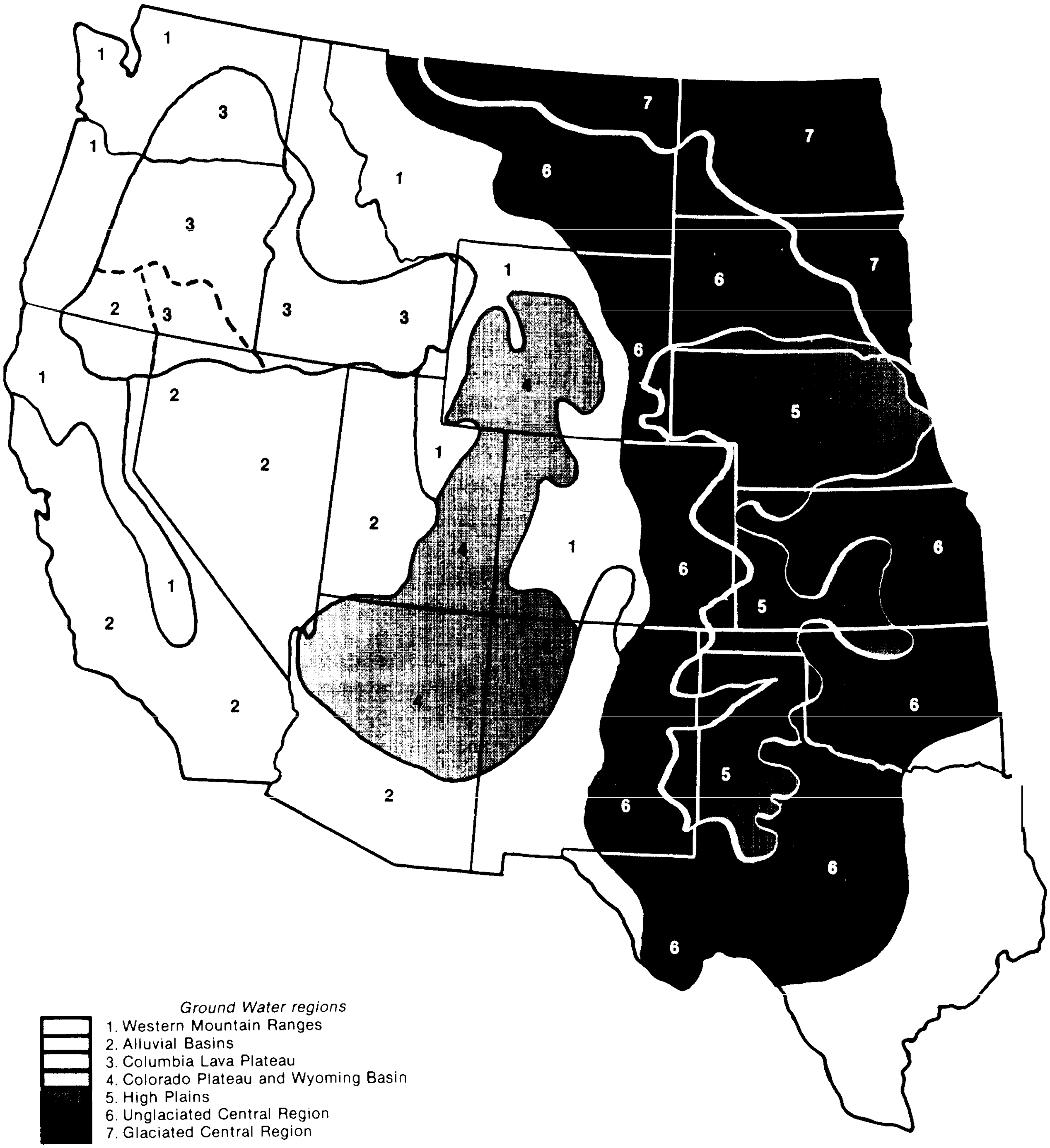
These regions are discussed in detail in appendix B.

Relationships Between Ground and Surface Waters

The distinction between ground water and surface water is largely arbitrary. Water moves between these two environments continuously. It is not accidental that those areas of the Western United States now experiencing, or beginning to experience, ground water supply or quality problems are commonly areas of sur-

*In May 1983, the U.S. House of Representatives passed a measure (H. R. 71) that would study and establish demonstration projects for ground water recharge in the High Plains. Other Western States facing ground water depletion were to be included in the study as well.

Figure 64.— The Major Ground Water Regions of the Western United States



SOURCE D Todd Ground *Water Hydrology* 2d ed (New York John Wiley & Sons Inc 1980) face water shortage. Only in certain special geological settings is it possible to decrease the amount of water contained in one part of the hydrologic cycle without also decreasing the amount in others.

Where ground water occurs in direct contact with surface water bodies such as lakes, ponds, or rivers, there will commonly be a movement of water between the two. The direction of this movement normally will be determined by the difference in altitude between the two sources. In arid and semiarid lands, where evapotranspiration losses normally far exceed precipitation amounts, the few perennial or intermittent streams are generated elsewhere and almost without exception lose water to ground water throughout the desert sections of their courses. Estimated ground water recharge in arid and semiarid areas may be as much as 10 times more effective than direct infiltration of precipitation (9). Therefore, changes in surface water supplies caused by technology may have significant consequences for nearby or distant ground water supplies.

Ground Water Quality

Ground water-quality problems are not necessarily unique to arid or semiarid areas. However, some pollution problems may reach critical levels more quickly than in more humid areas because of the low recharge rates of drier areas.

Precipitation reaching the ground contains only minor amounts of dissolved mineral matter. The quantity and type of mineral matter dissolved by this precipitated water, once it reaches the ground, depend on the chemical composition and physical structure of the rock or soil on which it falls as well as on the physical and chemical properties of the precipitation (e.g., temperature, acidity). Carbon dioxide, sulfate, and other natural and human-introduced, acid-forming compounds derived from the atmosphere and from organic materials in the upper soil layers form weak acids in combination with water and assist the solvent action of the water as it moves downward.

Most "salts" (dissolved materials) are added to ground water as a result of soil and rock weathering (table 70). Excess irrigation water percolating to the water table may contribute substantial quantities of salt. Water passing through the root zone of cultivated areas usually contains salt concentrations several times that of the applied irrigation water. Increases result primarily from the evapotranspiration process, which tends to concentrate the salts in irrigation waters. In addition, fertilizers, pesticides, and selective absorption of salts by plants and soil minerals will modify salt concentrations of percolating waters, Factors governing the increase of dissolved salt content of percolating waters include soil permeability, soil chemistry, drainage facilities, amount of water applied, type of crop(s), and climate, High concentrations of dissolved substances may be found in soils and ground water of arid and semiarid climates, where leaching is not effective in diluting the solutions. Similarly, poorly drained areas, particularly basins having interior drainage, such as much of Nevada and western Utah, often contain high concentrations. In some areas, such as the southern portion of the Ogallala aquifer in Texas and Oklahoma, high salinity may be the result of the original sedimentary deposition of the rocks under saline or briny waters.

Many ground waters contain salts in such concentrations as to make them unusable for ordinary water-supply purposes. Federal drinking-water standards recommend that total dissolved solids not exceed 500 parts per million (ppm). Specific limits of permissible salt concentrations for irrigation waters cannot be so precisely stated because of the wide variations in salinity tolerance among different plants (ch. IX). In general, a salinity level of 1,000 ppm is considered a hazard for most irrigation purposes in the United States, although the extent to which such water can be used successfully will depend on the quality of the soils involved, A well-drained soil, in certain cases, may produce a crop even using high-salinity water, whereas a poorly drained soil may fail to produce a crop using water of a similar or better quality. Keeping in mind this variability, a ma-

Table 70.—Sources and Effects of Dissolved Materials in Ground Water

Constituent or physical property	Source or cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, usually 1 to 30 ppm[a]	Forms hard scale in pipes and boilers and on blades of steam turbines
Iron (Fe)	Dissolved from most rocks and soils; also derived from iron pipes, More than 1 or 2 ppm of soluble iron in surface water usually indicates acid wastes from mine drainage or other sources	On exposure to air, iron in ground water oxidizes to reddish-brown sediment. More than about 0.3 ppm stains laundry and utensils. Objectionable for food processing. Federal drinking-water standards state that iron and manganese together should not exceed 0.3 ppm. Larger quantities cause unpleasant taste and favor growth of iron bacteria
Calcium (Ca) and magnesium (Mg)	Dissolved from moist soils and rocks, but especially from limestone, dolomite, and gypsum	Cause most of the hardness and scale-forming properties of water. Waters low in calcium and magnesium are desired in electroplating, tanning, dyeing, and textile manufacturing
Sodium (Na) and potassium (K)	Dissolved from most rocks and soils	Large amounts, in combination with chloride, give a salty taste, Sodium salts may cause foaming in steam boilers, and a high sodium ratio may limit the use of water for irrigation
Bicarbonate (HCO) and carbonate (CO_2)	Action of carbon dioxide in water on carbonate rocks	Produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot-water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium ‘ and magnesium cause carbonate hardness
Sulfate (SO_2)	Dissolved from many rocks and soils	Sulfate in water containing calcium forms hard scale in steam boilers. Federal drinking-water standards recommend that the sulfate content not exceed 250 ppm
Chloride (Cl)	Dissolved from rocks and soils; present in sewage **and found** in large amounts in ancient brines, seawater, and industrial brines	In large amounts in combination with sodium gives salty taste. In large quantities increases the corrosiveness of water. Federal drinking-water standards recommend that the chloride content not exceed 250 ppm
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils, but includes organic matter	Federal drinking-water standards recommend that the dissolved solids not exceed 500 ppm. Waters containing more than 1,000 ppm dissolved solids are unsuitable for many purposes
Hardness as $CaCO_2$ calcium carbonate	In most water, nearly all the hardness is due to calcium and magnesium.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate *hardness.* Any hardness in excess of that is called noncarbonated hardness
Acidity or alkalinity (hydrogen ion concentration, pH)	Acids, acid-generating salts, and free carbon dioxide lower pH. Carbonates, bicarbonates, hydroxides and phosphates, silicates, and berates raise pH.	A pH of 7.0 indicates neutrality in a solution. Values greater than 7.0 denote increasing alkalinity; values less than 7.0 indicate increasing acidity. Corrosiveness of water generally increases with decreasing pH
Dissolved oxygen (O_2	Dissolved in water from air and from oxygen given off in photosynthesis by aquatic plants.	Dissolved oxygen increases the palatability of water. Under average stream conditions, **4 ppm is usually necessary to maintain a varied fish fauna in good condition. For industrial uses, zero dissolved oxygen is desirable to inhibit corrosion**

[a]ppm parts per million

SOURCE **Paul R Ehrlich,** Anne H Ehrlich, and John P Holdren, Ecoscience *Population, Resources,* Enviorionment *[San Francisco* W. H. Freeman & Co , 1977) (Original source Charles B Hunt *Physiography of the United* States (San Francisco, W H Freeman & Co , 1967) jor factor affecting the suitability of ground water for irrigation increasingly will be the salinity level of the water (fig. 65).

"Hardness," another effect of the concentration of certain salts in water, also impacts on the suitability of water for irrigation. Hardness results from the presence or absence of compounds of calcium and magnesium. The U.S. Geological Survey (USGS) classifies hardness according to the amount of calcium carbonate or its equivalent that would be formed if the water were evaporated (table 71). "Hardness" varies across the Western United States (fig. 66).

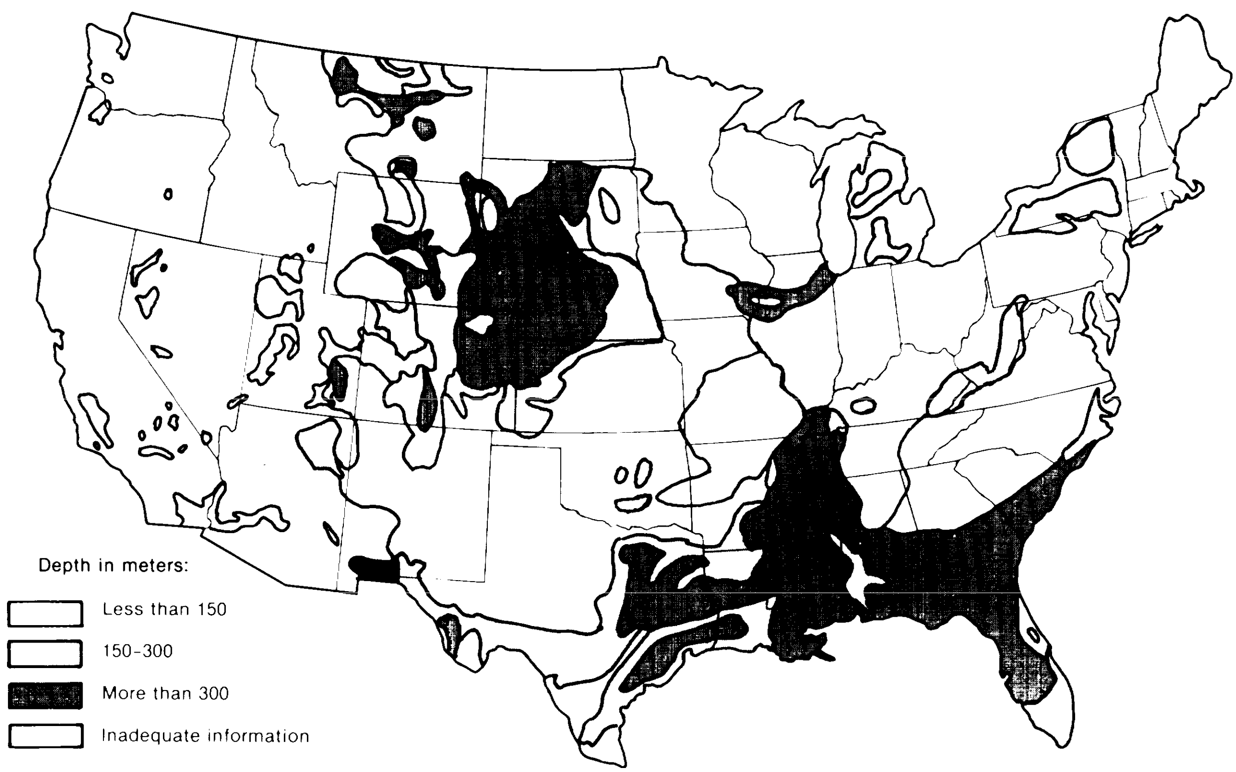
While hardness is an undesirable characteristic for many uses of water, some hardness is essential if soil quality is to be maintained. As water hardness decreases, the calcium and magnesium may be replaced by sodium, which will react with the soil and reduce its ability to transmit water. The Salinity Laboratory of the Department of Agriculture recommends the use of the Sodium Absorption Ratio (SAR) index, which measures the ratio of sodium to calcium and magnesium and can be directly related to the absorption of sodium by soil. Water containing as much as 40 percent sodium (relative to the concentration of calcium

Table 71 .—Hardness Classification

Parts per million $CaCO_3$	Classification
0-60	Soft
61-120	Moderately hard
121-180	Hard
More than 180	Very hard

SOURCE H Baldwin and C McGuinness, A *Primer on Ground Water,* U S Geological Survey, 1963

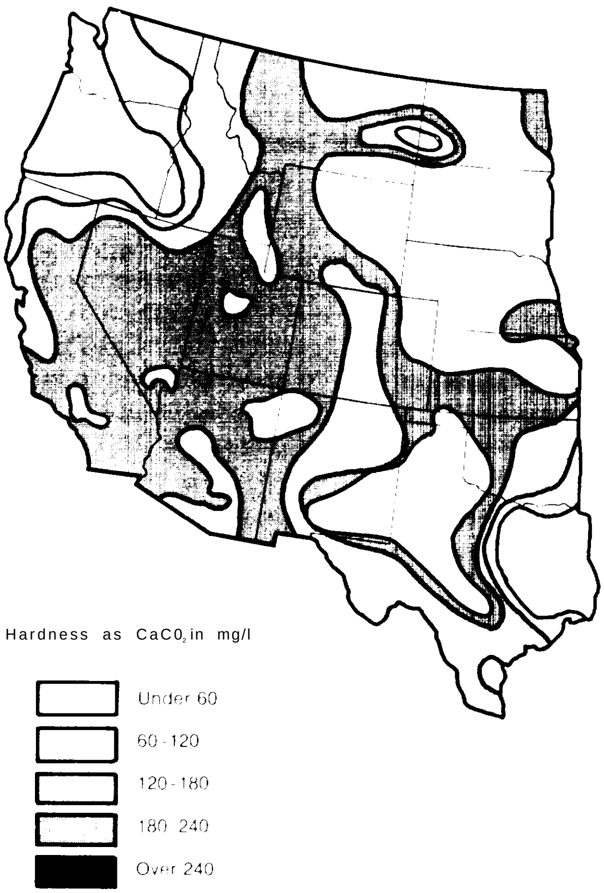
Figure 65.— Depths at Which Saline Ground Water Is Encountered



Saline water is defined here to contain more than 1,000 mg/l dissolved salts, a concentration that represents a high-salinity hazard for many irrigated crops.

SOURCE: D Todd, *Ground Water Hydrology,* 2d ed (New York" John W!ley & Sons, Inc , 1980).

Figure 66.—The Hardness of Ground Water in the Western United States
(areas shown represent average conditions)



SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980)

and magnesium) is classified as "good" for irrigation uses, while values as high as 60 percent are "permissible. " Sodium levels are generally low throughout the Western United States, at least in the shallow aquifers, with the exception of portions of the Texas-Gulf and Pacific Northwest regions (15), There is some indication that deeper aquifers of the northern Great Plains and interior basins of the Western region may occasionally have higher sodium levels that would render their use for irrigated agriculture undesirable.

Human activities may affect the quality of ground water in two major ways: 1) by accelerating the rate of buildup of compounds or components normally found in ground water, and 2) by adding or increasing the concentration of dissolved constituents during beneficia] use of water, The first results from plowing fields or any similar action that expedites the normal movement of water into and through soils containing soluble compounds. The second results from discharging inorganic chemicals, biological agents, and organic compounds associated with municipal, industrial, and agricultural uses into the environment through which water may move. [These are discussed in detail in chapter IV.)*

Detection of ground water-quality degradation depends largely on the existence of monitoring wells. It is highly probable that some potential sources of ground water pollution in the Western United States are not located near a water-quality monitoring station. Knowledge of the geographical distribution of and contributions to ground water-quality degradation is incomplete. Many criticisms of the surface water-quality monitoring network contained in the General Accounting Office (GAO) (14) critique apply equally to the ground water-quality monitoring network. These include problems related to taking samples at fixed time intervals, which may not coincide with the presence of the pollutant, and the location of the monitoring well network, which may not coincide with the potential sources of pollution. Moreover, GAO identified problems related to field and laboratory inconsistencies in the collection and analysis of water samples and the types of data analyses used.

In addition, because the general flow of ground water is not directly observable but must be inferred from mathematical models, the geographical extent of any pollutant source is much more speculative than is the case with surface water. It can be assumed that the pollutants in surface waters in any given area will generally be present in the ground water, modified in some cases by filtering or by chemical interactions with the soil or aquifer constituents. A more detailed discussion of water quality and its associated public health aspects is presented in chapter IV.

* Effects of acid rain are analyzed in the OTA assessment: *The Regional Implications of Transported Pollutants*, in press.

THE TECHNOLOGIES

Increasing Ground Water Supplies

Effective planning and management of ground water resources at a particular site must be based on the characteristics of the associated ground water region or basin within the region and on the interrelated nature of ground and surface water. Management objectives must take into account not only the geology and hydrology of the basin but also the economic, political, legal, and financial aspects of managing the water resource. Typically, optimum economic development of the water resources of an area requires an integrated approach that coordinates the use of both ground and surface water, Such development must consider both the quantity and quality of those resources to be successful.

With the exception of a decision not to extract ground water, most management technologies affecting water quantity may be considered active. They involve attempts to increase the recharge artificially to the aquifer above volumes that would occur under natural conditions. Technologies include water spreading and the use of recharge wells or pumping to induce recharge from natural surface water bodies. The choice of a given method, or combination of methods, is highly site-specific and will be governed by local topographic, geologic, climatic, and soil conditions; the quantity and quality of the water to be recharged; and the ultimate use for the water,

A fundamental requirement for artificial ground water recharge is that excess water be available, either locally or by import into a region, during all or part of each year, Without a supply of "excess" water during at least some portion of each year, artificial recharge technologies are not feasible. A number of areas exist in the Western United States that appear to have no water supply in excess of existing use patterns (ch. III). In some of these areas—for example, southern California and central Arizona—wastewater is increasingly used for ground water recharge. The implications of this practice for water quality are discussed below and in chapter IV.

Water Spreading

INTRODUCTION

Water spreading involves the construction of basins, pits, or barriers in or near natural stream channels to impound water and cause it to infiltrate the ground surface rather than leave the basin as surface runoff. This approach is most appropriate where the aquifer to be recharged is a near-surface, unconsolidated aquifer having few impermeable layers to impede either the vertical or horizontal flow of the water.

The typical ground-water recharge basin is excavated to a depth of 10 ft or more with side slopes as steep as the soil will allow when saturated. For some soils, special protection, such as broken rock, is required at the anticipated water surface to reduce wave erosion and the resultant turbidity in the water caused by bank erosion. Small check dams have been built in stream channels to impound surface runoff briefly and to increase the wetted surface area of the stream bed.

Experience in the operation of offstream ground-water recharge basins indicates that the surface area of the spreading basin is less important than the wetted perimeter. The bank area is the most important aspect of the wetted perimeter because falling sediment seems to clog this area less than on the bottom, The steeper the side slopes, the greater the recharge capability. The greater the perimeter of the basin, the more bank area available. Curvilinear basin sides provide a longer perimeter and result in a more esthetically pleasing facility in urban areas,

ASSESSMENT

No information is available on the extent of water spreading in the western United States. Information is available for two areas in California, the Tulare Basin and southern California, where a total of 173 off stream basin and pit facilities were in operation as of 1973. These produced a total of approximately 892,000 acre-ft of recharge annually. This amount is an average of slightly more than 5,000 acre-ft per facility and represents 40 percent of the total recharge that was accomplished in the State of California during the 1972-73 water year (11).

For these two facilities, the average cost of operating and maintaining surface recharge basins was $6.00 to $8.50/acre-ft, plus capital costs (land acquisition and construction) of $1.25/acre-ft (1973 dollars). The use of a coagulant to reduce the turbidity* of the influent water increased the cost of operation by an additional $3.l0/acre-ft. While these results are site-specific, they illustrate what can be accomplished in one area when recharge basin technology works and is used intensively.

The two primary limitations on the application of this technology are the availability of land and the avail ability of unappropriated surface water, In many areas of the Western United States, one or both of these will effectively make the technology impossible. A further limitation is the lack of a suitable geologic setting. Recharge basins and pits will work well only with a near-surface, unconfined aquifer or in the natural recharge area of the aquifer.

Recharge Wells

INTRODUCTION

A recharge well moves water from the surface to freshwater aquifers. Recharge wells are a way to increase ground water reserves where deep, confined aquifers must be recharged, or in urban areas, where land values preclude the development of water spreading,

Recent studies on the use and success of recharge wells are scarce. A few regions in the Western States have experience with this technology. At least 2,000 recharge wells are located in the agricultural lands of Idaho's Snake River plain (10), These wells are typically 2 to 3 ft in diameter and 20 to 30 ft deep, and are capable of accepting flows up to approximately 700,000 ft^3 (16 acre-ft) per day. The geology of the area consists of alternating layers of fractured and permeable basalt, a common volcanic rock. A study of the effect of these disposal wells on water quality revealed that ground water moved rapidly through fractures and channels in the basalt formations, that bacterial pollution persisted underground, and that suspended solids were reduced by downward percolation.

*Water clouded with suspended sediments

ASSESSMENT

In California, where artificial recharge is practiced most extensively of the Western States, recharge wells accounted for 12 percent of the recharge projects in 1959 but only 1 percent of the recharged water (8). Davis, et al. (2), present data showing an annual recharge of approximately 1,100 acre-ft/yr for a single well in the San Joaquin Valley, but stress the lack of experimental data. Todd (10) gives average values ranging from 200 to 400 acre-ft/yr for six sites in southern California and points out that the highest rates will occur in highly porous rock formations such as limestone and lavas.

According to USGS, recharge wells are "... justified only where the spreading method is not feasible" (l). Impermeable near-surface layers of rock or soil would render the spreading method geologically infeasible, while higher valued uses of land could render it economically infeasible.

For most aquifers, artificial recharge rates using recharge wells seldom equal pumping rates. The difficulty lies in the fact that pumping and recharging differ by more than just a simple change in direction, As water is pumped from a well, fine material present in the aquifer is carried through the coarser particles surrounding the well and into the well where it is removed with the extracted water. In the reverse direction, *any silt carried into* a recharge well will be filtered out by the coarser materials and will tend to clog the aquifer surrounding the well, Dissolved air carried to the aquifer by recharge water will similarly tend to clog the well. Bacteria, which will be a much more common constituent of recharge water than of natural ground water, can form growths on the well screen and the surrounding rock or soil, thereby reducing the effective recharge area of the well. The chemistry of the recharge water may not be in equilibrium with the aquifer or the natural ground water, thus producing chemical reactions that may reduce the permeability and porosity of the aquifer. In general, ground water recharge using wells will only be suitable for high-quality, treated water, and considerable experience is required to maintain optimum recharge rates. The recharge well is a technology that is limited to situations where there are no other options.

Improving Ground Water Quality

Introduction

In general, technologies to maintain or improve the quality of ground water are largely designed to prevent pollution. In most cases, once a ground water source has been polluted, it responds very poorly to attempts to restore its original quality,

Water reaches ground water levels by deep percolation from precipitation falling on the overlying land surface or through interconnected flow with surface water bodies (see ch. III). This recharge to ground water aquifers may be either artificial, as discussed above, inadvertent, or natural. Inadvertent recharge occurs as an unplanned result of some activity not designed specifically to recharge the ground water artificially, Included in this category is water from irrigation, cesspools, septic tanks, broken water mains, sewers, landfills, waste-disposal facilities, canals, and reservoirs. Whatever the source of recharge, degradation of the ground water quality may occur if polluted water is introduced. Once it has occurred, ground water pollution may be more difficult to detect than surface water pollution because of the relative inaccessibility of the water. Also, depending on the pollutant and the natural filtering by the aquifer materials, the subsurface pollution may be more difficult to control than surface water pollution, and it may move within the aquifer and persist for decades.

Technologies to improve ground water must be designed for a specific water-quality problem at a specific site. Their success will be determined by the extent to which the local geology, ground water movement, and nature of the contaminant are considered. All waters contain some amount of either dissolved or suspended contaminants. Technologies associated with ground water pollution must be focused largely on preventing pollutants from entering the ground water system. The sources of these pollutants are diverse and the list of potential pollutants is extensive, as discussed earlier in this chapter and in chapter IV.

One form of ground water pollution that sometimes may be dealt with technologically involves the intrusion of seawater into coastal aquifers. Seawater intrusion initially occurs when the coastal aquifer is pumped beyond its natural freshwater recharge capacity ("mined") or when freshwater recharge decreases naturally, In either case, seawater displaces or mixes with the freshwater in the aquifer. As little as 2 percent of seawater in an aquifer can render the water unpotable. In the coastal section of Texas and portions of California, for example, this problem already exists to varying degrees (15). The primary technologies for controlling saline water intrusion are:

1. Modification of pumping patterns, which typically involves construction of new wells at a site further inland.
2. Artificial recharge to balance withdrawals. This normally involves development of a supplemental water source,
3. Extraction barriers (a line of pumping wells along the coastal line), which create a trough in the water table into which the seawater flows. This water is then lifted to the surface and subsequently discharged back into the sea.
4. Injection barriers (a line of recharge wells along the coastal line), which create a "ridge" of freshwater beyond which the higher density seawater cannot penetrate,

This normally involves development of a supplemental water source.

Assessment

All technologies designed to improve ground water quality must be assessed in terms of:

- whether the contamination exists at a concentration sufficient to cause problems for the intended water use,
- the source of the ground water contamination, and
- the nature of the hydrogeologic environment.

The combinations and severity of impacts are complex, and in many cases largely undefined, in view of the current state of knowledge about ground-water flow regimes and the behavior of contaminants at a particular site.

pollution potential is largely dependent on whether the recharge to ground water is taking place above or below the water table. Elimination above the water table (e.g., by soil filtering, biological decomposition, chemical deposition] may be effective for some pollutants, generally organics. The exceptions are the major inorganic constituents, many organic pesticides, and viruses. As the types and volumes of contaminants being introduced into the ground water system increase, the traditional dependence on the soil as a filtering agent becomes less feasible. Many organic chemicals pass through the soil virtually unchanged and viruses may be unaffected by soil filtering. Thus, many of the contaminants now being introduced into the ground water system are effectively permanent for purposes of society's planning horizon.

The most problematical aspect of ground water pollution involves the duration of the decreased water quality and the most effective form of water-quality treatment. In this regard,

> An important aspect of ground water pollution is the fact that it may persist underground for years, decades, or even centuries. This is in marked contrast to surface water pollution. Reclaiming polluted ground water is usually much more difficult, time consuming, and expensive than reclaiming polluted surface water. Underground pollution control is achieved primarily by the pollution source, and secondarily by physically' entrapping and, when feasible, removing the polluted water from the underground (10).

In light of this technological limit, the management of ground water quality involves managing the potential sources of ground water pollution and control *before* the pollutant is introduced into the ground water system instead of treating the pollution after it occurs, This is an extremely complex matter, largely involving adjustments in the ways in which waterborne wastes are disposed rather than the technological means of purifying water once it is contaminated. With modifications, the technologies for controlling seawater intrusions into freshwater aquifers may be applied to the removal or isolation of any contaminant,

Improving Ground Water Withdrawal Efficiency

Introduction

An important consequence of the reliance on ground water for irrigated agriculture pumping has been the increased cost of obtaining water from this source. In the 1960's and early 1970's, when the rate of withdrawal and overdraft were rising rapidly, concerns grew about the effects of pumping on the long-term availability of ground water for irrigation. More recently, the fear of depletion has been displaced by the much more immediate concern that energy prices will make irrigation with ground water uneconomical in some areas, even with much of the water still in the aquifer.

Increasingly, when water must be lifted several hundred feet, energy costs tend to be the major component of water costs. The energy costs of pumping 1 acre-ft of water from various depths with alternative fuels as well as fuel prices have increased greatly for some areas in the last 10 years, and further increases are projected (table 72).

Assessment

Technologies to improve the efficiency with which ground water can be pumped from

Table 72.—Energy Costs for Pumping Ground Water (1977 constant dollars)

These costs are for pumping 1 acre-ft of ground water from various depths with alternative fuels and fuel prices for 1970-2000,

Fuel	Pump lift (ft)	Energy costs under alternative fuel prices		
		1970	1980	2000
Natural gas	100	$ 1.13	$ 4.56	$ 9.12
	200	2.30	9.29	18.58
	300	3.43	13.86	27.72
Electricity	100	7.52	8.88	17.76
	200	25.03	17.76	35.52
	300	22.55	26.64	53.28
LPG	100	7.32	12.60	26.20
	200	14.65	25.20	50.40
	300	21.98	37.80	75.59
Diesel	100	5.24	14.96	29.92
	200	10.59	30.00	60.00
	300	15.74	44.96	89.92

SOURCE The technical assumptions such as the amount of fuel and the pressure required to lift an acre-foot of water are based on Gordon Sloggett, *Energy and U S Agriculture" Irrigation Pumping, 1974.77* (Washington, D.C : U.S Department of Agriculture, September 1979). Other assumptions include a 60-percent pumping efficiency Fuel costs in 1977 constant dollars are natural gas ($/mcf) 0.39 in 1970, 158 in 1960, and 315 in 2000; electricity ($/kWh), 0.033 in 1970, **0.039 in 1980, and 0.078 in 2000 LPG (S/gal) 025 in 1970,043** in 1980, and 0.66 in 2000, diesel (S/gal) 028 in 1970, 080 in 1980, and 160 in 2000. The 1970 prices for LPG, and diesel are a national average obtained from *Agricultural* Prices, *Annual Summary* (Washington, D C U.S. Department of Agriculture, June 1977). The 1970 prices for electricity are a national average ob. tained from *Agricultural Prices,* October 1977 The 1970 price for natural gas was obtained by personal communications with Delbert Schwab, OSU. The 1980 prices reflect average prices paid by farmers in Nebraska, Kansas, Oklahoma, and Texas in January 1980 The prices were obtained through phone conversations with officials in those states Hans Landsberg, project director and co-authors *(Energy: The* Next *Twenty Years,* Cambridge, Mass , Ballinger, 1979, p 71) conclude that, on average, real fuel prices will double by the year 2000. Although long-term contracts consummated in the last several years suggest natural gas prices may rise faster than the prices of the other three fuels, we have chosen to illustrate the implications of a doubling of all fuel prices rather than attempt to estimate differential rates of increase

SOURCE K Frederick, and J Hanson, *Wafer for* Western *Agriculture* (Washing. ton, D C Resources for the Future, 1982)

underground aquifers are necessary to compensate for rising energy costs and declining water levels. In addition to changing the spacing and depth of wells drilled into the aquifer, the technologies involved are generally concerned with the type of pump employed and the fuel or energy source used to drive the pump. Technologies for improving the efficiency of the water well itself also may be important in certain cases,

IMPROVING PUMPING-SYSTEM EFFICIENCY

Pumping efficiency is the ratio of the theoretical to the actual energy input needed for a given water output. It is essentially the product of the efficiencies of the pump and the power unit. A new pump should have an efficiency of about 75 percent when properly installed, Internal combustion engines often reduce the efficiency of the pumping system by another 5 percent because of the gearhead. The power-system efficiency varies widely with engine type. Reasonable engine efficiencies are 90 percent for electric, 24 percent for natural gas, and 32 percent for diesel fuel. Overall attainable efficiencies for pumping systems are about 66 percent for electric, 17 percent for natural gas, and 20 percent for diesel (6),

Inefficient pumping systems result in unnecessarily high pumping costs. Recent tests by the High Plains Underground Water Conservation District No. 1 in Texas showed that some farmers pay twice or even three times as much for irrigation because of the sizing, staging, and condition of the pump. oversized pumps, specifically, were a major source of inefficiency. Commonly, the pumps had been designed years earlier to handle larger quantities of water than the well could currently yield (because of lowered water tables). Other sources of energy loss included improper staging to accommodate changes in water levels or additional lift requirements of newly installed sprinkler systems and reliance on worn pumps. The condition of the power unit, especially with natural gas internal combustion engines, was occasionally the source of some inefficiency, but those problems were not so severe as those involving the pumps.

Pump efficiency has a large effect on the cost of pumping water. According to calculations by Frederick and Hanson (table 73), energy costs may rise as much as 40 percent as the pump efficiency declines from 70 to 50 percent, and costs may rise another 67 percent with a decline to 30-percent efficiency. At 1980 energy costs (deflated to 1977 constant dollars), a decline in pump efficiency to 50 percent costs a farmer an additional $3.19/acre-ft with electricity compared to the costs of a 70-percent efficient well.

The type of fuel is as important as the pumping depth in determining a farmer's energy costs. Despite a fourfold rise in price since

Table 73.—The Effect of Pumping Efficiency on Pumping Costs (1977 constant dollars)

Energy costs to pump 1 acre-ft of ground water 200 ft with alternative fuels, fuel prices, and pump efficiencies.

Fuel	Pump efficiency	Fuel price 1970	1980	2000
Natural gas . . .	70	$ 1.97	$ 7.96	$15.93
	50	2.76	11.15	22.30
	30	4.60	18.58	37.16
Electricity ., ...	70	12.88	15.22	30.45
	50	18,04	21.31	42.62
	30	30.06	35.52	71.04
LPG	70	12,56	21.60	43.20
	50	17,58	30.24	60.48
	30	29,30	50.40	100.80
Diesel	70	9.08	25.71	51.43
	50	12.71	36.00	72.00
	30	21.18	60.00	120.00

SOURCE K Frederick and J Hanson, Water *for Western Agriculture* (Washington, D C Resources for the Future, 1982)

1970, natural gas continues to be the least expensive means of pumping (table 74). In 1980, natural gas was only half as expensive as electricity, the next least expensive source of energy. Diesel, as a result of rapid price increases in the last 2 years, is now the most expensive fuel.

Electricity accounts for 50 percent of the irrigated acreage served by onfarm pumps, and within the Pacific region virtually all irrigation pumps are electric (table 74). Abundant hydropower is the least expensive fuel in the Pacific Northwest. Electricity is the most important fuel in the Mountain States (74 percent) and accounts for substantial acreage in the Plains States (25 percent). Despite the 15-percent growth in electricity use between 1974 and 1977, expansion has been hindered because many electric utilities are near capacity and unwilling to add new irrigation customers because of peak load problems. One option for such cases might be to limit new customers to pumping during nonpeak hours.

The most rapid growth has been for diesel fuel, which increased by 723 percent between 1974 and 1977, Almost all of this growth came in the northern plains, the only area that uses substantial amounts of this fuel. Under the 1980 fuel costs listed in table 73, little further growth in diesel use is expected. Diesel fuel prices have jumped dramatically since 1978, and supplies have been erratic, especially at vital periods in the growing season.

Use of liquefied petroleum gas (LPG) has been concentrated in the Plains States. Although its use declined from 1974 to 1977, prospects for increased LPG use are good largely because of the supply or price problems with the alternatives. LPG prices have not risen like either diesel or natural gas (table 74), and in late 1979 there was a world surplus of LPG.

IMPROVING WELL EFFICIENCY

A water well is a hole or shaft, usually vertical, drilled or excavated in the earth to bring ground water to the surface. Many methods exist for constructing wells. Selection of a particular method depends on the purpose of the well, the quantity of water required, depth to ground water, geologic conditions, and economic factors. Shallow wells in unconsolidated aquifers, such as sand or gravel, may be dug by hand or machine, bored with an auger or constructed by driving a perforated pipe into the material. Deeper wells, or those completed in consolidated rocks, must be drilled using a cable tool or rotary drill.

Table 74.—Fuels Used for Irrigation (1,000 acres)

Region	Electricity 1974	Electricity 1977	Diesel 1974	Diesel 1977	Natural gas 1974	Natural gas 1977	LPG 1974	LPG 1977
Northern Great Plains	1,573	2,612	1,543	2,914	2,430	3,231	1,553	1,008
Southern Great Plains.	2,007	2,347	151	166	6,742	6,949	509	568
Mountain	4,297	4,500	307	350	1,152	1,104	184	136
Pacific	6,197	6,717	4	9	84	31	0	0
17 Western States	14,074	16,176	2,005	3,439	10,409	11,315	2,246	1,712

SOURCE K Frederick and J Hanson, *Water for Western Agriculture* (Washington, D C Resources for the Future, 1982) (Original source" Gordon Slogget, Energy *and U S Agriculture Irrigation Pumping, 1974-77* AER Report No 436 (Washington, D C U S Department of Agriculture, September 1979)

Photo credit © *Ted Spiegel,* 1982

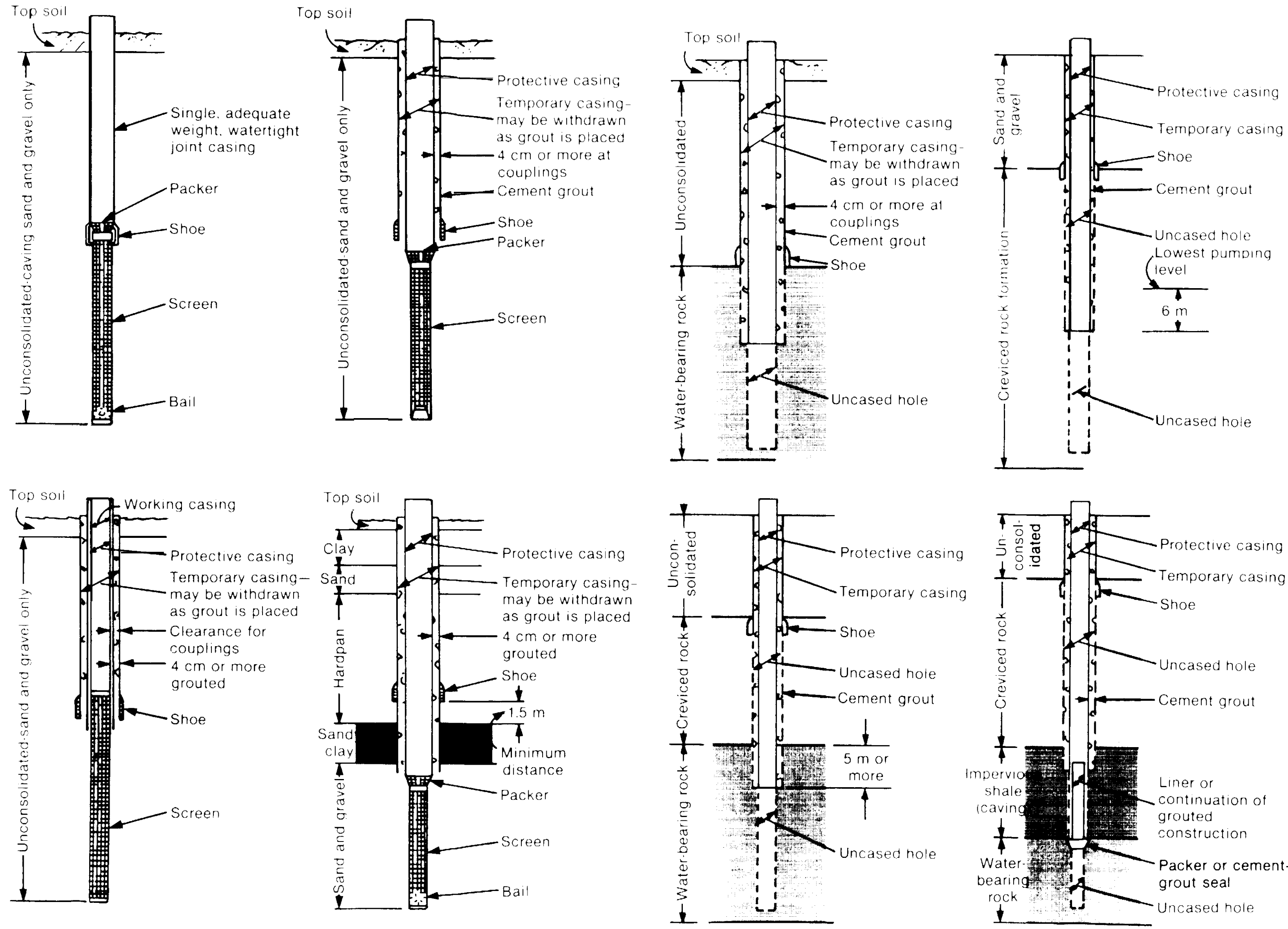
Drillers inspect a forest of the latest waterwell drilling rigs at the Pacific Northwest Exposition of the American Waterwell Association in Reno, Nev.

After a well has been drilled, it must be completed. This can involve the placement of casing, cementing of casing, placement of well screens, and gravel packing (fig. 67), These steps are necessary to ensure the stability of the well walls and to maintain a flow of water into the well through unconsolidated materials, Wells in consolidated rocks can often be left as open holes so that these completion techniques may not be required.

A new well, properly drilled, cased, and developed, should give years of satisfactory service with little attention. Many wells fail, however. They yield less water with time, a situation possibly associated with declining water tables. Yield decreases may also be a result of a faulty pump or poor well-construction techniques. Where the well is a factor, technologies exist that may be used to remedy the problem.

Problems associated with a declining water supply can sometimes be remedied by deepening the well. Where the problem in reduced yields is faulty well construction that involves poor casing connections, improper perforations of the casing, improper screens, incomplete placement of gravel packs, and poorly seated wells, repairs may be possible. Repairs to a well with one of these construction prob-

Figure 67.—Examples of Different Types of Wells



A. Examples of well construction in unconsolidated formations

B. Examples of well construction in consolidated formations

SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980).

lems may cost $8 to $12/ft (estimated), whereas constructing a new well would cost an average of $25/ft (estimated) (4).

The third and most prevalent cause of well failure results from corrosion or incrustation of well screens. These problems are caused by chemical reactions between the well-casing materials and the ground water or by precipitation of materials carried in solution by the ground water. Screens can be cleaned by shooting a string of vibratory explosives in the well or by adding hydrochloric acid to the well to dissolve the incrustation, followed by pumping to agitate and surge the water in the well, Where slime-forming organisms block screens, particularly in recharge wells, treatment with chlorine gas or hypochlorite solutions can remedy the problem. For improving yields of wells drilled in solid rock, concentrated acid solutions or shooting with explosives is often effective.

LIMITS OF TECHNOLOGIES RELATED TO GROUND WATER

Special Characteristics of Ground Water

Ground water has certain characteristics that make its manipulation in any predictable fashion a difficult task. As part of the hydrologic cycle, ground water cannot be managed separately. Any management scheme must recognize that it is inextricably linked to the surface water resources of a region. Those regions that have overcommitted their surface water resources, either from the quantity or quality standpoint, cannot depend on a supply of ‘‘new’ water from ground water supplies. Where surface water supplies are in short supply, it is likely renewable ground water supplies will also be in short supply. Similarly, in the Western United States, those areas with surface water supplies in excess of present requirements have ground water supplies that appear to be recharging naturally at rates at least equal to withdrawal.

Ground water is more diffuse than surface water. Legal and social practices in the past have generally treated ground water as if it existed in discrete underground bodies or streams. In fact, it is widely and unevenly distributed throughout most of the surface rocks of any given region. This characteristic means that the economic costs of ground water development for benefits received will be much higher than for development of the more concentrated surface water bodies.

Technologies designed to affect either the availability or quality of ground water generally must be applied at individual water wells. Thus, they are much more site-specific than are most other water-related technologies discussed in this assessment. This creates a number of unique problems in assessing the nature and degree of potential threats to the resource. Considerable information concerning local geology, recharge conditions, type of well construction, and the well’s intended use is required before these technologies can be used with confidence. Discussion of problems involving more than a single water well involves the extrapolation of well data, using assumptions concerning variations in geology, climate, and other environmental controls. While there will generally be less disagreement among hydrogeologists concerning some of these assumptions and extrapolation techniques, the nonhydrologist may often be at a loss to assess the conclusions accurately.

Complex ground water models have been developed over the past two decades to aid in the evaluation of ground water problems. * However, the use of these models has been restricted to a limited number of specialists. For the most part, ground water information is anecdotal and deals with such local problems as ground water decline, water-quality deterioration, and land subsidence as a result of the

*For an evaluation of methodologies, see the OTA assessment: Use *of Models for Water Resources Management, Planning, and Policy*, 1982.

overuse of ground water. Future management of ground water resources probably will involve the use of such computer simulation models because the behavior of the resource is so complex. This will require the development of a data-collection network for each application site that is much more extensive than that which now generally exists. Data collection and monitoring is a complex process that will strain the economic resources of most communities. It also requires a level of expertise that is rare at levels below that of State or Federal agencies.

Effects of Ground Water Overdrafting

Prolonged ground water overdrafting may lead to one or more undesired results. These include:

- progressive reduction in the total volume of the available ground and surface water supply, since these supplies are connected,
- development of uneconomic pumping conditions as depths increase,
- degradation of ground water quality,
- interference with other water rights as drawdown affects other parts of the aquifer, and
- land subsidence caused by lowered ground water levels.

The technologies to compensate for these effects are limited. There arc no known technologies, for example, to recover water storage space lost by land subsidence or to improve degraded water in aquifers.

It is estimated that ground water overdrafting is occurring in each of the nine major water resources regions of the Western United States (15) (table 75, fig. 68). The extent of this overdrafting, and the ability of affected aquifers to recover in a reasonable time period if present demands are diminished varies widely among these regions. This variation results from the highly complex and variable geology and climate of the region. As early as 1949, Warne "... drew attention to 'trouble spots' throughout the United States where heavy draft upon the water-bearing formations has resulted in the depletion of the underground water at a rapid rate." According to Warne, in 1949 these areas of concern already included "the Central Valley of California, the West Basin southwest of Los Angeles, the High Plains of Texas, south of Amarillo . . . and elsewhere" (3). States where ground water withdrawals are a high percentage of total water use, it can be assumed that problems of sustainability will develop with time.

By definition, ground water overdrafting is nonsustainable, since the water resource is being used at a rate greater than it becomes available. According to the WRC estimates of ground water supply and use in the Western United States, the present (1975) ground water overdraft represents 12 percent of the total water withdrawn from all sources in the Western region and is some 20 million acre-ft annually (15). This is almost 1 1/2 times the annual flow of the Colorado River.

Serious social disruptions may result when economic, social, or environmental systems develop, based on a limited surface/ground water supply. Arguments in favor of ground water mining are commonly economic in nature. It is argued that water in storage is of no value unless it is withdrawn. This argument is valid only to the extent that an infrastructure is not developed based on the limited supplies. As ground water supplies are depleted, surface water supplies commonly also become less available. Ground water becomes increasingly expensive to withdraw as water table levels decline. Ultimately, water must be imported in order to support the water-dependent infrastructure. As economic costs make this increasingly unfeasible, however, those areas may suffer some economic decline.

Two recent examples of this sequence are the Central Arizona Project (CAP) and the Central Valley Project (CVP) in California. A GAO report estimated that the total cost for these two projects, designed to replace water originally mined from local aquifers, would be *approx*imately $5 billion* (197'7 dollars) (13). The

*$1.5 billion for CAP and $3. 5 billion for CVP

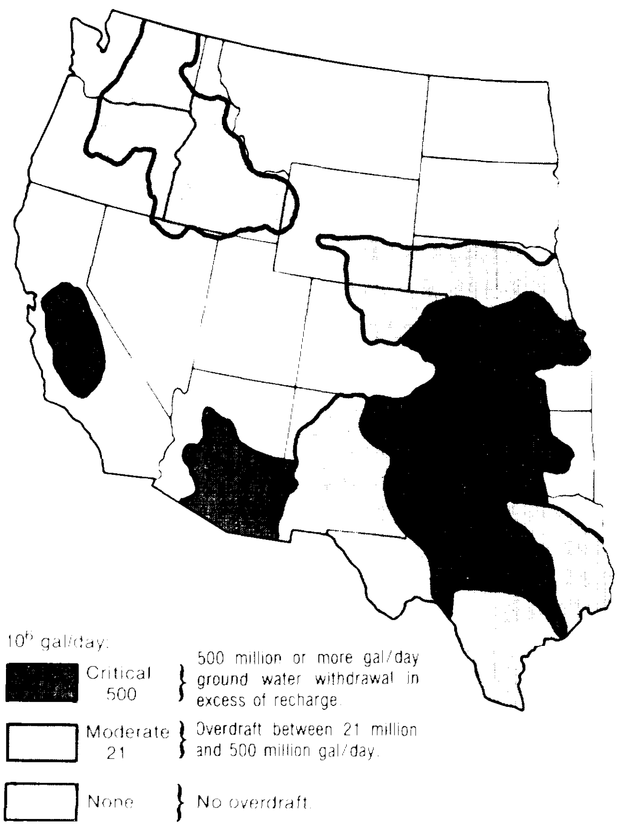
Table 75.—Ground Water Mining in the Western United States

The pressure on total water resources of a region Increase as the percentage of ground water mining Increases.

Region number	Subregion number	Name	Ground water mining as a percentage of annual off stream consumption
10		MISSOURI	17
	03	Missouri-Musselshell	1
	05	Western Dakotas	2
	06	Eastern Dakotas	7
	07	North and South Platte	13
	08	Niobrara-Platte-Loup	13
	09	Middle Missouri	16
	10	Kansas	41
	11	Lower Missouri	5
11		ARKANSAS-WHITE-RED	68
	01	Upper White	2
	02	Upper Arkansas	3
	03	Arkansas-Cimmaron [b]	100
	04	Lower Arkansas	2
	05	Canadian	85
	06	Red-Washita	55
	07	Red-Sulphur	1
12		TEXAS-GULF	50
	01	Sabine-Neches	8
	02	Trinity-Galveston Bay	19
	03	Brazes	78
	04	Colorado (Texas)	38
	05	Nueces-Texas Coastal	26
13		RIO GRANDE	16
	02	Middle Rio Grande	21
	03	Rio Grande-Pecos	46
	04	Upper Pecos	16
	05	Lower Rio Grande	1
15		LOWER COLORADO	53
	01	Little Colorado	7
	02	Lower Colorado Main Stem	27
	03	Gil	61
16		GREAT BASIN	16
	01	Bear-Great Salt Lake	3
	02	Sevier Lake	60
	03	Humboldt-Tonopah Desert	27
	04	Central Lahontan	3
17		PACIFIC NORTHWEST	5
	01	Clark Fork-Kootenai	2
	02	Upper/Middle Columbia	8
	03	Upper/Central Snake	4
	04	Lower Snake	7
	05	Coast-Lower Columbia	2
	07	Oregon Closed Basin	2
18		CALIFORNIA	8
	02	Sacramento-Lahontan	4
	03	San Joaquin-Tulare	10
	05	Central California Coast	10
	06	Southern California	8
	07	Lahontan-South	43

SOURCE K Frederick and J Hanson, Water for Western Agriculture (Washington, DC: Resources for the Future, 1962) (Original source U.S Water Resources Council, **The Nation's *Water Resources*** 1975-2000 (Washington, DC US Government Printing Office, 1978), vol 3, app II, table II-6

Figure 68.— Regions of Ground Water Withdrawal in Excess of Recharge



SOURCE J Bredehoeft 'Physical Limitations on Water Resources in the Arid West paper presented at Impacts of Limited Water for Agriculture in the Arid West Asilomar Calif., Department of Land, Air, and Water Resources, University of California Davis 1982

federally supported CAP will include the construction of canals to carry water from the Colorado River to the cities of Tucson and Phoenix, Ariz. The federally supported CVP is a large multipurpose project in California, consisting of 19I dams and related water conveyance systems and hydroelectric generating plants. The CVP's primary purpose is to provide irrigation water to the Sacramento and San Joaquin Valleys. According to the GAO Comptroller General:

> . . . it appears that the population and economies of the areas (Arizona and California) developed at higher rate than could be supported by the existing water supplly. Once such developments had taken place, crisis-oriented solutions had to be considered which involved large expenditures and which required Federal assistance.

According to a recent study by Resources for the Future* (4) ground water mining has two adverse effects on water costs. First is the increased pumping lift. On a regional or statewide basis, this increase may average not more than 1 to 3 ft a year, generally signifying an annual increase of 1 or 2 percent. On a farm-by-farm basis, however, there is a great deal of variation, and an individual irrigator may face a more rapidly declining water level.

A second effect is the decrease in saturated thickness as the aquifer is mined. As saturated thickness declines, so does well yield. Eventually, additional wells and pumps are needed to maintain the flow. For example, a center-pivot distribution system requires a minimum well yield of 600 gallons per minute (gpm).

At lower yields, farmers must either adopt a new irrigation system requiring fewer gallons per minute, add to the number of wells, or be satisfied with less than optimum coverage. These alternatives tend to increase production costs or decrease crop yields. In Texas, where declines in saturated thickness are especially serious, some farmers have installed eight or nine smaller pumps, each yielding 75 to 150 gpm, to reach adequate output. On farms with a center pivot or other sprinkler system, the decline in the aquifer's saturated thickness and its resulting problems may have a greater impact on water costs than do the increased energy costs resulting from greater pumping lifts.

In addition to other effects, subsidence** is often associated with ground water mining, As the ground water level drops, the bouyancy provided by the water is removed and the individual grains in unconsolidated aquifers move closer together, diminishing the ability of the aquifer to store water and causing the overlying land surface to sink, While there are a number of land use activities that may cause this phenomenon, in the Western United States ground water mining associated with irrigated agriculture has produced the bulk of the existing land subsidence problems.

*An independent, nonprofit economic analysis organization.
**The sink or collapse of the land surfaces.

The effects of subsidence on agriculture have been most extensive in those areas where ground water withdrawal for irrigation is common. For example, water withdrawal in the San Joaquin Valley of California produced subsidence of up to 20 ft by 1967 over an area of 2,500 square miles during 40 years, The gradual lowering of the land surface damaged expensive water-well casings, irrigation systems, buildings, and drainage and flood-control structures, and produced flow direction reversals in irrigation canals. In California's San Jacinto Valley, approximately 5,400 square miles of cropland have subsided at a rate of up to 1.2 ft/per year since measurements began in 1935, In some portions of the Valley, it has reached a total of 28 ft (12). Costs are high for repairing such damage, In California's Santa Clara Valley, subsidence costs during the same period were estimated at $15 million to $20 million.

A similar situation exists in the Texas-Gulf aquifers, where water withdrawals have been primarily for industrial and urban uses. Agricultural lands have been adversely affected by the resulting subsidence, During a 26-year period, 1943 to 1969, in the Houston area, a region some 15 miles in diameter suffered a 2-ft lowering of the surface. An area of about 60 miles, much of it rural land, suffered at least 6 inches of subsidence during the same period. These depressed land surfaces act as closed basins during heavy, hurricane-associated rainfall and thus periodically limit the land's usefulness for crop production.

CONCLUSIONS

Ground water use in the Western United States almost tripled between 1950 and 1975, and the percentage of the total water withdrawn in the region nearly doubled. Much of this increase has been made possible by technologies that have permitted the overdraft, or ''mining, ' of ground water, leading to the noticeable depletion of the resource in many areas. Attempts to recharge these ground water supplies artificially depend on a water surplus during at least some part of each year to use for recharge, In many of the areas most affected by ground water overdraft, the total available renewable water resources are being completely consumed each year.

Water quality is highly variable among the major ground-water resource regions of the Western United States, varying with ground-water recharge rates, rock chemistry, and human waste-disposal practices. With the exception of portions of the Pacific Northwest and eastern Texas, the ground water of the Western States is moderate to very "hard," with high concentrations of calcium and magnesium salts. When water having high levels of these, or any other salts, is brought to the surface and used for irrigation, evaporation losses lead to increases of soil-salinity levels. Irrigation return flows, with high levels of dissolved salts and agricultural chemicals, percolate back into the ground water, producing a further deterioration of the existing water quality.

Once a ground water aquifer becomes contaminated, relatively little can be done to remove or contain the contaminant. A few technologies have been investigated for dealing with ground-water contamination problems, but in general these have been very expensive to implement and have produced uncertain results. * Technologies effective against ground water pollution are those associated with surface and subsurface waste disposal and designed to prevent contaminants from reaching the aquifer. Better control of toxic and noxious substances in surface and subsurface waters will probably remain the only feasible ground water pollution-control technologies in the foreseeable future.

While irrigated agriculture has consumed the largest volumes of ground water in recent dec-

*OTA is currently conducting an assessment on ground water resources entitled: *Technologies To Measure, Monitor, and Mitigate Ground Water Contamination*, estimated delivery date late 1983.

ades in the Western United States, the percentage developed for municipal and industrial uses has become increasingly important. Many Western cities are now dependent on ground water. As ground water resources are degraded by ground water overdraft or quality largely caused by irrigated agriculture, the supplies on which these cities have become dependent also decline in both quantity and quality. While irrigated lands may be shifted to a use of lower value as water levels decline, cities cannot make this transition so easily. The social costs of declining water tables and increasing contamination of ground water resources of the Western United States must be addressed as both an agricultural and a broader social and public health problem. Until more understanding has been gained, the most appropriate ground water technology may be prudent and conservative water-use management.

CHAPTER X REFERENCES

1. Baldwin, H., and McGuiness, C., *A Primer on Ground Water*, U.S. Geological Survey, *1963.*
2. Davis, G., Lofgren, B., and Mack, S., *Use of Ground Water Reservoirs for Storage of Surface Water in the San Joaquin Valley, Calif.*, U.S. Geological Survey Water Supply Paper 1618, 1964.
3. Engineers Joint Council, *Principles of a Sound National Water Policy*, The National water Policy Panel of the Engineers Joint Council, publisher unavailable.
4. Frederick, K., and Hanson, J., *Water for Western Agriculture* (Washington, D. C.: Resources for the Future, 1982).
5. High Plains Associates, *Six-State High Plains Ogallala Aquifer Regional Resources Study, Summary: A Report to the U.S. Department of Commerce and the High Plains Study Council,* July *1982.*
6. High Plains Underground Water Conservation District No. 1 and Texas Department of Water Resources, *A Summary of Techniques and Management Practices for Profitable Water Conservation on the Texas High Plains*, Report 79-01, Lubbock, Tex., 1979.
7. National Water Commission, *Water Policies for the Future* (Port Washington, N, Y.: Water Information Center, Inc., *1973],* pp. 227-247.
8. Richter, R. C., and Chun, R. Y. D., "Artificial Recharge of Groundwater Reservoirs in California," *Jour. of the Irrig. Drain. Div.,* Am. Soc. Civil Engs., vol. **85, No.** IR4, 1959, pp. *1-27.*
9. Schoeller, H., "Arid Zone Hydrology, Recent Developments, UNESCO Arid Zone Research, 1959, in R. Ward, *Principles of Hydrology* (London: McGraw-Hill, 1975), p. *196.*
10. Todd, D., *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., *1980).*
11. U.S. Committee on Irrigation, Drainage and Flood Control, International Commission on Irrigation and Drainage, "Development of Techniques to Recharge Subterranean Aquifers to Conserve Surplus River Flows in the United States, " *Symposium of Athens, 1978,* pp. S2-S23.
12. U.S. Congress, Office of Technology Assessment, *Impacts of Technology on U.S. Cropland and Rangeland Productivity* (Washington, D. C.: U, S. Government Printing Office, OTA-F-166, August 1982).
13. U.S. General Accounting Office, "Ground Water: An Overview, " *1977.*
14. U.S. General Accounting Office, *Better Monitoring Techniques Are Needed to Assess the Quality of Rivers and Streams, vol. 1,* **1981.**
15. U.S. Water Resources Council, *The Nation Water Resources* **1975-2000,** *2nd National Water Assessment* (Washington, D. C.: U.S. Government Printing Office, 1978).