

um-137 through a sand aquifer demonstrated the use of several kinds of chemical and transport models. The rate of movement observed for strontium-90 was about 3 percent, and the rate of cesium-137 movement, about 0.3 percent of the ground-water movement rate in that system.

In surface-water systems the bulk of the water moves much more rapidly than in the systems cited above. However, the modeling of solute transport in such systems is complicated by the additional effect of a moving solid phase (suspended and bed sediment) interacting with solutes, as well as by much more important photochemical and biochemical factors.

As noted in earlier sections of this book dealing with chemical equilibrium, solids that participate in an equilibrium are usually assumed to be at standard state (activity=1). Therefore, models using equilibrium assumptions are somewhat limited in their capacity to evaluate systems in which the changing nature and quantity of participating solids at various places in the system is a matter of concern.

In those ground-water systems in which chemical processes may represent a more sensitive aspect of the model than physical transport, the appropriate models to use may be those in which chemical rather than physical processes are emphasized. Wigley and others (1978) and Plummer and Back (1980) demonstrated that one can describe flow rates in regional limestone aquifer systems and can develop much other information on their hydrologic properties by studies of major element chemistry, mass balances, and isotopic distributions. The principles used in these models were reviewed by Plummer and others (1983).

In theory, at least, the modeling of solute behavior in a carbonate system can be based on fairly simple equilibrium chemistry. The modeling of reactive solutes in granular aquifer material is a much more difficult task, and one that has by no means been reduced to a routine exercise.

The development of a mathematical model that has predictive usefulness is a substantial contribution to applied hydrologic science, but it is necessary to tailor the model to the specific system to which it is to be applied. *A proper perspective needs to be maintained, for some evaluations of hydrologic systems can be made with less detailed models than others.* The term "model" need not imply a massive computer-programmed approach. In any event, a conceptual model laid out in rather simple terms must always precede it. The more detailed model is then developed to fulfill the requirements of the study.

RELATION OF QUALITY OF WATER TO USE

An immediate purpose of the usual quality-of-water study is to determine if the water is satisfactory for a proposed use. Accordingly, the subject of water-analysis interpretation must often include some consideration of

standards and tolerances that have been established for water that is to be used for various purposes. Standards for water to be used for drinking and other domestic purposes have been established in many countries. Published literature contains tolerance levels and related data for constituents of water to be used in agriculture, in industry, for propagation of fish, and for a number of other specific purposes.

Water that is to be used as a public supply may be employed for many purposes. Therefore, the standards used to evaluate the suitability of water for public supply generally are more restrictive than those that would be applied to water for a small domestic or farm supply, although not necessarily more rigorous for individual components than the limits that apply for many industrial uses.

Water from mineral and hot springs is used medicinally in many places, and the mystic qualities of natural warm springs have been of great interest to man since prehistoric time. Medicinal uses have been summarized by Licht (1963) and will not be considered here.

An extensive survey of water-quality standards and review of the literature on the effects of solutes on uses of water was prepared by McKee and Wolf (1963). More recently, the U.S. Environmental Protection Agency sponsored a thorough study of water-quality and water-use interrelationships by a committee named by the National Academy of Science (NAS-NAE, 1972). Water uses for which standards were suggested include (1) recreation and aesthetics, (2) public water supplies, (3) freshwater aquatic life and wildlife, (4) marine aquatic life and wildlife, (5) agricultural uses, and (6) industrial water supplies. The subject can be considered only rather briefly here.

Domestic Uses and Public Supplies

Besides being chemically safe for human consumption, water to be used in the home should be free of undesirable physical properties such as color or turbidity and should have no unpleasant taste or odor. Harmful micro-organisms should be virtually absent; however, they are not usually considered in ordinary chemical analyses. The presence of harmful micro-organisms is considerably more difficult to ascertain than most other properties of water, but it is a highly important consideration. Over the years, great progress has been made in decreasing the incidence of waterborne disease, especially typhoid fever and cholera, and in the United States these two diseases have become rare.

Filtration of water taken from surface-water sources and disinfection, usually by addition of chlorine, have been the most effective means of controlling harmful organisms. In recent years increasing attention has been given to the occurrence in water of the protozoan *Giardia lamblia*, which can cause intestinal disturbances (giardia-

sis). This organism can be transported in an inactive cyst form that is resistant to chlorine (Lin, 1985). It is thought that waterborne giardiasis has become the most common waterborne disease in the United States (Lin, 1985).

The standard sanitary test for bacteriologic quality is the determination of total coliform bacteria concentration. The common species *Escherichia coli* occurs in great numbers in the intestinal tracts of warmblooded animals, and the presence of these and related bacteria in water is generally considered an index of fecal pollution. The coliform bacilli are not themselves directly harmful, but their presence in excessive numbers is considered suggestive of the possible presence of other species that are pathogenic. Although direct determination of pathogens is often advocated, the problems involved are large, and the substitution of such determinations for the simple coliform count is not likely to occur. As noted above, the sanitary condition of a water is not indicated by chemical testing alone. Thus, a water that is safe for drinking on the basis of its chemical composition may not be safe bacteriologically. This subject is not considered in detail here. Standards for the sanitary condition of public water supplies have been set and enforced at State or local governmental levels in the United States in past years. More recently, an increasing Federal involvement in establishing water-quality standards and arranging for their enforcement has developed.

Mandatory standards for dissolved constituents believed to be harmful to humans were first established in the United States in 1914 by the U.S. Public Health Service. These standards applied only to water used for drinking or preparing food in interstate common carriers. The standards were revised several times in ensuing years and were widely recognized as defining a safe water supply. However, they did not have a legal status except for water used in interstate commerce. This situation changed during the 1970's with passage of Federal legislation (1974 Safe Drinking Water Act). Standards for inorganic constituents in public water supplies that became effective in 1977 are given in tables 24 and 25. Concentrations indicated are not to be exceeded in water furnished to the public by water utility systems. The limits given are similar to those in the earlier (U.S. Public Health Service, 1962) standards and generally are similar to standards in other countries and recommended by the World Health Organization (1971). They generally follow recommendations given in the previously mentioned publication "Water Quality Criteria, 1972" (NAS-NAE, 1972). These interim standards are to be succeeded sometime in the future by more comprehensive standards.

When water supplies are found to exceed the limits given in tables 24 and 25, remedial action is required. Technology available for removal of the substances was summarized by Sorg (1978, 1979), by Sorg and Logsdon (1978, 1980), and by Sorg and others (1978). For some

solutes in these standards, notably nitrate nitrogen, removal by treatment processes may be impractical, and new sources of water may be required.

Besides the mandatory limits given in table 24, the 1962 U.S. Public Health Service standards (U.S. Public Health Service, 1962) also included secondary limits which were to be followed unless no better quality supply was available. Some of the constituents in this list are considered objectionable because they have undesirable physical effects, such as staining of laundry or scaling of water heating units, and none were thought to be health related. The limits for these substances are given in table 26 along with corresponding "potable water-quality goals" recommended by the American Water Works Association (American Water Works Association, 1981, p.71).

Table 24. National Interim Primary Drinking Water Regulations (U.S. Environmental Protection Agency, 1976)

Contaminant	Maximum contaminant level (mg/L, or as indicated)
Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd) .....	.01
Chromium (Cr) .....	.05
Lead (Pb) .....	.05
Mercury (Hg) .....	.002
Nitrate (as N)	10
(as NO ₃)	44
Selenium (Se) .....	.01
Silver (Ag) .....	.05
Radium-226 and -228 (Ra)	5 pCi/L
Gross alpha activity	15 pCi/L
Gross beta activity	4 millirem/yr ¹

¹Based on 2-L/d drinking-water intake except for tritium and strontium-90. Average annual concentrations for these elements that are assumed to result in 4-millirem/yr exposure are ⁹⁰Sr=8 pCi/L and ³H=20,000 pCi/L.

Table 25. National Interim Primary Drinking Water Regulations—Fluoride

Average annual maximum temperature		Maximum fluoride concentration (mg/L)
°F	°C	
53.7 or less	12.0 or less	2.4
53.8 - 58.3	12.1 - 14.6	2.2
58.4 - 63.8	14.7 - 17.6	2.0
63.9 - 70.6	17.7 - 21.4	1.8
70.7 - 79.2	21.5 - 26.2	1.6
79.2 - 90.5	26.3 - 32.5	1.4

In many areas of the United States the American Water Works Association goals for dissolved solids are not attainable, and in some places all available water supplies exceed 500 mg/L in dissolved solids. As a matter of fact, residents of some areas have used water containing more than 1,000 mg/L of dissolved solids all their lives. Although detailed medical data are not available, there do not seem to be any obvious detrimental effects on public health that can be attributed to such water supplies. Some of the undesirable impurities listed in the tables may be ingested in larger quantities from sources in the diet other than drinking water. The limits given in table 24, however, refer to substances known or thought to be toxic at low concentrations and should be followed as closely as possible.

The limits for radioactive substances in drinking water are viewed somewhat differently from those for nonradioactive solutes. It is generally agreed that the effects of radioactivity are harmful, and unnecessary exposure should be avoided. The limits given in table 24 are particularly strict for radium and for strontium-90.

Strontium-90 is a fission product, but radium occurs naturally and in some waters may exceed the limit. Both nuclides are preferentially absorbed in bone structure and are, therefore, especially undesirable in drinking water.

The lower limit of detection of solutes in water by taste is, of course, a function of individual sensitivity. Some substances can be detected in very low concentrations, however. Certain organic compounds impart taste when present at very low levels, and the taste and odor may be intensified by chlorination. Chlorophenols impart a noticeable taste when only a few micrograms per liter are present (Burttschell and others, 1959). Free-chlorine concentrations of a few tenths of a milligram per liter are

usually noticeable, also. On the other hand, many common solute ions cannot be detected by taste until concentrations of tens or even hundreds of milligrams per liter are attained. Chloride concentrations of 400 mg/L impart a noticeable salty taste for most people. Users may become accustomed to waters containing high concentrations of major ions, however, and prefer the taste of such water to the "tastelessness" of more dilute solutions.

A considerable literature exists on the subject of taste effects in drinking water. Taste thresholds for zinc, copper, iron, and manganese were explored by Cohen and others (1960). Bruvold and others (1967) made a statistical study of consumer attitudes toward tastes imparted by major ions.

The possible hazards presented by organic compounds that are in solution in drinking water are incompletely known or understood. Recently, techniques have been developed that are capable of detecting specific compounds at nanogram-per-liter concentrations, and a list of compounds that might be considered particularly undesirable has been proposed (Keith and Telliard, 1979). The actual establishment of limits had not been done by the end of 1984, however. This topic is considered further in the section "Synthetic Organics."

Among the classes of compounds that have been thought to be particularly undesirable are chlorinated or brominated hydrocarbons. It has been shown that compounds of this type are synthesized when water containing naturally derived organic material is chlorinated for disinfection.

The water-supply industry of the United States is justifiably proud of the fact that waterborne disease has been brought to an extremely low level of incidence in this country, and the practice of chlorination of water supplies has played an important role in this. Substitution of other disinfecting processes to minimize the still-uncertain risk of chlorinated hydrocarbons remains a rather warmly debated issue.

Some waters are corrosive toward metals in pipelines and water tanks, and as a result the water from the user's tap may at times be excessively high in lead, zinc, copper, cadmium, iron, or other metals. The extent to which this may represent a health problem is not well known because information on metal content of water actually consumed by the final users is sparse.

Damage to plumbing done by corrosive water represents a major expense to utilities and water users. Properties of water that might indicate its potential for corrosive effects are not generally considered in setting water quality criteria, and the whole subject of corrosion of metals by water remains inadequately understood. A review by Singley (1981) described a few past efforts to devise indices of corrosivity for water supplies.

Table 26. Nonmandatory standards and goals for dissolved substances

Substance	USPHS standard ¹ (mg/L)	AWWA potable water quality goals ² (mg/L)
Aluminum (Al)		<0.05
Chloride (Cl)	250	.....
Copper (Cu)	1.0	<.2
Iron (Fe) .....	.3	<.05
Manganese (Mn) .....	.05	<.01
Sulfate (SO ₄)	250	.....
Zinc (Zn)	5	<1
Total dissolved solids	500	<200
Total hardness		80

¹U.S. Public Health Service (1962).

²American Water Works Association (1981, p. 71).

Agricultural Use

Water required for nondomestic purposes on farms and ranches includes that consumed by livestock and that used for irrigation.

Water to be used by stock is subject to quality limitations of the same type as those relating to quality of drinking water for human consumption. Most animals, however, can tolerate water that is considerably higher in dissolved-solids concentration than that which is considered satisfactory for humans. There are few references in published literature that give maximum concentrations for water to be used for livestock. Range cattle in the Western United States may get accustomed to highly mineralized water and can be seen in some places drinking water that contains nearly 10,000 mg/L of dissolved solids. To be used at such a high concentration, however, these waters must contain mostly sodium and chloride. Water containing high concentrations of sulfate are much less desirable. An upper limit of dissolved solids near 5,000 mg/L for water to be used by livestock is recommended by some investigators, and it would seem obvious that for best growth and development of the animals their water supply should have concentrations considerably below the upper limit.

In the report by McKee and Wolf (1963), the upper limits of concentration for stock water include the following:

<i>Stock</i>	<i>Concentration (mg/L)</i>
Poultry	2,860
Pigs	4,290
Horses	6,435
Cattle (dairy)	7,150
Cattle (beef)	10,100
Sheep (adult)	12,900

These, in turn, were quoted from a publication of the Department of Agriculture of Western Australia. The 1972 Water Quality Criteria (NAS-NAE, 1972) give similar but somewhat lower maximum concentrations for major ions.

"Water Quality Criteria, 1972" also quotes limits for most of the minor elements listed in table 24 and for some others. Most of these suggested limits are well above values likely to be encountered in natural potable water except for fluoride, for which an upper limit of 2.0 mg/L is recommended. It is interesting to note that this is below the maximum fluoride limit listed in table 25 as tolerable for water for human consumption.

The chemical quality of water is an important factor to be considered in evaluating its usefulness for irrigation. Features of the chemical composition that need to be considered include the total concentration of dissolved matter in the water, the concentrations of certain potentially toxic constituents, and the relative proportions of some of the constituents present. Whether a particular

water can be used successfully for irrigation, however, depends on many factors not directly associated with water composition. A brief discussion of some of these factors is included here to show the complexity of the problem of deciding whether or not a given water is suitable. Readers interested in the subject can find more information in the other publications to which reference is made.

The part of the irrigation water that is actually consumed by plants or evaporated is virtually free of dissolved material. The growing plants do selectively retain some nutrients and a part of the mineral matter originally dissolved in the water, but the amount of major cations and anions so retained is not a large part of their total content in the irrigation water. Eaton (1954, p. 12) determined the quantity of mineral matter retained by crop plants and showed that it consists mostly of calcium and magnesium salts. The bulk of the soluble material originally present in the water that was consumed remains behind in the soil, normally in solution in residual water. The concentration of solutes in soil moisture cannot be allowed to rise too high because excessive concentrations interfere with the osmotic process by which plant root membranes are able to assimilate water and nutrients. Some substances of low solubility, especially calcium carbonate, may precipitate harmlessly in the soil as solute concentrations are increased, but the bulk of the residual solutes presents a disposal problem that must be solved effectively to maintain the productivity of irrigated soil. The osmotic processes by which plants are able to absorb water through their roots are discussed in the section titled "Membrane Effects."

The extent and severity of salt-disposal problems in irrigated areas depend on several factors. Among these factors are the chemical composition of the water supply, the nature and composition of the soil and subsoil, the topography of the land, the amounts of water used and the methods of applying it, the kinds of crops grown, the climate of the region, especially the amount and distribution of rainfall, and the nature of the ground-water and surface-water drainage system.

In most areas, the excess soluble material left in the soil from previous irrigations is removed by leaching the topsoil and permitting part of the resulting solution to percolate below the root zone and thence to move downward toward the ground-water reservoir. In areas where the water table beneath the irrigated land can be kept far enough below the surface, this process of drainage is reasonably effective. The necessary leaching may be accomplished by rainfall in areas where the precipitation is sufficient to saturate the soil deeply. The leaching process also occurs during the irrigation season, either with this purpose specifically in mind or when extra amounts of water are added in an effort to store an extra supply of water in the soil or to use unusually large

supplies of water that happen to be available. The need for leaching the soil is generally recognized by farmers who use highly mineralized irrigation water.

In areas where natural drainage is inadequate, the irrigation water that infiltrates below the root zone eventually will cause the water table to rise excessively, a process resulting in serious problems. "Seeped" (waterlogged) land in which the water table is at or near the land surface has become common in many irrigated areas of the United States and elsewhere. Such land has little value for agriculture but often provides a site for water-loving vegetation. Transpiration by such vegetation and direct evaporation from wet soil and open water surfaces can result in waste of large and economically significant quantities of water; also, the soil in such areas soon becomes highly charged with residual salts.

Although waterlogged areas generally have extensive saline accumulations, the quality of the water available was not always the primary cause of abandonment of the land. The reasons for failure of ancient irrigation enterprises include some things unrelated to water-management practices. According to Eaton (1950), however, failure to provide proper drainage to remove excess water and solutes must have played a large part in the decline of areas along the Tigris and Euphrates Rivers in what is now Iraq and may have been important elsewhere, also.

In most large irrigated areas it has become necessary to provide some means of facilitating the drainage of ground water so that the water table is held well below the land surface. In some areas this is accomplished by systems of open drainage ditches or by buried tile systems. In many places, the excess ground water is pumped out by means of wells. The extracted drainage water is higher in dissolved-solids concentration than the original irrigation water, owing to the depletion of the water itself and the leaching of soil and subsoil of saline material, fertilizers, and soil amendments. The concentration of solutes in the drainage water, however, is commonly small enough that the water can be reused for irrigation. In areas of intensive development, several such cycles can occur before the water is finally released.

For long-term successful operation of an irrigation project, all the ions present in the irrigation water that were not extracted by plants must be disposed of either by flowing away from the area in drainage or by storage in an innocuous form within the area. The relationship among total ion loads in an irrigated area can be expressed in terms of the ion inflow-outflow or salt-balance equation:

$$W_1 - W_0 \pm \Delta W_s = 0.$$

In this equation, the W_1 and W_0 terms represent total ion

loads into and out of the area over a finite time period, and the ΔW_s term represents the change in storage within the area during that period. Although this equation tends to obscure the importance of the time factor and is certainly an oversimplification, it has frequently been used to evaluate the performance of irrigation developments.

Scofield (1940) termed this general relationship the "salt balance" and made calculations of solute inflow and outflow on the basis of streamflow and water analyses. Scofield did not attempt to evaluate changes in ion storage except to term the salt balance unfavorable when storage was increasing and favorable when it was decreasing.

In the more highly developed irrigated areas where most of the water comes from a surface supply, as along the Rio Grande from the San Luis Valley in Colorado to Fort Quitman, Tex., and along the Gila River and its tributaries in Arizona, the drainage water returned to the stream by the upper irrigated areas is used again for irrigation in the next area downstream. The cycle of use and reuse may be repeated six times or more until the residual drainage is too small in quantity and too saline to have any further value.

Deterioration of ground-water quality associated with irrigation development is commonly observed. Moreover, the rate of deterioration is increased when water pumped from wells for drainage is reused in the vicinity for irrigation, for this practice increases the intensity of recycling and converts part of what would have been ion outflow into stored ions. If large amounts of water are pumped, the ground-water circulation pattern in the affected area may come to resemble a closed basin having no outflow. Obviously, the result of such overdevelopment will be ground water too saline for continued use for irrigation. The rates of movement of solutes through systems of this kind, however, are generally not well enough understood to permit a prediction of how long a period of time might be required to attain that result. In some areas the decline of the water table from pumping may be more rapid than the rate at which residual solutes move downward from the soil zone. Abandonment of ground-water-irrigated areas in the United States in recent years has generally been brought about by declining water levels, which resulted in decreased yields from wells. As energy costs have climbed, this decreased yield makes the cost of water from this source uneconomic.

Besides the general increase in major solute ion concentrations that irrigation drainage may cause in ground water underlying irrigated land, there may be additions of specific solutes that are undesirable. A major problem in some irrigated regions has been the increasing concentration of nitrate in ground water that has received drainage from fertilized irrigated fields. Some types of

pesticides also may persist in drainage water. The occurrence of selenium in irrigation drainage was noted in a preceding section of this book "Minor and Trace Constituents."

The need for consideration of details of the processes and concepts involved in the salt-balance equation is obvious. The storage term in the equation includes material held in the soil and subsoil, that in the saturated zone, and that in the material between. It includes dissolved ions and initially dissolved material that has precipitated as sparingly soluble minerals, as well as ions held by adsorption on mineral surfaces. The length of time required for a given addition to the storage term to be felt as a change in salinity of some specific fraction of the water supply can be estimated only when rates of the processes involved are approximately known. Some fairly sophisticated attempts to model solute circulation through irrigated areas have been made. A study of this type by Orlob and Woods (1967) pointed up the need for more information to improve ability to predict the effect of changes in water use on the quality of residual water. A digital computer model for an irrigated area in the Arkansas River valley in Colorado was developed by Konikow and Bredehoeft (1974). This model incorporated both hydrologic and water-quality parameters and was used to evaluate effects of hydrologic stress on total-solute concentrations in ground water and surface drainage.

The conservation of irrigation water by using the

smallest possible quantity runs the risk of encouraging solute accumulation. Water conservation is, of course, a desirable goal, but the need for solute removal must not be overlooked.

Dry-land agriculture is not without problems of salinity. In parts of the Northern Plains of the United States and adjacent areas of Canada, for example, grain crops are grown successfully by allowing lands to lie fallow in alternate years. Moisture from rain and snowmelt is partly conserved in the fallow ground for use by the crop in the succeeding year. In places this stored moisture has mobilized soluble material and issues from hydraulically favorable sites as saline seeps in which the water may contain high solute concentrations (Thompson and Custer, 1976).

In addition to problems caused by excessive concentrations of dissolved solids, certain constituents in irrigation water are especially undesirable, and some may be damaging even when present in only small concentrations. One of these constituents that has received considerable attention is boron. This element is essential in plant nutrition and is sometimes added to fertilizer in small amounts because some soils in humid regions are deficient in boron. A small excess over the needed amount, however, is toxic to some types of plants.

Work done around 1930 by the U.S. Department of Agriculture showed that the plants most sensitive to excess boron included citrus fruit trees and walnut trees.

Table 27. Relative tolerance of crop plants to boron

[In each group, the plants first named are considered more sensitive, and the last named more tolerant. After U.S. Dept. of Agriculture Handbook 60 (U.S. Salinity Laboratory staff, 1954)]

Sensitive	Semitolerant	Tolerant
Lemon	Lima bean	Carrot
Grapefruit	Sweetpotato	Lettuce
Avocado	Bell pepper	Cabbage
Orange	Pumpkin	Turnip
Thornless blackberry	Zinnia	Onion
Apricot	Oat	Broadbean
Peach	Milo	Gladiolus
Cherry	Corn	Alfalfa
Persimmon	Wheat	Garden beet
Kadota fig	Barley	Mangel
Grape (Sultanina and Malaga)	Olive	Sugar beet
Apple	Raggedrobin rose	
Pear	Fieldpea	Palm (<i>Phoenix canariensis</i>)
Plum	Radish	Date palm (<i>P. dactylifera</i>)
	Sweetpea	Athel (<i>Tamarix aphylla</i>)
American elm		Asparagus
Navy bean	Tomato	
Jerusalem-artichoke	Pima cotton	
Persian (English) walnut	Acala cotton	
Black walnut	Potato	
Pecan	Sunflower (native)	

Later work summarized by the U.S. Salinity Laboratory Staff (1954) is shown in part in table 27. The Salinity Laboratory also developed a rating table that indicates the permissible boron concentrations in irrigation water for three classes of plants (table 28).

The toxicities of other minor constituents of irrigation water generally have received less attention than boron. However, experiments with plants growing in nutrient solutions and in test plots have shown that certain other elements may be damaging to plants, even in very low concentrations (NAS-NAE, 1972, p. 338-345). Some of these elements, notably molybdenum, selenium, and cadmium, may accumulate in plant tissues and cause toxicity when the plants or seeds are consumed by animals. Lithium in water in small concentrations (0.06 to 0.10 mg/L) has been shown to be damaging to citrus trees (Bradford, 1963).

The term "alkali" is commonly used throughout the Western United States to refer to efflorescent deposits of white material or salt crusts that appear where water evaporates from soil surfaces. The word does not necessarily imply anything about the composition of the material. In some irrigated soils, patches of dark-colored alkali are present, and this material is commonly called black alkali. The dark color is caused by organic material leached from the soil. Black alkali is mostly sodium carbonate, and soil where it occurs has a high pH along with other undesirable properties. White alkali deposits commonly are predominantly sodium sulfate and chloride but may also contain calcium and magnesium. Soils of high salinity interfere with crop growth, and a high pH may decrease the solubility of some essential elements.

The process of cation exchange already has been discussed. It occurs in irrigated soil and may influence soil properties, especially when concentrations of solutes are high. An irrigation water having a high proportion of sodium to total cations tends to place sodium ions in the exchange positions on the soil-mineral particles, and water having mostly divalent cations reverses this process. The particles in the soil having the highest exchange capacity per unit weight are the clay minerals. These minerals preferentially adsorb divalent ions, and when their exchange sites are occupied by calcium and magne-

sium, the physical properties of the soil are optimal for plant growth and cultivation. If the exchange positions become saturated with sodium, however, the soil tends to become deflocculated and impermeable to water. A soil of this type is difficult to cultivate and may not support plant growth.

The cation-exchange process is reversible and can be controlled either by adjusting the composition of the water, when this is possible, or by using soil amendments. The condition of a sodium-saturated soil can be improved by applying gypsum, which releases calcium to occupy exchange positions. The soil also may be treated with sulfur, sulfuric acid, ferrous sulfate, or other chemicals that tend to lower the pH of the soil solution. The lower pH brings calcium into solution by dissolving carbonates or other calcium minerals.

The tendency of a water to replace adsorbed calcium and magnesium with sodium can be expressed by the sodium-adsorption ratio, which has been discussed in the section titled "Sodium-Adsorption Ratio (SAR)."

Investigators agree that deposition of some of the dissolved ions in irrigation water can occur as a result of concentration effects and related changes and that some of the calcium and bicarbonate can be expected to precipitate as calcium carbonate. Such a reaction might be considered a form of ion storage in the salt-balance equation. Doneen (1954) pointed out that gypsum also could be deposited from irrigation water without doing any harm to soils. Neither of these precipitation reactions can be expected to remove all the ionic species involved, and rather than make arbitrary subtractions of these ions from inflow or outflow terms in the salt-balance equation, as most writers have done, it might be better to incorporate them into the storage term. A working salt-balance equation complete enough to have practical usefulness should contain a storage term that includes a number of different components, including the precipitates.

In considering the effects that might follow from precipitation of carbonates from irrigation water, Eaton (1950) suggested that if much of the calcium and magnesium originally present were precipitated, the residual water would be considerably higher in proportion of sodium to the other cations than it had been originally.

Table 28. Rating of irrigation water for various crops, on the basis of boron concentration in the water

Rating	Class of water		Sensitive crops (mg/L)	Semitolerant crops (mg/L)	Tolerant crops (mg/L)
		Grade			
1	Excellent	.....	<0.33	<0.67	<1.00
2	Good	.....	.33-0.67	.67-1.33	1.00-2.00
3	Permissible	.....	.67-1.00	1.33-2.00	2.00-3.00
4	Doubtful	.....	1.00-1.25	2.00-2.50	3.00-3.75
5	Unsuitable	.....	>1.25	>2.50	>3.75

Some waters in which the bicarbonate content is greater than an amount equivalent to the total of the calcium and magnesium could thus evolve into solutions containing mostly sodium and bicarbonate and would have a high pH and a potential for deposition of black alkali.

Although the relationships suggested above are somewhat oversimplified, the U.S. Salinity Laboratory Staff (1954, p. 75) made studies showing that some additional hazard does exist when waters high in bicarbonate and low in calcium are used for irrigation. It was proposed, therefore (U.S. Salinity Laboratory Staff, 1954, p. 81), that waters containing more than 2.5 meq/L of residual sodium carbonate are not suited for irrigation, that those containing 1.25–2.5 meq/L are marginal, and that those containing less than 1.25 meq/L are probably safe. (Residual sodium carbonate is defined as twice the amount of carbonate or bicarbonate a water would contain after subtracting an amount equivalent to the calcium plus the magnesium.)

The residual sodium carbonate concept appears to ignore two major factors in the chemical behavior of carbonate species that must have some influence. As pointed out in earlier sections of this book, calcium carbonate tends to precipitate independently and thus leaves magnesium in solution. Although the conditions in irrigated soils might favor deposition of mixed carbonates, their existence does not seem to have been demonstrated. A more recent paper by Eaton and others (1968) suggested that precipitation of magnesium might occur by combination with silica. The second factor is the production of carbon dioxide in the soil by plants. This is a major source of bicarbonate ions and in some irrigated soils may provide much more of this material than the irrigation water originally contained.

From this brief discussion it should be evident that the relationships between water quality and the feasibility of using water for irrigation are not simple. Increasing difficulties that can be expected as salinity of the water supply increases could be translated into economic effects. A decrease in crop yield accompanied by increased costs in water and land management occurs as the water becomes less suitable.

Generalizations regarding sensitivity of crops to salinity of water supply were made by the U.S. Salinity Laboratory Staff (1954, p.67). A list of crops arranged in three groups with respect to their tolerance toward salinity shows that, generally, crops tolerant to boron also are tolerant to salinity. According to this list, the more sensitive species include fruit trees and beans and the more tolerant include the date palm, asparagus, beets, Bermuda grass, cotton, sugar beets, and barley. Most vegetables and field and forage crops are included in the moderately tolerant group.

A diagram widely used for evaluating waters for irrigation, published by the U.S. Salinity Laboratory

(1954, p.80), is reproduced in figure 51. Specific conductance, as an index of dissolved-solids concentration, is plotted on one axis, and the sodium-adsorption ratio on the other. The diagram is divided into 16 areas that are used to rate the degree to which a particular water may give rise to salinity problems and undesirable ion-exchange effects in soil.

Water having a specific conductance greater than 5,000 $\mu\text{mho/cm}$ is used with some success in certain areas, where soil conditions, crops grown, and irrigation techniques are suitable. The hydrologist needs to consider local experience before arbitrarily stating whether a given water is usable or not. Salinity problems, however, may be slow to develop and may be observable only in decreased crop yields or in other respects less easy to evaluate. A water of high salinity must always be viewed with suspicion until proof of its safety for a specific use is obtained.

Industrial Use

The quality requirements for industrial water supplies range widely, and almost every industrial application has its own standards. For some uses such as single-pass condensing of steam or for cooling or for concentrating ores, chemical quality is not particularly critical and almost any water may be used. At the opposite extreme, water approaching or equaling the quality of distilled water is required for processes such as the manufacture of high-grade paper or pharmaceuticals, where impurities in the water would seriously affect the quality of the product. Modern maximum-pressure steam boilers may require makeup water less concentrated than the average distilled water of commerce, and very pure water is desirable in nuclear reactors to minimize radioactivity induced by neutron activation of the dissolved species.

It is not the purpose of this book to review the subject of industrial water-quality standards in any detail. Some idea as to the varied nature of the requirements for certain industries can be obtained from table 29. This table is based on data presented by the U.S. Federal Water Pollution Control Administration (1968). Additional consideration of industrial water-quality requirements was given by McKee and Wolf (1963). The NAS-NAE (1972) publication "Water Quality Criteria, 1972" includes a section on industrial water that describes both quality and quantity requirements.

The standards given in table 29 represent maximum values permitted in the water at the point of use, after any necessary treatment but before adding any internal conditioners that may be needed during the process. The increasing stringency of requirements for boiler-feed water as the steam pressure increases is particularly noticeable. The absence of an entry in the table indicates either that no limit for the constituent or characteristic has been given or that the constituent cannot attain objectionable

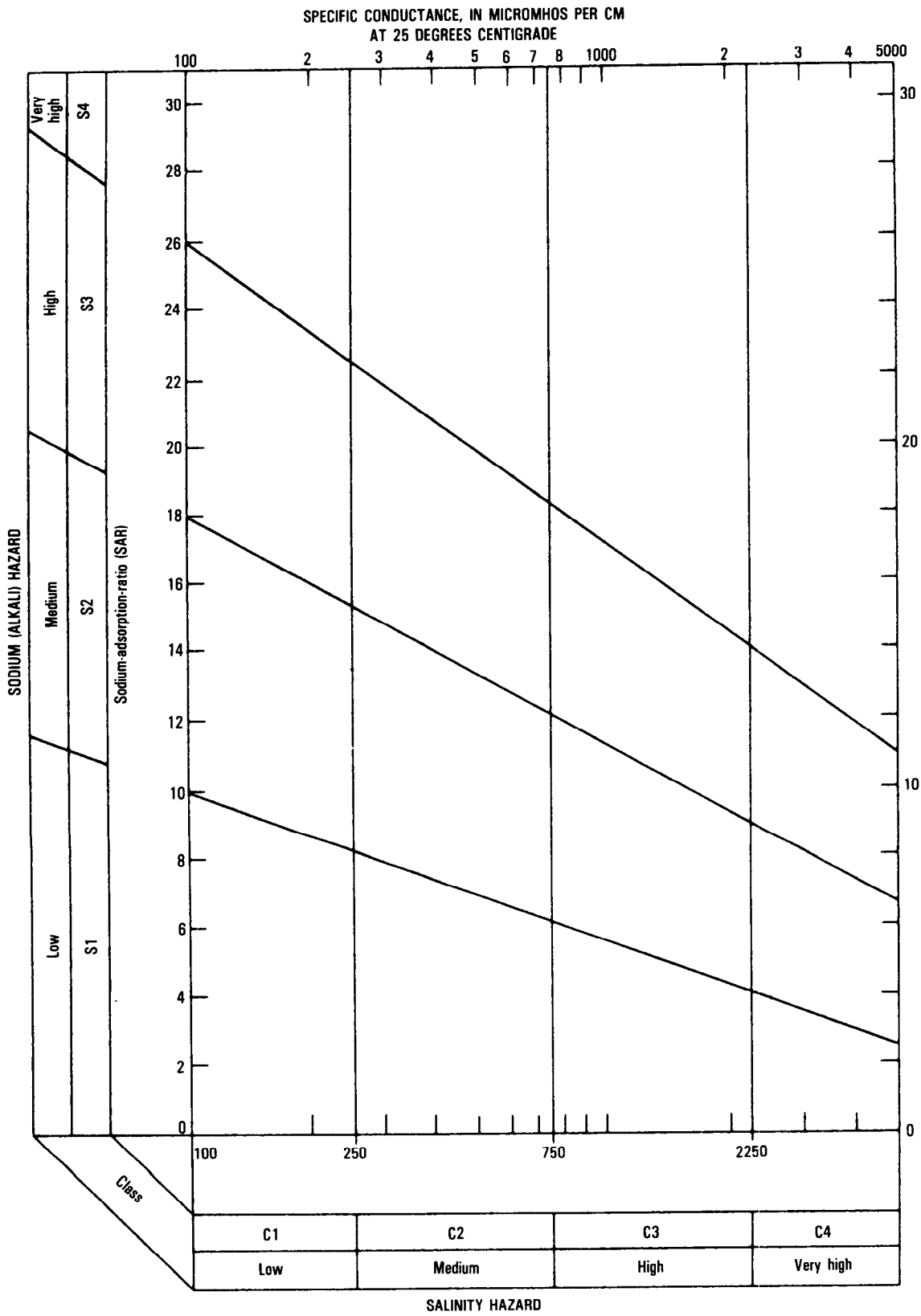


Figure 51. Diagram for use in interpreting the analysis of irrigation water. Adapted from U.S. Salinity Laboratory staff (1954).

levels if the water meets the other specifications. Water used for processing food or beverages must also meet drinking-water standards.

It is technically possible to treat any water to give it a composition suitable for special uses. If the water requires extensive treatment, however, especially if large amounts of water are involved, it may not be economically feasible to use some supply sources. Industrial plants having large water requirements are commonly located with reference to availability of water.

Although water temperature is not a chemical property and has not received much consideration here, the temperature of a supply and the seasonal fluctuation of that temperature are major considerations in the use of water for cooling by industry. In some areas, ground water is used extensively for this purpose because its temperature is uniform and is below air temperatures during warm weather. Some industries have recharged ground-water aquifers with cold water from surface streams each winter and have withdrawn the cool stored water in the summer when the regularly used surface supply is too warm for efficient cooling. In the past there were instances of industrial plants located along the same stream using and reusing the water for cooling until the temperature of the water for many miles of river was far above normal levels. Excessively high temperatures deplete dissolved oxygen and interfere with normal stream ecology, an effect sometimes called thermal pollution. In recent years these practices have been regulated to prevent undesirable ecologic stress.

Industrial expansion has contributed greatly to increasing per capita use of water in the United States. Much of the industrial use, however, is nonconsumptive. That is, the water is not evaporated or incorporated into the finished product, but is released after use without significant change in quantity, possibly with an increased load of dissolved or suspended material or perhaps with very little change from its original composition. As water supplies have become more fully used, however, many industries have found it necessary to conserve and reuse water that in former years would have been allowed to flow down a sewer or back to a surface stream. In some places, reclaimed sewage has been used for certain non-critical industrial purposes.

Recirculation of water that is depleted by evaporation, as in a cooling tower, introduces concentration factors, and intensified reuse can be expected to raise the average solute concentration in effluents.

Recreational and Esthetic Uses

Considerable attention is now being paid to recreational uses of rivers and lakes for such purposes as swimming, fishing, and boating and for simple esthetic enjoyment. The cost of restoring water bodies that have

lost their value for such purposes because of pollution may be substantial, but there is strong public support in many places for the aim of creating or protecting waters for these purposes.

Water for swimming and other sports in which water is in contact with the skin obviously must conform to sanitary requirements. Fish that are sought by anglers require clean water and a good supply of dissolved oxygen. Certain metal ions may be lethal to fish and other aquatic life forms when present at levels near or below the limits given for public water supplies. Copper, zinc, and aluminum, which are not among the metals for which limits are prescribed for public water supplies, are toxic to fish and many other species of aquatic life. The absence of fish from low-pH lakes in Europe and North America is believed to be the result of aluminum brought into solution by precipitation having a low pH ("acid rain") (Cronan and Schofield, 1979).

One of the important factors in the assimilation of dissolved metal ions by aquatic biota is the tendency for increasing concentrations in species higher in the food chain. One of the more insidious effects of mercury-containing waste that enters rivers and lakes is an increase in mercury content of fish to the extent that they become dangerous to eat. Some species of fish are more sensitive than others to ions and organic solutes, and certain combinations of ions may exert synergistic effects. McKee and Wolf (1963) compiled many references on the effects of dissolved material on fish. Water-quality requirements for fish have been summarized by NAS-NAE (1972).

Although highly impure water is attractive in appearance when viewed from a distance, it is obvious that even the lowest standards of pollution control must aim to produce a product reasonably pleasing to the senses of the viewer from close at hand, while walking along the shore or riding over the water in a boat. The surroundings of the water body are an important part of this esthetic impression.

WATER-MANAGEMENT CONCEPTS AND PROBLEMS

The term "water-quality management" is frequently used in recent literature. Sometimes it is used as a synonym for "pollution control." Most of the time, however, it implies the use and development of water resources in a way that maintains water quality at the optimum level. This may involve many administrative and engineering activities concerned with decreasing the pollution loads contributed to streams through better and more complete sewage treatment, cleaning up existing pollution by dredging and other means, and designing and building storage facilities to increase low flows of streams and thus to decrease quality fluctuations, or any of a number of related activities. The use of the term also implies that enough is known about the natural-water circulation