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Guidelines for Minimizing Salinity Buildup in Groundwaters of Utah

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GUIDELINES FOR MINIMIZING SALINITY BUILDUP
IN GROUNDWATERS OF UTAH

by

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and
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HYDRAULICS AND HYDROLOGY SERIES

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ABSTRACT

In arid Utah practically all of the replenishable surface water supplies are nearly fully developed. At least some groundwater resources are being used in every basin. Groundwater use is expanding throughout the state and in some areas the draft is nearly equal to the sustained yield. Irrigated agriculture is the major water user. Multiple reuse of water is common in many areas, but as salinity increases with each cycle of usage, salinity also is usually the limiting factor for usefulness. Effective control of salinity buildup will permit more efficient and more extensive use of the state's waters with potentially large benefits to irrigated agriculture.

This report describes physical and chemical processes which contribute to salinity buildup and suggests methods that might be used to control it. Some areas are described where groundwater salinity is becoming a serious problem in the state. Hypothetical cases of salinity buildup are portrayed graphically to illustrate the relationship to time and the effects of the various processes. Emphasis is upon groundwater, but control of surface water salinity is also addressed as these resources are often inextricably interrelated.

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Edward P. Fisk
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INTRODUCTION

Need for Salinity Control Guidelines

Since pioneer times, streams and springs have been the principal sources of water in Utah. In recent years, the ratio of groundwater to surface water used has gradually increased, and groundwater now supplies about 20 percent of the water needs of the state. Surface waters and groundwaters are so intimately interrelated in some localities that they must be considered as one resource. In some parts of the state groundwater is used to supplement surface water supplies, and in other areas it is used exclusively.

Historically Utah has experienced relatively few groundwater salinity problems that have been induced by man. In other states of the arid west, poorly planned development of groundwater has sometimes led to serious conditions of increasing salinity, declining water levels, and other symptoms of short-sighted groundwater exploitation. Utah's groundwater development has been fairly slow, yet salinity problems are emerging in some areas and may be imminent elsewhere. The advent of the multi-stage vertical turbine pump in Utah has provided the mechanical means of rapidly inducing groundwater management problems.

Groundwater development has been slow in Utah for several reasons. In many areas, surface waters were less expensive and able to supply the demand. Vast areas are underlain by saline groundwater unfit for most common uses. Groundwater cannot be found in large quantities at other localities. Geologic, climatic, and economic factors

have restricted groundwater development to certain areas. Some of these are already overdeveloped, whereas others could accommodate further development.

By law all waters found in the state belong to the State of Utah except water on Indian lands and possibly on federal lands. Water users must obtain a right from the state to divert and use water, and it must be used in a beneficial way. An elaborate system of water rights has developed as the State Engineer has sought to equitably allocate the limited quantities of available surface and groundwater.

Virtually all of the water rights were allocated before salinity problems became a major concern. The quality of waters in the state has been affected as a natural result of the way the water rights developed. Formerly water users with senior rights had no obligations to subsequent users with regard to quality of water and had few obligations with regard to quantity. Since practically every use degrades water quality, society is coming now to recognize that users have some obligations for restraint in impairing water quality for others.

Fortunately the older water laws and water rights systems can be modified through legislative and judicial actions to protect water quality. A strategy and policies for protection of groundwater quality is now evolving at both state and federal levels. Already a permit system has been established in Utah to regulate the quality and disposal of waste water. Specific regu-

lations have been enacted to protect groundwater quality; more are in the process of formulation. Attention needs to be given to localities with specialized problems that require individualized treatment within the framework of overall state laws, policies, and regulations.

Upstream water users have little economic incentive to be concerned over the effects of their use on the quality of water discharged to downstream users. Often they are unaware of the salinity problems arising from their usage. Where salinity is the quality problem, restoration of water quality costs more than irrigated agriculture and other uses can pay. The alternative is adoption of water use techniques aimed at the control of salinity. Hopefully, practical guidelines can be developed for optimum utilization, protection, and perpetuation of the quality of groundwater supplies.

Rational optimization of water use should be approached in the future jointly with respect to water quality, quantity, and economics. Guidelines to protect the quality of surface water supplies are being developed in profusion by numerous agencies operating within the state and the nation. These agencies have done relatively little with respect to groundwater quality.

Purpose and Scope of Report

The purpose of this report is to present a number of alternatives for the control of salinity in groundwater and evaluate their application in the Utah setting. Several groundwater basins and watercourses in Utah could benefit from a moderation of salinity buildup in their groundwaters. Individual problem areas will be assessed, and specific salinity control measures will be suggested.

Agricultural consumptive use results in more salinization of groundwater than does any other activity of

man in the arid west, but other sources of man-induced salinization also need to be considered. Most saline groundwaters are of natural origin, and there is usually little that can be done about them. Nevertheless, the processes governing natural salinity are usually near equilibrium in that the salinity of groundwater at any given point remains nearly constant, unless disturbed by man. It's the processes of man-induced salinity over which we have some control.

Groundwaters, like surface waters, naturally increase in salinity in a downstream direction. Since salinization cannot be economically reversed, the focus of this report will be upon retarding the processes that result in salinity increases associated with the activities of man and, consequently, are somewhat controllable.

Efforts to control salinity loadings require more than an understanding of scientific principles. Human relations, equity, economics, history, law, and compromise are also essential considerations. Water quality regulations seem to be needed as a result of population growth and the resultant competition for the available water supplies. With the sparse population of pioneer times in Utah, salinity buildup in groundwater or surface water was not a serious problem. Now that the population has grown to a size that most water is used and reused, salinity buildup has become of widespread concern. In humid regions, salinity is diluted and carried away by the relatively abundant fresh water; but in arid Utah, this only happens on a small scale and downstream water users must accept the salinity.

When the interests of downstream water users are ignored, severe hardships result. Forbidding beneficial upstream use would have the same effect. An optimal balance exists whereby the most beneficial and most economic use of water may be obtained for all users.

Utah attempts to follow a general objective of preserving the integrity of its waters for the benefit of its citizens. To reach this objective, new regulations may be required and modifications to antecedent water laws not in

harmony with the objective may be necessary. Without getting into economic and humanistic principles, this report will hopefully advance some worthwhile guidelines for the protection of the salinity of the state's groundwaters.

GEOLOGIC AND HYDROLOGIC FRAMEWORK

Groundwater Regions

Utah has been classified into three regions or provinces, each having its own distinguishing geologic, physiographic, and hydrologic characteristics. These regions extend into adjoining states. Based upon typical modes of occurrence of the groundwater within them, they were delineated and named by Thomas (1952) as the Arid Basins, Western Mountain Ranges, and the Colorado Plateau groundwater regions (see Figure 1). Somewhat different names are used when reference is made to these same regions as geologic or as physiographic provinces.

Arid Basins

The Arid Basins groundwater region covers roughly the western one-third of Utah, most of Nevada, and significant portions of California and Arizona. Within Utah, this region consists of about 36 broad, desert basins separated largely by long, narrow, north-south trending mountain ranges. Surface elevations of these desert basins range between 4200 ft (1280 m) and 5000 ft (1520 m). Approximately one-fourth of this region is mountainous. Virtually no water flows from this region in Utah as it is a topographically closed area called the Bonneville Basin.

There are two subregions in Utah. The smaller one is the Sevier Lake subregion to the southeast, and the larger one is the Great Salt Lake subregion to the north and west. A small strip of eastern Nevada is in the Bonneville Basin and is included in the Great Salt Lake subregion. There is a small underflow of groundwater from the

Sevier Lake subregion northward into the Salt Lake subregion and southward into the Colorado River drainage area of Washington County.

Rocks comprising the mountain ranges of this region are mainly limestones with lesser amounts of quartzites, sandstones, shales, pyroclastics, and volcanic rocks. These ranges were formed during late Tertiary and Quaternary time by a characteristic orographic process known as basin and range faulting. The intervening basins often are filled to considerable depths by nonmarine, consolidated to unconsolidated, Tertiary and Quaternary deposits of wide variety, including minor amounts of volcanics. The valley fill deposits are underlain by the same Precambrian and Paleozoic bedrock materials that compose the mountain ranges.

Western Mountain Ranges

The Western Mountain Ranges groundwater region in Utah is composed of the Wasatch and Bear River Ranges, the Uinta Mountains, and a few intermontane valleys. This region receives more precipitation than the other regions because of its generally higher elevation and consequently is the source of considerable groundwater recharge for all three regions.

The Wasatch and Bear River ranges extend southward from the Utah-Idaho boundary nearly 200 mi (320 km) into central Utah. A few peaks exceed 11,000 ft (3350 m) in elevation. The Wasatch Range is composed mainly of limestones, quartzites, dolomites, sandstones, and shales, with lesser amounts of

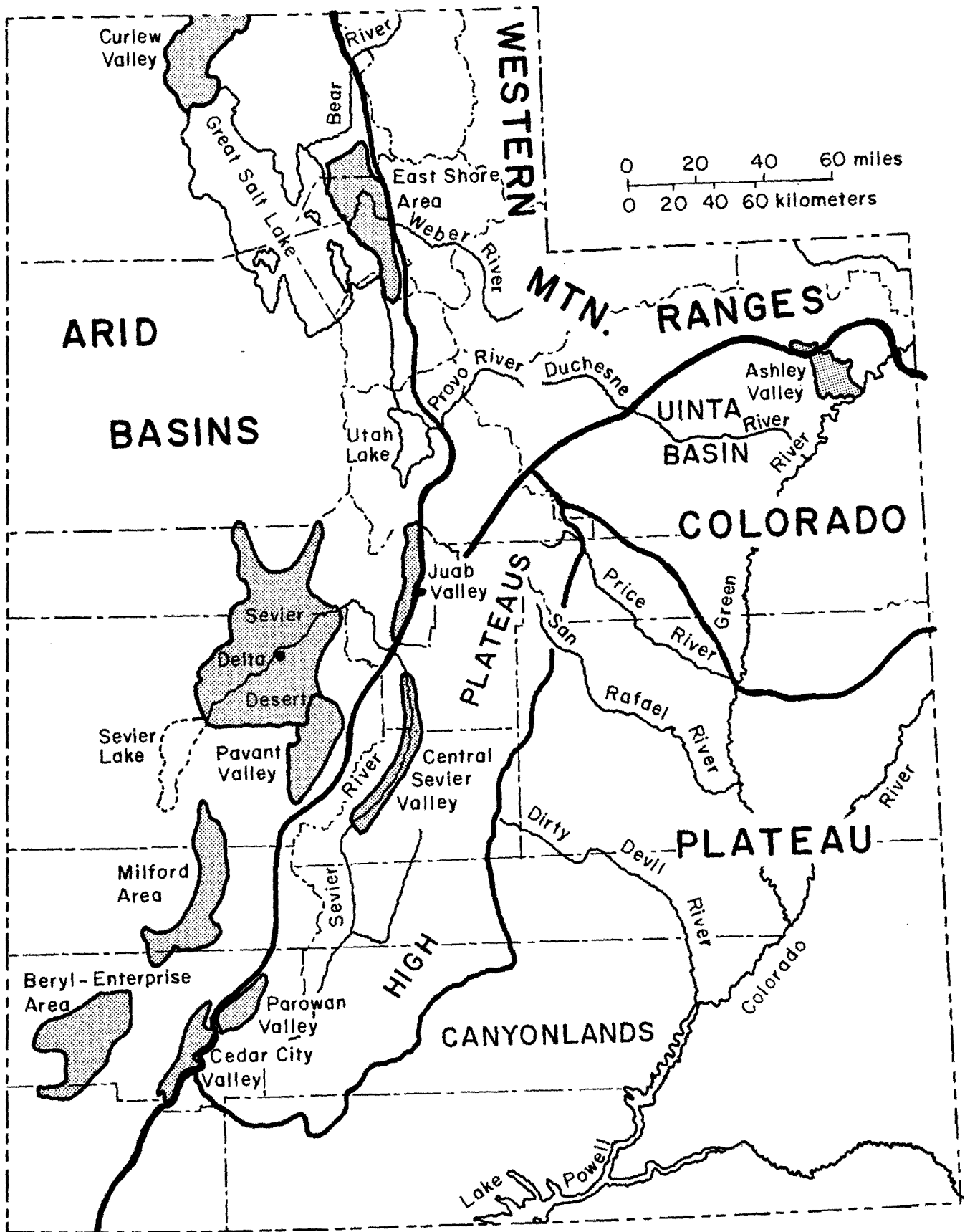


Figure 1. Utah location map.

igneous intrusive and extrusive rocks as well as unconsolidated fluvial, glacial, and alluvial deposits. Similar rock types compose the Bear River Range and underlie the valleys of the region. The rock formations of these ranges are extensively faulted and folded.

The Uintas are an east-west trending, anticlinal uplift approximately 150 mi (240 km) long with peaks above 12,000 ft (3660 m) in elevation. The broad structure has a Precambrian quartzitic sandstone core flanked by younger sedimentary rocks and unconsolidated alluvial and glacial deposits.

Colorado Plateau

The Colorado Plateau groundwater region covers the southeast half of Utah. Based primarily upon geologic structure and topographic elevations, this region is divided into the Uinta Basin, the High Plateaus, and the Canyonlands subregions. Nearly the same rock types are found in all three subregions. Bedrock is at the land surface throughout the region except for a few broad alluviated areas in the Uinta Basin. Even there the alluvium is relatively thin.

The Uinta Basin is a large synclinal structure sharing its north flank with the south flank of the Uinta Mountains anticlinal uplift. Its southern extremity is manifest in the Book Cliffs, which overlook the Canyonlands subregion to the south. The basin is composed largely of Mesozoic sedimentary rocks overlain in most areas by nonmarine Tertiary sediments, glacial deposits, and alluvium.

The High Plateaus subregion is an elevated topographic continuation of the Wasatch Range, which then curves south and west toward the southwest corner of the state. Elevations reach above 11,000 ft (3350 m) in the High Plateaus subregion which drains into both the Canyonlands and the Sevier Lake subregions. Mesozoic and Tertiary

sediments and extrusives underlie the High Plateaus subregion. They have been complexly faulted and folded.

The Canyonlands subregion is of simpler geology and generally lies at lower elevations. It contains a long reach of the Colorado River and several of its tributaries. Mesozoic sandstones and shales predominate. The formations are nearly horizontal but there are a few areas where abrupt upwarps occur. The Cretaceous Mancos Shales outcrop in large areas of the northern part of this subregion. This marine formation is noted for the salinity it imparts to percolating waters.

Groundwater Occurrence

As runoff moves over the land surface and through stream channels, some seeps into the earth and becomes groundwater. Permeability and porosity are physical properties of earth materials which control the movement and quantity of groundwater. The stratigraphy, mineralogy, and chemistry of the water-bearing materials also affect groundwater quality. Together these factors control the quantities and qualities of groundwaters obtained from wells and springs.

Groundwater is found in the pores, fractures, cavities, and other void spaces of earth materials. For estimating groundwater reserves and well yields, the shapes and dimensions of the aquifers must be considered. Under natural conditions in the Utah environment, relatively small amounts of water annually recharge the groundwater reservoirs and comparable amounts are discharged. Although fluctuating from wet to dry periods, the amount of water in storage is normally near equilibrium. Extraction of groundwater by man can profoundly disturb natural equilibrium conditions and can affect water quality as well.

Unconsolidated Deposits

Unconsolidated earth formations usually have the highest porosities and permeabilities and thus make the most productive aquifers when saturated with groundwater. Sands and gravels are normally the best aquifers, while silts and clays impede or prevent the flow of groundwater. These unconsolidated materials are products of erosion which have been transported and deposited by natural forces. Often they are given generic names, such as alluvium, pyroclastics, or lacustrine or glacial deposits, without regard to particle sizes. Alluvium refers to stream-borne deposits but it may contain small amounts of other types of sediments. Over geologic time alluvium may become lithified by deposition of cementing materials in its pores and by compaction.

In the Arid Basins region, hundreds and even thousands of feet of alluvium have been deposited as the mountain ranges have been uplifted and eroded throughout late Tertiary and Quaternary time. The older alluvium has become lithified to various degrees in most basins. Considerable thicknesses of lacustrine deposits are found in several basins, mostly dating from the Pleistocene Epoch. In a few basins, volcanic rocks and pyroclastics are interbedded with the alluvium. Evaporation of surface water and evapotranspiration of groundwater over geologic time has left enormous amounts of salt and saline waters in some areas.

Unconsolidated water-bearing alluvium in the Western Mountain Ranges is mainly found in relatively small, long, narrow mountain valleys. One notable exception is Cache Valley, which more rightfully belongs in the Arid Basins region because of its physiographic and geologic structure. On the other hand, groundwater occurrence in the alluvium of the High

Plateaus subregion is quite like that of the Western-Mountain Ranges.

In the central Uinta Basin, there are several broad alluviated valleys, but the unconsolidated alluvium is very thin, averaging only about 50 ft (15 m) in thickness. Much of this alluvium is derived from glacial erosion of the Uinta Mountains. Large quantities of groundwater are not found in the unconsolidated alluvium of this subregion.

The vast Canyonlands subregion is practically devoid of alluviated valleys. Aside from a very few small basins, like Spanish and Castle valleys near Moab, there are only trivial amounts of unconsolidated alluvial deposits scattered throughout that entire area.

Mountain Water Courses

The longer streams of the Western Mountain Ranges groundwater region and the High Plateaus subregion have some special characteristics which bear upon groundwater salinity. The Bear, Weber, Provo, and Sevier Rivers drain mountain highlands of bedrock outcrops and have relatively long, narrow valleys with some significant tributaries. The unconsolidated alluvium of these valleys is usually very thin. It is broad in some reaches and virtually absent where the streams cascade over bedrock exposures.

The alluviated areas of these valleys are irrigated and thus groundwater salinity tends to increase. The streams have relatively small flows except during the snowmelt period in the spring. Reservoirs have been constructed along these streams to retain water for irrigation. This makes very efficient use of the water but results in repeated cycles of water usage with reduced downstream flow and increased salinity. The reduced flow of the streams, the repeated reuse of the water, the leaching of soils beneath the irrigated lands, and the evaporation

from the reservoirs combine to raise the salinity of waters found in Utah's mountain watercourses.

Bedrock Aquifers

The consolidated rock formations of Utah are generally of low porosity and permeability and do not yield water readily to wells. Nevertheless, they underlie the entire state, including the alluviated areas, and constitute an enormous groundwater reservoir. Unfortunately, most of this water is saline and either dates from the time the rocks were formed or has been underground for tens of thousands of years. Groundwater salinity normally increases with depth, because fresh waters infiltrating from the land surface tend to flush the shallower horizons more effectively. In low lying areas where groundwater is rising to the land surface, the reverse may be true.

All of the mountain ranges of the state are composed of bedrock formations of fairly low salinity, such as limestones and quartzites. They receive the most precipitation, yet their ability to retain or store water is poor. Water infiltrating the mountain ranges usually drains out of them slowly to sustain the base flow of streams, springs, and underflow into adjoining alluvial basins. Consequently, groundwaters and surface waters emanating from Utah's mountain ranges are normally of very low salinity. Water wells drilled in and near the mountains usually yield higher quality water than those drilled at greater distances. Because wells in bedrock are typically of low yield, it is preferred to drill wells in the coarse-grained alluvium close to the mountains to get higher yields and lower salinity.

In some of the Arid Basins, groundwater of acceptable quality is obtained from limestones and other permeable bedrock aquifers even far removed from the mountains. This is likewise true in the Colorado Plateau region where some

sandstones and other permeable bedrock aquifers have been flushed with fresh waters. This latter region also contains bedrock which has not been flushed of its original saline water and minerals. Some Colorado Plateau bedrock formations contain almost inexhaustible sources of soluble saline minerals which are continually degrading groundwater and surface water resources. The Arid Basins region has similar salinity problems except that the source of the salinity is mainly from leaching and subsequent concentration of salts by evaporation in more recent times.

Springs and Seeps

Percolating groundwaters follow the path of least resistance, and form springs and seeps where forced to emerge at the land surface. There are literally thousands of springs and seeps in Utah (Mundorff 1971). The great majority yield water of low salinity and are located in or near mountains from which their water supply is derived. Others occur in valleys far removed from the mountains. Springs are found in bedrock as well as in unconsolidated deposits. Flow paths to the springs are controlled by the geometric configurations and relationships of pervious and impervious formations. Depending upon underground conditions, springs may have various discharge rates, water qualities, temperatures, and other characteristics.

Several large springs in the state yield saline groundwaters (Milligan et al. 1966). All of the more saline springs yield waters high in sodium chloride (Mundorff 1970). Saline springs often contaminate downstream groundwaters, surface waters, and the land surface; nevertheless, some of these saline waters are put to beneficial uses. Milligan et al. (1966) describe the impact of several saline springs upon surface waters of the state.

At most spring sites transpiration by hydrophytes and phreatophytes and

direct evaporation cause greater salt concentrations downstream than found in the emerging groundwater. Isolated springs in areas where all the water evaporates cause a salt problem even though the original water may be quite fresh.

Quaternary Hydrology

Although mountain building and erosion have continued, the general physiographic features of Utah are still much the same as they were at the beginning of the Quaternary Period. In this period of roughly one million years, profound hydrologic processes took place during what is commonly called the Ice Ages or Pleistocene Epoch and during the brief 10,000 years following the last Ice Age, called the Recent or Holocene Epoch.

During the Pleistocene Epoch, there were times when the temperatures were slightly cooler and precipitation was greater than today. These conditions gave rise to numerous glaciers which waxed and waned in the high mountains of the Western Mountain Ranges region. Products of glacial and stream erosion were transported to the valleys by streams that were considerably larger and more powerful than those of today. Lakes, streams, and abundant vegetation were present in what are now desert lands. One large lake covered 20,000 mi (52,000 km²) of the Arid Basins regions and was almost 1000 ft (305 m) deep at the site of its present remnant, the Great Salt Lake. Lake sediments

added to glacial and fluvial deposits in filling many of the valleys. Much erosion took place in the Colorado Plateau region. Canyons were incised, but the valleys were not filled with sediments as in the Arid Basins region.

At the peak wet periods, fresh water was abundant. Younger alluvium and shallow bedrock formations were charged with fresh water. During dry climatic stages, perhaps like the present Holocene Epoch, precipitation was insufficient to maintain the glaciers, lakes, high stream flows, and vegetation. As the lakes dried up, the salts in their waters were concentrated until brines and salt deposits remained. Vegetation consumed more of the available soil moisture leaving more concentrated saline groundwater. Soluble minerals continued to dissolve in diminishing quantities of groundwater, and there was less fresh water to dilute the salinity buildup.

Each of these great climatic fluctuations lasted many thousands of years. It has been less than 150 years since man first began to modify the natural balance of water quality in Utah. For more than the first century, the water users were little concerned with water quality, but attitudes have changed. It may be feasible now to implement plans for minimizing salinity effects. Positive steps should be taken now to preserve and enhance the quality of our water resources within the limitations imposed by beneficial use.

SALINITY IN WATERS OF UTAH

General Statement

Definition

Salinity is defined as ionized mineral matter dissolved in water. The mineral matter (salts) may be specified by individual anions and cations, but that detail will not be used in this report. The amount of salinity in a given water is expressed as total dissolved solids (TDS) and specified either in terms of the weight of salt in solution or, more commonly, as a concentration or weight of salt per unit volume of water. The concept of concentration is particularly relevant because it is salinity concentration that largely determines the degree to which the use of water is impaired and that needs to be reduced in salinity control programs.

Measurement

Direct laboratory determination of TDS is usually made by evaporating a known volume of water to dryness at 180°C, weighing the residue, and expressing the results in milligrams per liter (mg/l) of solids dissolved in the water so analyzed. This method inherently includes small amounts of dissolved constituents that are not salts, such as oxides and organic matter. Furthermore, approximately half of the bicarbonate ions are converted to water vapor and carbon dioxide, which escape measurement. Sometimes the dried residue contains water taken into the crystalline structure of certain minerals such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Despite these problems, this method of estimating salinity is widely used because it is simple and practical.

Another method for estimating salinity is to measure the electrical conductivity of a given water and apply a relationship based on regression between the two variables. The speed and low cost of electrical conductivity measurements make this indirect method very attractive. The electrical conductivity of a water solution, however, depends not entirely upon the quantities of mineral species present but also upon their degree of ionization. Normally, this limitation does not create an important problem because fully ionized mineral salts predominate over other species in natural waters.

Other less common methods of estimating salinity include the summation of ionic species from chemical analyses, measurement of the specific gravity of water, and titration of a given water solely for its chloride-ion content.

Causes of Buildup in Nature

Salinity as a concentration is increased either by adding salt or by removing water without reducing the dissolved minerals. Salt may be added by leaching minerals from soils or aquifers or by commingling with more saline solutions. Water may be removed naturally by evaporation or by extraction of soil moisture by plants. Physico-chemical processes of lesser magnitude also occur in nature and slightly affect water salinity, but they will not be examined in this report.

The fundamental physical processes may occur independently or simultaneously in salinizing a given groundwater.

For example, a portion of the water in soil may be extracted by plant roots while the remaining water may be gaining dissolved salts by the leaching of soil minerals.

Factors Contributing to Salinity Buildup

Climate and Geography

The arid climate of Utah contributes to higher salinity levels in the natural waters of the state. Most salts are dissolved as weathering exposes geologic formations and water leaches the salts from the weathered materials. Waters percolating underground may also leach soluble minerals or mix with connate waters, mineralized spring waters, or other sources of salt loading. Salinity concentrations are less in humid climates because larger volumes of water are available to leach the soluble salts from exposed earth materials and to dilute surface and groundwater flows.

In Utah, these diluting conditions only occur at higher elevations. Streams leaving mountain areas largely recharge the desert aquifers with high quality water. Underground flows from the mountains are of almost equally good quality. Generally, both ground and surface water qualities deteriorate with distance from the mountains.

Salinization also is more severe in arid climates because the stream flows are not large enough to carry the salts to the sea. Much of the total salt content leached from mountain areas and valley surface formations is left in lowland soils or aquifers where natural concentration processes have produced brackish waters. In addition to the closed Arid Basins where these waters end up in the ultimate sink, large areas within the Colorado Plateau seldom contribute runoff to the rivers, implying that their soils and underlying groundwaters become gradually more saline over time as they accumulate

salts from precipitation and surface weathering.

Evaporation and Transpiration

Evaporation is a major process that increases the salinity of water in Utah. Climatic factors that contribute to the scarcity of water by favoring higher evapotranspiration losses include solar radiation, wind, temperature, low humidity, and degree of cloud cover. Potential evaporation rates are relatively high in this arid region.

The surface waters in the state, in amounts determined by these factors, are subject to more withdrawals by evaporation than augmentation by precipitation and thus experience a resultant concentration of dissolved minerals. Natural lakes, streams, ponds, and seeps concentrate salinity as do man-made reservoirs, lagoons, ponds, irrigated fields, and canals. In the Arid Basins region, the loss of water from salt lakes, playas, and salt flats is also of considerable magnitude. Evaporation or sublimation of snow and ice, of precipitation directly from the land surface, and from interception by vegetation are processes which detract from the availability of fresh waters and indirectly contribute to their salinity.

Vegetation extracts nearly pure water from the root zone of the soil and loses it to the atmosphere through transpiration. This consumptive use of water by plants can greatly increase the salinity of the remaining soil moisture. Some plants actually bring salts to the soil surface and leave them behind when they die. Some plants, called phreatophytes and hydrophytes, transpire unusually large amounts of water. The salinity increase and waste of water caused by such plants has reached alarming proportions in the arid western states. Twenty years ago Marsell (1962) reported that phreatophytes consumed 1.5 million ac-ft (185,000 ha-m) of water annually in Utah. Infestations of

such water wasting plants have spread widely since then, mainly by canals and irrigation waters. Efforts to eradicate this tenacious vegetation have been costly and largely futile. Many phreatophytes are salt-tolerant and can thrive in the saline conditions they cause. They are a menace in both the high mountain valleys and lowlands of Utah. Phreatophytes and other non-productive vegetation often abound around springs and seeps where they contribute to water losses and to salinity increases. They should be replaced by beneficial vegetation that does not use so much water.

Weathering and Erosion

Rocks and unconsolidated materials at the land surface experience continuous weathering by the forces of nature. This results in the physical and chemical decomposition of these earth materials. Removal of the products of weathering, through erosion and leaching, is mainly accomplished by the movement of water, and less available water means that salts are moved in higher concentrations. As the products of weathering are removed by erosion, new materials become exposed, and the process continues.

Precipitation is the ultimate source of the waters of Utah. When it falls from the sky, it contains only insignificant amounts of dissolved minerals. As it moves over the land surface, down drainage channels, and through the soil, it comes into contact with soluble earth materials, which begin to dissolve. Moving surface water also causes erosion and picks up salt from the suspended matter and earth materials that it encounters. The more soluble the exposed materials are, the more readily salinity buildup occurs. Thus streams tend to increase salinity downstream that may be intensified somewhat by evaporation from the lakes along their courses.

During high stages of stream flow, water enters permeable earth materials in the channel banks or flood plain only to return slowly to the stream during low stages. This water is known as bank storage and it can increase in salinity by the solution of minerals while underground, by evaporation in oxbow ponds, or by the extraction of pure water by vegetation associated with the river.

The salinity of surface waters varies seasonally with the activity level of the natural processes of salinity buildup. The salt concentration of surface water is usually lowest during periods of high discharge, although total salt load may be highest. This is because exposure time to soluble minerals is low, groundwater contributions to the stream are relatively small, and the dilution volume is great.

Significant portions of stream flow may enter the groundwater (particularly during periods of high flow), or groundwater may flow into streams (particularly during low flows). Salinity exchanges between surface waters and groundwaters can be of considerable magnitude locally.

Groundwater Mineralization

Whenever water seeps below the land surface, it is usually destined to increase in salinity because of three major processes. The first is the extraction and transpiration of relatively pure water by plants from the soil as previously mentioned.

The second process is that of the leaching of minerals from the earth materials through which groundwater percolates. Leaching may occur in the soil or subsoil or in consolidated or unconsolidated formations of all types and at all depths. Some formations are particularly laden with soluble, saline minerals and cause rapid increase in salinity of waters percolating through

them. Among these are marine and fresh-water evaporites, pyroclastics, other marine sediments, and some ore bodies. The salinity concentration depends on the combination of equilibrium salinities over the different routes traveled by the flow. With the usual slow motion of percolating groundwater and the large surface area of minerals exposed to it, increase of salinity is roughly in proportion to distance traveled while the total volume of salt leached out is roughly proportional to the volume of groundwater. Many physical, chemical, and biological factors influence this process. For example, as water enters the soil it may absorb carbon dioxide from bacterial or other organic sources in addition to the carbon dioxide it may have absorbed from the atmosphere. Groundwater charged with carbon dioxide becomes more aggressive in the solution of minerals, especially carbonate minerals.

Salinity increase depends upon the solubility and amount of the salts contained in the formation and on chemical interactions among individual minerals available for leaching by groundwater. Solubility depends largely upon the particle size of the minerals, the chemical species involved, and the bonding between the salts and the mineral grains. Permeability of the formations, exposure time, and other factors are also involved.

Temperature is an important factor in solubility. Groundwaters which percolate deep below the land surface normally experience a rise in temperature of roughly 1°F/100 ft or roughly 1°C/100 m. Geothermal gradients may be appreciably higher than this in geologically active areas. Other factors being equal, flowlines that move to greater depths bring greater salinity. Groundwaters may rise from greater depths and are normally more saline. Passageways may allow deep groundwaters to rise along faults and fractures in bedrock formations.

Thermal springs are mostly of this origin.

The third major process that will increase groundwater salinity is the commingling of relatively fresh groundwaters with connate or other more saline groundwaters. Connate waters are entrapped in sedimentary formations for eons of time. As the overburden of these sedimentary formations is removed by erosion, their connate waters are gradually displaced by mixing with relatively fresh meteoric waters that have more recently percolated underground. Other geologic sources of saline groundwaters include the deep percolation of lake brines, dying volcanic activity, mineralized solutions escaping from igneous intrusions, and crustal deformation and faulting conducive to the rise of saline groundwaters from greater depths. Where these waters rise to the surface, thermal or mineralized springs occur.

Man Induced Sources of Salinity Buildup

General Background

The activities of man often intensify the water salinizing processes described above and add others besides (salts added by municipal and industrial uses). Individual effects of salinity buildup are compounded when water is reused. Man's uses of water may increase salinity by all combinations of mineral additions or pure water extractions. Along rivers or from aquifers, the same water is often used repeatedly. Such reuse can occur indefinitely as long as the residual water quality remains satisfactory. Reuse, however, is a salinizing process in which salinity levels become the factor limiting the number of times reuse is possible. Water resources management thus needs to focus on minimizing the salt buildup associated with a given use.

In Utah an estimated average of 4100 mgd ($15.5 \times 10^6 \text{ m}^3/\text{d}$) of water

were used in 1975 for all use categories except the generation of hydroelectric power (Murray and Reeves 1977). This number includes some reused water. An estimated 60 percent of the water used was consumed by evaporation, transpiration, or otherwise removed from the water environment (Murray and Reeves 1977). Irrigated agriculture accounts for about 90 percent of this consumptive loss of water in Utah. About 20 percent of the water used in 1975 was groundwater; the balance was taken from surface-water sources.

Irrigated Agriculture

As of 1975, about 85 percent of the water diverted or pumped in Utah (for purposes other than hydroelectric power generation) was for irrigated agriculture. About 14 percent of that was groundwater and the balance was surface water (Murray and Reeves 1977). Almost two-thirds of this water was estimated to have been consumptively used (2,400,000 ac-ft or 296,000 ha-m in 1975), although some of it may have entered the groundwater reservoir and was not entirely lost. Large amounts of water are involved in irrigation. Consequently control of salinity buildup is very important for agriculture in Utah and its impact on other water users can be appreciable.

Four basic processes are involved in salinity increase in irrigated agriculture. They are evaporation of applied water, transpiration by crops, displacement of saline groundwater, and leaching of minerals from the soil or subsoil by the applied water. The first two processes are collectively called evapotranspiration by irrigation engineers and agriculturalists. Evaporation takes place from canals, distribution ditches, irrigation furrows, moist soil, tailwater streams, drainage ditches, sprinkler streams and from plant leaves when sprinklers are used. Evapotranspiration by crops depends upon a great number of factors, such as climate, atmospheric conditions,

size and type of plants, and irrigation techniques.

Excess waters flowing from the irrigated fields usually contain more dissolved and suspended minerals than when they were diverted for irrigation. This increase in salinity is caused by contact with soluble minerals on the land surface.

After having been concentrated by evapotranspiration, the waters which enter the soil usually will leach soluble minerals from the soil and subsoil. These salinized waters may seep into drains, nearby streams, or other surface waters and degrade them. They may percolate into deeper aquifers and continue to increase in salinity. They could eventually be returned to the land surface for reuse after having emerged from springs, wells, drains, or gaining streams.

It has been estimated that roughly 11 percent of all water diverted for irrigation in Utah is lost in conveyance before or after application to the fields (Murray and Reeves 1977). The salinity of that water is increased by the processes of evapotranspiration and leaching, yet no beneficial use has been made of it. Some detailed studies of canal seepage losses have been made in Utah by the U.S. Geological Survey in cooperation with the Utah Department of Natural Resources (Cruff and Hood 1976, Cruff and Mower 1976, Cruff 1977, and Cruff 1980). The average net seepage losses for the canals investigated in these studies was about 8 percent over an aggregate length of 128.7 mi (207 km). Major seepage losses sometimes occurred in relatively short reaches of some canals. A few canals actually gained water from canal seepage and deep percolation of irrigation return flow from topographically higher lands.

The application of excessive amounts of irrigation water can contribute greatly to salinity buildup through

needless leaching, erosion, and evaporation. A small measure of excess water is necessary to prevent salt accumulation in the root zone and for assurance that all parts of a given field receive at least the minimum water requirement for each application. It is economically infeasible to apply the precise amount of water required at every point in an irrigated field. This is because plant requirements may vary throughout a field as well as soil conditions, topography, and the mechanics of water application. For these practical reasons, it is customary to apply generous amounts of water to get maximum crop yields. However, crops are often overirrigated for reasons of negligence, ignorance of crop requirements, inflexible water delivery schedules, spills and leaks, the requirement of use to perpetuate water rights, poorly graded fields, lack of metering devices, and many other manifestations of poor management. Practical economics may make correction of these problems too expensive to be justified by the water saved. Big financial investments in irrigation efficiency largely for the benefit of downstream water users are not attractive ventures for upstream users with senior water rights.

The efficient reuse of water in agriculture is a major cause of salinity increase for both surface water and groundwater. Nevertheless, this practice is very desirable in Utah's dry climate. The reuse of water should be promoted and optimized for maximum benefits to all concerned when salinity effects are considered. Irrigated agriculture can use reclaimed sewage or industrial waste waters as well as its own surface and subsurface return flow. Reuse of water is a well established practice in Utah. Waters of the Sevier River system are reused for irrigation probably five to ten times in the course of this 200 to 300 mi (320 to 480 km) system (Christensen et al. 1979). In 1975 about 1000 ac-ft (120 ha-m) of reclaimed sewage was used for irrigation in Utah (Murray and Reeves 1977). Waste oil-field waters of

low salt content are used for irrigation in Ashley Valley. Often water rights are predicated upon the reuse of irrigation return flow and other waste waters.

Reuse tends to increase salt concentrations downstream. While most nutrients and organic pollutants are diminished by natural processes between repeated uses of water, salinity is normally increased by natural processes both above and below ground level. Any practical methods to reduce salinity buildup and thus permit further reuse of water would effectively enhance Utah's limited water supply.

Faulty water-well design and operation can cause unnecessary salinity increases. The failure to exclude withdrawals from the more saline aquifers in the water being pumped is a common fault in irrigation-well design. Although the water of a more saline aquifer may be diluted to acceptable levels by waters of the less saline aquifers of the same well, an increment of salinity is needlessly added to the active system which could prevent subsequent reuse of the water. At other times, wells are drilled too deep in an effort to obtain higher productivity, and more saline aquifers are tapped as a result. Even when such wells are plugged back to shallower aquifers, the plugging methods are often inadequate. Withdrawals should be planned by aquifer in a well managed groundwater system.

Wells that are pumped too heavily may induce saline waters to rise through natural but weak barriers and needlessly increase the salinity of the well's discharge. Saline groundwaters may move into less saline aquifers through improperly abandoned water wells, oil wells, or exploratory borings. This groundwater salinization could be induced by nearby pumpage or by natural head differences.

Besides irrigated crop production, other branches of agriculture add

small concentrations of dissolved minerals to groundwater and surface water. Large concentrations of livestock can cause appreciable salinity increases locally. Industries related to agriculture, such as dairies, livestock feedlots, and others may constitute large point sources of salinity. In those cases the hazard of other water pollutants is usually greater than the threat of major salinity buildup. In 1975 an average of 37 mgd (140,000 m³/d) of water were used for livestock in Utah. Of this amount about 30 percent was consumptively used (Murray and Reeves 1977). In some areas, unregulated windmill pumps supplying water for livestock and naturally flowing water wells overflow a considerable amount of water and thereby increase salinity by evapotranspiration of nonproductive vegetation and by leaching of the soil downstream.

Urban and Domestic Wastes

Public water supplies in Utah delivered an average of 300 mgd (1.1 x 10⁶ m³/d) for domestic use and 27 mgd (100,000 m³/d) for industrial use during 1975 (Murray and Reeves 1977). The per-capita delivery rate was 331 gpd (1250 l/d), the highest in the conterminous United States and almost double the national average. The estimated consumption was 130 mgd (490,000 m³/d) or about 40 percent of the water delivered. About 55 percent of the water supplied was groundwater. A good share of the estimated water delivered probably was returned to the groundwater reservoir. A portion of the domestic use of water is for watering lawns and gardens, and this use contri-

butes salinity buildup through evapotranspiration and leaching of soils. Water used domestically will increase in TDS about 320 mg/l per cycle of use on the average (Weinberger et al. 1966). Salinity increase from urban and domestic sewage is considerable in heavily populated areas, such as Salt Lake City. Salinity buildup from urban and domestic sources may be only 5 percent to 6 percent of that generated by agriculture in the state.

Solid-waste dumps and landfills discharge saline minerals to subsoils when water is allowed to pass through the dumps and leaching occurs. Rainfall, surface runoff, and groundwater can cause leaching of solid wastes. Salinity buildup from leaching of solid-waste disposal sites can be important on a local scale. Storm runoff, especially where salt is used for de-icing of city streets, can also be a source of salinity of limited magnitude.

Industrial Wastes

Salinity increases from industrial sources vary widely in magnitude and areal extent. Industrial sources include oil-field brines, mine tailings leachates, mine drainage waters, leaky evaporation ponds, faulty wells, unplugged exploratory holes, and a wide variety of others. Normally industrial sources are highly localized and may be very concentrated. On the whole, salinity generated by industry in Utah is probably less than that of urban and domestic sources (U. S. Water Resources Council 1971). Indeed many small industries of the state dispose of their wastes in municipal disposal facilities.

CONTROL OF SALINITY BUILDUP

General Background

As there are two fundamental processes that lead to salinity buildup, there are two basic control approaches, the addition of fresh water or the reduction of salt loading. The analysis required to select a specific approach needs to find a method that will work physically and be practical in terms of relevant legal, economic, political, and environmental factors.

Approximately half of Utah's land drains into the Colorado River where damages to Lower Basin users and an international treaty provide the incentive for salinity-control measures. Although the other half of Utah with the great majority of its population drains into Great Basin salt sinks, the federal government now requires all states to follow nationwide water-quality regulations. In contrast to the humid eastern states, Utah may have good reasons to permit salinity buildup through more cycles of beneficial reuse of water. Numerous factors need to be considered in the development of a state philosophy on salinity control.

It may be economically unfeasible to reduce water salinities in Utah unless additional reuse of the waters can be made to generate the needed funds. Salinity control activities may violate some economic, legal, or other constraints at one locality, but not at another. At any given locality the most efficient process may not be allowed and a physically less desirable scheme of salinity control would then have to be adopted. A selection of alternatives will have to be made for the solution of each specific salinity problem. In some

cases salinity buildup is accompanied by an increase in contamination. Controls aimed at the reduction of contamination could be more stringent than if salinity were the only problem. Salinity is not usually considered to be a contaminant until it reaches such high concentrations that the water is rendered unfit for most ordinary uses.

There are numerous variations and combinations of the two basic salinity-control methods. Downstream water users generally benefit the most from net salinity improvements; consequently, cooperative schemes along a stream could be more successful in controlling salinity than individual efforts at one locality. Ultimately, water management methods are going to have to recognize that different water users are affected differently by salinity and match the salinity in available waters with needs.

Means of Controlling Salinity Buildup

Weather Modification

A measurable increase in precipitation can be achieved through cloud seeding techniques developed during the past 30 years in the western United States. Increases in annual precipitation as high as 15 to 20 percent may be attainable under favorable conditions in certain mountainous areas. Increased precipitation would mean increased runoff, infiltration, and groundwater supplies, all of lower salinities.

Vegetative Techniques

Recent experiments in clearing alternate strips of mountain forests

have demonstrated the possibility of obtaining greater net runoff and infiltration of snowmelt. Considerably less moisture is lost to vegetative interception and slightly more snow falls in such cleared areas. Techniques that increase net runoff and infiltration should be of value in reducing salinity in streams and groundwater.

The removal of vegetation from forested areas also would salvage considerable moisture that otherwise would be lost to transpiration. According to Hart and Lomas (1979), areas completely cleared of dense stands of spruce and fir trees in Utah would consume about 2400 gal/ac/day (22 m³/ha/day) less during the summer than before clearcutting. This could mean more runoff and infiltration of fresh water to reduce salinity in streams and groundwater if patterned logging is encouraged and erosion and re-vegetation are adequately controlled. A positive erosion control program combining minimum soil disturbance, quick re-establishment of vegetative cover, and treatment of disturbed areas during the intervening period would probably be necessary for effective salinity control. Economic justification of such a program depends more upon the enhanced water supply and land use benefits than upon reduced salinity alone.

The eradication of phreatophytes and hydrophytes along streams and in wet areas in Utah could result in a large salvage of fresh water and a consequent reduction in salinity buildup. This generally worthless vegetation, largely spread by man's negligence, is found in high mountain valleys as well as in desert lowlands where surface waters and groundwater are at or near the land surface. Where they are of value in erosion control, phreatophytes should be replaced by productive crops or by vegetation that does not waste water. Drainage of wetlands does not always eliminate phreatophytes. Most of them, once established, are able to send roots to considerable depths in

the subsoil to obtain water. This is not to suggest the eradication of productive crops which happen to be phreatophytes, such as alfalfa. The removal of phreatophytes is no longer a simple political problem since they are considered by some persons to provide valuable wildlife habitat, while others consider both the phreatophytes and the wildlife to be costly, detrimental, and artificially implanted.

Evaporation Reduction

Evaporation from lakes, streams, seeps, and wetlands not only increases salinity, but loses a valuable resource at the same time. The narrowing of stream channels, the filling of oxbow lakes, and the drainage of wetlands would all reduce excess evaporation and its resultant salinity buildup. The basic tradeoff here is with possible environmental harm to wildlife habitat.

There are substances which could reduce lake evaporation if spread as a thin monomolecular film on lake surfaces (Hughes et al. 1974). However, these have not been used much in the past because they are costly and are dispersed by wind and wave action and some may interfere with vital processes of aquatic life and human recreation. Two approaches to reducing lake evaporation hold some promise. One is the diking of broad shallow areas of lakes where the added water storage is not worth the evaporation loss that accompanies it. The other, for deeper lakes, is a method of thermal destratification to suppress evaporation described by Hughes et al. (1975). This technique appears to have additional benefits of enhanced water quality and habitat for aquatic life. The estimated annual potential volume of water salvageable by destratification of Lake Powell is about 140,000 ac-ft (17,300 ha-m) (Hughes et al. 1975). The power generating capacity of this much water, the salinity reduction, and enhanced water supply for Lower Basin users certainly should make this a viable scheme.

Utah Lake is a good example of a large shallow lake that suffers an enormous loss of water to evaporation. The useful storage capacity of Utah Lake is 220,000 ac-ft (27,000 ha-m), and it covers about 80,900 ac (32,700 ha) (U.S. Water Resources Council 1972) with an average depth of less than 7 ft (2 m). Estimated annual evaporation from the lake is 325,000 ac-ft (40,000 ha-m), which is more than half of the estimated inflow (U.S. Bureau of Reclamation 1973). This represents a doubling of salinity concentrations, equivalent to the loading of roughly 240,000 tons (217,000 metric tons) of salt per year assuming the average outflow salinity is over 1100 mg/l as reported by Hely et al. (1971). If groundwater storage were used to hold most of the water now in surface storage, all but a small portion of the lake could be diked off, a considerable amount of salinity buildup could be prevented, and much valuable lake bottom land reclaimed. Even if salinity were to increase in alternative groundwater storage, an enormous amount of water would still be conserved annually. Present plans for the diking of Goshen and Provo bays should reduce evaporation in Utah Lake by only one-third (U.S. Bureau of Reclamation 1973). The Central Utah Project plans to import into Utah Valley an amount of water somewhat less than the total annual evaporation losses of Utah Lake.

The drainage of swamps, springs, and seeps can reduce evaporation by substantially reducing water surface area exposed to the atmosphere. Water from such areas can be conveyed by pipes or ditches to stream channels or points of usage. Waste of water by transpiration usually can be reduced at the same time by this method since such localities are usually choked with nonproductive vegetation.

Numerous artesian flowing wells in the state are allowed to flow continuously to waste. Sometimes small wells pumped by windmills are allowed to

overflow. Such needless exposure of water to evapotranspiration by non-beneficial vegetation leads to significant water loss and salinity buildup.

One of the main advantages of storing water underground is that little or no evaporation takes place. In some areas the storage of excess surface waters underground is a viable alternative to surface reservoirs. This could be a significant measure to reduce salinity buildup in Utah. An offsetting disadvantage is that many aquifers contain soluble minerals which dissolve in the stored water and this may partly offset the reduction in salinity buildup afforded by underground storage. Aquifers used for artificial recharge and storage should contain a minimum of soluble matter. Although evaporation does not occur to any significant extent underground, there may be some small losses of the stored water by seepage away from the main aquifer. Water stored underground might in some localities raise the water table high enough to cause undesirable effects, but a well managed groundwater reservoir can result in improvement of water-logged areas.

Extraordinary Water Supplies

The importation of high quality water will reduce salinity buildup by allowing more beneficial use of local water supplies before salinity limitations are reached. Of course, the importation of water implies also the importation of dissolved minerals and the burden of disposal of those salts.

Exportation of water may imply salinity buildup if significant quantities of water are removed that otherwise would have provided a higher dilution factor. Sometimes the exportation of water is justified on a salinity basis to prevent the loss of the water to a salt lake or a playa or to lower a water table and thereby to stop evapotranspiration. Exportation of highly concentrated brines to evaporate

tion ponds may also be an important salinity control measure.

Desalination of brackish or saline waters is an effective but very expensive way to reverse salinity buildup. Tertiary treatment of sewage effluents also will accomplish similar results. There have been many small-scale applications for these processes throughout the world but the costs have been too high to use such waters generally for agriculture wherein the greatest quantities of water are needed. Disposal of the brines from desalination plants has to be carefully planned.

Bypass Channels

Many Utah streams cross outcrops of bedrock and alluvial formations that contain large amounts of soluble saline minerals and that are easily erodable. The salinity of such streams and of shallow groundwater in such areas rapidly increases as the water passes over or through these formations. This salinity buildup could be avoided by the use of lined channels built across those areas. Flood waters probably would follow natural channels, but a substantial portion of the annual surface flow and underflow could be diverted.

Saline springs and other point sources of saline waters could be diverted into lined channels to prevent salinity buildup in streams or in downstream groundwater recharge areas. Such waters could then be conducted away to evaporation ponds, salt lakes, playas, or deep aquifers for disposal, or used as a transportation medium. Care must be taken to make sure that concentrated waste waters never reach streams or fresh groundwater reservoirs.

Well Reconstruction

Many old water wells, exploratory wells, and stratigraphic test holes are

abandoned without provision for the prevention of commingling of saline and fresh groundwaters. Any man-made hole, mine shaft, or tunnel may encounter saline groundwater that was not previously in hydraulic communication with fresh groundwaters. Unless these structures are properly sealed to prevent flow between aquifers during and after usage, they can be serious point sources of salinity above and below ground. Active brine disposal wells can leak brine into shallow fresh water aquifers from beneath without any apparent indications at the land surface.

The injection of oil field brines, mine waste waters, and other saline waste waters into deep saline aquifers is a recommended practice to prevent contamination of surface waters and shallow groundwaters. Active water wells should be plugged off where they may have included saline aquifers in their productive intervals and pumping rates should be reduced as needed to prevent the coning upward of saline groundwater into their discharges. Wells with severely corroded casings or grouting failures can permit saline waters to contaminate fresh waters and should be thoroughly regouted or otherwise sealed.

Fresh waters may flow down faulty wells and mix with saline groundwaters below. This does not contribute to salinity buildup, but it does cause the loss of fresh water.

Sometimes pressure ridges can be developed by fresh water injection to inhibit lateral encroachment of saline waters. These measures have been used successfully in some coastal areas to prevent sea water intrusion. A hydraulic doublet (a combination injection-production system) may be effective in preventing vertical coning of saline groundwaters, but only under very favorable conditions. Water wells that induce saline water migration into their own discharge from overpumpage should

be reduced in production rates and supplementary water obtained.

Use of Brackish Water

After all feasible actions have been taken to prevent salinity buildup and nothing is left but brackish or saline waters, one more cycle of reuse of such waters may be feasible under some conditions. In the Arid Basins region which has only internal drainage, any reuse of water that can be made before it is lost to saline lakes or evaporation is desirable. In the drainage area of the Colorado River getting the ultimate use from the water may have to be left to downstream water users. Downstream effects can be partly eliminated by final evaporation or deep aquifer injection.

As salinities increase in a downstream direction, one way to increase water use may be to progressively cultivate more salt-tolerant crops or grasses. By finding ways to live with it, this technique partially counteracts the effects of salinity buildup. Drainage has a bearing on the ability of some crops to grow when irrigated with saline water. If subsurface drainage is sufficiently free, tolerant crops will flourish when saline water is applied that normally would kill them under poor drainage conditions (Rhoades 1977). Highly permeable soils or artificial drainage systems are desirable and necessary when irrigation waters are brackish. Larger quantities of irrigation water are needed under these conditions to flush away the concentration of salt that results from evapotranspiration. Sometimes, waste waters from industry, mining, or sewage treatment plants can be used.

Irrigation Efficiency

The relationship between irrigation efficiency and downstream salinity is complex and uncertain. Efforts to control salinity through increased

irrigation efficiency may not have the expected effects. Implementation of selected salinity control programs may be constrained by economic, legal, and psychological considerations.

Ideally, an increase in irrigation efficiency would reduce downstream salinity buildup by decreasing leaching of the soil and subsoil and leaving more water in the stream for downstream users. Sufficient applied water is still required to move accumulating salts below the root zone, but higher irrigation efficiencies minimize deep seepage of water that can cause unnecessary leaching (Rhoades and Suarez 1977).

Techniques that can be used in reducing salinity buildup include the lining of canals, ditches, ponds, and reservoirs, and the regulation of leaks and waste of water on land surface. The use of trickle irrigation and other more efficient methods of application, irrigation at night to reduce evaporation losses, irrigation scheduling, and the use of hothouses and hydroponic farming of truck crops could also contribute to a reduction in salinity buildup. The leveling or grading of irrigated land to prevent localized ponding and uneven water application can also increase irrigation efficiency.

The installation of surface or subsurface drains should reduce evaporation by lowering the water table, intercepting water and thereby retard salt leaching from very deep percolation, and still convey highly soluble salts away from the root zone. New drains may cause a short-term increase in salinity as the surface soils are leached, but should cause an overall reduction in the long range by reducing evapotranspiration and deep percolation (Rhoades 1974).

More drastic methods of reducing salinity buildup include the elimination of irrigation of highly saline soils and the transfer of irrigated agriculture to soils of low salinity. Water applications on lands of exceptionally high

soil and subsoil permeabilities should be carefully managed to prevent waste of water and excessive leaching with the deep percolation often associated with the large water applications used to irrigate crops on such soils. Irrigation with municipal waste waters may not reduce salinity buildup directly but could free high quality water for dilution downstream.

The uncertainty associated with predicting the effects of these measures largely stems from the variability found in soils, underground formations, and subsurface flow paths. Different geohydrologic conditions can make major changes in the effectiveness of alternative salinity control measures.

Miscellaneous

Occasionally high quality waters encounter highly mineralized formations such as evaporites and pyroclastics. The diversion of these waters before the encounter could effect a measure of salinity reduction. Such an alternative could be very costly, especially for groundwater, but is physically possible. The suppression of saline groundwater discharge is another possibility that could be effective in some cases.

The use of salt for road de-icing and for water softening is a small but locally significant cause of salinity buildup in Utah. Perhaps nonsaline substitutes can be found for these activities.

Reversal of Hydraulic Gradients in Arid Basins

Groundwater Recirculation

Several arid basins of western Utah contain closed or nearly closed groundwater basins. Some of these basins have very shallow water tables or playas in their topographically lower areas where water is wasted to the atmosphere by evapotranspiration and residual salts accumulate. Groundwater is used for

irrigation in several of these basins. Hydraulic gradients naturally were low before pumpage for irrigation began in the lowlands of those basins. Under these circumstances, natural hydraulic gradients are reversed and large groundwater sinks can be created where pumpage is considerable. If subsurface conditions permit, this can lead to recirculation of groundwater and the inducement of saline waters into the system from areas of natural discharge or from deep groundwater sources.

Recirculation of groundwater can cause salinity buildup due to the concentration of salts by evapotranspiration and by the leaching of the soils, alluvium, and intervening geologic formations through which the returning waters percolate. Often groundwaters are more saline than surface waters, and thus their salinities start from a higher level with correspondingly less latitude for tolerable salinity buildup. In some areas where groundwater is less saline than surface waters, it can be used to dilute the surface waters for irrigation, but recirculation of this mixture can still eventually lead to salinity buildup. As water consumption leaves salt, salts accumulate in any system without a natural outlet, and man's use of water tends to accelerate salinization and spread these salts over a larger area.

Some groundwater is pumped from confined aquifers and recirculation is not possible. In this case salinity may often be washed below the root zone where it will effect neither the topsoil nor the principal aquifers. Partially confined aquifers may still be subject to the salinity buildup associated with recirculation. The flow paths of recirculating groundwaters can be quite circuitous, adding greatly to both travel distance and travel time. Longer travel time may not impede ultimate salinity buildup because the overall exposure to soluble minerals underground remains about the same. Reduced exposure to evapotranspiration,

however, will minimize salinity buildup. One recirculation cycle may take as much as several years to complete, and a given system will normally contain flow paths of greatly varying flow lengths and encounters with evapotranspiration and soluble minerals. Water management programs for such basins need to emphasize water use patterns that will minimize water movement along flow paths that accelerate salinity buildup and perhaps the discharge of salt brines to locations where they can no longer reach the principal aquifers. Further analysis of these problems requires examination of specific examples which follow. (See Figure 1 for locations.)

Beryl-Enterprise District

In some areas of Utah sizable groundwater sinks occur due to pumpage for irrigation and other uses. If the aquifers tapped in these localities are unconfined or only partially confined, then the hazard of salinity buildup is present due to recirculation and reuse of groundwater. Even in cases of confined aquifers, there is the possibility of inducing saline groundwaters to flow into a sink from closely associated aquifers of low-quality water.

A groundwater sink has existed in the Beryl-Enterprise district of southwestern Utah since 1964 (Bolke et al. 1973). This closed water table depression has increased the amount of deep seepage from irrigation that is recirculated and has caused a modest salinity buildup (Mower 1981). As the water table depression expands, poorer quality water will move laterally into the sink from the north and east, thus accelerating the salinity buildup (Handy et al. 1969).

Milford Area

Although no significant reversals of hydraulic gradients have taken place around Milford, there is an area south of Milford mainly irrigated with groundwater where a portion of the groundwater

supplies is probably being recirculated. Partial recirculation can take place where there is no large groundwater sink. Records of old wells in the general area show that the groundwater is recharged locally by deep percolation from the irrigated lands, canal seepage, and occasionally by the Beaver River (Waite 1954). Water levels in the area have declined generally since heavy pumpage began.

Groundwater quality in the Milford area has deteriorated over time, apparently from recharge by irrigation water or from encroachment of poorer quality groundwater whose movement is induced by pumpage for irrigation (Mower and Cordova 1974). The principal groundwater reservoir of the area is composed of unconsolidated Quaternary deposits without effective confining strata. It was estimated that in water year 1971 approximately 53 percent of the recharge to the principal groundwater reservoir in the Milford area was derived from infiltration from farms and from canal losses (Mower and Cordova 1974). Another strong contributor to salinity buildup is the waste of groundwater by evapotranspiration, mainly by phreatophytes, in the area's lowlands. Annual losses were estimated by Mower and Cordova (1974) to be 24,000 ac-ft (3000 ha-m) in 1971.

Pavant Valley

Some areas of Pavant Valley are pumped heavily for irrigation, and the hazard of salinity buildup is present. All districts of the valley show long-term water level declines due to pumpage of groundwater, especially in the McCornick, Greenwood, Pavant, and Kanosh districts (Herbert et al. 1980).

The dissolved solids in the waters of two wells located in the Kanosh district of Pavant Valley have increased from about 2000 mg/l to more than 5000 mg/l, while water levels have declined generally in that vicinity since 1957

(Herbert et al. 1980). The salinity increase is due to recirculation of irrigation water (Mower 1967) and from the inducement of poor quality groundwater into the vicinity from the north and west by the heavy pumpage. A water table depression has formed in Township T23S, R6W, and an estimated 25 to 50 percent of the annual pumpage there returns to the groundwater reservoir, where it can be recirculated (Handy et al. 1969).

The recent infestation of saltcedar in Pavant Valley is a serious threat to agriculture in the valley because of the water it wastes. These detrimental plants should be eradicated (Mower 1965).

Sevier Desert

Groundwater quality has deteriorated in the shallow artesian aquifer in the lower Sevier River valley near the town of Lynndyl. This increase in salinity is due to infiltration of inferior quality water (that has already been used and reused a number of times by upstream irrigators) from the river, from canals, and from irrigated lands. Near Delta a body of relatively fresh (TDS as low as 250 mg/l) shallow groundwater is percolating slowly toward the southwest. These waters originated from recharge from the Sevier River before irrigation was practiced upstream, and they are followed by more saline groundwater derived from more recent river recharge (Mower and Feltis 1968). Recirculation of these irrigation return flows will, if continued, lead to further deterioration of the water quality.

An estimated 135,000 to 175,000 ac-ft (17,000 to 22,000 ha-m) of groundwater are wasted annually in lowlands of the Sevier Desert through evapotranspiration in areas mostly covered by phreatophytes (Mower and Feltis 1968). Accordingly, a large salt residue has formed in the lower reaches of this closed basin. Pumpage for irrigation

has caused a decline of groundwater levels in the Delta area resulting in some water saving.

No appreciable groundwater sinks have developed yet that could reverse the flow of saline water back into the wells from the lowlands, but the hazard could develop in the future. The cooling water demands of the Intermountain Power Project, the largest fossil fueled power complex in the world, will have to be carefully managed to avoid substantially altering the present water supply system and consequently the salinity balance of the area. The project plans to remove salt from the region by discharging it to evaporation ponds for permanent storage.

East Shore Great Salt Lake

Water levels have declined in certain portions of the East Shore area of the Great Salt Lake since the 1950s (Herbert et al. 1980). The decline has not been universal because the increased use of surface water in the area has redistributed groundwater recharge. Significant reductions in water quality have not been associated with the water level declines, except possibly in a small area near Woods Cross (Bolke and Waddell 1972). Groundwater percolates in artesian aquifers from the east towards the Great Salt Lake and slowly rises into the lake shore area. Feth et al. (1966) estimated that something on the order of 20,000 ac-ft (2500 ha-m) of groundwater leak into the lake annually from the East Shore area. If the prevailing hydraulic gradients are reversed by pumpage, saline lake water could be induced into shallow aquifers of the East Shore area.

Cedar City and Parowan Valleys

The quality of groundwaters in the Cedar City and Parowan basins generally is very high. However, water levels are declining slowly due to pumpage, mainly for irrigation. There is very little

outflow of surface and subsurface water from these basins. Therefore, practically all of the groundwater leaving these basins is by means of evapotranspiration, estimated by Bjorklund et al. (1978) to be approximately 87,000 ac-ft (11,000 ha-m) annually. Likewise a considerable amount of surface water also leaves the basins by evapotranspiration. Despite the high water quality, this evapotranspiration adds substantially to salt concentration, and salts are accumulating in the lowlands of the basins. The groundwaters of the basins are unconfined to partially confined; consequently, recirculation of irrigation waters may be occurring. Evidently no significant groundwater sinks have developed, but the possibility is present if water levels continue to decline. Salinity buildup is occurring in groundwater in the heavily pumped areas where recirculation is probably taking place (Bjorklund et al. 1978). Continued water level declines could readily induce salts to move from the playas and lowlands into the irrigated areas.

Curlew Valley

In the Kelton area of Curlew Valley in Northern Utah unconfined groundwater has deteriorated in quality and water levels have declined in response to irrigation pumpage. Apparently a small groundwater sink has formed around some irrigation wells; but due to the low permeability of the subsoils, only about 10 percent of the pumped water returns to the aquifer for recirculation (Baker 1974). Nevertheless, the increased salinity is attributed to recirculation of irrigation waters by Baker (1974). There are also deeper saline waters present that may be induced into the pumped area.

Leaching of Saline Minerals

Saline Formations and Springs

There are areas in Utah where severe salinity buildup occurs with

the solution of saline minerals by percolating groundwaters. When such waters emerge as springs or are pumped from wells, they contribute substantially to deterioration of surface water quality and limit the use and reuse of other local waters with which they mix. Natural deposits of halite, gypsum, anhydrite, other evaporites, marine shales, pyroclastics, and other saline bedrock or alluvial formations are the main salt sources. Many springs in Utah are naturally saline. Their locations and characteristics have been described by Milligan et al. (1966) and by Mundorff (1970, 1971).

Uinta Basin

In the Uinta Basin, surface and groundwaters increase in salinity as they move downstream toward the Green River. The rise is predominantly in sodium and sulfate ion concentrations (Mundorff 1977). Early Tertiary and Cretaceous saline sedimentary formations, as well as alluvium derived from these formations, underlie the areas where salinities increase. The main causes of salinity buildup are believed to be agricultural return flow, canal seepage, and waterlogging from irrigation adding to the natural contact with these saline formations. Canal losses in northern Uinta Basin are probably more than 10 percent of their flow (Hood and Fields 1978). The Steinaker Reservoir has caused a salinity increase in Ashley Creek due to evaporation from the reservoir, irrigation practices, and increased total evapotranspiration (Hood 1977). Irrigated agriculture in Uinta Basin annually yields an estimated 220,000 tons (200,000 metric tons) of salt to the Colorado River system and reduces flow by about 447,000 ac-ft (55,000 ha-m) (USDA-SCS 1979).

Currently there is an average increase to about 700 mg/l in dissolved solids concentrations in the Duchesne River from the highlands of the Uinta Mountains to the lower reaches approaching the Green River (Hood and Fields

1978). Exportation of high quality water from the Uinta highlands by the Central Utah Project may further increase salinity in the Duchesne River by an estimated 50 percent near Randlett and will reduce stream flow at the same time (Mundorff 1977). During periods of low flow, groundwater supplies most of the streamflow, and dissolved solids sometimes exceed 3000 mg/l in the lower reaches of major streams in the basin. The Mancos Shales, the Uinta Formation, and the Green River Formation are among the chief sources of salinity. Some streams of the basin lose water in their upper reaches and regain the water downstream after it has gained appreciable salinity while percolating underground (Willardson et al. 1979).

Certain soils have a high buffering capacity that causes them to behave as salt sources or salt sinks (Willardson and Hanks 1976). Some soils in Ashley Valley of Uinta Basin have this high "buffering" capacity. By adjusting irrigation management practices, salts can be accumulated within soil zones above the water table for several years and then released as desired without affecting crop yields (King and Hanks 1973, 1975). However, in a practical sense this would be very difficult to accomplish on a large scale. Over long periods of time, a salt balance would have to be maintained, but releases could be made on a calculated schedule in wet years (Jensen 1975).

Price River

Surface waters in the central portion of the Price River Basin have a salinity buildup due to contact with Mancos Shales and other saline formations, irrigation return flow from saline subsoils, and to a limited extent from municipal wastes. Mundorff (1972) reports that surface waters entering the central portion of the basin in 1969 and 1970 contained dissolved solids concentrations less than 400 mg/l, whereas flows leaving the central portion were in excess of 2700 mg/l.

San Rafael and Dirty Devil Basins

The San Rafael River Basin and the Dirty Devil River Basin yield relatively high quantities of salt to the Colorado River. These increases in salinity are likewise attributed to contact with saline geologic formations in the lowlands augmented by agricultural activities. These two river systems yield an estimated 200,000 tons (182,000 metric tons) of salt per year each to the Colorado River including suspended saline sediments.

Central Sevier Valley

In addition to the general salinity buildup in a downstream direction within the surface waters and groundwaters of the Sevier River Valley, stepwise increases in salinity occur in areas with exposed saline geologic formations. The marine Arapien Shale is the source of much of the salt in the Sevier Valley.

Saline groundwater occurs mainly in the Redmond-Gunnison subbasin of the Central Sevier Valley and along the east side of the Aurora-Redmond subbasin in association with the Arapien Shale, which outcrops extensively on the east side of both subbasins. The discharge of groundwater from areas underlain by the Arapien Shale at or near the surface adds dissolved minerals to the surface waters there (Young and Carpenter 1965). Rock salt is mined from a small outcrop of Arapien Shale on the Redmond Hills anticline about 2 3/4 mi (4.4 km) west of Axtell, Utah, and gypsum is found in the Arapien Shale at many localities.

A very large increase in salinity occurs in the Sevier River near Richfield. A nearly two-fold increase occurs in the river between Sigurd and Salina and another significant increase occurs between Redmond and Gunnison (Hahl and Cabell 1965 and Christensen et al. 1979). These pro-

nounced salt increases are believed to be due largely to salt leaching from the Arapien Shale in those vicinities.

Shallower aquifers in the Central Sevier Valley yield more saline waters than do the deeper aquifers, and alkali and salts have accumulated locally on the land surface. The lowering of water levels by increased pumpage would stop the surface accumulation of salt and probably reduce salinity in some shallower aquifers (Young and Carpenter 1965).

Juab Valley

In southern Juab Valley, sediments derived from the Arapien Shale contribute chlorides and sulfates to waters along the east side of the valley. Nearer the center of the valley, groundwaters are slightly saline due to erosional products from the Arapien Shale, recirculation of irrigation water, and to evapotranspiration from natural wetlands on the valley floor (Bjorklund and Robinson 1968).

Hypothetical Considerations

While salinity control measures ideally should be initiated with the beginning of water usage, this has rarely been done. To provide better appreciation of the rates at which salinity may increase and how effective remedial actions may be, a few hypothetical cases will be considered. This type of analysis is useful for the planning of salinity control measures.

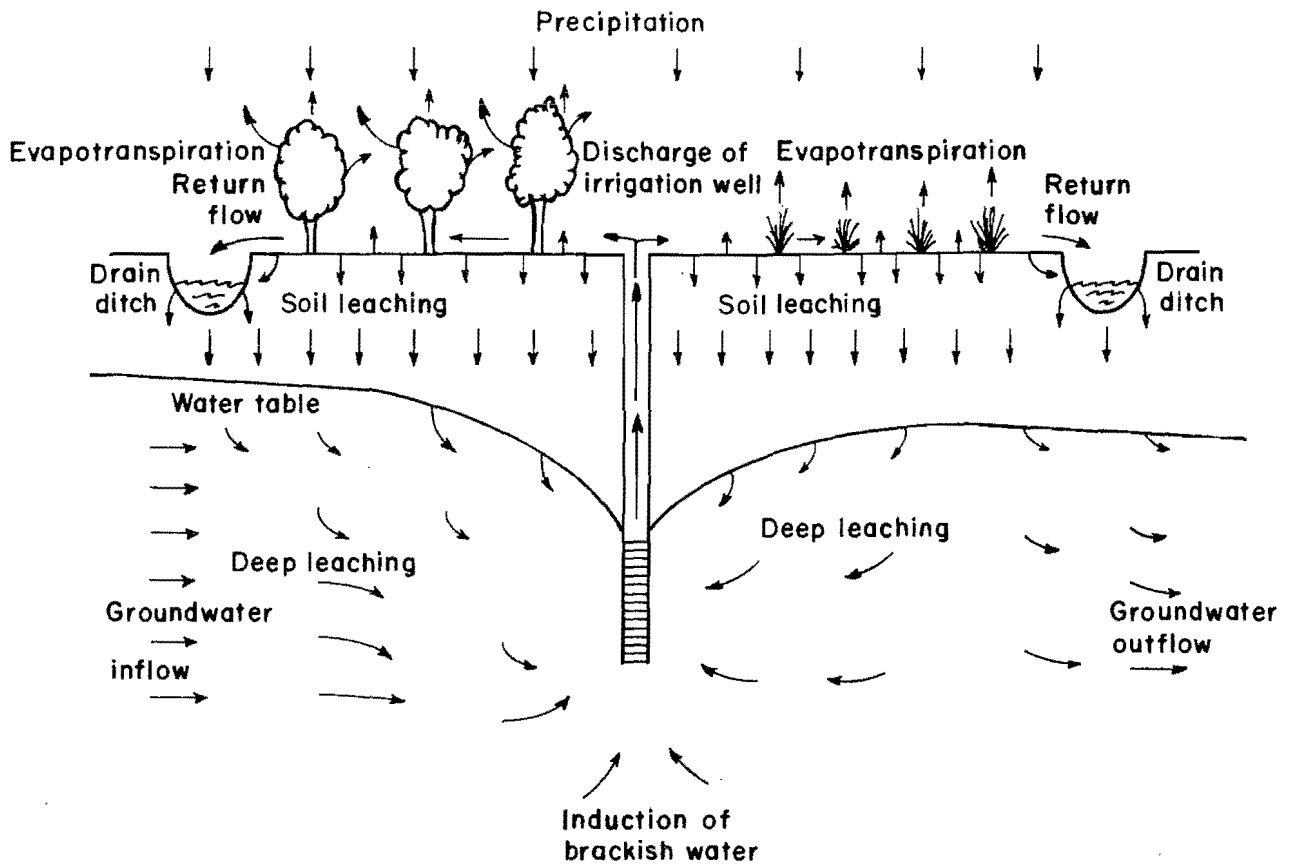
A study should begin by examining the physical conditions of the specific locality under investigation. Sketch maps and profiles should be made depicting the known physical conditions both above and below ground level. Figure 2 illustrates how these sketches may appear. This particular example shows a groundwater sink with recharge. If no groundwater recharge were present, then the left half of the diagram would look more like the right half. Once all known

relevant physical aspects of a problem are recognized, a more generalized water and flow chart should be constructed as a guide for mathematical or computer analysis. Figure 3 is a flow diagram that might accompany the example of Figure 2. Both water flow and salt transport can be accounted for, but some steps may be omitted if it is known that physically those particular processes are not significant. Figure 4 is an example of a more complex groundwater-surface water flow chart that may be employed in one of the ensuing hypothetical cases with conjunctive use.

The first and simplest case to be considered is that of a closed groundwater basin or a groundwater sink with a single water table aquifer wherein there is no recharge, leaching, chemical precipitation, or saline water intrusion (a much simplified case of Figures 2 and 3). If this basin or part of a basin is irrigated using the groundwater only, salinity will increase in proportion to the amount of evapotranspiration by crops, assuming no surface return flow is exported from the basin. If an initial average salinity of 500 mg/l is assumed for the system and 2 percent of the basin's groundwater reserves are extracted and applied to crops annually, the average salinity of the system will rise with time, depending upon the irrigation efficiencies as shown by the family of curves drawn in the lower and right-hand portions of Figure 5. Irrigation efficiencies of 60, 70, 80, and 90 percent were assumed for the 2 percent as well as for 4 and 8 percent annual extraction rates also shown on Figure 5.

When the deep percolation from excess water applied at the land surface reaches the water table, it is highly concentrated, depending on the irrigation efficiency, and tends to accumulate upon the top of the unconfined groundwater body. A tenfold increase in salinity results from a 90 percent irrigation efficiency providing there is no chemical precipitation of

a) Profile



b) Plan View

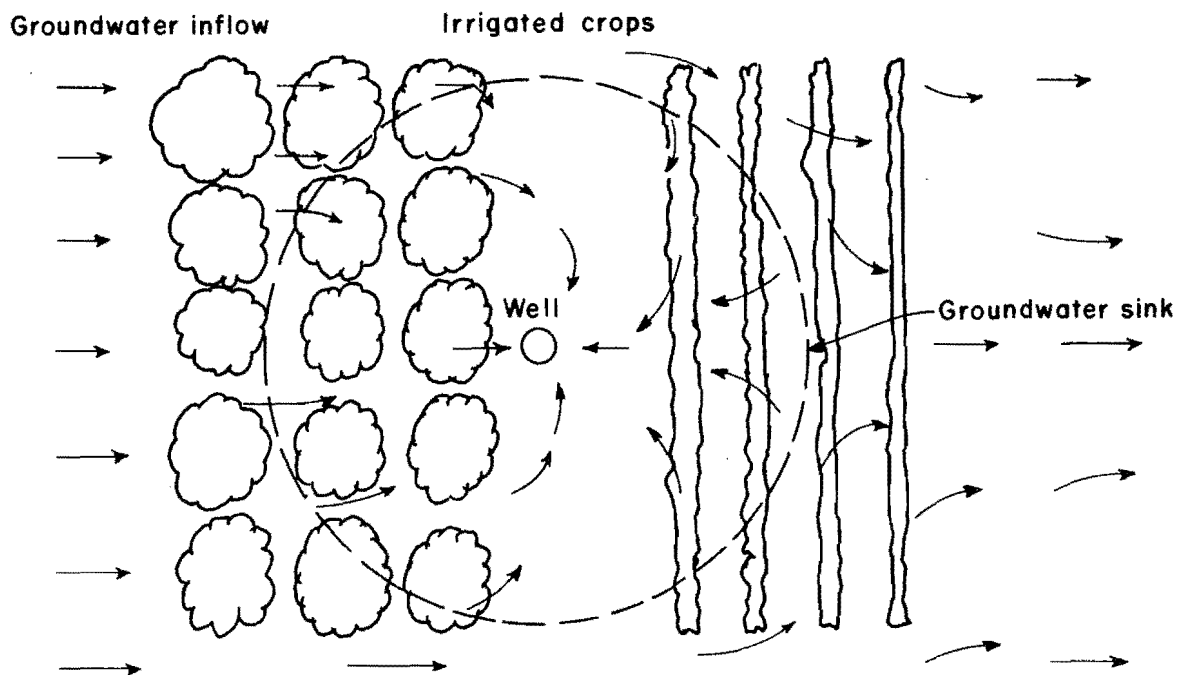


Figure 2. Generalized water flow diagram for groundwater sink with recharge.

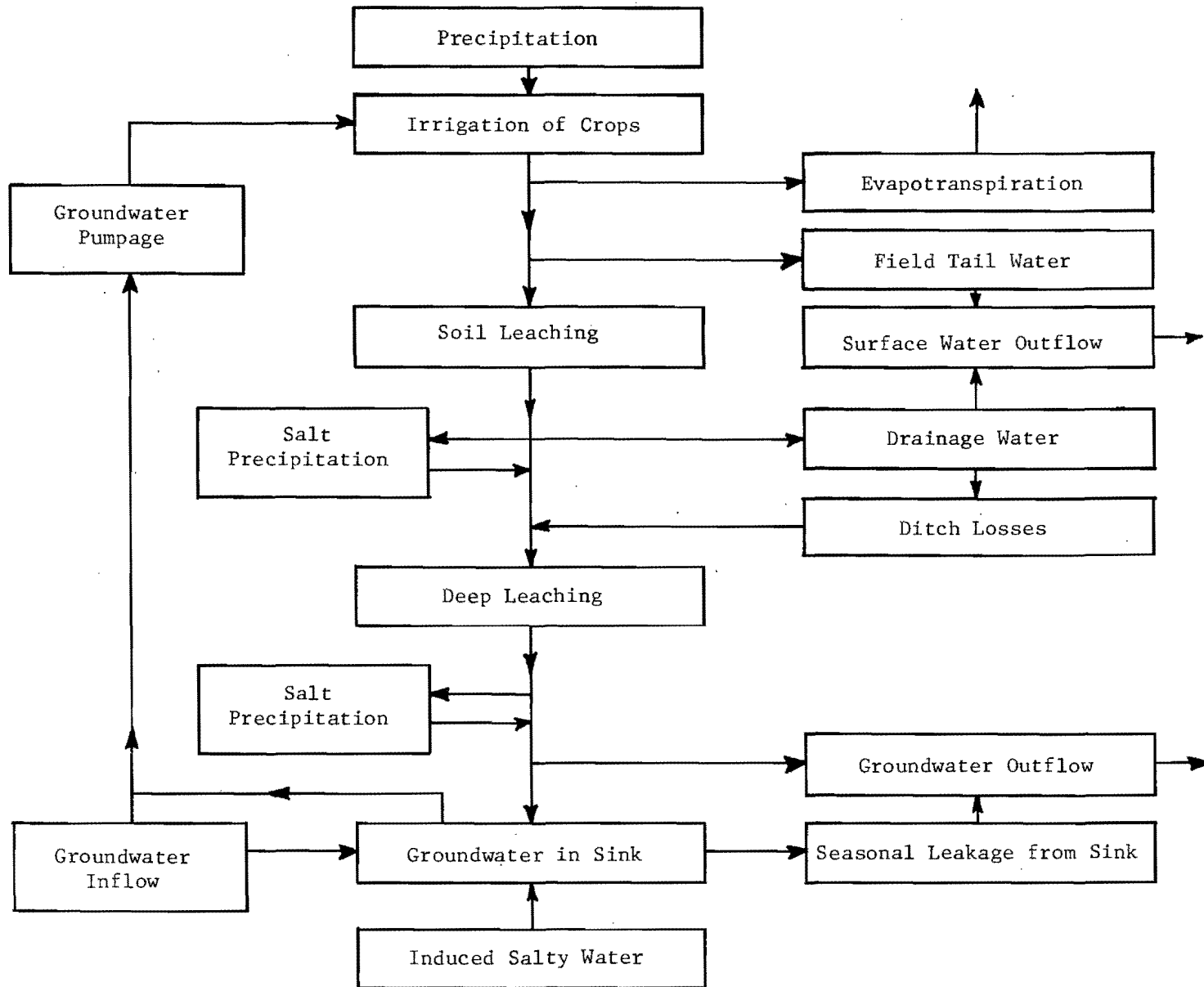


Figure 3. Water and salt flow chart for groundwater sink.

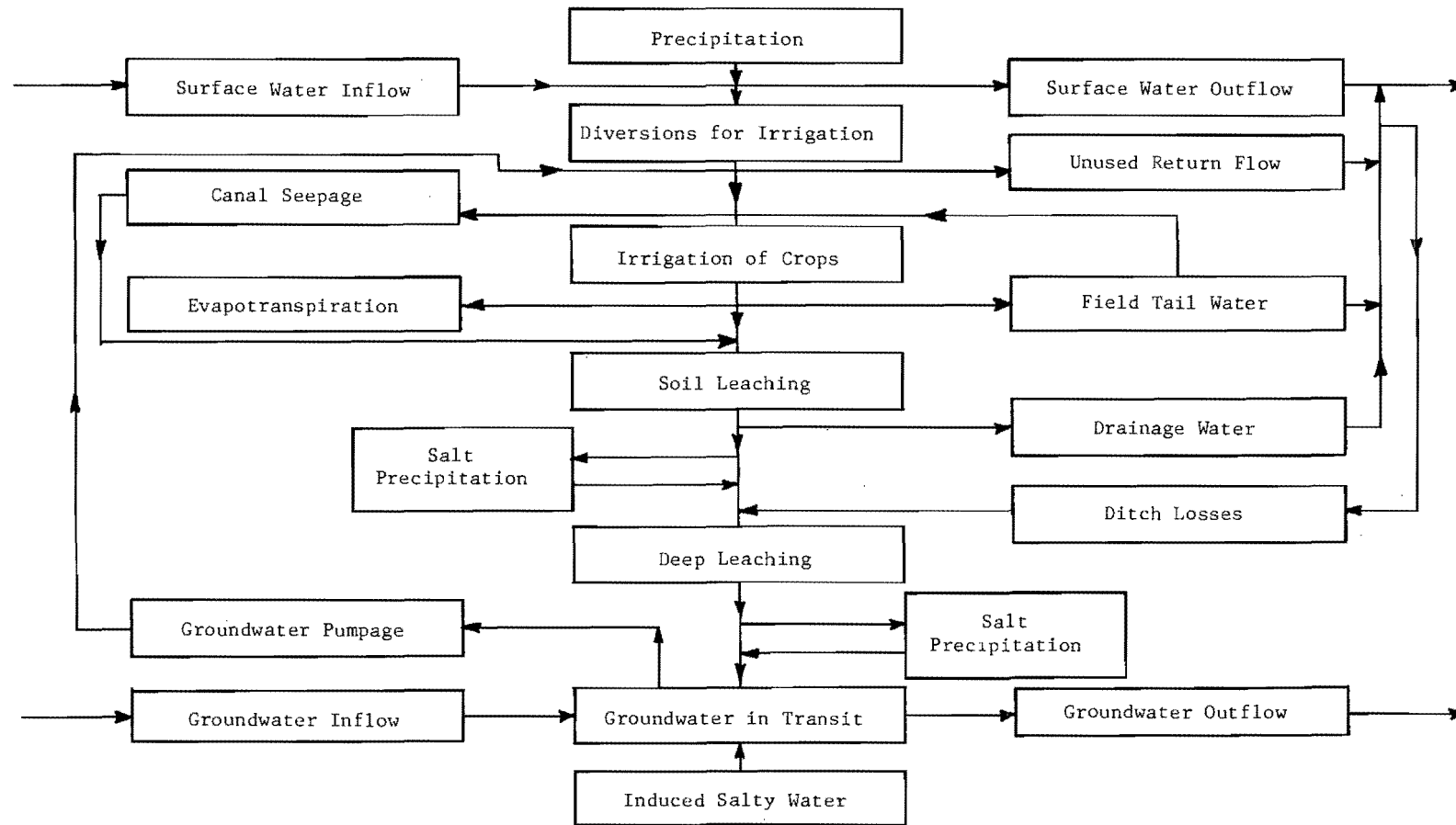


Figure 4. Water and salt flow chart for conjunctive use irrigation.

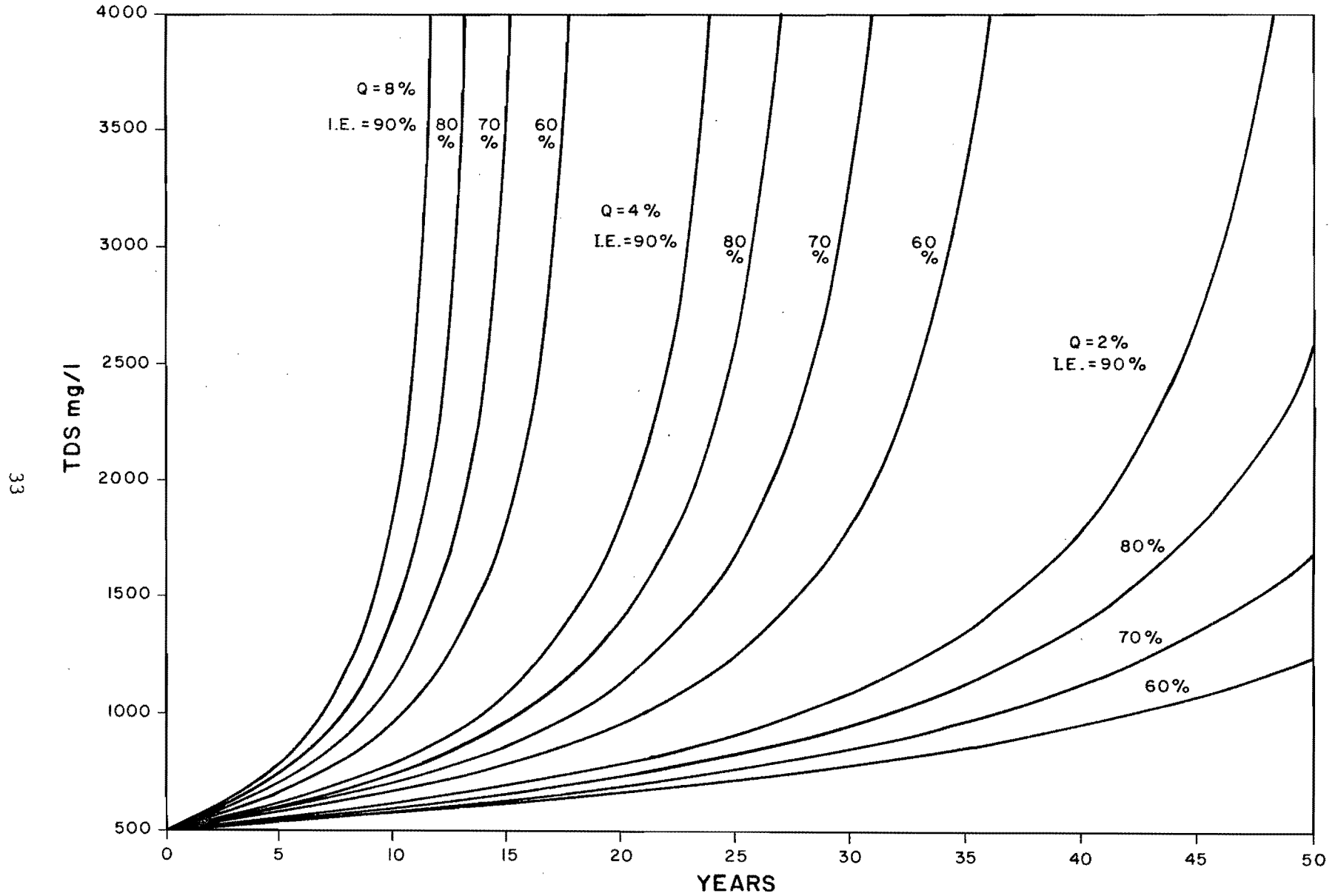


Figure 5. Salinity buildup curves for various hypothetical discharge rates and irrigation efficiencies in a simple groundwater sink.

salts below the land surface. For the purposes of these examples, it is assumed that the saline return water all moves laterally to enter the fully penetrating well or wells from its position atop the main groundwater body. It is further assumed that the saline water moves into the wells in proportion to its thickness of accumulation on top of the fresh water and that the wells then yield water of a salinity equivalent to the average salinity of the entire closed reservoir under consideration.

In nature, stratification of the shallow formations often delays the return of used saline water to the underground reservoirs, and wells do not usually produce from the entire aquifer thickness. For these reasons, salinity buildup in the discharge of wells may not be as rapid as the hypothetical curves indicate. The higher irrigation efficiencies in each family of curves imply that correspondingly more crops are produced from the same amounts of pumped water. Thus the ratio of salinity levels to crops produced is the same for each family of curves. The relative size of the bounded aquifer or groundwater sink obviously has a great effect upon actual salinity buildup as controlled by the percent of the water extracted annually.

When the groundwater is recharged by independent underflow of 500 mg/l TDS, salinity buildup is appreciably mitigated. If, for example, in the case where 2 percent of the reservoir volume is pumped annually and the water is used with an irrigation efficiency of 70 percent, an annual recharge equal to the net groundwater extraction (evapotranspiration losses) will cause a linear salinity buildup as shown in Figure 6. At zero time the line depicting this buildup is tangent to the curve in Figure 5 that represents 70 percent irrigation efficiency. Had another irrigation efficiency been used in this example, the salinity buildup line would have been tangent to the

curve representing that irrigation efficiency. Also shown on Figure 6 are curves depicting intermediate rates of recharge corresponding to 50 percent and 25 percent of the net groundwater extractions. Any form of recharge by low salinity water will tend to suppress, but not stop, salinity buildup when groundwater is used for irrigation. When the groundwater system is not closed and groundwater is both entering and leaving an area under consideration, water quality generally will be sustained in that area, but a plume of more saline water will drift along with the regional flow.

On the other hand, if salinity is added to the groundwater system by the leaching of the subsoil, alluvium, or other geologic formations, or by the intrusion of saline groundwaters induced by the pumpage, salinity buildup will accelerate above the rates established for the normal production of crops. In Figure 6 is shown the salinity buildup anticipated when 50 mg/l and 150 mg/l, respectively, of TDS are leached by deep percolating return flow. The effects of leaching alone are relatively small compared to the salinity buildup due to evapotranspiration. Were corresponding amounts of salts to be deposited in the subsurface formations by chemical precipitation, then the two curves would be plotted equal vertical distances below the 70 percent irrigation efficiency curve. In areas of Utah where saline formations are known to occur, salinity increases due to leaching could be appreciably higher than those modest values depicted in Figure 6.

When brackish or saline waters are induced into pumping wells, salinity increases may be accelerated as shown in Figure 6 wherein salinity buildup is indicated for two hypothetical cases. One curve represents the theoretical increase of salinity for an induced surcharge of brackish groundwater of 5000 mg/l of TDS that amounts to 5 percent of the water pumped annually in the example

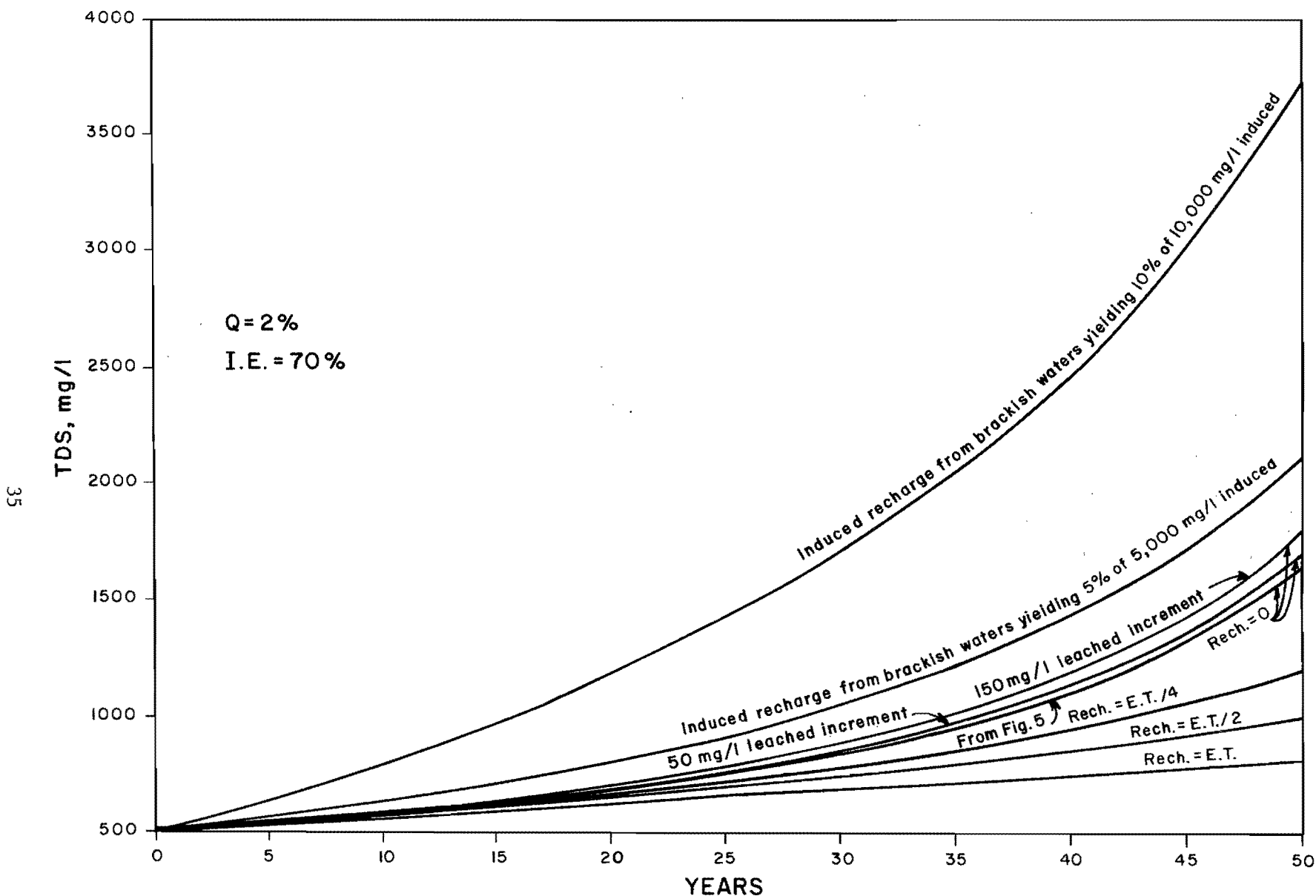


Figure 6. Salinity buildup curves for various hypothetical recharge rates, leaching rates, and brackish water induction rates.

of Figure 6. The other curve represents an extra 10 percent of 10,000 mg/l TDS groundwater added to the annual pumpage. The intrusion of saline waters can be appreciable in some cases as shown in this example. Much higher salinities than 10,000 mg/l exist in some groundwaters of Utah. The foregoing examples were given to illustrate the effects of various phenomena taken one at a time. These effects regarding salinity are usually compounded in actual practice and an infinite variety of hypothetical situations may be portrayed by algebraically adding possible effects.

In addition to the remedial effects of natural or artificial recharge as illustrated on Figure 6, other remedial methods may be investigated in a similar fashion. Methods of salt removal may be studied as well as those of dilution. Unfortunately salt removal is a difficult task. The most saline waters of a given groundwater irrigation system exist underground between the root zone and the upper portions of the aquifer.

Horizontal drains have been used successfully to remove saline water from below the root zone although the purpose of drains more often may be the removal of any kind of water to relieve waterlogging and promote plant growth. If salinity is to be controlled, the use of agricultural drains appears to be a practical solution. The permanent removal of such waters from the system poses another problem. Such waters may have to be evaporated to dryness, injected into deep aquifers, or conveyed out of the area.

If relatively high irrigation efficiencies can be attained and drains can intercept reasonably large portions of the concentrated deep percolation water, significant salinity control can result. Figure 7 is an illustration of what may happen under ideal conditions. It is assumed for this example that an 80 percent irrigation efficiency (20 percent return flow by deep seepage) is attained in a closed

groundwater reservoir that is being pumped at the rate of 2 percent of its volume annually. The idealized curve corresponding to these conditions is taken from Figure 5 and drawn on Figure 7. It is then assumed that the water table is shallow enough to allow the agricultural drains to intercept 25, 50, and 75 percent of the deep percolation below the root zone and that this water is removed from the system. These intercepted amounts are equivalent to what is known as leaching fractions of 5, 10, and 15 percent, respectively. The word "leaching" in this case has no relationship to the same word used elsewhere in this report. No recharge, leaching, or other conditions are assumed. A significant control of salinity can be made under these conditions.

If recharge by water of the same salinity is assumed in addition to agricultural drains, other hypothetical cases may be considered. For example, if a groundwater reservoir that yields 4 percent of its volume annually to agricultural use at an irrigation efficiency of 80 percent is drained at a leaching fraction of 10 percent and receives recharge equal to all or half of the net pumpage, then its overall salinity buildup curves would appear as depicted on Figure 8. The salinity buildup curve representing no effects other than the 80 percent irrigation efficiency, as was shown on Figure 5, is shown on Figure 8 for comparison.

In addition to the foregoing examples, the same principles could be used to estimate salinity buildup rates in a wide variety of other situations. When practical applications are made, simplification of the systems is required to keep the hypothetical calculation simple. Consequently, only rough approximations to natural conditions can be made in most cases.

In none of the foregoing examples were salinities ever reduced. It is extremely difficult to reduce salinities

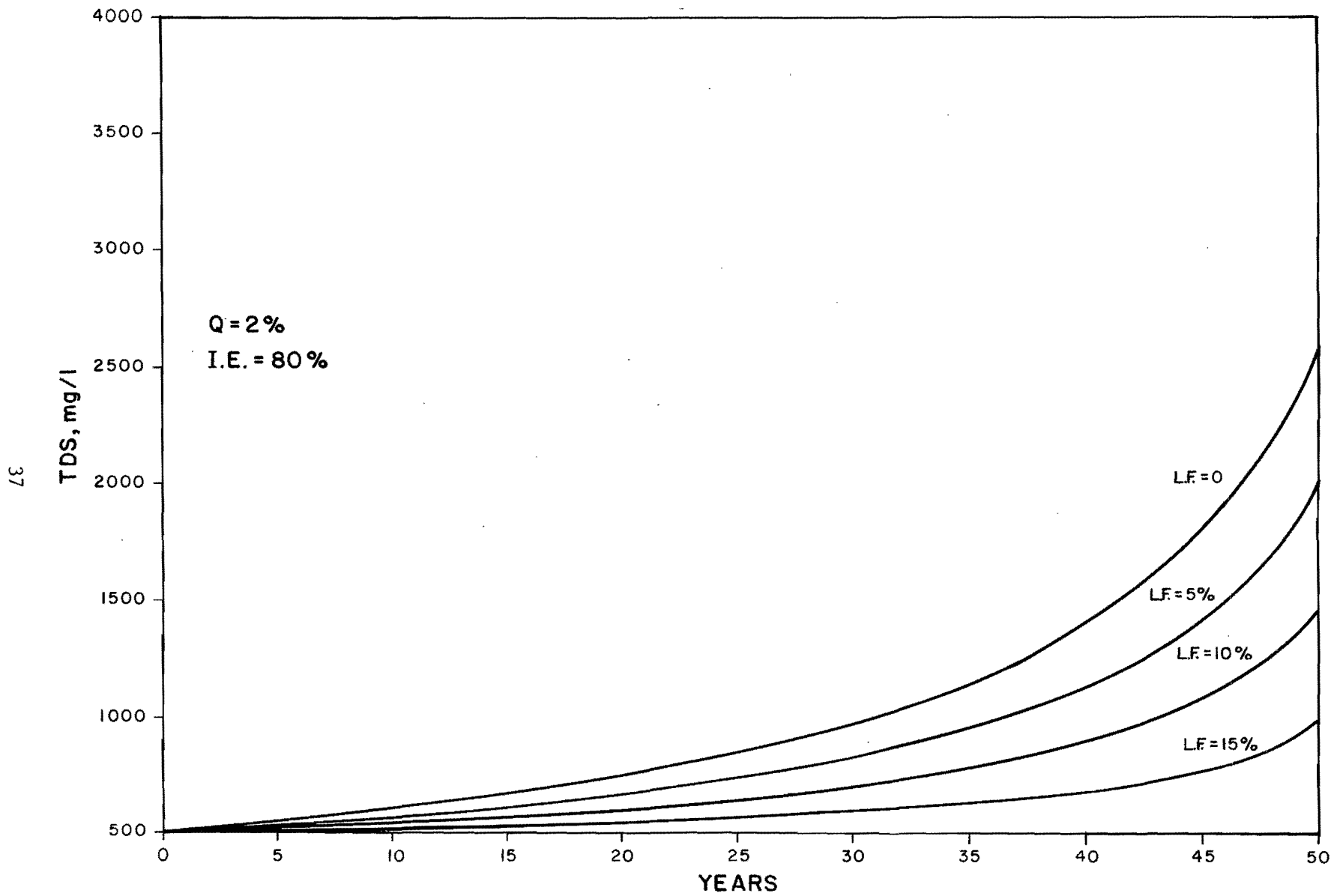


Figure 7. Hypothetical salinity improvement using agricultural drains at various leaching fractions.

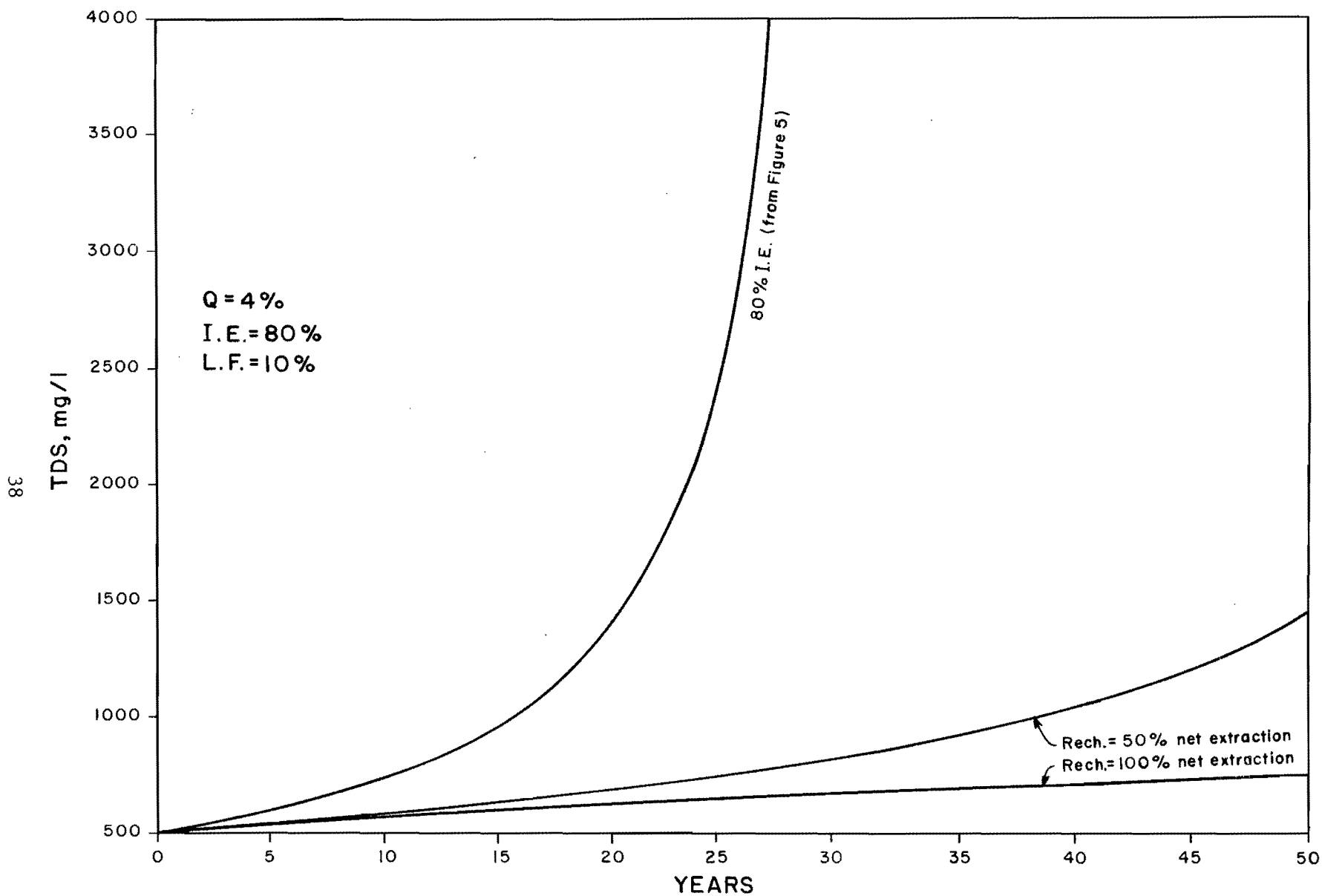


Figure 8. Hypothetical salinity improvement using agricultural drains with recharge.

in the face of a continuous use of groundwater that concentrates salts so rapidly as does irrigated agriculture. Only the bottom curve of Figure 8 showed any tendency to reduce the rate of salinity buildup. In that hypothetical case the salinity would have ultimately stabilized at 900 mg/l. The only way to reduce salinity and still raise crops in such cases would be to import water for recharge having appreciably lower salinity than the baseline groundwater salinity, perhaps in conjunction with the export of saline drainage water.

By way of summary, the hypothetical cases described above indicate that there is usually a long period of groundwater use before salinities adversely affect agriculture. This is roughly a 25 to 30-year period and may represent an opportune time to begin more intensive salinity control measures. In real situations this period may be extended by various causes such as very inefficient use of water or the salvage of evapotranspiration losses to phreatophytes. Cropping patterns also may vary during the early history of a newly developed area. By the time 25 to 30 years of agricultural and water quality history have taken place, the groundwater users of a basin should have the needed data and the necessary plans for salinity control of their particular locality. The foregoing guidelines and alternatives should be of value in the planning process.

Evaluation of Salinity Control Measures

General Background

Physically, the ideal salinity control program would maximize the beneficial use of water achievable with a given level of salinity buildup. Economically, the cost of achieving greater beneficial use needs to be compared with the resulting benefits. Environmentally, withdrawals for beneficial use reduce instream flow values and harm the aquatic resources in

natural seepage areas. Institutionally and politically, control implementation is complicated where control measures must be installed by upstream users or on third party lands for the benefit of downstream users. All of these factors vary widely among geographic problem areas, and analyses must be situation specific.

Salinity control planning combines measure selection with choices on when to initiate them. The difficulty in avoiding groundwater salinity problems suggests early action, but water users hesitate to make large investments until they experience a significant problem. The delay is aggravated as upstream users are slower to recognize a problem than the downstream water users who usually experience difficulties first and more intensely.

In Utah's geologic setting, groundwater salinity problems are localized, such as the recirculation of groundwater trapped in a groundwater sink. Where this has occurred in the Beryl-Enterprise district of Escalante Valley, roughly 150 mi² (390 km²) have been affected, but in other parts of the state, groundwater sinks are still limited to smaller areas. However, recirculation typically extends outside the boundaries of a sink, and water management needs to be evaluated over the larger area.

There are many factors to consider when selecting the proper moment to implement a salinity control program. Each measure within such a program may be best initiated at a different time and an entire sequence of measures may have to be adopted. Outside of legal, psychological, and economic considerations, scientific parameters necessary for selection of salinity controls and selection of an implementation schedule include water quality criteria for intended uses, geographic areas involved, benefits anticipated, wildlife impacts, and extent of salinity improvements desired.

Water Quality Criteria

Water quality criteria for municipal use, published by the State of Utah (Utah Department of Health 1979), allow up to 2000 mg/l of dissolved solids where no better water can be obtained. The federal government (Federal Register 1979) allows only 500 mg/l of dissolved solids in drinking water, but calls it a secondary regulation which is not necessarily grounds for rejection of a water that exceeds it. Water quality criteria for agriculture have more flexibility as drainage, climate, and soil types are also to be considered along with crop varieties. The U. S. Salinity Laboratory Staff (1954) has published a classification of irrigation water suitability based upon salinity hazard combined with sodium hazard. Some salt-tolerant crops can be grown using waters that contain up to 4000 mg/l, but only under extremely favorable circumstances. Hem (1970) has published upper limits of dissolved salts in waters for livestock and poultry. A general upper limit of 5000 mg/l is sometimes recommended for livestock.

Optimization Planning

The most common method of predicting the time when a water supply will become too saline for use is to extrapolate historical water quality data at a given locality. If the data indicate a gradual rise in salinity, then a time can be estimated when the water salinity will reach an upper limit of acceptable salinity for a given use, provided no unforeseen impacts and adjustments for predictable influences have been made. The upper limit of salinity tolerance depends upon the use, the locality, and could vary somewhat in time. For many uses, water users experience inconvenience and some losses at salinity levels lower than the permissible standards, and this provides some incentive for early action. When multiple water sources are commingled, surface water salinity patterns between flood and base flows need to be

integrated with the more constant groundwater salinity levels.

Relatively slow groundwater movement means that salinity control measures often do not become effective for some time after implementation. The time required for project approval, funding, and construction are also to be considered. Ideally, salinity control measures should be in effect long before maximum salinity limits are reached to obviate the hardships of using marginal quality water. High interest and inflation rates, present water laws, and lack of cooperation among groups of water users are the main deterrents to salinity control projects.

Linear and dynamic programming and basin salinity models are useful computerized techniques, which can be adapted to the selection, timing, and management of salinity control measures (Khan 1982). Thorough scientific investigations have to be made in each locality where salinity buildup is a problem to provide data and parameters for use with these techniques. Physical, economic, and other decisive factors are also utilized in these methods of finding optimum solutions to complex problems.

Recirculation of Groundwater

Salinization as water moves downstream is basically the same problem whether the flow occurs in long watercourses or in groundwater sinks, except it is more acute and localized where a groundwater sink occurs. In the Arid Basins region, the purpose of salinity control may be to preserve water quality to enable reuse of the water more times, while in the Colorado Plateau region the goal is to reduce salinity loading for downstream users.

The first measures to be taken to control salinity associated with the recirculation of groundwater are those that reduce the extraction of groundwater, reduce the deep percolation of applied irrigation waters, and stop the

infiltration of water from canals and ditches. The reduction of water movement through soils and formations with high soluble salt loads must be another primary goal.

Once water levels have been lowered sufficiently to stop the waste of water by phreatophytes and other nonproductive vegetation, irrigation efficiency can be improved so that groundwater pumpage can be regulated to obtain optimum crop yields. If these measures are not sufficient, one can plan irrigation for less than full yield, plant crops that use less water, or retire saline soils underlain by saline formations from irrigation. Saline aquifers should be sealed from all wells.

The importation of high quality water is always desirable where pumping levels are declining and creating groundwater sinks. Artificial recharge of flood runoff in the non-cropping season is advisable if the water cannot be imported when needed.

Practically all of the foregoing measures could be used with equal success where recirculation of surface waters has caused salinity buildup. Present water rights laws should be amended to encourage water quality preservation through incentives.

Salt Water Encroachment from Terminal Lakes

The Great Salt Lake and other terminal lakes and playas normally present no problems of salinity encroachment as long as groundwater gradients are toward the lakes. There may come a time, however, in the Arid Basins region where heavy use of groundwater upstream may permanently or seasonally reverse the normal hydraulic gradients and cause seepage of saline groundwaters away from some lakes or playas. This could happen in the Cedar City-Parowan basins, in the Sevier

Desert area, or near the Great Salt Lake. Fortunately these terminal lakes are underlain by very fine-grained lake sediments, hydraulic gradients are low, and the associated evaporation and transpiration tend to stabilize lake levels and hydraulic gradients. If lake bed permeabilities were high, some salt water could percolate from beneath such lakes despite the fresh water inflow because of specific weight differentials. Also salt water bodies left from prehistoric times may remain in the vicinity of terminal lakes and playas. Their occurrences may appear anomalous when viewed only in the context of the present-day groundwater systems.

If the demand for groundwater supplies continues to increase in Utah, there is a real danger of salt water encroachment from terminal lakes and playas by reversal of gradients that might seriously degrade existing groundwater sources. Methods of combating such encroachment include artificial recharge around the lakes using low quality waste brackish water, pumpage of the encroaching brines to evaporation ponds, or into the brackish lake, and the control of inflow to the lakes or playas.

Salinity Control Measures

Table 1 is a list of salinity control measures. Some are probably too sophisticated for present day application to many localities. Only a few of the more practical ones have been employed in Utah, but as salinities continue to rise in several areas, an increasing number of such measures will have to be used. Many of these measures are of a universal nature and their implementation almost anywhere in the state should improve salinity downstream. Others may be effective for salinity control in some areas but not in others.

Table 1. Outline of salinity control measures.

A. Agricultural measures to improve salinity and get better yields

1. Line canals and ditches or use pipelines
2. Line tailwater and high elevation surface drainage ditches
3. Improve on-farm efficiency
 - a. Install accurate flow measuring devices
 - b. Apply water at optimum rates
 - c. Schedule water at optimum times
 - d. Use improved application methods
 - e. Level land for optimum application
 - f. Use contour plowing where needed.
 - g. Minimize soil leaching
 - h. Install drains where effective
 - i. Irrigate when evaporation rates are lowest
 - j. Use special tillage and mulches
4. Drain waterlogged areas
5. Replace nonproductive vegetation by crops or pasture
6. Leach soils only during wet years
7. Reduce erosion
8. Optimize reuse of water
9. Minimize use of soil conditioners
10. Optimize importation or exportation of water
11. Use reclaimed sewage or industrial effluents
12. Retire saline lands from irrigation
13. Develop nonsaline lands for irrigation
14. Develop more salt-tolerant crops
15. Plant more salt-tolerant crops downstream
16. Develop and plant crops that use less water
17. Promote hydroponic farming and hothouses
18. Retard crop transpiration with antitranspirants

B. General measures to increase water supply and improve salinity

1. Lower shallow water tables to stop evapotranspiration
2. Eradicate nonproductive phreatophytes and hydrophytes
3. Bypass losing stream channels
4. Import high quality water
5. Desalinize with proper disposal or use of salts
6. Inhibit evaporation of lakes and reservoirs
7. Reduce surface areas of lakes and reservoirs
8. Modify weather to increase precipitation
9. Fill oxbow lakes and other nonbeneficial water bodies
10. Use patterned clearcutting of highland vegetation

C. Measures to reduce salinity directly or indirectly

1. Divert water around saline areas in lined channels
2. Prevent recharge to saline rocks and alluvium
3. Plug improperly abandoned wells and exploratory holes
4. Line all disposal ponds, pits, and lagoons
5. Suppress discharge of mineralized springs

Table 1. Continued.

6.	Evaporate saline waters to dryness
7.	Inject saline waters in deep saline aquifers
8.	Encapsulate solid, liquid, and saline wastes
9.	Stop flowing wells
10.	Improve water well design to exclude salinity
11.	Improve well pumping to decrease inducement of salinity
12.	Artificially recharge nonsaline formations
13.	Reduce soil erosion
14.	Use pressure ridges or troughs to prevent saltwater intrusion
15.	Find more uses for saline waters
16.	Find substitutes for highway deicing and water softening salts
17.	Use mine drainage or oil field waters
18.	Use tertiary treatment of municipal and industrial waste waters
19.	Use subsurface barriers to control salt water flow
20.	Dike off playas
21.	Store saline waters for release during floods

D. Legal measures that could affect salinity buildup

1.	Revise water rights laws to encourage efficient use of water through incentives
2.	Add salinity control considerations to water law
3.	Regulate salt storage in the Arid Basins region
4.	Regulate salt buildup in the Colorado Plateau region
5.	Recognize minimum flows to maintain water quality as a beneficial use

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