

# ACHIEVING A SUSTAINABLE IRRIGATED AGROECOSYSTEM IN THE ARKANSAS RIVER BASIN: A HISTORICAL PERSPECTIVE AND OVERVIEW OF SALINITY, SALINITY CONTROL PRINCIPLES, PRACTICES, AND STRATEGIES

P. Lorenz Sutherland  
Conservation Agronomist  
USDA-Natural Resources Conservation Service  
318 Lacey, La Junta, Colorado 81050-2039  
Voice: 719-384-5408 Fax: 719-384-7869  
lorenz.sutherland@co.usda.gov or drcrop@rural-com.com

## INTRODUCTION

### Nature of Agricultural Salt Problems

Salinity is defined as the concentration of dissolved mineral salts in waters and soils. The concentration can be expressed either on a mass or chemical equivalent basis. Expressed on a mass basis readers are probably most familiar with the units of milligrams per liter (mg/l) or parts per million (ppm). The major solutes comprising dissolved salts are the cations (sodium, calcium, magnesium, potassium) and the anions (sulfate, chloride, bicarbonate, carbonate, nitrate). Sometimes the term hypersalinity will be used. In this case, reference is being made to the concentration of not only the dissolved minerals listed above, but also include other constituents that may include manganese, boron, lithium, fluoride, barium, strontium, aluminum, rubidium, and silica.

Salinity is often expressed as a coalesced parameter representing the aggregated concentration of the dissolved minerals. This parameter which most people are familiar is either expressed as the electrical conductivity, specific conductance, or total dissolved solids. Sometimes hydrologists like to distinguish specific conductance from measured electrical conductivity. In this case, the electrical conductivity hereby referred to, as EC is the reciprocal of the solution resistance measured between two electrodes and the specific conductance (SC) is then the value accounting for variations in the conductivity cell used in the laboratory or field. For our discussion EC and SC are used interchangeably; both have been multiplied by the appropriate "cell constant" and corrected for temperature and normalized to 25 degrees centigrade. Soil salinity is typically measured in a saturation soil extract ( $EC_e$ ), a saturated paste ( $EC_p$ ), or *in situ* by electroconductometric methods by measuring the apparent bulk conductivity,  $EC_a$ .

The units for EC can sometimes be confusing. The unit for the conductivity per unit volume of 1  $cm^3$  is siemens per centimeter (cm) but this unit is much too large. Consequently, the most common working units are the millisiemen per cm (mS/cm), the decisiemen per meter (dS/m) which is equal to the traditional millimhos per cm (mmhos/cm) unit dimension for expressing EC (mS/cm = dS/m = mmhos/cm).

## **Source of Agricultural Salt Problems**

The primary origin of salts is the chemical weathering of geological materials and anthropogenic processes. Congruent, incongruent dissolution, and redox reactions are responsible for salt accumulation in soils and waters by chemical weathering. The anthropogenic salinization processes are driven by evapotranspiration which are discussed briefly as follows.

The concentrations of soluble salts increase in soils as the soil water is removed to meet its atmospheric demand by evaporation and transpiration. The salts, which are left behind concentrate in the shrinking soil-water volume with each successive applied irrigation; passing through the soil profile. Furthermore, soils with shallow, saline water tables can become salinized as the result of the upward flux of water and salt into the rootzone. It is these soluble salts that if not managed, will eventually build up in irrigated soils to the point that crop yield is adversely affected.

## **PHYSIOGRAPHIC FEATURES AND AGROECOLOGY OF THE ARKANSAS RIVER BASIN**

### **Physiographic Features**

The Arkansas Valley originates upstream from Leadville, Colorado, at an elevation of more than 14,000 feet. A notable feature of the Arkansas River Drainage Basin, which encompasses about 26,150 square miles including the Cimarron River watershed, is that its headwaters are at the highest point (14,433 ft above mean sea level) in Colorado. The river leaves the state downstream at the lowest point in Colorado of less than 3,400 feet elevation. Between these two points the river flows about 360 miles through Colorado. The river's transition from the mountains to the plains is near Canon City, 36 miles west of Pueblo. West of this transition the river gradient averages 40 feet per mile; east of this point the river gradient is reduced to a little less than nine feet per mile.

The Sawatch Mountain Range separates the basin from the Colorado River Drainage Basin on the northwest; the Rio Grande Drainage Basin by the Sangre de Cristo, and Culebra Ranges on the southwest. There are 23 peaks in these three mountain ranges that have elevations greater than 14,000 feet above sea level. On the north the Mosquito Mountain Range and Monument Divide also referred to as the Palmer Lake Divide or Palmer ridge, separates the northern boundary from the South Platte River Drainage Basin.

The basin is typically divided into two physiographic provinces; to the west is the Southern Rocky Mountain Province while to the east is the Great Plains Province. The division between the two provinces is approximately at the 105-degree parallel (longitude). The Southern Rocky Mountain Province consists primarily of the mountain area underlain by Precambrian igneous and metamorphic rock formations. Late Cretaceous marine shales and limestones underlie the Great Plains Province. The Great Plains Province can be further divided into the "Colorado Piedmont" and the "Raton Section." A parallel line divides them approximately 25 miles south of the Arkansas River representing the elevated plain north of the line and the trenched peneplain south of the line.

Surface and groundwater irrigation water, return flows, and irrigation ditch overflow are the primary water sources. Surface water supplies consist of both direct-diverted, native waters and transmountain diverted water imported in to the Arkansas River Basin. Since 1996 all diversions of tributary groundwater (wells) for irrigation including those within the proposed project area are subject to specific augmentation requirements. Based on whether the groundwater source is used as supplemental or sole source water supply for irrigation purposes, a percentage of the total water pumped is to be replaced to the Arkansas River. This replacement of these so-called presumptive stream depletions are placed to prevent material injury to senior surface water rights and depletions to the Colorado-Kansas stateline flows under the Colorado-Kansas Compact.

## **Agroecology**

Settlers arriving in the area relied on cultivated irrigated crops. As early as 1853 it was recorded that in addition to corn and wheat, the potato, rutabaga, and beet were easily cultivated. Other crops that drove the early production system of the region were alfalfa, watermelon, first grown in 1878; and cantaloupe, first-grown in 1884. In 1896, the Rocky Ford Melon Growers Association was organized to bring producers together into one marketing group. Melons were shipped with the brand name "Rocky Ford" cantaloupe, a name that remains widely known across the country.

By 1905, four seed companies had developed businesses in Rocky Ford. By 1907, one of these, the Rocky Ford Seed Breeders Association, was selling 30 tons of cantaloupe seed per year to growers in the Imperial Valley of California. By 1925 ninety percent of the cucumber seed and 75 percent of the cantaloupe seed planted in the United States were grown in Otero County. However, the perishability of these commodities and price fluctuations led farmers to seek a more diversified irrigated agriculture.

The crop introduced to fill the void turned out to be the sugar beet. Much of the original irrigation development has been tied to the sugar beet industry. At the peak of the industry, 22 sugar beet processing facilities operated in southeastern Colorado. Ultimately, the valley had more factories than the farmers and land were able to support. This coupled with lower yields, caused by poor quality irrigation water, sugar-pricing problems, and outbreaks of beet blight ("curly top") resulted in sharp decline and elimination of profits. All but one of the factories had closed by 1967 and all are presently closed.

Another key crop in the development of the agricultural heritage was Pascal celery. It was through the efforts, in part, of the Pierce Seed Company of Pueblo that the "Pueblo celery" became recognized as high quality celery surpassing that of the products produced in Michigan and California. The Pueblo Pascal celery, which was characterized by its crispness, whiteness, and distinctive nutty flavor, soon became the preferred choice over the Golden celery grown elsewhere. By 1919, shipments amounted to 500 refrigerated railcars, each carrying 40,000 pounds.

The celery grown from what were called the Booth Gardens fields near Pueblo was being served on the tables of hotels in New Orleans and St. Louis during the early 1900's. The celery was served in the dining cars of the Missouri Pacific and Santa Fe railroads. Between 1923 and 1927 it was this celery grown near Pueblo, Colorado, that President Coolidge and his wife wanted for their holiday White House dinners.

One of the most notable celery producers by the name of Charley Barnhart became the largest celery producer in the area (Evans, 1994). He was considered the leader in celery production, overcoming the many cultural problems including the method of planting the stalks back three times during the year. Although most of the crop went to market during the Thanksgiving and Christmas holidays, Barnhart advanced the storage technique of placing celery in trenches covered with straw and soil. Under favorable conditions this allowed the celery to be kept as late as April of the following year and marketed when prices were high. Celery met a similar fate to that of the sugar beet. The sugar beet leafhopper and the aster yellows virus proved disastrous to the local celery industry. The last celery crop was grown in 1981.

Although the "Rocky Ford" cantaloupe, sugar beet, and the "Pueblo Pascal" celery were two of the earliest crops critical to development of the valley, other crops have proved to be adaptable to the area. Crops currently grown include corn, grain sorghum, alfalfa, soybean, dry bean, wheat, onions, tomato, potato, watermelon, honeydew, cucumber, cabbage, cantaloupe, chile, wine grapes, cabbage, apples, sweetcorn, raspberries, pumpkins, black-eyed peas, green beans, squash, cherry, plum, okra, barley, parsnip, winter turnip, garlic, turf, and zinnia flowers for seed. One will find a cornucopia of fresh vegetables in today's roadside markets including a host of chile pepper varieties, spelled "chile" not "chili" (Domenici, 1983). The first pepper to be grown was the cherry pepper. In 1961 just a year later, Denver's Dreher Pickle Packing Co. contracted three acres. By 1996, the acreage grew to almost 800 acres and has come to include many of the pungent as well as non-pungent chile peppers with household names such as 'Big Jim', and 'Anaheim'. Just as the "Pueblo celery" dominated the early 20<sup>th</sup> century, the "Pueblo chile", is becoming a recognized important part of the agricultural commodity system. A mirasol (meaning 'looking at the sun') chile, it is a preferred pungent type for many culinary uses including salsas.

Two seed companies remain as leaders in the development, culture, and marketing of curcubit and other specialty seeds worldwide. Melon development continues as well. The "Rocky Sweet," a cross between a cantaloupe and honeydew was grown commercially for the first time in 1985 and is steadily becoming a favorite for the melon connoisseur.

A part of the special agricultural production heritage of the middle reach of the basin relates to the dominance of the small farmer many of who are of southern European decent. Most came to the United States during the early 1900's to work in the Colorado Fuel and Iron (CF&I) steel mill. Looking for alternate income sources during mill slowdowns, they started small truck farms and developed roadside markets. Although the farms have tended to become larger over time the small truck farm operations still play a very important role in today's production system.

## **A HISTORICAL PERSPECTIVE OF IRRIGATION DEVELOPMENT AND ITS CURRENT STATUS**

### **Regional Irrigation History**

Much of the interesting irrigation history in the southwest surrounds the debate that all puebloan groups including the Rio Grande Valley of New Mexico practiced irrigation before the Coronado expedition. It has been asserted without a great deal of evidence that these puebloans learned to

irrigate from the Chacoan Anasazi. It is important to note though that protohistoric Sonoran irrigated agriculture was observed by both the Coronado and Ibarra expeditions. However, the records of Coronado did not mention anything about the engagement of Rio Grande puebloans in irrigated agriculture.

This other side of the debate suggests that not all puebloan groups inherited the knack for irrigation; that it were the encomenderos and missionaries that imposed the irreversible reliance on irrigated culture (Wozniak, 1998) on the native peoples of this region that would eventually become Colorado and New Mexico. One substantial piece of evidence to support the push of intensive agriculture came out of the Espejo expedition starting in 1582. The expedition included visits to a number of pueblos including those of the Piro and Salinas Provinces in the vicinity of present-day Socorro, New Mexico. It was reported that corn was being irrigated with dams and canals apparently from the Rio San Jose or Rio Cubero Rivers that looked to have been built by the Spaniards (Hobbs, 1997). Just previous to the Espejo expedition, reports from the Rodriguez-Chamuscado expedition in 1581 provided positive evidence of puebloan irrigation just north of present-day Bernalillo. Cornfields were being irrigated from what is assumed to be Las Huertas Creek that drains the north slopes of the Sandia Mountains. In a region that neither Espejo nor the Chamuscado expeditions had explored, Gaspar Castano de Sosa reported all six pueblos in the Sante Fe area that his expedition visited in 1591 had canals for irrigation.

The generally accepted beginning of Spanish irrigation in the region, however, was marked by the construction start of an irrigation ditch or *Acequia madre* (mother ditch) for the Tewa Pueblo in 1598. Under the Spanish repartimiento and encomienda system the demands compelled the Puebloans to intensify agricultural production through irrigation during the seventeenth century. The demanding system for labor, the inclination for Puebloans to hunt rather than farm; economic exploitation and religious persecution as history recounts, led to the Pueblo Revolt of 1680 which decimated the Spanish settlements.

This brings us to the Spanish Colonial New Mexico period following the Reconquest of New Mexico. This period was ushered in with a new economic regime; one that focused on land grants rather than encomiendas. With the exception to Diego de Vargas himself, the Spanish settlers were required to support themselves by their own labors. Rehabilitation and development of new acequia madres was of primary consideration.

Much of Colorado's irrigation history is centered in the Arkansas River Basin. The richness of the agricultural heritage as related to irrigation is significantly enhanced from the geographic setting where the Arkansas River divided the future state. This was the border separating Mexico and the United States between the years 1803 (Louisiana Purchase) and 1848 (Treaty of Guadalupe Hidalgo), which signaled the end of the Mexican-American War.

The first known attempt at modern irrigation within this region of the Spanish Territory is documented to have been near Pueblo. In the summer of 1787 ten years after his appointment, Juan Bautista de Anza, the Governor of the Spanish New Mexico Province entered into a treaty with the Jupe tribe of the Comanche Indians (McHendrie, 1952). It was one of the outcomes of this treaty that led to the establishment of the first recorded irrigation system.

Leading up to the treaty there were hit-and-run raids by the Comanche Indians on the Ute villages, Spanish hamlets, and pueblos along these northern regions of the territory. Previous attempts to squash the Jupe Comanche raids were unsuccessful. The Spanish would advance over Raton Pass or Sangre de Cristo Pass only to have the Jupe Comanche Indians spot dust clouds and campfires of Spanish soldiers and then perspicaciously retreat to western Kansas to safety (Quillen, 1994). The raids, led primarily by Chief Cureno Verde (Green Horn), tormented and menaced the Spanish settlers and villagers to the point that in 1779, Governor Anza led a military party to the Jupe Comanche hunting grounds on Greenhorn Creek. It was a location on Greenhorn Creek, a tributary to the St. Charles River where Verde was engaged in battle and killed (Aschermann, 1994). An ancestor of Anza's cartographer has recently disputed the original marked site of this battle (Vigil, 2001). Because of the original mistranslation of the Spanish word "zanja" coupled by retracing the mileage in Anza's diary it is now thought that the battle was fought near the intersection of Water Barrel Road and Burnt Mill Road. Greenhorn Peak, the highest within the Wet Mountains, just southwest of present-day Pueblo and readily visible from the proposed project area is named in honor of this battle.

Anza had not only demonstrated his leadership abilities as a military leader but also as an expert frontiersman. He had already founded San Francisco (San Francisco Presidio) and Mission Dolores in 1776 and earned the name "Great Colonizer." As a part of the treaty that Governor Anza had orchestrated with the Jupe Comanche following the untimely death of Verde, Anza sent about 20 Spanish farmers and artisans to settle a colony with the tribe who had given in to the Spaniards and were willing to settle in villages.

This colony was built on the banks of the San Carlos (St. Charles) River at the confluence of the Arkansas River. It was named "San Carlos de Jupes." Provided with seeds to plant and sheep and cattle, the Spaniards with their Comanche counterparts constructed a ditch that took water from the San Carlos (St. Charles) to irrigate a large tract of land that had been sodbroken and put into cultivation. The Colony was eventually abandoned.

There are at least two accounts for the lack of success of the venture. The lack of leadership by the successor to Governor Anza who died in 1788 coupled with the Comanche's lack of enthusiasm for the manual labor required for irrigated farming and homes contributed to the Colony's demise. Another account suggests that the death of a woman who had been admired by Chief Paruanarimuco contributed to abandonment; that the Comanche viewed the woman's death as a divine sign of disapproval (Aschermann, 1994). As a result they deserted the settlement and other Spanish colonists weren't interested in moving to San Carlos.

There are accounts of several early unsuccessful attempts of irrigation and farming in the basin following the Louisiana Purchase. These include a ditch that was built near Bent's Fort in 1832 in which about 40 acres of corn, beans, squash, and melons were planted. However, Indian ponies grazing on the growing crops thwarted any kind of productive harvest.

Probably the first record of what could be considered a successful irrigation venture was the establishment of the settlement in 1841 of what would become known as "El Pueblo" (Fort Pueblo). Along with the trading post there was extensive acreage cultivated until Ute and Apache Indians killed the Mexican inhabitants in 1854. An irrigation enterprise was established in 1846 where the Taos Trail crossed Greenhorn Creek (Aschermann, 1994). The location became known as John

Brown's Store near present day Rye. In the same area a settlement of French-Canadian hunters and their Indian wives were reported farming in the Greenhorn Valley in 1847 by G.F. Ruxton (Taylor, 1963). In the same year, the Bent Brothers under the guidance of John Hatcher, downstream of present day Trinidad on the Purgatoire River (El Rio de Las Animas Perdidas en Purgatorio) dug an irrigation ditch.

In 1853 a report by Lieutenant Beckwith traveling with Gunnison's exploration party showed that six Mexican families were diverting water out of Greenhorn Creek using the ditches previously constructed by John Brown. It was also in 1853 that a ditch was dug for purposes of irrigation by Charles Autobees on the west bank of the Huerfano River.

In 1859, at the same location where Beckwith reported the diversion of water from Greenhorn Creek, Zan Hicklin and his wife Estefana who was Charles Bent's daughter established one of the largest irrigated farming operations. Using the ditches originally dug by John Brown and employing large numbers of Mexican laborers, the Hicklin's cultivated a total of 380 acres. This water right associated with the appropriation of this water was the earliest adjudicated appropriation in the basin (March 31, 1859) in the name of Hicklin Ditch on Greenhorn Creek.

The first two water rights on the main-stem of the Arkansas were decreed 30 days apart in 1861; the second to be that of the Bessemer ditch. By the middle 1880's the main-stem and tributaries of the Arkansas were fully appropriated. Water right decrees later than 1887 are little more than flood rights providing water only during snow melt and after summer rainstorm events; the last decreed right is 1933. Major irrigation development required large scale financing to enlarge the very early diversions. Most of the systems were constructed between 1874 and 1890.

### **Contemporary Irrigation**

Historically, the area of land irrigated in the Arkansas Valley has remained relatively stable. In 1969 the U.S. Bureau of Reclamation (1969) estimated the land irrigated equal to about 415,000 acres. In the mid 1980's the estimated number of irrigated acres was cited to be about 411,000 acres, of which 56,000 acres are located in the upper portions of the basin (Dash and Ortiz, 1996, Litke and Appel, 1986). The seasonal water supply in the basin is subject to considerable fluctuation. Waters native to the Arkansas River, its tributaries, and water imported into the basin via the Frying Pan Arkansas Project, are used and reused. The basin also includes a number of storage reservoirs. Institutionally Arkansas River Drainage Basin (Water Division II) is divided into 13 Water Districts. For a complete description of the operations of the various water systems, the reader is referred to Abbott (1985).

**Arkansas River Mainstem.** In the upper reach of the Arkansas River above Pueblo Reservoir (Districts 11 12) water is diverted to irrigate alfalfa, hay, or irrigated pasture, and serves small orchards. Major conveyance systems include the South Canon Ditch, Pump Ditch and the Crooked Ditch, Canon City Hydraulic Ditch, Fruitland Ditch, Grandview Ditch, Canon City and Oil Creek (Mill) Ditch, Fremont County Ditch, Union, Hannenkratt ditch, and the Lester and Atteberry ditch.

Below Pueblo Reservoir Major irrigation conveyances diverting from the main stem of the Arkansas River in Water District 14 are the Bessemer Ditch, Colorado Canal, Rocky Ford Highline Canal, and Oxford Farmers Ditch. There are also several small irrigation ditches including the Hamp-Bell, West Pueblo, Riverside Dairy, Excelsior, and Collier.

Above John Martin Reservoir the Otero, Catlin, Holbrook, Fort Lyon Storage, Rocky Ford, Fort Lyon, and Las Animas Consolidated Canals headgates are all in Water District 17. The canal and ditch systems on the mainstem below John Martin Reservoir are in Water District 67; these include the Fort Bent Canal, Keesee, Amity Canal, Lamar Canal, Hyde, Manvel, X-Y Canal and Graham Ditch, Buffalo Canal and Sisson Ditch. Although the diversion of the Frontier Ditch is physically located in Colorado just west of the state line it irrigates cropland in Kansas and therefore considered a Kansas ditch.

**Arkansas River Tributaries.** There are a number of significant water conveyance systems that divert water from Arkansas River tributaries. Included in the Wet Mountain Valley, located in Custer and Fremont County is the DeWeese-Dye ditch; located on Fourmile, Hardscrabble, and Beaver Creeks are Park Center, Hardscrabble ditch, and Brush Hollow Supply Ditch.

Other tributaries with minor diversions include Fountain Creek and the Apishapa River. Serving the terrace lands on Fountain Creek between Colorado Springs and Pueblo are the Fountain Mutual ditch and the Chillicott Canal. Limited water is diverted for irrigation in the upper reach of the Apishapa River from the Escondito, Salisbury and Widderfield ditches

As previously mentioned the main tributary of the St. Charles River, is Greenhorn Creek the location of the earliest priority in the Arkansas River basin: the Hicklin ditch, with a water right from spring 1859. Smaller ditches include St. Charles Flood, Tucker, Fairhurst,, McDowell, Chase, Wagner, Eagle, Fisher, Bryson, and Anderson.

Diversions on the upper Huerfano River include the Medano Ditch and small direct diversions on Pass, Williams, and Turkey Creeks convey water to a number of ranches near Red Wing, Colorado. Other diversions include the Orlando Ditch, Huerfano Valley, Farmers Nepesta, and Welton Ditch. Also there are waters used for irrigation supply from the Cucharas River, tributary to the Huerfano River. These are Middle Creek, Wahatoya Creek, Abeyta Creek, Bear Creek, and Santa Clara Creek, and the Gomez Ditch.

The other tributary supplying significant water for irrigation is the Purgatoire River. Diverted through eight structures on the Purgatoire River's, water is delivered to 11 ditch companies and entities from the Bureau of Reclamation's "Trinidad project." Diverting water from the north side of the river include the Salas, Burns and Duncan, Hoehne, Model Inlet/Johns Flood, El Moro, and Picketwire. The Lewelling-McCormick, South Side, Victor Florez, and Chilibi Ditches divert water from the south side of the Purgatoire River. Downstream from the Purgatoire Canyon and above the confluence with the Arkansas River are the headgates of the Ninemile and the Highland Canals.

**Drainage Districts.** Within the Arkansas River Drainage Basin, 29 separate drainage districts, many of which are now inactive, were established by statute during the early twentieth century. These included the May Valley, Wiley of Big Bend, Pleasant Valley, Vista del Rio, East May Valley,



McClave, Deadman, Lubers, Kornman, Riverview, Granada, Holly, Hasty, Arbor, Prowers, A.B.S. Company East Farm, Las Animas Consolidated, Consolidated Extension, A.B.S. Company No.1, A.B.S. Company No. 2, Olney Springs, King Center, Ordway No.1, Valley View, Crowley, Numa, Grand View, Patterson Hollow, and Holbrook.

## **RELATIONS OF SALINITY TO SELECTED PHYSIOGRAPHIC FEATURES IN THE ARKANSAS RIVER BASIN**

The areal and seasonal salinity characteristics within the Arkansas River Basin have been studied extensively (Cain, 1985, Dash and Ortiz, 1996). The information has included data for both the surface and groundwater resources. The information has emphasized electrical conductivity (specific conductance), its areal spatial, temporal variability and relationship to streamflow. Concentrations of dissolved solids and major ions have also been examined.

One of the first comprehensive studies was that conducted by Miles (1977). A key finding of this study was that an estimated 14 percent of the total salt load with the basin can be attributed to irrigation; industrial and municipal uses contributes about 8 percent with the remaining 78 percent resulting from natural sources. For the period studied (1965-1972) approximately 1.4 million tons of salt were diverted annually in the irrigation water from Canon City to the Colorado-Kansas stateline.

### **Areal and Temporal Distribution of Salinity and Relationship to Streamflow**

The median electrical conductivity (EC) of the Arkansas River increases with increasing distance downstream (Figure 1). The lowest values occur in the upper reach. Small increases occur above Canon City. At Canon City the median EC is 0.3 dS/m or about 240 ppm. Between Canon City and Pueblo the salinity nearly doubles. The largest increases occur between La Junta and Las Animas. From the headwaters of the river to the Colorado-Kansas State line the salinity increases nearly 30 fold. The median salinity at the stateline is about 4.1 dS/m (3,820 ppm). The maximum salinity is about 6.5 dS/m.

As expected the lowest salinity occurs during late spring, the periods of high snowmelt and flow. Conversely, the greatest salinity occurs during the winter months in periods of low surface flow and higher proportion of groundwater accounting for the overall streamflow. As such there is strong correlation between salinity and streamflow. Seasonally and spatial log-log relations have been shown to best represent the inverse relation between salinity and streamflow. These relationships can be used to accurately estimate EC from measured or simulated streamflows.

The distribution of the dissolved chemical constituents and relationships of EC to dissolved solids are also very important particularly in evaluating waters suitability and calculating mass balances. The waters of the Arkansas River are primarily gypsiferous (calcium sulfate). The sulfate concentration ranges from about 40 percent (0.71 meq/l) of the total anions (1.78 meq/l) in the headwaters to 85 percent (47.8 meq/l) at the stateline.

In terms of cations, there occurs almost 6 times as much dissolved calcium (0.9 meq/l) as sodium (0.15 meq/l) in the upper reaches. The ratio of calcium to sodium decreases with increasing distance downstream. The concentrations become almost equal below John Martin Reservoir.

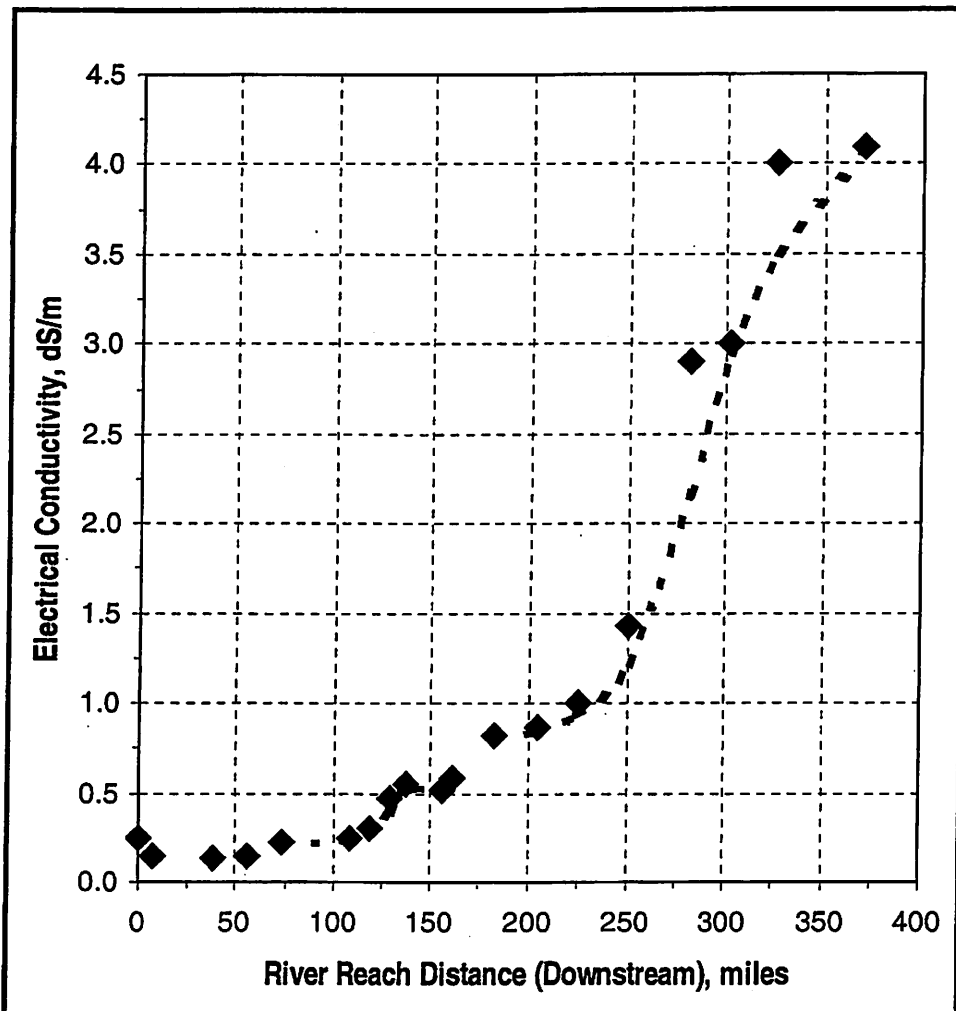


Figure 1. Spatial variation of surface water salinity in the Arkansas River Drainage Basin.

## MANAGING FOR SUSTAINED CROP PRODUCTIVITY AND WATER RESOURCE PROTECTION

### Grow Suitable Salt Tolerant Crops

The adverse effects of salts on plants are generally divided into three categories; 1) the osmotic effect (total salt effect), 2) specific ion effects, and 3) the indirect effects caused from soil dispersion due to excess sodium. The emphasis of this technical note is placed on the first two categories; osmotic effects and to lesser importance the tolerance of plants to foliar salt injury caused by specific ion effects. The indirect soil dispersion effect and the management of infiltration problems will be addressed in a separate technical note.

**Osmotic Effect.** The plant extracts water from the soil by exerting an absorptive force in response to a gradient along the soil-plant-atmospheric-continuum; one that is greater than that adsorptive force that holds water within the soil matrix. When the plant cannot exert enough energy to extract sufficient water from the soil matrix the plant develops water stress.

Similarly, as the salt concentration of the water within the soil matrix increases, the energy that the plant needs to exert also increases. Increased salt concentrations narrows the gap between the soil water and internal plant energy potential. This is referred to as the osmotic effect caused by the increase in the osmotic potential of the root-zone soil solution. In order to maintain a suitable energy gradient for water uptake to occur, non-halophytes (glycophytes) require additional expenditure of metabolic energy. This additional energy expenditure shift would normally go to building dry matter and other plant functions.

For our purposes here, soil salinity is expressed as the mean electrical conductivity of a saturated-soil extract of the root zone,  $EC_{e(avg)}$ . The SI unit expressing electrical conductivity is decisiemens per meter. The osmotic potential (bars) of the root zone soil water at field capacity can be approximated with the relation,  $OP_{fc} = -0.725EC_{e(avg)}^{1.06}$ .

All crop plants do not respond to salinity in the same way; some produce acceptable yields at higher soil salinity levels than others do. Each crop species has an inherent ability to make the needed osmotic adjustments enabling them to extract more water from a saline soil. This ability for some crops to adjust to salinity is extremely useful. In areas where the accumulation of salinity within the soil profile cannot be controlled at acceptable levels, an alternative crop can be selected that is more tolerant resulting in the production of better economical yields.

**Yield Response Functions.** The relative salt tolerance of most agricultural crops is known well enough to provide general guidelines about salt tolerance for making management decisions. The salt tolerance of any given crop can best be illustrated by plotting the potential yield, sometimes referred to as the relative yield, as a function of soil salinity. The potential yield ( $Y_r$ ) or relative yield, expressed as a percent, is defined as the yield under saline conditions ( $Y_a$ ) relative to the yield under non-saline conditions ( $Y_m$ ):

$$Y_r = (Y_a/Y_m)100 \quad (1)$$

Although it has been shown that the relation between potential yield and soil salinity follows a sigmoidal curve, a piece-wise linear response function (Figure 1, solid line) is used to easily describe the potential yield/soil salinity relation for acceptable crop yields. Two intersecting straight-line segments represent this linear piece-wise response function. One of the segments has a slope of zero. This means that the yield potential is constant across a range of soil salinity. The second line segment is a salinity-dependent line whose slope describes the yield reduction per unit increase in soil salinity. The point where the two line segments intersect specifies the threshold soil salinity ( $EC_{e(ct)}$ ) or the maximum mean root zone soil salinity at which yield reductions will not occur. Yield reductions will occur when soil salinity levels exceed this threshold value.

Mathematically, this piece-wise function can be represented as follows:

When,  $EC_{e(avg)}$  is greater than or equal to  $EC_{e(ct)}$ ,

$$Yr = 100 - b(EC_{e(avg)} - EC_{e(ct)}) \quad (2)$$

and when,

$EC_{e(avg)}$  is less than  $EC_{e(ct)}$ ,

$$Yr = 100 \quad (3)$$

where  $b$  is the slope of the second line segment expressed as the percent yield decrease per unit increase in soil salinity,  $EC_{e(avg)}$ . Rearranging Equation 2 the soil salinity at which a given yield potential can be obtained may also be calculated:

$$EC_{e(avg)} = (100 + bEC_{e(ct)} - Yr) / b \quad (4)$$

Likewise, the slope ( $b$ ) of the line can also be calculated by rearranging Equation 2,

$$b = 100 / (EC_{e(avg)[0\% \text{ Yield}] - EC_{e(avg)[100\% \text{ Yield}])} \quad (5)$$

where  $EC_{e(avg)[0\% \text{ Yield}]}$  and  $EC_{e(avg)[100\% \text{ Yield}]}$  are soil salinities at 0 yield potential and 100% yield potential, respectively. The analysis of tolerance field data shows that crops with similar tolerances form groups. The upper boundaries and relative tolerance rating have been assigned to these groups as shown by the thick-segmented lines (Figure 2). The four (4) regions between the lines define specific divisions for relative crop salt tolerance. These groups are classified as sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T). Field soil salinity values that fall beyond the dotted line are considered to be unsuitable for most crops of economic importance.

Although these groups are arbitrary, they are particularly useful in those instances where insufficient field data for a crop is available, but a relative rating can be assigned based on field experiences and local observations. The yield response of a crop that has been given a relative tolerance can be then be described (Table 1).

Table 1. Relative crop salt tolerances.

Relative Crop Salinity Tolerance Rating	$EC_{e(avg)[0\% \text{ Yield}]}$ $EC_{e(avg)[100\% \text{ Yield}]}$		Slope (b) [Equation 5]
	----- dS/m -----		-% per dS/m -
Sensitive (S)	7.0	1.3	17.5
Moderately Sensitive (MS)	16.0	3.0	7.7
Moderately Tolerant (MT)	24.0	6.0	5.6
Tolerant (T)	32.0	10.0	4.6

Appendix 1 lists the salinity thresholds ( $EC_{e(ct)}$ ) and slopes, ( $b$ ) for the most common crops and plants. In addition, these species have been rated as sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T). The reader is referred to Maas (1990) for an expanded list of crops and their salinity tolerance.

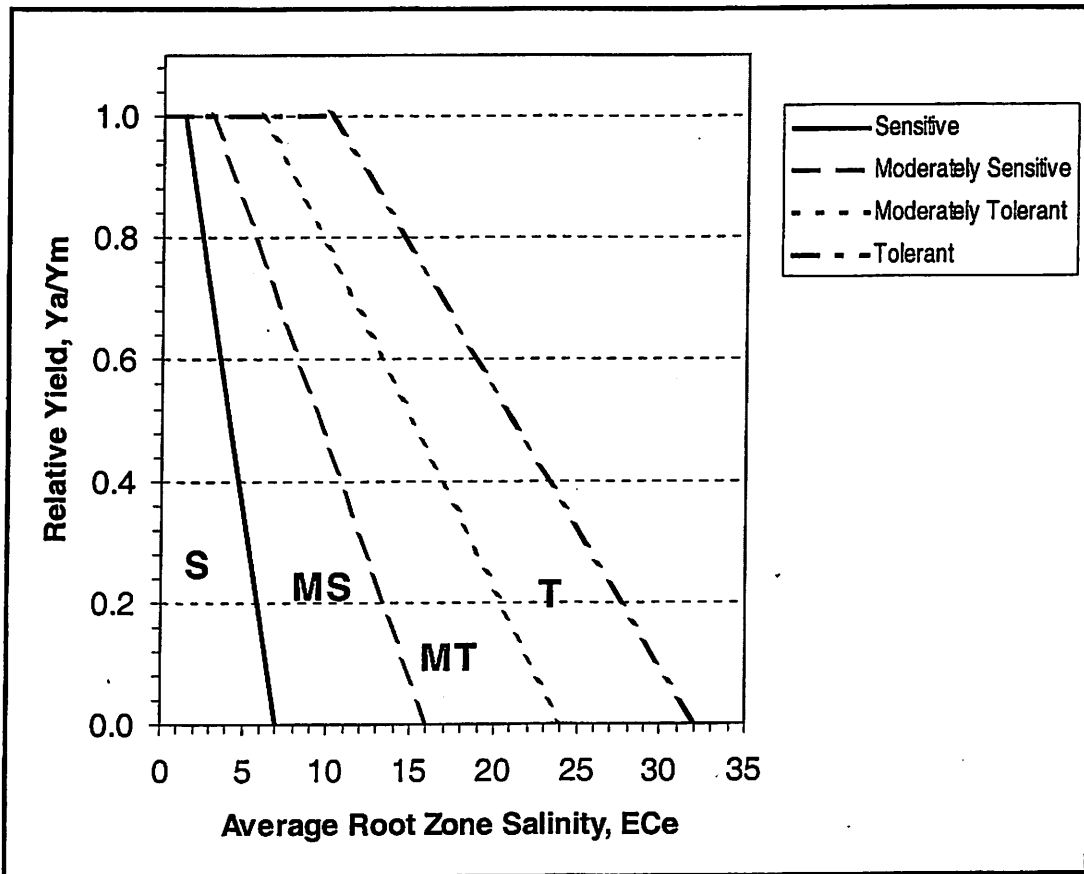


Figure 2. Crop yield response to salinity and categories for classifying salinity tolerance.

It is important to note that for the most part the threshold soil salinity values that are cited were established from field studies where chloride was the predominant anion. In preparation of saturated-soil extracts in the laboratory, gypsum ( $\text{CaSO}_4$ ) will be dissolved. For soils that are dominated by gypsum, the  $\text{EC}_{e(\text{avg})}$  may range from 1 to 3 dS/m higher than non-gypsiferous soils at the same moisture content and electrical conductivity of the soil water,  $\text{EC}_{\text{sw}}$ . This means that values of  $\text{EC}_{e(\text{ct})}$  for crops grown on soils dominated by gypsum may exceed table values by as much as 2 dS/m.

If the soil salinity levels greatly exceed the tolerance of all of the crop selections options and yield potentials of less than 100 percent are not acceptable, "reclamation" leaching may be necessary prior to any cropping. There are two conditions where reclamation leaching are most likely to be necessary. The first condition is where an inverted soil salinity profile (accumulated salts decreases with soil depth) has developed. This condition is most familiar where salts have accumulated in the presence of a shallow water table. The second condition is where a regular soil salinity profile (accumulated salts increases with soil depth) exists at excessive levels caused by inadequate leaching. The goal of reclamation leaching must be to reduce the salt concentration in the upper portion of the root zone to a level that approaches the crop tolerance.

**Susceptibility of Crops to Foliar Salt Injury Due to Sprinkler Irrigation.** Foliar salt injury has been observed on a number of crop species. Similarly to the varying response of crops to soil

salinity, species vary widely in their response to this injury from sprinkler irrigation utilizing saline waters. The foliar injury, commonly referred to as "salt burn", is caused by leaf absorption of excess concentrations of sodium and chloride.

Of all crop species evaluated, citrus and deciduous fruit trees, like apricot, plum, and almond, are the most susceptible to foliar injury. The extent of the injury may go beyond considerable leaf necrosis and may also include leaf defoliation. Among the herbaceous crops, plants belonging to the Solonaceae family is generally the most sensitive. This would include potato, tomato, and peppers.

Table 2 provides some general guidelines for determining the susceptibility of crops to foliar salt injury from sprinkler irrigation based on the concentrations of sodium or chloride. These data represent field studies where the sprinkling occurred during daytime hours.

Table 2. Tolerance of crops to foliar salt injury from water applied using sprinkler irrigation methods.

Critical Sodium (Na+) or Chloride (Cl-) Concentrations (meq/l)			
← Tolerant >20	10-20	5-10	→ Sensitive <5
Cauliflower Sugarbeet Cotton Sunflower	Alfalfa Sorghum Safflower Barley Corn	Grape Pepper Tomato Potato	Plum Citrus sp Almond Apricot

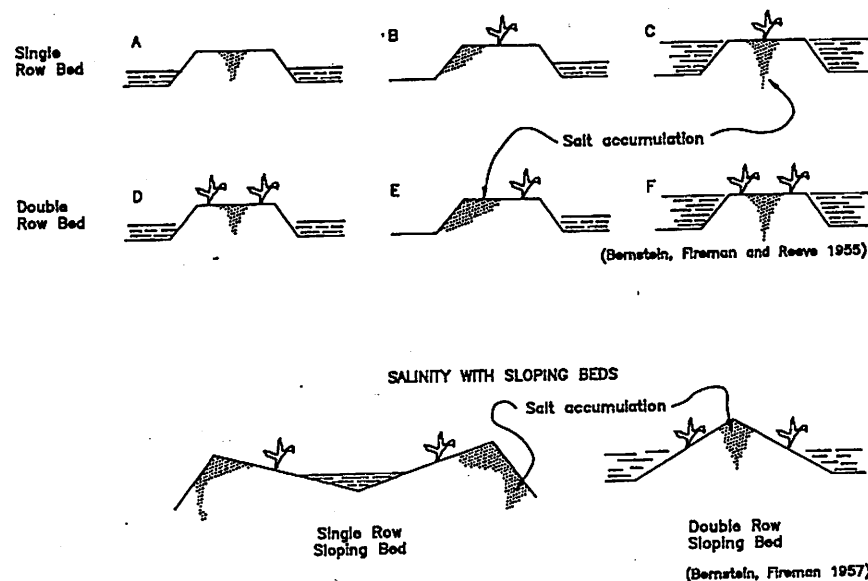
There appears not to be a correlation between a crops tolerance to soil salinity and its susceptibility to foliar injury. Two examples include strawberry and avocado; both are very salt sensitive crops, but field data shows the risk of foliar injury to be negligible. Changes in management have been shown to reduce the risk of foliar salt injury. These include irrigating at night, avoiding periods of hot, dry winds, increasing sprinkler droplet size, and increasing rates of application.

**Stages of Growth.** The soil salinity/crop tolerance relations in Appendix 1 apply primarily to responses from the late seedling growth stages to maturity. Field data on the variable crop tolerance during the early stages of growth (i.e. germination, emergence and seedling growth) are extremely limited. As a general rule most plants are tolerant during germination. After germination, plants may then become sensitive during emergence and the development of the seedling. Past studies have shown that increased salt concentrations may delay emergence, but does not affect final emergence. However, secondary conditions such as soil crusting could result in reduced crop stands. A general recommendation is that a soil salinity level of 4 dS/m in the seed zone will delay emergence seedling growth.

## Use Planting and Tillage Procedures that Prevent Excessive Salinity Accumulation in the Seedbed

A number of crops tend to be sensitive to salinity during germination and seedling establishment. Stand losses can occur particularly when raised beds or ridges are employed. These losses can be significant even when the average salinity levels in the soil and in the irrigation water are moderately low particularly under furrow irrigation. Since salts move with the water, the salt accumulates progressively towards the surface and center of the raised bed or ridge. Thus the greatest damage occurs when a single row of seeds is planted in the middle of the bed. This is so because salts tend to accumulate under furrow irrigation in those regions of the seedbed where the water flows converge and evaporate this problem is magnified when saline waters are used for irrigation (Bernstein and Fireman, 1957).

Seedbed planting systems and furrows need be designed to minimize this problem. This can be accomplished by considering alternative bed-furrow configurations and irrigation practices that involve seedbed shape, seed placement and irrigation techniques including alternate furrow irrigation. Figure 3 illustrates typical salt patterns in flat and sloping beds.



**Figure 3. Salt accumulation patterns of flat and sloping beds as influenced by irrigation practice (Adapted from Bernstein and Fireman, 1957; Bernstein, *et al.*, 1955).**

## Deliver Irrigation Water to Fields Efficiently

Unmistakably, the strategy for sustaining crop productivity and reducing the risk of salinity hazards of irrigated lands requires good irrigation management. The basis for good irrigation management for salinity control is timely uniform irrigations, applied in an adequate quantity to meet the crop's consumptive use (evapotranspiration) and at the same time satisfy the leaching requirement.

In addition, the causal and interacting elements of good irrigation water management include the delivery system and the method and manner of irrigation. For example water delivery based on predetermined amounts or preset periods without consideration of seasonal variations generally encourages over-irrigation. A consequence of these institutional constraints is limited adoption of higher efficient irrigation such as sprinkler and drip. The optimum water delivery infrastructure is one that can provide metered, controlled water nearly on a continuous basis so that the soil water content in the rootzone can be kept within prescribed limits.

The other two factors that must be considered as an overall strategy is controlling (i) seepage losses and (ii) maintaining drainage systems. Excessive loss of irrigation water from canals constructed in permeable soil contributes to not only the mineral dissolution of the underlying geologic materials, but contributes significantly to the manifesting of high water tables and soil salinization. Every effort should be taken to minimize these seepage losses.

The maintenance of the drainage system is also a key factor. Both in-field tile lines and open drains should be kept in working order. As far as sustaining irrigated agriculture it may well be necessary to reactivate many of the drainage districts in the basin.

### **Apply Irrigation Water in an Efficient Manner that Minimizes the Leaching Fraction and Resulting Deep Percolation**

There are three simple rules regarding salinity. First rule is that regardless of the river system salinity is the result of both salt loading, and salt concentration. Salt loading occurs from mineral weathering and dissolution of soluble salts. On the other hand, salt concentration occurs from plant uptake of water driven by evapotranspiration, thus leaving the salts behind. This leads to the second rule-irrigation always increases salt concentration.

When the accumulation of salts in the soil root zone become excessive to the point of affecting crop yield, they can easily be leached in the absence of a water table. The goal is to move a portion of the salts below the root zone (deep percolation) by passing irrigation water through the root zone.

**Leaching and Deep Percolation.** Clearly, if the volume of water applied can be minimized in a quantity not to exceed a crop's requirement, then the amount of salt added to the soil can be minimized. For example, water immediately below John Martin Reservoir contains about 3.3 tons of salt for every acre-foot of water diverted.

Leaching, as the key factor in controlling the soluble salts, is accomplished by applying an amount of water that is in excess of the crops seasonal evapotranspiration and runoff. This excess amount of water is called the leaching fraction (LF), normally expressed in the decimal form. As an example, a LF of 0.5 means that 50% of the water infiltrating into the soil profile passes through and out of the root zone.

The strategy is to optimize the leaching fraction to an acceptable minimum. The basis for attaining a minimum LF is two-fold. First as the LF decreases the precipitation of the dissolved salts applied in the irrigation water increases. The precipitation of salts consists of calcium, bicarbonate,



and sulfates as carbonates and gypsum. The salt precipitation results in a decrease of the amount of salt in the soil and subsequent discharge from the rootzone. Second, reducing the amount of water passing through the root zone reduces the risk of additional dissolution of weathered minerals from substrata from the percolating water. The extent to which the LF can be minimized is limited by (i) the irrigation system, (ii) a crop's tolerance to an increase in the root zone salinity.

To demonstrate the effect of leaching fraction on soil profile salinity, an example is given using the expected dissolved salt constituents of water diverted at two different landscape positions and six different leaching fractions. Figures 4a and 4b compare the soil profile salinity distribution and the precipitation-dissolution of gypsum when irrigated with water composition expected of that below John Martin Reservoir compared to that expected between John Martin and Pueblo Reservoirs. Below John Martin Reservoir (Figure 4a) the leaching fraction increases as the average expected soil  $EC_e$  in the absence of a water table decreases ranging from 6.9 dS/m at a 3 percent LF to an  $EC_e$  of 2.5 dS/m at LF equal to 40 percent. [Note that the  $EC_e$  is about half of the EC of the soil water.] Above John Martin (Figure 4b) the average expected soil  $EC_e$  in the absence of a water table ranges from 3.1 dS/m at a 3 percent LF to an  $EC_e$  of 1.2 dS/m at LF equal to 40 percent. This illustrates the greater potential of reducing the leaching fraction of waters within the middle reach. To keep the salts balanced so that the soil profile  $EC_e$  is equal to 2.5 ( $EC_w = 5$ ) we can minimize the LF to 40 percent and 5 percent using water diverted below and above John Martin Reservoir, respectively.

**Leaching Fraction Estimation.** In order to estimate the LF and the amount of water required, only three pieces of information are needed; (i) the crop threshold soil salinity,  $EC_{e(ct)}$ , (ii) the salinity of the irrigation water,  $EC_w$ , and (iii) seasonal maximum evapotranspiration ( $ET_m$ ) of the crop. Figure 5 shows the relation between the leaching fraction, LF, and the ratio  $F_c$ . This ratio ( $F_c$ ) is the crop threshold salinity divided by the irrigation water salinity ( $F_c = EC_{e(ct)}/EC_w$ ). This relation shows that for any particular crop, the LF exponentially increases as the salinity of the water increases (ratio decreases).

Knowing the threshold salinity,  $EC_{e(ct)}$ , for a given crop and the electrical conductivity of the irrigation water,  $EC_w$ , the necessary leaching fraction (LF) can be graphically determined from Figure 5. For a more accurate LF estimation the exponential relations shown in Figure 5 can be simplified for any particular crop. The "classical" method (Rhoades, 1974) of determining the LF is described by the following equation:

$$LF = EC_w / (5EC_{e(ct)} - EC_w) \quad (6)$$

In recent years (Rhoades, *et al.*, 1992b) it has been shown that the LF is affected by the net water application. To account for this effect two additional relationships have been developed. Since the net water application can be related to the irrigation system these relations are divided into two categories, namely (i) conventional and (ii) high frequency. Under "conventional irrigation" where there are relatively large net water applications, a higher leaching fraction is required at the same value of  $F_c$  as compared to high frequency irrigation (small net water applications). Conventional irrigation scenarios where net water applications are relatively large include deep rooted crops grown under surface irrigation. High frequency irrigation scenarios include shallow rooted crops under surface irrigation or where sprinkler or drip irrigation systems are used.

**Figure 4a. Soil profile salinity resulting from irrigation of known composition-lower reach of Arkansas River below John Martin Reservoir.**

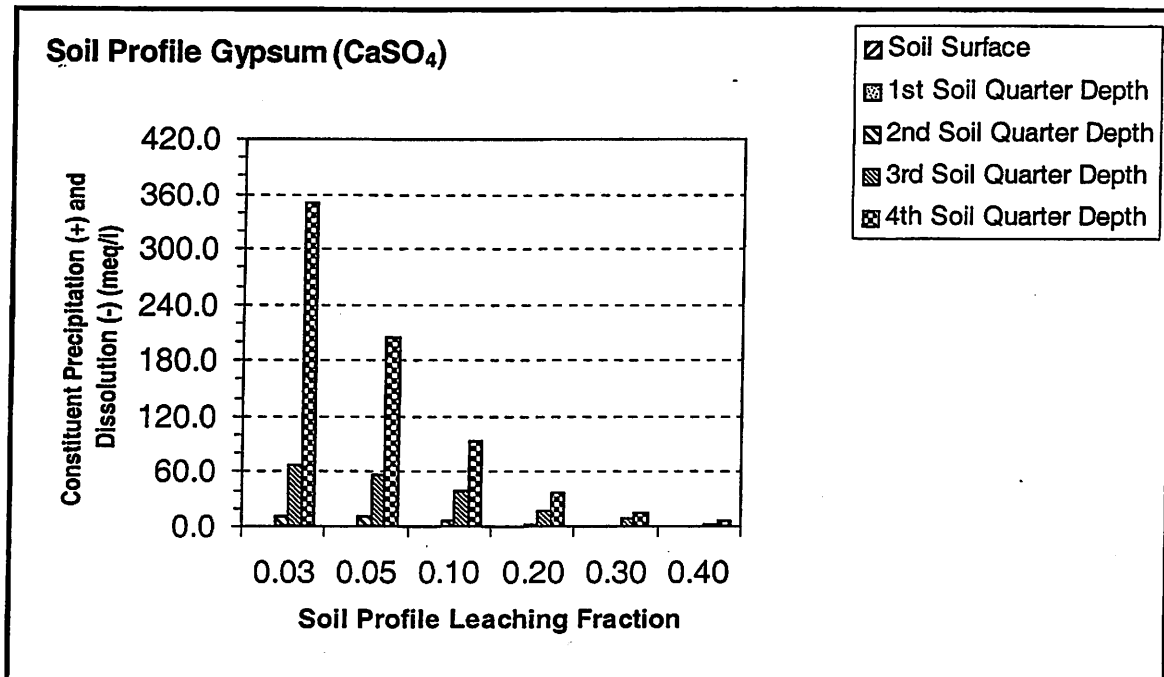
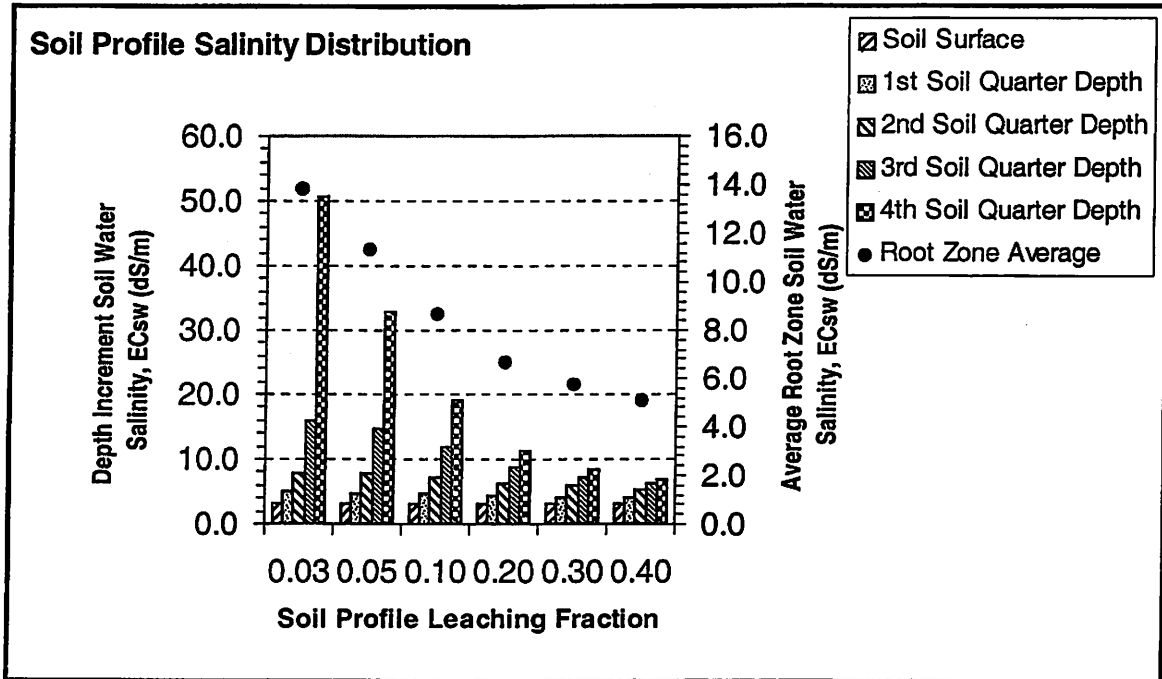
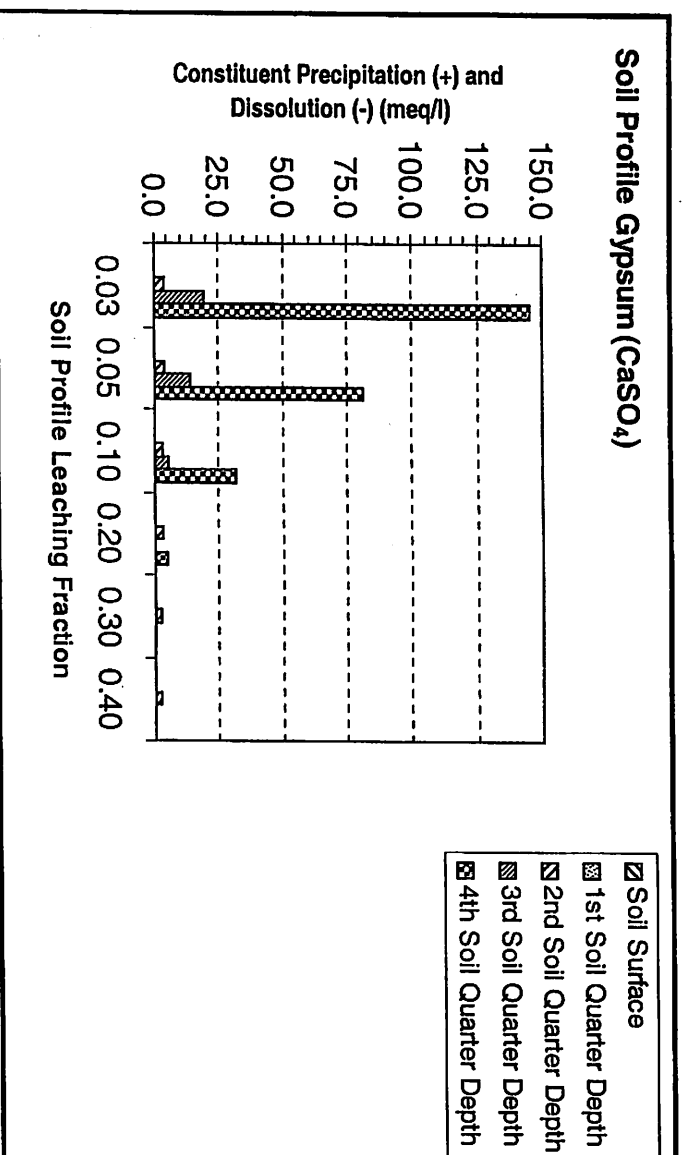
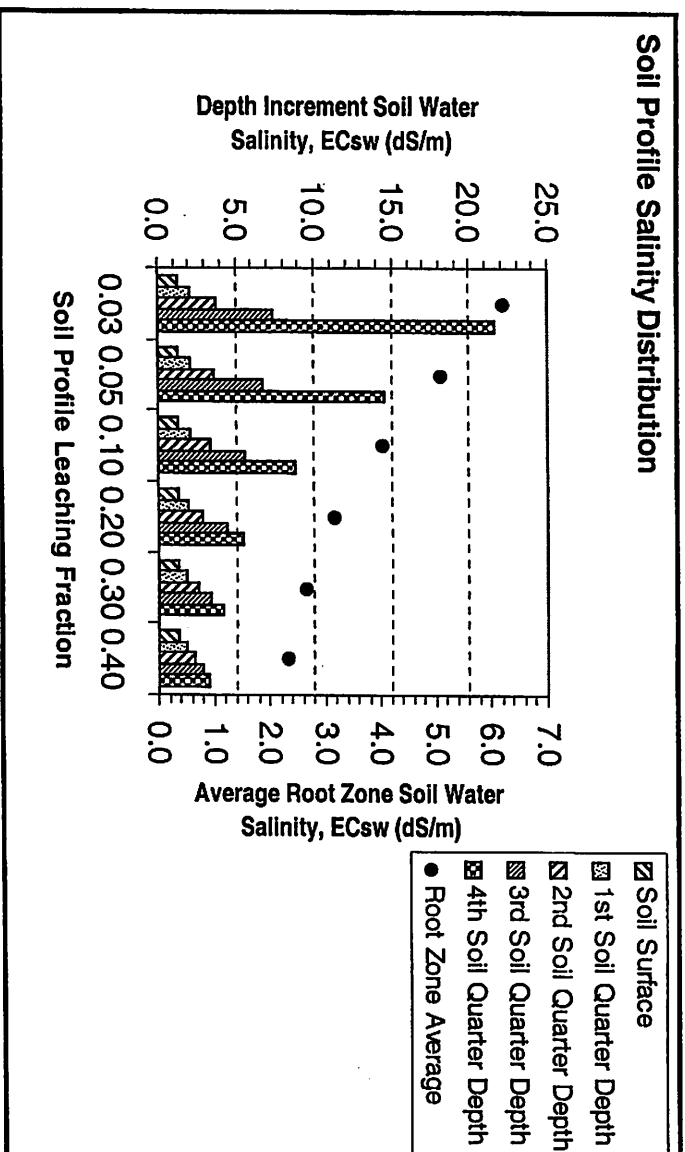
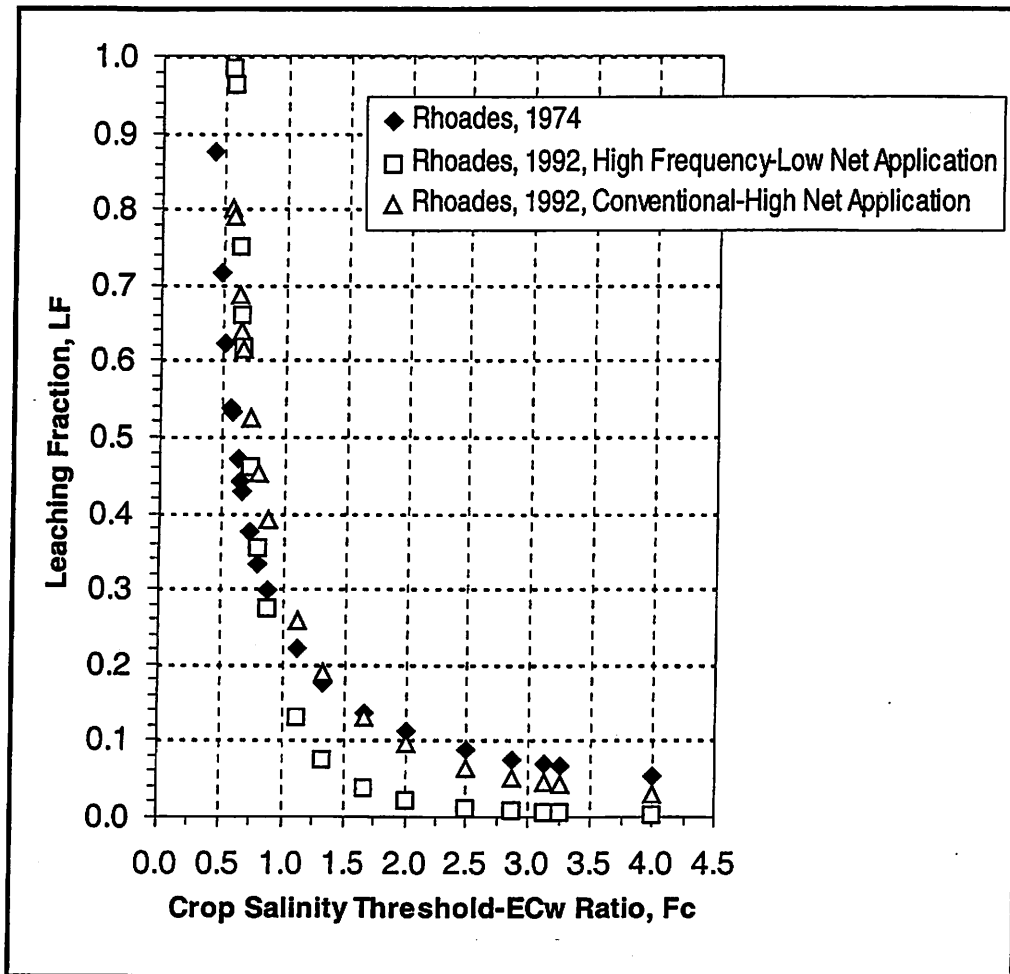


Figure 4b. Soil profile salinity resulting from irrigation of known composition-middle reach of Arkansas River between John Martin Reservoir and Pueblo Reservoir.





**Figure 5. Relationship between the crop salinity threshold-water salinity (ECw) ratio and the leaching fraction.**

The exponential relations for the conventional irrigation (CI) and high frequency irrigation (HF) can be calculated as follows:

$$LF = 0.1794 / (Fc)^{3.0417} \quad (\text{High Frequency Irrigation-HF}) \quad (7)$$

$$LF = 0.3086 / (Fc)^{1.7020} \quad (\text{Conventional Irrigation-CI}) \quad (8)$$

The gross irrigation requirement (GIR) or annual depth of water (sum of irrigation plus effective rainfall) that is required to meet both the maximum crop evapotranspiration ( $ET_m$ ) and the leaching requirement (excluding runoff) can then be calculated:

$$GIR = ET / (1 - LF) \quad (9)$$

where the  $ET$  and  $GIR$  are expressed in inches. The portion of water that is applied for the leaching,  $L_r$ , (inches) can then be calculated:

$$L_r = GIR - ET \quad (10)$$

Field studies and observations have shown that as a general rule the timing of leaching is not critical as long as the crop tolerance threshold is not exceeded during critical periods or extended time periods. Alternative timings include each irrigation, at selected seasonal irrigations or less frequently. It must be noted that water losses attributed to deep percolation that occur during the season, particularly with surface irrigation systems, are often in excess of the leaching fraction. A careful analysis must be done to determine whether or not the amount of water required for salt leaching will be satisfied by the field's irrigation inefficiency.

### **Provide Adequate Drainage**

The third rule of salinity control and its management is that if a field is to be irrigated it must be drained. The lack of adequate drainage leads to (i) waterlogging, (ii) secondary soil profile salinization resulting from the upward capillary flux, and (iii) impaired movement and operation of farm equipment.

In order to reduce the risk of waterlogging and secondary soil profile salinization, drainage should be provided. In the absence of natural drainage artificial drainage will be needed. There are fundamentally two purposes of drainage. First, sufficient drainage is required to discharge the excess precipitated salts that have accumulated from previous irrigation and those salts of the infiltrated water into the soil which are in excess of the crop evapotranspiration demand. Second, the water table, if present needs to be kept at the proper depth. This permits adequate root development by minimizing the net flux of salt-laden groundwater upwards into the rootzone.

### **Monitor Irrigation Adequacy and Soil Profile Salinity**

A very important consideration in achieving a sustainable irrigated agroecosystem susceptible to salinity hazards is to monitor rootzone soil salinity levels and distributions. The periodic assessment and inventory can serve as critical means to guide management including the adequacy of leaching and drainage. On a large-scale or regional basis temporal and spatial information can be useful to delineate regions of drainage problem areas and salt-loading areas.

The proper framework to guide management practices in controlling salinity can be best outlined as follows (Rhoades, 1997, Rhoades, *et al.*, 1997):

- 1) Adequate knowledge of the temporal trends in the level, extent, magnitude and spatial distribution of rootzone soil salinity within irrigated cropland fields.
- 2) Ability to ascertain the impact of changes in management practices and provide a course of action for evaluating irrigation and drainage system adequacy and effectiveness.
- 3) Ability to pinpoint salinity hazards and analyzes the inherent causes, whether management-induced.
- 4) Capability to isolate parts of individual fields and areas of large-scale irrigated regions where excessive deep percolation is occurring.

If the outcomes identified within this framework are to be achieved traditional observation methods are no longer appropriate. The framework requires the need for repeated measurements in both

time and space that accurately describe salinity patterns. Obtaining the needed information using conventional soil sampling and laboratory-analysis procedures is not practical and cost prohibitive.

A set of practical salinity assessment procedures and *in situ* techniques for measuring soil salinity in the field has been developed. Large intensive and extensive data sets can be collected using these techniques and methodologies; they provide a systematic means for describing salinity condition both spatially and temporally. Most importantly it allows practitioners to evaluate management effects. These salinity assessment procedures involve the geospatial measurement of the bulk soil electrical conductivity (ECa) directly in the field. The methodology and instrumental techniques can be integrated into a system that is rapid and mobile. Several variations of the mobile apparatus, including what has become known as the "Salty-Dawg", and the "Salt-Sniffer", are currently being utilized. These self-propelled units are comprised of commercially available components.

An example of the application of this technology in the Arkansas River Drainage Basin is shown in Figure 6. In order to assess alternative conservation treatment the field-scale soil salinity conditions were characterized and mapped using the dual pathway parallel conductance model (DPPC). The description of the model, its theory, mechanization, and example applications are provided elsewhere (Rhoades, 1990, 1992, 1993, 1994; Rhoades, *et al.* 1989a, 1989b, 1990, 1999; Lesch *et al.*, 1992, 1995a, 1995b, 1997, 1998, 2000).

## **ALTERNATIVE STRATEGIES FOR CONTROLLING SALINITY OF WATER RESOURCES**

### **Interception, Isolation of Drainage Water and its Subsequent Reuse**

One alternative strategy to control the salinity is to intercept drainage waters before they are returned to the river. These waters are then substituted for the less saline water of the original water supply. The drainage waters that have been intercepted and isolated from can then be applied during the irrigation season to the more salt-tolerant crops grown in the rotation. The process is repeated with the continued successive reuse of the drainage water and its application to the increasingly salt tolerant crops. Once the water's capacity has been depleted and become too saline for any of the crops in the rotation the water can be discharged or treated. This kind of irrigation scheme was been shown to be extremely successful (Rhoades, 1989, Rhoades, *et al.*, 1988a, 1988b, 1989c).

### **Changes in Landuse**

Another alternative is one that removes land from irrigation that have been shown to adversely affect receiving water supplies. There may be circumstances where irrigation is occurring on hydrogeologic landscapes, where the salt-loading and degradation of the water resource is severe enough, that warrants the consideration of eliminating irrigation of those lands.

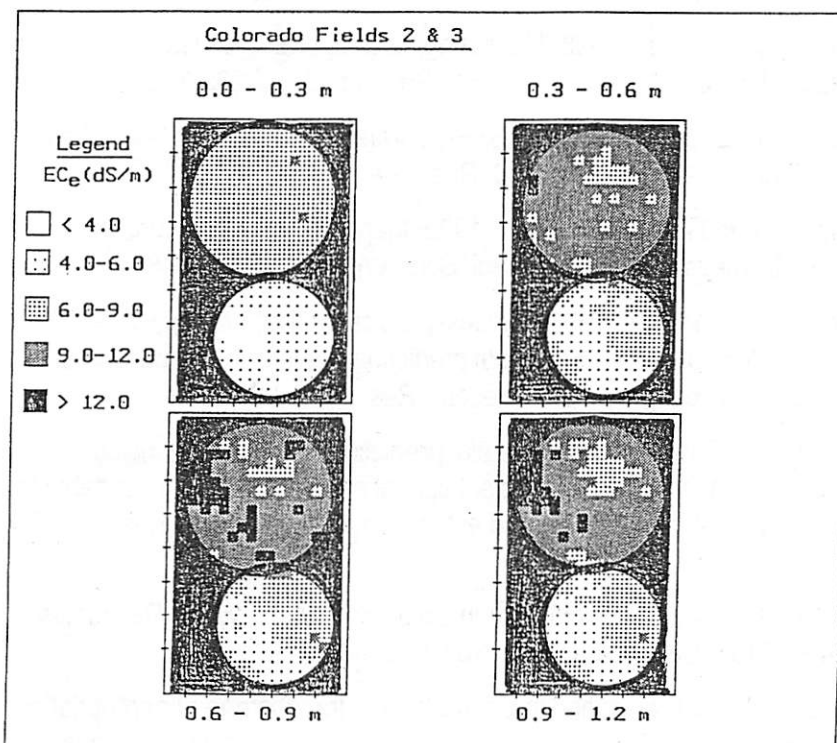
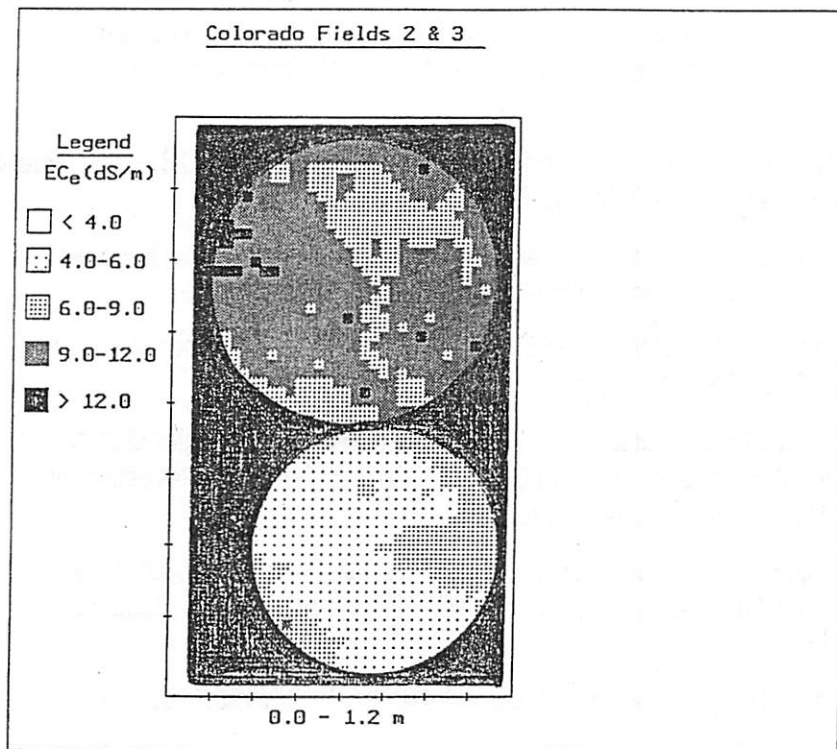


Figure 6. Survey of depth specific levels of soil salinity and mapping of selected center pivots-Pueblo County, Colorado, 1996.

## REFERENCES

- Abbott, P.O. 1985. Description of Water Systems Operations in the Arkansas River basin, Colorado. Water Resources Investigation. Rept. 85-4092, U.S. Geological Survey, Lakewood, CO.
- Aschermann, A. 1994. "Winds in the Cornfields-Ghost Towns and Settlements, 1787-1872, Pueblo County", Pueblo County Historical Society, Pueblo, CO. 55 pp.
- Bernstein, L. and M. Fireman. 1957. Laboratory studies on salt distribution in furrow irrigated soil with special reference to the pre-emergence period. *Soil Sci.* 83:249-263.
- Bernstein, L. and M. Fireman, and R.C. Reeve. 1955. Control of salinity in the Imperial Valley, California. USDA-ARS, ARS-4-4. 16pp.
- Cain, D. 1987. Relations of Specific Conductance to Streamflow and Selected Water Quality Characteristics of the Arkansas River Basin Colorado. Water Resources Investigations Report 87-4041, US Geological Survey, Lakewood, CO.
- Dash, R.G. and R.F. Ortiz. 1996. Water-Quality Data for the Arkansas River Basin, Southeastern Colorado, 1990-1993. Water Resources Investigations Report 95-464, US Geological Survey, Denver, CO
- Domenici, P. 1983. "The correct way to spell chile." *Congressional Record* 129:149.
- Evans, J.H. (1994) "That famous Barnhart celery", Pueblo County Historical Society, *In: Pueblo Lore compendium #5*, 1995, 9-10.
- Hobbs, G.J., Jr. 1997. Colorado water law: An historical overview. *Water Law Review* 1(1):1-15.
- Lesch, S.M., J.H. Herrero, and J.D. Rhoades. 1998. Monitoring for temporal changes in soil salinity using electromagnetic induction techniques. *Soil Sci. Soc. Am. J.* 62:232-242.
- Lesch, S. M., J. D. Rhoades, and D. L. Corwin. 2000. ESAP-95 Version 2.01R User Manual and Tutorial Guide. Res. Rept. No. 146. USDA-ARS, Riverside, CA
- Lesch, S. M., J. D. Rhoades, L. J. Lund and D. L. Corwin. 1992. Mapping soil salinity using calibrated electromagnetic measurements. *Soil Sci. Soc. Am. J.* 56(2):540-548.
- Lesch, S. M., D. J. Strauss and J. D. Rhoades. 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques: 1. Statistical prediction models: A comparison of multiple linear regression and cokriging. *Water Resour. Res.* 31:373-386.
- Lesch, S. M., D. J. Strauss and J. D. Rhoades. 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques: 2. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. *Water Resour. Res.* 31:387-398.
- Litke, D.W. and C.L. Appel. 1989. Estimated Use of Water in Colorado, 1985. . Water Resources Investigations Report 88-4101, US Geological Survey, Lakewood, CO
- McHendrie, A.W. 1952. The early history of irrigation in Colorado, and the doctrine of appropriation. *In: A Hundred Years of Irrigation in Colorado: 100 Years of Organized and Continuous Irrigation, 1852-1952*, Colorado Water Conservation Board and Colorado Agricultural and Mechanical College, Fort Collins, CO.



- Maas, E.V. 1990. Crop Salt Tolerance. *In: Tanji, K.K. (ed.), Agricultural Salinity Assessment and Management*. ASCE Manuals and Repts. on Engineering Practice No. 71.
- Miles, D.L. 1977. "Salinity in the Arkansas Valley of Colorado." Cooperative Extension Service and Environmental Protection Agency, Interagency Agreement Rept. EPA-IAG-DR-0544, Denver, CO.
- Quillen, E. 1994 "Why a marker for Pike, and none for a competent commander?" Denver Post, Sept 6, Denver, CO.
- Rhoades, J.D. 1974. Drainage for Salinity Control. *In: J. van Schilfgaarde (ed.), Drainage and Agriculture*. Agronomy Monograph No. 17, American Society of Agronomy. pp. 433-461.
- Rhoades, J.D. 1989. Intercepting, isolating and reusing drainage waters for irrigation to conserve water and protect water quality. *Agric. Water Mgmt.* 16:37-52.
- Rhoades, J. D. 1990. Determining soil salinity from measurements of electrical conductivity. *Commun. Soil Sci. & Plant Anal.* 21(13-16):1887-1926.
- Rhoades, J. D. 1992. Instrumental field methods of salinity appraisal. *In: G. C. Topp, W. D. Reynolds and R. E. Green (eds.); Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*. SSSA Special Pub. No. 30, pp. 231-248.
- Rhoades, J. D. 1993. Electrical conductivity methods for measuring and mapping soil salinity. *In: D. L. Sparks (ed.), Advances in Agronomy*. Vol. 49:201-251.
- Rhoades, J. D. 1994. Soil salinity assessment: Recent advances and findings. ISSS Sub-Commission Conference, Acapulco, Mexico, July 10- 16, 1994.
- Rhoades, J.D. 1997. Sustainability of Irrigation: An Overview of Salinity Problems and Control Strategies. *In: Footprints of Humanity: Reflections on Fifty Years of Water Resource Development, Proceedings of the Canadian Water Res. Assoc., 1997 Annual Conference, Lethbridge, Alberta.*
- Rhoades, J.D., F.T. Bingham, J. Letey, A.R. Dedrick, M. Bean, G.J. Hoffman, W.J. Alves, R. V. Swain, P.G. Pacheco and R.D. LeMert. 1988a. Reuse of drainage water for irrigation: results of Imperial Valley study. I. Hypothesis, experimental procedures and cropping results. *Hilgardia*. 56:1-16.
- Rhoades, J.D., F.T. Bingham, J. Letey, G.J. Hoffman, A.R. Dedrick, P.J. Pinter and J.A. Replogle. 1989. Use of saline drainage water for irrigation: Imperial Valley study. *Agric. Water Mgmt.* 16:25-36.
- Rhoades, J. D., F. T. Bingham, J. Letey, P. J. Pinter, Jr., R. D. LeMert, W. J. Alves, G. J. Hoffman, J. A. Replogle, R. V. Swain and P. G. Pacheco. 1988b. Reuse of drainage water for irrigation: results of Imperial Valley study. II. Soil salinity and water balance. *Hilgardia*. 56:17-44.
- Rhoades, J.D., F. Chanduvi, and S.M. Lesch. 1999. Soil Salinity Assessment: Methods and Interpretations of Electrical Conductivity Measurements. FAO Irrigation and Drainage Paper, No. 57. Food and Agriculture Organization of the United Nations, Rome, Italy

- Rhoades, J.D., A. Kandiah, and A.M. Mashali. 1992. The Use of Saline Waters for Crop Production. FAO Irrigation and Drainage Paper No. 48. Rome, Italy.
- Rhoades, J. D., S. M. Lesch, R. D. LeMert and W. J. Alves. 1997. Assessing irrigation/drainage/salinity management using spatially referenced salinity measurements. *Agr. Water Mgt.* 35:147-165.
- Rhoades, J. D., S. M. Lesch, P. J. Shouse and W. J. Alves. 1989b. New calibrations for determining soil electrical conductivity-depth relations from electromagnetic measurements. *Soil Sci. Soc. Am. J.* 53(1):74-79.
- Rhoades, J. D., N. A. Manteghi, P. J. Shouse and W. J. Alves. 1989a. Soil electrical conductivity and soil salinity: New formulations and calibrations. *Soil Sci. Soc. Am. J.* 53(2):433-439.
- Rhoades, J. D., P. J. Shouse, W. J. Alves, N. A. Manteghi and S. M. Lesch. 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. *Soil Sci. Soc. Am. J.* 54(1):46-54.
- Taylor, R.C. 1963. Colorado South of the Border. Sage Press, Denver, CO.
- Vigil, K. 2001. *"Historic battleground-Puebloan pinpoints 1779 site of Cuerno Verde-Anza battle."* Pueblo Chieftain, July 16, 2001, Pueblo, CO.
- Wozniak, F.E. 1998. Irrigation in the Rio Grande Valley, New Mexico: A study and annotated bibliography of the development of irrigation systems, RMRS-P-2, USDA-FS, Rocky Mountain Research Station, Fort Collins, CO. 204 pp.

## APPENDIX I-Salt Tolerance of Selected Crops

Common Name of Crop	Botanical Crop Name	Soil Salinity		Soil Solution Osmotic Potential		Rating
		Threshold, EC <sub>e</sub> , dS/m	Slope, %	Threshold OP <sub>1c</sub> , bars	Slope, %	
Alfalfa	<i>Medicago sativa</i>	2.0	7.3	-1.51	-1.94	MS
Almond	<i>Prunus dulcis</i>	1.5	19.0	-1.11	-1.25	S
Apple	<i>Malus sylvestris</i>					S
Apricot	<i>Prunus armeniaca</i>	1.6	24.0	-1.19	-1.24	S
Asparagus	<i>Asparagus officinalis</i>	4.1	2.0	-3.24	-4.99	T
Avocado	<i>Persea americana</i>					S
Barley	<i>Hordeum vulgare</i>	8.0	5.0	-6.57	-11.77	T
Beet, red	<i>Beta vulgaris</i>	4.0	9.0	-3.15	-3.66	MT
Bermudagrass	<i>Cynodon dactylon</i>	6.9	6.4	-5.62	-7.96	T
Blackberry	<i>Rubus sp.</i>	1.5	22.0	-1.11	-1.20	S
Broadbean (faba bean)	<i>Vicia faba</i>	1.6	9.6	-1.19	-1.51	MS
Broccoli	<i>Brassica oleracea botrytis</i>	2.8	9.2	-2.16	-2.58	MS
Bromegrass, mountain	<i>Bromus marginatus</i>					MT
Bromegrass, smooth	<i>Bromus inermis</i>					MS
Brussel sprouts	<i>Brassica oleracea gemmifera</i>					MS
Cabbage	<i>Brassica oleracea capitata</i>	1.8	9.7	-1.35	-1.68	MS
Canola (rapeseed)	<i>B. napus</i>					MT
Cantaloupe (muskmelon)	<i>Cucumis Melo</i>					MS
Carrot	<i>Daucus carota</i>	1.0	14.0	-0.73	-0.92	S
Cauliflower	<i>Brassica oleracea botrytis</i>					MS
Celery	<i>Apium graveolens</i>	1.8	6.2	-1.35	-1.79	MS
Cherry, sand	<i>Prunus Besseyi</i>					S
Cherry, sweet	<i>Prunus avium</i>					S
Clover, alsike	<i>Trifolium hybridum</i>	1.5	12.0	-1.11	-1.37	MS
Clover, berseem	<i>Trifolium alexandrinum</i>	1.5	5.7	-1.11	-1.50	MS
Clover, ladino	<i>Trifolium repens</i>	1.5	12.0	-1.11	-1.37	MS
Clover, red	<i>Trifolium pratense</i>	1.5	12.0	-1.11	-1.37	MS
Clover, strawberry	<i>Trifolium fragiferum</i>	1.5	12.0	-1.11	-1.37	MS
Clover, sweet	<i>Melilotus sp.</i>					MT
Corn, grain	<i>Zea mays</i>	1.7	12.0	-1.27	-1.54	MS
Corn, forage	<i>Zea mays</i>	1.8	7.4	-1.35	-1.75	MS
Corn, sweet	<i>Zea mays</i>	1.7	12.0	-1.27	-1.54	MS
Cotton	<i>Gossypium hirsutum</i>	7.7	5.2	-6.31	-10.66	T
Cowpea	<i>Vigna unguiculata</i>	4.9	12.0	-3.91	-3.99	MT
Cucumber	<i>Cucumis sativus</i>	2.5	13.0	-1.91	-2.13	MS
Date palm	<i>Phoenix dactylifera</i>	4.0	3.6	-3.15	-4.50	T
Drybean	<i>Phaseolus vulgaris</i>	1.0	19.0	-0.73	-0.88	S
Eggplant	<i>S. melongena esculentum</i>	1.1	6.9	-0.80	-1.08	MS
Fescue, tall	<i>Festuca elatior</i>	3.9	5.3	-3.07	-4.08	MT
Fig	<i>Ficus carica</i>					MT
Flax	<i>Linum usitatissimum</i>	1.7	12.0	-1.27	-1.54	MT
Grama, blue	<i>Boutteloua gracilis</i>					MS
Grape	<i>Vitis sp.</i>	1.5	16.0	-1.11	-1.30	MS
Grapefruit	<i>Citrus paradisi</i>	1.8	16.0	-1.35	-1.52	S
Guar	<i>Cyamopsis tetragonoloba</i>	8.8	17.0	-7.27	-5.60	T
Guayule	<i>Parthenium argentatum</i>	15.0	33.0	-12.79	-4.33	T
Kale	<i>B. oleracea acephala</i>					MS
Lettuce	<i>Lactuca sativa</i>	1.3	13.0	-0.96	-1.18	MS
Milkvetch, Cicer	<i>Astragalus cicer</i>					MS
Millet, foxtail	<i>Setaria italica</i>					MS
Oats	<i>Avena sativa</i>					MT

## APPENDIX I-Salt Tolerance of Selected Crops

Common Name of Crop	Botanical Crop Name	Soil Salinity		Soil Solution Osmotic Potential		Rating
		Threshold, EC <sub>e</sub> , dS/m	Slope, %	Threshold OP <sub>1c</sub> , bars	Slope, %	
Okra	<i>Abelmoschus esculentus</i>					S
Onion	<i>Allium cepa</i>	1.2	16.0	-0.88	-1.06	S
Orange	<i>Citrus sinensis</i>	1.7	16.0	-1.27	-1.45	S
Orchardgrass	<i>Dactylis glomerta</i>					MS
Parsnip	<i>Pastinaca sativa</i>					S
Pea	<i>Pisum sativum</i>					S
Peach	<i>Prunus Persica</i>	1.7	21.0	-1.27	-1.35	S
Peanut	<i>Arachis hypogaea</i>	3.2	29.0	-2.49	-1.87	MS
Pear	<i>Pyrus communis</i>					S
Pepper	<i>Capsicum annum</i>	1.5	14.0	-1.11	-1.33	MS
Plum (seedling)	<i>Prunus domestica</i>	1.5	18.0	-1.11	-1.27	S
Plum (fruit-bearing)	<i>Prunus domestica</i>	2.6	31.0	-2.00	-1.59	S
Potato	<i>Solanum tuberosum</i>	1.7	12.0	-1.27	-1.54	MS
Prune	<i>Prunus domestica</i>	1.5	18.0	-1.11	-1.27	S
Pumpkin	<i>Curculita. pepo pepo</i>					MS
Radish	<i>Raphanus sativus</i>	1.2	13.0	-0.88	-1.10	MS
Rice	<i>Oryza sativa</i>	3.0	12.0	-2.32	-2.56	S
Ryegrass, perennial	<i>Lolium perenne</i>					MT
Safflower	<i>Carthamus tinctoris</i>					MT
Sesame	<i>Sesamum indicum</i>					S
Sorghum	<i>Sorghum bicolor</i>	6.8	16.0	-5.53	-4.59	MT
Soybean	<i>Gycine max</i>	5.0	20.0	-3.99	-3.11	MT
Spinach	<i>Spinacia oleracea</i>	2.0	7.6	-1.51	-1.93	MS
Squash, summer	<i>C pepo melopepo</i>	4.7	9.4	-3.74	-4.24	MT
Squash, scallop (winter)	<i>C pepo melopepo</i>	3.2	16.0	-2.49	-2.46	MS
Strawberry	<i>Fragaria sp.</i>	1.0	33.0	-0.73	-0.78	S
Sudangrass	<i>Sorghum sudanense</i>	2.8	4.3	-2.16	-2.94	MT
Sugarbeet	<i>Beta vulgaris</i>	7.0	5.9	-5.70	-8.46	T
Sugarcane	<i>Saccharum officinarum</i>	1.7	5.9	-1.27	-1.70	MS
Sunflower	<i>Helianthus annus</i>	4.8	5.0	-3.82	-5.28	MT
Sweet potato	<i>Impomoea batatas</i>	1.5	11.0	-1.11	-1.39	MS
Tangerine	<i>Citrus reticulata</i>					S
Timothy	<i>Phleum pratense</i>					MS
Tomato	<i>Lycopersicon lycopersicum</i>	2.5	9.9	-1.91	-2.28	MS
Trefoil, birdsfoot (big)	<i>Lotus uliginosus</i>	2.3	19.0	-1.75	-1.78	MS
Trefoil, birdsfoot (narrowleaf)	<i>Lotus corniculatus</i>	5.0	10.0	-3.99	-4.41	MT
Trefoil, birdsfoot (broadleaf)	<i>Lotus corniculatus arvensis</i>					MT
Triticale	<i>X Triticoseale</i>	6.1	2.5	-4.93	-8.76	T
Turnip	<i>Brassica rapa</i>	0.9	9.0	-0.65	-0.87	MS
Vetch, common	<i>Vicia angustifolia</i>	3.0	11.0	-2.32	-2.63	MS
Watermelon	<i>Citrullus lanatus</i>					MS
Wheat, common	<i>Triticum aestivum</i>	6.0	7.1	-4.84	-6.25	MT
Wheat, semidwarf	<i>Triticum aestivum</i>	8.6	3.0	-7.09	-18.65	T
Wheat, Durum	<i>Triticum turgidum</i>	5.9	3.8	-4.76	-7.53	T
Wheatgrass, crested	<i>Agropyron sibiricum</i>	3.5	4.0	-2.74	-3.79	MT
Wheatgrass, fairway crested	<i>Agropyron cristatum</i>	7.5	6.9	-6.14	-8.75	T
Wheatgrass, intermediate	<i>Agropyron intermedium</i>					MT
Wheatgrass, tall	<i>Agropyron elongatum</i>	7.5	4.2	-6.14	-11.16	T
Wheatgrass, western	<i>Agropyron smithii</i>					MT
Wildrye, Canadian	<i>Elymus canadensis</i>					MT
Wildrye, Russian	<i>Elymus Junceus</i>					T