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# Assessment of Water Quality for Irrigation Under the South Platte Water Conservation Project

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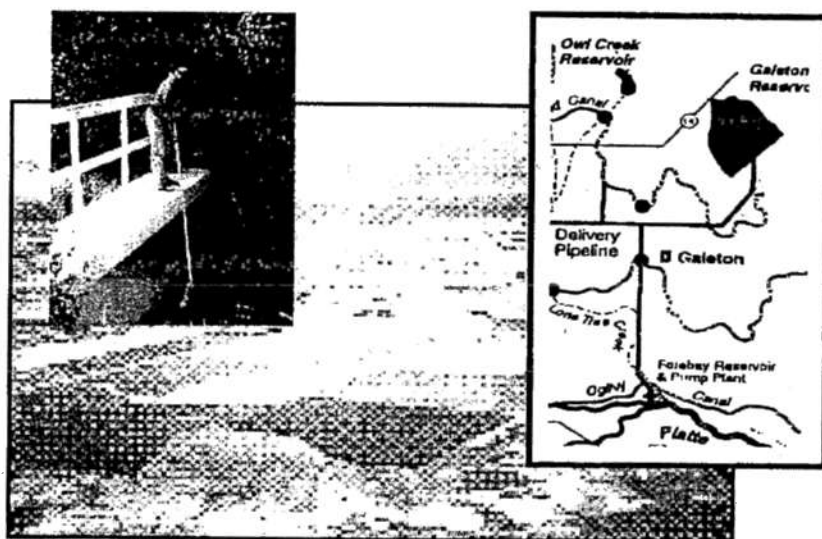
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**DRAFT**

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## ABSTRACT

A reconnaissance-stage investigation was conducted to assess the suitability of waters exchanged under the proposed South Platte Water Conservation Project (SPWCP) for sustainable irrigated agriculture. The aim of the project is to develop a lower-quality unappropriated supply that can be exchanged with agriculture for higher-quality irrigation water, more suitable to municipal needs along the northern front range of Colorado. The key to insuring that such an arrangement proves a "win-win" situation is for the lower-quality source to be of sufficiently good quality for irrigated agriculture. Soils, crops, and agricultural workers must not be harmed by the exchange. Water-quality criteria for the major constituents of concern to irrigated agriculture were reviewed and summarized. Results are presented from field studies of current conditions within the project command area and at the proposed new water diversion point. These conditions were analyzed and compared to predict future implications for the SPWCP. Results from the present study indicate that the SPWCP is indeed viable, but only if carefully managed. The greatest concern is the anticipated increase in the salinity of the water supply under the new project, compared to the salinity of the current supplies. Preliminary analysis indicated that this increase will range from about 40%, on the average, for a low yield (exchange potential) of about 27 million m<sup>3</sup> (22,000 ac-ft) to about 120% for a high yield of 80 million m<sup>3</sup> (65,000 ac-ft). These higher salinity levels might require 25% to 70% more infiltrated irrigation water in the area. The increased infiltrated volume would be needed to leach out from the soil the additional salts introduced in the SPWCP water to insure that soil salinity in the region is not raised above current levels. The amount of increased irrigation water required will be lower for a low yield since less-available, but higher-quality, flow could be diverted. The increased irrigation water required also will be lower if water diverted under the SPWCP can be mixed with higher-quality water from upstream diversions (and the resulting mix spread over a larger area). Measures taken to reduce extraneous salt loading (from mineral weathering, fertilization, and upward flow from saline high water tables) would further reduce irrigation requirements. Secondary concerns are the occurrence of periodically high concentrations of microbial contaminants and significant concentrations of nitrate nitrogen and bicarbonate ion at the proposed new water diversion. Clear direction for project planning and management will require additional field studies, better definition of management options, and further modeling to predict future conditions under management alternatives. Specific recommendations are made regarding each of these issues.

## INTRODUCTION

The front range of Colorado, like many arid regions in the western United States, is experiencing tension between economic sectors that compete for limited water resources. As urban areas grow, their need for high-quality water also grows. Most of the higher-quality supplies, in the form of upstream and transmountain diversions, have been appropriated for prior use by the agricultural sector for irrigation. Hence, cities and industries increasingly look to acquire agricultural water rights to satisfy their rising demand. These rights can be obtained either through direct "buy-out" or through carefully-arranged transfer and exchange agreements. If agricultural water rights are bought, the land they once irrigated will become dryland and production will drop drastically. If, on the other hand, higher-quality irrigation water, more suitable to municipal needs, can be exchanged for a lower-quality unappropriated source, then productive irrigated agriculture can be sustained. The key to insuring that such an arrangement proves a "win-win" situation is for the lower-quality source to be of sufficiently good quality for irrigated agriculture. Soils, crops, and agricultural workers must not be harmed by the exchange.

Anticipating continued growth in the urban corridor along the northern front range, the Northern Colorado Water Conservancy District (NCWCD) has planned the development of the South Platte Water Conservation Project (SPWCP). The goal of the project is to "divert, when in priority, the unappropriated waters of the South Platte River and subsequently exchange this water for a like amount of water at upstream locations on the Poudre River using a series of intra-ditch and river exchanges" (NCWCD 1996). Two irrigation canal systems would receive water under the SPWCP: the Larimer & Weld Canal, owned and operated by the Larimer & Weld Irrigation Company of Eaton, and the New Cache la Poudre Canal, owned and operated by the New Cache la Poudre Irrigating Company of Lucerne. The project would allow municipal users to exchange lower-quality downstream water with agricultural users for higher-quality upstream water.

In June, 1998, the NCWCD commissioned Colorado State University to study the suitability of the SPWCP exchange scheme for the long-term sustainability of irrigated agriculture under the proposed project command. The study was a reconnaissance-stage investigation with the intent of exploring the viability of the proposed project in view of possible water-quality impacts. This report summarizes the findings of the study. It outlines current knowledge on recommended criteria for water quality constituents of concern to irrigated agriculture. In addition, it describes current conditions, pertinent to water quality, in the command area and at the proposed point of diversion for the project. Finally, it uses modeling studies to assess these conditions, and makes recommendations in light of current water quality criteria and the anticipated future conditions under the SPWCP.

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## **DESCRIPTION OF THE SPWCP**

On December 23, 1992 NCWCD filed with the Division No. 1 Water Court in Greeley a total of eleven water rights applications associated with the proposed SPWCP. Description of the water rights applications is given in NCWCD (1996). Some of these applications were amended in 1997 to include a proposed new storage facility known as Galeton Reservoir. Current plans for the SPWCP call for a diversion of currently unappropriated flow near the confluence of the Cache la Poudre and South Platte Rivers to a forebay reservoir where a pumping station would transfer the water through a buried pipeline (Figure 1). During the annual diversion period, primarily the fall and winter months, the pipeline would carry water with an anticipated capacity of about  $11.3 \text{ m}^3/\text{s}$  ( $400 \text{ ft}^3/\text{s}$ ) northeast to the proposed new Galeton Reservoir (about 80,000 acre-ft of storage). During the irrigation season, flow would be diverted out of the storage reservoir to a pipe network for distribution to exchange points along the lower reaches of the Larimer & Weld Canal (Eaton Ditch) and the New Cache la Poudre Canal (Greeley No. 2 Canal), as shown in Figure 1. The land area anticipated to receive water diverted under the SPWCP is about 70,000 acres.

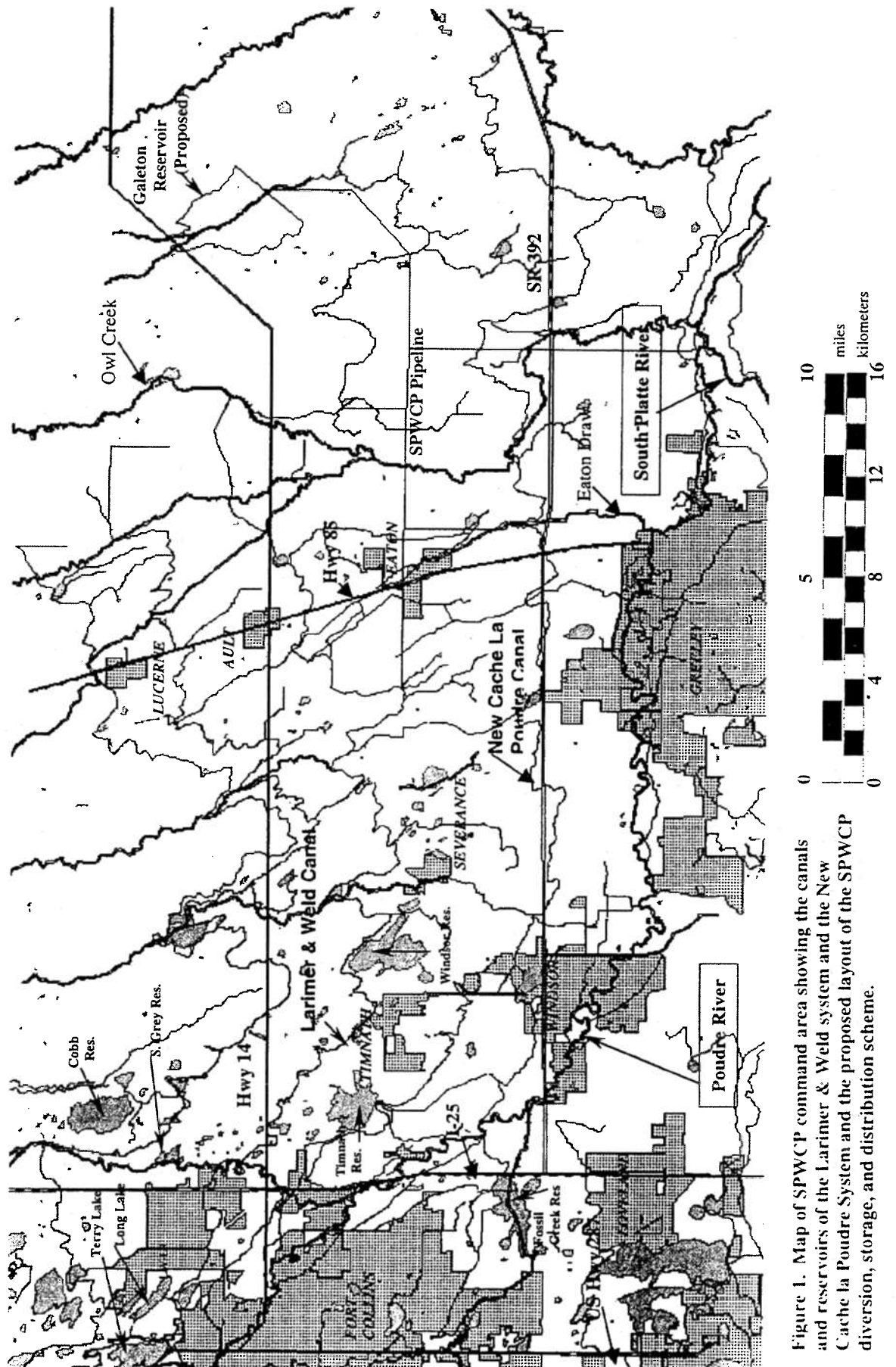


Figure 1. Map of SPWCP command area showing the canals and reservoirs of the Larimer & Weld system and the New Cache la Poudre System and the proposed layout of the SPWCP diversion, storage, and distribution scheme.

## WATER QUALITY CRITERIA FOR IRRIGATION

### Salinity and Major Ions Criteria

The most serious threat to the long-term sustainability of irrigated agriculture is salinization. Salinity problems usually appear in intensively-irrigated alluvial valleys within a few decades to a few hundred years of the commencement of large-scale irrigation. In fact, about 25% of the world's irrigated land currently is affected by waterlogging and salinity due to saline high water tables (Tanji 1990, Ghassemi et al. 1995). It has been estimated that 2.5 to 5 million acres of mostly prime agricultural land are becoming severely damaged through irrigation-induced salinization each year (Umali 1993, Kovda 1983). The losses to crop production, when measured in economic terms, can be staggering. Ghassemi et al. (1995) estimated that worldwide productivity loss is valued at about \$10 billion per year. Others argue, however, that though losses to agricultural production are indeed high, the costs of providing facilities for adequate management sometimes are even higher (National Research Council 1989).

Irrigation waters typically carry 50 to 2000 mg/l of dissolved salts (carbonates, bicarbonates, sulfates and chlorides of calcium, magnesium, sodium, and potassium). Hence, total water applications of 0.75 to 1.5 m (2.5 to 5.0 ft) over an irrigation season can result in total seasonal salt loads of 0.5 to 30.1 metric tons per hectare (0.2 to 13.4 tons per acre). Irrigation and drainage must be carefully managed to maintain salt concentrations in the root-zone soil water that do not damage crop production.

The seasonal salt balance for an irrigated field is illustrated in Figure 2. Changes in water stored on the ground surface and lateral movement of subsurface water are assumed to be negligible. Hence, the major water flux components (expressed in appropriate volumetric units) are irrigation water applied to the land surface  $Q_a$ , surface runoff water  $Q_r$ , precipitation  $Q_p$ , infiltrated irrigation  $Q_i$  (applied irrigation water,  $Q_a$ , minus surface runoff occurring during irrigation), upward flow from a shallow water table  $Q_u$ , evapotranspiration  $Q_{et}$ , and deep percolation  $Q_w$ . Surface runoff,  $Q_r$ , though it includes runoff that occurs during rainfall events, usually is dominated by runoff of excess applied irrigation water. Precipitation minus runoff that occurs during rainfall is referred to as effective precipitation,  $Q_{pe}$ . The volume of water stored in the root zone at any time is referred to as  $S_{sw}$ . Each of the fluxes has a respective associated salt concentration (expressed in mass per unit volume, usually mg/l)  $C_a$ ,  $C_r$ ,  $C_p$ ,  $C_i$ ,  $C_u$ ,  $C_{et}$ , and  $C_w$ . The concentration of stored soil water is  $C_{sw}$ . The products of the seasonal water fluxes and their associated concentrations yield the total seasonal salt mass fluxes. Since the concentrations of precipitation water and evapotranspiration are negligible, the products  $Q_p C_p$  and  $Q_{et} C_{et}$  are taken as zero. Another source of salt to the root zone is the amount that may be dissolved out of the soil matrix and/or applied in soil fertilizers (typically as  $SO_4$  in ammonium sulphate applications of N and salts present in manure applications),  $X_d$  (expressed in mass units). In the case of salt precipitation, this term would be negative. Hence, the seasonal root zone (subsurface) salt balance equation can be estimated as



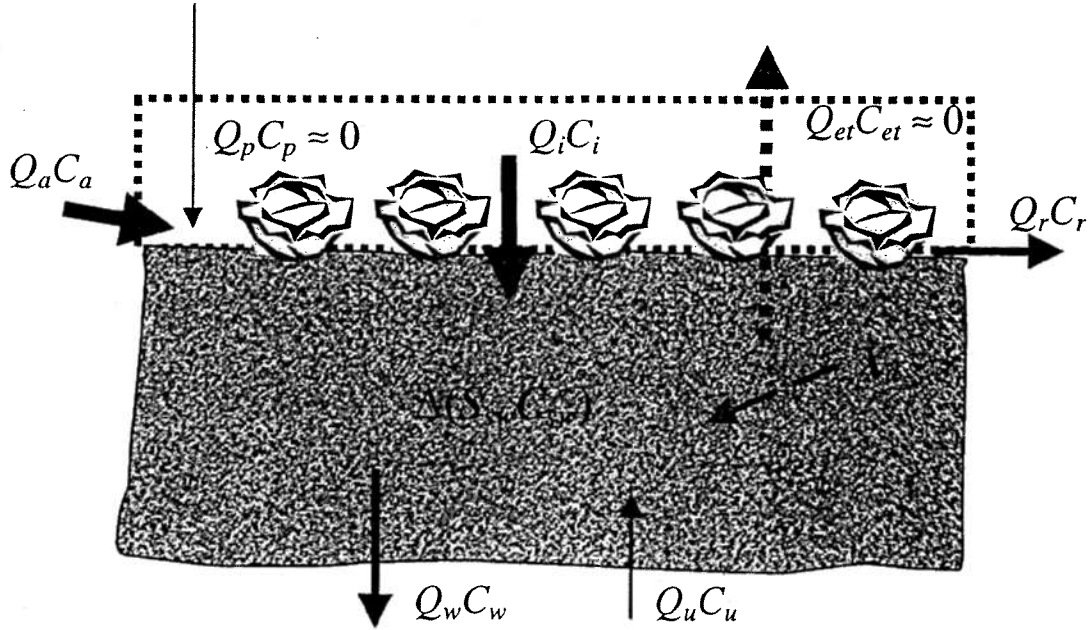


Figure 2. Root zone salt balance.

$$Q_i C_i + Q_u C_u - Q_w C_w + X_d = \Delta(S_{sw} C_{sw}) \quad (1)$$

Where  $\Delta(S_{sw} C_{sw})$  represents the total seasonal change in salt stored in the root zone.

Excessive soil water salinity,  $C_{sw}$ , can cause a reduction in crop yield. High salinity levels reduce the availability of soil water due to high osmotic potential and also can cause specific ion toxicity. Affects on crop production usually are expressed in terms of yield reduction as a function of the salinity of a saturated soil extract,  $C_e$ . For soil water contents near field capacity, the value of soil water concentration,  $C_{sw}$ , is estimated typically as 2 to 3 times the concentration at saturation,  $C_e$ .

The root zone salt balance in equation (1) reveals that the only practical way to maintain acceptable soil salinity is to make sure that enough irrigation water is infiltrated both to meet the crop water demand,  $Q_{et}$ , and to flush salts downward through the root zone as  $Q_w C_w$ . This salt flushing, or leaching, must not be excessive, however. If  $Q_w$  is larger than the natural drainage capacity, a shallow water table may build up, causing a return flow through upward capillary movement,  $Q_u$ . Though  $Q_u$  can be beneficial in reducing the amount of  $Q_i$  that is needed to meet net crop demands (that is,  $Q_{et} - Q_{pe}$ ), it often is accompanied by a high salinity concentration,  $C_u$ . In many cases, artificial

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drainage systems eventually will become necessary to keep  $Q_u C_u$  at an acceptable level. Also, larger amounts of applied  $Q_i$  can mobilize larger amounts of weathered mineral salts,  $X_d$ . A proper balance must be achieved: apply enough  $Q_i$  so that  $Q_w C_w$  is adequate, but not so much that  $Q_u C_u$  and  $X_d$  become problems.

The soil leaching process can be described using an empirical relationship presented by Bouwer (1969):

$$C_w = E_L C_{sw} + (1 - E_L) C_i \quad (2)$$

$\downarrow$   
 $2-3\% C_e$

wherein  $E_L$  is the leaching efficiency (Boumans and van der Molen 1964). This model assumes that the water draining from the root zone can be considered a mixture of irrigation water that has passed unchanged through the root zone and soil water that has been displaced by the irrigation water (Hillel 1998). The value of  $E_L$  depends primarily on the size distribution of the water-filled soil pores and the extent of soil cracking. It varies between about 0.2 for heavy soils to about 0.6 for light soils.

The effects of soil salinity on yield of crops that are common to the SPWCP command area are summarized in Table 1. The table provides  $C_e$  levels, expressed in units of electrical conductivity (dS/m), at which various yield reductions (in %) would be expected to occur. Since total dissolved solids cause an increase in the electrical conductivity of water, electrical conductivity (specific conductance) is used as a convenient surrogate measure of salinity. The general sensitivity rating of each crop also is given in Table 1. These data were derived from controlled experiments (Maas 1990).

**Table 1. Effect of Soil Salinity (Saturated Extract) on Yield of Major Crops in SPWCP Command Area (Maas 1990).**

Crop	Sensitivity Rating	Salinity Levels (dS/m) Causing Different Yield Reduction (%)			
		0%	10%	25%	50%
Corn	Moderately Sensitive	1.7	2.5	3.8	5.9
Alfalfa	Moderately Sensitive	2.0	3.4	5.4	8.8
Dry Beans	Sensitive	1.0	1.5	2.3	3.6
Sugar Beets	Tolerant	7.0	8.7	11.0	15.0
Barley	Tolerant	8.0	10.0	13.0	18.0
Wheat	Moderately Tolerant	6.0	7.4	9.5	13.0
Oats	Moderately Tolerant	-	-	-	-
Carrots	Sensitive	1.0	1.7	2.8	4.6
Onions	Sensitive	1.2	1.8	2.8	4.3
Cabbage	Moderately Sensitive	1.8	2.8	4.4	7.0

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High concentrations of some specific ions can threaten crop production. Ions of particular concern are sodium, bicarbonate, and chloride.

Though high concentrations of sodium can impair the availability of calcium and potassium to plant roots (Bernstein 1964, Maas and Grieve 1987), the most prevalent problems posed by sodium are those associated with soil physical characteristics. In general, when sodium ion concentrations are high relative to the combined concentrations of calcium and magnesium, clay particles in the soil tend to disperse. This, in turn, causes impairment in the storage and transmissive properties of the soil due to altered geometry and continuity of soil pores. A useful measure of the potential hazard is the sodium adsorption ratio (SAR):

$$SAR = Na^+ / (Ca^{2+} + Mg^{2+})^{0.5} \quad (3)$$

wherein the concentrations of the ions are expressed in molarities [(mg/l)/equivalent weight]. Higher SAR values indicate a higher dispersion potential of a water. However, for a given SAR value, the dispersion potential decreases as the total salinity increases (Pratt and Suarez 1990). A general rule of thumb is that sodium problems are rare when SAR values are less than about 6, increasing problems are encountered when values range from 6 to 9, and significant problems occur when values exceed about 9.

In waters having high bicarbonate ( $HCO_3^-$ ) concentrations, there is a tendency for Ca to react with  $HCO_3^-$  in the soil to precipitate  $CaCO_3$ . The net result is an increase in SAR (Feigin et al. 1991). Hence, an adjusted sodium adsorption ratio ( $SAR_{adj}$ ) has been introduced to account for the change in calcium solubility:

$$SAR_{adj} = Na^+ / (Ca_x^{2+} + Mg^{2+})^{0.5} \quad (4)$$

wherein  $Ca_x^{2+}$  is a function of the total salinity of the water and of the ratio  $HCO_3^- / Ca^{2+}$  where the concentrations of  $HCO_3^-$  and  $Ca^{2+}$  are expressed in meq/l. Values of  $Ca_x^{2+}$  increase with increasing total salinity concentration and decrease with increasing values of  $HCO_3^- / Ca^{2+}$  (Metcalf & Eddy 1991).

In addition to its affect on SAR, bicarbonate in high concentrations can react with micronutrients in the soil, reducing their availability to crops. In concentrations exceeding 150 mg/l, bicarbonate has been known to physiologically damage plant roots, causing a reduction in nutrient absorption (California Fertilizer Association 1985, Wallace 1992). Waters significantly affected by discharges from wastewater treatment plants tend to have high bicarbonate concentrations.

Chloride, like sodium, can be toxic to some plants when present in high enough concentration in the soil solution. Green beans, onions, carrots, and lettuce are especially vulnerable (Ayers and Westcot 1985, Maas 1986, Maas 1990). These crops will suffer

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yield loss at  $\text{Cl}^-$  concentrations above about 350 mg/l. Corn and cabbage are moderately tolerant, not suffering yield loss until concentration reaches 525 mg/l. Alfalfa can tolerate concentrations up to 700 mg/l, while sugar beets, wheat, and barley are highly tolerant, withstanding concentrations up to 2100-2450 mg/l.

Currently, no standards exist in Colorado law that govern maximum concentrations of salinity or major ions in waters used for irrigation of agricultural crops. The  $\text{Cl}^-$  standard for domestic water supply in Colorado is 250 mg/l (30-day average).

### **Microbial Contaminants Criteria**

Pathogens in irrigation water can pose hazards to human health both directly and indirectly. Disease can spread to farm workers through direct contact with contaminated water and with wet vegetative surfaces or by inhalation of aerosols produced by sprinklers. Threats to the general public occur through ingestion of active pathogens that survive on produce that has come in contact with irrigation water. This is especially of concern in the case of raw-edible vegetable crops, like the onions, carrots, and cabbage grown in the SPWCP command area.

Microbial contaminants in irrigation waters are derived primarily from animal wastes and treated human wastes that are discharged into streams. A variety of different pathogens can be isolated from wastewater. They fall into four categories: bacteria, protozoa, helminths (worms), and viruses (Rowe and Abdel-Maguid 1995). These organisms are transported in irrigation streams to the agricultural environment where they can survive for considerable periods of time. Fecal coliform bacteria can survive (at temperatures of 20 to 30°C) in soils for up to 70 days and on crops for up to 30 days. Corresponding soil and crop survival times for protozoa, helminths, and viruses are 20 days and 10 days, many months and 60 days, and 100 days and 60 days, respectively (Feigin et al 1991, Rowe and Abdel-Maguid 1995).

There is no conclusive epidemiological evidence that connects disease outbreak with pathogens in irrigation water or on wetted crops. Hence, the establishment of criteria for microbial contaminants in irrigation water has been controversial. The World Health Organization (WHO 1989) recommends a standard of 1000 colony-forming units (CFU) per 100 ml and a helminth egg concentration of not more than one per liter for general irrigation of crops likely to be eaten raw. However, the authors of the report emphasize that their guidelines are based upon the current lack of epidemiological evidence and not upon potential health risk. In some developed countries, however, standards are much more stringent. In California and Arizona, standards require no more than 2.2 CFU/100 ml for the geometric mean of five samples taken from water used to irrigate crops to be eaten raw. Single water samples must not show concentrations exceeding 23 CFU/100 ml in California and 25 CFU/100 ml in Arizona (California Department of Health 1978, Arizona Department of Health Services 1983). Arizona

standards further require a virus count of less than one enteric virus per 40 ml of water sample and no detectable *entamoeba histolytica*, *giardia lamblia*, and *ascaris lumbricoides* in waters irrigating raw-edible crops. Standards in Israel require no more than 12 CFU/100 ml in at least 80% of samples and no more than 2.2 CFU/100 ml in at least 50% of samples taken from water used to irrigated crops to be eaten raw. A recent study by Israeli researchers (Armon et al 1994) showed the presence of significant numbers of microbial contaminants on vegetables irrigated with contaminated waters. They recommended that wastewater effluents used for irrigation of raw-edible crops be treated to levels resulting in no detectable contamination.

Current Colorado law does not specify standards for microbial contamination of waters used for agricultural irrigation. The current standard for fecal coliform in streams providing domestic water supply (before treatment) and secondary-contact recreation is 2000 CFU/100 ml. For primary-contact recreation, like swimming, the standard is 200 CFU/100 ml (Colorado Department of Public Health and Environment 1998).

### **Nutrients Criteria**

The primary nutrients that occur in Colorado streams are nitrogen, potassium, and phosphorus. Nitrogen and phosphorus are especially prevalent in waters affected by treated waste flows. These nutrients are beneficial to crop growth and to enhanced crop yields, and usually they are added in significant amounts to agricultural land as fertilizers. However, when present in excessive amounts in the soil, they can be detrimental to crop growth. The quality of marketable yield can be affected. High nutrient problems can cause other indirect problems to the agricultural system.

Streams that receive treated municipal wastewater and runoff from livestock feedlots often show significant concentrations of nitrogen. Municipal sewage effluent contains nitrogen (N) in four major forms: nitrite ( $\text{NO}_2^-$ ), nitrate ( $\text{NO}_3^-$ ), ammonium ( $\text{NH}_4^+$ ), and organic. Irrigation with waters containing these ions, if not properly managed in conjunction with fertilizer applications, can cause excessive vegetative growth and not enough fruit and seed production, can delay maturity and harvestability, and can reduce quality of produce. For example, experiments by Feigin et al. (1978) revealed a substantial reduction in sucrose level of sugar beets due to uptake of large amounts of N derived from sewage effluent. Evidence from studies recently conducted by the Western Sugar Company suggest that any N applied to sugar beets in the second phase of the growing cycle, usually after July 1 in Colorado, is harmful to net returns from sugar production. Excessive N also can cause reduced starch content in potatoes (Task Force on Water Reuse 1989, Bouwer and Idelovitch 1987) and excessive protein production in malting barley, which reduces brewing quality. Ayers and Westcott (1985) report that total N concentrations in excess of 30 mg/l can cause severe damage to susceptible plants.

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Nitrate in irrigation water can leach through the soil profile and contaminant underlying groundwater. Accumulation of  $\text{NO}_3^-$  in aquifers and the subsequent flow to wells or to adjacent surface water bodies is of concern since high concentrations pose dangers to human and animal health if ingested. In recent years, much attention has been given to establishing standards and controls for  $\text{NO}_3^-$  concentrations in agricultural return flows. Such assessments, however, must keep in mind the contribution to the problem made by  $\text{NO}_3^-$  present in waters diverted to agriculture.

Phosphorus (P), like N, is essential to crop growth and enhanced crop yields. However, high concentrations in the soil can result in micronutrient deficiencies (e.g. in copper, iron, and zinc) (Ryden and Pratt 1980). Large amounts of P also can contribute to algal blooms in reservoirs and canals, potentially causing maintenance problems to irrigation structures.

For waters classified for agricultural use in Colorado, the standards for maximum  $\text{NO}_3^-$ -N and  $\text{NO}_3^-$ -N are 100 mg/l and 10 mg/l, respectively. There are no agricultural standards for ammonia N or organic N. However,  $\text{NH}_3$ -N standards have been defined for waters classified for aquatic life and domestic water supply (Colorado Department of Public Health and Environment 1998). No standards at all have been defined for P.

### **Alkalinity Criteria**

Waters in Colorado's lower-elevation streams commonly exhibit pH values above 8.0. Waters with high pH, while not a problem in themselves, can contribute to alkaline conditions in soils. High soil pH reduces nutrient availability (copper, manganese, zinc, iron, phosphorus) (Page et al 1990; Jessica Davis, Soil and Crop Science Dept., Colorado State Univ., personal communication). The actual effect on soils is highly dependent on the buffering characteristics of the soil itself. Ayers and Westcot (1985) recommended an upper limit of 8.4 for the pH of waters used for irrigation.

There are no standards for the pH of waters used for irrigation of agricultural crops in Colorado. However, standards for recreation and aquatic life require that  $6.5 \leq \text{pH} \leq 9.0$  (Colorado Department of Public Health and Environment 1998).

### **Trace Elements Criteria**

Many trace elements can pose problems to irrigated soils and crops when present in high enough concentrations. The elements of major concern to agriculture are Al, Ar, Be, B, Cd, Cr, Cu, F, Fe, Pb, Mn, Mo, Ni, Se, V, and Z. Recommended standards for irrigation water are listed in Table 2 along with current Colorado standards for agriculture and domestic water supply (Gates et al 1993, Colorado Department of Public Health and

Environment 1998). Cyanide (CN) is also of concern. The recommended standard, and that currently adopted by Colorado, for CN is 0.2 mg/l.

**Table 2. Recommended Standards for Trace Elements in Irrigation Water along with Current Colorado Standards for Agriculture and Drinking Water Supply**

Constituent	Recommended Standard (mg/l)	Current Colorado Standards (mg/l)	
		Agriculture <sup>1</sup>	Domestic Water Supply <sup>2</sup>
Al.	5.00	None	None
Ar	0.10	0.10	0.05
Be	0.10	0.10	0.004
B	0.50	0.75	None
Cd	0.01	0.01	0.005
Cr (Total)	1.00	None	None
Cr III	None	0.10	0.05
Cr VI	None	0.10	0.05
Cu	0.20	0.20	1.00
F	1.00	None	2.00
Fe	5.00	None	0.30
Pb	5.00	0.10	0.05
Mn	0.20	0.20	0.05
Mo	0.01	None	None
Ni	0.20	0.20	0.10
Se	0.02	0.02	0.05
V	0.10	None	None
Zn	2.00	2.00	5.00

Notes:

<sup>1</sup> All agricultural standards are 30-day averages

<sup>2</sup> Domestic water supply standards are 30-day averages with the exception of standards for Ar, Cd, Cr III, Cr VI, and Pb, which are 1-day averages

## CONDITIONS IN THE PROJECT COMMAND AREA

### Water Quality in the Canals and Reservoirs

Field data were collected to describe current water quality conditions in the water-delivery systems of the Larimer & Weld Canal and the New Cache la Poudre Canal. A total of twelve sampling locations were selected within the Larimer & Weld Canal as indicated in Figure 3. Samples also were taken from five reservoirs within the system. The sampling locations within the Larimer & Weld System are numbered beginning with the letters LW and are described briefly in Table 3. Eight sampling locations were selected within the New Cache la Poudre Canal (Figure 3). In addition, samples were taken from three reservoirs supplying the system and from the Eaton Draw where it flows into the New Cache la Poudre Canal near the intersection of Weld County road (CR) 39 and CR70. Sampling locations, beginning with the letters NC, are briefly described in Table 3.

Samples for salinity and major ions, microbial contaminants, nutrients, alkalinity, and trace elements were taken at selected locations and over the course of the irrigation season. The number and location of samples varied according to each constituent and are described in the following sections. Results of the sampling program are summarized.

#### *Salinity and Major Ions in the Canals and Reservoirs*

The relationship between electrical conductivity and salinity in the Larimer & Weld and New Cache la Poudre canal systems is illustrated in Figure 4. The figure displays plots of corresponding measurements of electrical conductivity and total dissolved solids (*TDS*) determined from lab analysis of selected field samples. The fitted regression lines indicate that an  $EC_w$  equal to 1 dS/m is equivalent to about 753 mg/l in the Larimer & Weld Canal and about 781 mg/l in the New Cache la Poudre Canal.



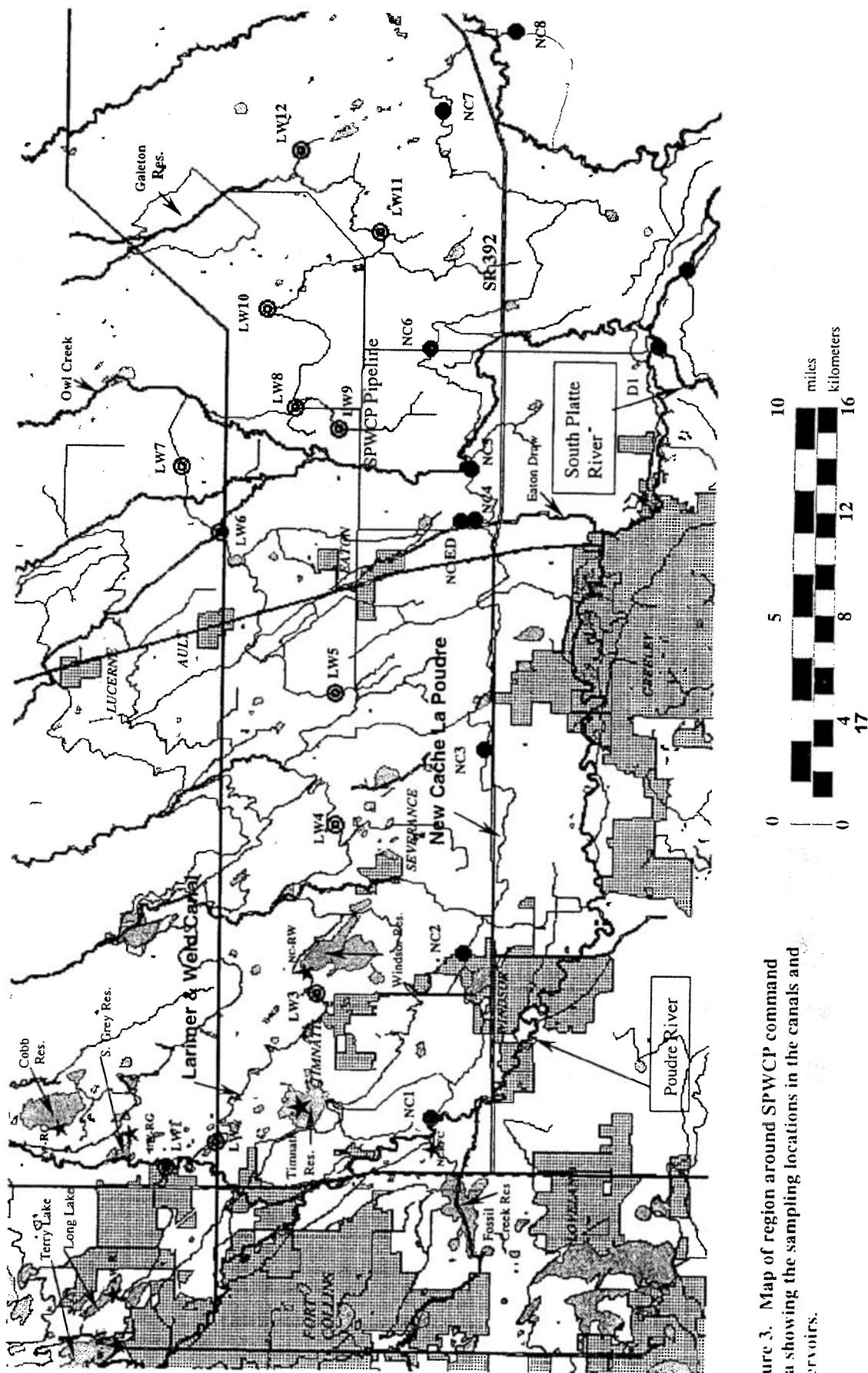
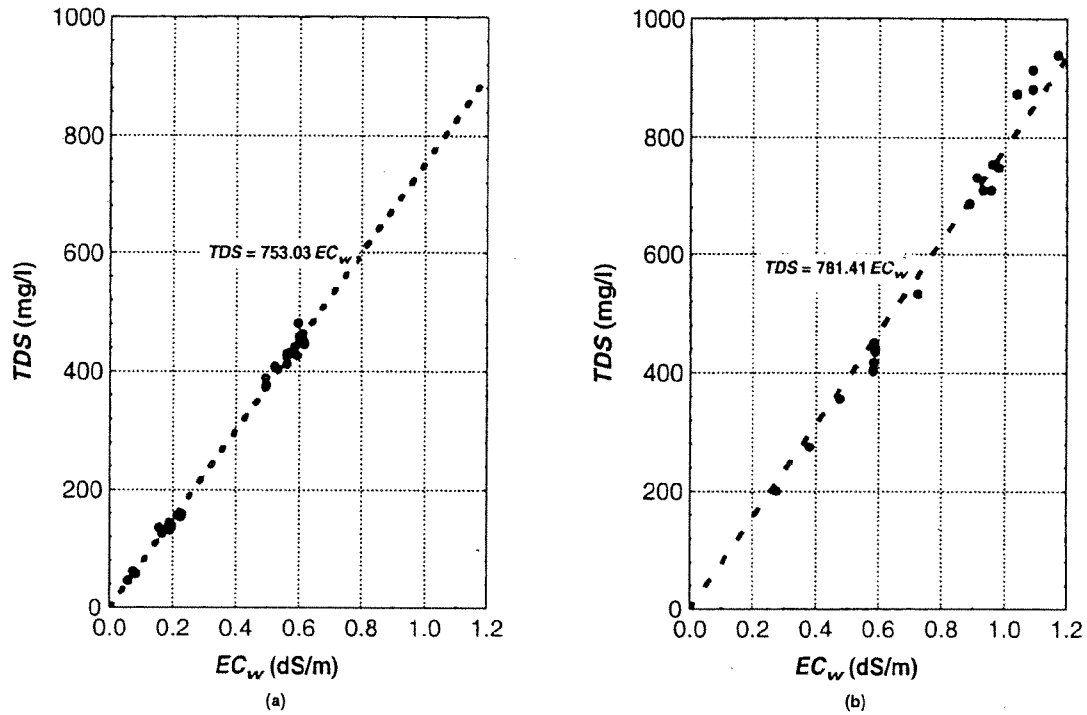


Figure 3. Map of region around SPWCP command area showing the sampling locations in the canals and reservoirs.

Table 3. Description of Sampling Locations.

Larimer & Weld Canal System	
Location No.	Description
LW1	Head of Larimer & Weld Canal on Cache la Poudre River, about 1 mile west of where highway (Hwy) 287 bends westward at Terry Lake
LW2	Bridge where Larimer County Road 5 crosses canal near Hwy 14
LW3	Bridge where Hwy 25 crosses canal near Greeley county road (CR) 76
LW4	Bridge where CR25A crosses canal near CR76
LW5	Bridge where CR33 crosses canal near CR76
LW6	Bridge where CR39 crosses canal near Hwy 14
LW7	Bridge over canal near intersection of CR43 and CR84
LW8	Outlet to Owl Creek extension near intersection of CR54 and CR78
LW9	Bridge where CR45 crosses canal near CR76
LW10	Bridge where CR51 crosses canal near CR80
LW11	Bridge where CR55 crosses canal near CR74
LW12	Bridge where CR59 crosses canal near CR78
LW-RT	Outlet of Terry Lake reservoir
LW-RL	Outlet of Long Pond reservoir
LW-R8	Outlet of Reservoir No. 8
LW-RG	Outlet of South Grey Reservoir
LW-RC	Outlet of Cobb Lake Reservoir
New Cache la Poudre Canal System	
Location No.	Description
NC1	Head of New Cache la Poudre Canal on Cache la Poudre River, about 2 miles downstream of Timnath
NC2	Bridge over canal on CR19 north of Hwy 392
NC3	Bridge over canal on CR29 north of Hwy 392
NC4	Bridge over canal at diversion gate no. 74
NC5	Bridge over canal on CR43 north of Hwy 392
NC6	Bridge over canal on CR49 north of Hwy 392
NC7	Bridge over canal on CR61 north of CR70
NC8	Bridge over canal on CR68 at BM
NC-ED	Eaton Draw at inlet to New Cache la Poudre Canal
NC-RFC	Outlet of Fossil Creek Reservoir
NC-RT	Outlet of Timnath Reservoir
NC-RW	Outlet of Windsor Reservoir



**Figure 4.** Measured total dissolved solids (TDS) versus measured electrical conductivity ( $EC_w$ ) for samples taken from (a) the Larimer & Weld Canal and (b) the New Cache la Poudre Canal.

One of two available specific conductance meters (Hach Model 44600 and Orion Model 128) was used to measure electrical conductivity in each of the canal sampling locations at seven different times during the irrigation season. Sampling times included those during the early season (before July 10) when canal flows were dominated by river diversions, and during the late season (after July 10) when reservoir releases made up a large portion of the canal flows. Typically, four to five measurements were taken across the canal at each location and measured values were averaged. Coefficient of variation (absolute value of ratio of standard deviation to mean) in the measurements was below 1% in all cases. The average values of the electrical conductivity of the water ( $EC_w$ ), reported in units of dS/m, are plotted for the Larimer & Weld Canal in Figure 5 and for the New Cache la Poudre Canal in Figure 6.

The salinity ( $EC_w$ ) at the head of the Larimer & Weld Canal (LW1) was found to be very low, ranging from 0.05 to 0.10 dS/m over the season and averaging 0.08 dS/m.

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The remaining sampling points were located downstream of where the release from Terry Lake flows into the canal. Typically, on each day that samples were taken, salinity was found to increase in a downstream direction. This increase was thought to be due primarily to higher-salinity inflows from reservoirs and return flows from the lands above the canal. At given locations, salinity tended to increase over the irrigation season, with a decrease appearing toward the end of the season. At LW2, upstream, salinity ranged from 0.17 to 0.62 dS/m and averaged 0.43 dS/m. At LW12, downstream, values ranged from 0.22 to 0.74 dS/m and averaged 0.52 dS/m. The overall average salinity computed over the sampling points (not including LW1) and over the season was 0.50 dS/m. This value falls well within the category "no restriction on use" given in Pescod (1992). That is, under good drainage conditions and in the absence of soil salt dissolution, these water salinity levels would not be expected to create soil salinity levels adverse to crop productivity. An assessment of these salinity levels for current soil conditions in the project command area is presented below in the section "Implications for the Proposed Project".

At the head of the New Cache la Poudre canal (NC1), measured salinity levels varied from 0.27 to 0.72 dS/m, averaging 0.49 dS/m over the season. As in the case of the Larimer & Weld Canal, the general trend was for salinity to increase over the irrigation season and to increase in a downstream direction along the canal. At sampling location NC2, upstream, measured salinity ranged from 0.59 to 1.04 dS/m, averaging 0.77 dS/m. Sampling location NC8, at the far end of the system, showed salinity levels ranging from 0.62 to 1.15 dS/m, with a seasonal average of 0.85 dS/m. The overall average salinity for the canal water over the irrigation season was 0.82 dS/m. Irrigation water salinity at this level is classified by Pescod (1992) in the category of "slight to moderate restriction on use". These results are comparable to results derived from data collected in the summer of 1992 by the New Cache la Poudre Irrigating Company and analyzed by NCWCD. Figure 7 shows a plot of the system-averaged  $EC_w$  values for samples collected in the New Cache la Poudre canal over that season.

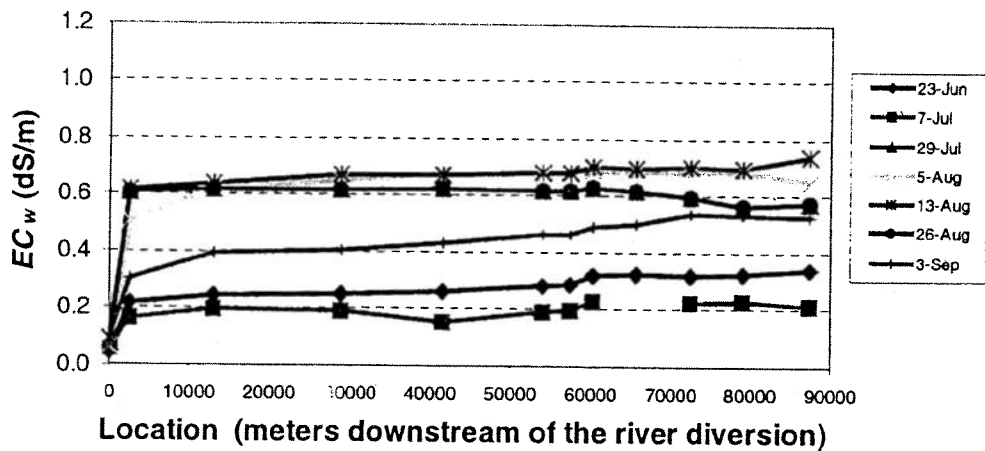


Figure 5. Electrical conductivity of water sampled at locations along the Larimer & Weld Canal.

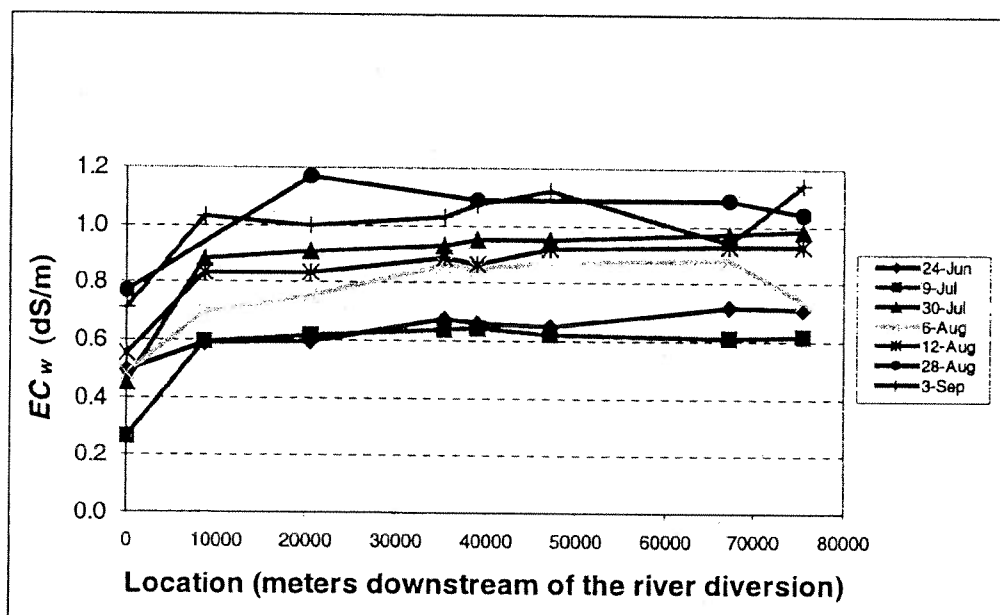


Figure 6. Electrical conductivity of water sampled along the New Cache la Poudre Canal.

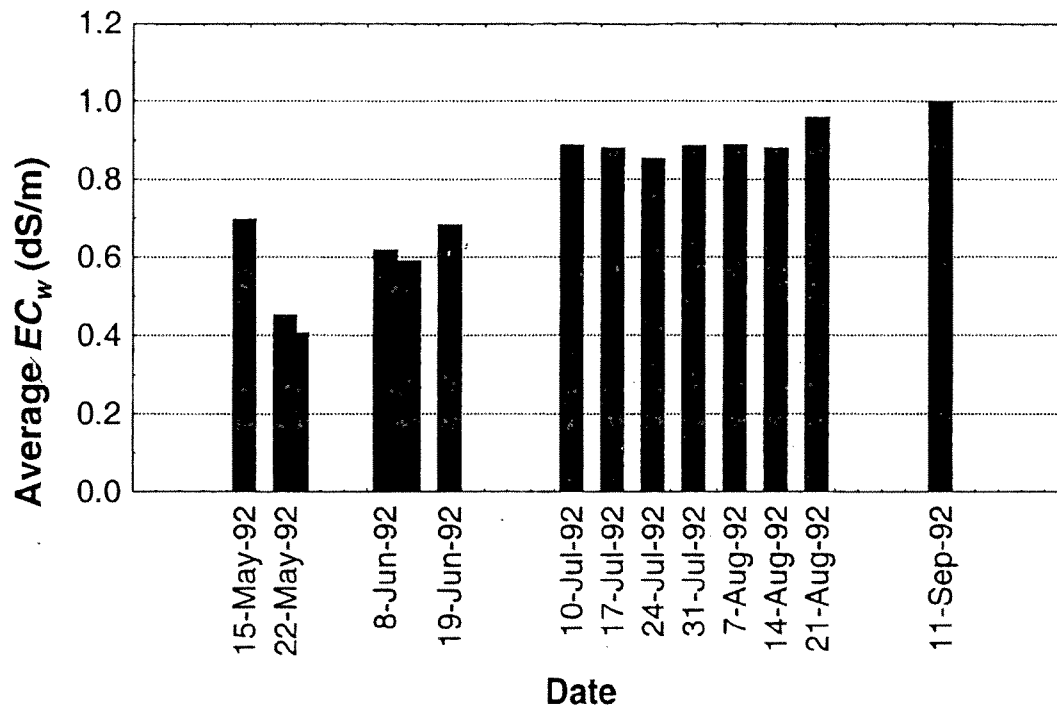


Figure 7. Average  $EC_w$  measured in the New Cache la Poudre Canal in 1992.

Electrical conductivity was measured anywhere from two to five times in the outlet streams from the reservoirs of each system. Results are illustrated for four of the five reservoirs serving the Larimer & Weld system in the plots of Figure 8 (data for South Grey Reservoir, where only one sample of 1.44 dS/m was taken on July 30, is not plotted). Data for two of the three reservoirs serving the New Cache la Poudre system are shown in the plots of Figure 9 (data for Timnath Reservoir, where only one sample of 1.35 dS/m was taken on August 28, is not plotted). Salinity at the outlets of the reservoirs serving the Larimer & Weld system ranged from about 0.58 to 1.44 dS/m during the later part of the season when reservoir flow made up a large portion of total canal flow. Salinity in the reservoirs serving the New Cache la Poudre system ranged from about 0.48 to 1.35 dS/m. The higher salinity in the reservoirs, compared to the river diversions at the head of the canals, is thought to be due to evaporative salinization in the reservoirs and inflow of surrounding saline groundwater and surface runoff.

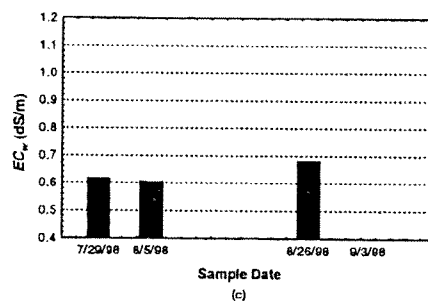
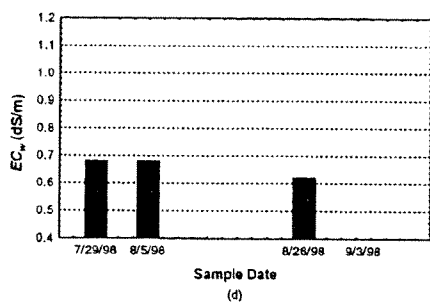
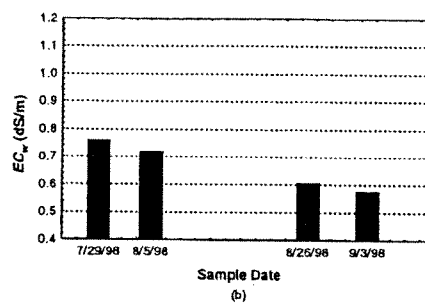
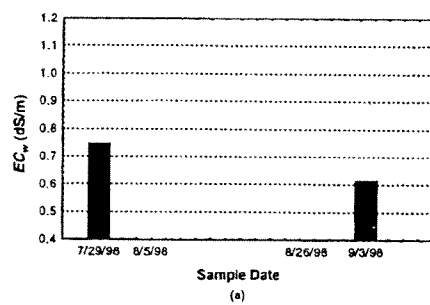
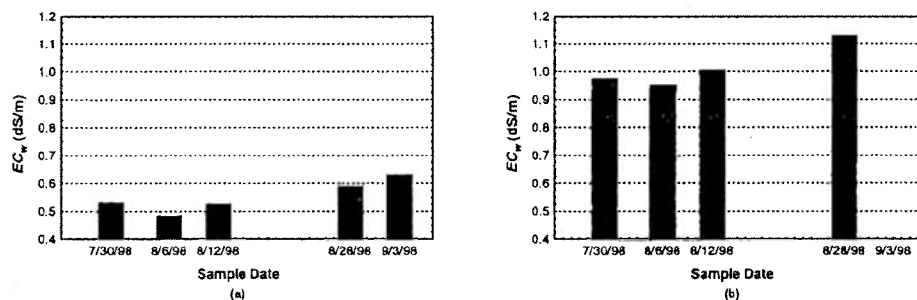


Figure 8. Salinity of outlet streams from (a) Terry Lake, (b) Long Pond, (c) No. 8, and (d) Cobb Lake reservoirs in the Larimer & Weld system.



**Figure 9. Salinity of outlet streams from (a) Fossil Creek and (b) Windsor reservoirs in the New Cache la Poudre System.**

The following major dissolved ions were measured three times at selected locations in each of the two systems: Ca, Mg, Na, K,  $CO_3$ ,  $HCO_3$ ,  $SO_4$ , and Cl. Results are summarized in Tables 4 and 5 for the Larimer & Weld and New Cache la Poudre systems, respectively, for each sampling date. Plots of  $HCO_3$  along each of the two canals are shown in Figures 10 and 11. The only item for concern is the relatively high concentration of  $HCO_3$  found in the New Cache la Poudre system during the latter part of the season. Figure 10 shows that the recommended maximum concentration was exceeded by as much as about 25%.

The sodium adsorption ratio was computed for each of the sampling locations where Ca, Mg, and Na were measured. Results are summarized in Tables 4 and 5. SAR values at all locations in both systems were very small, indicating no current tilth or permeability problems related to excess sodium. The predominant cation in the waters of both systems was Ca.



**Table 4. Major Ion Concentrations and Computed SAR in Water Grab Samples from the Larimer & Weld System.**

Sampling Date: 7 July, 1998																	
Constituent	Sampling Location												LW-RT	LW-RL	LW-R8	LW-RG	LW-RC
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12					
Ca (mg/L)	7	18.9	18.9	18.9	19.7	19.8	19.9	23.6	-	23.6	23.2	23.2	-	-	-	-	-
Mg (mg/L)	1.4	6.4	6.9	6.9	7	7.1	7.1	8.3	-	8.3	8.2	8.5	-	-	-	-	-
Na (mg/L)	2.8	7.2	7.1	6.5	7.3	7.4	7	8	-	7.1	8.5	8.7	-	-	-	-	-
K (mg/L)	0.3	0.8	0.6	0.6	0.8	0.8	0.6	1	-	0.8	0.8	0.9	-	-	-	-	-
CO <sub>3</sub> (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	-	<0.1	<0.1	<0.1	-	-	-	-	-
HCO <sub>3</sub> (mg/L)	29.2	48.4	49.9	51.4	54.9	59.8	57.1	59.7	-	59.1	59.7	61.3	-	-	-	-	-
SO <sub>4</sub> (mg/L)	3.4	41.8	51	44.7	43.3	45.1	44.3	54.9	-	50.5	50.6	50.3	-	-	-	-	-
Cl (mg/L)	0.8	1.3	1.2	1.5	1.2	1.7	1.7	2	-	1.9	1.7	1.8	-	-	-	-	-
SAR	0.36	0.51	0.50	0.46	0.51	0.51	0.48	0.51	-	0.45	0.54	0.55	-	-	-	-	-
Sampling Date: 29-30 July, 1998																	
Constituent	Sampling Location												LW-RT	LW-RL	LW-R8	LW-RG	LW-RC
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12					
Ca (mg/L)	8.9	52.7	53.5	53.2	53.9	53	54.1	55.1	55.9	52.4	51.9	51.5	55.3	69.5	55.9	106.9	67.8
Mg (mg/L)	2.1	27	27.2	27.5	28	27.3	27.4	27.2	27.1	26	25.4	24.3	26.2	33.9	27.5	85.3	33.9
Na (mg/L)	2.4	28.6	27.3	27.4	27.1	28.1	28.6	29.3	31.6	27.3	27.2	26.9	24.2	35.9	26.7	55.6	25.6
K (mg/L)	0.6	1.2	1.8	1.9	1.8	1.7	1.5	1.7	1.8	1.5	1.6	1.5	2.6	1.4	1.5	1.2	1
CO <sub>3</sub> (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
HCO <sub>3</sub> (mg/L)	25.8	136.5	129.5	131.2	108.7	103	102	130.9	144.5	110.9	131.2	103.3	159.4	129.2	232.6	167	93.3
SO <sub>4</sub> (mg/L)	16.8	195.2	177.2	194.7	187.9	193.6	195.3	178.5	197.5	188.2	182.6	183.5	178.7	182.8	183.4	613	210.2
Cl (mg/L)	0	16	32.3	17.6	33.7	16	16.6	34.1	15.8	15.7	16.3	16	17.3	15	13.5	23.8	13.3
SAR	0.27	1.13	1.07	1.07	1.05	1.10	1.11	1.14	1.22	1.09	1.09	1.09	0.89	1.03	1.24	1.37	0.95
Sampling Date: 26, 29 August, 1998																	
Constituent	Sampling Location												LW-RT	LW-RL	LW-R8	LW-RG	LW-RC
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12					
Ca (mg/L)	9.7		46.5	47.8	-	-	-	-	52.3	-	-	54.4	70	57.9	59.4	-	69.4
Mg (mg/L)	2.1		22.2	23.2	-	-	-	-	25.4	-	-	25.1	29.5	27.5	30.4	-	35.6
Na (mg/L)	1.4		20	20.3	-	-	-	-	23.2	-	-	23.8	25.6	29.4	29.7	-	22
K (mg/L)	0.7		2.1	2	-	-	-	-	2.3	-	-	2.1	1.9	2.1	2.1	-	3.1
CO <sub>3</sub> (mg/L)	<0.1		<0.1	<0.1	-	-	-	-	<0.1	-	-	<0.1	<0.1	<0.1	<0.1	-	<0.1
HCO <sub>3</sub> (mg/L)	103.8		130.9	144.5	-	-	-	-	110.9	-	-	103.3	102	129.5	131.2	-	108.7
SO <sub>4</sub> (mg/L)	180.5		178.5	197.5	-	-	-	-	188.2	-	-	183.5	195.3	177.2	194.7	-	187.9
Cl (mg/L)	30.6		34.1	15.8	-	-	-	-	15.7	-	-	16	16.6	32.3	17.6	-	33.7
SAR	0.15		0.85	0.85	-	-	-	-	0.93	-	-	0.94	0.91	1.12	1.10	-	0.75

**Table 5. Major Ion Concentrations and Computed SAR in Water Grab Samples from the New Cache la Poudre System.**

Sampling Date: 9 July, 1998										
Constituent	Sampling Location									
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RFC	NC -RW
Ca (mg/L)	28.4	56	52.8	58.9	55.8	59.9	57.1	56.3	-	-
Mg (mg/L)	9.6	26.3	28.4	29.8	26.6	28.7	27.4	27.6	-	-
Na (mg/L)	10.6	27.9	30.1	31	32.7	27.4	30.9	31.7	-	-
K (mg/L)	1	2.1	2.1	2.2	2.3	2.6	2.8	2.8	-	-
CO <sub>3</sub> (mg/L)	<0.1	45.2	<0.1	<0.1	43	46.2	<0.1	<0.1	-	-
HCO <sub>3</sub> (mg/L)	70.9	26.4	121.7	124.2	21.7	14	126.7	117.1	-	-
SO <sub>4</sub> (mg/L)	73.3	230.2	163.4	176.5	259.9	245.9	137.9	194	-	-
Cl (mg/L)	3.6	18.4	15.8	15.3	4.4	17.1	16.2	4.8	-	-
SAR	0.62	1.09	1.17	1.16	1.27	1.03	1.19	1.22	-	-
Sampling Date: 30 July, 1998										
Constituent	Sampling Location									
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RFC	NC -RW
Ca (mg/L)	41.2	76.2	79.9	80	85.7	85.9	84.2	84.3	36.1	76.2
Mg (mg/L)	16.5	41.7	45.8	47	47.1	48	46.5	46.6	17.5	48.5
Na (mg/L)	21.8	46.5	50.8	52.4	52	55.6	56.7	57.7	24.4	48.5
K (mg/L)	1.5	2.8	2.7	3	3	2.7	5.4	6.8	2	2.4
CO <sub>3</sub> (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	25.4	<0.1	<0.1	<0.1	<0.1
HCO <sub>3</sub> (mg/L)	139.7	159.9	171.1	169.8	173	130.1	182.3	181.5	143.5	171.9
SO <sub>4</sub> (mg/L)	112.8	300.7	313.6	337.5	343.7	335.6	340.9	337.7	130.8	359.8
Cl (mg/L)	15.7	16.2	16.5	15.6	15.8	16.8	17.6	18.4	15.4	15
SAR	1.02	1.50	1.58	1.62	1.58	1.68	1.73	1.76	1.17	1.51
Sampling Date: 29 August, 1998										
Constituent	Sampling Location									
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RFC	NC -RW
Ca (mg/L)	59.3	48.2	93.2	-	91.9	-	90.3	87.7	-	84.4
Mg (mg/L)	30.7	23.6	69.4	-	66.1	-	60.6	60.4	-	68.5
Na (mg/L)	49.1	45.4	78.3	-	76.1	-	68.6	69.5	-	72.3
K (mg/L)	4.7	4.9	6.5	-	5.8	-	5.8	6.2	-	5.2
CO <sub>3</sub> (mg/L)	33.8	48.5	<0.1	-	<0.1	-	<0.1	<0.1	-	24.2
HCO <sub>3</sub> (mg/L)	<0.1	<0.1	189.1	-	188.6	-	173	163.7	-	108.6
SO <sub>4</sub> (mg/L)	337.8	306.6	478.2	-	461	-	460.2	462.8	-	530
Cl (mg/L)	16.1	14.4	18.4	-	19.5	-	18.3	19.8	-	18.2
SAR	1.82	1.89	2.11	-	2.08	-	1.93	1.97	-	2.00

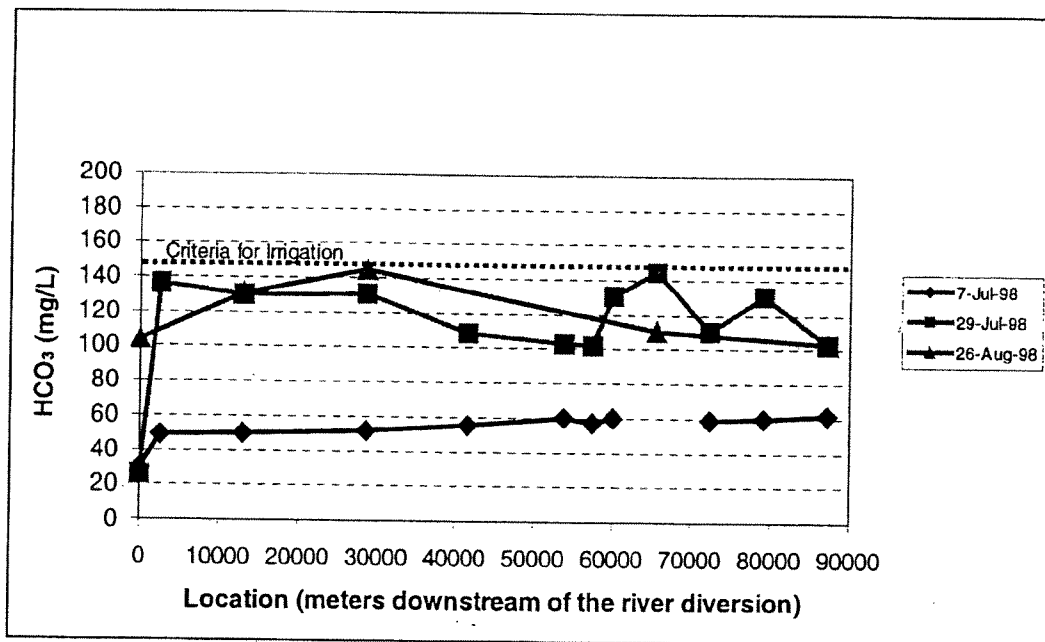


Figure 10. Bicarbonate concentration of water sampled along the Larimer & Weld Canal.

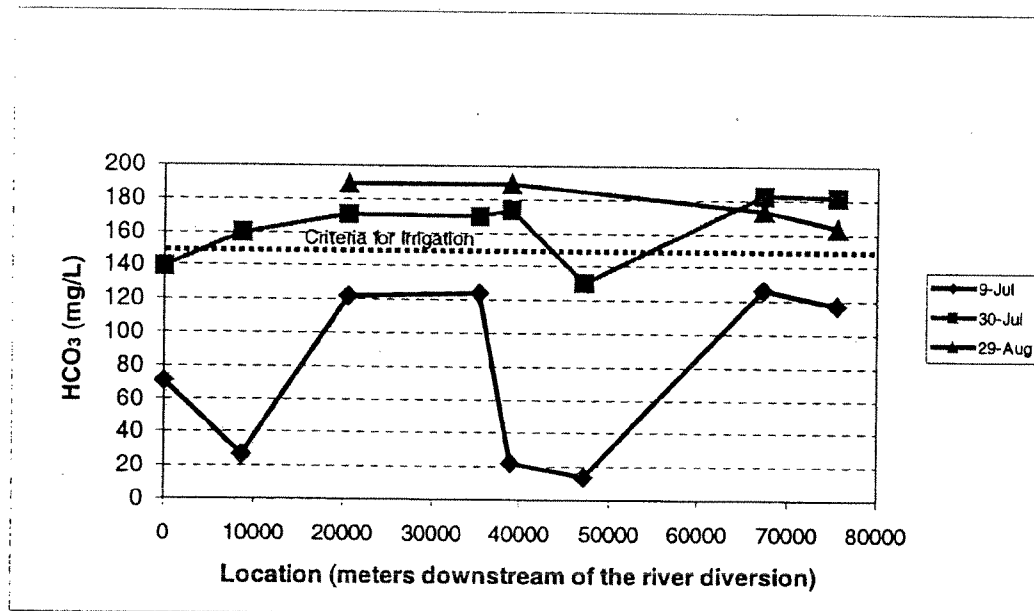


Figure 11. Bicarbonate concentration of water sampled along the New Cache la Poudre Canal.

### *Microbial Contaminants in the Canals and Reservoirs*

Samples were taken three times from selected locations in each of the systems for evaluation of fecal coliform. Results, expressed in colony forming units (CFU) per 100 ml are summarized in Table 6 for each of the locations and are plotted in Figures 12 and 13 for the Larimer & Weld and New Cache la Poudre canal locations, respectively. The current accepted criteria of a maximum of 1000 CFU/100 ml is shown on both plots. Typically, the data indicate no current concern regarding microbial contamination in the Larimer & Weld Canal. However, concentrations at locations in the New Cache la Poudre Canal were at times quite large. Further investigation is required to determine the source of the contamination.

**Table 6. Fecal Coliform Concentrations (CFU/100 ml) in Water Grab Samples in the Larimer & Weld and New Cache la Poudre Systems.**

Larimer & Weld System																
Sampling Date	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW-RT	LW-RL	LW-R8	LW-RG
14-Jul-98	<100	-	200	500	-	-	500	-	530	-	-	900	-	-	-	-
29-Jul-98	600	-	440	530	-	-	-	-	1400	-	-	810	5	26	16	26
26-Aug-98	53	-	590	530	-	-	-	-	-	-	-	550	3	23	4	23
New Cache la Poudre System																
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC-RT	NC-RFC	NC-RW					
9-Jul-98	200	-	300	-	400	-	-	1700	-	-	-					
30-Jul-98	12000	-	310	-	2000	-	4600	9700	-	400	180					
29-Aug-98	130	-	200	-	2000	-	600	1200	-	10	310					

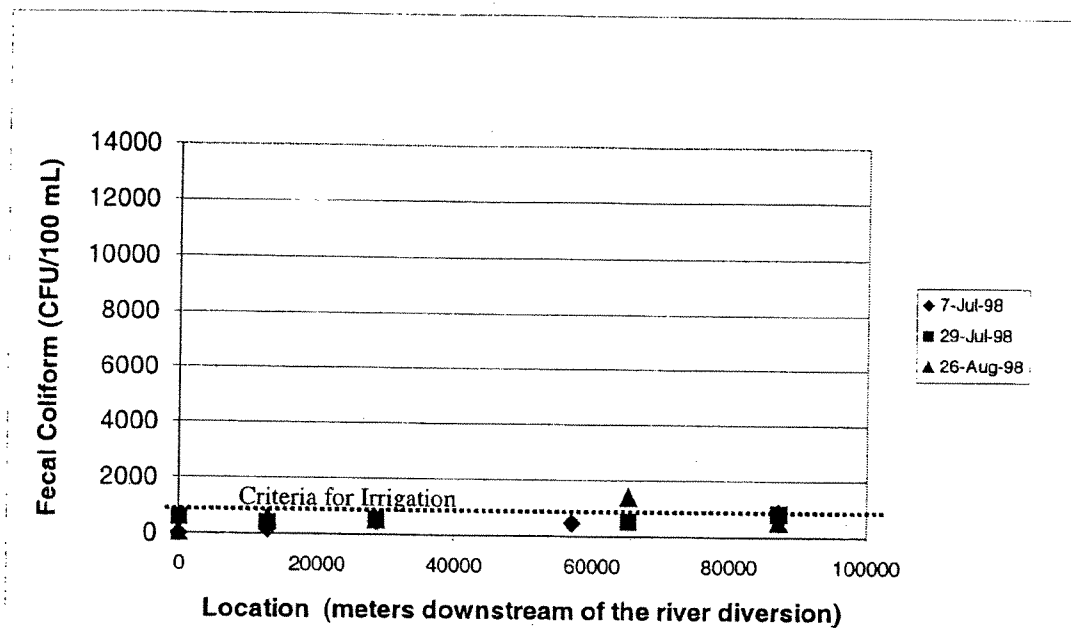


Figure 12. Fecal coliform concentrations in water grab samples at locations along the Larimer & Weld Canal.

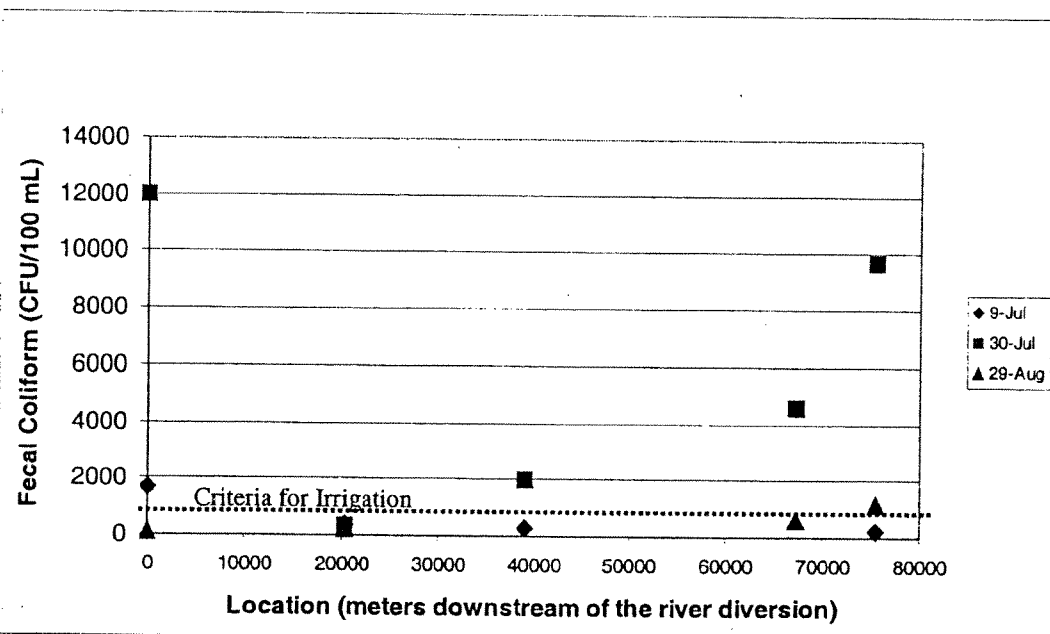


Figure 13. Fecal coliform concentrations in water grab samples at locations along the New Cache la Poudre Canal.

### Nutrients in the Canals and Reservoirs

Tables 7 and 8 summarize concentrations of  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$ , and P for selected sampling locations in the two systems. Plots of  $\text{NO}_3\text{-N}$  along each of the canals are shown in Figures 14 and 15. Measured concentrations were relatively low in both systems throughout the season. They tended to increase in the downstream direction along the canal, probably reflecting the higher concentrations of return flows to the canals from lands up the contour.

Table 7. Nutrient Concentrations in Water Grab Samples from the Larimer & Weld System.

Sampling Date: 7 July, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -R8	LW -RG	LW -RC
P (mg/L)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\text{NO}_3\text{-N}$ (mg/L)	0.00	0.10	0.12	0.12	0.12	0.19	0.21	0.35	0.00	0.27	0.29	0.35	-	-	-	-	-
Sampling Date: 29-30 July, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -R8	LW -RSG	LW -RC
P (mg/L)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	<0.1
$\text{NO}_3\text{-N}$ (mg/L)	0	0.4	0.4	0.8	0.8	0.5	0.7	1.1	1.3	0.6	0.7	0.7	0.4	0.3	0.3	0.1	0.1
$\text{NH}_4\text{-N}$ (mg/L)	<0.01	-	-	-	-	<0.01	-	-	<0.01	-	<0.01	<0.01	<0.01	<0.01	<0.01	-	<0.01
Sampling Date: 29 Aug, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -R8	LW -RSG	LW -RC
P (mg/L)	0.1	-	0.3	-	-	-	-	-	-	-	-	0.1	-	-	-	-	-
$\text{NO}_3\text{-N}$ (mg/L)	0.8	-	1.1	1.3	-	-	-	-	0.6	-	-	0.7	0.7	0.4	0.8	-	0.8

**Table 8. Nutrient Concentrations in Water Grab Samples from the New Cache la Poudre System.**

Sampling Date: 9 July, 1998											
Constituent	Sampling Location										
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RT	NC -RFC	NC -RW
P (mg/L)	-	-	-	-	-	-	-	-	-	-	-
NO <sub>3</sub> -N (mg/L)	0.5	0.5	0.4	0.8	0.7	0.7	0.8	0.8	-	-	-
Sampling Date: 30 July, 1998											
Constituent	Sampling Location										
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RT	NC -RFC	NC -RW
P (mg/L)	0.3	0.2	0.2	0.1	0.2	0.1	0.4	0.5	-	0.5	0.1
NO <sub>3</sub> -N (mg/L)	1.3	1.0	1.2	0.9	2.1	1.8	2.8	3.8	-	1.9	0.3
Sampling Date: 29 Aug, 1998											
Constituent	Sampling Location										
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RT	NC -RFC	NC -RW
P (mg/L)	0.3	-	0.3	-	-	-	-	-	-	-	-
NO <sub>3</sub> -N (mg/L)	0.3	-	1.0	-	-	-	-	-	0.1	0.4	<0.1

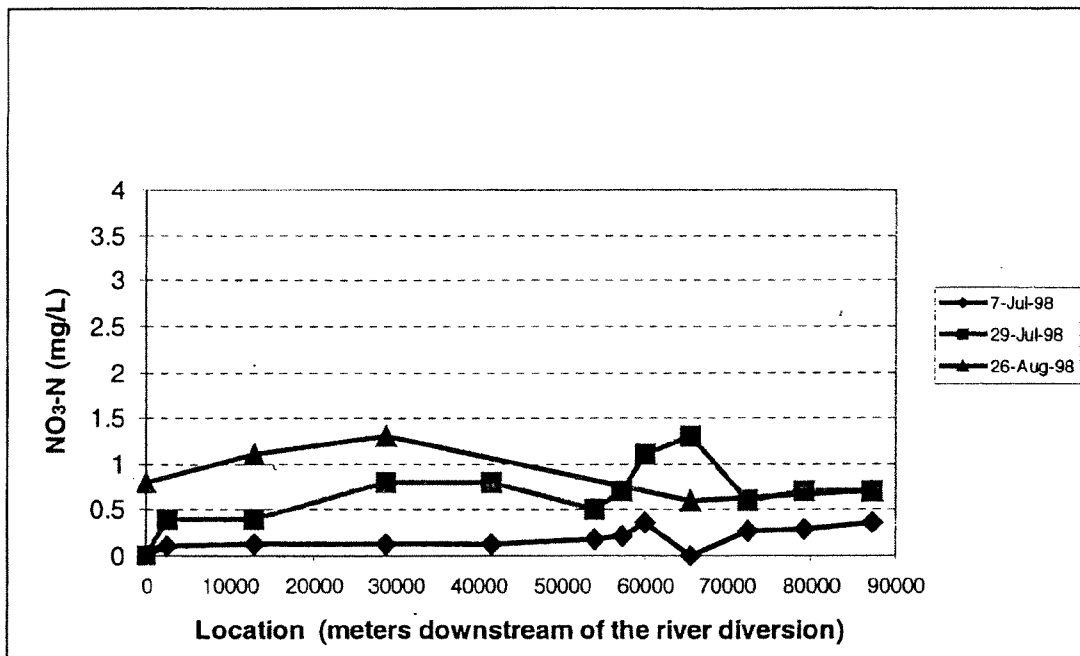


Figure 14. Nitrate-nitrogen concentrations in water grab samples at locations along the Larimer & Weld Canal.

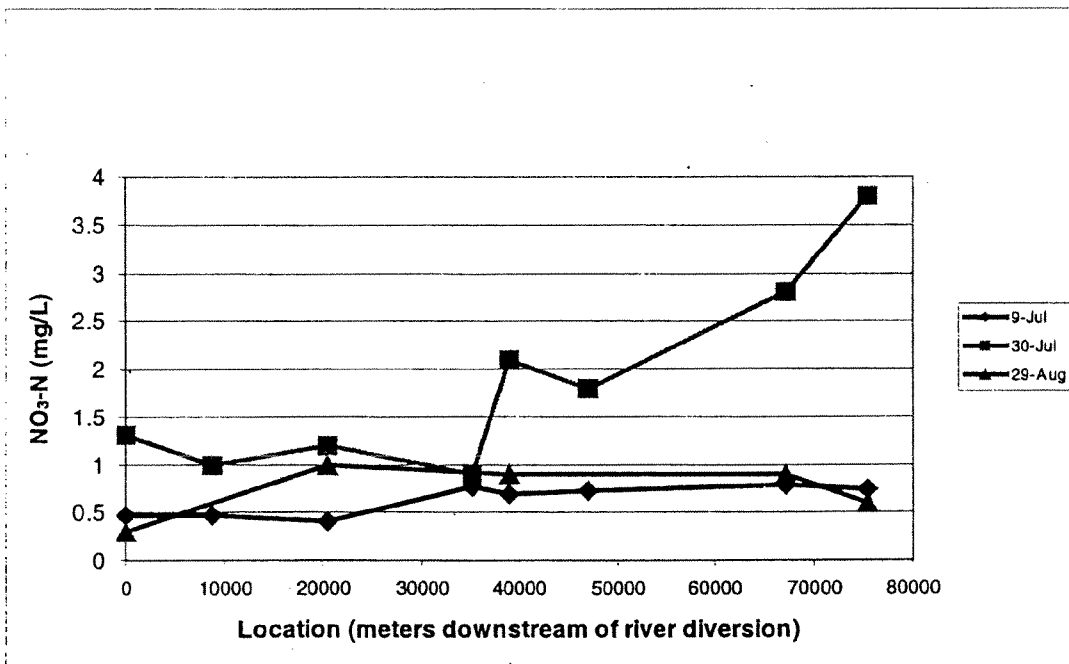


Figure 15. Nitrate-nitrogen concentrations in water grab samples at locations along the New Cache la Poudre Canal.



### Alkalinity in the Canals and Reservoirs

The pH and CaCO<sub>3</sub>-alkalinity concentrations were analyzed for selected water samples as measures of water alkalinity. Results are summarized in Tables 9 and 10 for the Larimer & Weld system and New Cache la Poudre system, respectively. These data indicate no current alkalinity problems in the irrigation waters.

### Trace Elements in the Canals and Reservoirs

Water samples were analyzed for the following trace elements at selected locations on one or two occasions: Al, Cd, Cr, Cu, Fe, Pb, Mn, Mo, Ni, V, and. Zn. Results are summarized in Tables 11 and 12. Concentrations of these trace elements were well within recommended maximum values.

**Table 9. pH and Alkalinity (as CaCO<sub>3</sub>) in Water Grab Samples from the Larimer & Weld System**

Sampling Date: 7 July, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -RG	LW -R8	LW -RC
pH	7.6	7.8	7.9	7.7	7.8	7.7	7.8	7.8	-	7.9	7.7	7.8	-	-	-	-	-
CaCO <sub>3</sub> (mg/L)	24	40	41	42	45	49	47	49	-	48	49	50	-	-	-	-	-
Sampling Date: 29 July, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -RG	LW -R8	LW -RC
pH	7.5	7	7.3	7.2	7.2	7.5	7.1	8.1	7.3	7.4	7.4	7.3	7.7	7.5	8	7.7	7.3
CaCO <sub>3</sub> (mg/L)	21	112	106	108	89	84	84	107	118	91	108	85	76	191	137	106	
Sampling Date: 29 August, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -RG	LW -R8	LW -RC
pH	8	-	8	8	-	-	-	-	7.9	-	-	8	8	8.2	-	8.2	8.1
CaCO <sub>3</sub> (mg/L)	33	-	89	85	-	-	-	-	92	-	-	92	88	89	-	112	138

**Table 10. pH and Alkalinity (as CaCO<sub>3</sub>) in Water Grab Samples from the New Cache la Poudre System.**

Sampling Date: 9 July, 1998											
Constituent	Sampling Location										
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RT	NC -RW	NC -RFC
pH	8.1	8.8	8	8.1	8.7	8.8	8.2	8.1	-	-	-
CaCO <sub>3</sub> (mg/L)	58	22	100	102	18	11	104	96	-	-	-
Sampling Date: 30 July, 1998											
Constituent	Sampling Location										
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RT	NC -RW	NC -RFC
pH	8.2	8.4	8.4	8.4	8.3	8.6	7.7	7.8	7.1	8.3	-
CaCO <sub>3</sub> (mg/L)	115	131	140	139	142	107	149	149	5	118	-
Sampling Date: 29 August, 1998											
Constituent	Sampling Location										
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RT	NC -RW	NC -RFC
pH	10	-	8.3	-	8.2	-	8.4	8.3	-	10	8.3
CaCO <sub>3</sub> (mg/L)	<0.1	-	155	-	155	-	142	134	-	<0.1	89

Table 11. Trace Element Concentrations in Water Grab Samples from the Larimer & Weld System.

Sampling Date: 29 July, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -R8	LW RG	LW -RC
Al (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.02	<0.1
Fe (mg/L)	0.02	0.09	0.01	0.02	0.04	0.15	0.1	<0.01	0.01	0.03	0.08	0.02	<0.01	<0.01	<0.01	0.07	<0.01
Mn (mg/L)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	<0.01	0.01	0.01	0.01	0.01	0.01
Cu (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Zn (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Ni (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.01	<0.1	<0.1	0.04	<0.1
Mo (mg/L)	<0.01	0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	0.01	0.01	<0.01
Cd (mg/L)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.05	<0.005
Pb (mg/L)	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.07	0.04
V (mg/L)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	-	<0.05
	<0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	-	0.01
Sampling Date: 26 August, 1998																	
Constituent	Sampling Location																
	LW1	LW2	LW3	LW4	LW5	LW6	LW7	LW8	LW9	LW10	LW11	LW12	LW -RT	LW -RL	LW -R8	LW RG	LW -RC
Al (mg/L)	0.1	-	-	-	-	-	-	-	-	-	-	0.1	-	-	-	-	-
Fe (mg/L)	<0.1	-	-	-	-	-	-	-	-	-	-	<0.01	-	-	-	-	-
Mn (mg/L)	0.01	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-
Cu (mg/L)	<0.01	-	-	-	-	-	-	-	-	-	-	<0.01	-	-	-	-	-
Zn (mg/L)	<0.01	-	-	-	-	-	-	-	-	-	-	<0.01	-	-	-	-	-
Ni (mg/L)	<0.1	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-
Mo (mg/L)	0.01	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-
Cd (mg/L)	<0.005	-	-	-	-	-	-	-	-	-	-	<0.005	-	-	-	-	-
Cr (mg/L)	0.02	-	-	-	-	-	-	-	-	-	-	0.03	-	-	-	-	-
Pb (mg/L)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

**Table 12. Trace Element Concentrations in Water Grab Samples from the New Cache la Poudre System.**

Sampling Date: 30 July, 1998										
Constituent	Sampling Location									
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RFC	NC -RW
Al (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fe (mg/L)	0.16	0.12	0.07	0.02	0.04	0.01	0.01	0.06	0.06	0.07
Mn (mg/L)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cu (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Zn (mg/L)	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ni (mg/L)	<0.01	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Mo (mg/L)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cd (mg/L)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cr (mg/L)	0.03	0.02	0.03	0.06	0.03	0.02	0.03	0.02	0.03	0.03
Sampling Date: 29 August, 1998										
Constituent	Sampling Location									
	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8	NC -RFC	NC -RW
Al (mg/L)	0.3	-	0.4	-	-	-	-	-	0.3	-
Fe (mg/L)	0.15	-	0.33	-	-	-	-	-	0.1	-
Mn (mg/L)	0.02	-	0.02	-	-	-	-	-	0.01	-
Cu (mg/L)	0.03	-	0.03	-	-	-	-	-	0.03	-
Zn (mg/L)	0.02	-	0.04	-	-	-	-	-	0.02	-
Ni (mg/L)	0.05	-	0.05	-	-	-	-	-	0.04	-
Mo (mg/L)	0.02	-	0.03	-	-	-	-	-	0.02	-
Cd (mg/L)	<0.005	-	<0.005	-	-	-	-	-	<0.005	-
Cr (mg/L)	0.09	-	0.09	-	-	-	-	-	0.08	-

## Groundwater Conditions in the Project Command Area

The major hydrogeologic zones underlying the study region consist of deep alluvial deposits and shallower formations underlain by shale. Schneider and Hillier (1978) reported measured depths to water table during the irrigation season in 25 pumping wells within the deep alluvium of the study region during the early 1960s and in six pumping wells during the mid 1970s. Respective measured depths averaged about 5.1 m (16.7 ft) and 3.7 m (12 ft). Groundwater salinity was measured in 33 pumping wells in the early 1960s and in six wells in the mid 1970s. Average measured salinity was 2.8 dS/m and 1.9 dS/m, respectively. Bruce and McMahon (1998) reported a median  $EC_w$  of 2.1 dS/m for shallow groundwater in the South Platte alluvium underlying irrigated land. A measurement of well water taken under the present study on July 3, 1998 just south of Ault revealed a value of 1.6 dS/m. No data could be found specific to the region underlain by the shale layers.

## Soil Conditions in the Project Command Area

Soils in the command area are made up primarily of deep clay loams, loams, sandy loams, and loamy sands. The major soil classes are, in order of prevalence, Otero-Thedalund-Nelson, Nunn-Dacono-Altvan, Olney-Kim-Otero, Weld-Colby, and Valent-Vona-Osgood (USDA 1980). The layout and configuration of the irrigated fields of the region are indicated in the satellite image displayed in Figure 16 (dated early September 1997).

Data on soil salinity were collected from 32 fields (about 10 to 30 acres in size) spread over the proposed command area. Three Geonics™ EM-38 electromagnetic induction probes were used to measure bulk soil electrical conductivity to a depth of about 1.0 m (3.3 ft) at 24 to 65 points (average 57) within each field. Each of the sampled fields was numbered beginning with the letters S. The soil type, method of irrigation, crop, and number of samples collected for each sampled field are summarized in Table 13. Calibration equations, based upon soil texture, were used to convert probe readings into estimates of electrical conductivity of the saturation extract of the soil,  $EC_e$ . A set of four soil samples were collected to a depth of 1.0 m (3.3 ft) at one location within each field to check the calibration equations against laboratory estimates of  $EC_e$ .

Figure 17 provides "box and whisker" plots of the statistics of estimated  $EC_e$  values for each of the sampled fields. The upper and lower "whiskers" indicate the maximum and minimum measured values, respectively. The upper and lower edges of the large boxes represent the 75<sup>th</sup> percentile and 25<sup>th</sup> percentile values, respectively. The median (50<sup>th</sup> percentile) value is represented by the dark square. Field-averaged values of  $EC_e$  ranged from 0.60 to 7.03 dS/m. The average value over all of the sampled fields was 2.82 dS/m. Threshold salinity values for corn and alfalfa are shown on the plots for

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comparison. In 21 out of 32 fields, average salinity levels exceeded threshold salinity levels for the respective crops. In 25 of the 32 fields surveyed, the 75<sup>th</sup> percentile value exceeded the threshold salinity levels. Threshold salinity levels were exceeded in 75% of the sprinkler-irrigated fields and in 60% of the surface-irrigated fields. In 44% of the sprinkler-irrigated fields and in 25% of surface-irrigated fields, average salinity levels exceeded 3 dS/m. The tendency for sprinkler-irrigated fields to have higher salinity levels may be due to lower leaching fractions.

A similar study was conducted in the summer of 1998 on 53 dry bean fields throughout Weld county (Jessica Davis, Soil and Crop Science Dept., Colorado State Univ., personal communication). Soil samples revealed that 60% of these fields had average salinity levels exceeding the threshold level of 1 dS/m for dry beans.



Figure 16. Satellite image (early September, 1997) under SPWCP regional map, showing layout of irrigated fields.

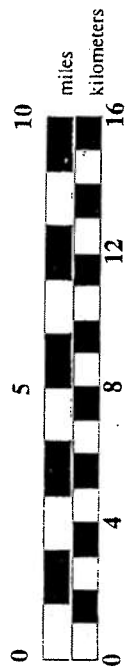


Table 13. Summary of Characteristics of Fields Sampled for Soil Salinity in the Command Area

Field I.D. No.	Soil Type	Irrigation Type	Crop	No of. Samples
S1	Kim loam (1-3% slopes)	furrow	corn	64
S2	Olney fine sandy loam (1-3% slopes)	furrow	sugar beets	65
S3	-	furrow	sugar beets	65
S4	-	furrow	corn	61
S5	Haverson loam (0-1% slopes)	sprinkler	corn	60
S6	Haverson loam (1-3% slopes)	furrow	corn	51
S7	Vona sandy loam (1-3% slopes)	sprinkler	corn	59
S8	Vona loamy sand (3-5% slopes)	sprinkler	alfalfa	59
S9	Vona loamy sand (5-9% slopes)	sprinkler	corn	64
S10	Otero sandy loam (3-5% slopes)	sprinkler	alfalfa	62
S11	Kim Loam (1-3% slopes)	furrow	corn	59
S12	Columbo clay loam (0-1% slopes)	furrow	corn	24
S13	Columbo clay loam (0-1% slopes)	furrow	corn	60
S14	Otero sandy loam (1-3% slopes)	furrow	corn	57
S15	Olney fine sandy loam (1-3% slopes)	sprinkler	alfalfa	61
S16	Otero sandy loam (1-3% slopes)	furrow	sugar beets	63
S17	Fort Collins loam (1-3% slopes)	furrow	beans	58
S18	Kim Loam (0-1% slopes)	furrow	sugar beets	57
S19	Otero sandy loam (3-5% slopes)	sprinkler	corn	63
S20	Valent sand (0-3% slopes)	furrow	corn	56
S21	Otero sandy loam (1-3% slopes)	furrow	corn	60
S22	Otero sandy loam (1-3% slopes)	sprinkler	corn	58
S23	Olney fine sandy loam (1-3% slopes)	furrow	corn	52
S24	Olney loamy sand (1-3% slopes)	sprinkler	beans	59
S25	Paoli loam (0-1% slopes)	furrow	sugar beets	50
S26	Dacono clay loam (0-1% slopes)	sprinkler	corn	58
S27	Bankard sandy loam (0-3% slopes)	sprinkler	beans/ sugar beets	63
S28	Lona loamy sand (0-3% slopes)	border	alfalfa	46
S29	Haverson loam (0-1% slopes)	sprinkler	corn	58
S30	Colby loam (0-1% slopes)	furrow	corn	61
S31	Colby loam (1-3% slopes)	furrow	onions	46
S32	Dacono clay loam (0-1% slopes)	furrow	onions	53



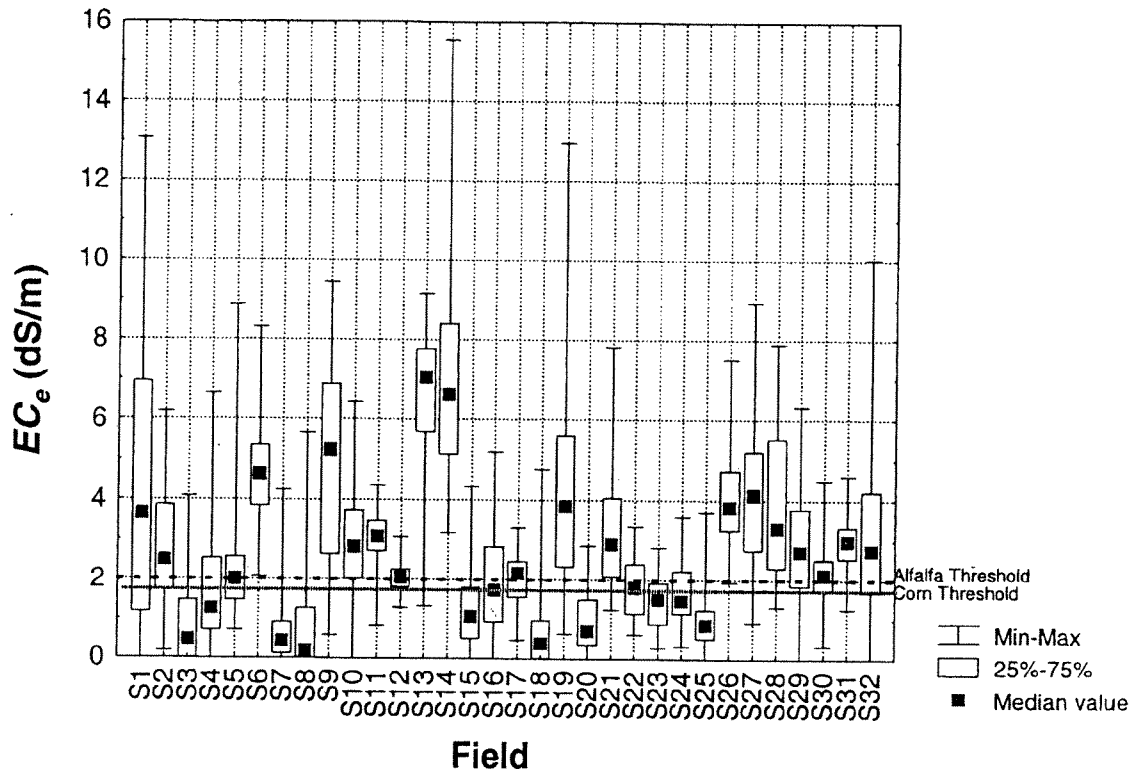


Figure 17. Electrical conductivity of soil saturation extract for fields surveyed in the command area. The threshold salinity levels for corn and alfalfa are indicated on the plot.

#### Crops in the Project Command Area

The major crops in the command area of the proposed project are corn for grain, corn for silage, alfalfa hay, dry beans, sugar beets, barley, wheat, oats and vegetables (including carrots, onions, cabbage, and others)(Colorado Agricultural Statistics Service 1998).

#### Irrigation Practices in the Project Command Area

The command area is predominantly irrigated by surface methods: furrow irrigation for row crops and border irrigation for hay crops. However, an increasing number of center pivot sprinkler systems, supplied by canal water, are being introduced into the region, especially in the east (Figure 16).

## WATER QUALITY AT THE PROPOSED POINT OF DIVERSION

Water quality in the South Platte River, near the proposed point of diversion to the new project, was characterized by sampling from a location near the confluence (point D1 as shown in Figure 2), and from the location corresponding to the USGS stream gage at Kersey (point D2 in Figure 2). Results are summarized in Table 14. Figure 18 shows plots of  $EC_w$  at both locations.

Table 14. Constituents in Grab Samples Collected at the Confluence and at Kersey.

Constituent	Confluence	Kersey
Sample 24 June, 1998		
EC (dS/m)	1.13	1.09
Sample 30 July, 1998		
pH	8	8
EC (dS/m)	1.15	0.98
Ca (mg/L)	107.1	80.8
Mg (mg/L)	48.7	35.6
Na (mg/L)	79.2	80.2
SAR	2.24	2.63
K (mg/L)	5.5	4.8
B (mg/L)	0.06	0.17
CO <sub>3</sub> (mg/L)	<0.1	<0.1
HCO <sub>3</sub> (mg/L)	214.9	192.2
SO <sub>4</sub> (mg/L)	334.1	265
Cl (mg/L)	32.1	34.4
NO <sub>3</sub> (mg/L)	27.1	19.9
NO <sub>3</sub> -N (mg/L)	6.1	4.5
Hardness as CaCO <sub>3</sub> (mg/L)	467	348
Alkalinity as CaCO <sub>3</sub> (mg/L)	176	158
TDS (mg/L)	855	717
F. coli (July 14)	>25000	24000
P (mg/L)	0.3	0.3
Al (mg/L)	<0.1	<.1
Fe (mg/L)	0.15	<.01
Mn (mg/L)	0.01	0.01
Cu (mg/L)]	<0.01	<0.01
Zn (mg/L)	0.01	0.01
Ni (mg/L)	<0.01	<0.01
Mo (mg/L)	0.01	0.01
Cd (mg/L)	<0.05	<0.05
Cr (mg/L)	0.03	0.02
Ba (mg/L)	0.06	0.05

*Kersey always lower*

Table 14. Constituents in Grab Samples Collected at the Confluence and at Kersey (Cont.)

Sample 6 August, 1998		
EC (dS/m)	1.11	0.86
Sample 12 August, 1998		
EC (dS/m)	1.31	1.21
Sample 29 August, 1998		
pH	8.4	8.3
EC (dS/m)	1.29	1.26
Ca (mg/L)	128	112.3
Mg (mg/L)	60.8	53.4
Na (mg/L)	89.8	102.3
SAR	2.30	2.80
K (mg/L)	7.1	7.6
B (mg/L)	0.24	0.25
CO <sub>3</sub> (mg/L)	<0.1	41.4
HCO <sub>3</sub> (mg/L)	282.2	189.6
SO <sub>4</sub> (mg/L)	493.6	475.5
Cl (mg/L)	37.8	34.5
NO <sub>3</sub> (mg/L)	28.7	22.1
NO <sub>3</sub> -N (mg/L)	6.5	5
Hardness as CaCO <sub>3</sub> (mg/L)	569	500
Alkalinity as CaCO <sub>3</sub> (mg/L)	231	155
TDS (mg/L)	1135	1044
F. coli (July 14)	2100	600
P (mg/L)	0.4	0.4
Al (mg/L)	0.3	0.3
Fe (mg/L)	0.07	0.18
Mn (mg/L)	0.02	0.02
Cu (mg/L)]	0.03	0.03
Zn (mg/L)	0.04	0.03
Ni (mg/L)	0.04	0.04
Mo (mg/L)	0.02	0.02
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	0.1	0.09
Ba (mg/L)	0.06	0.06
Sample 3 September, 1998		
EC (dS/m)	1.35	1.27

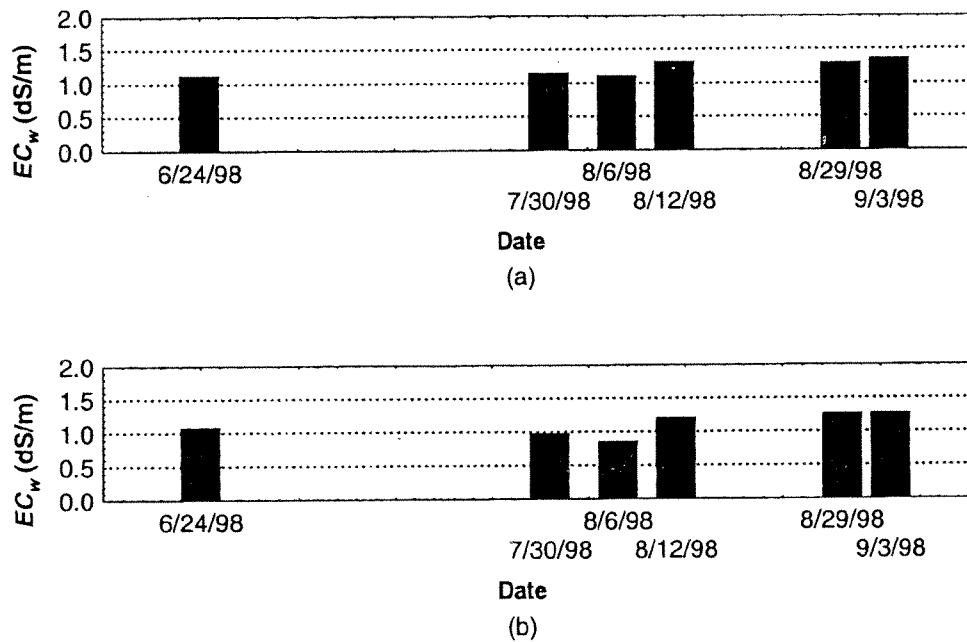


Figure 18. Electrical conductivity of water sampled at (a) the confluence of the South Platte and Cache la Poudre Rivers and at (b) the USGS Gaging Station at Kersey

Data collected and reported by the USGS NAQWA study at Kersey over the period April 1993 to September 1997 also were analyzed. Periodic measured values of  $EC_w$  and of the combined concentration of nitrate nitrogen and nitrite nitrogen are plotted in Figures 19 and 20, respectively. Typically, minimum concentrations occur in May and June. Off and on, over the period from October 1993 to September 1994, hourly measurements of  $EC_w$  were made in the South Platte River at Kersey by the USGS. These values, plotted in Figure 21, reveal a maximum of 1.74 dS/m occurring in August and a minimum of 0.58 dS/m occurring in June. An exponential relationship between  $EC_w$  and flow rate in the South Platte River at Kersey was developed from data collected by the USGS and is shown in Figure 22.

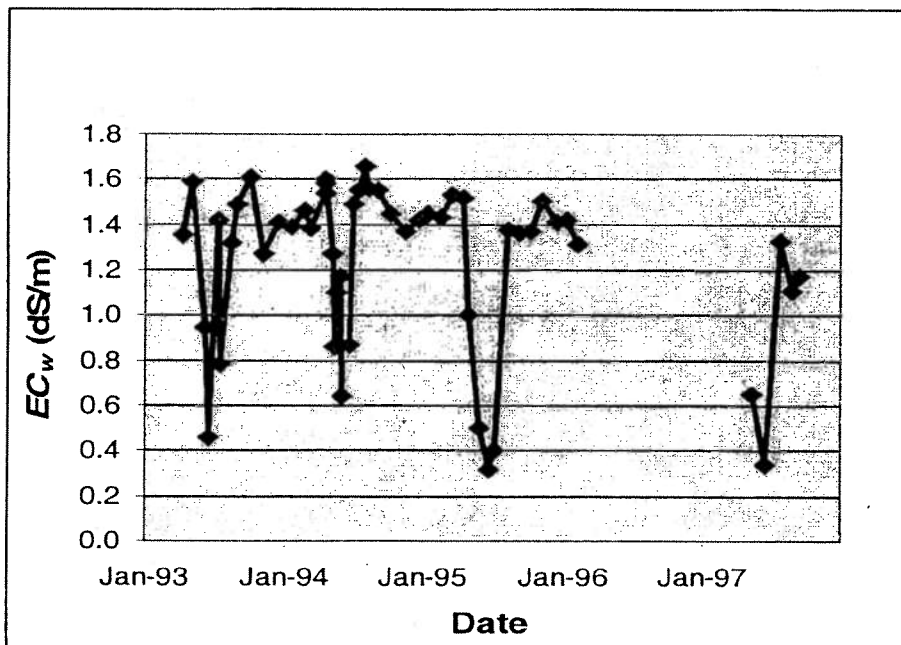


Figure 19. Electrical conductivity of water sampled from the South Platte River at the USGS gauging site near Kersey under the USGS NAQWA study

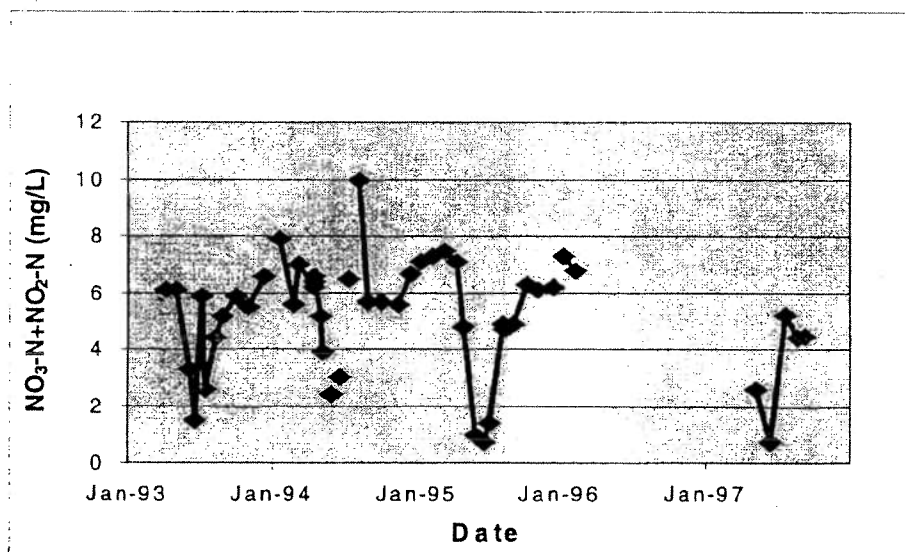


Figure 20. Total nitrate N and nitrite N concentration in water sampled from the South Platte River at the USGS gauging site near Kersey under the USGS NAQWA study

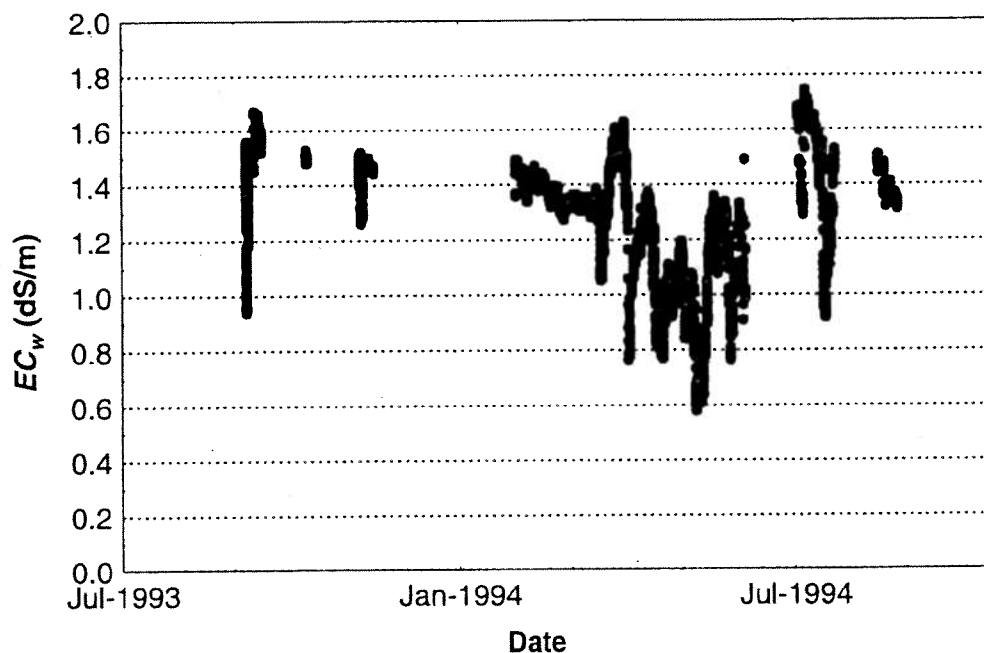


Figure 21. Hourly measurements of electrical conductivity of water in the South Platte River at the USGS gauging site near Kersey under the USGS NAQWA study.

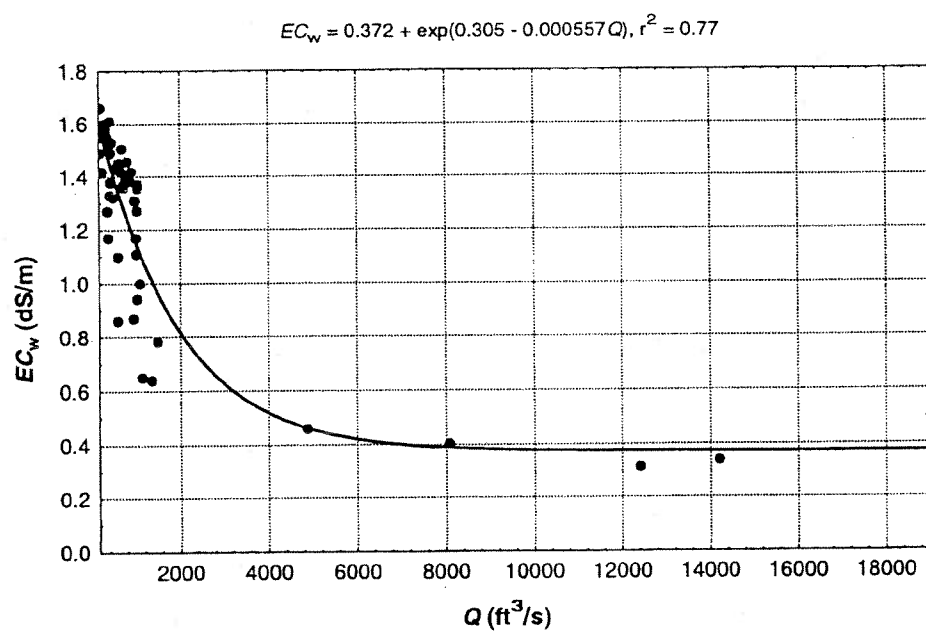


Figure 22. Relationship between salinity and flow rate in grab samples taken from the South Platte River at Kersey by the USGS.

## IMPLICATIONS FOR THE PROPOSED PROJECT

Current conditions in the command area and in the vicinity of the proposed river diversion were analyzed and compared in light of water quality criteria to predict impacts of the proposed project on the agricultural system. Each of the major water quality criteria were considered.

### Salinity and Major Ions Implications

Data collected in the Larimer & Weld Canal and the New Cache la Poudre Canal revealed seasonal average salinity levels of 0.50 dS/m (about 380 mg/l) and 0.82 dS/m (about 625 mg/l), respectively. Thus, the overall average for water applied to lands under both canals was about 0.66 dS/m (500 mg/l). Under good drainage conditions, adequate leaching fractions, and negligible salt sources derived from fertilization and/or mineral weathering, only marginal soil salinity problems would be expected to occur using irrigation water of this quality (Pescod 1992). However, the average salinity level ( $EC_e$ ) of soils in the 32 fields sampled in the region was about 2.8 dS/m (about 2200 mg/l), well above the threshold level for all crops grown in the area. This relatively high salinity level indicates that extraneous salt sources (salt sources other than the applied irrigation water) are present.

The magnitude of current extraneous salt sources was estimated from an analysis of a representative seasonal root zone salt balance for the command area. Next, predictions were made of future irrigation requirements under the SPWCP. It was assumed that the current extraneous salt load would not significantly increase under future conditions associated with the new SPWCP. It is known, however, that the salinity of the water diverted under the SPWCP will likely be higher than that presently in the waters of the Larimer & Weld and New Cache la Poudre canal systems. Given this situation, an investigation was conducted to predict the increased volume of infiltrated irrigation water, and associated increased leaching fraction, that would be required to prevent soil salinity in the command area from increasing above present levels. Several different management alternatives were considered. Acknowledging uncertainty due to spatial-temporal variability and measurement error, it was assumed that the variables in the analysis were distributed in probability over physically-reasonable ranges of values.

### *Analysis of Current Extraneous Salt Loading*

The root zone salt balance model, expressed in equations (1) and (2), was used as a tool to estimate current extraneous salt sources in the SPWCP command area. Assuming negligible seasonal change in salt stored in the root zone (i.e.  $\Delta S_{sw} C_{sw} \approx 0$ ), equations (1) and (2) were solved simultaneously for  $C_w$  and for the extraneous salt load term ( $X_d + Q_u C_u$ ). The assumption of negligible  $\Delta S_{sw} C_{sw}$  seems reasonable for the loam, sandy loam, and loamy sand soils of the region. The total water storage capacity of these soils, under typical irrigated conditions, is only about 0.1 m (Cuenca 1989, Stegman

et al. 1980). Total salt content in the root zone of the soils undoubtedly is changing. However, soil salinity over the region probably has approached a near-equilibrium condition on the average, meaning that the average total change over the course of a single season probably is not very large. The extraneous salt load term,  $(X_d + Q_u C_u)$ , represents the combined contribution of mineral weathering, fertilization and upward flow from a saline high water table. Estimated ranges of values of  $(X_d + Q_u C_u)$  were computed for current field conditions. This required that reasonable ranges of values for the input variables be considered based upon field data and upon knowledge of similar conditions elsewhere.

Distributions of values for  $C_i$  and  $C_{sw}$  were estimated from the field data collected in this study. Values of  $C_{sw}$  were expressed as equivalent saturation extract concentrations since the root zone salt balance model was applied to leaching conditions (where the water content would be close to saturation). Direct measurements of seasonal volumes of infiltrated irrigation,  $Q_i$ , and deep percolation,  $Q_w$ , for the study region were not available. Instead, values were calculated using estimated distributions of the net irrigation water required,  $(Q_{et} - Q_{pe})$ , for the crops grown in the region and estimated distributions of leaching fractions ( $LF = Q_w/Q_i$ ).

Two different approaches were used to derive estimates for the net irrigation requirement,  $(Q_{et} - Q_{pe})$ . Approach A used average values of  $(Q_{et} - Q_{pe})$  computed using the Kimberly Penman equation in conjunction with field water balances and climatic data (collected from a single station northeast of Greeley), as reported in Walter and Altenhoffen (1993). In approach B, seasonal values of  $Q_{et}$  and effective precipitation,  $Q_{pe}$ , were calculated by the author from daily data collected at agricultural meteorological stations near Ault, Lucerne, and Greeley. Daily  $Q_{et}$  values were calculated using estimates of potential evapotranspiration computed with the Kimberly Penman equation (Jensen et al. 1990) as reported by the Colorado Climate Center (1998) (using climatic data collected over the past seven years) and using crop coefficients reported in Jensen et al. (1990). Daily values of  $Q_{pe}$  were estimated as 75% of daily measured  $Q_p$ . In other words, it was assumed that 25% of the rainfall that occurred resulted in surface runoff. It also was assumed that rainfall events did not result in significant deep percolation. The two approaches resulted in mean values of  $(Q_{et} - Q_{pe})$  of about 0.36 m and 0.50 m, respectively.

Values of  $LF$  were derived from recent field studies reported by Crookston (1995), Podmore (1995), and Walter (1995). These studies suggest that the leaching fraction ranges from about 0.15 to as high as about 0.75. Values of  $Q_w$  and  $Q_i$  were calculated from the relationships:  $Q_w = Q_i - (Q_{et} - Q_{pe})$  and  $Q_i = Q_w/LF$ . Reduction in net irrigation requirement due to possible upward flow,  $Q_u$ , was not explicitly considered. Ranges and distributions of values for leaching efficiency,  $E_L$ , for the soils of the region were extracted from similar studies conducted elsewhere (Gates and Grismer 1989, Bouwer 1969, Pillsbury et al. 1965). These values were used in equation (2).



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A method called Monte Carlo simulation was used to compute the probability distributions and statistics for  $C_w$  and  $(X_d + Q_u C_u)$  using the probability distributions and statistics for the input variables. In Monte Carlo simulation, a mathematical model [in this case, equations (1) and (2) along with the relationships described above] is solved for numerous possible sets of values (called realizations) that the input variables could take on. A statistical computer model, @RISK™ (Palisade Corporation 1997), was used to generate each realization of values for the input variables by sampling out of their assumed probability distributions. The considered probability distributions and associated statistics (mean, standard deviation, minimum, maximum) for the input variables are summarized in Table 15 for approaches A and B.

The assumed correlation structure (expressed with Spearman rank order correlation coefficient) between the variables used in the statistical model is summarized in the matrix of Table 16. Correlation values range between -1 and 1, with a value of -1 indicating perfect inverse correlation between the probability distributions of two variables, and a value of 1 indicating perfect direct correlation (Vose 1996). This correlation structure prevents consideration of unreasonable combinations of values for the input variables. For example, it is unlikely that a high seasonal value of  $C_{sw}$  would occur in a field with a high seasonal value of  $LF$ . Hence, a fairly strong inverse correlation of -0.75 between these two variables was assumed, as indicated in Table 16. When the statistical model generated a high value from the distribution of  $LF$ , it also tended to generate a low value from the distribution of  $C_{sw}$ , for use in solving equations (1) and (2). In the absence of field data, these values seem reasonable, based upon the author's experience and judgement; however, other correlation values can be considered.

The computed distributions and statistics for  $C_w$  and  $(X_d + Q_u C_u)$  are summarized in Table 15 for a Monte Carlo simulation with 500 realizations for approaches A and B. These results suggest that a substantial amount of extraneous salt is entering the soil system from mineral weathering, fertilization and/or upward flow from saline high water tables. The average total amount was estimated at 1189 kg/ha (0.53 tons/acre) for alternative A and 1651 kg/ha (0.74 tons/acre) for alternative B. To improve one's intuitive understanding of these quantities, it is helpful to note that increasing the salinity concentration of the infiltrated irrigation water by 131 mg/l (0.2 dS/m) would have the same effect. Further study will be necessary to differentiate the sources of these additional salts. The computed average value of  $C_w$  was about 1400 mg/l (1.8 dS/m). This value corresponds closely to recent measurements of the salinity of underlying groundwater in the area, as reported in the previous section "Groundwater Conditions in the Project Command Area".

### Prediction of Future Irrigation Requirements Under the SPWCP

To assess the impact of increased  $C_i$  under the SPWCP, equations (1) and (2) were solved to estimate values of  $Q_i$  and  $LF$  that would be *required* to maintain the current range of root-zone soil salinity. Associated values of  $C_w$  also were computed. In this analysis, the values of  $(X_d + Q_u C_u)$  previously computed for current field conditions were assumed to remain unchanged in their relative variability. This means that if

**Table 15. Assessment of Current Field Conditions to Estimate Leaching Water Salinity and Extraneous Salt Load (Mineral Weathering, Fertilization and Upward Flow) Using Approaches A and B for Estimating Net Irrigation Requirement.**

<b>Approach A</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	500	75	350	650
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$LF$	Truncated Normal	0.50	0.20	0.15	0.75
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
<b>Computed Variable</b>					
$Q_i$ (m)	PearsonV	<b>0.77</b>	0.52	0.28	1.72
$C_w$ (mg/l)	Inverse Gaussian	1402	656	387	4124
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
<b>Approach B</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	500	75	350	650
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$LF$	Truncated Normal	0.50	0.20	0.15	0.75
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
<b>Computed Variable</b>					
$Q_i$ (m)	PearsonV	<b>1.06</b>	0.39	0.46	2.39
$C_w$ (mg/l)	Inverse Gaussian	1402	656	387	4124
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-

**Table 16. Spearman Correlation Matrix for Variables in the Salt Balance Analysis.**

	$C_i$	$C_{sw}$	$Q_{et}$	$LF$	$E_L$	REF	DRF
$C_i$	1.00	0.75	0.00	0.00	0.00	0.00	0.00
$C_{sw}$	0.75	1.00	0.00	-0.75	-0.75	0.00	0.00
$Q_{et}$	0.00	0.00	1.00	0.25	0.00	0.90	0.00
$LF$	0.00	-0.75	0.25	1.00	0.25	0.00	0.00
$E_L$	0.00	-0.75	0.00	0.25	1.00	0.00	0.00
REF	0.00	0.00	0.90	0.00	0.00	1.00	0.00
DRF	0.00	0.00	0.00	0.00	0.00	0.00	1.00

measures were taken to reduce the average value of  $(X_d + Q_u C_u)$  over the area, proportional changes in the standard deviation, minimum, and maximum values would occur. The possibility that a net increase in the average value of  $(X_d + Q_u C_u)$  might occur, due to increased values of  $Q_i$ , was not considered. This assumption may need to be more rigorously tested.

Five different management alternatives for the SPWCP were considered:

1. *Alternative 1 - No Reduction in Average Extraneous Salt Load, No Mixing of SPCWP Water with Upstream Water.* This alternative assumed that no measures would be adopted to reduce salt loading from mineral weathering, fertilization, and upward flow. Also, irrigation water diverted under the SPCWP would not be mixed with higher-quality water from upstream diversions.
2. *Alternative 2 - 50% Reduction in Average Extraneous Salt Load, No Mixing of SPCWP Water with Upstream Water.* Under this alternative, measures (such as improved drainage and/or reduction in fertilizer applications) would be taken to decrease average salt load over the command area by 50%. No mixing of water would take place.
3. *Alternative 3 - 50% Reduction in Average Extraneous Salt Load, 50/50 Mixing of SPCWP Water with Upstream Water.* Measures would be taken to reduce average salt load by 50%. Water diverted under the SPWCP would be mixed in a 50/50 ratio with upstream water (assumed to have salinity concentrations equal to those under current conditions).
4. *Alternative 4 - No Reduction in Average Extraneous Salt Load, 50/50 Mixing of SPCWP Water with Upstream Water.* Under this alternative, field management would not be improved to reduce salt loads. Water diverted under the SPWCP would be mixed in a 50/50 ratio with upstream water.
5. *Alternative 5 - 75% Reduction in Average Extraneous Salt Load, 50/50 Mixing of SPCWP Water with Upstream Water.* This alternative was considered as the optimal condition that could be achieved under assumed system characteristics. Measures would be taken to reduce average salt load to fields by 75%. Water diverted under the SPWCP would be mixed in a 50/50 ratio with upstream water.

The data presented under the section "Water Quality at the Proposed Point of Diversion" revealed considerable seasonal variability in the salinity of available river flows. Also, it was found that the lowest salinity levels occur during spring and summer months when the demand for diversions from the river is highest. Hence, the salinity of water diverted under the SPWCP will depend upon the total volume of water diverted by the project. Since the project will have a junior priority, it is unlikely that it will be able to divert a large volume during high-demand periods when the salinity tends to be lowest. If a lower yield (exchange potential) of water is deemed acceptable to the project (to be determined by on-going demand studies), a larger fraction of the total diversion can occur during periods when the salinity is low. On the other hand, if a higher yield is required, more water will have to be diverted during low-demand periods when the salinity is higher. A high-yield and a low-yield scenario were considered in the present study.

Recent historic records (1970 – 1994) of available monthly river flows and calls on the river were evaluated, in conjunction with derived flow-salinity relationships, to estimate the average salinity of diversions that would occur under alternative project yields. It was found that a high firm annual yield of about 80 million m<sup>3</sup> (65,000 ac-ft) could be extracted with a temporal pattern that would result in an average salinity of about 1100 mg/l. This would represent an increase of about 120% over the current average water salinity in the canal systems. On the other hand, if a low firm annual yield of about 27 million m<sup>3</sup> (2,000 ac-ft) were sufficient to meet exchange demands, the average salinity level could be reduced to about 700 mg/l, representing a 40% increase over current supplies.

It was assumed that salinity concentrations of SPWCP diversions will further increase by 5 to 10% due to evaporative concentration in the proposed Galetton Reservoir. Hence, a reservoir evapo-concentration fraction, *REF* was employed in the analysis, assuming a normal distribution over the range 0.05 to 0.10, with a mean of 0.075. For example, an *REF* value of 0.075 would indicate a 7.5% increase in the salinity of water diverted by the SPWCP due to evaporative concentration during storage in Galetton Reservoir. A salt load reduction fraction, *SLRF*, was used to model the fractional decrease in salt load brought about by improved drainage and/or fertilizer management. A value of *SLRF* = 0.50 means that measures will be taken to result in a 50% decrease in extraneous salt load, ( $X_d + Q_u C_u$ ).

A Monte Carlo simulation of 500 possible realizations of the salt balance was carried out. Summary statistics for input variables and for computed output for each of the alternatives are summarized in Table 17 using approach A for estimating net irrigation requirement and the high-yield scenario for estimating average salinity of SPWCP supplies. Table 18 presents similar results using approach A and the low-yield scenario. Summary statistics for each of the management alternatives under approach B are presented in Tables 19 and 20 for the high-yield and low-yield options, respectively.

Comparing results in Table 17 with those in Table 15 shows that average values of  $Q_i$  may need to increase by 45% to 70 % over current conditions if the mean net irrigation requirement is 0.36 m and the project must have a high yield. For a low-yield scenario, the increase in average  $Q_i$  would be 25% to 52%. If the mean net irrigation requirement is 0.50 m, the results in Tables 18 and 19 indicate that average values of  $Q_i$  may need to increase by 47% to 71% for a high-yield condition and by 26% to 54% for low-yield. In other words, the additional infiltrated irrigation water required to leach salts out of the root zone is a larger fraction of the current estimated infiltration water under approach A, compared to approach B. It will also be larger for a project that must produce a high yield of water than for a project with a low-yield requirement. The increase in  $Q_i$  is needed to achieve *LF* values that would insure that soil salinity does not rise in response to the increased salinity of applied irrigation water. Under both approach A and approach B, and under both high- and low-yield scenarios, required values of  $Q_i$  typically decreased progressively from Alternative 1 to Alternative 5. Even with

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increased  $Q_i$ , it was found that soil salinity would increase on somewhere between about 5% to 20% of the fields in the area served by the project. Mixing of irrigation waters appears to have the greatest impact on reducing the required values of  $Q_i$ . The resulting larger volume of mixed water would be applied over a proportionately larger command area. Also, for alternatives that include mixing, the predicted salinity of leaching water,  $C_w$ , was 1479 mg/l (2 dS/m) for high-yield and 1383 mg/l (1.8 dS/m) for low yield. This compared to respective values of 1624 mg/l (2.2 dS/m) and 1431 mg/l (1.9 dS/m) for alternatives without mixing. The required incremental increase in  $Q_i$  possibly could be obtained from reduction of surface runoff (facilitated by conversion to sprinklers or surge irrigation) and reduction in canal seepage. Conversion to more salt-tolerant crops to allow increased root-zone salinity under a portion of the land might also be considered.

#### *Future Major Ions and SAR Under the SPWCP*

Data collected in the canal systems and at the proposed river diversion site reveal relatively high  $\text{HCO}_3$  concentrations. Concentrations in the New Cache la Poudre Canal currently exceed recommended criteria by as much as about 25% during the late season. Concentrations at the proposed diversion site were found to exceed the criteria by as much as about 90%. The implications for damage to crop production are difficult to predict but could be significant.

**Table 17. Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Extraneous Salt Load and Water Mixing Using Approach A for Estimating Net Irrigation Requirement and Using a High-Yield Scenario (Cont. on next page).**

<b>Alternative 1: No Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	1100	165	850	1350
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{at} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.31	0.75	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1624	666	585	3601
LF	NonParametric	0.59	0.26	0.15	0.89
Fraction of Fields with Increased Salinity = 0.22					
<b>Alternative 2: 50% Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	1100	165	850	1350
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{at} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.25	0.72	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1624	666	585	3601
LF	NonParametric	0.58	0.26	0.15	0.89
Fraction of Fields with Increased Salinity = 0.17					
<b>Alternative 3: No Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	800	120	600	1000
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{at} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.25	0.68	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1478	644	499	3379
LF	NonParametric	0.61	0.20	0.15	0.88
Fraction of Fields with Increased Salinity = 0.15					

**Table 17 (Cont.). Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Salt Load and Water Mixing Mixing Using Approach A for Estimating Net Irrigation Requirement and Using a High-Yield Scenario**

<b>Alternative 4: 50% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	800	120	600	1000
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.16	0.63	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1479	644	499	3379
LF	NonParametric	0.60	0.19	0.15	0.88
Fraction of Fields with Increased Salinity = 0.10					
<b>Alternative 5: 75% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	800	120	600	1000
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.75	0.15	0.45	1.00
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.12	0.62	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1479	644	499	3379
LF	NonParametric	0.58	0.19	0.15	0.87
Fraction of Fields with Increased Salinity = 0.06					

**Table 18. Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Extraneous Salt Load and Water Mixing Using Approach A for Estimating Net Irrigation Requirement and Using a Low-Yield Scenario (Cont. on next page).**

<b>Alternative 1: No Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	700	105	525	875
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
Computed Variables					
$Q_i$ (m) Required	NonParametric	1.17	0.64	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1430	636	473	3301
LF	NonParametric	0.60	0.19	0.15	0.88
Fraction of Fields with Increased Salinity = 0.12					
<b>Alternative 2: 50% Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	700	105	525	875
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
Computed Variables					
$Q_i$ (m) Required	NonParametric	1.08	0.59	0.33	2.40
$C_w$ (mg/l)	Inverse Gaussian	1431	635	473	3301
LF	NonParametric	0.58	0.18	0.15	0.88
Fraction of Fields with Increased Salinity = 0.10					
<b>Alternative 3: No Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	600	90	450	750
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
Computed Variables					
$Q_i$ (m) Required	NonParametric	1.10	0.60	0.40	2.40
$C_w$ (mg/l)	Inverse Gaussian	1382	627	447	3223
LF	NonParametric	0.59	0.18	0.15	0.88
Fraction of Fields with Increased Salinity = 0.11					



**Table 18 (Cont.). Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Salt Load and Water Mixing Mixing Using Approach A for Estimating Net Irrigation Requirement and Using a Low-Yield Scenario**

<b>Alternative 4: 50% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	600	90	450	750
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{or} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.01	0.56	0.39	2.40
$C_w$ (mg/l)	Inverse Gaussian	1383	627	447	3223
LF	NonParametric	0.56	0.17	0.15	0.88
Fraction of Fields with Increased Salinity = 0.05					
<b>Alternative 5: 75% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	600	90	450	750
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{or} - Q_{pe}$ (m)	Truncated Normal	0.36	0.05	0.27	0.45
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1189	2045	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.75	0.15	0.45	1.00
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	0.96	0.53	0.39	2.40
$C_w$ (mg/l)	Inverse Gaussian	1383	627	447	3223
LF	NonParametric	0.54	0.17	0.15	0.88
Fraction of Fields with Increased Salinity = 0.07					

**Table 19. Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Extraneous Salt Load and Water Mixing Using Approach B for Estimating Net Irrigation Requirement and Using a High-Yield Scenario (Cont. on next page).**

<b>Alternative 1: No Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	1100	165	850	1350
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.81	1.03	0.45	3.33
$C_w$ (mg/l)	Inverse Gaussian	1624	666	585	3601
LF	NonParametric	0.59	0.26	0.15	0.89
Fraction of Fields with Increased Salinity = 0.22					
<b>Alternative 2: 50% Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	1100	165	850	1350
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.74	0.99	0.45	3.33
$C_w$ (mg/l)	Inverse Gaussian	1624	666	585	3601
LF	NonParametric	0.58	0.26	0.15	0.89
Fraction of Fields with Increased Salinity = 0.19					
<b>Alternative 3: No Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	800	120	600	1000
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.73	0.94	0.45	3.33
$C_w$ (mg/l)	Inverse Gaussian	1479	644	499	3379
LF	NonParametric	0.61	0.20	0.15	0.88
Fraction of Fields with Increased Salinity = 0.10					

**Table 19 (Cont.). Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Salt Load and Water Mixing Mixing Using Approach B for Estimating Net Irrigation Requirement and Using a High-Yield Scenario**

<b>Alternative 4: 50% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	800	120	600	1000
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_d C_d)$ (kg/ha)	Pearson VI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.61	0.87	0.45	3.33
$C_w$ (mg/l)	Inverse Gaussian	1479	64	499	3379
LF	NonParametric	0.60	0.19	0.15	0.88
Fraction of Fields with Increased Salinity = 0.12					
<b>Alternative 5: 75% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	800	120	600	1000
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_d C_d)$ (kg/ha)	Pearson VI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.75	0.15	0.45	1.00
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.56	0.86	0.45	3.33
$C_w$ (mg/l)	Inverse Gaussian	1479	64	499	3379
LF	NonParametric	0.58	0.19	0.15	0.87
Fraction of Fields with Increased Salinity = 0.11					

**Table 20. Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Extraneous Salt Load and Water Mixing Using Approach B for Estimating Net Irrigation Requirement and Using a Low-Yield Scenario (Cont. on next page).**

<b>Alternative 1: No Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	700	105	525	875
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.63	0.88	0.46	3.33
$C_w$ (mg/l)	Inverse Gaussian	1431	635	473	3301
LF	NonParametric	0.60	0.19	0.15	0.88
Fraction of Fields with Increased Salinity = 0.12					
<b>Alternative 2: 50% Reduction in Avg. Extraneous Salt Load, No Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	700	105	525	875
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.50	0.81	0.46	3.33
$C_w$ (mg/l)	Inverse Gaussian	1431	635	473	3301
LF	NonParametric	0.58	0.18	0.15	0.88
Fraction of Fields with Increased Salinity = 0.10					
<b>Alternative 3: No Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	600	90	450	750
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	-	-	-	-	-
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.53	0.84	0.55	3.33
$C_w$ (mg/l)	Inverse Gaussian	1383	627	447	3223
LF	NonParametric	0.58	0.18	0.15	0.88
Fraction of Fields with Increased Salinity = 0.10					

**Table 20 (Cont.). Prediction of Future Seasonal Irrigation Requirement and Leaching Water Salinity Under Five Alternatives for Reduction in Salt Load and Water Mixing Mixing Using Approach B for Estimating Net Irrigation Requirement and Using a Low-Yield Scenario**

<b>Alternative 4: 50% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	600	90	450	750
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.50	0.10	0.20	0.80
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.40	0.77	0.54	3.33
$C_w$ (mg/l)	Inverse Gaussian	1383	627	447	3223
LF	NonParametric	0.56	0.17	0.15	0.88
Fraction of Fields with Increased Salinity = 0.06					
<b>Alternative 5: 75% Reduction in Avg. Extraneous Salt Load, 50/50 Mixing of SPWCP Water with Upstream Water</b>					
Input Variable	Probability Distribution	Mean	Standard Deviation	Minimum	Maximum
$C_i$ (mg/l)	Truncated Normal	600	90	450	750
REF	Truncated Normal	0.08	0.01	0.05	0.10
$C_{sw}$ (mg/l)	Truncated Lognormal	2370	1670	400	7000
$Q_{et} - Q_{pe}$ (m)	Truncated Normal	0.50	0.08	0.38	0.63
$(X_d + Q_u C_u)$ (kg/ha)	PearsonVI	1651	2841	-	-
$E_L$	Truncated Normal	0.55	0.10	0.40	0.70
SLRF	Truncated Normal	0.75	0.15	0.45	1.00
<b>Computed Variables</b>					
$Q_i$ (m) Required	NonParametric	1.34	0.74	0.54	3.33
$C_w$ (mg/l)	Inverse Gaussian	1383	627	447	3223
LF	NonParametric	0.54	0.17	0.15	0.88
Fraction of Fields with Increased Salinity = 0.06					

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## SUMMARY AND RECOMMENDATIONS

A reconnaissance-stage investigation, addressing the suitability of waters exchanged under the proposed SPWCP for sustainable irrigated agriculture, has been completed. Water-quality criteria for the major constituents of concern to irrigated agriculture have been reviewed and summarized. Field studies were conducted to describe current conditions within the project command area and at the proposed new water diversion point. These conditions were analyzed and compared to predict future implications for the SPWCP.

The appeal of the SPWCP is in providing a means to meet urban water demands without "drying out" productive agricultural communities. The challenge lies in making sure that a lower-quality water source will work for agriculture. Results from the present study indicate that the SPWCP is indeed viable, but only if carefully managed. The greatest concern is the anticipated increase in the salinity of the water supply under the new project, compared to the salinity of the current supplies. Preliminary analysis indicates that this increase will be about 40% for a low-yield (22,000 ac-ft) project and about 120% for a high-yield (65,000 ac-ft) project. Such increases will likely require significant additional amounts of infiltrated irrigation water in the area. The increased infiltrated volume would be needed to leach out the additional salts present in the SPWCP water to insure that soil salinity in the region is not raised above current levels. Results indicate that the amount of increased irrigation water required will be less if water diverted under the SPWCP can be mixed with lower-quality water from upstream diversions and if measures can be taken to reduce extraneous salt loading.

To more accurately predict the additional irrigation water that may need to be applied to fields, a more refined study needs to be conducted. Additional work needs to be done in the field:

1. *Water samples need to be collected in the canal and reservoir systems for several more irrigation seasons.* This will provide understanding of the magnitude and temporal variability of the salinity of current water supplies.
2. *Water samples need to be collected throughout the year in the vicinity of the proposed diversion for several more years.* This will enhance understanding of the magnitude and temporal variability of salinity of the proposed new source of water supply. In particular, it will indicate whether or not salinity levels are increasing in the Cache la Poudre and South Platte Rivers.
3. *The evapo-concentration of water to be stored in Galeton Reservoir needs to be better estimated.* This will require more detailed prediction of reservoir surface area and seepage to groundwater, and analysis of climatic conditions determining water surface evaporation in the area.

4. *The soil salinity over the command area needs to be better described.* Broad surveys of soil salinity should be conducted using EM-38 probes on about 50 fields [with at least 50 samples per 4 to 8 ha (10 to 20 acres)] over several seasons (at least twice per season). Fields should be located over both the alluvium and shale hydrogeologic units. This will refine the understanding of the actual severity of soil salinity over the command area under current conditions, including estimates of spatial and temporal variability. Discussions with NRCS personnel indicate that they are open to a cooperative investigation of this type.
5. *The depth and salinity of underlying groundwater in the region must be quantified.* Data from this study, in addition to anecdotal evidence from the field, suggests that portions of the region may be affected by upward flow from saline high water tables. A battery of observation wells needs to be installed and monitored to document groundwater conditions over a period of time.
6. *The factors contributing to high soil salinity levels in the region need to be better understood.* Several field sites should be selected for detailed studies of water and salt balances. Values of  $Q_a$ ,  $C_a$ ,  $Q_r$ ,  $C_r$ ,  $Q_b$ ,  $C_b$ , and  $\Delta S_{sw}C_{sw}$  should be carefully measured using flumes, salinity probes, and soil analysis. Depth and salinity of underlying groundwater also should be measured under each field, along with amounts of applied fertilizer. Values of  $Q_{et}$  should be estimated from climatic data and/or evaporation gauges. Rain gages should be set up to measure  $Q_p$ . These measurements will allow estimates of  $Q_w$ ,  $C_w$ , and  $(X_d + Q_u C_u)$  to be calculated from the water balance and salt balance equations. Perhaps, such studies could be conducted in conjunction with the NCWCD IMS group.

Options for managing the SPWCP need to be better defined. Both technical and economic feasibility should be included in consideration of the following:

1. *The potential for mixing SPWCP water with water from upstream sources needs to be further explored.* This will require better estimates of demand for exchanges on the current diversions from the Cache la Poudre River, including CBT waters. Also, special consideration should be given to the conjunctive operation of the SPWCP with the proposed new Cache la Poudre storage project.
2. *Prospects for reducing extraneous salt loading by reducing application of manure and commercial fertilizers need to be better defined.* This will require an analysis of the availability of N from increased  $\text{NO}_3$  and  $\text{NO}_2$  concentrations in diversions under the SPWCP.
3. *The potential for reducing surface runoff and canal seepage to offset increasing infiltrated water needs to be studied.* This will require estimation of runoff reduction that reasonably can be achieved through adoption of surge and sprinkler irrigation. Consideration also should be given to the possibility that reduced flushing of surface salts will occur due to reduced surface runoff. Measures for reducing canal seepage should be studied.



4. *Installation of subsurface drainage facilities must be considered for areas affected by saline high water tables.* Optimal reduction in upward flow of salts,  $Q_w C_w$ , under alternative designs should be estimated (Gates et al. 1989).

Further modeling needs to be done to predict future conditions that may develop under alternative management conditions:

1. *More detailed modeling of salinity of diversions under the SPWCP needs to be conducted.* The statistics of the salinity of water diverted under a variety of different project yields (exchange potentials) need to be predicted accounting for variability in river flows, calls on the river, demands for exchanges, and flow-salinity relationships.
2. *Current levels of extraneous salt loading in the region need to be calculated under alternative assumptions about field conditions.* The effect of varying levels of change in stored soil salts,  $\Delta S_{sw} C_{sw}$ , should be considered. Estimates of current extraneous salt loading affect predictions of required  $Q_i$  and  $LF$  under the SPWCP.
3. *The sensitivity of predicted variables of interest to input variables should be more broadly studied.* A variety of different correlation structures and statistics (mean, CV, minimum, and maximum values) for input variables should be considered. The impact on the statistics of predicted variables should be noted. For example, preliminary model studies indicate that predicted results are moderately sensitive to the input values of the leaching efficiency,  $E_L$ .
4. *The possibility that increased  $Q_i$  values under the SPWCP could lead to increased extraneous salt loading, through increased mobilization of mineral salts, should be considered.*
5. *The feasibility of actually reducing soil salinity levels, rather than simply preventing their elevation, should be considered.*

Issues of secondary concern, related to potentially adverse impact, are the periodically high microbial concentrations,  $\text{NO}_3\text{-N}$  and  $\text{NO}_2\text{-N}$  concentrations, and  $\text{HCO}_3$  concentrations that have been measured in the waters at the proposed diversion site. The following recommendations are made:

1. *Water samples need to be collected throughout the year in the vicinity of the proposed diversion for several more years, to be analyzed for fecal coliform,  $\text{NO}_3\text{-N}$ ,  $\text{NO}_2\text{-N}$ , and  $\text{HCO}_3$ .* This will enhance understanding of the magnitude and temporal variability of these constituents at the proposed new source of water supply. In particular, it will indicate whether or not increasing trends are present in the Cache la Poudre and South Platte Rivers.

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2. *Given that microbial concentrations appear to periodically exceed current standards for irrigation water, the sources need to be carefully identified and mitigation measures need to be considered.* In addition to fecal coliform, the presence of protozoa, helminths, and viruses needs to be investigated. The feasibility of tertiary treatment at the sources should be studied.
  3. *Means to account for elevated N concentrations must be developed.* Additional N in the SPWCP waters can prove beneficial to most crops, if managed to offset the need for manure and commercial fertilizer applications. However, possible detrimental impacts of elevated N on sugar beet and malting barley production need to be further studied.

Finally, successful implementation of the SPWCP project will require careful monitoring and evaluation. Plans will be needed for periodic data collection to assess water quality constituents in the command area. Measurements must be evaluated in light of adopted standards, and remedial measures must be developed for implementation in the case of standard violation.

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