Groundwater response and salt removal in a saline-seep soil in southern Alberta

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Buckland, G.D. and Hendry, M.J. 1992. **Groundwater response and salt removal in a saline-seep soil in Southern Alberta**. Can. Agric. Eng. **34**:125-134. A study comparing subsurface drainage and irrigation, alone and in combination, was conducted for three years on a severe saline seep (electrical conductivity of saturated soil extract, EC_e, up to 51 $dS \cdot m^{-1}$) in southern Alberta. Changes in soil salinity and response of groundwater and soil water to imposed treatments of irrigated non-drained, irrigated drained, non-irrigated drained and control were determined. Immediately following irrigation, groundwater gradients generally changed from upward to downward. Upward gradients were observed in the non-irrigated treatments, except in the control treatment where downward gradients occurred following rainfalls of 54 mm or more. Soil matric potential at the 0.15-m depth was usually at or above field capacity (30 kPa) for all treatments. Irrigation and rainfall induced downward matric potential gradients between soil depths of 0.15 and 0.60 m. After three years, average profile EC_e (0-1.2 m) of the irrigated non-drained, irrigated drained, non-irrigated drained and control treatments were 67, 60, 104 and 99% of initial levels, respectively. Corresponding sodium adsorption ratios were 79, 79, 131 and 120%. Desalinization in the irrigated non-drained and irrigated drained treatments is attributed to changes in groundwater and soil matric potential gradients resulting from irrigation. Minor desalinization also occurred in some years in the non-irrigated drained and control treatments and is attributed to high rainfall events. All treatments resalinized during the non-irrigated season, in one or more years, but the relative degree of resalinization was greatest in the irrigated non-drained treatment. Results suggest irrigation had a dominant effect in removing salt from the soil of this study and subsurface drainage had a minor effect. Control of salinity in this soil using irrigation, drainage, or both, may not be practical because upward groundwater gradients and overwinter resalinization restricted salt removal and may not be desirable because of potential off-site impacts.

Une étude comparant le drainage souterrain et l'irrigation, seuls et combinés, a été menée pendant trois ans dans le sud de l'Alberta relativement à une petite source très salée (conductivité électrique d'extrait de sol saturé, EC_e, atteignant 51 $dS \cdot m^{-1}$). On a déterminé les modifications de la salinité du sol par rapport à différents traitements: irrigation sans drainage, irrigation avec drainage, drainage sans irrigation et correctif. Immédiatement après l'irrigation, les gradients d'eau souterraine, d'ascendants qu'ils étaient, ont généralement eu tendance à devenir descendants. Des gradients «ascendants» ont été observés lors des traitements sans irrigation, à l'exception du traitement correctif où l'on a relevé des «gradients descendants» après des précipitations de 54 mm ou plus. Le potentiel capillaire du sol à 0,15 m de profondeur était habituellement équivalent ou supérieur à la capacité au champ (30 kPa) et ce, pour tous les traitements. L'irrigation et les précipitations ont provoqué des «gradients de potentiel capillaire descendants» entre des profondeurs de sol de 0,15 et 0,60 m. Après trois ans, le profil moyen EC_e (0-1,2 m) des traitements avec irrigation sans drainage, irrigation avec drainage, drainage sans irrigation et correctif étaient respectivement de 67, 60, 105 et 99 % des niveaux initiaux, les taux d'absorption de sodium correspondants étant de 79, 79, 131 et 120%. Le dessalement, dans les traitements avec irrigation sans drainage et irrigation avec drainage, est attribué à des changements survenus dans les gradients d'eau souterraine et les gradients de potentiel capillaire à cause de l'irrigation. Un faible dessalement a également été observé au cours des traitements par drainage sans irrigation et correctif et sont attribués à de fortes chutes de pluie. On a aussi observé un «ressalement» pour tous les traitements durant la période de non-irrigation, en une année ou plus, cependant que le degré relatif de «ressalement» était supérieur pendant le traitement par irrigation sans drainage. Les résultats laissent supposer que l'irrigation a eu un effet important sur l'extraction du sel contenu dans le sol à l'étude, et que le drainage souterrain n'a eu qu'un effet secondaire. Le contrôle de la salinité dans ce sol, par irrigation, drainage, ou les deux à la fois, peut n'être pas pratique parce que les gradients ascendants et le «ressalement» durant l'hiver ont abaissé le pourcentage d'extraction du sel; il peut également n'être pas souhaitable à cause d'impacts hors du site.

INTRODUCTION

Soil salinity is a major agronomic problem which affects both dryland and irrigated land in semi-arid regions of the North American Great Plains (Doering and Sandoval 1981). Within southern Alberta, 11% of the arable land is affected by salinity (Sommerfeldt et al. 1984). Subsurface grid drainage is one method recommended for reclaiming saline soils. As of 1985, subsurface drainage had been installed on about 270 irrigated parcels and 160 dryland parcels in southern Alberta (Harker and Mikalson 1986).

The benefit of using subsurface drainage to reclaim saline land under irrigation in southern Alberta is well documented. After two years of irrigation following drainage, Buckland et al. (1986) found relative reductions in soil salinity of up to 26% in the upper 2 m of soil at two sites. Rapp (1968) reported a mean reduction in salinity of 68% in the upper 0.9 m of soil following three years of irrigation. Also after three years of irrigation, Sommerfeldt and Paziuk (1975) found relative reductions in salinity of 33% in the upper 1.2 m of soil. Similar results are reported by Bennett et al. (1982) and van Schaik and Milne (1962).

In contrast to salinity of irrigated land, the merit of using subsurface grid drainage to reclaim dryland salinity is not well established. An unpublished two year study by Vander Pluym et al. (1985) reported results at six locations in southern Alberta which varied depending upon site, year and drain depth. In general, however, salinity decreased in the upper 0.3 m of soil at most sites.

Irrigation, in the absence of drainage, has also been examined as a method of controlling soil salinity. Rapp (1968) found irrigation could be used to reduce soil salinity when leaching water was applied, but the extent of salt removal was not as great as when subsurface drainage was also provided. In contrast, McMullin et al. (1983) and van Schaik and Milne (1967) found only limited salt removal in undrained, saline soils subjected to irrigation. Both of the latter studies questioned whether sustained salinity control could be achieved with irrigation alone, partly because the soil resalinized between seasons.

Studies to date have not compared subsurface drainage, with and without irrigation, simultaneously under similar soil conditions. As well, few studies have used a control treatment to establish natural changes in soil salinity concurrently with imposed treatments. The main objective of this study was to compare the relative effect of irrigation and subsurface drainage, alone and in combination, in leaching salts from a saline-seep soil and to compare the extent of salt removal to changes which occur naturally. Another objective was to determine the effect that these treatments had on groundwater and soil water and how this related to the observed changes in soil salinity.

MATERIALS AND METHODS

Site background

The study site (SE 2-9-16-W4) is a saline seep located about 60 km southeast of Lethbridge, Alberta in a basin of extensive salinization. The cause of salinity in the basin (and at the selected study site) was examined by Hendry and Buckland (1990). Dryland farming predominates upslope of the study site and as a result of crop-fallow rotation, groundwater recharge occurs. The recharge water passes through glacial till surficial material and enters the shallow, layered bedrock. The recharge water travels laterally down gradient within the bedrock and discharges at or near the study site. Salinization occurs because the flat-lying bedrock is truncated by the overlying till which results in groundwater discharge.

The area recharging groundwater to the seep extends for up to 13 km (Hendry and Buckland 1990). Because of this it is not practical to control salinity within the seep by continuous cropping of the recharge area. Thus, the most practical methods to control salinity are within the seep itself by providing artificial drainage and/or leaching water via irrigation, to reduce groundwater discharge and flush soil salts, respectively.

Soils at the study site are predominantly saline phases of Gleyed Brown Solodized Solonetz which suggests a long-term influence of groundwater and salinization (Agriculture Canada Expert Committee on Soil Survey 1987). Parent material consists of a sandy loam to clay fluvial-lacustrine veneer overlying 1.5-2.5 m of clay loam till, which in turn overlies interbedded layers of sandstone, shale and lignitic bedrock. Surficial geology and representative groundwater conditions are given in Fig. 1.

Site design and monitoring

In April, 1984, soil sampling was conducted on a 25-m grid within a 2.0 ha area of the seep (Fig. 2). Soil samples were taken at depth intervals of 0-0.15, 0.15-0.30, 0.30-0.60, 0.60-0.90 and 0.90-1.20 m. Sample holes were then deepened to 2.0 m and hydraulic conductivity was determined using the auger-hole method (van Beers 1983). Watertable wells were subsequently installed in each hole and watertable levels were monitored two or three times per week from May to October. Soil samples were analyzed to determine electrical conductivity (EC_e) and sodium adsorption ratio (SAR_e) of the saturation extract using standard methods (Rhoades 1982). Results of the watertable readings and soil analyses were used to determine the uniformity of salinity related features within the saline seep and to establish subsequently the locations of the treatments. Results of the hydraulic conductivity tests were used to determine subsurface drain spacing.

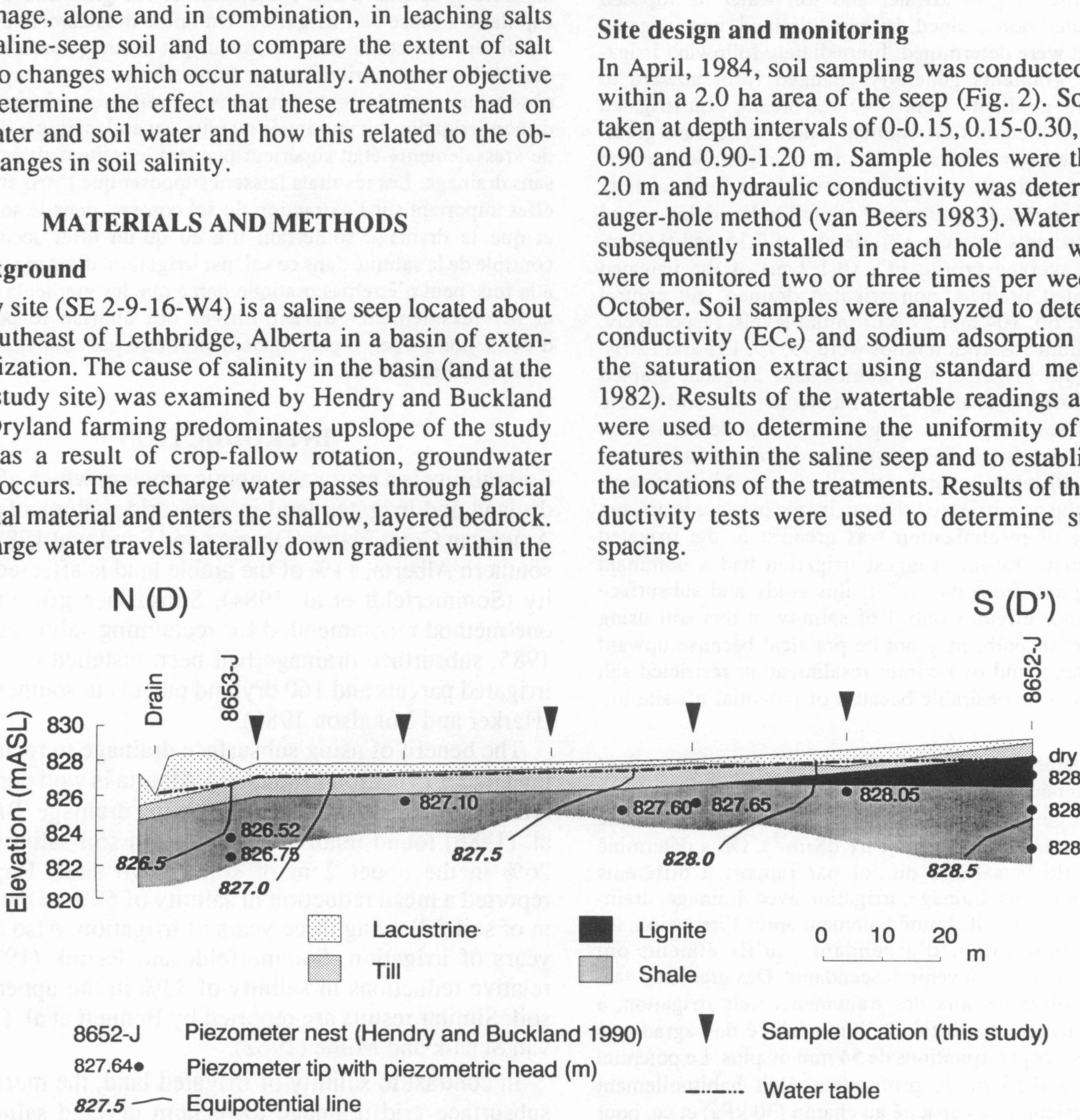

Fig. 1. Representative geology and groundwater flow at the study site. Location of cross-section is shown in Fig. 2. Data were obtained from this study and unpublished data of Hendry and Buckland (1990).

Subsurface drains (100-mm diameter corrugated polyethylene drain tubing wrapped with a polyester filter) were installed in December 1984, in two areas of the saline seep (Fig. 2). Three parallel drains were installed in each area at spacings of 12.5 m and at a depth of 1.2 m. The spacing of 12.5 m was determined from the Hooghoudt equation (Wesseling 1983) using a mean plot hydraulic conductivity of 0.13 $m \cdot d^{-1}$, a drainage coefficient of 3 $mm \cdot d^{-1}$ and a design watertable depth of 0.9 m. Two areas of the seep were left undrained. During 1985 a sprinkler irrigation system was constructed on a drained and undrained area of the seep (Fig. 2).

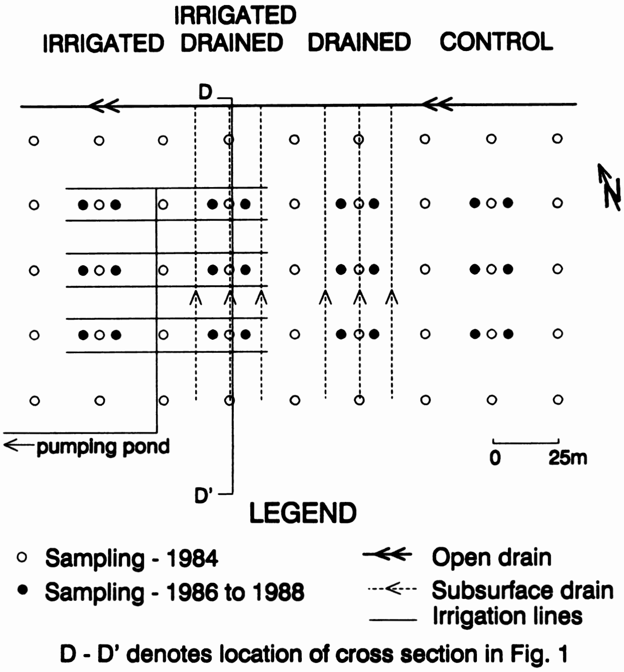

Fig. 2. Site plan.

Monitoring instrumentation was installed during 1985 at six locations within each of an irrigated non-drained (I), irrigated drained (ID), non-irrigated drained (D) and control (C) treatment (Fig. 2). Instrumentation at each location consisted of piezometers at 1.2- and 2.4-m depths, tensiometers at 0.15-, 0.30-, 0.60- and 0.90-m depths and a watertable well at 2.0-m depth. For the ID and D treatments, all instrumentation was installed at drain midspacing.

In May 1986, prior to irrigation, soil samples were collected at all monitoring locations at depths of 0-0.15, 0.15-0.30, 0.30-0.60, 0.60-0.90 and 0.90-1.20 m. Thereafter, soil samples were collected within a 0.5-m radius of the same locations and at the same depth increments following completion of irrigation in October 1986, 1987 and 1988 and before irrigation in May 1987 and 1988. Soil samples were analyzed to determine EC_e, soluble cations (Ca, Mg, Na, K), soluble anions (SO_4, Cl, HCO_3, CO_3) and SAR_e of the saturation extract using standard methods (Rhoades 1982).

Sprinkler irrigation was conducted from June through September during 1986, 1987 and 1988 for 5 or 6 hr per day and 2 or 3 days per week. Water applied by irrigation was measured with a 1.2-m diameter calibrated pan. Total irrigation applications are given in Table I. The irrigation water had an average EC of 0.3 $dS \cdot m^{-1}$ and SAR of 0.4.

Table I: Seasonal water budgets for periods between spring (May) and fall (Oct.) soil samplings

	1986	1987	1988
Rainfall (mm)	185	221	158
Irrigation (mm)	893	774	726
Class A Pan Evaporation (mm)	979	1232	1125
Pan Coefficient	0.54	0.53	0.52
ETp (mm)	527	647	585
Net Suplus/Deficit (mm)			
Irrigated	551	348	299
Dryland	–342	–426	–427

Evaporation was measured on site using a Class A pan. Potential evapotranspiration (ETp) was estimated using pan coefficients of Doorenbos and Pruitt (1977). Total wind run and relative humidity, which were required to determine pan coefficients, were obtained from daily records maintained in Lethbridge by Agriculture Canada. Rainfall was recorded on site. Pan evaporation, rainfall and ETp are given in Table I. Pan evaporation and ETp estimates are similar to those given by Foroud et al. (1989) for the area. Vegetation on the seep was salt tolerant and included Wild Barley (*Hordeum jubatum* L.), Kochia (*Kochia scoparia* (L.) Schrad.) and Red Samphire (*Salicornia rubra* A. Nels.), or the soil was bare.

Groundwater levels and soil matric potential were determined prior to and following irrigation. Drain outflow was determined during the irrigation season from the center drain of the ID and D treatments using a continuous recorder and calibrated V-notch weir. During the non-irrigation season drain outflow was determined with a bucket and stopwatch. Drain effluent samples were collected once or twice weekly from May to October and monthly thereafter. Effluent samples were analyzed for the same constituents and by the same methods as the soil samples. Total salt removal through the drains was determined from these measurements.

Statistical analyses

Statistical analyses were conducted on the 1984 EC_e data to determine the uniformity of salinity distribution within the seep in east to west and north to south directions. A oneway analysis of variance and modified least-significant difference test was used.

Salinity parameters (EC_e and SAR_e) for 1986 to 1988 soil samples were analyzed statistically using a t-test between mean differences as described by Jones and Matloff (1986). Comparisons were made between sampling dates within treatments, and among treatments for the May 1986 sampling only. Because of the large number of comparisons involved, mean differences are not shown and only means and standard errors are given.

RESULTS

Background salinity and watertable levels

The analysis of variance on the 1984 EC_e data indicated no significant differences in EC_e within the seep from an east to west direction, but did indicate a significantly (5% level) higher EC_e in the north part of the seep compared to the south (data not shown). Because of this, treatments were established in an east to west direction as shown in Fig. 2 and sampling within treatments was conducted in a north to south direction.

Results of background monitoring of the watertable prior to imposing the treatments (1984) are given in Fig. 3. All areas exhibited similar watertable levels and changes in levels. Average watertable levels for the four areas where treatments were subsequently established ranged from 0.44 to 0.79 m below ground.

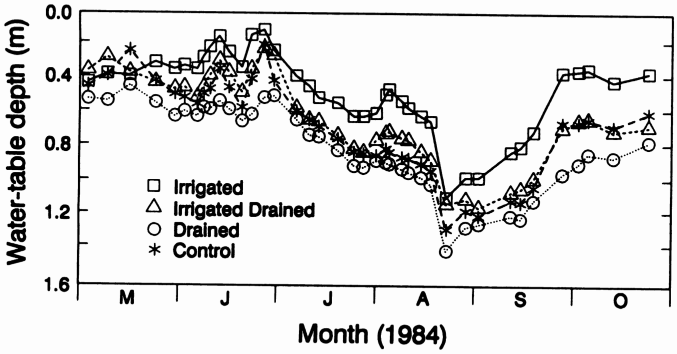

Fig. 3. Mean watertable fluctuations within the treatment areas during 1984, prior to imposing the treatments.

Groundwater response

Mean (n=6) monthly watertable depths for May to October, 1986 to 1988, are given in Fig. 4a. In May 1986 watertable levels were similar between the I and C treatments and were shallower than those of the ID and D treatments. From June to September the watertable was maintained at a relatively shallow depth in the I and ID treatments by irrigation (Fig. 4c). For the D and C treatments the water table receded from June to August in response to low rainfall and high ETp in 1986 and 1987. Subsequent rises in the watertable occurred during or immediately following the high rainfall months of September 1986 and August 1987. In June and July of 1988 the watertable in the C treatment remained relatively shallow (about 0.6-m deep) in response to high rainfall in June, while the watertable in the D treatment remained at a relatively constant depth of about 1.0 m.

Average monthly hydraulic gradients between the watertable and 2.4-m depth piezometers are given in Fig. 4b. The C treatment exhibited upward (discharge) gradients during the spring and summer months. Following the high rainfall month of September 1986, however, the average gradient reversed to downward (recharge). Gradients for the I and D treatments were upward for all months. Gradients for the ID treatment, however, were downward for the irrigation months of June to September 1986 and June 1987. The least negative gradients occurred in the I and ID treatments compared to the D and C treatments.

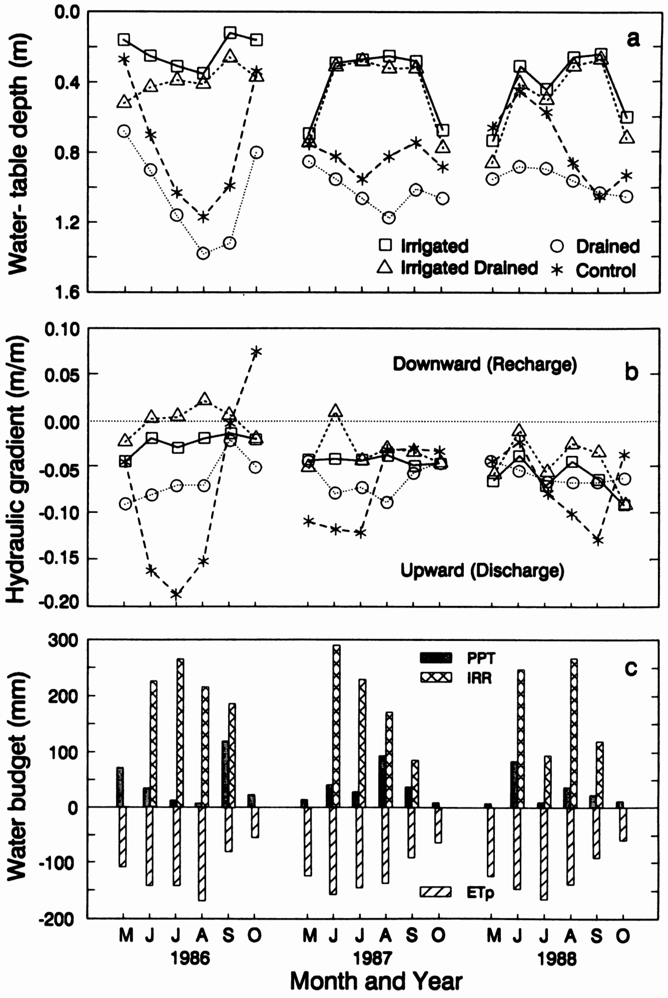

Fig. 4. Mean monthly average a) watertable depths, b) gradients between 2.4-m piezometers and the watertable, and c) water budget, for the four treatments.

Detailed watertable fluctuations for the May to October period were similar within treatments for all years. Data from 1987 are given in Fig. 5a as representative. During irrigation (June 2 to September 17) the I and ID watertables exhibited a cyclic rise-and-fall pattern according to post- and pre-irrigation readings. The watertable in the D and C treatments gradually declined throughout May to August, responding only slightly to rainfall events. A 54-mm rainfall on August 16 resulted in a sharp rise in the C watertable but resulted in only a slight and time-lagged rise in the D watertable.

Detailed vertical hydraulic gradients during 1987 for the I and ID treatments (Fig. 5b) also exhibited a cyclic pattern. Pre-irrigation gradients were generally upward while post-irrigation gradients were downward or less negative. Gradients in the C treatment were upward except following the 54-mm rainfall on August 16 which induced downward gradients. Downward gradients in the C treatment were also observed following a 59-mm rainfall in September, 1986 (data not shown). Gradients were upward within the D treatment.

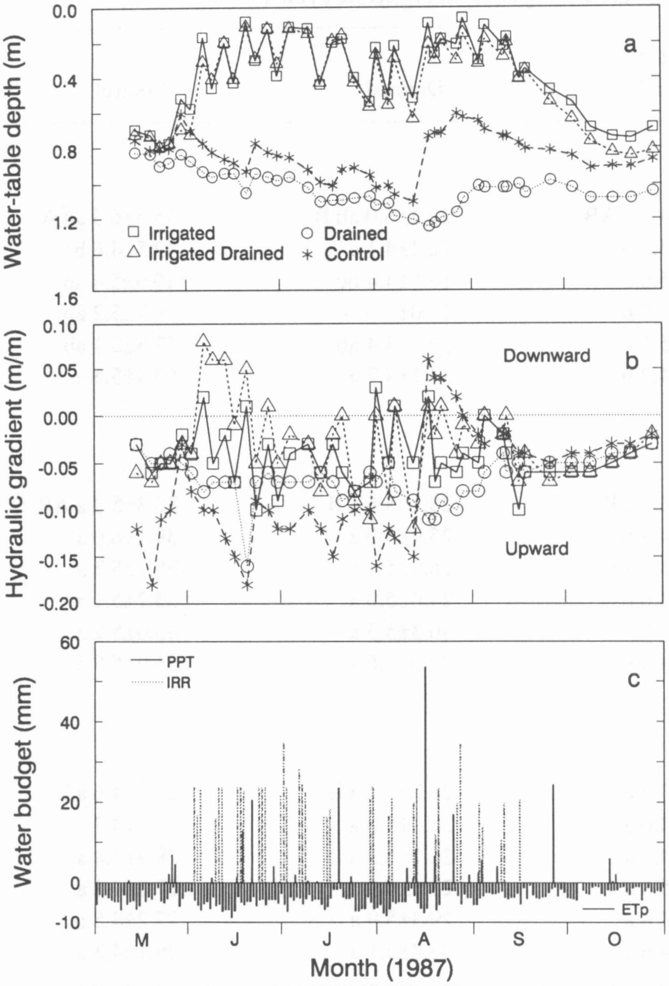

Fig. 5. Detailed a) watertable depths, b) gradients between 2.4-m piezometers and watertable, and c) daily water budget, for the four treatments during 1987.

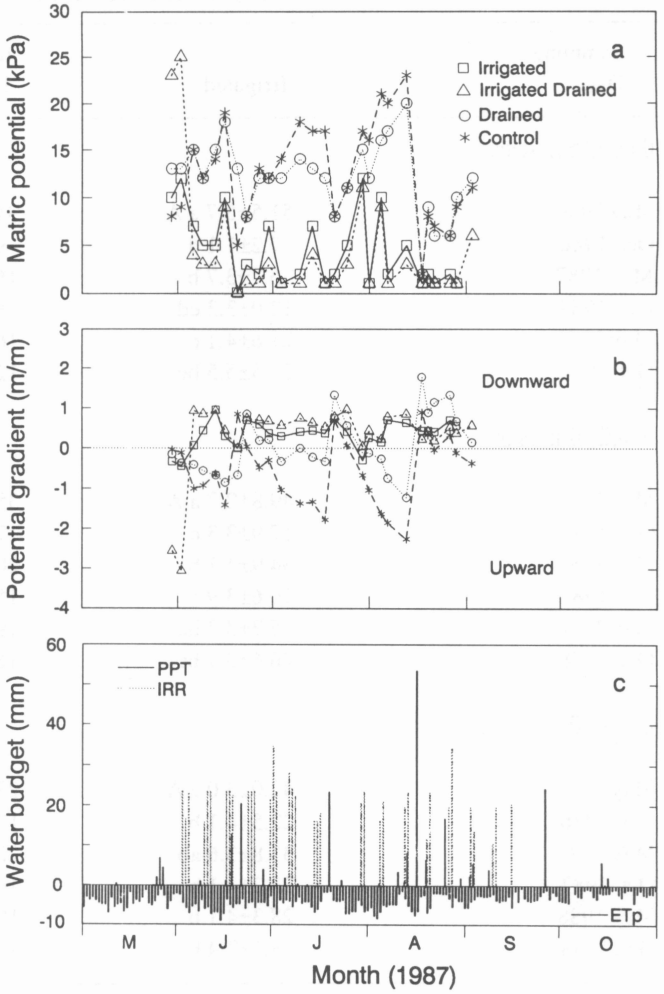

Fig. 6. Detailed a) soil-moisture tension at 0.15-m depth, b) tension gradients between 0.15 and 0.60 m, and c) daily water budget, for the four treatments during 1987.

Soil matric potential

Soil matric potential at a depth of 0.15 m and potential gradients between depths of 0.15 and 0.60 m, for the May to October period of 1987, are given in Fig. 6a and 6b, respectively. Soil matric potential at the 0.60-m depth, not shown, remained relatively constant. Therefore, changes in matric potential gradients usually reflected changes in soil matric potential at the 0.15-m depth. Assuming a matric potential of 30 kPa approximates field capacity, then all treatments had soil moisture contents at or above field capacity at a 0.15 m depth at all times (Fig. 6a).

During irrigation, matric potential in the I and ID treatments declined and followed a cyclic pattern (Fig. 6a), with lower matric potentials corresponding to post-irrigation and post-rainfall readings (Fig. 6c). During irrigation, matric potential gradients for the I and ID treatments were downward (Fig. 6b). This frequently occurred because the watertable rose above the 0.15-m depth (Fig. 5a). Matric potential gradients for the D and C treatments were usually upward but changed to downward following major rainfall events. The latter reflects lower soil matric potential at a depth of 0.15 m compared to 0.60 m, rather than a water-table rise above the 0.15 m-depth tensiometer (Fig. 5a).

Soil salinity

Mean EC_e levels during the 1986 to 1988 period are given in Table II. In the May 1986 sampling, EC_e in the 0 to 0.15-m depth was significantly higher in the I and C treatments than in the D treatment. Differences between treatments, however, became less apparent with depth. When salinity of the upper 1.2 m of soil was considered, only the I treatment EC_e levels were significantly different from the other treatments.

Within the I treatment, EC_e was significantly lower at all depth intervals following completion of irrigation in October 1988 compared to pre-irrigation EC_e in May 1986. In the ID treatment, EC_e was significantly lower in the upper 0.6 m of soil following the three years of irrigation. There was a tendency for both the I and ID treatments to resalinize between fall and spring soil sampling but this was significant only in the I treatment.

In the 0 to 0.15-m depth of the D and C treatments, EC_e was significantly lower in October 1986 compared to May

Table II: Soil salinity (EC_e, dS•m^{-1}) for the four treatments over three yearly irrigation cycles

Sampling Date	Irrigated	Irrigated Drained	Drained	Control
0 to 0.15-m depth				
May 1986	51.5±5.7 a A	34.9±4.8 a AB	21.3±6.0 ab B	45.5±6.5 ab A
Oct. 1986	7.2±1.1 d	9.4±3.2 b	12.4±4.1 c	32.5±4.6 b
May 1987	35.7±3.7 b	16.9±5.6 b	16.6±4.4 bc	40.0±5.4 ab
Oct. 1987	12.0±3.3 cd	8.0±2.8 b	17.0±5.0 bc	36.7±5.2 ab
May 1988	21.6±4.1 c	16.4±5.1 b	29.5±5.4 ab	43.3±5.1 ab
Oct. 1988	24.5±5.5 bc	12.9±4.2 b	33.1±4.7 a	50.4±5.5 a
0 to 0.60-m depth				
May 1986	49.8±2.7 a A	35.3±3.7 a B	28.1±5.6 a B	38.3±5.9 a AB
Oct. 1986	17.9±3.3 c	17.9±4.9 b	25.9±5.0 a	39.1±6.0 a
May 1987	34.9±4.1 b	20.7±5.8 ab	26.0±5.0 a	35.7±5.3 a
Oct. 1987	20.6±3.9 c	15.2±4.6 b	24.6±5.0 a	33.7±5.1 a
May 1988	25.7±3.3 bc	19.5±5.0 b	30.3±5.5 a	33.0±5.2 a
Oct. 1988	26.6±3.7 bc	16.1±4.4 b	29.6±4.6 a	36.9±5.5 a
0 to 1.20-m depth				
May 1986	42.0±3.0 a A	28.0±3.5 a B	25.7±5.4 a B	29.3±4.6 a B
Oct. 1986	22.5±4.1 b	17.8±4.0 a	24.0±5.0 a	31.9±4.7 a
May 1987	31.8±3.6 ab	20.0±4.7 a	26.1±5.2 a	28.2±4.4 a
Oct. 1987	24.2±4.1 b	16.6±5.0 a	23.6±4.9 a	27.2±4.2 a
May 1988	28.3±4.1 b	19.5±4.8 a	29.3±5.9 a	27.2±4.5 a
Oct. 1988	28.1±3.4 b	16.9±4.6 a	26.8±5.1 a	29.1±4.3 a

Values are means ± standard error, n = 6.

a-d Treatment means within columns followed by the same letter do not differ significantly (5% level) as determined using mean-difference t-tests.

A,B Means within rows (May 1986 only) followed by the same letter do not differ significantly (5% level) as determined using mean-difference t-tests.

1986. By completion of the study in October 1988, EC_e was higher, but not significantly so, in the surface 0.15 m of soil. There was little change in EC_e of the D or C treatments in the 0 to 1.2-m soil depth over the three years.

Because of the initial differences in EC_e among the treatments (May 1986 sampling), comparisons among treatments are given in Fig. 7a-c on a relative basis (ie: EC/EC_o, where EC_o represents the May 1986 soil sampling and EC represents subsequent samplings). This was done because relative salt removal from soil is independent of the initial salinity level (Harker and Mikalson 1990).

Both the I and ID treatments had similar relative changes in soil salinity (Fig. 7a-c) and the greatest reductions occurred following the first year of leaching. Likewise, the D and C treatments exhibited similar relative changes except the surface 0 to 0.15-m depth of the D treatment salinized more so than the C treatment through 1988. In October 1988 relative salinity in the upper 1.2 m of soil was 67, 60, 104 and 99% of original levels, respectively, for the I, ID, D and C treatments.

Changes in SAR_e (Table III, Fig. 7d-f) were similar to those observed for EC_e with the following exceptions. In the I and ID treatments, reductions in SAR_e occurred concurrently with reductions in EC_e but to a lesser degree. Where increases in EC_e occurred, SAR_e also increased, but usually to a greater degree. For the D and C treatments, SAR_e frequently increased while EC_e decreased, remained constant or increased slightly. The trend towards increasing SAR_e was significant only in the surface soil of the D and C treatments. Following the three years, the relative SAR_e of the 1.2 m of soil was 79, 79, 131 and 120%, respectively, for the I, ID, D and C treatments.

An approximate salt balance was done by determining the additions and removals of salt from the treatments. Over the three years, net salt removal from the 1.2-m soil profile in the I, ID and C treatments was 195, 174 and 44 t•ha^{-1}, respectively (Table IV). For the D treatment 8 t•ha^{-1} of salt

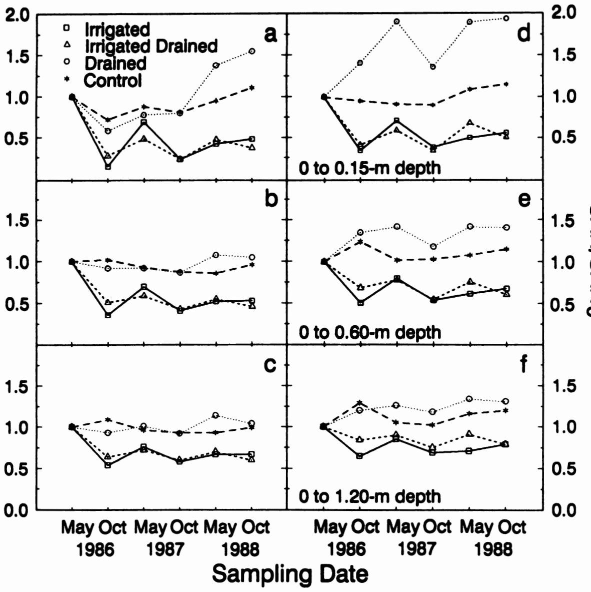

Fig. 7. Relative changes in a-c) soil salinity (EC/EC$_o$) and d-f) soil sodicity (SAR/SAR$_o$) for increasing cumulative soil depths for the four treatments.

accumulated in the soil despite the removal of about 44 t•ha^{-1} of salt in drainage effluent. Most of the salt removed from the soil of the ID treatment, including that added in the irrigation water, was recovered in the 180 t•ha^{-1} of salt in the drain effluent. The above calculations of salt removal from the soil are based on differences in the total dissolved salt content of the saturation extracts between May 1986 and October 1988, and assume an average soil bulk density of 1.4 Mg•m^{-3} in the 1.2-m soil profile. Because of differences in saturation percentage and ionic composition of the saturation extracts, results for salt removal from the soil may differ slightly from results based on EC$_e$ measurements (Table II and Fig. 7a-c).

DISCUSSION

The similarity in both the relative and absolute salt removal between the I and ID treatments, and between the D and C treatments, suggests that irrigation had the greatest influence in removing salt from this soil compared to subsurface drainage. Changes in hydraulic gradients from upward to downward (or less negative) following irrigation likely caused the extent of leaching observed. Thus, irrigation modified both the watertable levels and potential direction of shallow groundwater flow in this saline-seep soil.

Relative salt removal in the I and ID treatments is similar to that reported in previous studies (van Schaik and Milne 1962; Sommerfeldt and Paziuk 1975; Bennett et al. 1982). Salt removal was greatest during the first year of leaching and diminished in subsequent years, likely because irrigation applications were progressively lower from 1986 to 1988. Although this resulted in a progressively deeper watertable, the downward hydraulic gradients decreased and this restricted leaching.

Irrigation performed equally as well in removing salts with or without drainage. This could have occurred either because of failure of the drainage system in the ID treatment or because of better natural drainage in the I treatment. We have no evidence to suggest the subsurface drainage was not performing as designed in the ID treatment. The similarity in water-table levels during 1984 and in hydraulic gradients from 1986 to 1988 suggests equal internal drainage among the I and ID treatments. We offer the following explanation. Irrigation of a small area without drainage would cause a groundwater mound to develop beneath the I treatment. This would result in horizontal watertable gradients and subsequent lateral flow of water and salt towards the adjacent buffer areas. Monitoring of watertable wells in the buffer area adjacent to the I treatment revealed lateral watertable gradients of 0.02 to 0.03 from the I treatment (data not shown). The horizontal hydraulic conductivities, from auger-hole tests, were 0.048 and 0.027 m•d^{-1} for the I and ID treatments, respectively. Thus, lateral flow from the I treatment would be slightly greater than in the ID treatment, which could also account for the similar rate-of-fall of the watertable between the I and ID treatments following irrigation. We also observed evidence of increasing salinity adjacent to the I treatment, in the form of increased salt crust, which supports lateral flow of salts. Had a larger (field) area been irrigated without the benefit of subsurface drainage then perhaps less salt removal would have occurred in the I treatment because lateral gradients would be diminished.

Salt removal in the D and C treatments occurred to a limited degree in the surface 0.15 m of soil in 1986 despite average watertables about 1.0 m in depth and upward gradients from piezometers and tensiometers. Both the shallow watertable and upward gradients would normally be interpreted to indicate the potential for continued salinization. The slight salt removal likely resulted from the extended dry periods which allowed recession of the watertable, followed by short periods of high rainfall, which leached salts. The presence of downward gradients following the periods of high rainfall in 1986 and 1987 in the C treatment supports this interpretation.

The watertable was lower in the D treatment, compared to the C treatment, but the extent of salt removal was also lower. This is contrary to expectations and might be due to several factors. First, the average hydraulic conductivity in the C treatment (0.222 m•d^{-1}) was considerably higher than in the D treatment (0.068 m•d^{-1}) and this would allow more rapid lateral migration of water and salt from the C area. Also, upward gradients persisted at all times in the D treatment and this could have restricted leaching. The drains in the D treatment were also placed at relatively shallow depth (1.2 m) and this may have also contributed to restricted leaching.

Resalinization of the upper soil was observed during the non-irrigated season in all treatments over at least one year of this study, and was most pronounced in the I and ID treatments. Salt accumulation can be attributed to capillary rise of water in response to evapotranspiration or in response to the soil freezing. Both mechanisms of water and salt accumulation are reported in Alberta (van Schaik and Rapp 1970; Fullerton and Pawluk 1987) and they would be accentuated under the moist to wet soil conditions which resulted from irrigation. Some salts originated from the irrigation water but this amounted to less than 3% of the total salt

Table III: Soil sodicity (SAR_e) for the four treatments over three yearly irrigation cycles

Sampling Date	Irrigated	Irrigated Drained	Drained	Control
0 to 0.15-m depth				
May 1986	42.5±4.8 a A	35.9±3.8 a A	21.8±4.5 b B	49.1±11.3 b A
Oct. 1986	14.4±1.9 ab	14.9±3.2 b	30.9±14.8 ab	46.5±11.7ab
May 1987	30.5±2.6 b	21.1±5.0 b	41.6±17.5 ab	44.7±8.8 ab
Oct. 1987	16.2±2.8 bc	12.1±3.7 b	29.7±9.9 a	44.0±7.9 ab
May 1988	21.4±3.2 bc	24.5±5.8 ab	41.2±11.4 a	53.6±9.2 ab
Oct. 1988	23.9±3.3 bc	17.8±5.9 b	42.1±6.2 a	56.7±8.8 a
0 to 0.60-m depth				
May 1986	36.9±2.2 a A	32.6±2.1 a AB	24.1±3.7 a B	37.5±6.6 a AB
Oct. 1986	19.0±3.2 c	22.5±5.3 b	32.6±9.7 a	46.4±9.4 a
May 1987	29.5±2.6 ab	25.3±5.3 ab	34.2±9.5 a	38.2±5.4 a
Oct. 1987	20.1±2.6 c	18.0±4.6 b	28.6±6.4 a	38.5±4.6 a
May 1988	22.8±1.5 c	24.7±5.8 ab	34.4±7.8 a	40.3±5.9 a
Oct. 1988	25.2±2.3 bc	20.0±5.8 b	34.0±5.1 a	43.1±6.3 a
0 to 1.20-m depth				
May 1986	32.7±1.6 a A	26.8±1.7 a B	22.6±3.4 a B	29.1±4.1 a AB
Oct. 1986	21.2±2.6 b	22.5±3.0 a	27.1±6.0 a	37.6±6.0 a
May 1987	27.8±1.9 ab	24.0±2.6 a	28.4±6.0 a	30.7±3.5 a
Oct. 1987	22.5±2.3 b	20.2±2.5 a	26.6±5.2 a	29.7±3.4 a
May 1988	23.1±1.4 b	24.5±3.8 a	30.3±6.3 a	33.7±4.3 a
Oct. 1988	25.8±1.6 b	21.1±3.8 a	29.7±4.5 a	35.0±4.5 a

Values are means ± standard error, n = 6.

a-c Treatment means within columns followed by the same letter do not differ significantly (5% level) as determined using mean-difference t-tests.

A,B Means within rows (May 1986 only) followed by the same letter do not differ significantly (5% level) as determined using mean-difference t-tests.

Table IV: Approximate salt balance (t•ha^{-1}) for the four treatments

	Treatment			
Source	Irrigated	Irrigated Drained	Drained	Control
Salt Additions				
Irrigation Water	5.0	5.0	–	–
Rainfall	0.2	0.2	0.2	0.2
Salt Removals				
Soil†	195.4	174.0	–8.0‡	44.4
Drains	–	180.0	43.9	–

†1.2-m soil profile, determined as difference in total dissolved solid content of saturation paste extracts between May 1986 and October 1988 samplings.

‡Negative value indicates an accumulation of salts.

removed from the soil in the I and ID treatments. Long-term studies in the region have not observed salt accumulation from irrigation water (Chang and Oosterveld 1981).

It is unlikely that either irrigation or drainage or both can be used to effectively reclaim this soil in the short term. In the laboratory, Harker and Mikalson (1990) found that salt removal from this soil may be limited by a low hydraulic conductivity. Our study suggests that upward groundwater gradients and overwinter resalinization will further limit salt removal. Salinity control might be achievable in the long term with either drainage and/or irrigation; however, both alternatives are probably not feasible because of high costs of irrigation and drainage development and the likelihood of low production returns.

Irrigation of this saline soil, in the absence of drainage, may have detrimental long-term effects on adjacent land. Salts removed from the I treatment may have moved laterally and resulted in salinization of adjacent land.

Sommerfeldt and Paziuk (1975) also irrigated and drained a saline soil of lower salinity for three years at a site about 3 km away in the same basin. They achieved reclamation of the soil with a net salt removal of 11.2 t•ha^{-1}. This is about 6% of the salt load of 180 t•ha^{-1} observed in the ID treatment of this study. Thus, drainage of this high salinity soil may also have off-site impacts when the saline drainage effluent is discharged into surface-water courses. The tendency of the soil to resalinize over winter also suggests that high salt loading would continue in future years.

SUMMARY AND CONCLUSIONS

Salt removal and groundwater and soil-water response to irrigation and/or drainage were determined in a saline-seep soil. More salt was removed, and salt removal occurred to greater depths, in I and ID treatments compared to D and C treatments. Salt removal in the I and ID treatments was related to changes in groundwater gradients from upward to downward as manipulated by irrigation. Salt removal in the C and D treatments occurred in certain years despite the presence of a shallow watertable and upward groundwater gradients. This salt removal also appeared to be related to changes in groundwater gradients from upward to downward which followed periods of high rainfall.

Salt removal in the I and ID treatments was greatest in the first year and diminished in subsequent years. After three years, salinity in the upper 1.2 m of soil was similar for the I and ID treatment and was about 60 to 65% of original levels. For the D and C treatments salinity in the upper 1.2 m of soil remained essentially unchanged after three years but sodicity increased significantly in the upper 0.15 m of soil. Salt leached from the ID treatment, which was about 180 t•ha^{-1}, could pose an environmental hazard to surface-water courses. For the I treatment, salt removed from the soil was about 194 t•ha^{-1} and may have moved laterally outside the irrigated area and resulted in off-site salinization. Reclamation of this soil does not appear to be practical or desirable.

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