DRAINAGE AND IRRIGATION MANAGEMENT FOR CANAL SEEPAGE CONTROL AND LAND RECLAMATION

by

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ABSTRACT

Deep interceptor drains are commonly used to control canal seepage in southern Alberta, Canada. Recently, shallow grid drainage was introduced. A study was initiated in 1987 to assess the effectiveness of grid drainage to intercept canal and natural groundwater seepage and reclaim the resulting saline affected land.

Using a groundwater flow model, MODFLOW, it was found that a single deep interceptor drain would have failed to intercept all canal seepage and maintain the water table downslope of the canal below the 1.0 m design water table depth. Conversely, simulations indicated that with a grid drainage system, all canal and natural groundwater seepage would be intercepted and the water table would remain below the design water table depth, with or without irrigation recharge that would maintain a steady state salt balance.

Field data showed that the water table generally remained below the 1.0 m design water table depth with grid drainage. Exceptions were found in a severely salt affected area near the canal where the water table remained above the design water table depth most of the time. This occurred because drain spacing was too wide at this location and the flow to the drains was restricted, possibly, because of smearing of the trench during drain installation.

The benefits of fall irrigation were demonstrated using three test plots near the canal. Under center pivot irrigation management common to southern Alberta, no significant reclamation was achieved over a fourteen month period. When additional fall irrigation (374 mm) was applied, EC_e and SAR_e of the upper 0.30 m of the soil were reduced by 18 and 13%, respectively. One major limitation to fall irrigation was insufficient internal drainage.

RESUME

Dans le sud de la province de l'Alberta, Canada, les drains intercepteurs profonds sont communément utilisés pour intercepter le suintement provenant des canaux d'irrigation. Récemment, un réseau de drainage souterrain conventionnel a été utilisé à cette fin. A l'automne 1987, une étude a été entreprise afin de déterminer l'efficacité d'un reseau de drainage souterrain conventionnel pour l'interception du suintement aux abords des canaux d'irrigation et la réhabilitation des terres salines affectées par ce suintement.

Le modèle informatique MODFLOW a été utilisé pour simuler le régime des eaux souterraines aux abords du canal. Les résultats indiquèrent qu'un drain intercepteur profond n'intercepterait pas la totalité du suintement provenant du canal. Il fut aussi démontré que la nappe phréatique en aval du drain intercepteur profond demeurerait, de façon générale, trop pres de la surface du sol. Par contre, il fut démontré, à partir de ces simulations, qu'un système de drainage souterrain conventionnel intercepterait la totalite du suintement originant du canal et qu'une partie du suintement naturel serait aussi interceptée. De façon générale, ces mêmes simulations indiquèrent qu'avec un système de drainage souterrain conventionnel, la nappe phréatique demeurerait suffisamment profonde.

Les données recueillies sur l'ensemble de la superficie drainée avec un système de drainage conventionnel (44 ha) démontrèrent que la nappe phréatique était généralement sous la profondeur de design de 1.0 m. Le drainage n'était insuffisant qu'aux abords du canal où les problèmes de salinité étaient plus sévères. D'après les donnees de conductivité hydraulique recueillies près du canal, l'espacement actuel des drains était trop distant à cet endroit. De plus, il appert possible qu'il y ait eu lissage des parois de

la tranchée lors de l'installation des drains avec la charrue taupe, ce qui entrainerait l'obstruction de l'écoulement des eaux vers les drains.

Des essais d'irrigation automnale réalisés entre septembre 1987 et octobre 1988 ont démontré l'avantage de cette technique. Aucune réhabilitation significative a été observée au niveau des deux parcelles soumises à un régime conventionnel d'irrigation par pivot central. Au contraire, lorsqu'une quantité additionnelle d'eau (374 mm) était appliquée par irrigation automnale intensive, EC_e et SAR_e des premiers 0.30 m du profile du sol chutèrent de 18% et 13% respectivement pendant les 14 mois de l'étude. Une des principales restrictions à l'irrigation automnale intensive était le manque de drainage interne.

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A	Empirical factor.
B	Top width of the water surface in the canal.
cm	Centimetre.
C	Volume of water lost through the wetted perimeter of the canal prism or actual salt concentration.
C_1	Salt concentration of the irrigation water.
C_o	Initial salt concentration.
^oC	Degrees Celsius.
C.O.	Canal opening.
Coll.	Collector.
d	Depth of impermeable barrier below drain centre.
d_e	Hooghoudt's equivalent depth.
d_l	Depth of irrigation water for leaching.
d_s	Depth of soil.
$dS\ m^{-1}$	Decisiemens per metre.
Dia.	Diameter
DWD	Design water table depth.
D_1	Depth of water in the canal.
D_2	Half the sum of the distances between: 1) the barrier and the water surface in the canal; and 2) the barrier and the required water table depth at the edge of the irrigated area.
E	East.
EC_a	Bulk soil electrical conductivity.
EC_{dw}	Electrical conductivity of the drainage water.
EC_e	Electrical conductivity of the saturation extract.
$\overline{EC_e}$	Average electrical conductivity of the root zone saturated extract after leaching.
EC_{gw}	Electrical conductivity of the groundwater.
EC_{iw}	Electrical conductivity of the irrigation water or electrical conductivity of the irrigation water including effective precipitation.
EC_o	Initial electrical conductivity.
Erfc	Mathematical function.

f	Drainable porosity or specific yield.
Fig.	Figure.
FIR	Final infiltration rate.
FSL	Full service level.
GHB	General Head Boundary.
h	Height of water table above drain centre at drain mid-spacing.
ha	Hectare.
hs	Difference in elevation between the selected root zone depth at the edge of the irrigated field and the water surface in the canal.
H	Water table height above the canal bed at a distance X from the canal centre line.
H_o	Abrupt change in canal full service level at t=0.
I#	Infiltration rate #.
Irr.	Irrigation.
ID	Inside diameter.
k	Leaching constant.
kg	Kilogram.
km	Kilometres.
K	Hydraulic conductivity.
K_a	Hydraulic conductivity above drain centre.
K_b	Hydraulic conductivity below drain centre.
K_y	Horizontal hydraulic conductivity.
K_z	Vertical hydraulic conductivity.
K_1	Hydraulic conductivity of soil material adjacent to canal section.
K_2	Weighted hydraulic conductivity between root zone depth and barrier.
l	Litres.
L	Length of the canal.
L'	Drain spacing.
LF	Leaching fraction.
LSD	Least significant difference.
m	Metres.
meq	Milliequivalents.

mm	Millimetres.
min.	Minutes.
N	North.
N.P.	Non perforated.
N/A	Not applicable or not available.
%	Percent.
piezo.	Piezometer.
Prob	Probability.
PVC	Polyvinyl chloride.
q_s	Drainage coefficient.
q_p	Drain outflow.
Q	Canal flow rate.
Q_1	Volumetric seepage rate per unit length of canal.
Q_2	Terminal volumetric seepage rate per unit length of canal.
Q_3	Additional capacity needed in the first drain (deep interceptor) due to canal seepage.
r	Drain radius.
s	Canal seepage loss per km of canal in percent or time in seconds.
Seas.	Season.
S	Volumetric canal seepage loss.
SAR_e	Sodium adsorption ratio of the saturation extract.
SAR_o	Initial sodium adsorption ratio of the saturation extract.
SD	Standard deviation.
SDF	Standard deviation factor.
SMRID	St. Mary River Irrigation District.
t	Time since the canal full service level was abruptly changed or time or student's t-value for statistics (t-test).
t^o	Temperature or average annual temperature of the region.
T	Transmissivity of the phreatic aquifer, which is equal to K_y times the aquifer thickness.
UC	Uniformity coefficient.

USBR	United States Bureau of Reclamation.
V	Mean velocity of flow.
V_{dw}	Total volume of drainage water.
V_{sd}	Total volume of soil drained.
w	Empirical factor.
WTW	Water table well.
X	Distance from the canal centre line or distance between canal centre line and the edge of the irrigated area.
Y	Critical water table depth.
yr	Year.
Z	Depth of impermeable barrier below ground surface.
θ	Soil volumetric water content.

1. INTRODUCTION

In the province of Alberta, only 4% of the arable land is irrigated, but it produces 20% of the agricultural output. Of this, an estimated 20 to 30% of the irrigated land is reported to be affected by salinity and waterlogging, with at least 70% attributable to canal seepage (Alberta Agriculture, 1985). Thus, there are potential benefits to be gained from controlling canal seepage.

Deep interceptor drains are commonly used to control seepage from large irrigation canals. Typically, 150 to 300 mm diameter clay tile or perforated polyethylene tubing is placed adjacent to the canal at depths varying from 2 to 4 m below ground. A gravel chimney is placed above the drain to prevent seepage from bridging over the drain (Figure 1).

Shallow grid drainage involves placing a series of parallel, regularly spaced 100 mm diameter flexible, corrugated, polyethylene tubes throughout the saline/waterlogged areas downslope of the canal at depths of 1.0 to 1.8 m (Figure 2). The use of subsurface drainage to control seepage adjacent to large irrigation canals is not extensively used in Alberta. In theory, grid drainage should be superior to deep interceptor drainage since it has the added advantage of controlling canal seepage while providing a sink for leaching water, thereby accelerating reclamation.

The standard method of irrigation scheduling, replenishing of consumptive use at a specified moisture depletion level, was found to be inadequate to cause leaching of salts during the growing season at a site where canal seepage was controlled by a deep interceptor drain (McMullin et al., 1983). However, these researchers found that during the fall season, when evapotranspiration is minimal, irrigation may result in significant reclamation. Further

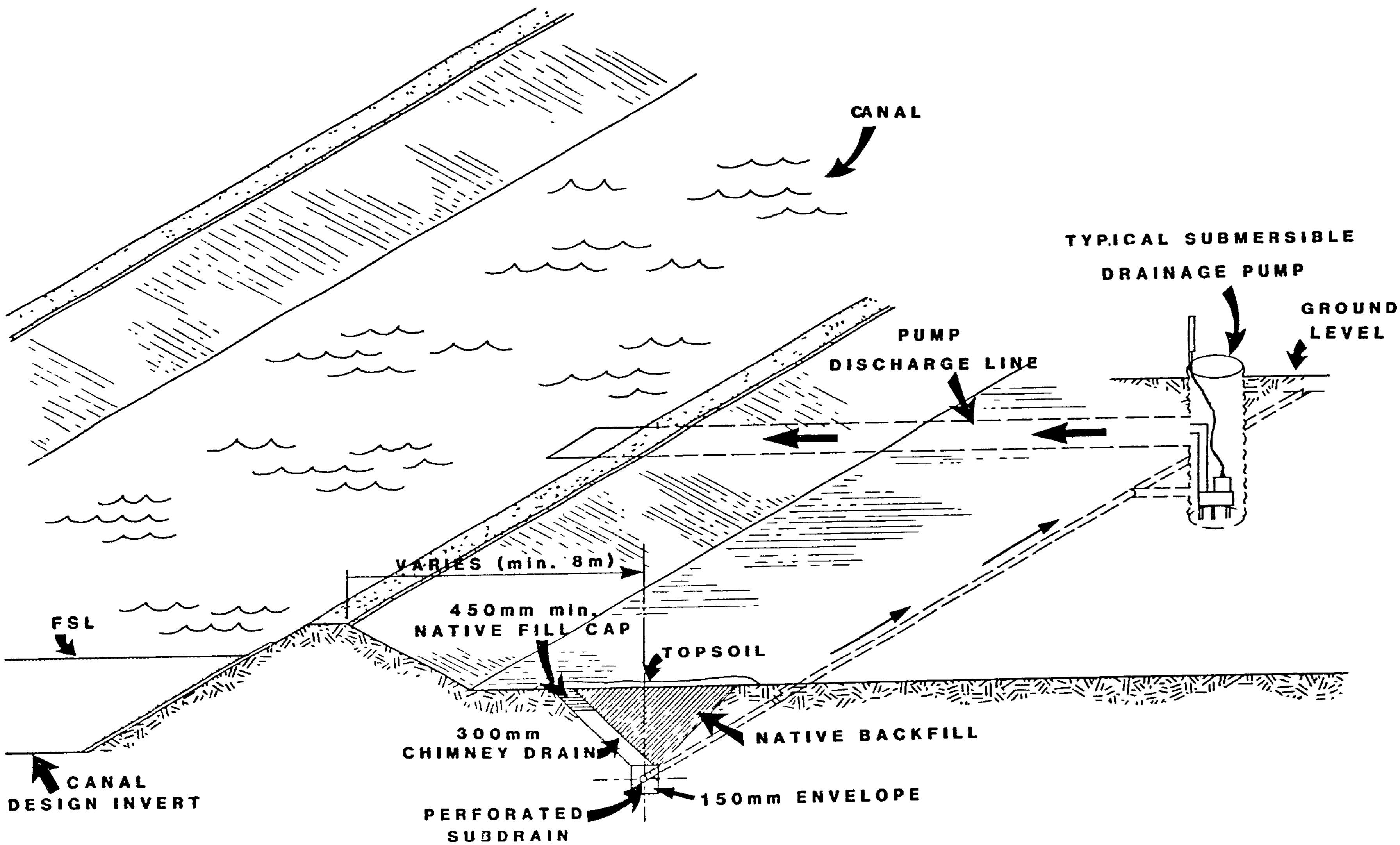

Fig. 1. Canal seepage control using deep interceptor drainage.

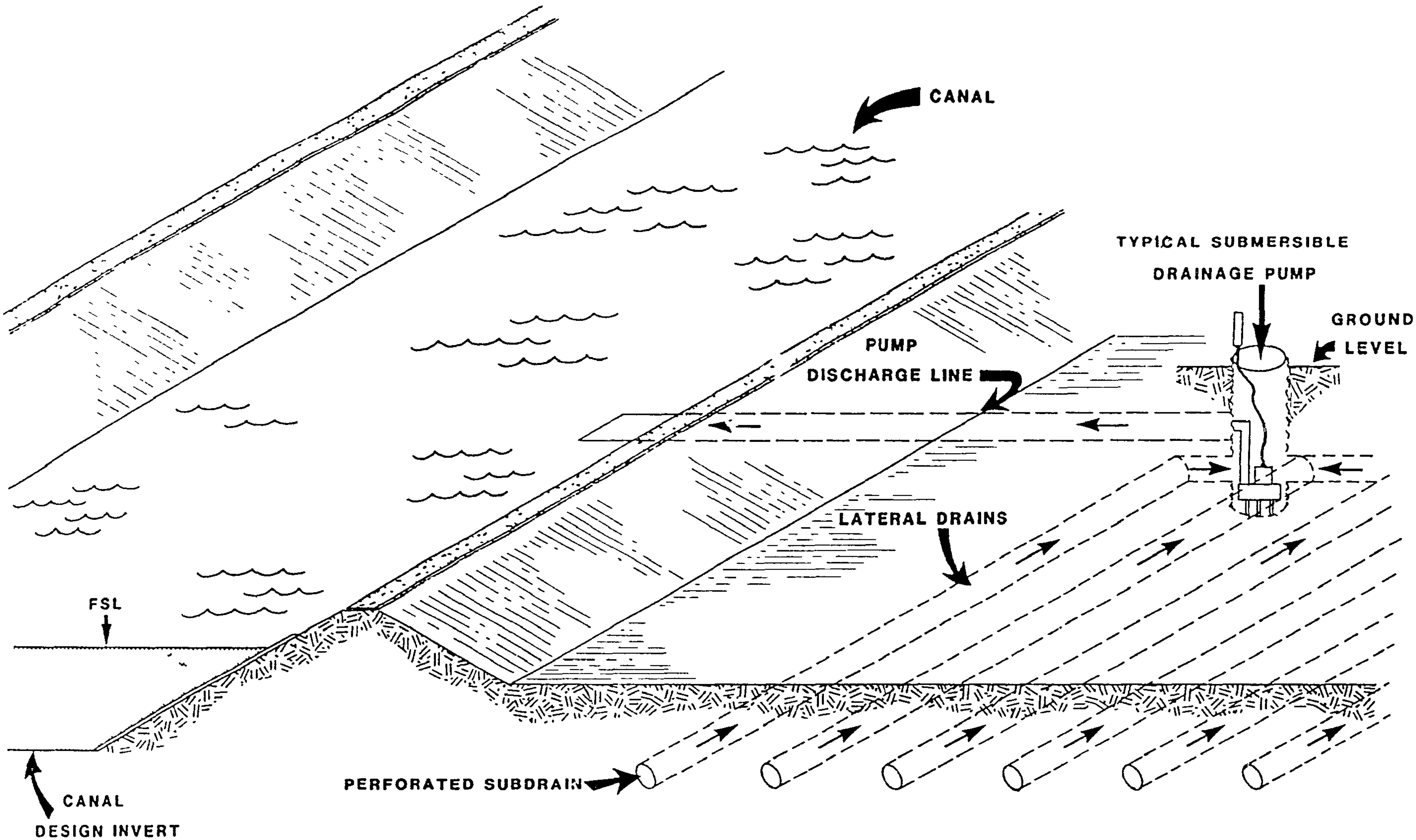

Fig. 2. Canal seepage control using grid drainage.

findings suggested, however, that because of the lack of drainage, the rise in the water table caused by fall irrigation may result in further soil salinization.

Thus, there may be a net advantage in using grid drainage in conjunction with fall irrigation to control canal seepage and reclaim salt affected lands.

1.1 Objectives

The objectives of this study were to:

1) Determine and understand the hydrogeologic features of a grid drained canal seepage and salt affected area by:
   - determining the geologic features of the area.
   - measuring actual drain outflows, water table heights and piezometric heads.
   - modelling the groundwater flow regime using a finite difference groundwater flow model (MODFLOW), with and without canal seepage control measures, and irrigation recharge to simulate leaching of salts.

2) Determine the effectiveness of grid drainage to control canal and natural groundwater seepage by:
   - measuring actual drain outflows and water table elevations at three test plots.

3) Verify the effectiveness of fall irrigation in conjunction with grid drainage to reclaim canal seepage salt affected land by:

- performing intensive fall irrigation at a test plot and measuring pertinent soil and water quality parameters to verify the reclamation process.
- compare soil and water quality parameters obtained from an intensely fall irrigated soil to those obtained from two plots under normal centre pivot irrigation management.

4) Recommend reclamation management methods for canal seepage control and reclamation.

1.2 Scope

Although several methods exist to control or intercept canal seepage (canal lining, canal rehabilitation, deep interceptor drainage, grid drainage, pump wells, etc.) the scope of this study was limited to drainage techniques, specifically, deep interceptor drainage and grid drainage.

Field data were obtained under a cold, semi-arid continental climate. The experimental site was under the influence of the Chinook wind which is a strong warm and dry westerly wind causing major temperature fluctuations, particularly during winter. Results apply to a dense clay loam till ($K < 0.05$ m day^{-1}) underlain by a permeable pressurized coal aquifer at a depth of 6 m, which in turn overlies sedimentary mudstone. Salinity data pertained to saline soils dominated by sulphate salts and may not apply to soils dominated by chlorides.

2. LITERATURE REVIEW

2.1 Soil salinization in southern Alberta

2.1.1 The origin of soils

The landscape of Alberta is generally the result of the Wisconsin glaciation, which was the last of the four glaciation events occurring during the Pleistocene Epoch (Acton and Crosson, 1978). As a result of the ice retreat some 15,000 years ago, virtually all of Alberta is covered by a veneer of undulating glacier deposits, ranging in thickness from a few to over one hundred meters (Pohjakas, 1982).

Glacial till is the most extensive geologic parent material. Till comprises approximately 70 percent of the surface deposits. Large areas of lacustrine sediments as well as deposits of fluvial and aeolian materials have also been reported (Pawluk and Bayrock, 1969).

A dominant characteristic of the irrigated soils in southern Alberta is that they are often underlain by glacial till, often within 1.0 m of the ground surface (Paterson, 1983). Shallow tills may impede the vertical movement of water (Bennett et al., 1982).

2.1.2 The nature and origin of soluble salts

The northern interior plains of North America are among the largest sulfate rich land areas in the world (Hendry et al., 1986). Sulfates frequently cause much of the groundwater to be unsuitable for domestic and agricultural use. Sodium sulfate salts in the soils of the North American plains have reportedly caused about 4% of the arable land to be unproductive. Sulfate salts are dominant in Saskatchewan (Henry et al., 1987) and Alberta (Pohjakas, 1982). The solubility of various salts is shown in Table 1. Data indicate that the solubility of sulfates is generally lower than that of chlorides.

Table 1. Solubility of salts in pure water at 20° Celsius (After Henry et al., 1987).

Salt	Chemical formula	Solubility (grams l^{-1})
Sodium sulfate	Na_2SO_4	160
Magnesium sulfate	$MgSO_4$	300
Calcium sulfate	$CaSO_4$	2
Sodium chloride	NaCl	264
Magnesium chloride	$MgCl_2$	353
Calcium chloride	$CaCl_2$	427
Calcium carbonate	$CaCO_3$	0.01

Bresler et al. (1982) identified three different natural sources of salts common to arid and semi-arid soils: 1) atmospheric deposition; 2) weathering of rocks and minerals; and 3) fossil salts.

Most of the atmospheric salt deposition originates from sea water and occurs primarily in the form of rain (Bresler et al., 1982). Atmospheric salt deposition decreases exponentially with increasing distance from the sea and reaches a relatively uniform level at 50 to 150 km from the coast. An estimated 10 - 20 kg ha^{-1} of atmospheric salts are reported to be deposited annually on the interior continent. From mass balance calculations, however, Hendry et al. (1986) concluded that atmospheric sulfate cannot be considered as a major contributor to sulfates found in southern Alberta tills.

Hendry and Schwartz (1982) indicated that a complex set of mineral dissolution processes operating mainly in the soil zone and to a lesser extent along the entire groundwater flow path adds significant quantities of Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, and SO_4^{2-} ions in groundwater. Mermut and Arashad (1987) examined the significance of sulfide oxidation to soil salinization in southeastern Saskatchewan. Their research leads to the conclusion that much of the salts found in the soils of Saskatchewan was likely produced by oxidation during the inter-glacial period.

In Alberta, the total sulfate content of the upper brown, gypsiferous, weathered till zone (up to 20 m thick) exceeds that of the underlying grey non-weathered till zone (up to 25 m thick) by 500% (Hendry et al., 1986). They also found that all sulfates in the non-weathered till zone and 20% of the sulfates in the weathered till zone could have been derived from sulfate rich bedrock fragments incorporated into the till during deposition. The remaining 80% of the sulfate in the weathered till zone was believed to be derived from oxidation of organic sulphur which was incorporated into the till from the bedrock during glaciation.

Fossil salts are not believed to be a major source of sulfate salts in southern Alberta. Only a small portion of the Bow River Irrigation District and a greater part of the Eastern Irrigation District overlie saline marine deposits (Alberta Agriculture, 1985).

Other sources of salts may include fertilizers, agricultural amendments, or livestock and poultry manures applied to soils and irrigation water (Rhoades, 1974). Since the introduction of sulfur bearing fertilizers in 1980, it is believed that 10 to 30 kg ha^{-1} of sulfur (S) is applied annually in Alberta (Hendry et al., 1986). However, they concluded that sulfur fertilizers cannot be considered to contribute to the total sulfate (SO_4^{2-}) reservoir in the till since the chemistry of the groundwater after their introduction did not change significantly. Chang and Sommerfeldt (1988) reported that the quality of irrigation water in Alberta is excellent ($EC_{iw} < 0.3$ dS m^{-1}). Considering that most farmers in Alberta apply 0.20 to 0.30 m of irrigation water annually, approximately 160 to 240 kg ha^{-1} yr^{-1} of salts could potentially be added by irrigation water alone.

In summary, most of the salts found in the soils are sulfates originating from the oxidation of organic sulfur incorporated into the till by bedrock erosion during glaciation. Minor sources may include weathering of rock fragments incorporated into the till during glaciation, irrigation water, fertilizers, livestock and poultry manure and atmospheric deposition.

2.1.3 Causes and extent of soil salinization

Salinity problems are most pronounced in arid and semi-arid regions where rainfall is generally insufficient to flush accumulated salts out of the crop root zone (Bresler et al., 1982). A shallow water table will enhance soil salinization (Van Schaik and Milne, 1963). Water from a high water table rises close to the soil surface by capillary action and is either taken up by the plant or evaporated from the soil surface. Soluble salts are then left behind and precipitate within the root zone which then salinizes, unless leached.

Shallow groundwater is often identified as the main cause of soil salinization in Alberta (Pohjakas, 1982). It can be the result of over-irrigation, discharge of groundwater from upper to lower areas or canal seepage.

2.1.4 Measurement of soil salinity

Soil salinity can be determined in the laboratory on samples taken from the field or directly in the field using resistivity or electromagnetic inductive techniques (Rhoades, 1982a; Cameron et al., 1981). The common laboratory method for measuring soil salinity is to determine the concentration of soluble salts present in the saturated extract of a soil sample (Rhoades, 1982b). In this method, water is added to a given weight of soil until the soil is saturated and just reaches the flow point. This condition is referred to as the saturated paste. After at least four hours, water present in the paste is extracted with the aid of a suction apparatus. This extract is referred to as the saturation extract. The extract is then analyzed for electrical conductivity (EC_e) and soluble Ca^{2+}, Mg^{2+} and Na^+ contents. The EC_e is commonly used to express soil salinity. Increasing EC_e reflects increasing total salt content. The ionic constituents of a soil are also used to determine the sodium adsorption ratio of the saturation extract (SAR_e). The SAR_e is used to express the relative activity of sodium ions in exchange reactions with soils and is calculated as follows (U.S. Salinity Laboratory, 1954):

$$SAR_e = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \qquad [1]$$

Where SAR_e = Sodium adsorption ratio of the saturation extract (dimensionless)

The soluble ionic concentrations are expressed in meq l^{-1}. Table 2 gives the chemical limits generally accepted for the classification of salt affected soils.

Table 2. Classification of salt affected soils (After U. S. Salinity Laboratory, 1954).

Soil	EC_e ($dS\ m^{-1}$)	SAR_e	pH
Saline	> 4	< 13	< 8.5
Saline sodic	> 4	> 13	± 8.5
Nonsaline sodic	< 4	> 13	8.5 to 10

Soil salinity can also be measured in situ from bulk soil, electrical conductivity measurements (EC_a). Either the four electrode probe or the inductive electromagnetic soil conductivity method can be used (Brown et al., 1982). These instruments were developed on the theory that for any soil there is, at a given water content (reference water content), a linear relationship between bulk electrical conductivity (EC_a) and salinity (Rhoades and Corwin, 1984).

With the surface positioned, four electrode probe, soil electrical resistance is measured between a pair of electrodes while a current is passed through the soil between another pair of electrodes (Rhoades and Corwin, 1984). This method is reported to have the advantage of sampling a larger volume of soil than with soil samples. It is also known to be a simple and fast method which is particularly well suited to routine salinity monitoring and mapping.

A modification of the surface positioned, four electrode probe is the single EC_a probe in which four electrodes are moulded into a PVC probe as spaced rings. This probe is often referred to as the "Martek probe" and allows measurement of soil salinity with discrete soil depth intervals (Rhoades and Corwin, 1984). The portable unit includes a probe which is attached to a shaft through which the electrical wires are passed and connected to a meter. This type of probe allows for EC_a and soil temperature measurements. Electrical conductivity measurements are automatically standardized to a temperature of 25°C. Inexpensive, single EC_a, four electrode, burial probes can also be constructed and buried in the soil for repeated measurements at the same location (Rhoades, 1979). A single meter can then be used to read EC_a at various probes.

The electromagnetic induction instrument, commonly known as the "Geonics EM-38" allows measurement of bulk soil salinity (EC_a) at the soil surface. This instrument, which has the shape of a carpenter's level, imposes a primary electromagnetic field on the soil which in turn induces current flow in the soil. The induced current is directly proportional to EC_a (Rhoades and Corwin, 1984). In practice, an operator traverses the field with the instrument suspended just above the ground and notes changes in EC_a readings. The EM-38 senses EC_a of the surface 1.0 to 1.2 m of soil with the instrument in the vertical position and to approximately 0.5 m when in the horizontal position (Henry et al., 1987). Electromagnetic induction instruments are particularly well suited for mapping soil salinity (Rhoades and Corwin, 1984).

EC_a varies with soil texture and moisture (Rhoades and Corwin, 1984). A good understanding of the soil properties is therefore required when using on-site EC_a determination instruments. Measurements of EC_a should be conducted at a constant soil moisture content to eliminate variations due to soil moisture. For irrigated soils, EC_a should be measured after an irrigation when soil moisture content is likely to have reached field capacity. Under dryland conditions, EC_a should be measured in early spring, preferably in fallow land (Rhoades and Corwin, 1984). EC_a can be related to EC_e using calibration curves developed for various soil textures (Rhoades, 1981; McKenzie et al., 1989).

2.1.5 Detrimental effects of soil salinization

Crop production is reduced when excessive accumulation of soluble salts exist in soils. Reductions in crop yields result from osmotically produced water stresses which plants encounter when grown under saline conditions and from specific nutritional imbalances and toxicities that are created when certain salt constituents, such as chloride, sodium and boron, are individually in excess (Rhoades, 1974). Table 3 gives the salt tolerance of common crops grown in southern Alberta.

Table 3. Salt tolerance of some agricultural crops (After Maas and Hoffman, 1977).

Crop	Salinity (EC_e) at initial yield decline (threshold) ($dS\ m^{-1}$)	Percent yield decrease per unit increase in EC_e beyond threshold
Alfalfa	2.0	7.3
Barley	8.0	5.0
Flax	1.7	12.0
Hard wheat	6.0	7.1
Potatoes	1.7	12.0
Soft wheat	6.0	7.1
Sudan grass	2.8	4.3
Sugar beets	7.0	5.9

Excessive sodium may indirectly decrease plant growth due to its detrimental effect on soil structure. Yousaf et al. (1987) found that as the sodium content of soil increased, clay dispersion increased and consequently, hydraulic conductivity decreased. Gal et al. (1984) suggested that soils with a higher sodium content were more likely to form a surface crust when irrigated. Their results also indicated that most sodic soils exhibit a much lower infiltration rate than non-sodic soils.

2.2 Soil salinity control and reclamation

2.2.1 Critical depth

In a semi-arid area, the permissible depth of the water table with respect to the soil surface must not only provide sufficient aeration within the root zone but must also ensure that the water table is sufficiently deep to prevent upward capillary flow of saline water into the root zone (U.S. Salinity Laboratory, 1954). Van der Berg (1973) suggested that most of the upward capillary flow of saline water to the root zone occurs during the non-irrigated season and a net downward flow prevails during irrigation. However, studies conducted in southern Alberta indicate that upward migration of salts into the root zone occurs during the irrigation season. For example, van Schaik and Milne (1963) observed a three fold increase in salinity during the irrigation season under a grass crop with a controlled water table depth of 0.90 m.

Several studies have been undertaken to determine the depth of the water table which would prevent further upward capillary flow of saline groundwater. This depth is often referred to as the "critical depth". Van der Berg (1973) suggested values ranging from 1.2 to 1.5 m for sandy and clay soils, and 1.5 to 2.0 m for soils of intermediate texture. These values pertain to irrigated conditions.

Van Schaik and Stevenson (1967) found that a net capillary rise of salts to a bare clay loam soil surface would not occur provided the water table was maintained at a depth of 1.0 m or deeper and water applications (irrigation and/or rain) between June 1st and November 1st were 150 mm or more. However, they did report significant salt accumulation in a grass covered soil under similar conditions.

Buckland et al. (1986a) examined leaching of soil salts with subsurface drains installed at different depths. At one site, after 2 years of irrigation, the average salinity of the upper 2.0 m of the soil profile was reduced to 91, 88 and 74% of original values for drain depths of 0.76, 1.22 and 1.68 m, respectively. Resalinization occurred with the shallowest (0.76 m) drains which suggested that the 0.76 m drain depth did not provide sufficient water table control to prevent the upward migration of salts.

Vander Pluym et al. (1985) defined the critical depth for dryland fields as the shallowest water table depth where desalinization occurs. Critical depth values obtained from six subsurface drained fields in this study were variable and ranged from 0.6 to 3.2 m. Although the experimental sites were cropped to annual cereals, they were usually covered with weeds or were bare.

McMullin and Read (1983) studied the contribution of groundwater to consumptive water use of crops under dryland conditions in lysimeters, and found that nearly half the consumptive use of barley was derived from groundwater when the water table was at a 1.2 m depth, while a water table at 1.8 m supplied one quarter of the consumptive use. Cropped treatments, compared to bare, were found to have a higher groundwater use (5.75 times greater). Groundwater consumptive use for clay loam soils was 1.3 times that of a loamy sand soil. It was suggested that a 1.2 m water table depth was too shallow to prevent salinization in the root zone in either clay loam or loamy sand soils in areas where there is a large deficit of rainfall versus consumptive use.

An approximation of the critical depth under dryland conditions can be obtained from the following equation (Kovda, 1973):

$$y = 170 + 8t^{\circ} \pm 15 \qquad [2]$$

where y = critical water table depth (cm)
t° = average annual temperature of the region ($^{\circ}C$)

For southern Alberta (average temperature of 5.4°C), the above equation would yield a critical depth of 2.13 m. Beke (1989) is presently conducting research on the critical depth for conditions in southern Alberta. Preliminary results suggested that a value of at least 2.0 m should be used for a uniform clay loam soil under dryland conditions.

Water table depth requirements for adequate aeration of the root zone are not as severe as those for salinity control (Van der Berg, 1973). Salinity control is therefore the main consideration in the selection of the water table depth in a semi-arid region.

2.2.2 Leaching requirements and methods

The only practical way to reduce excessive salinity in soils is to leach the salts out by passage of lower salinity water through the active root zone depth of soil. The first requisite for leaching is adequate drainage. In the case of sodic soils, application of appropriate amendments may be required (Rhoades, 1982a).

Leaching requirements can be divided into two distinct categories: 1) requirements for the initial reclamation of salt affected soils; and 2) requirements to maintain a steady state salt balance. In an ideal porous matrix system without pore bypass, dissolution of precipitated salts, salt diffusion constraints or hydrodynamic dispersion, the salt concentration of soil water passing a given depth in the soil profile should drop to the concentration of the applied water when the volume of applied water equals the pore space of the soil volume to be leached (Rhoades, 1982a). However, the efficiency of leaching is reported to be lower because of considerable bypass though macropores, especially in structured soils.

Rhoades (1982a) indicated that approximately 70% of soluble salts initially present in a medium textured soil will be removed by continuous ponding with a depth of leaching water equivalent to the depth of soil to be reclaimed. This corresponds to 1.5 to 2.0 pore volumes of water which must pass through the soil to achieve the same level of reclamation. When reclamation is achieved by intermittent ponding or by sprinkling, water requirements can be reduced by about one third (Hoffman, 1980). This was thought to occur because a larger proportion of water flows through fine pores in drier soils and hence, there is more efficient displacement of the soluble salts by the leachate.

Various empirical equations were developed to predict the leaching requirements for reclaiming salt affected soil. Hoffman (1980) presented the following equation describing salt removal by continuous ponding:

$$\frac{C}{C_o} \times \frac{d_l}{d_s} = k \qquad [3]$$

where C_o = initial salt concentration

C = actual salt concentration

d_l = depth of irrigation water for leaching

d_s = depth of soil

k = a leaching constant.

The leaching constant is dependent upon soil type and is 0.45 for organic soils, 0.30 for fine textured soils (clay loam), and 0.1 for coarse textured soils (sandy loam). Leaching by intermittent ponding is independent of soil type and the following equation is given (Hoffman, 1980):

$$\frac{C}{C_o} \times \frac{d_l}{d_s} = 0.1 \qquad [4]$$

In equations [3] and [4], the salt concentration of the irrigation water (C_i) can be incorporated to account for poor quality irrigation waters by substituting ($C-C_i/C_o-C_i$) for (C/C_o).

Harker and Mikalson (1989) found that salinity and sodicity of moderate (EC_e = 15 dS m^{-1}) and highly (EC_e = 76 dS m^{-1}) saline sodic sulfate dominated soil cores were improved throughout the 0.5 m depth when leached by continuous ponding with good quality irrigation water. They found that leaching curves could be described by the following equation:

$$\frac{C}{C_o} \times \frac{d_l}{d_s} = 0.25 \qquad [5]$$

Jury et al. (1979) conducted a study on the leaching (ponded or unsaturated) of sandy loam and clay loam soils placed in large outdoor lysimeters. Salts were composed of mixed sulfate, bicarbonate and chloride anions. Their results lead to the following relationship:

$$\frac{C}{C_o} \times \frac{d_l}{d_s\theta} = 0.8 \qquad [6]$$

where θ = soil volumetric water content

It was found that 60% and 80% of the total salts were removed with 2 and 4 pore volumes of leaching water, respectively.

McMullin and Karkanis (1983) found that, for Alberta soils, the equation developed by Jury et al. (1979) is superior to that developed by Hoffman (1980). This was attributed to the more easily leached, chloride dominated soils studied by Hoffman (1980).

McMullin (1983) conducted laboratory leaching experiments on a saline clay loam. A disturbed soil sample with a uniform EC_e of 7 dS m^{-1} was placed in columns. Leaching water was applied intermittently with trickle emitters at a rate of 11 mm hr^{-1}, with each application totalling 26 mm. The following relationship was proposed:

$$\frac{C}{C_o} = 0.954 \ \mathrm{Log}_{10} \ d_s \ (\mathrm{mm}) - 0.341 \ \mathrm{Log}_{10} \ d_l \ (\mathrm{mm}) - 0.997 \qquad [7]$$

Handbook No. 60 (U.S. Salinity Laboratory, 1954) recommends bringing the salinity of the soil solution in the root zone near the threshold level required by the plant. Considering that plants are relatively insensitive to high salinities in the lower portion of the root zone, Rhoades (1982a) used average salinity of the root zone as a criterion to reclaiming soils to meet crop requirements.

As discussed earlier, chemical amendments may be required to reclaim sodic soils (SAR_e>13; Table 2, section 2.1.4). High sodium concentrations have an adverse effect on soil hydraulic conductivity and infiltration rate. Generally, the effect of chemical amendments is to increase calcium on the exchangeable complex at the expense of sodium. The replaced sodium is removed either to greater depths or out of the profile by leaching water (Loveday, 1984).

Amendments that provide soluble calcium include gypsum ($Ca_2SO_4.2H_2O$), lime ($CaCO_3$) and calcium chloride ($CaCl_2.2H_2O$) (Hoffman, 1980). Other amendments produce calcium in calcareous soils by enhancing the conversion of calcium carbonate to the more soluble calcium sulfate. They include sulfuric acid, sulfur, lime sulfur, pyrite, and iron and aluminum sulfates. Gypsum, sulfur and sulfuric acid are the most common amendments for reclamation because of their relatively low cost and proven effectiveness (Hoffman, 1980). Generally, the response of fine textured soils to chemical amendments is better than that of coarse textured soils (Hoffman, 1980).

Subsoiling to increase soil permeability of sodic soils was not found to be beneficial unless an indurated layer was broken (Hoffman, 1980; Bole, 1986). The use of saline irrigation water will also improve the infiltration rate (Agassi et al., 1981; Oster and Schroer, 1979) and hydraulic conductivity (Minhas and Sharna, 1986). Reclamation can be enhanced by the presence of plants (Hoffman, 1980). However, to get a plant established, some leaching must be done prior to the establishment of the salt tolerant crop.

In irrigated soils, salts accumulating in the root zone must be leached to maintain a steady state salt level that is below the crop threshold level. Without leaching, salts accumulate in direct proportion to the salt content of the irrigation water and the depth of water applied. The leaching requirement (LF) necessary to maintain a steady state salt content is defined as the fraction of the irrigation water that must be leached through the root zone to control soil salinity at any specified level. The LF is determined as follows (U.S Salinity Laboratory, 1954):

$$LF = \frac{EC_{iw}}{EC_{dw}} \times 100 \qquad [8]$$

where LF = leaching fraction required (%)

EC_{iw} = electrical conductivity of irrigation water including effective precipitation (dS m^{-1})

EC_{dw} = electrical conductivity of the drainage water (dS m^{-1})

The EC_{dw} is determined from the relative salt tolerance of the least salt tolerant crop to be grown. Except for some specialty crops, a 25% yield reduction in the least salt tolerant principal crop can be used (USBR, 1978).

Rhoades (1982a) divided the root zone in four successive layers and assumed that 40% of the crop consumptive use was derived from the upper layer, 30% from the second, 20% from the third and 10% from the lower. He then related the average salinity of the root zone ($\overline{EC_e}$) to the leaching fraction (LF). The following equation approximates his findings for conventional irrigation management (Frenkel, 1984):

$$\overline{EC_e} = EC_{iw} \times 0.2 \quad (1+1/LF) \qquad [9]$$

where $\overline{EC_e}$ = average salinity of the root zone saturated extract after leaching (dS m^{-1})

LF = leaching fraction expressed as a decimal

Note that this equation is valid for $0.10 < LF < 0.40$. For example, the resulting $\overline{EC_e}$ when LF = 0.12 and EC_{iw} = 2.0 dS m^{-1} would be 3.7 dS m^{-1}. Accepting that the plant threshold EC_e should be used to evaluate leaching (Rhoades, 1982a), this

LF would be adequate for barley but not for alfalfa (Table 3, section 2.1.5).

Leaching fractions (LF) obtained with equation [9] are much lower for crops of high salt tolerance than those calculated with equation [8]. However, they are similar for crops of low salt tolerance (Rhoades, 1982a).

2.3 Canal seepage control

2.3.1 Theory of canal seepage

Many attempts have been made to quantify canal seepage. Worstell (1976) compiled 765 seepage measurements obtained from 15 western states over a 20 year period. Measurements were made by ponding or seepage meters. Ponding tests suggested average values of 0.07 m day^{-1} for clay, 0.24 m day^{-1} for silt, 0.29 m day^{-1} for loam and 0.48 m day^{-1} for sand. These values were thought to be somewhat higher than the true mean since measurements were made on canals where high seepage losses were expected.

Moritz's formula computes total seepage loss as follows (Hagan, 1973):

$$S = 3266\ C \sqrt{\frac{Q}{V}} \qquad [10]$$

where S = volumetric canal seepage loss ($m^3\ day^{-1}\ km^{-1}$)

Q = canal flow rate ($m^3\ s^{-1}$)

V = mean velocity of flow ($m\ s^{-1}$)

C = volume of water lost through the wetted perimeter of the canal prism ($m^3\ m^{-2}\ day^{-1}$).

Values of C vary between 0.125 for clay or clay loam, 0.201 for sandy loam, 0.512 for a mixture of sand and rocks and 0.671 for sand with gravel.

Kostiakov's formula qualitatively considers soil hydraulic conductivity as well as canal flow to predict canal seepage (Hagan, 1973):

$$S = s \frac{Q\ L}{100} \qquad [11]$$

where S = volumetric canal seepage loss $(m^3\ s^1)$
Q = canal flow rate $(m^3\ s^{-1})$
L = canal length (km)
s = canal seepage loss per km of canal (%)

with s calculated as follows:

$$s = \frac{A}{Q^w}$$

The empirical factors A and w depend on a qualitative assessment of soil hydraulic conductivity. Values of A and w vary as follows: 0.70 and 0.30 respectively for materials of low hydraulic conductivity; 1.90 and 0.40 respectively for materials of medium hydraulic conductivity; and 3.40 and 0.50 respectively for materials of high hydraulic conductivity.

The previous equations predict canal seepage when free drainage prevails. When groundwater is at a limited depth, seepage values obtained with Eq. [11] must be reduced accordingly. Hagan (1973) presented the following reduction factors for a water table depth of 3.0 m: 0.41, 0.36, 0.35, and 0.32 for canal flow values of 10, 20, 30, and 50 $m^3\ s^{-1}$ respectively. No values were presented for water table depths less than 3.0 m.

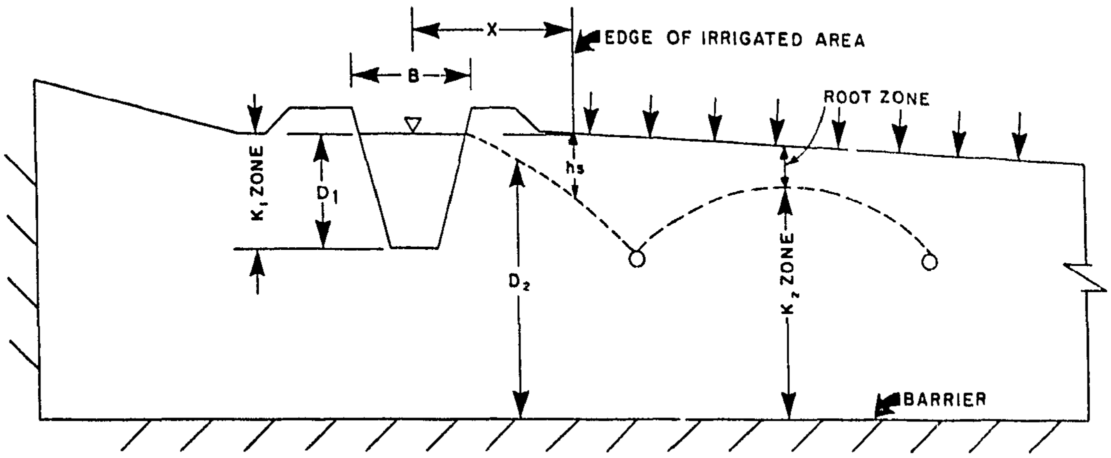

Fig. 3. Measurements needed for estimating canal seepage and interceptor drain flow rate. (After USBR, 1978).

The USBR (1978) presented a seepage calculation method that uses quantitative values of soil hydraulic conductivity as well as considering canal geometry. Canal seepage under free drainage conditions can be estimated as follows (Figure 3):

$$Q_1 = \frac{1000\ K_1\ \ (B + 2D_1)}{3.5} \qquad [12]$$

where Q_1 = volumetric seepage rate per unit length of canal (m^3 day^{-1} km^{-1})

K_1 = hydraulic conductivity of soil material adjacent to canal section (m day^{-1})

3.5 = factor used to adjust K values to seepage losses from ponding tests

B = top width of the water surface in the canal (m)

D_1 = depth of water in the canal (m)

Equation [12] estimates seepage for free drainage and does not account for a decreasing seepage rate as the water table mound approaches the bottom of the canal and eventually, the operating level of the canal. At this latter point, the terminal seepage rate, Q_2 ($m^3\ km^{-1}\ day^{-1}$), can be calculated as follows:

$$Q_2 = \frac{Q_1\ (B - 2D_1)}{(B + 2D_1)} \qquad [13]$$

Predicted flows obtained from the previous equations are accurate as long as soil properties, and consequently seepage along the canal, remain constant. Actual seepage measurements monitored near Rupert, Idaho suggested that canal seepage can vary as much as 18 fold within a 30 m interval along a canal (Worstell, 1976). The hydraulic conductivity of soils and surficial geologic materials in southern Alberta can be highly variable (eg. Hendry, 1983). Canal seepage may therefore be highly variable in southern Alberta.

Ferris et al. (1962) used a solution analogous to heat flow to predict the lateral extent of the seepage mound on either side of the canal. Their equation is as follows:

$$H = H_o\ \mathrm{Erfc} \sqrt{\frac{X^2 f}{4Tt}} \qquad [14]$$

where H = water table height above the canal bed (m) at a distance X (m) from the canal centre line

T = transmissivity of the phreatic aquifer ($m^2\ day^{-1}$), which is equal to K_y ($m\ day^{-1}$) times the aquifer thickness (m)

t = time since the canal full service level was abruptly changed (days)

H_0 = abrupt change in canal full service level at t = 0 (m)

f = drainable porosity (or specific yield) of material adjacent to the canal (dimensionless)

Erfc= mathematical function

Figure 4 illustrates the extent of seepage predicted by equation [14] for several soil hydraulic conductivity values. In deriving Figure 4, the following assumptions were made: the aquifer thickness was 10 m; and f was determined from a curve relating f to K as given by the USBR (1978). As shown in Figure 4, both the height to which the water table rises downslope from the canal and the distance to which the water table rise occurs, increase with increasing horizontal hydraulic conductivity (K_y).

2.3.2 Deep interceptor drainage

Theoretically, an interceptor drain lowers the water table downslope from the drain to a depth equal to that of the drain, and the distance downslope to which it is effective in lowering the water table is infinite (Soil Conservation Service, 1973). This is true provided there is no accretion to groundwater within that distance. In reality, this situation is unlikely because downslope irrigation and precipitation may result in groundwater recharge. Groundwater recharge in source areas upslope of irrigation canals may also cause accretion to the groundwater in areas downslope of the canal (Hendry and Buckland, 1990). Measurements made on the SMRID main canal in the Taber area (CH2M Hill, 1986) suggested that the water table may rise above the level of the interceptor drain within a few meters downslope of the drain.

Sharma and Chawla (1974) developed an analytical solution for steady state seepage from a canal to an interceptor drain assuming the soil below the canal to be homogeneous and

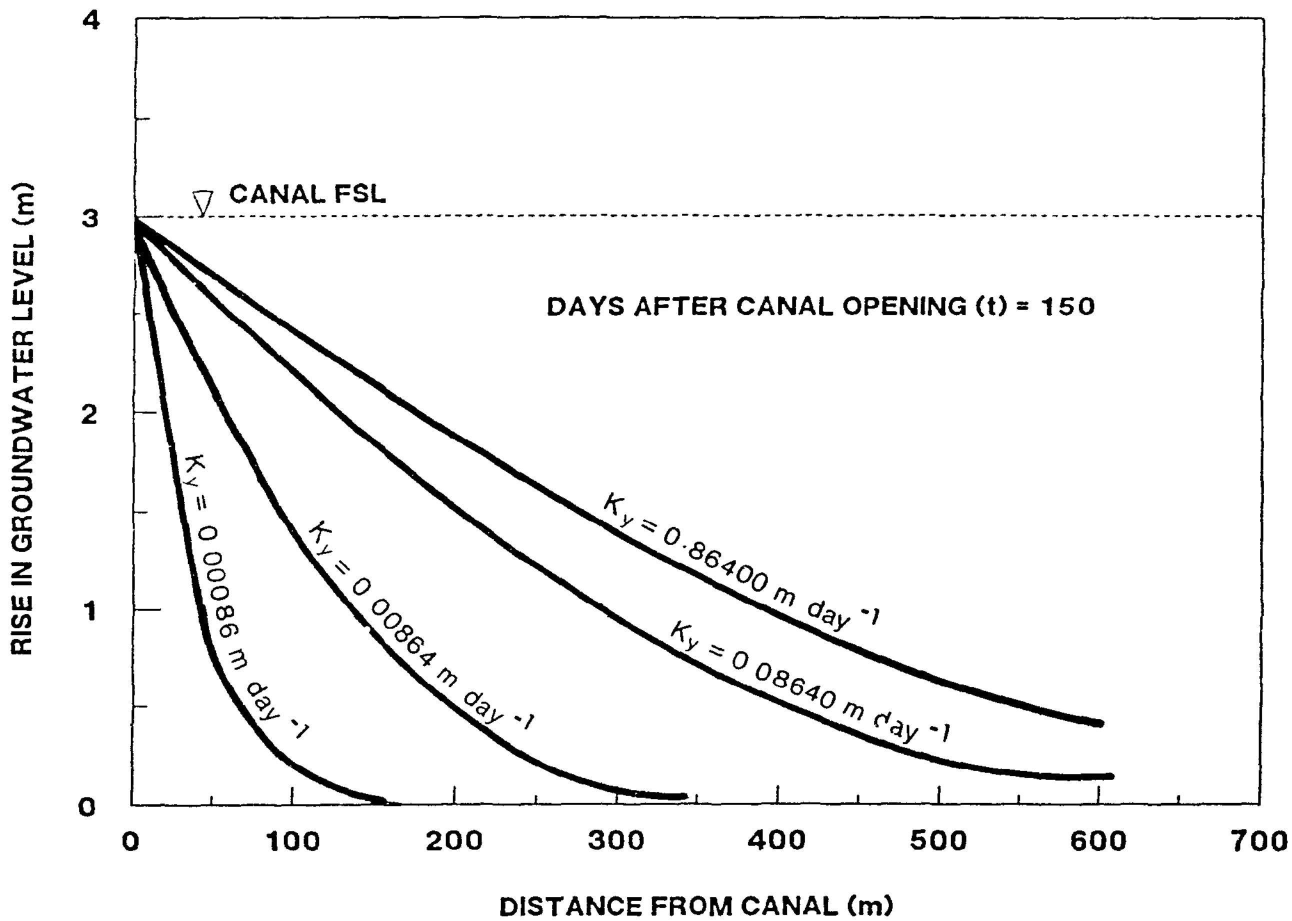

Fig. 4. Estimated rise in groundwater levels at various distances downslope of the canal without seepage control measures (After Ferris et al., 1962).

isotropic. No provisions were made for other sources of recharge. They concluded that locating the drain farther away from the canal resulted in a greater lowering of the water table beyond the drain although this resulted in a shallower water table between the canal and the interceptor drain.

Willardson et al. (1971) used an electric analogue to model the flow system of an existing interceptor drain in a sandy soil in the Imperial Valley of California. Measured flows exceeded 6.0 $m^3\ min^{-1}\ km^{-1}$. Simulations showed that with the interceptor drain placed at the canal invert elevation, maximum interception occurred when the interceptor was located from 7 to 14 m away from the edge of the water surface in the canal. When the drain was placed below the canal invert, it was shown that maximum interception occurred when the interceptor was placed as far as possible from the canal and as deep as practical. Making the drain as permeable as possible was also proved advantageous.

The USBR (1978) gave the following equation to determine the flow of an interceptor drain (see Figure 3):

$$Q_3 = \frac{K_2\ D_2\ hs}{X} \times 1000 \qquad [15]$$

where Q_3 = additional capacity needed in the first drain (deep interceptor) due to canal seepage ($m^3\ km^{-1}\ day^{-1}$)

K_2 = weighted hydraulic conductivity between root zone depth and barrier ($m\ day^{-1}$)

D_2 = half the sum of the distances between: 1) the barrier and water surface in the canal; and 2) the barrier and required water table depth at the edge of the irrigated area (m)

hs = difference in elevation between the selected root zone depth at the edge of the irrigated field and the water surface in the canal (m) (Figure 3)

X = distance between canal centre line and the edge of the irrigated area (m)

Deep interceptor drains are commonly used to intercept canal seepage within the irrigation districts of southern Alberta. As an example, an estimated 22 km of deep interceptor drains were reported to be installed to control canal seepage along the SMRID main canal in the Taber and Bow Island areas (Chaudhary, 1987).

Results of a post-construction groundwater level monitoring program undertaken from April to December, 1984 in the Taber area suggested that the deep interceptor drains were effective in maintaining the water table at or below its natural level downslope of the drains (CH2M Hill, 1986). Their report also indicated that after the deep interceptors were installed that farmers were able to cultivate previously waterlogged lands right up to the toe of the canal. Chaudhary (1987) however, indicated that an understanding of the stratigraphy and groundwater movement was essential and must be gained through properly conducted hydrogeological investigations during planning and design of the seepage control works.

Robertson and Hendry (1985) studied the effectiveness of a deep interceptor drain along the SMRID main canal in the Taber area. Based on interpretations of groundwater data, they concluded that canal seepage was not migrating downslope of the interceptor drain.

Millette et al. (1989) used groundwater data and computer simulations to study the effectiveness of deep interceptor drains at four sites along the SMRID main canal in the Taber and Bow Island areas. They concluded that deep interceptor drains were performing adequately except where there was, in the canal area, natural groundwater seepage and/or a permeable aquifer below the level of the interceptor drain.

In the province of Saskatchewan, deep interceptor drains are not extensively used to control canal seepage due to their high cost of installation (Ireland, 1989). Conversely, in Pakistan and the western United States, deep interceptor drains are commonly used to control canal seepage but information relative to their actual effectiveness is limited or nonexistent (Brockway, 1989; Broughton, 1989; Jimsen, 1989).

2.3.3 Grid drainage

Grid drainage problems, both theoretical and experimental, are divided into steady and transient states. In southern Alberta, the theory of steady state drainage is used to design drainage systems although field experiments have evaluated transient state concepts (Buckland et al., 1987a; Rapp, 1962). The steady state theory is defined as a uniform, steady rate of recharge to the drainage system which, under specified conditions (of drain depth and spacing, depth to barrier and hydraulic conductivity), will cause the water table between drains to rise to and remain at a constant height provided the rate of recharge is constant.

Hooghoudt's equation for determining spacing of subsurface grid drains was first developed by Donnan and was later modified to account for resistance due to convergence of flow lines near the drains (Wesseling, 1983). The equation is (Figure 5):

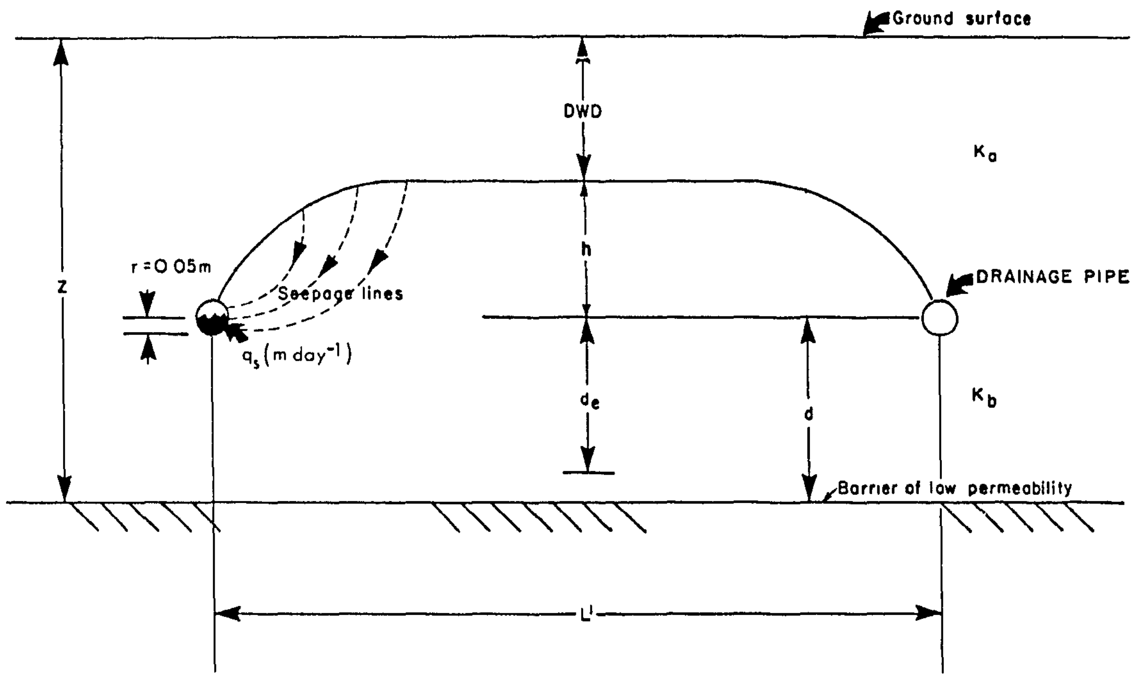

Fig. 5. Symbols and geometry of Hooghoudt's equation for spacing of grid drains.

$$L'^2 = \frac{8K_b d_e h + 4K_a h^2}{q_s} \qquad [16]$$

where L' = drain spacing (m)

K_a = hydraulic conductivity above drain centre (m day^{-1})

K_b = hydraulic conductivity below drain centre (m day^{-1})

h = height of water table above drain centre at drain mid-spacing (m)

q_s = drainage coefficient (m day^{-1})

d = depth of impermeable barrier below drain centre (m)

d_e = Hooghoudt's equivalent depth (m)

Hydraulic conductivity values can be obtained in the field using the auger hole method as described by van Beers (1979). The drainage coefficient (q_s) depends primarily on the climate, the crop grown and irrigation management. Buckland et al. (1987b) suggested a value of 1 mm day^{-1} under irrigation management practices common to southern Alberta. The same authors used a design water table depth (DWD) of 1.0 m. Their selection was based on the findings of van Schaik and Milne (1963). Hooghoudt's equivalent depth (d_e) depends on d and L' and must be found using a trial and error process by matching L' and d_e (Wesseling, 1983).

In Alberta large scale use of grid drainage to intercept canal seepage and reclaim saline land downslope of irrigation canals began in 1986. Grid drainage is now used as a canal seepage control measure over 10 km of canal. Results of a follow-up study indicated that grid drainage was particularly adequate where natural groundwater seepage was present near the canal (Millette et al., 1989).

In Saskatchewan, grid drainage is not extensively used to specifically control seepage from irrigation canals (Ireland, 1989). In the western United States, irrigation canal companies prefer deep interceptor drainage to grid drainage because they do not want to pay for drainage outside of their right-of-way (Trott, 1989). In Egypt and Pakistan, grid drainage is installed for canal seepage interception and water table control but few monitoring programs, if any, are specifically designed to assess the effectiveness of grid drainage to intercept canal seepage (Broughton, 1989).

2.4 Summary

The causes and extent of soil salinity problems, as well as methods to measure, control and reclaim soil salinity, are extensively reported in the literature. Although many authors have reported analytical or empirical solutions to estimate canal seepage and flow to an interceptor drain, few have dealt with the effectiveness of deep interceptor drains or grid drainage for canal seepage control and reclamation of canal seepage affected land.

Most studies dealing with the field performance of deep interceptor drains emphasized the aspect of water table control, with little emphasis on salinity reclamation. The potential of reclaiming, by leaching, a canal seepage affected land drained with a deep interceptor drain was only discussed by McMullin et al. (1983).

Most literature relating grid drainage to canal seepage control was from work done in southern Alberta. Although a recent study discussed the relative effectiveness of deep interceptor and grid drainage to control canal seepage and reclaim canal seepage affected lands (Millette et al., 1989), very little emphasis was given to the soil salinity aspect. The lack of available literature clearly indicates the need for research and documentation of the field effectiveness of drainage, and particularly grid drainage, for canal seepage control and reclamation of canal seepage affected lands.

3. MATERIALS AND METHODS

3.1 Experimental design

The present study can be divided into two distinct experiments:

1. A groundwater flow study designed to understand the local groundwater flow regime of an area affected by canal seepage and salinity, and the effect of groundwater on the performance of canal seepage control measures (deep interceptor or grid drainage) and subsequent reclamation.
2. A more detailed test plot investigation (3 test plots) designed to: 1) evaluate the effectiveness of a grid drainage system to control canal seepage and maintain the water table below the design water table depth; and 2) evaluate the benefits of fall irrigation to reclaim a saline area affected by canal seepage.

For the test plot investigation, three treatments were established: 1) highly saline, standard pivot irrigation management (Plot #1); 2) highly saline, standard pivot irrigation management plus additional solid set fall irrigation (Plot #2); and 3) moderately saline, standard pivot irrigation management (Plot #3).

3.2 Site description

The site selected for this study was located 19 km southwest of Bow Island, about 100 km east of Lethbridge (Figure 6). The field was situated along the St. Mary River Irrigation District main canal which was built in the early 1950's and was rehabilitated during the winter of 1985 to 1987. Canal capacity is approximately 35 m^3 s^{-1}.

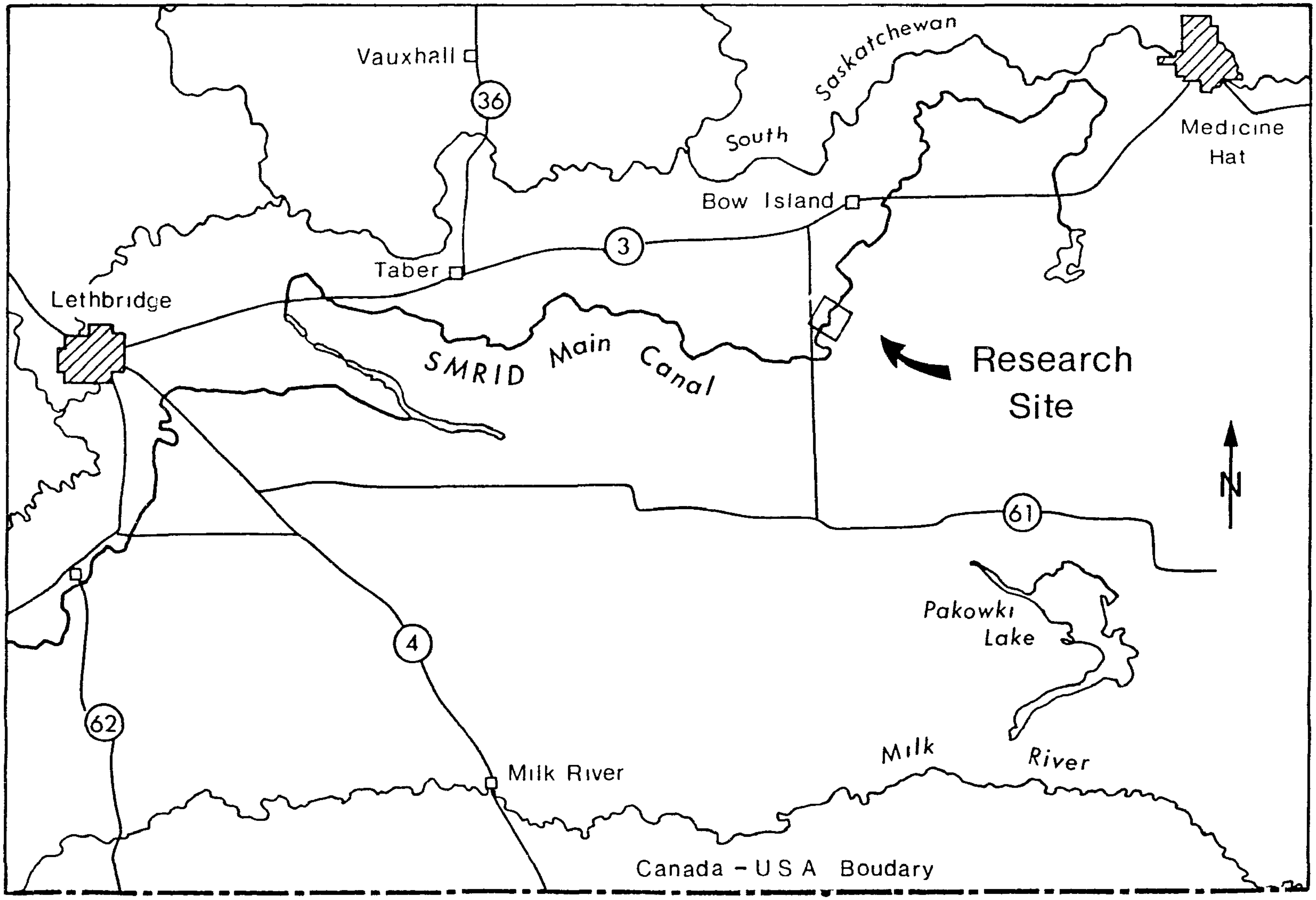

Fig. 6. Site location plan.

The Bow Island area is one of the driest in Canada, averaging 317 mm of annual precipitation with 75% occurring during the growing season (Alberta Agriculture, 1989). The region experiences an annual moisture deficit of 300 mm (Government of Alberta, 1969). This region also experiences severe Chinook winds averaging 20.4 km hr^{-1} gusting up to 171 km hr^{-1} (Environment Canada, 1982b)[1]. Only 4% of the days are reported to be calm (Hawrelak et al., 1976). The Bow Island area, which is one of the warmest in Alberta, offers 2400 corn heat units (Alberta Corn Committee, 1989). Summers are generally hot with maximum daily temperatures reaching 40.6°C. Winters are generally cold with daily minimum temperatures reaching -40.6°C (Environment Canada, 1982a).

The topography of the area is undulating. Surface material is primarily ground moraine with patches of fluvial, lacustrine and aeolian deposits (Government of Alberta, 1969).

Both dryland and irrigated agriculture are practiced near the study site. Typical crops grown within the area include wheat, alfalfa, canola, mustard, flax, sunflower, sugar beets, beans, potatoes, corn and peas. The majority of the irrigation systems are either centre pivot or side roll sprinklers covering a quarter section of 64.8 ha. A small area is irrigated by gravity.

The gradual build-up of saline/waterlogging problems downslope of the SMRID main canal necessitated the installation of a grid drainage system in September 1986 to control canal and natural groundwater seepage (Figure 7). Drain spacing was 15 m for the first 250 m downslope of the canal and 30 m thereafter. Mean drain depth was 1.4 m. Corrugated polyethylene tubing which was covered with a

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[1]Wind data for the Lethbridge area. Winds in the Bow Island area are slightly less severe.

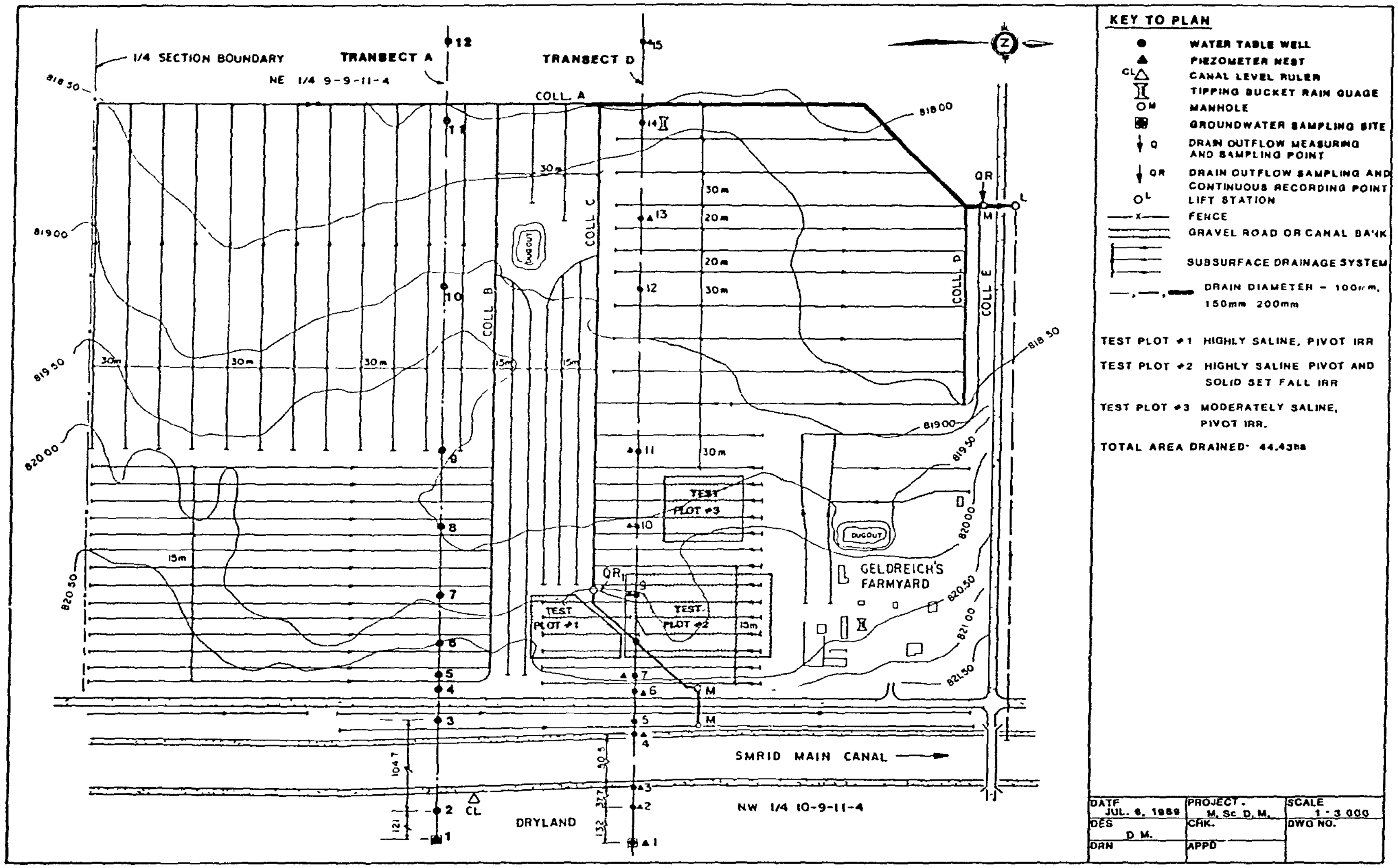

Fig. 7. Field layout of the experimental site and test plots.

conventional polyester filter sock was used. Drains were installed with a Wolfe Model 250 drain plow (Plate E1; Appendix E).

The geologic material specific to the experimental site consisted of glacial till 5.0 to 6.0 m deep which in turn overlay bedrock or coal. Fluvial material overlying till was found in the southern and northeastern portions of the site. (Detailed geology is discussed in section 4.1.1).

The experimental site was pivot irrigated. Alfalfa was grown on the western half of the quarter section and soft wheat (1987) and oil seeds (1988) were grown east of the farm dugout (Figure 7). A good crop cover was established over most of the experimental site except in the test plot areas. Most of test plot #1 and the southern part of test plot #2 were bare, while a fairly good crop was present on the remainder of plot #2 and plot #3.

3.3 Instrumentation

3.3.1 Groundwater investigation

Test drilling and installation of piezometers and water table wells was initiated in February 1987 and was completed in December 1987. Two water table well transects (transects A and D; Figure 7) were installed. Each transect consisted of 12 to 15 water table wells which extended from 200 m upslope of the canal to about 675 m downslope. Eleven piezometer nests (47 piezometers) were installed along transect D.

Water table wells were installed at depths of 3.0 m except at the outside edge of the canal bank (transect D) where the depth was 6.0 m. Wells consisted of 50 mm ID PVC pipes slotted with a saw at 100 mm intervals through their entire length. Boreholes were backfilled with drill cuttings and the surface 200 mm of the boreholes were backfilled with bentonite.

Piezometers were constructed of 38 or 50 mm ID PVC pipe with a 150 or 500 mm plastic wound well screen intake zone. Piezometers were completed with a sand pack around the screen and a bentonite seal placed above the sand pack. Boreholes were then backfilled with drill cuttings and the surface 200 mm were backfilled with bentonite.

A 30° V-notch weir with a continuous Steven's type F recorder was placed at the outlet of collector A to monitor drain outflow of the entire drained area (Figure 7). A tipping bucket rain gauge was installed on the site to monitor precipitation.

3.3.2 <u>Test plot instrumentation</u>

As discussed in section 3.1, three treatments were established for the test plot investigation: 1) highly saline, pivot irrigation; 2) highly saline, pivot and solid set irrigation; and 3) moderately saline, pivot irrigation. Each treatment was assigned one test plot. Test plot locations within the study area are shown in Figure 7.

Test plot #1 (0.318 ha) was located in a highly saline area. Two water table well transects (transects B and C; Figure 8) were installed to monitor water table fluctuations. Drain spacing was 15 m and mean drain depth was 1.20 m. The test plot was under standard centre pivot irrigation management.

Instrumentation in test plot #2 was more detailed because this plot was used to determine the performance of the drainage system and to evaluate fall irrigation. Three water table well transects were monitored, with more detailed instrumentation at transect E to observe the shape of the

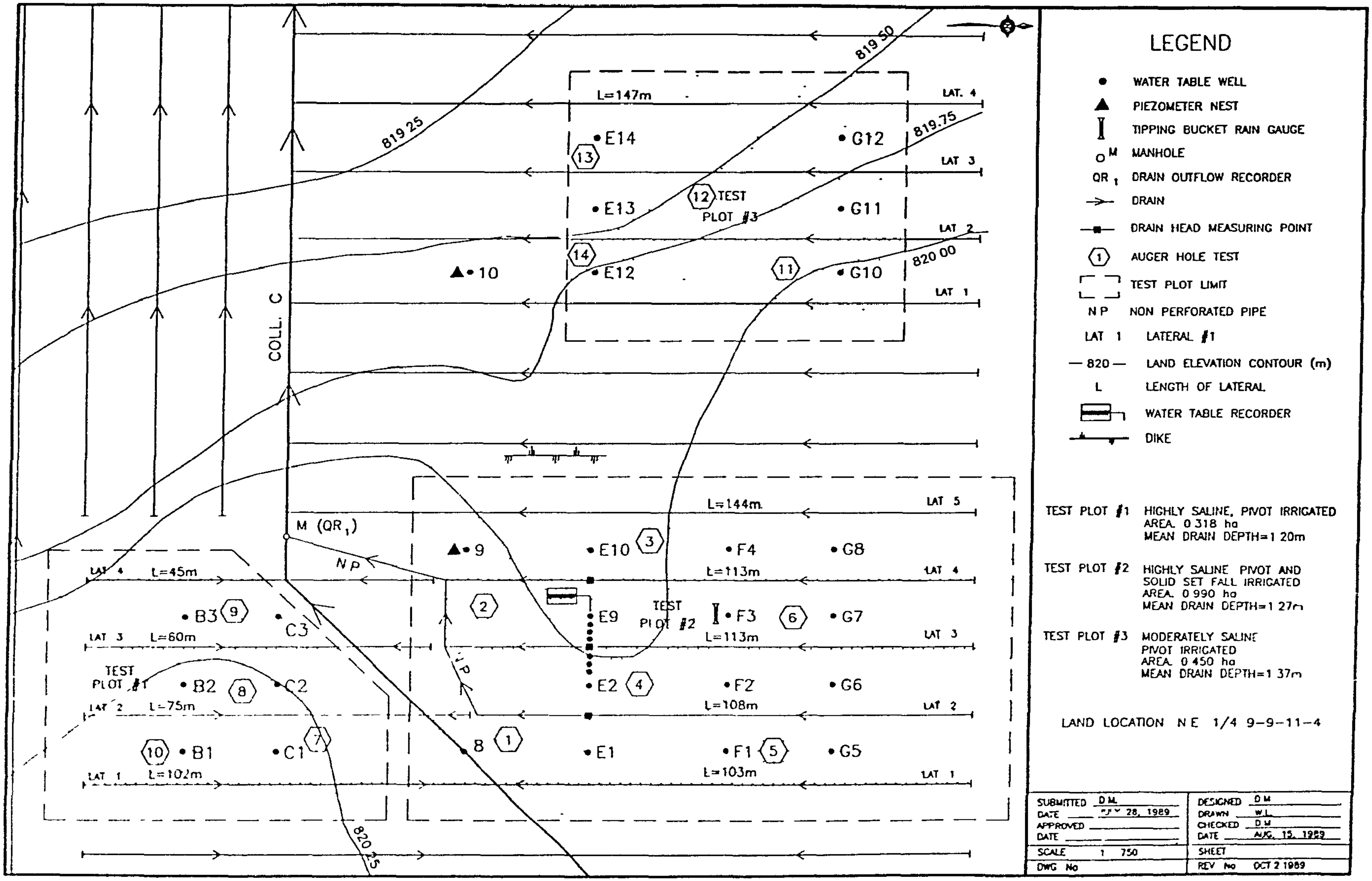

Fig. 8. Detailed description of the test plots.

water table (Figure 8). A total of 18 water table wells were installed (10 at transect E). A continuous Stevens type i water table recorder was placed at well E9. Drain spacing was 15 m and mean drain depth was 1.27 m. Three laterals were joined by a 100 mm non-perforated corrugated polyethylene pipe which discharged into a drain outflow metering station located at collector C, 5 m east of the junction of Lateral 5 and the collector (Figure 8). The metering station included a 910 mm ID corrugated steel manhole with a 15° V-notch weir and a Stevens type F water level recorder. Non-perforated vertical pipes were bored into the three laterals under study, along transect E, to verify the head in the drains. A tipping bucket rain gauge was placed near well F3 to measure irrigation. Test plot #2 was under standard centre pivot and intensive solid set fall irrigation managements. Fall irrigation is discussed in Section 3.4.3.

Two water table well transects were installed in test plot #3 (transects E and F; Figure 8) for a total of 6 water table wells. Drain spacing was 15 m and the average drain depth was 1.37 m. The site was under standard centre pivot irrigation management.

Water table wells in all test plots consisted of 19 mm ID PVC tubing slotted with a saw at 100 mm intervals through its entire length. Boreholes were dug with a 76 mm hand auger and backfilled with auger cuttings. The upper 200 mm of the boreholes were backfilled with bentonite.

3.4 Experimental procedure

3.4.1 Groundwater investigations and modelling

At the time of drilling, lithologic logs were developed. Information concerning the nature of the material (genetic origin, colour, texture and moisture) was noted. Texture was determined on site by hand texturing. Occasional samples were collected for particle size analyses.

Single well response tests as described by Hvorslev (1951) were performed on the piezometers to determine the in situ hydraulic conductivity of the various geologic units.

Monitoring of water levels in the water table wells began in March 1987 and for the piezometers in February 1988. Monitoring was conducted weekly or every second week, with the high frequency corresponding to canal opening (turn-on) and closure (shut-down). Additional monitoring included measurement of drain outflow at collector A (bucket and stopwatch along with a calibrated weir and continuous recorder) and sampling of drainage water for electrical conductivity (EC_{dw}) and temperature.

Groundwater samples were collected from selected upslope water table wells for determination of EC_{gw} and temperature. Canal water level was measured weekly, or every second week, and temperature and EC_{iw} of the canal water was measured monthly. Daily precipitation and temperature records were obtained from the Bow Island Alberta Agriculture district office. Precipitation records were compared with those measured by a tipping bucket rain gauge placed at the research site. Irrigation records were maintained by the farmer and the irrigation district. Data collection ended in mid-February of 1989.

Groundwater flow modelling was performed to gain a broad understanding of the local groundwater flow regime in the area and its effect on the performance of canal seepage control measures (grid or deep interceptor drainage) and subsequent reclamation. Simulations were carried out using the modular, three dimensional, finite difference groundwater flow model (MODFLOW) developed by McDonald and Harbaugh (1988). This model was selected because of: (1) its proven reliability in many different studies (Robertson, 1988); (2) its capability of simulating grid drainage and deep interceptor drainage conditions; and (3) its user friendly design based on a modular format and comprehensive user's guide.

The model allows for recharge, evapotranspiration, rivers (canals), surface and subsurface drains, constant head sources and wells. It also offers a General Head Boundary (GHB) package. A GHB consists of a source outside the modeled area which allows for flow in and out of a cell in the modeled area at a rate proportional to the head difference between the source and the cell (McDonald and Harbaugh, 1988). Simulations can be run for both steady and transient state conditions.

Transect D was selected for steady state modelling (Figure 7). The 870 m long transect was divided into three rows, each 20 m in width, and 70 columns (Figure 9). The length of the columns along the cross section downslope of the canal was 7.5, 10 or 15 m depending on whether the grid drain spacing was 15, 20 or 30 m. Based on the local geologic layering, the number of vertical model layers was set at 7.

Input data required included ground elevation, thickness of each geological unit and horizontal (K_y) and vertical (K_z) hydraulic conductivities. Horizontal hydraulic conductivities were obtained from the single well response tests performed on the piezometers (Hvorslev, 1951) or from auger hole hydraulic conductivity tests (Van Beers, 1979). The ratio of K_y/K_z of the fluvial material was assumed to be 10, which is within the range proposed by Freeze and Cherry (1979). The same ratio was used for weathered and unweathered bedrock (Hendry, 1983). Weathered tills were considered to be isotropic with respect to hydraulic conductivity as suggested

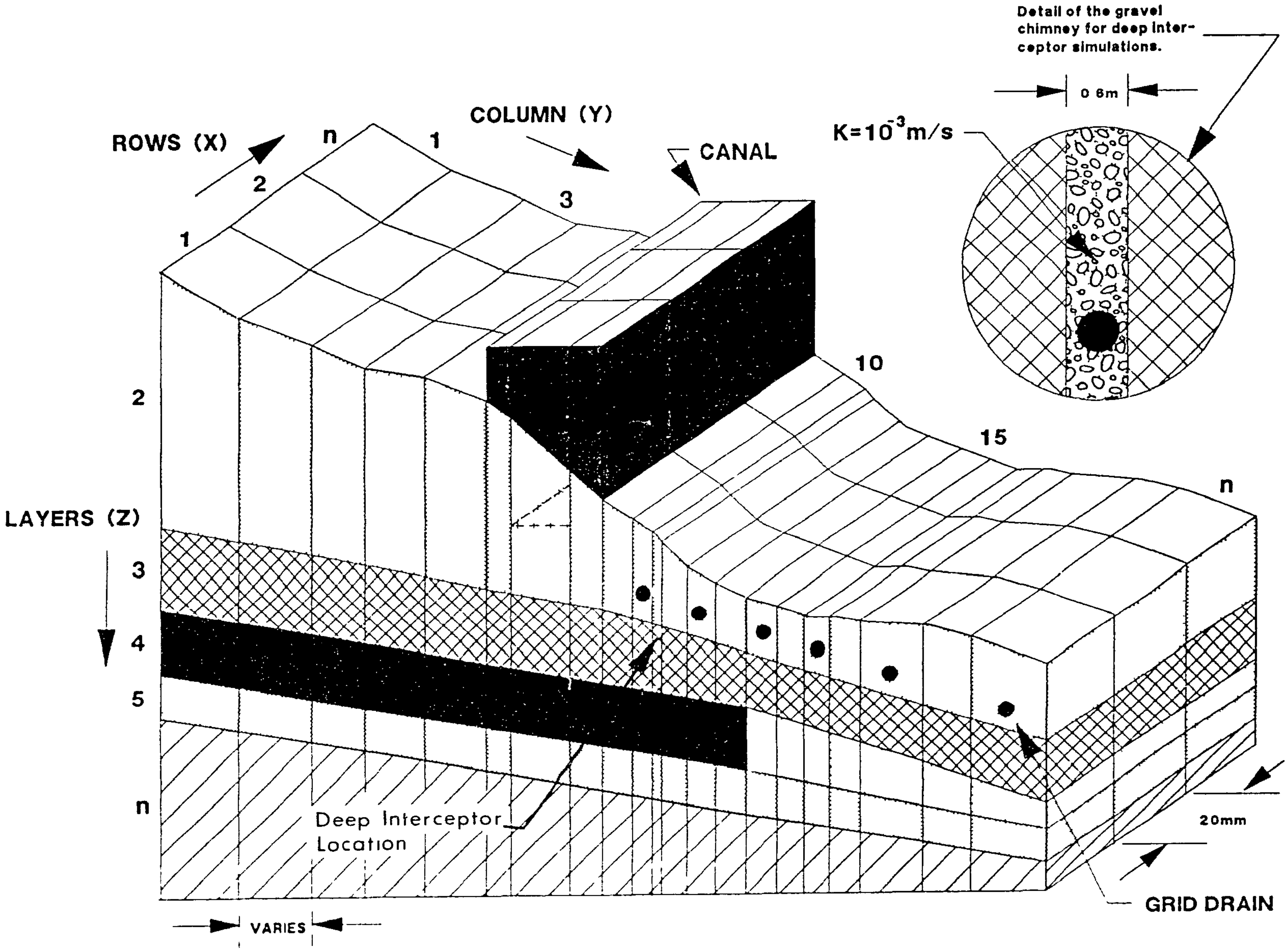

Fig. 9. Typical three dimensional cross section used for groundwater flow modelling.

by Robertson and Hendry (1985). Minor adjustments were made to values of K_y and K_z during model calibration.

The river package was used to simulate canal effects. When determining the hydraulic conductivity of the canal bed, it was assumed that seepage was controlled by the hydraulic conductivity of the surrounding material.

General Head Boundaries (GHB) were set at the first and last column, for each row, in order to account for external recharge and discharge at both ends of the cross section. Heads in the GHB's were set according to piezometric heads obtained from the nearest piezometer nest. Additional GHB's were placed along the cells of row 1 and 3, beginning 230 m downslope of the canal to account for lateral flow. Heads in the lateral GHB's were set so that simulated lateral hydraulic gradients would match those observed between transects A and D (Figure 7).

Downslope of the canal, it was assumed that irrigation and precipitation exactly met the crop demand thereby cancelling the effect of evapotranspiration. The effect of evapotranspiration upslope of the canal was neglected as this field was summer fallowed. Special attention was given to selecting model calibration data so that it would be representative of the steady state conditions observed during the summer.

Predicted drain outflows were calibrated to theoretical drain outflows using equation [15] for deep interceptor drainage and equation [16] for grid drainage. The procedure involved running the model to determine the predicted drain outflow, comparing the predicted drain outflow to the theoretical drain outflow calculated with equations [15] or [16] and then applying a matching factor to equilibrate the drain outflows.

The model was first calibrated by adjusting the model parameters in a trial and error process until the results of the simulations were in general agreement with the observed heads (±20 cm) and theoretical drain outflows. Once calibrated, five additional simulations were generated by varying the type of drainage system, the amount of recharge, the time of year and the presence or absence of the irrigation canal. In all, the several simulations generated were:

1. canal on, deep interceptor drainage
2. canal on, grid drainage
3. canal on, no artificial drainage
4. canal on, deep interceptor and recharge
5. canal on, grid drainage and recharge
6. winter conditions, no canal, no evapotranspiration, no recharge, grid drainage.

For simulating grid drainage, drains were placed according to specifications indicated on the construction drawings (Figure 7). Deep interceptor drainage was simulated by removing the grid drains and placing a deep interceptor drain 1.28 m below the canal invert (3.33 m deep) and approximately 5 m from the toe of the canal bank. A gravel chimney, 0.6 m wide, was added above the drain. The hydraulic conductivity of the gravel was assumed to be at 1×10^{-3} $m\ s^{-1}$ (Cedergren, 1977). The recharge package was used to simulate irrigation required to maintain a steady state salt balance. The recharge rate used was 0.26 mm day^{1}, which approximates the leaching fraction (35 mm yr^{-1}) required to maintain low salinity in the root zone of an alfalfa crop (Robertson, 1988). Robertson's calculations were based on equation [8]. For the winter simulation, the GHB's were changed to hydraulic head values which were measured during the winter months.

3.4.2 Test plot investigations

Monitoring of water table levels at the detailed test plots began in late July 1987 and ended in mid-February of 1989. Monitoring of the water table levels was done weekly or every second week with the high frequency corresponding to canal opening or closure. Additional readings were collected prior to and/or after a major irrigation event and after an important precipitation event to assess water table drawdown over time. Intensive measurements were also recorded during the fall irrigation experiment (Section 3.4.3). At each monitoring session, drain outflow at the outlet of the three laterals at test plot #2 (QR_1 - Figure 8) was measured using a bucket and stopwatch. Drainage water was sampled for EC_{dw} determination and temperature was recorded.

The soil profile was described according to the Canadian System of Soil Classification (Canada Soil Survey Committee, 1978). A total of nine 1 m deep soil pits were studied. Soil profile descriptions included common horizon sequences, hand texturing, soil structure, horizon boundary, colour, gleying, effervescence, pores, roots, consistence, clay films, parent geological material and moisture status. Site features such as slope class, land use, erosion and stoniness were also noted. Soil samples for chemical and physical analysis were taken in each horizon. Pits were then deepened to a depth of 2.4 m using a 100 mm Dia. hand auger. Materials were described according to geologic origins, soil texture (hand texturing), presence or absence of a water table and an impermeable layer.

Soil samples were also collected at four depths (0-0.15, 0.15-0.30, 0.30-0.60 and 0.60-0.90 m) at each mid-spacing water table well location (transects B, C, E, F and G) prior to and after the 1987 fall irrigation on Sept. 2 and Oct. 6, in late April 1988 as well as before and after the 1988 fall irrigation on Aug. 29 and Oct. 19. Samples were prepared for routine salinity analysis by being air dried and ground to 2 mm maximum diameter. All soil samples were then analyzed for electrical conductivity (EC_e), soluble Ca^{2+}, Mg^{2+}, and Na^{+} content and sodium adsorption ratio of the saturation extract (Rhoades, 1982b).

Hydraulic conductivity in the upper 2.4 m of the soil profile was determined at 14 locations (Figure 8) using the auger hole methods as described by Van Beers (1979). Hydraulic conductivity of the material above drain centre (K_a) was determined during irrigation. Hydraulic conductivity below drain centre (K_b) was determined in late fall when the water table had fallen below drain centre.

Soil infiltration rate was measured with a ring infiltrometer. The apparatus (Plate E8, Appendix E) consisted of a metal cylinder, 450 mm in Dia., which was driven 0.20 m into the soil. Infiltration was measured by ponding water inside the cylinder and measuring the rate of water added to maintain a constant ponded depth (25 mm). To avoid lateral flow, a 900 mm Dia. mound was built around the cylinder. Water was ponded between the mound and the cylinder at all times to prevent edge effects and maintain a vertical flow below the central infiltration cylinder (Jensen, 1983). The duration of the test was at least 24 hours. A total of 4 infiltration tests were conducted: one on plot #1 and #3 and two on plot #2.

3.4.3 Fall irrigation experiment

Fall irrigation was defined as any irrigation (pivot or solid set) occurring between August 29 and October 10 (canal closure). Fall irrigation was conducted in both 1987 and 1988. Pivot irrigation during this period was as usual. Each plot received one pivot fall irrigation each year. Solid set fall irrigation was conducted on test plot #2 only. A total of nine solid set irrigations were applied, 4 in 1987 and 5 in 1988. The solid set irrigation system consisted of 50 mm ID PVC tubing with 88 Nelson 20-04, 2.0 mm Dia. impact sprinklers mounted on 45 mm aluminum risers. Spacing between each of the eight laterals was 9.1 m and sprinkler spacing along the laterals was 12.2 m.

Test plots were subsoiled to a depth of 0.60 m prior to initiating irrigation in 1987. Plots were not subsoiled in 1988. Prior to commencing fall irrigation, the crop was chopped and the surface soil was cultivated to a depth of 0.30 m. Soil samples were collected one day before the first fall irrigation and a week after the last irrigation of the year for routine salinity determination (section 3.4.2).

Each irrigation event was 24 to 48 hours in duration, depending on the capacity of the soil to take water. Before and after each irrigation event, water table levels at the three test plots, drain outflow at the outlet of the three laterals (QR_1, Figure 8) and salinity of the drainage water were recorded. Water applications were measured by a series of 64 one litre, 100 mm ID catch containers grouped into two sets on test plot #2. The catch container layout was set up according to Jensen (1983). A control can was filled to the expected catch depth at the beginning of irrigation and placed on the canal bank to determine evaporation loss which occurred from the cans during irrigation. The difference between depth of water in the control can at the beginning and end of irrigation was assumed to be equivalent to evaporation occurring in each catch container. Precipitation was obtained from a tipping bucket rain gauge placed in the farmer's yard.

Surface runoff from test plot #2 was measured with a bucket and a stopwatch from a 90° V-notch weir placed across a 0.30 m dike built in a depression 9 m west of the western edge of the plot (Figure 8). During irrigation, observations pertaining to weather (wind, precipitation, temperature), infiltration and surface sealing were also recorded.

4. RESULTS AND DISCUSSION

4.1 Geology and Groundwater

4.1.1 Geology

The geology of the experimental site consisted of an overburden unit, 6 to 7 m deep, which overlay bedrock or coal (Figure 10). The overburden was primarily ground moraine glacial till. In some areas, fluvial material (0.0 to 1.4 m deep, sandy loam to clay loam) covered the clay loam till unit. Generally, the fluvial unit was thicker upslope and at the canal, then decreased in thickness or pinched out downslope of the canal to become deeper towards the southwestern and northeastern portions of the quarter section. Pockets of lacustrine material were also found within the fluvial unit. Glacial till was the predominant surface material along transect D and test plot #3 while a mixture of fluvial, lacustrine and till was found at the other test plots (Figure 7).

Bedrock of the Foremost Formation was layered and lenticular and consisted of mudstone, claystone and minor inclusions of shale. A coal seam, 0.5 to 2.0 m thick, overlay bedrock near the canal at a depth of 5 to 6 m (Figure 10). The coal seam was continuous upslope of the canal but pinched out approximately 250 m downslope of the canal.

4.1.2 Groundwater

Piezometric head data obtained on March 16, 1988, indicated that natural groundwater exerted a major influence on water levels at the experimental site (Figure 11). Prior to canal opening, recharge water from upslope of the canal entered a highly permeable coal seam which in turn discharged into the till and bedrock units downslope of the canal. Downslope of the coal seam, recharge water entered deeper layers and dissipated through natural drainage. This coal seam appears to be the major cause of groundwater buildup in

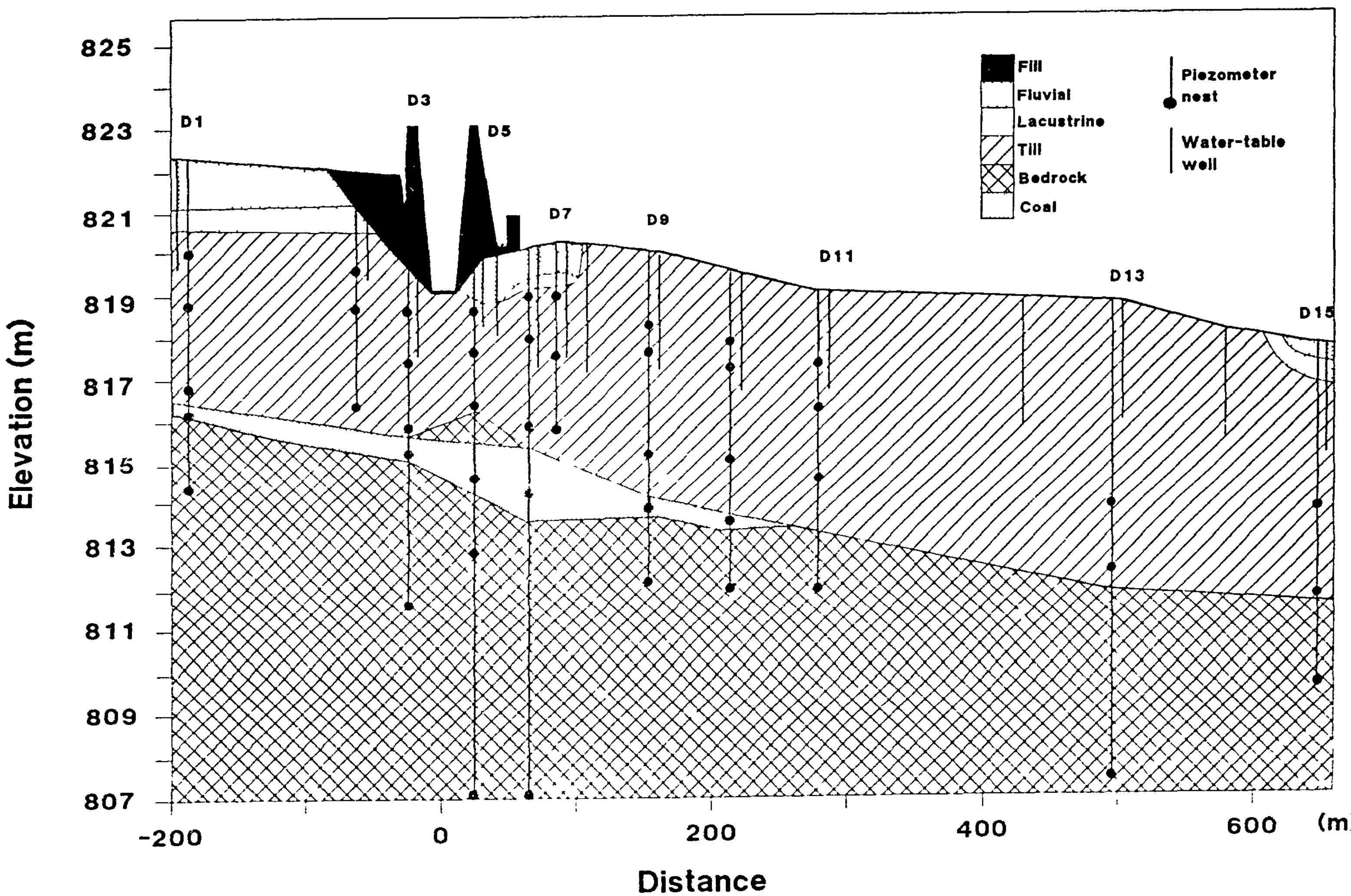

Fig. 10. Geology and groundwater instrumentation.

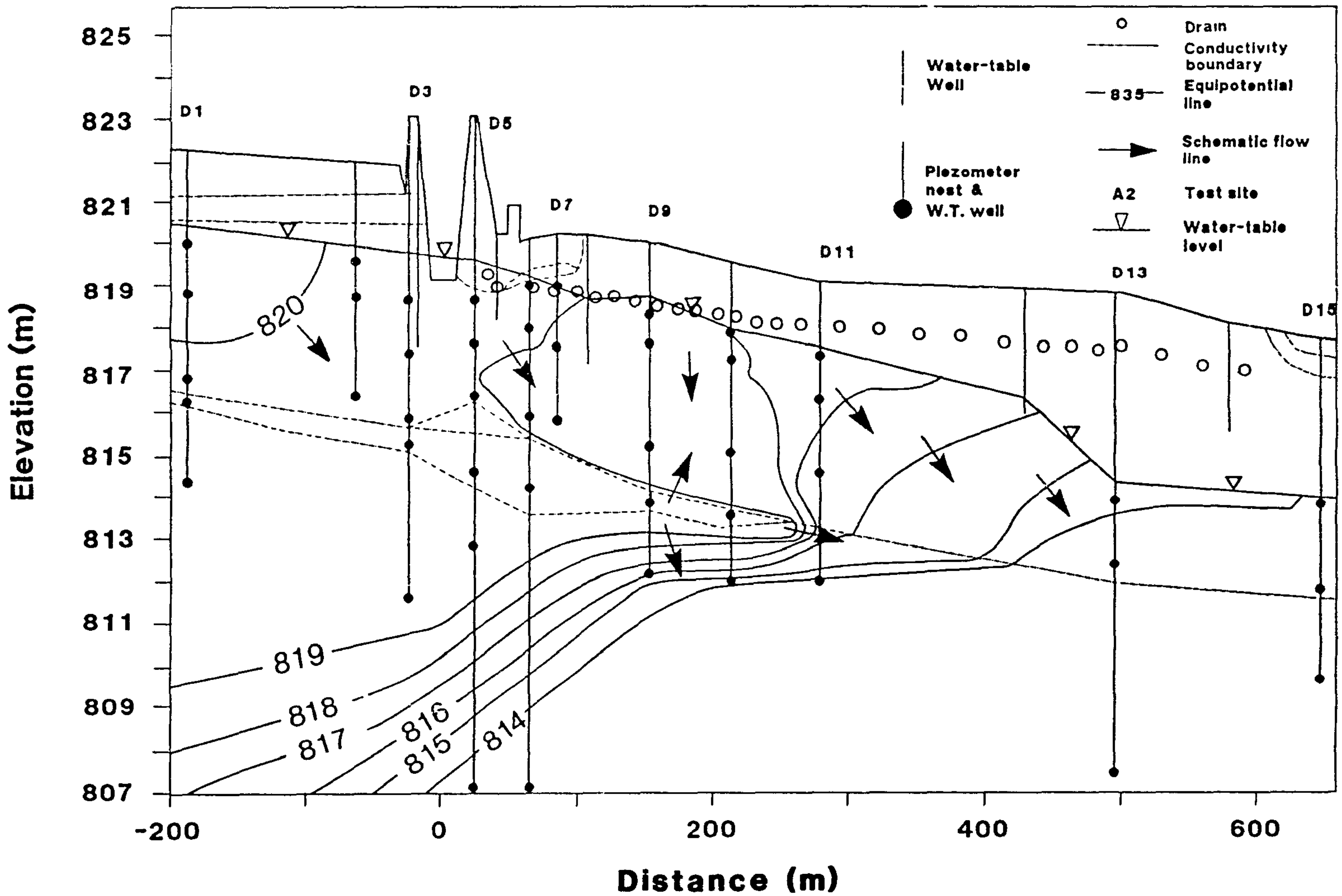

Fig. 11. Actual groundwater flow prior to canal opening; March 16,1988.

the vicinity of the canal prior to canal opening.

As the canal opened a water table mound formed on either side of the canal and pressure in the coal seam increased (Figure 12). The rise in piezometric heads after canal opening suggests that canal water recharged the groundwater and that a correlation existed between canal level and the piezometric head in the coal seam.

Darcy's Law was applied to determine the amount of water seeping from the coal horizon to the overlying till unit. Calculations indicated that the amount of seepage originating from the downslope portion of the coal seam was comparable to an annual rainfall of 8 mm. Nevertheless, the evapotranspiration of this amount of water annually could soon cause soil salinization problems given the high salt content (EC_{gw} of about 10 dS m^{-1}) of the groundwater in the coal seam.

Thus, salinity at the experimental site appears to result partially from groundwater discharge from the coal seam, and partially from canal seepage.

4.2 Groundwater flow modelling

Details of the model layering and the hydraulic conductivities used in the simulations are presented in Figure 13. Minor adjustments to hydraulic conductivities were required when calibrating the transect. First, the hydraulic conductivity of the till unit at the downslope canal bank was reduced from 0.0300 m day^{-1} to 0.0024 m day^{-1} to account for the compaction of the downslope canal bank. When calibrating the cross section, the hydraulic conductivity of the coal seam was increased from 0.3110 m day^{-1} to 4.3200 m day^{-1}.

Spacing of the existing drains was 15 m for the first 280 m downslope of the canal and 20 or 30 m thereafter. Depth of

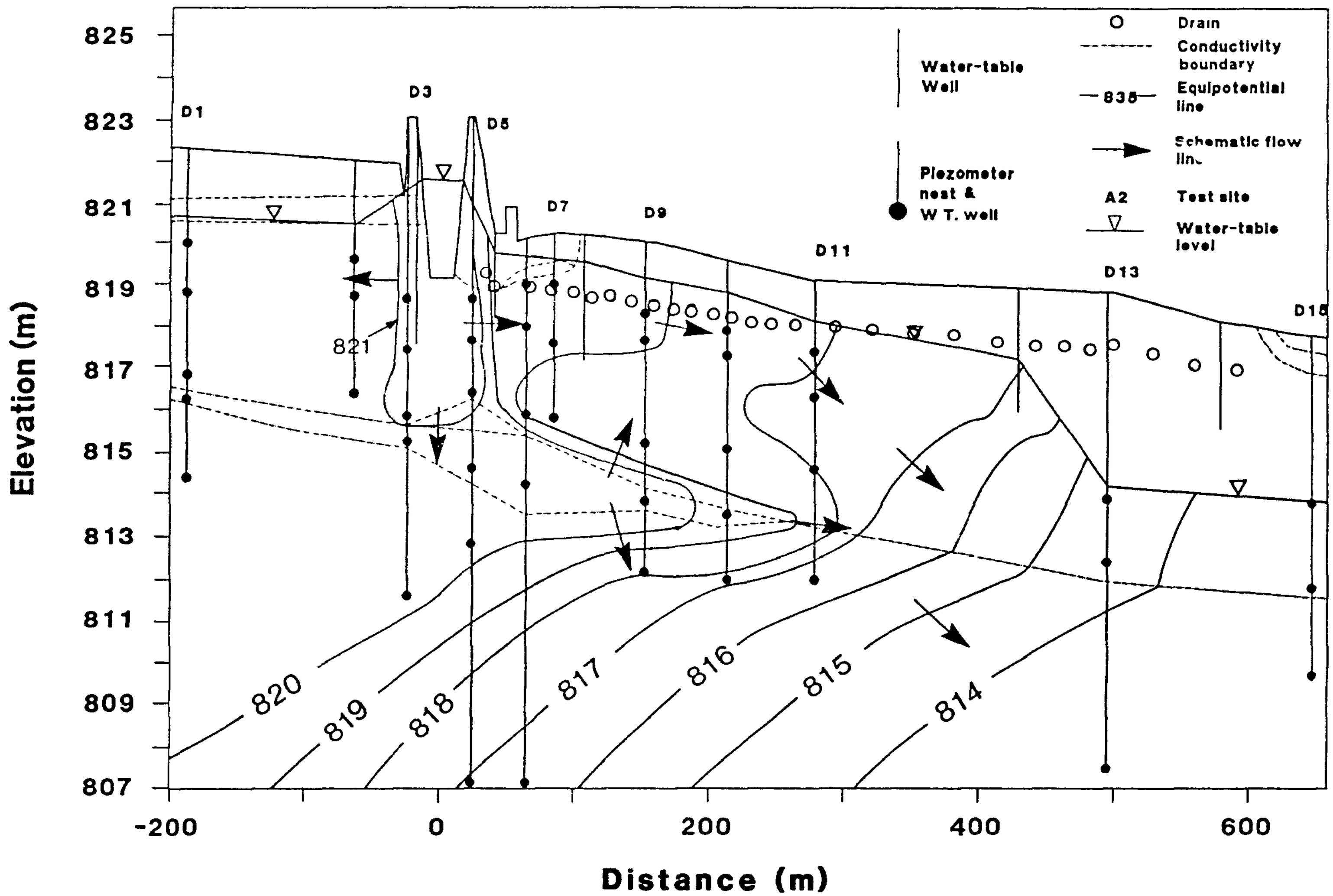

Fig. 12. Actual groundwater flow for the main irrigation season; April 11 to July 31, 1988.

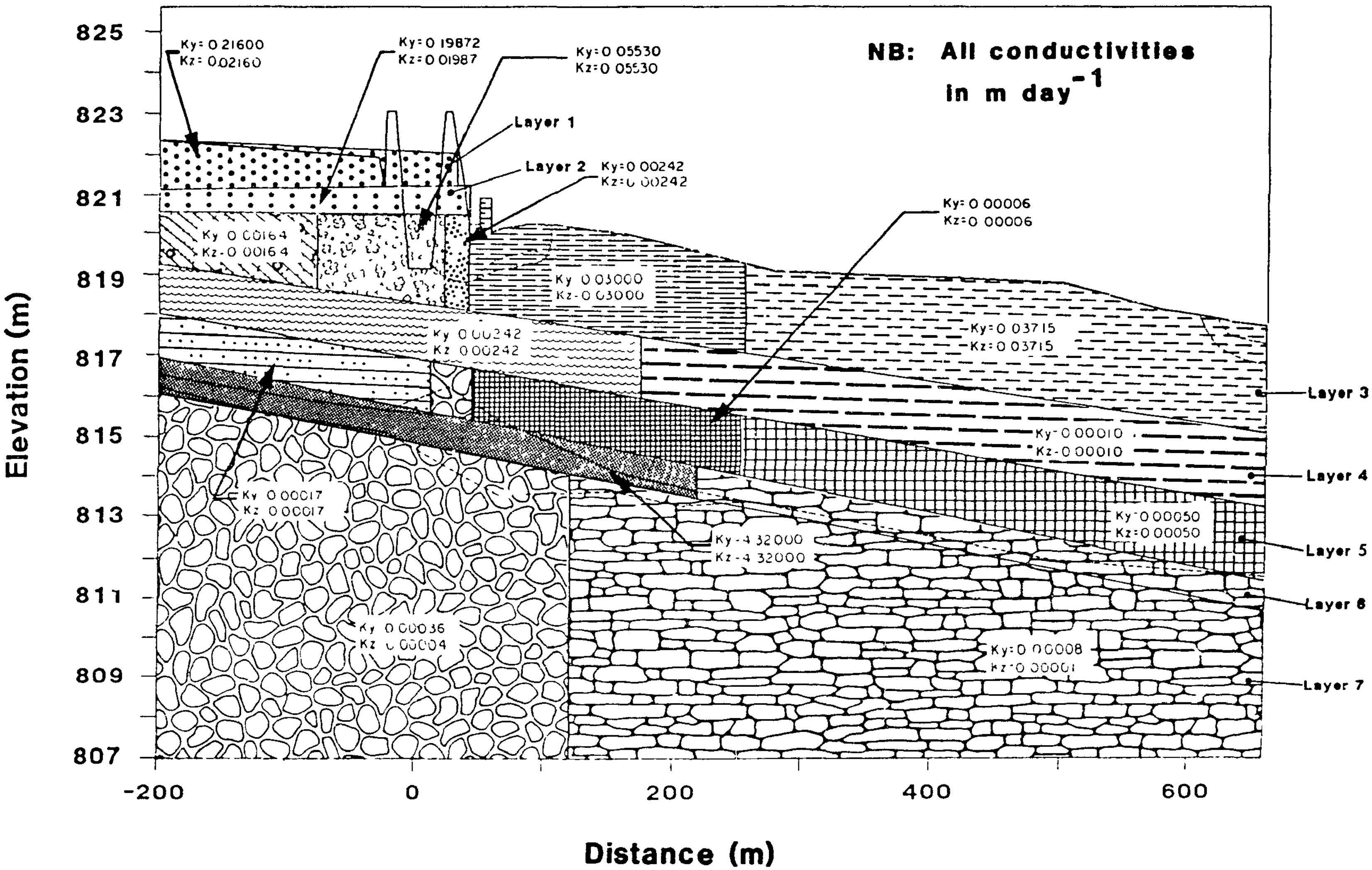

Fig. 13. Hydraulic conductivities used for the groundwater flow modelling.

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the drains was 1.34 m. The transect was first calibrated with the existing grid drainage system. The deviation of the simulated heads to actual heads measured on August 22, 1988 was 0.16 m (Table 4). The model was then run for winter conditions and simulated heads compared well with heads measured on February 14, 1989 (Table 5). Some of the water table wells and piezometers were either damaged, frozen or still recovering and thus, were not used for calibration.

After calibration, the model was run with a deep interceptor drain. Then, drains were removed. Resulting steady state water table levels during irrigation for grid, deep interceptor and no-drain conditions are shown in Figure 14. Results indicated that the zone of influence of a deep interceptor drain was less than 50 m. Conversely, grid drainage maintained the water table below the 1.0 m DWD over the entire downslope area.

Simulations were also generated under an irrigation recharge of 0.26 mm day^{-1}, which approximates the leaching fraction required to maintain low salinity in the root zone of an alfalfa crop (Robertson, 1988). The resulting water table level with a deep interceptor was at ground surface for the entire irrigated area (Figure 15). On the other hand, with grid drainage, the water table would remain below the 1.0 m DWD over most of the area.

Simulated drain and canal seepage flows for the deep interceptor and grid drainage simulations under irrigation (no recharge) appear in Table 6. Predicted grid drainage flow (7.72 l min km^{-1}) compared well with the actual drain outflow measured on August 22, 1988 (11.78 l min km^{-1}). Predicted deep interceptor flow was also in close agreement with that predicted by equation [15] (section 2.3.2, i.e. 0.84 l min^{-1} km^{-1}). Simulated canal seepage, on the other hand, was lower than that predicted by equation [13] (section 2.3.1, i.e. 14.5

Table 4. Comparison of the measured and simulated hydraulic head data for the calibration of transect D (August 22, 1988).

	Coordinates		Hydraulic head (m)		
Well #	Distance from canal (m) †	Layer	Simulated	Measured	Absolute deviation
D1	-195.0	3	820.34	820.17	0.17
		4	820.35	819.92	0.43
		5	820.42	820.25	0.17
		6	820.49	820.48	0.01
		7	820.48	820.52	0.04
D2	-63.0	2	820.53	820.55	0.02
		3	820.58	820.59	0.01
		5	820.47	820.64	0.17
D3	-25.3	2	820.98	821.18	0.20
		3	820.98	821.19	0.21
		4	820.93	821.18	0.25
		5	820.61	821.16	0.55
		6	820.34	820.51	0.17
		7	820.34	820.50	0.16
D4	25.2	2	821.10	821.10	0.00
		3	821.10	821.12	C.02
		4	821.08	821.13	0.05
		5	820.65	821.09	0.44
		6	820.26	820.46	0.20
		7	820.27	820.26	0.01
D7	75.9	3	818.92	819.24	0.32
		4	818.96	819.20	0.24
		5	819.57	819.39	0.18
D8	106.9	3	818.78	819.16	0.38
D9	151.6	3	818.61	818.59	0.02
		5	819.37	819.46	0.09
		6	820.03	820.11	0 08
		7	820.04	819.97	0.07
D10	211.6	3	818.31	818.29	0.02
		5	819.37	819.00	0.37
		6	820.01	819.98	0 03
		7	819.39	819.14	0.25
D11	279.1	3	817.72	817.50	0.22
		4	817.72	817.67	0.05
		5	817.56	817.46	0.10
D12	429.1	3	816.46	816.51	0.05
D13	494.1	5	815.99	815.68	0.31
D15	657.4	4	814.84	814.60	0.24
		7	814.86	814.74	0.12
			Mean absolute deviation		0.16

† A negative distance indicates that the well was located upslope of the canal

Table 5. Comparison of the measured and simulated hydraulic head data for the calibration of transect D (February 14, 1989).

	Coordinates		Hydraulic head (m)		
Well #	Distance from canal (m) +	Layer	Simulated	Measured	Absolute deviation
D1	-195.0	4	819.69	819.50	0.19
		5	819.68	819.50	0.18
		6	819.68	819.77	0.09
		7	819.67	819.78	0.11
D2	-63.0	3	819.82	819.78	0.04
		3	819.52	819.81	0.29
		5	819.90	819.52	0.38
D3	-25.3	3	819.47	819.44	0.03
		4	819.47	819.50	0.03
		5	819.47	819.51	0.04
		6	819.47	819.65	0.18
		7	819.47	819.76	0.29
D4	25.2	3	819.41	819.26	0.15
		3	819.41	819.26	0.15
		4	819.41	819.25	0.16
		5	819.42	819.27	0.15
		6	819.43	819.56	0.13
		7	819.42	819.60	0.18
D5	35.6	3	819.06	819.45	0.39
D7	75.9	3	818.88	818.54	0.34
		4	818.90	818.75	0.15
		5	819.14	818.98	0.16
D8	106.6	3	818.75	818.30	0.45
D9	151.6	3	818.58	818.57	0.01
		3	818.58	818.45	0.13
		5	818.97	818.97	0.00
		7	819.31	819.31	0.00
D10	211.6	3	818.22	817.87	0.35
		3	818.22	818.02	0.20
		5	818.31	817.94	0.37
D11	279.1	3	817.53	817.12	0.41
		4	817.53	816.82	0.71
		5	817.53	817.05	0.48
		7	817.54	816.65	0.89
D13	494.1	5	814.93	814.78	0.15
		6	814.93	814.92	0.01
		7	814.94	814.49	0.45
D15	657.4	5	814.25	814.17	0.08
		7	814.26	814.18	0.08
			Mean absolute deviation		0.22

+ A negative distance indicates that the well was located upslope of the canal

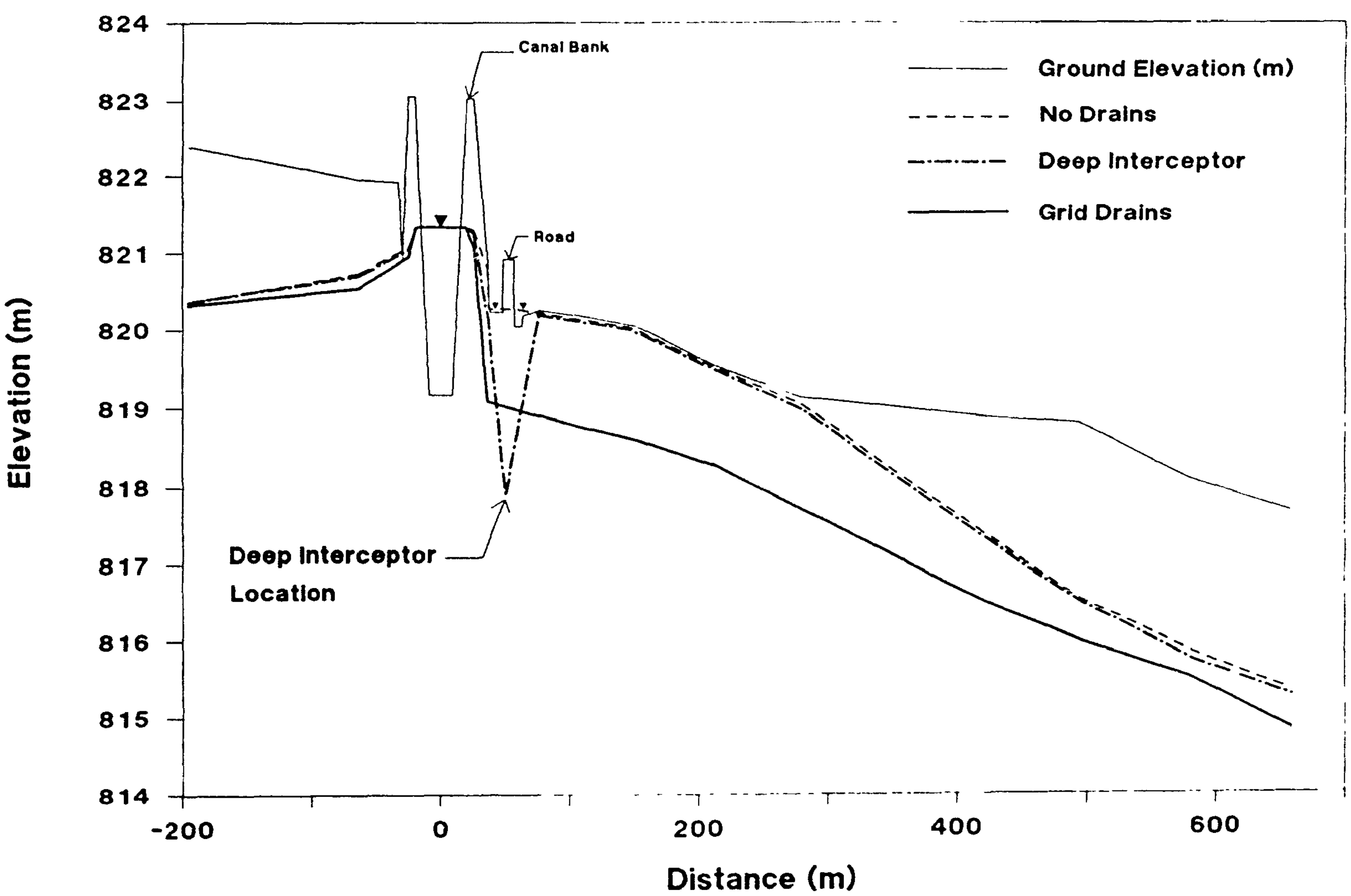

Fig. 14. Simulated water table response during irrigation.

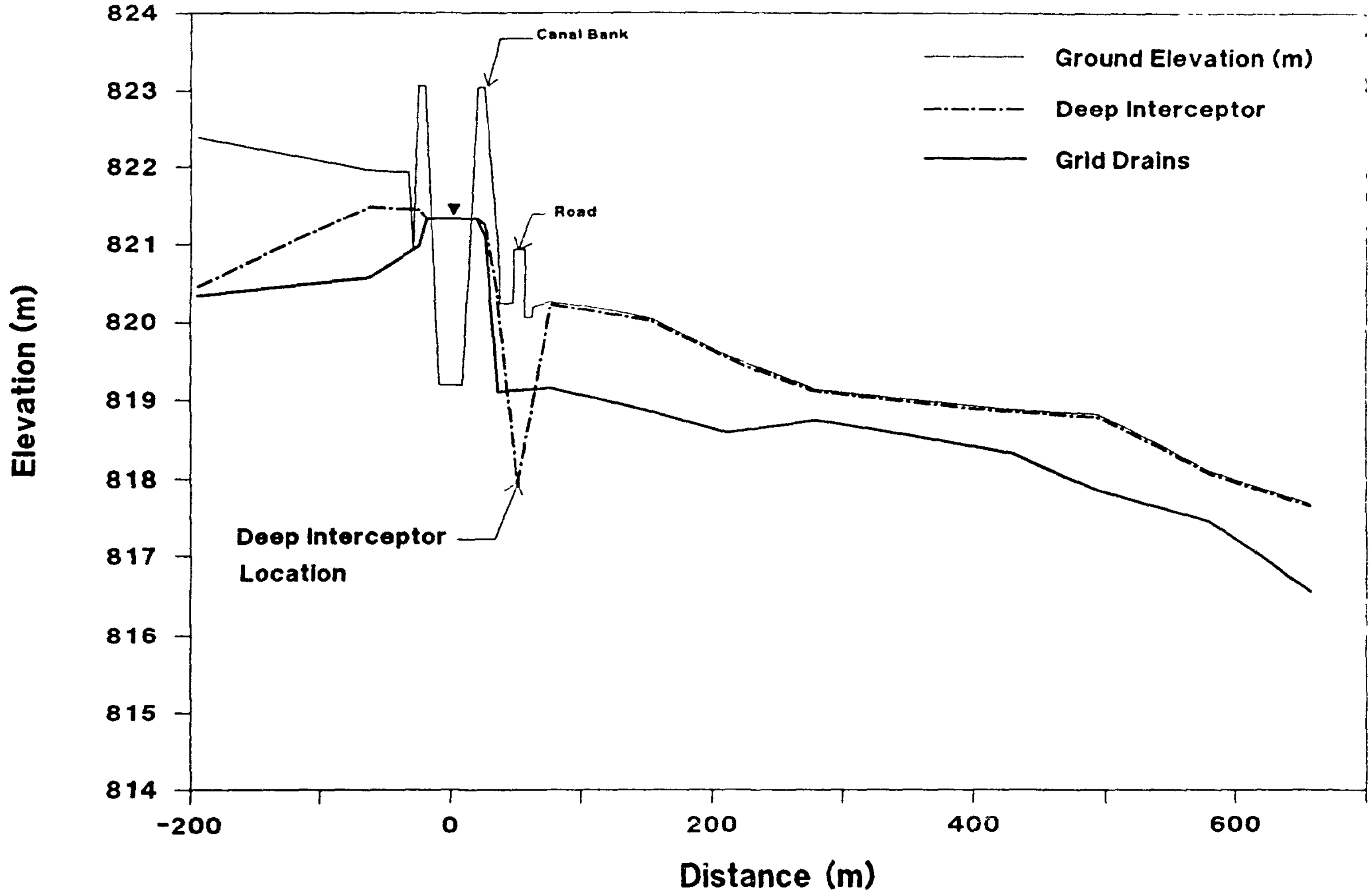

Fig. 15. Simulated response of interceptor drains to irrigation recharge.

1 min^{-1} km^{-1}). Increasing the hydraulic conductivity of the canal bed material did not result in an increase in canal seepage, suggesting that the surrounding material was responsible for limiting canal seepage. The presence of a dense till 2.0 m below the canal (K_y = 0.002 m day^{-1}), which cannot be accounted for by equation [13], may explain why the value of canal seepage predicted by that equation is greater than that obtained by simulation. Canal seepage was greater with grid drainage because the resulting hydraulic gradient near the canal was twice that with deep interceptor drains.

Table 6. Simulated canal seepage and drain outflow under existing land management (1 min^{-1} km^{-1}).

Type	Simulations	
	Deep interceptor	Grid drainage
Canal seepage	3.77	6.53
Drain outflow	1.14	7.72

Results, presented in Table 6, indicate that a deep interceptor could collect only 30% of the canal seepage. Most of the canal seepage appeared to bypass the deep interceptor, probably by entering the permeable coal seam located about 3 m below the deep interceptor drain. Conversely, grid drainage intercepts all canal seepage as well as some natural groundwater seepage.

In summary, groundwater simulations indicated that a deep interceptor would fail to intercept all canal seepage and would not maintain the water table below the 1.0 m DWD because of natural groundwater accretions. Conversely, grid drainage would intercept all canal seepage and would maintain the water table below the 1.0 m DWD, with or without irrigation recharge that would maintain a steady state salt balance.

4.3 Physical characteristics of the test plots

4.3.1 Soil classification

Horizon designations and morphological descriptions of six selected soil pits excavated in the test plot area (see location on Figure 16) are given in Appendix A. Based on these soil profiles, soils were classified according to the Canadian System of Soil Classification (Canada Soil Survey Committee, 1978) and mapped as illustrated in Figure 16.

Soils in the test plot area were of the Chernozemic order and were generally saline with salinity levels decreasing with distance from the canal. Topography was relatively flat and parent material was mostly till with a significant percentage of fluvial or lacustrine material overlying glacial till near the canal.

At test plot #1, soils were predominantly saline Orthic Gleysol (northeastern area) with a significant percentage of saline carbonated Gleyed Brown Chernozem. Soils were mostly developed from lacustrine parent material (0 to 1.0 m deep) overlying glacial till.

At test plot #2, soils were primarily saline carbonated Orthic Brown with minor inclusions of saline Orthic Gleysol and saline or saline carbonated Gleyed Brown Chernozem. Soils of the northern half of the test plot developed on fluvial material overlying glacial till which surfaced south of Transect F (Figure 8). Depth of the fluvial deposit at the northern edge of the plot was 1.0 m.

Test plot #3 was found to be mostly saline Orthic Brown with a significant inclusion of saline Solonetzic Brown following the path of a depression traversing the plot in a southeast - northwest direction. Soils at test plot #3 originated from glacial till.

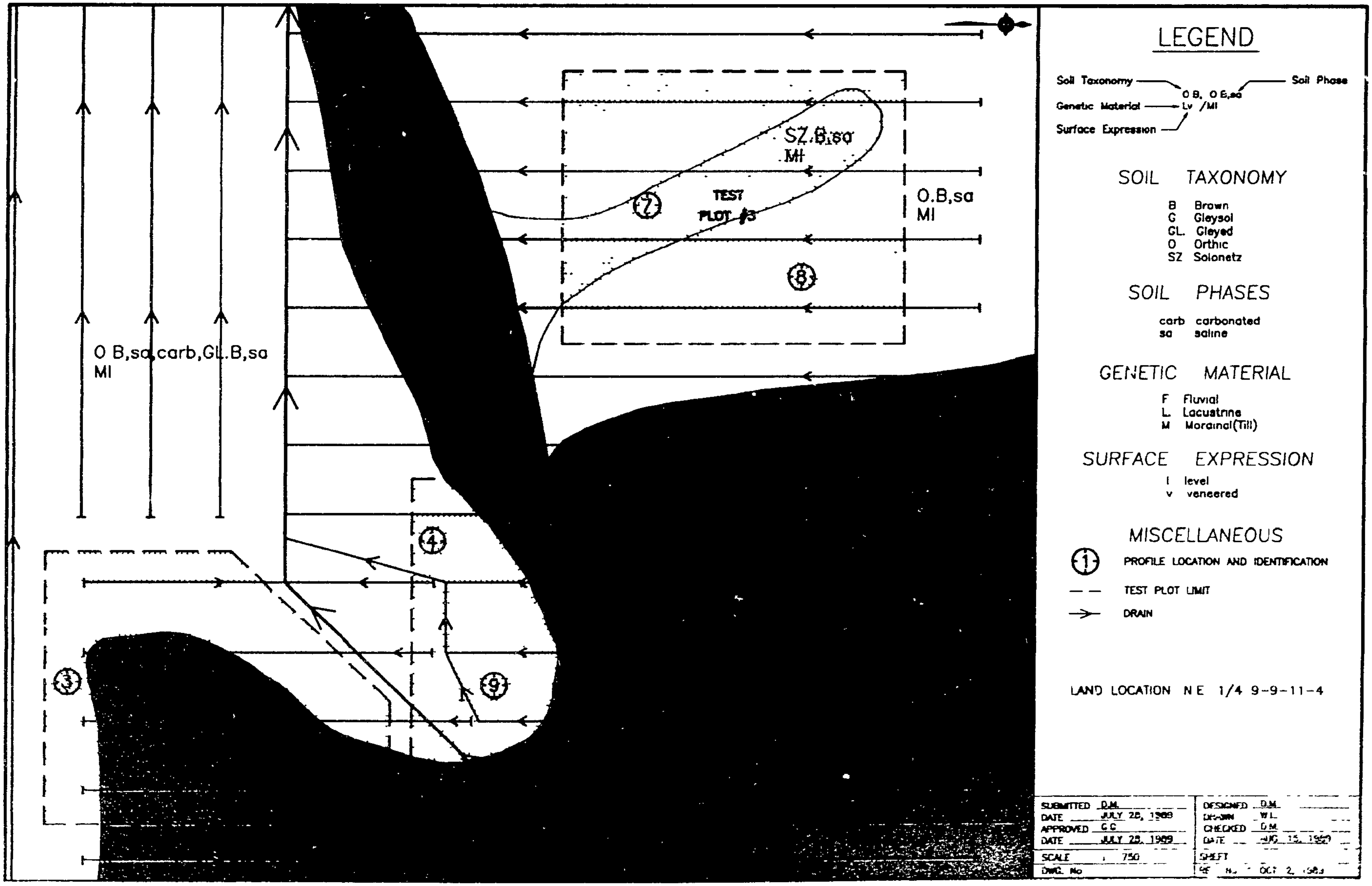

Fig. 16. Soil classification map for the test plot area.

4.3.2 Initial soil salinity

Initial values of EC_o, SAR_o and pH measured on September 2, 1987, prior to the first fall irrigation, are presented in Table 7. Results indicated that, according to the U. S. Salinity Laboratory (1954), soils at test plot #1 were saline sodic while those at test plots #2 and #3 were saline. Saline sodic patches were also present in test plot #2 in the depression along transect E (Figure 8). At test plot #1, EC_o and SAR_o decreased with depth while pH increased marginally. At test plots #2 and #3, both EC_o and SAR_o increased with depth but pH was not found to vary with depth.

Table 7. Initital† soil salinity at the test plots.

Test plot	Depth (m)	EC_o (dS m^{-1})	SAR_o	pH	Classification‡
1	0.00 - 0.15	16.7	19.6	8.2	Saline sodic
	0.15 - 0.30	15.7	19.4	8.1	
	0.30 - 0.60	13.5	18.1	8.4	
	0.60 - 0.90	10.8	16.2	8.4	
2	0.00 - 0.15	9.6	10.8	8.0	Saline
	0.15 - 0.30	10.2	11.7	7.9	
	0.30 - 0.60	11.8	15.3	8.0	
	0.60 - 0.90	12.4	16.1	8.1	
3	0.00 - 0.15	5.6	6.8	8.0	Saline
	0.15 - 0.30	6.7	7.7	7.9	
	0.30 - 0.60	8.2	10.4	7.9	
	0.60 - 0.90	10.1	14.3	8.2	

† Sampled on Sept. 02, 1987
‡ U.S. Salinity Laboratory (1954)

Figures 17 and 18 show the spatial distribution of the initial surface soil salinity and sodicity (EC_o and SAR_o) within the test plot area. In general, EC_o and SAR_o followed a similar trend and decreased with distance from the canal. The highest EC_o and SAR_o values were recorded at test plot #1.

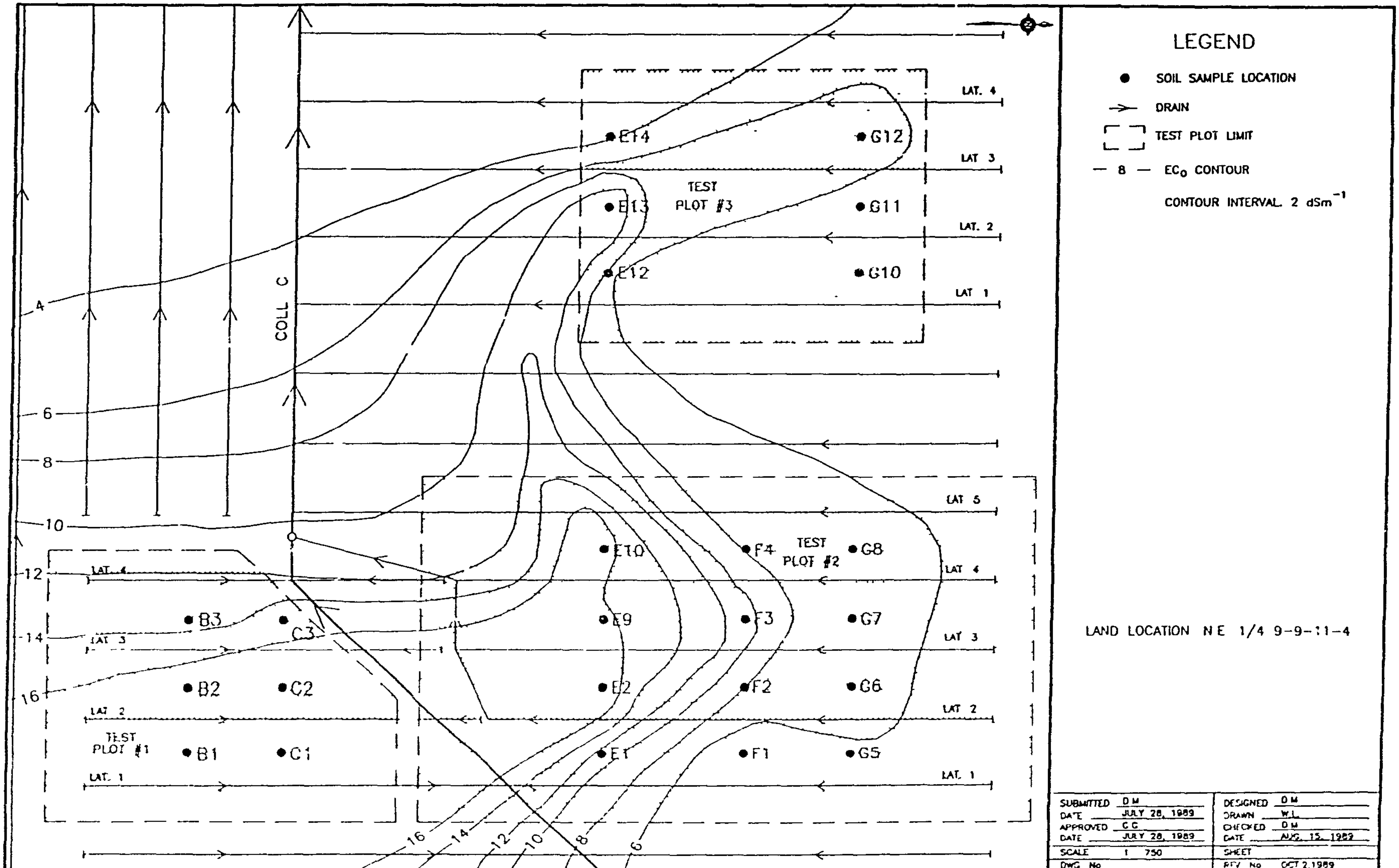

Fig. 17. Initial surface soil salinity (EC_o) in the test plot area; 0.0 to 0.3 m depth.

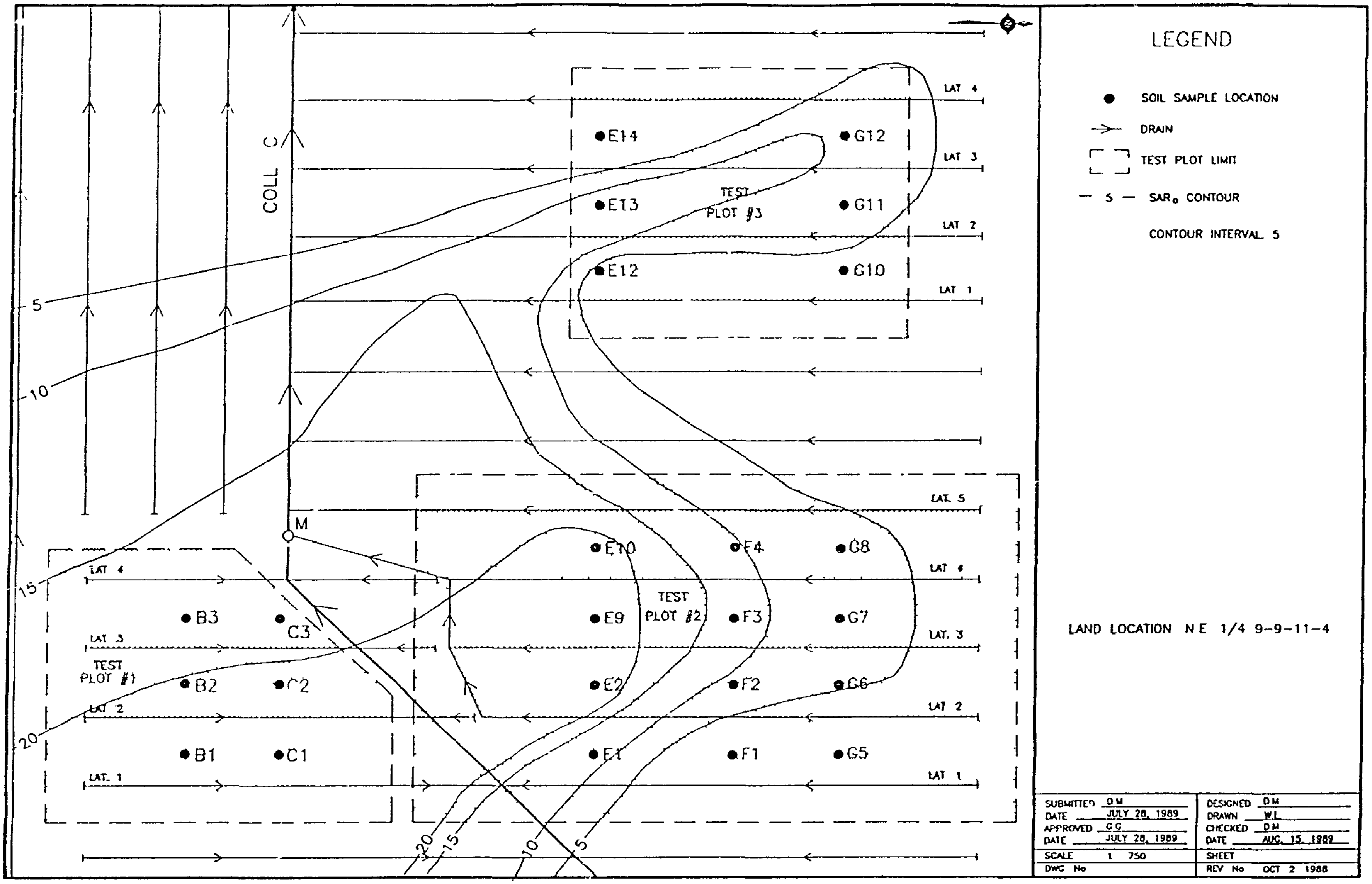

Fig. 18. Initial surface soil sodicity (SAR_o) in the test plot area; 0.0 to 0.30 m depth.

4.3.3 Hydraulic conductivity

Auger hole hydraulic conductivities (K_a and K_b) are presented in Table 8. Location of the test holes are shown in Figure 8. The mean hydraulic conductivity of the soil material above drain centre (K_a) at test plot #1 was 0.049 m day^{-1} and was not significantly different (0.05 level of significance) from that measured at test plot #2 (0.040 m day^{-1}). The average K_a value for plots # 1 and #2 was 0.044 m day^{-1}. Because of the relatively low water table at test plot #3 (section 4.4.1), values of K_a could not be obtained using the auger hole method.

The mean hydraulic conductivity of the soil material below drain centre (K_b) was 0.043 m day^{-1} at test plot #1, 0.028 m day^{-1} at test plot #2 and 0.025 m day^{-1} at test plot #3. Results of a Fisher least significant difference test showed that there were no significant differences in K_b between the three plots. A t-test comparing K_a with K_b found that the mean K_a at test plot #1 was not significantly different from K_b (0.05 level). A similar conclusion was found for test plot #2.

Soil hydraulic conductivity can also be derived from drain outflow and water table elevation data. Houghoudt's equation (Eq. [16]) can be transformed to a linear equation as follows:

$$\frac{q_s}{h} = \frac{8d_e\ K_b}{L'^2} + \frac{4K_a h}{L'^2} \qquad [17]$$

A graph of q_s/h vs h was plotted using 75 values of drain outflow (q_p) and water table head (h) (Figure 19). The following equation was developed:

Table 8. Hydraulic conductivities determined by the auger hole method.

		K_a		K_b	
Test plot	Testhole	Hydraulic conductivity (m day^{-1})	Dominant material	Hydraulic conductivity (m day^{-1})	Dominant material
1	7	0.041	Till	0.029	Till
	8	0.135	Till	0.131	Till
	9	0.028	Till	0.020	Till
	10	0.036	Till	0.045	Till
	Mean †	0.049	Till	0.043	Till
	SDF	0.304		0.353	
2	1	N/A	Till	0.068	Till
	2	0.047	Till	N/A	Till
	3	0.030	Till	0.009	Till
	4	0.027	Till	0.038	Till
	5	0.067	Fluvial	0.028	Till
	6	N/A	Fluvial	N/A	Till
	Mean †	0.040	Till	0.028	Till
	SDF	0.182		0.369	
3	11	N/A	Till	0.028	Till
	12	N/A	Till	0.022	Till
	13	N/A	Till	0.055	Till
	14	N/A	Till	0.011	Till
	Mean †	N/A ‡	Till	0.025	Till
	SDF	N/A		0.289	
overall Mean †		0.044	Till	0.031	Till
overall SDF		0.236		0.324	

† geometric means (Buckland, 1988).
‡ water table too low for measurement.
SDF: standard deviation factor (Buckland, 1988).

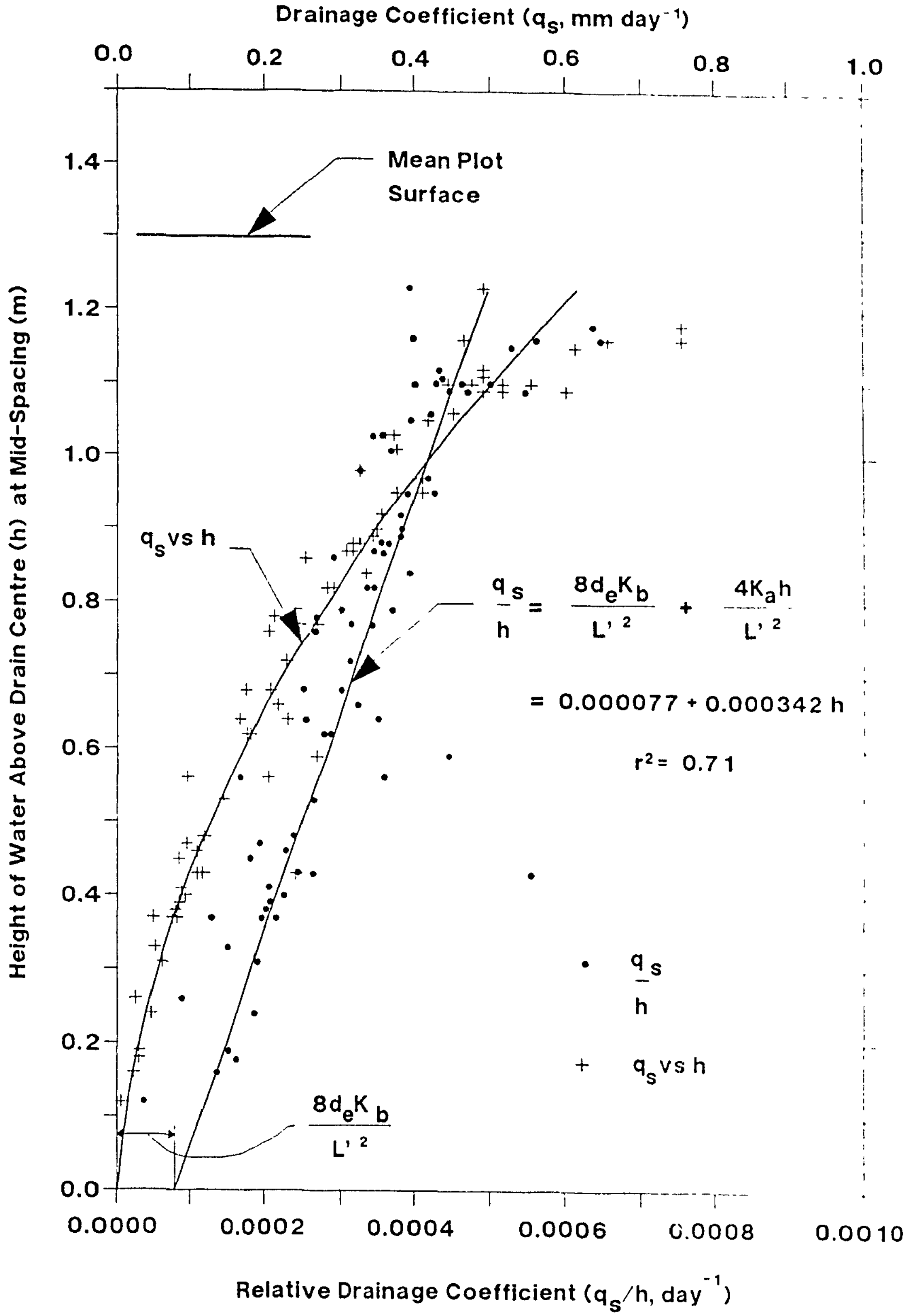

Fig. 19. Graph of q_s/h vs h for a two layered soil (test plot #2).

$$\frac{q_s}{h} = 0.000077 + 0.000342\ h \qquad [18]$$

$$r^2 = 0.71$$

From equation [18], K_a = 0.019 m day^{-1} and K_b = 0.003 m day^{-1}. The above values were obtained assuming a drain depth of 1.3 m, a depth to barrier (d) of 1.1 m and an equivalent depth (d_e) of 0.83 m.

Table 9. Summary of saturated hydraulic conductivities for test plot #2.

Method	K_a (m day^{-1})	K_b (m day^{-1})
Auger hole	0.0400	0.0280
Drain outflow and water table measurements	0.0190	0.0030
Single well response test	N/A	0.0008

The previous K_a is approximately 50% of the 0.040 m day^{-1} found with the auger hole method (Table 9). The value of K_b obtained from drain outflow and water table head data (0.003 m day^{-1}) was only 10% of that obtained with the auger hole method, (0.028 m day^{-1}) but greater than that obtained from single well response tests performed at four 2.0 m deep piezometers (0.0008 m day^{-1}). The mean K_b value obtained from the 0.5 m screened intake zone piezometers was however in the order of the 0.0004 m day^{-1} hydraulic conductivity value found by Hendry (1982) for the small scale fractures of tills in the area. It is possible that piezometers did not traverse large scale fractures because spacing between large scale fractures (0.004 m to 0.63 m) exceeded the length of the 0.5 m screened intake zone (Hendry, 1982). Conductivities obtained from those four single well response tests may therefore have been representative of the conductivity of the small scale fractures.

With the auger hole method, K_b was measured over a soil interval of at least 1.0 m. Thus it is likely that at least one large scale fracture was intercepted. This would explain why the K_b value obtained with the auger hole method was in the order of that of large scale fractures (0.017 m day^{-1}; Hendry, 1982). The average K_b values obtained from drain outflow and water table head data (0.003 m day^{-1}) was between that of small scale fractures (0.0004 m day^{-1}) and large scale fractures (0.017 m day^{-1}). One hypothesis is that most of the flow entering the drainage system below drain centre originated from large scale fractures but smearing of the trench that occurred when drains were plowed in restricted the flow. Asselin and Trottier (1989) showed that under saturated conditions, the drainage plow can destroy the structure of heavy clays in the vicinity of the trench and thus cause a severe restriction to the flow to the drains.

The discrepancy between K_a values obtained with the auger hole method and that obtained from drain outflow and water table head data is not as pronounced. One hypothesis is that smearing of the upper portion of the trench was not as important because the soil moisture content during installation was lower. Therefore, obstruction to the flow entering the drain through the upper section of the trench, was less important.

4.3.4 Soil infiltrability

Modified double ring infiltrometers were used to measure the soil infiltration rate at the three test plots. Results are presented in Table 10. At test plot #1, no data were obtained due to failure of the apparatus. At test plot #2, infiltration tests were performed adjacent to water table wells (WTW) E2 and F2 (Figure 8). Surface soil at water table well E2 was bare and a hard surface crust had developed. Surface soil salinity (EC_e = 17.4 dS m^{-1}) and sodicity (SAR_e = 21.4) were severe. These surface soil conditions were representative of those found at test plot #1 and south of transect E at test plot #2. The measured final infiltration rate (FIR) at WTW E2 was 1.5 mm day^{-1}.

Table 10. Infiltration rates at selected sites within the test plot area.

Test #	Plot #	Location†	FIR (mm day^{-1})	Vegetation	Texture‡	EC_e§ (dS m^{-1})	SAR_e§
I1	2	WTW E2	1.5 2.1¶	Bare	SL/SL	17.4	21.4
I2	2	WTW F2	128.0	Wheat	SL/LS-SL	8.7	7.7
I3	3	WTW G10	140.0	Wheat	SL/CL	2.0	2.1

† See Figure 8 for locations.
‡ Soil textures are for depths of 0.20 and 0.40 m.
¶ After cultivation of the soil surface.
§ 20 cm depth.
FIR Final infiltration rate.

To have a better understanding of the mechanism and the effect of surface crusting on FIR, surface soil at ring #I1 (WTW E2) was allowed to dry and then tilled to a depth of 0.15 m and the surface was roughened. An infiltration test was then repeated. The initial rate of infiltration dropped to approximately 30 mm day^{-1} within 10 minutes and then remained constant for the next 300 minutes. Thereafter, it dropped substantially and reached a FIR of 2.1 mm day^{-1}. The FIR obtained after cultivation does not appear to be different from that obtained prior to cultivation considering the normal variability in infiltration rate data. The infiltration rate during this second test decreased substantially with time and it is believed that low FIR was the result of soil swelling and dispersion caused by the high SAR_e. This mechanism was also believed to be responsible for the formation of a surface crust when the soil was later allowed to dry.

These results suggest that surface swelling and dispersion play a major role in limiting the infiltration rate of saline sodic soils. These findings are supported by Shainberg (1984) who reported that irrigating sodium rich soil with low electrolyte concentration water can cause chemical dispersion of the soil surface, thereby enhancing the formation of a low conductivity surface crust when soils are allowed to dry.

However, because soil salinity at WTW E2 was relatively high (EC_e = 17.4 dS m^{-1}), one could have suspected that high electrolyte concentration in the soil solution would have outweighed the influence of exchangeable Na and prevented surface dispersion. One plausible explanation for the progressive decrease in the infiltration rate observed during the test is that dilution of the surface, saline soil solution with fresh irrigation water (EC_e = 0.3 dS m^{-1}) occurred at an early stage of the infiltration test. This may have resulted in chemical dispersion and consequently, progressive sealing of the surface soil. Therefore, soil infiltration appeared to be a major factor in limiting soil reclamation at test plot #1 and part of test plot #2, south of transect E.

Infiltration test #I2 (WTW F2) was performed at a location representative of surface soil conditions at test plot #2, north of transect E and most of test plot #3 (EC_e = 8.7 dS m^{-1} and SAR_e = 7.7). Results suggested that a lower level of soluble Na combined with a good crop cover helped maintain the FIR at 128.0 mm day^{-1}.

Surface soil conditions where infiltration test #I3 was performed were representative of those found at test plot #3. The FIR was 140.0 mm day^{-1}. The presence of a well established crop cover combined with low salinity and sodicity levels (EC_e = 2.0 dS m^{-1}, SAR_e = 2.1) prevented surface dispersion and sealing.

4.4 Drainage system performance at the test plots

4.4.1 Water table fluctuations

Figures B3 through B5 show representative water table elevation hydrographs for each test plot (Appendix B). Table 11 is a summary of this data and gives the frequency, in percent, when the water table was shallower than the 1.0 m DWD.

Table 11. Frequency of occurrence of the water table (in %) above the DWD[†] for the period August 1, 1987 to October 10, 1988.

	Period				
	End of 1987[‡] Irrig. Seas.	Winter[¶] 1987-1988	Main 1988[§] Irrig. Seas.	End of 1988[‡] Irrig. Seas.	Aug-1,1987 to Oct-10,1988
TEST PLOT #1					
Transect B	100	71	100	31	71
Transect C	100	56	100	50	76
Average	100	63	100	40	73
TEST PLOT #2 (solid set fall irrigated)					
Transect E	100	56	100	96	93
Transect F	100	56	93	85	87
Transect G	100	56	100	88	90
Average	100	56	98	90	90
TEST PLOT #3					
Transect E	91	63	100	30	66
Transect G	86	11	36	0	35
Average	88	35	68	16	51
ENTIRE DRAINED AREA					
Transect A	4	0	5	0	3
Transect D	57	41	70	22	52
Average	32	22	42	12	29

† 1.0 m (Buckland et al., 1987b).
‡ August 1 to October 10.
¶ October 11 to April 10.
§ April 11 to July 31.

From this table, it appears that individual transects performed similarly within each test plot. A statistical analysis (two sample t-test or Fisher's LSD test) showed that water table levels at each transect, within the same plot, were not significantly different at the 0.05 level of significance except at test plot #3. Water table levels at transect E (test plot #3) were usually shallower than those at transect G.

Data indicated that at the end of the 1987 irrigation season, (August 1st to October 10) the water table at test plot #1 remained continuously above the DWD (Table 11). In 1988, the water table rose above the 1.0 m DWD only 40% of the time. The poor performance of the drainage system at the end of the 1987 irrigation season, compared to 1988, can be attributed to the abnormally wet month of August 1987 when 96.1 mm of rain was received. Normally, only 33 mm of rain occurs in August (Appendix C). On the other hand, the period covering the end of the 1988 irrigation season was drier than normal (Appendix C) and less irrigation water (45 mm in 1988 compared to 81 mm in 1987, Appendix D) was applied due to water restrictions imposed by the irrigation district in August 1988.

The water table at test plot #1 was above DWD 63% of the time during winter and 100% of the time during the main 1988 irrigation season (April 11 to July 31st). Although the period covering the main 1988 irrigation season was relatively dry (81.5 mm compared to 162.4 mm normally, Appendix C), intensive irrigation during that period (339.0 mm in 1988 compared to 216 mm in 1987, Appendix D) more than compensated for the drought conditions.

All the water table readings at test plot #2 were above design water table depth at the end of the 1987 irrigation season. A relatively wet month of August combined with intensive solid set fall irrigation, (section 4.5) may explain why water table elevations were always above the DWD. During the winter of 1987-88, the performance of the drainage system at test plot #2 was similar to that at test plot #1. Fifty-six percent of the water table readings were found to be above DWD. In 1988, during the first half of the irrigation season, 98% of the water table readings were above the DWD. Similarly, 90% of the water table readings were above the DWD at the end of the 1988 irrigation when intensive solid set irrigation was practiced.

Drains within test plot #3, and in particular at transect G, which was more representative of average field conditions, performed better. In the fall of 1987, shallow water table readings (88%) could be attributed to a relatively wet month of August. During winter 1987-88, the water table was above the DWD only 35% (11% at transect G) of the time, with shallower readings observed in early winter. During the first half of the 1988 irrigation season, 68% of the water table readings were above the DWD. In the fall of 1988, the percentage of shallow water table readings decreased to 16%. Transect E did not perform as well as transect G, at test plot #3, due to surface runoff accumulating near the transect. Soil salinity was also more severe near transect G (Figure 17).

As shown in Table 11, the drainage system at the test plots did not perform as well as the drainage system in the entire field. Only 29% of the water table readings at transects A and D were above the DWD. Shallow water table readings at transect A and D were recorded near the canal, within the first 250 m downslope of the canal, where salinity related problems were more acute.

A water table drawdown event for each test plot is given in Figure 20. Precipitation was negligible during the

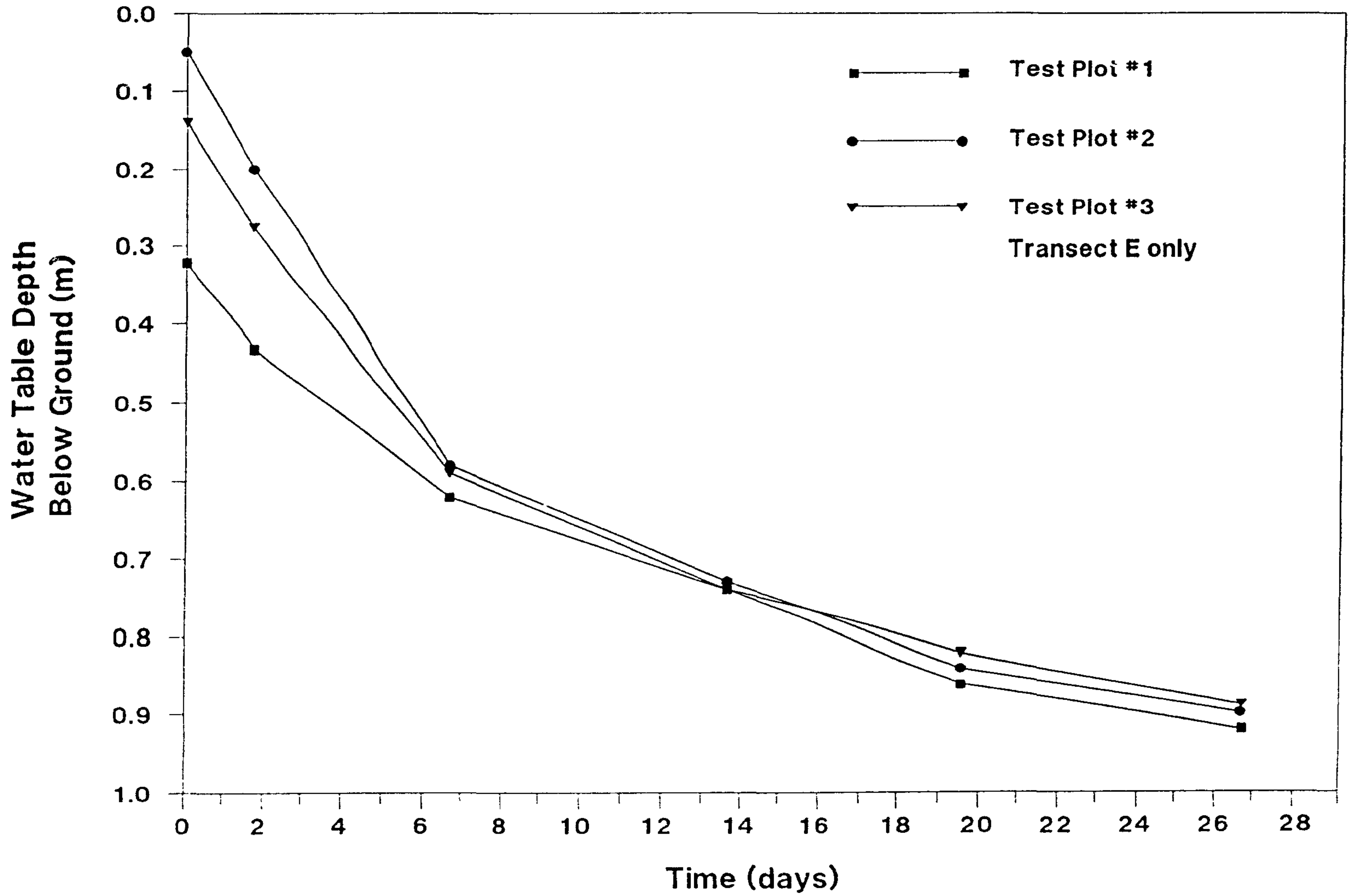

Fig. 20. Sample water table drawdowns at the test plots
(Measurements started on September 29, 1987).

drawdown events. The average rate of water table drawdown for the first 6 days was 0.044 m day^{-1} at test plot #1, 0.079 m day^{-1} at test plot #2 and 0.075 m day^{-1} at test plot #3. The rate of fall of the water table at test plot #1 was slower due to the lower initial level of the water table. Keeping in mind that K_b values of the three test plots were not significantly different at the 0.05 level of significance, this data suggests that K_a at test plot #3 was about the same as K_a of test plots #1 and #2. However, the drainage system at test plot #3 had a better performance than at test plots #1 and #2 (Table 11). This is because the drawdown curve for test plot #3 was obtained from data measured along transect E only. Soil salinity at transect E was higher than that of the remainder of test plot #3 (Figure 17). Thus, K_a along transect E was probably lower than that of the remainder of the test plot. Consequently, this combined with the effect of surface runoff ponding near transect E, would explain why the drainage system at test plot #3 did not perform as well near transect E but had a better overall performance compared to that observed at test plots #1 and #2 (Table 11).

Considering that most crops grown in the area require a water table depth of 0.60 to 0.80 m for optimum growth (Van der Berg, 1973) and that a one time rise in the water table from a depth of 0.8 to 0.1 m can cause an 80% reduction in the yield of barley (Van de Goor, 1983), data from Figure 20 suggest that the drainage system did not provide for sufficient drainage in the test plot areas.

Drain spacings for conditions met at test plot #1 and #2 were calculated using Houghoudt's equation (Eq. [16]) and hydraulic conductivities measured using the auger hole method (Table 8). At test plot #1, drain depth, DWD and depth to barrier (d) were set at 1.2, 1.0 and 1.2 m, respectively. For test plot #2, drain depth, DWD, and (d) were 1.3, 1.0 and 1.1 m, respectively. The drainage coefficient (q_s) in both cases was set at 1.0 mm day^{-1} (Buckland et al., 1987b). The resulting drain spacing was 7.4 m for test plot #1 and 7.7 m for test plot #2. The above calculations suggest that the actual 15 m drain spacing at test plots #1 and 2 was too wide and should have been about 7.5 m. Drain depths at test plots #1 and 2 (1.2 and 1.3 m, respectively) were shallower than the design 1.4 m depth due to slope limitations. A greater drain depth would have meant a wider calculated spacing (Eq. [16]).

4.4.2 Drain outflow and salinity of the effluent

Figures 21 and 22 present drain outflow hydrographs and variations in the salinity of the drainage water as related to water applications for test plot #2 and the entire drained area. Table 12 summarizes data presented in Figures 21 and 22 during irrigation. Peak and mean drain outflows and drainage water salinity levels (EC_{dw}) are presented for both the main irrigation season and the end of the irrigation season.

Table 12. Drain outflow and salinity of the effluent.

		Drain outflow (q_p, mm day^{-1})		Salinity (EC_{dw}, dS m^{-1})	
Drainage site		Main irr. seas.†	End irr. seas.‡	Main irr. seas.†	End irr. seas‡
Test	Mean	0.14	0.39	17.3	17.2
Plot #2	Peak	0.32	1.17	18.3	19.5
Entire field	Mean	0.09	0.05	8.8	9.0
(Coll.A)	Peak	0.31	0.27	10.4	12.2

†April 11, 1988 to July 31, 1988.
‡August 1, 1987 to October 10, 1987 and August 1, 1988 to October 10, 1988.

At test plot #2, mean drain outflow for the 1988 main irrigation season (April 11 to July 31) was 0.14 mm day^{-1} (Table 12). A peak value of 0.32 mm day^{-1} was recorded on June 29, 1988 following a 36 mm rain and a 27 mm irrigation (Figure 21). Salinity of the drainage water (EC_{dw}) at test plot #2 averaged 17.3 dS m^{-1} with a peak value of 18.3 dS m^{-1} observed on June 30, 1988 (q_p = 0.288 mm day^{-1}). Drain outflow measured

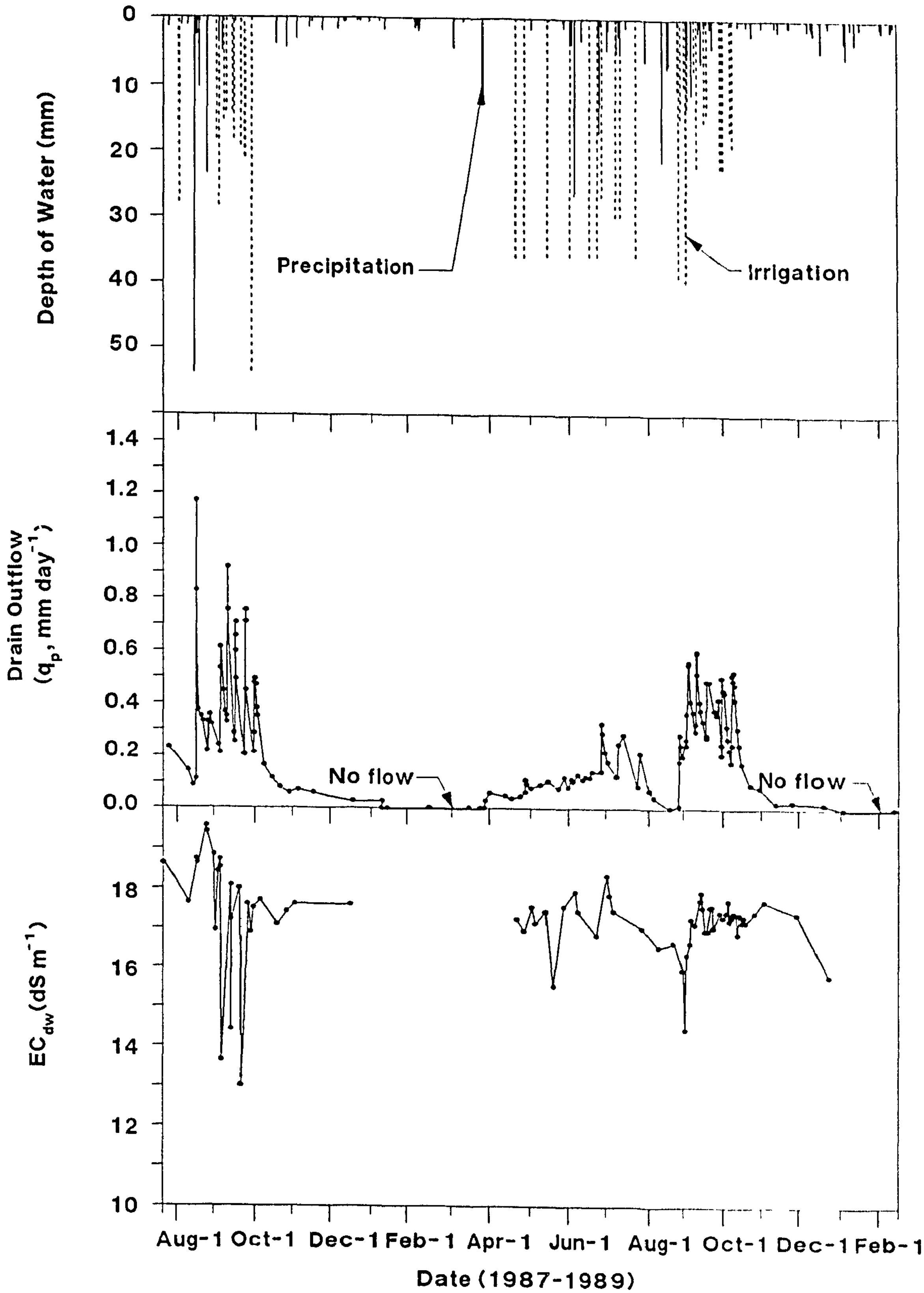

Fig. 21. Drain outflow hydrograph and salinity of the effluent at test plot #2.

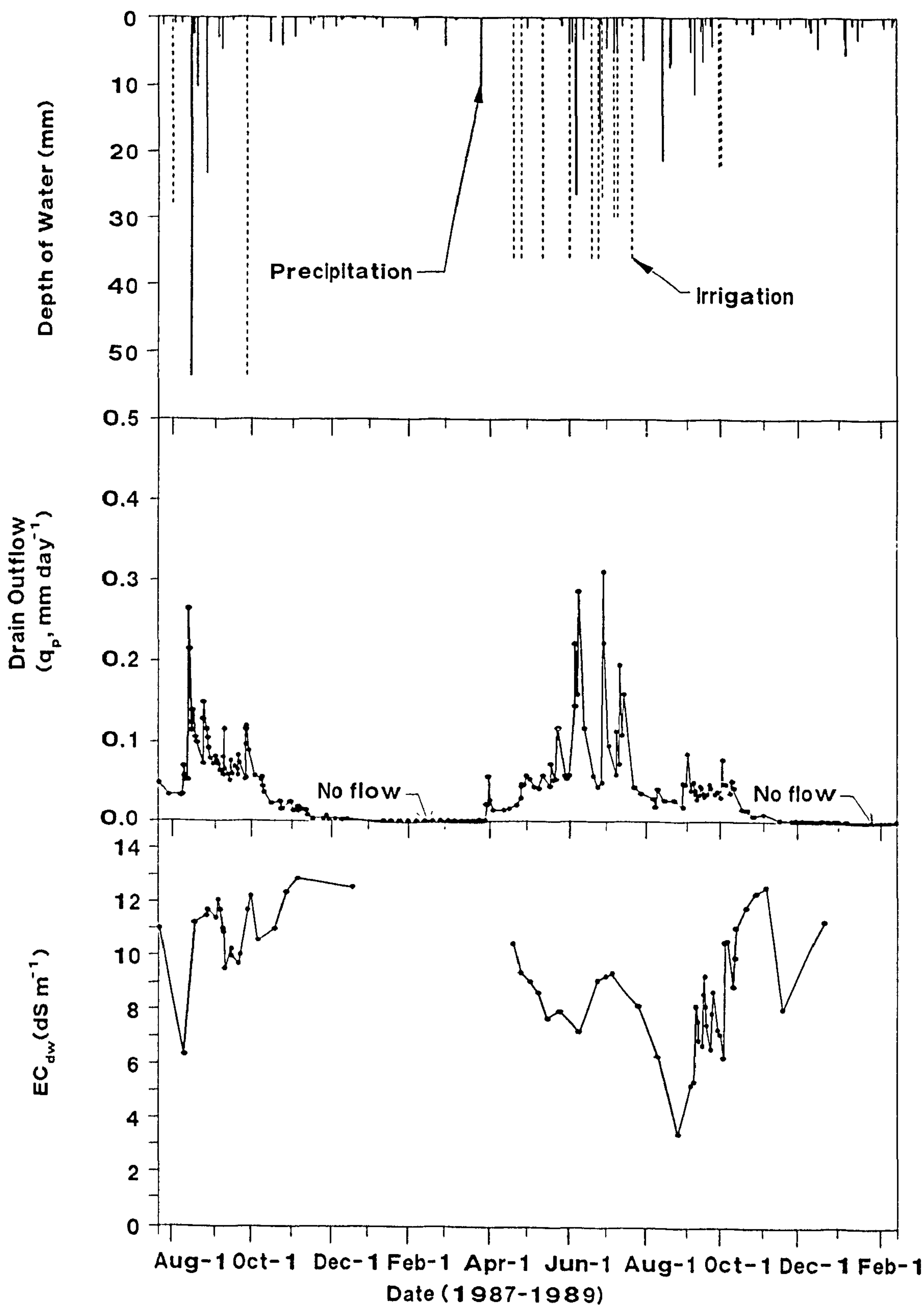

Fig. 22. Drain outflow hydrograph and salinity of the effluent at the outlet of collector A.

for the entire drained area for the main irrigation season (mean = 0.09 mm day^{-1}, peak = 0.31 mm day^{-1}) were in close agreement with those measured at test plot #2 for the same period.

At the end of the irrigation season, the mean and peak drainage coefficients measured at test plot #2 (0.39 mm day^{-1} and 1.17 mm day^{-1}, respectively) exceeded those measured for the entire drained area. This is because the water table was shallower at the test plot (Table 11). Salinity levels observed at the end of the irrigation season were similar to those observed during the first half of the irrigation season at both test plot #2 and the entire field drained.

None of the mean q_p values exceeded the design 1.0 mm day^{-1} design drainage coefficient (q_s). Only one drain outflow measurement (q_p) of 1.17 mm day^{-1} observed at test plot #2 on August 14, 1987 following a 54 mm rain, exceeded q_s. Data presented in Figure 21, however, show that within a day, q_p receded below the design drainage coefficient. The fact that drain outflow at test plot #2 seldom exceeded q_s during the fall, even though the water table was normally above the design water table depth of 1.0 m (Table 11), further suggests that the drain spacing was too wide.

Hooghoudt's equation (Eq [16]) can be rearranged to predict drain outflow (q_s) as follows:

$$q_s = \frac{8K_b\ d_e\ h + 4K_a h^2}{L'^2} \qquad [19]$$

Actual values of drain spacing and hydraulic conductivities measured, at test plot #2, with the auger hole method (Table 8) were entered in eq [19]. A value of d_e of

0.83 m was used (Wesseling, 1983). The average value of "h" measured at test plot #2 at each monitoring event, during fall irrigation, was entered and "q_s" was then calculated. The predicted q_s was further compared with the actual q_p measured at the outlet of the three laterals (QR; Figure 8). This analysis suggested that the actual q_p at test plot #2 was, on the average, 4.0 times lower ($n = 48$; $r = 0.8$) than the predicted q_s.

One explanation to this discrepancy could be that Houghoudt's equation [16] does not apply to this particular situation of canal seepage and groundwater recharge because the assumption of the presence of an impermeable layer below drain center was not exactly met. However, Houghoudt's equation should yield a good approximation of q_p considering that the upward seepage from the underlying coal seam was only 0.04 mm day^{-1} (section 4.1.2).

Another more plausible explanation to this discrepancy is that smearing of the trench occurred when drains were plowed-in and thus flow to the drainage system was restricted because of the lower conductivity of the soil at the trench. Smearing of the drain trench, within the test plot area, was very likely considering that drains were installed under shallow water table conditions and that the clay content of the soil, at drain level, normally exceeded 30% (Asselin and Trottier, 1989).

4.4.3 Drainable porosity

Drain outflow data and water table elevations measured during the September 29, 1987 water table drawdown at test plot #2 (Figure 20) were used to estimate soil drainable porosity (f) at the test plot. Drainable porosity was defined as follows:

$$f = \frac{V_{dw}}{V_{sd}} \qquad [20]$$

f = drainable porosity (dimensionless)
V_{dw} = total volume of drainage water (m^3)
V_{sd} = total volume of soil drained (m^3).

Drainable porosities obtained from drain outflow and water table drawdown data were low and ranged between 0.004 to 0.007 (Table 13). When deriving these values, it was

Table 13. Drainable porosity at test plot #2 as estimated using drain outflow and water table level data.

Depth from soil surface (m)	f
0.05 - 0.20	0.005
0.20 - 0.60	0.004
0.60 - 0.90	0.007

assumed that surface evaporation from the bare soil was negligible although some may have occurred when the water table was near the soil surface. If as suggested by Foroud (1989) the surface evaporation was equivalent to PE when the water table was shallower than 0.20 m, then the drainable porosity for the 0.05 to 0.20 m depth interval would be 0.03. PE was estimated according to a procedure described by Foroud et al. (1989). At depths of 0.60 to 0.90 m, the assumption of negligible evaporation is probably correct considering that data were recorded in the fall and that surface evaporation decreases with increasing water table depth (Gardner and Fireman, 1958). Values presented in Table 13 are within the range of values found by Buckland et al.(1986b) for a clay loam till. Their values, determined using drain outflow, ranged from 0.001 to 0.143.

4.5 Fall irrigation

4.5.1 Water balance

As discussed in section 3.4.3, fall irrigation was defined as any irrigation (pivot or solid set) occurring between August 29 and October 10. All experimental plots received 53 mm of pivot applied fall irrigation in 1987 and 45 mm in 1988 (Table 14). Solid set fall irrigation was applied at test plot #2 only. In 1987, four solid set irrigations totalling 148 mm were applied. In 1988, five solid set fall irrigations were completed, resulting in a water application of 226 mm. The average rate of water application with the solid set irrigation system was 40 mm day^{-1}. The mean Christiansen sprinkler uniformity coefficient (UC; Jensen, 1983) was 94% for pivot irrigation and 68% for solid set.

Table 14. Depth of water applied at the test plots during the fall irrigation experiment.

Description	1987 (Sep-02 to Oct-06)†			1988 (Aug-29 to Oct-19)†		
	Plot #1	Plot #2	Plot #3	Plot #1	Plot #2	Plot #3
Irrigation (mm)						
Pivot	53	53	53	45	45	45
Solid set		148			226	
Precipitation (mm)	8	8	8	35	35	35
Surface runoff (mm)	34‡	44	0	6‡	26	0
Net water application (mm)	27	165	61	74	280	80

† Dates are those of the soil samplings prior to and after a fall irrigation.
‡ Estimated based on field observations.

Water table levels at test plots #1 and #3 were slightly affected by the pivot fall irrigation events (Figures B3 and B5). This suggests that most of the irrigation water was used to replenish the soil moisture reserve and that very little leaching was actually achieved. Also, the relatively high rate of water application achieved with pivot irrigation resulted in significant water losses through surface runoff, particularly at test plot #1, which exhibited saline sodic features (section 4.3.2).

The major limitation to solid set fall irrigation at test plot #2 was surface runoff (Table 14) caused primarily by insufficient internal drainage (Figures 23 and 24) and poor infiltration. As shown in Figures 23 and 24, the water table rose nearly to the soil surface during each fall irrigation but the drainage coefficient (q_p) never exceeded the 1.0 mm day^{-1} DWD (q_s; Figures 25 and 26) expected for a mean water table depth of 1.0 m (Buckland et al., 1987b). As discussed earlier (section 4.4.1), drain spacing at the test plot was too wide. A drain spacing of 7.7 m would have provided better internal drainage and consequently, more leaching would have been achieved. Equation [16] indicates that, in fact, the drainage coefficient for a 0.10 m deep water table, and a 7.7 m drain spacing is 7 mm day^{-1} provided smearing of the drainage trench is negligible.

Only a small percentage of the water applied during fall irrigation (precipitation and irrigation) actually reached the drainage system (Table 15). An estimated 24% of the water applied replenished the soil moisture reserve. This estimate was assumed to be equivalent to the extra amount of water required to bring the water table nearly to the soil surface at the beginning of the fall irrigation period compared to that required for subsequent irrigations. Corrections were made for differences in initial transient storage, e.g. differences in initial water table levels at the beginning of

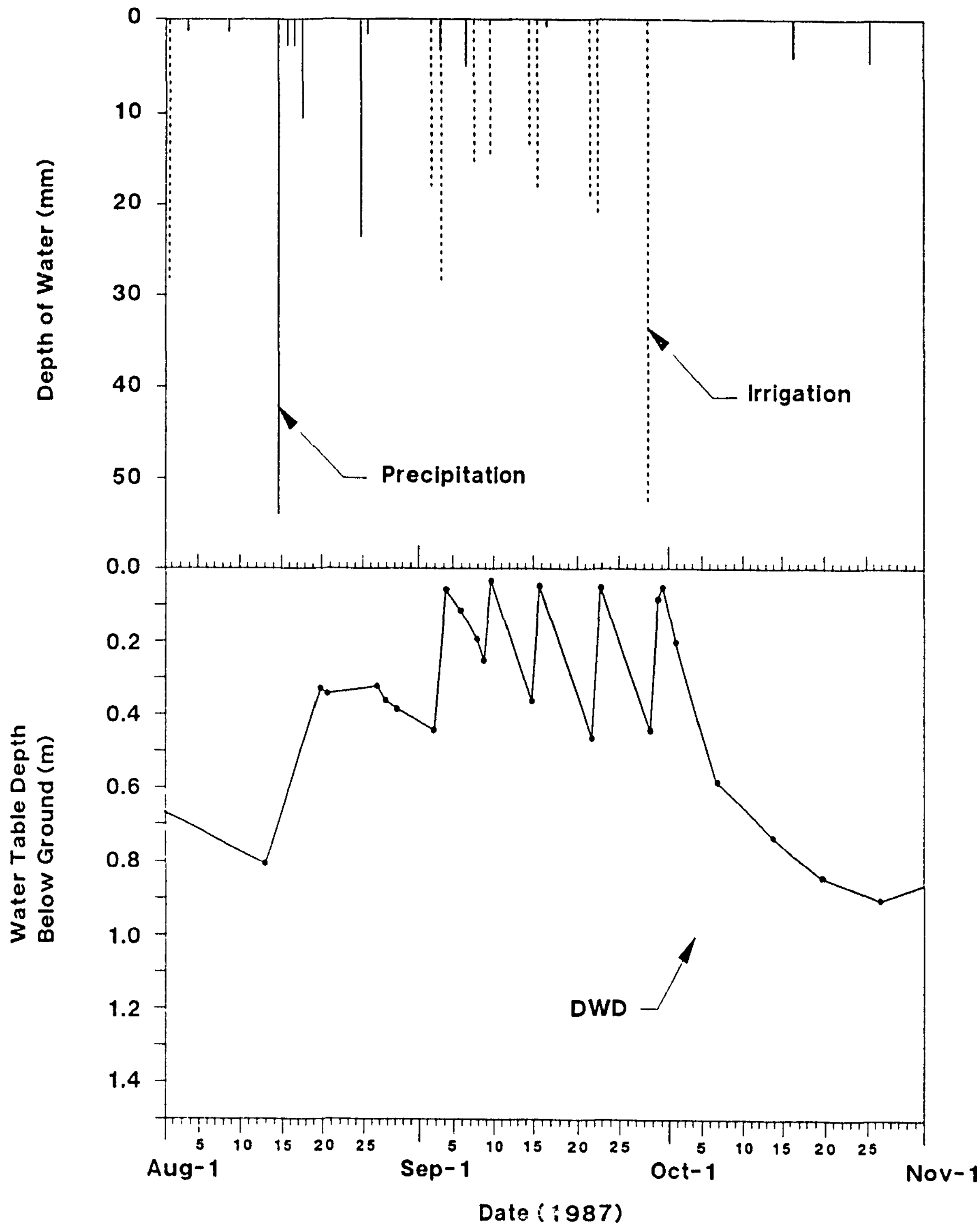

Fig. 23. Water table fluctuations as related to water applications at test plot #2 during the fall of 1987.

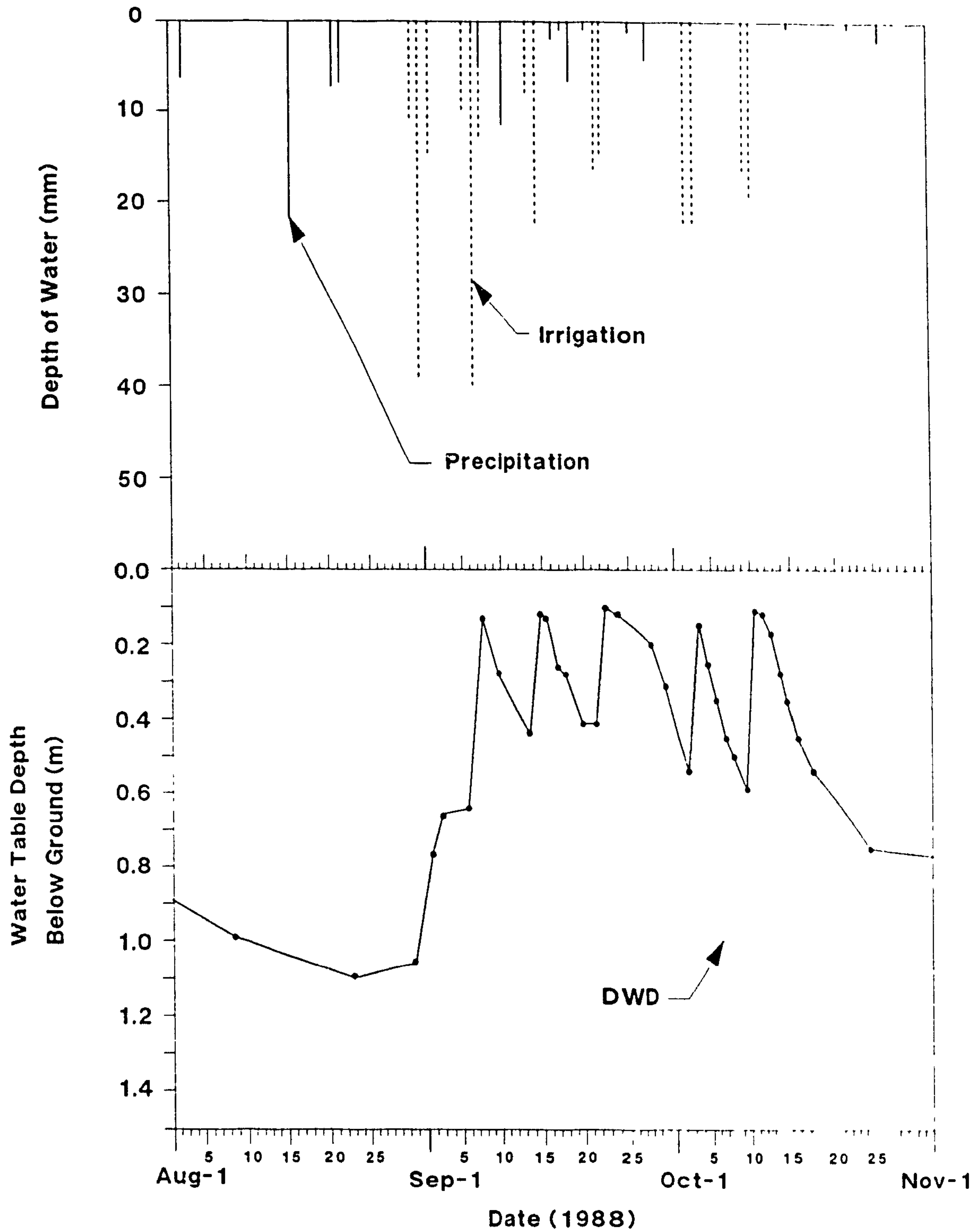

Fig. 24. Water table fluctuations as related to water applications at test plot #2 during the fall of 1988.

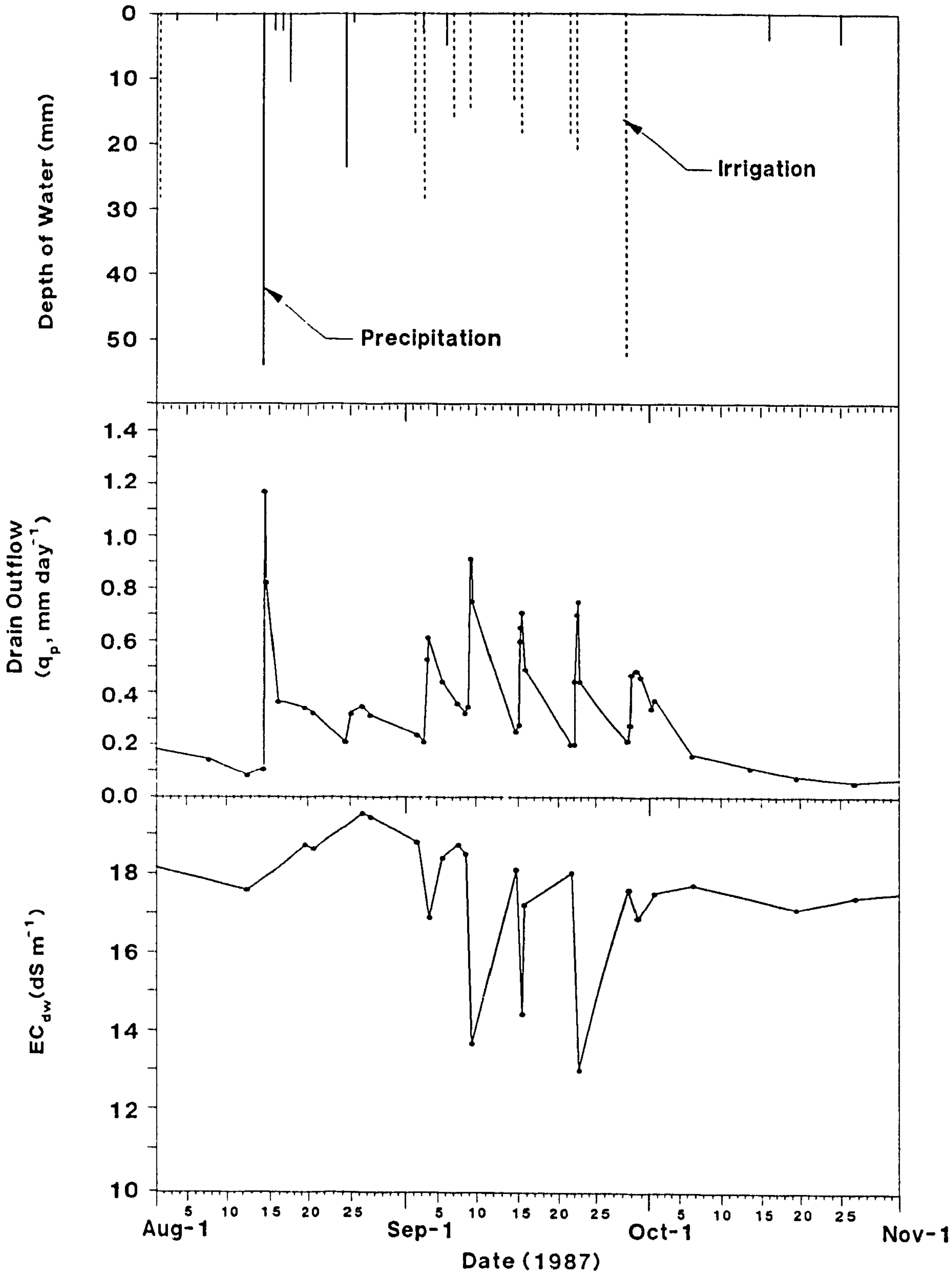

Fig. 25. Drain outflow hydrograph and salinity of the effluent at test plot #2 during the fall of 1987.

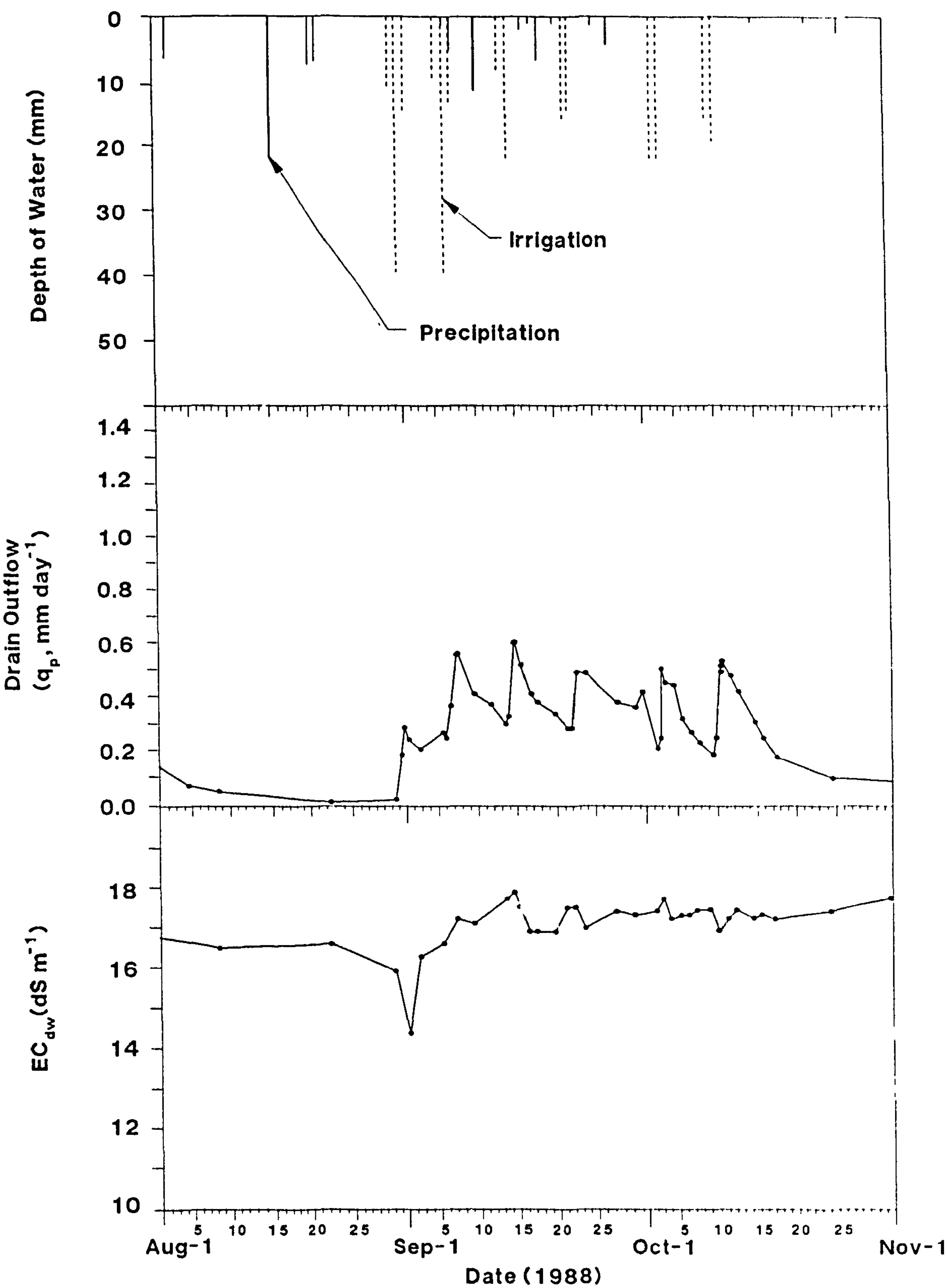

Fig. 26. Drain outflow hydrograph and salinity of the effluent at test plot #2 during the fall of 1988.

Table 15. Water balance for the fall irrigation experiment at test plot #2.

Description	Fall irrigation period 1987 (Sep-02 to Oct-06)‡	1988 (Aug-29 to Oct19)‡	1987-88
Net irrigation	157†	245†	402†
Precipitation (mm)	8	35	43
Drain outflow (mm)	13	17	30
Replenishment of the soil moisture reserve (mm)	16	93	109
Evaporation and/or evapotranspiration (mm)	136	170	306

† Pivot and solid set irrigation.
‡ Dates are those of the soil samplings prior to and after a fall irrigation season.

each irrigation. In 1987, less irrigation water was required to replenish the soil moisture reserve (16 mm in 1987 compared to 93 mm in 1988) because more water (irrigation and precipitation) was applied to the test plot in August 1987 prior to the first fall irrigation (124.1 mm) compared to that applied during the same period in 1988 (42.3 mm).

Data in Table 15 suggest that 69% of the total water applied during fall irrigation was lost through surface evaporation or evapotranspiration. The apparent actual evapotranspiration of 306 mm was slightly greater than the 263 mm potential evapotranspiration predicted with the equation developed by Foroud et al. (1989) for the corresponding time frame but lower than the measured 419 mm Class A pan evaporation for Vauxhall (Environment Canada, 1989).

4.5.2 Soil reclamation

Figure 27 presents the initial soil salinity (EC_o) prior to commencing fall irrigation in September 1987 as well as relative soil salinity profiles (EC_e/EC_o) for each test plot at four different periods during the experiment. At the end of the first fall irrigation experiment (October 1987), soil

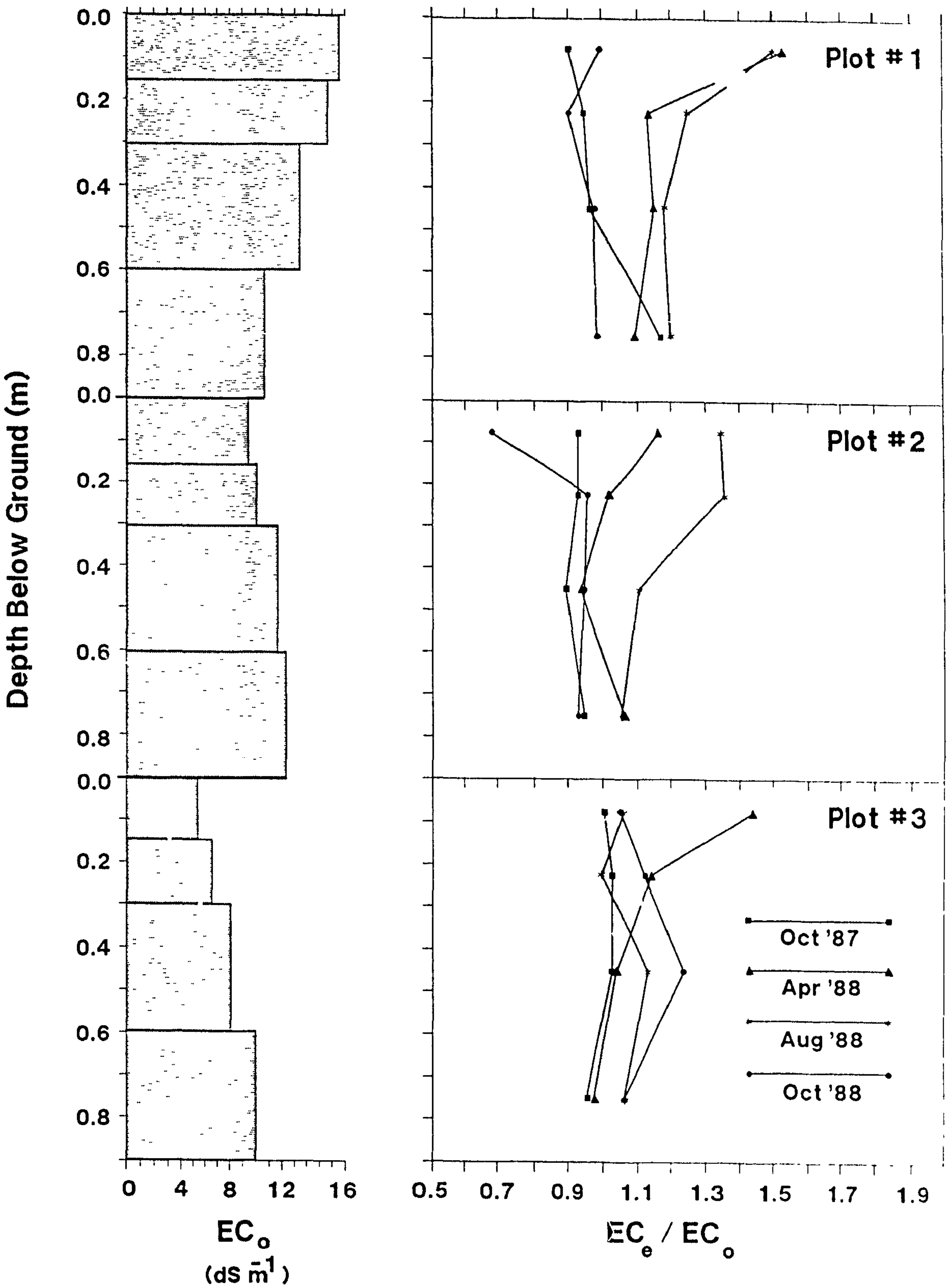

Fig. 27. Salinity at mid-spacing compared to that measured on September 2, 1987.

salinity had decreased at test plot #1 and #2 but increased slightly at test plot #3. A paired t-test was conducted to verify if salinity levels (EC_e) observed after fall irrigation in 1987 were different from those observed prior to fall irrigation. The ratios of EC_e/EC_0 were tested against a ratio of 1 (no change), assuming a two tailed test. Results (Table 16) indicated that all the changes observed at test plots #1 and #3 were not significant at the 0.05 level. At test plot #2, which was pivot and solid set irrigated, results suggested a significant drop in soil salinity of the upper 0.6 m and 0.9 m of the soil profile following the first fall irrigation season (0.05 level of significance). However, changes in the soil salinity of the upper 0.15 m and 0.30 m of the soil profile were not significant. Although the EC_e/EC_0 ratios of the upper 0.6 m and 0.9 m of the soil profile (0.91 and 0.92, respectively) were significantly different from 1 (no change) at the 0.05 level, such a difference may be considered limited considering the usual variability in EC_e data.

Thus, the decrease in soil salinity (EC_e) at test plot #2, following the 1987 fall irrigation experiment was very limited. This was probably due to the small amount of water leached through the upper 0.30 m of the soil profile to replenish the soil moisture reserve of the underlying horizons because of intense rainfall that occurred in August (Appendix C). Thus, soil salinity data following the first year of fall irrigation do not show any major decrease in salinity and therefore suggest no real benefit of fall irrigation.

During the winter of 1987-88, soil salinity at test plots #1 and #3 rose above the initial soil salinity levels ($EC_c/EC_0 > 1$) but resalinization at test plot #2 was not as pronounced. Results of a paired t-test comparing spring 1988 to October 1987 samplings indicated that salinity of the upper 0.15, 0.30, 0.60 and 0.90 m of the soil profile had significantly increased at test plot #1 (0.05 level of

Table 16. Initial soil salinity levels (EC_o) before the first fall irrigation in September 1987 and subsequent relative salinity levels (EC_e/EC_o) for the three treatments.

Sampling Site	EC (dS m^{-1}) Sep-02 1987		EC_e/EC_o Oct-06 1987		Apr-28 1988		Aug-29 1988		Oct-19 1988	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 - 15 cm depth										
Plot #1 †	16.68	3.23	0.90	0.16	1.53*	0.37	1.50**	0.19	1.00	0.24
Plot #2 ‡	9.56	5.04	0.93	0.30	1.16	0.40	1.34	0.54	0.68**	0.22
Plot #3 ¶	5.55	3.00	1.01	0.25	1.44	0.50	1.06	0.47	1.05	0.31
0 - 30 cm depth										
Plot #1 †	16.21	2.17	0.92	0.11	1.33**	0.20	1.38**	0.16	0.95	0.17
Plot #2 ‡	9.87	4.56	0.93	0.21	1.09	0.28	1.34*	0.43	0.82*	0.26
Plot #3 ¶	6.12	2.81	1.02	0.18	1.29	0.29	1.03	0.40	1.08	0.31
0 - 60 cm depth										
Plot #1 †	14.87	0.75	0.95	0.03	1.24*	0.19	1.28*	0.23	0.97	0.14
Plot #2 ‡	10.82	3.13	0.91*	0.13	1.02	0.17	1.22*	0.27	0.88	0.24
Plot #3 ¶	7.16	2.49	1.02	0.12	1.17*	0.13	1.08	0.25	1.16	0.20
0 - 90 cm depth										
Plot #1 †	13.53	0.95	1.02	0.03	1.19	0.19	1.25*	0.24	0.97	0.09
Plot #2 ‡	11.36	2.60	0.92*	0.12	1.03	0.14	1.16*	0.20	0.90	0.20
Plot #3 ¶	8.16	2.85	1.00	0.11	1.10**	0.04	1.07	0.17	1.13*	0.12

† Highly saline, pivot irrigation
‡ Highly saline, pivot and solid set irrigation
¶ Moderately saline, pivot irrigation
* Significantly different from September 2, 1987 sampling at 0.05 level (paired t-test)
** Significantly different from September 2, 1987 sampling at 0.01 level (paired t-test)
SD Standard deviation

significance). At test plot #2, the same paired t-test analysis showed that the upper 0.30, 0.60 and 0.90 m of the soil had experienced significant resalinization over winter (0.05 level of significance). At test plot #3, only the upper 0.15 m and 0.30 m of the soil significantly resalinized during winter (0.05 level of significance).

Resalinization occurred at test plots #1 and #2 during summer 1988, but surface soil salinity at test plot #3 appeared to have decreased during the same period (Figure 27). Results of a paired t-test comparing August to April, 1988 salinity levels indicated that summer resalinization of the upper 0.30, 0.60 and 0.90 m of the soil profile at test plot #2 was significant. Conversely, resalinization at the other test plots was not significant (0.05 level of significance).

At the end of the second year of fall irrigation, soil salinity at test plot #1 was virtually back to original levels while salinity at test plot #3 remained higher ($EC_e/EC_o > 1$). However, at test plot #2, final salinity readings were below original levels. Data presented in Table 16 confirm that only test plot #2 experienced significant reclamation (0.05 level of significance) over the 14 month experiment. Salinity of the upper 0.15 m of the soil profile was 68% of the initial value while that of the upper 0.30 m had been reduced to 82%. Data shown in Table 16 also suggest that salts may have been leached from the upper 0.60 m and 0.90 m of the soil profile at test plot #2, but final EC ratios were not found to be significantly different from 1 (0.05 level of significance).

Leaching and salinity data for the upper 0.3 m of the soil profile at test plot #2 (Tables 15 and 16), before and after the 1988 fall irrigation experiment were used to evaluate the leaching constant (k) in Hoffman's equation (eq [4]). The following values were used: $EC_e = 8.09$ dS m^{-1}; $EC_o = 13.22$ dS m^{-1}; $EC_l = 0.3$ dS m^{-1}; $d_s = 0.3$ m; and $d_l = 0.053$ m.

Depth of irrigation water for leaching (d_l) was assumed to be the sum of the depth of water collected by the drainage system between both soil samplings, pre- and post-1988 fall irrigations plus the amount required to replenish the soil moisture reserve below the upper 0.30 m of the soil profile at the beginning of the 1988 fall irrigation experiment. It was also assumed that the depletion level of the moisture reserve between the water table and 0.30 m from the soil surface was 50% of that of the overlying soil horizon. This lead to a (k) of 0.11 which closely agrees with the 0.1 value proposed by Hoffman (1980) for intermittent ponding but is lower than the 0.25 value found by Harker and Mikalson (1989) for continuous ponding. On the other hand, the actual EC ratio of 0.62 is lower than the value of 0.78 predicted by McMullin's equation (Eq. [7]) which was developed for intermittent ponding of a sulphate dominated soil.

Figure 28 presents the initial soil sodicity (SAR_0) prior to commencing fall irrigation in September 1987 as well as relative soil sodicity profiles (SAR_e/SAR_0) for each test plot at four different stages during the study. At the end of the first fall irrigation experiment in October 1987, data showed that SAR_e changed only marginally at test plot #1. At test plot #2, SAR_e increased near the soil surface but decreased with depth while at test plot #3, increases in SAR_e were observed at mid-depths (0.15 to 0.60 m depth) but changes at other depths were negligible. A paired t-test testing the ratios of SAR_e/SAR_0 against a ratio of 1 (no change) indicated that none of these changes were significant at the 0.05 level of significance (Table 17).

Sampling in April of 1988 (Figure 28) suggested that the surface SAR_e of test plot #1 had increased over winter. At test plot #2, SAR_e decreased slightly near the soil surface while at test plot #3, results suggested that an increase in surface SAR_e had occurred over winter. However, results of a

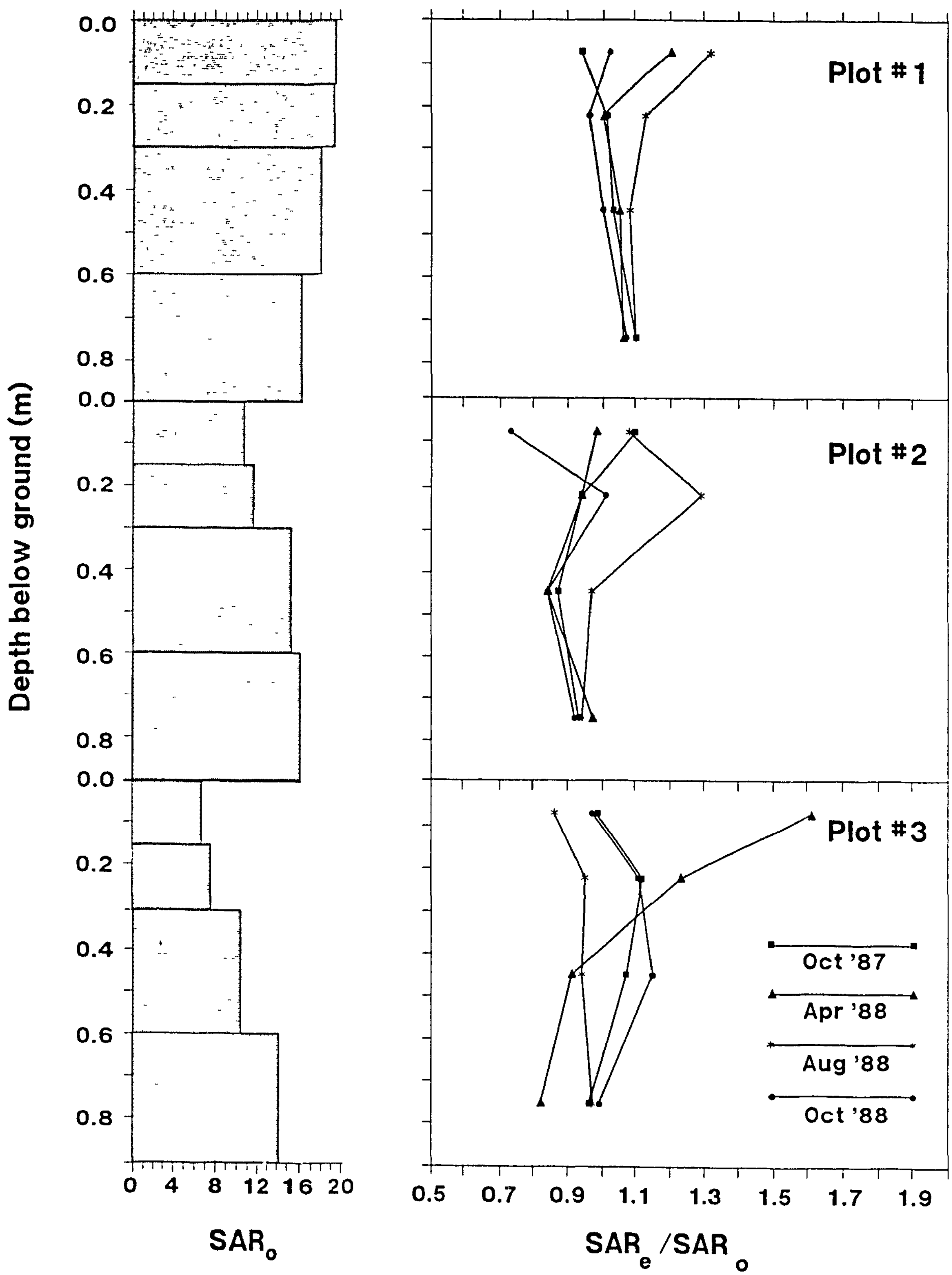

Fig. 28. Sodicity at mid-spacing compared to that measured on September 2, 1987.

Table 17. Initial soil sodicity levels (SAR_o) before the first fall irrigation in September 1987 and subsequent relative sodicity levels (SAR_e/SAR_o) for the three treatments.

Sampling Site	SAR Sep-02 1987 Mean	SAR Sep-02 1987 SD	SAR_e/SAR_o Oct-06 1987 Mean	Oct-06 1987 SD	Apr-28 1988 Mean	Apr-28 1988 SD	Aug-29 1988 Mean	Aug-29 1988 SD	Oct-19 1988 Mean	Oct-19 1988 SD
0 - 15 cm depth										
Plot #1 †	19.63	3.09	0.94	0.13	1.20**	0.12	1.32**	0.11	1.02	0.22
Plot #2 ‡	10.77	7.53	1.10	0.76	0.98	0.23	1.08	0.60	0.73*	0.39
Plot #3 ¶	6.77	5.07	0.98	0.45	1.61	1.32	0.86	0.56	0.97	0.44
0 - 30 cm depth										
Plot #1 †	19.53	1.74	0.98	0.07	1.10	0.11	1.22**	0.12	0.99	0.15
Plot #2 ‡	11.24	7.51	1.02	0.41	0.96	0.18	1.19	0.43	0.87	0.43
Plot #3 ¶	7.21	4.87	1.05	0.43	1.42	0.91	0.91	0.43	1.04	0.40
0 - 60 cm depth										
Plot #1 †	18.79	0.94	1.00	0.04	1.07	0.09	1.15*	0.13	0.99	0.10
Plot #2 ‡	13.27	5.80	0.95	0.18	0.90*	0.13	1.08	0.28	0.85*	0.23
Plot #3 ¶	8.80	3.58	1.06	0.26	1.16	0.39	0.92	0.30	1.10	0.24
0 - 90 cm depth										
Plot #1 †	17.93	1.22	1.03	0.04	1.07	0.08	1.13	0.16	1.02	0.10
Plot #2 ‡	14.21	4.85	0.94	0.15	0.92*	0.09	1.03	0.21	0.88*	0.20
Plot #3 ¶	10.64	2.70	1.03	0.17	1.05	0.22	0.94	0.21	1.06	0.13

† Highly saline, pivot irrigation
‡ Highly saline, pivot and solid set irrigation
¶ Moderately saline, pivot irrigation
* Significantly different from September 2, 1987 sampling at 0.05 level (paired t-test)
** Significantly different from September 2, 1987 sampling at 0.01 level (paired t-test)
SD Standard deviation

paired t-test comparing the spring 1988 to October 1987 samplings indicated that there had been no significant increase in soil sodicity at any of the test plots over the 1987-88 winter period (0.05 level of significance).

Following the summer of 1988 (August soil sampling), SAR_e at test plots #1 and 2 increased, particularly near the soil surface (Figure 28). At test plot #3 however, SAR_e dropped below initial levels. Results of a paired t-test comparing the August 1988 to April 1988 samplings indicated that the increase in sodicity at test plot #1 was significant (0.01 level) but changes observed at test plots #2 and 3 were not significant (0.05 level of significance). SAR_e at test plot #1 increased during summer because Na increased (Data not shown).

During the 1988 fall irrigation experiment, SAR_e at test plot #1 dropped to nearly its original level (Figure 28). Conversely, SAR_e at test plot #3 increased during the same period and final SAR_e values returned to nearly original levels, or slightly above. At test plot #2, data shown on Figure 28 suggest that a sharp reduction in sodicity occurred during fall irrigation, particularly at shallower depths. Results presented in Table 17 confirm that a reduction in SAR_e occurred during fall irrigation at test plot #2 and that only plot #2 had reached sodicity levels which were significantly lower than those measured at the beginning of the experiment. This significant drop in SAR_e at test plot #2, following two years of fall irrigation, could be attributed to a decrease in Na levels.

Soil salinity and sodicity data indicated that no significant reclamation was achieved under normal pivot irrigation management as performed on test plots #1 and #3 (Tables 16 and 17). On the other hand, when additional fall irrigation water was applied via a solid set irrigation system (test plot #2), data showed that soil reclamation of the upper 0.30 m of the soil profile occurred (EC_e/EC_o = 0.82).

At test plot #2, data suggested that most of the leaching of the upper 0.30 m of the soil profile occurred at an early stage in the fall irrigation period when the water table was first brought nearly to the soil surface. This was accomplished at either the first and or second fall irrigation of the year (Figures 23 and 24). This is because water required to replenish the soil moisture reserve below a depth of 0.30 m had to leach through the surface 0.30 m horizon. Reclamation during subsequent fall irrigation events was limited because of restricted internal drainage, although some leaching was still occurring at an average rate of 0.5 mm day^{-1}.

4.6 Farmer satisfaction

Since the installation of the drainage system in the fall of 1986, the farm owner noticed improvement in trafficability, particularly within the test plot area. Prior to the installation of the drainage system he was unable to drive a tractor through test plots #1 and #2 during the summer months. The year following installation of grid drainage, he was able to seed the entire field and subsoiled to a depth of 0.6 m.

Crop response was not, however, as noticeable. The first year following drainage, most of the area that was bare prior to drainage remained as such (Plate E3). In 1988, weeds, and particularly Kochia (Kochia scoparia), grew over most of the previously bare area (Plate E4). Improvements in crop establishment were noticed by the farmer within the less severely affected areas (plot #3 and the rest of the field). In 1989, it was indicated that crop establishment was better, particularly at test plot #2.

The farmer also noticed that the severely salt affected area has not expanded since the installation of the drainage system, and may even have receded.

5. SUMMARY AND CONCLUSIONS

A groundwater flow study was undertaken to understand the local groundwater flow regime of a canal seepage affected area and its effects on the performance of grid and deep interceptor drainage to control seepage and reclaim a saline canal seepage affected land. A more detailed test plot investigation was also undertaken within this area to evaluate the effectiveness of grid drainage to intercept seepage and to verify the benefits of fall irrigation to reclaim a severe saline canal seepage affected area.

Results of the groundwater flow modelling indicated that a deep interceptor drain at the experimental site would have failed to intercept all canal seepage and maintain the water table downslope of the canal below the 1.0 m DWD. This was due to the presence of a coal seam at a depth of 6.0 m in the canal area which discharged groundwater downslope of the canal. It was shown that most of the canal seepage would bypass the deep interceptor drain and recharge into the coal seam, which in turn would discharge saline brackish water to the overlying till and underlying bedrock layers over a distance extending 250 m downslope of the canal. On the other hand, simulation with a grid drainage system indicated that all canal seepage would be intercepted and that the water table would remain below the 1.0 m DWD, with or without irrigation recharge that would maintain a steady state salt balance.

Actual field data showed that, in general, the water table remained below the 1.0 m DWD at the 44 ha grid drained site. Exceptions were found in the severely salt affected area near the canal (about 10% of the total area) where the water table remained generally above the DWD. This was thought to be indicative of the actual 15 m drain spacing being too wide. A 7.5 m drain spacing in this area was found to be more appropriate. The hydraulic conductivity of the clayey till at this location was particularly low (K_a = 0.04 m day^{-1}; K_b = 0.03 m day^{-1}). The drain depth was also shallower than normal, e.g. 1.2 to 1.3 m compared to a design depth of 1.4 m. This would explain, in part, why the drain outflow at test plot #2, where the water table often reached the soil surface, seldom exceeded the design drainage rate of 1.0 mm day^{-1} calculated for a 1.0 m water table depth.

It was also shown that measured drain outflows were four times lower than the theoretical flows predicted by Houghoudt's equation. One explanation of this discrepancy was that smearing of the drainage trench occurred when drains were plowed-in and thus, flow to the drainage system was restricted due to the low conductivity of the soil material at the trench.

Drainable porosity within the severely salt affected area was also found to be extremely low. Data from a drain outflow and water table recession event suggested a porosity value ranging from 0.004 to 0.007 for the upper 0.9 m of the soil profile.

Results of a fall irrigation experiment clearly demonstrated the benefits of this irrigation practice. At the two test plots where centre pivot irrigation management common to southern Alberta was practiced, no significant reclamation was achieved over two fall irrigation experiments (14 month period). On the other hand, when additional water (374 mm) was added with a solid set sprinkler irrigation system during the fall of 1987 and 1988 (September, October), significant soil reclamation of the upper 0.15 m of the soil profile was achieved. Salinity (EC_e) decreased by 32% and sodicity (SAR_e) decreased by 27%. Similarly, EC_e and SAR_e of the upper 0.30 m of the soil profile dropped by 18 and 13%, respectively. Reducing the drain spacing to about 7.5 m within the test plot area would have enhanced reclamation under solid set, fall irrigation management by improving internal drainage, and thus leaching. It is unlikely that significant reclamation would have been achieved at the pivot irrigated sites should the drain spacing be narrower since insufficient water was applied to promote enough leaching.

Results from this study suggest that when natural groundwater accretions exist within close proximity to a canal, grid drainage is more appropriate to control canal seepage. Grid drainage has the added advantage of providing a sink when leaching is performed.

When designing a grid drainage system for a severely salt affected area similar to that encountered within the test plot location (clay loam till, K = < 0.05 m day^{-1} EC_e > 10, SAR_e > 10), drain spacing should not exceed 10.0 m. This would allow for a faster rate of reclamation and should help maintain the water table below the 1.0 m DWD, thus preventing further resalinization. This drain spacing is still greater than the 7.7 m spacing calculated for test plot #2 for a drain depth of 1.3 m. However, a 10 m spacing should be adequate, providing that drain depth is greater or equal to 1.4 m and smearing of the drainage trench is marginal.

Once drainage has been installed, it is recommended that fall irrigation practices follow. Results indicated that, under normal irrigation management, no significant soil reclamation could be achieved. When fall irrigating, soil infiltration problems may occur. Irrigating at low application rates enhanced infiltration.

6. RECOMMENDATIONS FOR FURTHER RESEARCH

As a result of the research conducted, it is suggested that the following topics are worthy of further research:

1) Additional work should be conducted to quantify the actual amount of irrigation water infiltrating through the soil surface under solid set, centre pivot and flood irrigation systems.

2) The critical water table depth under irrigation management for southern Alberta conditions should be evaluated. The critical depth should be determined for cropped and uncropped conditions. This would allow better calculations of subsurface drain spacing.

3) A water balance, taking into account precipitation, irrigation, evapotranspiration, soil moisture, soil reservoir action, and drainage should be conducted, using long term climatic data, to determine probabilities of occurence of various water table heights for different drainage rates. This could provide better guidance for the selection of design drainage coefficients to determine drain spacing. The simulation model used for this study should take into consideration artesian pressure which often occurs, due to the presence of a shallow pressurized coal seam.

4) There is a need to verify the effectiveness of various chemical amendements aimed at improving the infiltrability of soils exhibiting sodic features. The effectiveness of various tillage and cropping methods should also be investigated.

5) The potential hazard of smearing of the drainage trench which may occur when subsurface drains are installed with a trenchless plow under shallow water table conditions should also be carefully examined.

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APPENDIX A

Soil Profile Descriptions

Table A1. Morphological descriptions of soil profile #1.

Horizon	Depth (m)	Description
Apksa	0.00 - 0.08	Brown, dark brown (10YR 4/2 m); sandy loam; moderate, coarse granular; very friable, plentiful very fine and fine, oblique, exped roots; moderately porous; weak effervescence.
ABgsak	0.08 - 0.28	Dark gray (10YR 4/1 m); sandy loam; common fine yellowish red (5YR 4/6 m) prominent mottles; moderate, medium and coarse, angular blocky; firm, few micro and very fine, oblique inped roots, slightly porous, weak effervescence.
Bmgjsa	0.28 - 0.42	Dark grayish brown (10YR 4/2 m); sandy loam; common fine yellowish brown (10YR 5/6 m), faint mottles; moderate, medium and coarse, prismatic; very friable; few micro, vertical, imped roots; moderately porous.
Bm	0.42 - 0.56	Brown (10YR 5/3 m); sandy loam to loamy sand; amorphous; loose; few micro, vertical, imped roots; highly porous.
BC	0.56 - 0.76	Brown (10YR 5/3 m); sandy loam to sandy clay loam; amorphous; firm; few, micro, vertical, imped roots; slightly porous.
Ce	0.76 - 1.00	Dark brown, brown (10YR 4/3 m); clay loam; amorphous; firm; slightly porous; moderate effervescence.
	1.00 - 1.50	Clay to silty clay.
	1.50 - 1.75	Clay loam to silty clay loam.
	1.75 - 2.25	Clay loam to clay.
	2.25 - 2.40	Clay loam.

Classification[†] : Saline Carbonated Gleyed Brown

[†] Canada Soil Survey Committee (1978).

Table A2. Morphological descriptions of soil profile #2.

Horizon	Depth (m)	Description
Apsa	0.00 - 0.12	Very dark grayish brown (10YR 3/2 m); sandy to sandy clay loam; strong, medium and coarse, angular blocky; moist: firm, dry: extremely hard; very few, micro, oblique, exped roots; slightly porous.
ABgsa	0.12 - 0.26	Very dark grayish brown (10YR 3/2 m); sandy to sandy clay loam; common, fine and medium dark reddish brown (5YR 3/3 m) prominent mottles; strong, medium, angular blocky; very firm; very few, micro, vertical, exped roots; slightly porous.
Bgsa	0.26 - 0.46	Grayish brown (10YR 5/2 m); clay loam; many, medium and coarse brown, dark brown (7.5YR 4/4 m) distinct mottles; moderate, medium and coarse, prismatic; friable; few micro and very fine, vertical, inped roots; slightly porous.
II Ckgsa	0.46 - 1.0	Brown (10YR 5/3 m); clay loam; few, fine, yellowish brown (10YR 5/6 m) faint mottles; amorphous; sticky; plastic; very few, micro and very fine, vertical, inped roots; slightly porous; strong effervescence; 1 to 3% gravely.
	1.00 - 1.20	Sandy clay loam.
	1.20 - 1.50	Loam to sandy clay loam.
	1.50 - 2.40	Sandy clay loam.

Classification [†] : Saline Orthic Gleysol

[†] Canada Soil Survey Committee (1978).

Table A3. Morphological descriptions of soil profile #4.

Horizon	Depth (m)	Description
Apsk	0.00 - 0.10	Dark brown (10YR 3/3 m); sandy clay loam; moderate, medium and coarse, granular; friable, dry: hard; plentiful, very and fine, oblique, exped roots; moderately porous; weak effervescence.
Bms	0.10 - 0.28	Dark brown (10YR 3/3 m); sandy clay loam; strong, medium and coarse, angular blocky; very firm; few micro and very fine, oblique, inped roots; slightly porous; 1% gravely.
Cksa	0.28 - 0.76	Brown (10YR 5/3 m); clay loam; amorphous; firm; very few, micro to very fine, vertical, inped roots; slightly porous; strong effervescence; 5% gravelly.
Ccasa	0.76 - 1.00	Brown (10YR 5/3 m); loam; moderate, medium, angular blocky; friable; slightly porous; moderate effervescence; 5% gravelly.
	1.00 - 1.20	Sandy clay loam to loam.
	1.20 - 1.50	Sandy clay loam to loam to clay loam.
	1.50 - 1.80	Loam.
	1.80 - 2.10	Sandy clay loam.
	2.10 - 2.40	Loam to sandy clay loam.

Classification[†]: Saline Carbonated Orthic Brown.

[†] Canada Soil Survey Committee (1978).

Table A4. Morphological descriptions of soil profile #5.

Horizon	Depth (m)	Description
Apsa	0.00 - 0.16	Dark brown (10YR 3/3 m); sandy loam to sandy clay loam; strong, medium and coarse, granular; firm, very hard, very few, micro and very fine, oblique, exped roots; moderately porous.
ABgsa	0.16 - 0.25	Very dark greyish brown (10YR 3/2 m); sandy loam to sandy clay loam; common, fine and medium, strong brown (7.5YR 5/6 m) distinct mottles; strong medium and coarse, angular blocky; very firm; very few micro, oblique, inped roots; slightly porous; 2% gravely.
Bgsa	0.25 - 0.48	Brown, dark brown (10YR 4/3 m); clay loam; few fine, dark yellowish brown (10YR 4/4 m) faint mottles; moderate, coarse, prismatic; firm; very few, micro to very fine, vertical, inped roots; slightly porous; 2% gravelly.
Ck1	0.48 - 0.82	Brown (10YR 5/3 m); clay loam; amorphous; friable; very few, micro, vertical, inped roots; slightly porous; strong effervescence; 5 to 10% gravelly.
Ck2	0.82 - 1.00	Dark grayish brown (10YR 4/2 m); clay loam to loam; amorphous; very friable; slightly porous; moderate effervescence; 5 to 10% coarse fragments.
	1.00 - 1.20	Loam to clay loam
	2.30 - 1.50	Loam.
	1.50 - 2.10	Loam to sandy clay loam.
	2.10 - 2.40	Loam.

Classification[†] : Saline Orthic Gleysol.

[†] Canada Soil Survey Committee (1978).

Table A5. Morphological descriptions of soil profile #6.

Horizon	Depth (m)	Description
Apksa	0.00 - 0.09	Dark brown (10YR 3/3 m); sandy loam; granular, moderate, medium and coarse, granular; moist: very friable, dry: very hard; few, very fine and fine, vertical and oblique, exped roots; moderately porous; weak effervescence.
ABsak	0.09 - 0.20	Dark brown (10YR 3/3 m); sandy loam; amorphous; firm; few, very fine and fine, vertical, inped roots; slightly porous; weak effervescence.
Bmsak	0.20 - 0.40	Brown, dark brown (10YR 4/3 m); sandy loam; moderate, medium and coarse, prismatic; friable; very few, very fine and fine, vertical, inped roots; moderately porous; weak effervescence.
Bmsa	0.40 - 0.75	Dark yellowish brown (10YR 4/4 m); sandy loam; weak, medium and coarse, prismatic; very friable; very few, very fine and fine, vertical, inped roots; moderately porous.
Cksa	0.75 - 1.00	Brown, dark brown (10YR 4/3 m); loam; amorphous; sticky plastic; very few, micro, vertical and inped roots; slightlv porous; moderate effervescence.
	1.00 - 1.20	Sandy clay loam to loam.
	1.20 - 1.50	Clay loam.
	1.50 - 1.80	Clay loam to loam.
	1.80 - 2.10	Loam to clay loam.
	2.10 - 2.40	Sandy clay loam to loam.

Classification[+] : Saline Carbonated Orthic Brown.

[+] Canada Soil Survey Committee (1978).

Table A6. Morphological descriptions of soil profile #7.

Horizon	Depth (m)	Description
Aps	0.00 - 0.24	Dark brown (10YR 3/3 m); sandy loam; moderate, medium and coarse, granular; very friable, hard; plentiful, very fine and fine, oblique, exped roots; moderately porous; 1% gravelly.
Bnjts	0.24 - 0.35	Brown, dark brown (10YR 4/3 m); sandy clay loam; strong, medium and coarse, subangular blocky; firm; few micro and very fine, oblique, inped and exped roots; slightly porous; clay films; 3% gravelly.
Cks	0.35 - 0.76	Yellowish brown (10YR 5/4 m); clay loam; amorphous; friable; very few, micro and very fine, vertical, inped roots; slightly porous; strong effervescence; 5% gravely.
Ck	0.76 - 1.00	Brown (10YR 5/3 m); clay loam; moderate, medium and coarse, angular blocky; friable; very few, micro, vertical, inped roots; slightly porous; moderate effervescence; 5% gravelly.
	1.00 - 1.20	Sandy clay loam.
	1.20 - 1.50	Loam to clay loam.
	1.50 - 2.40	Sandy clay loam.

Classification† : Saline Solonetzic Brown.

† Canada Soil Survey Committee (1978).

APPENDIX B

Simulated Groundwater Flow Paths
and
Representative Water Table Hydrographs

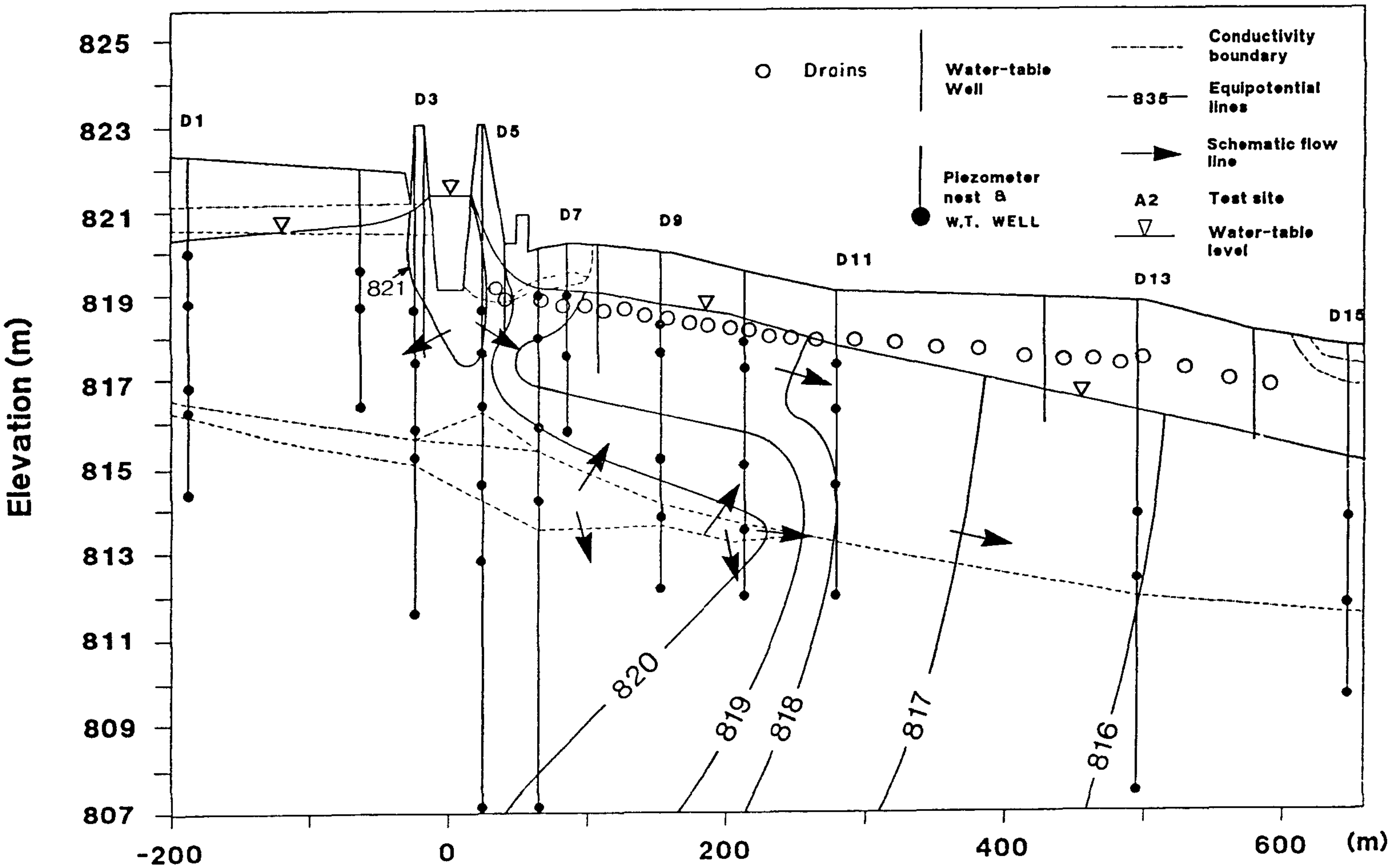

Fig. B1. Simulated groundwater flow with grid drainage; August 22, 1988.

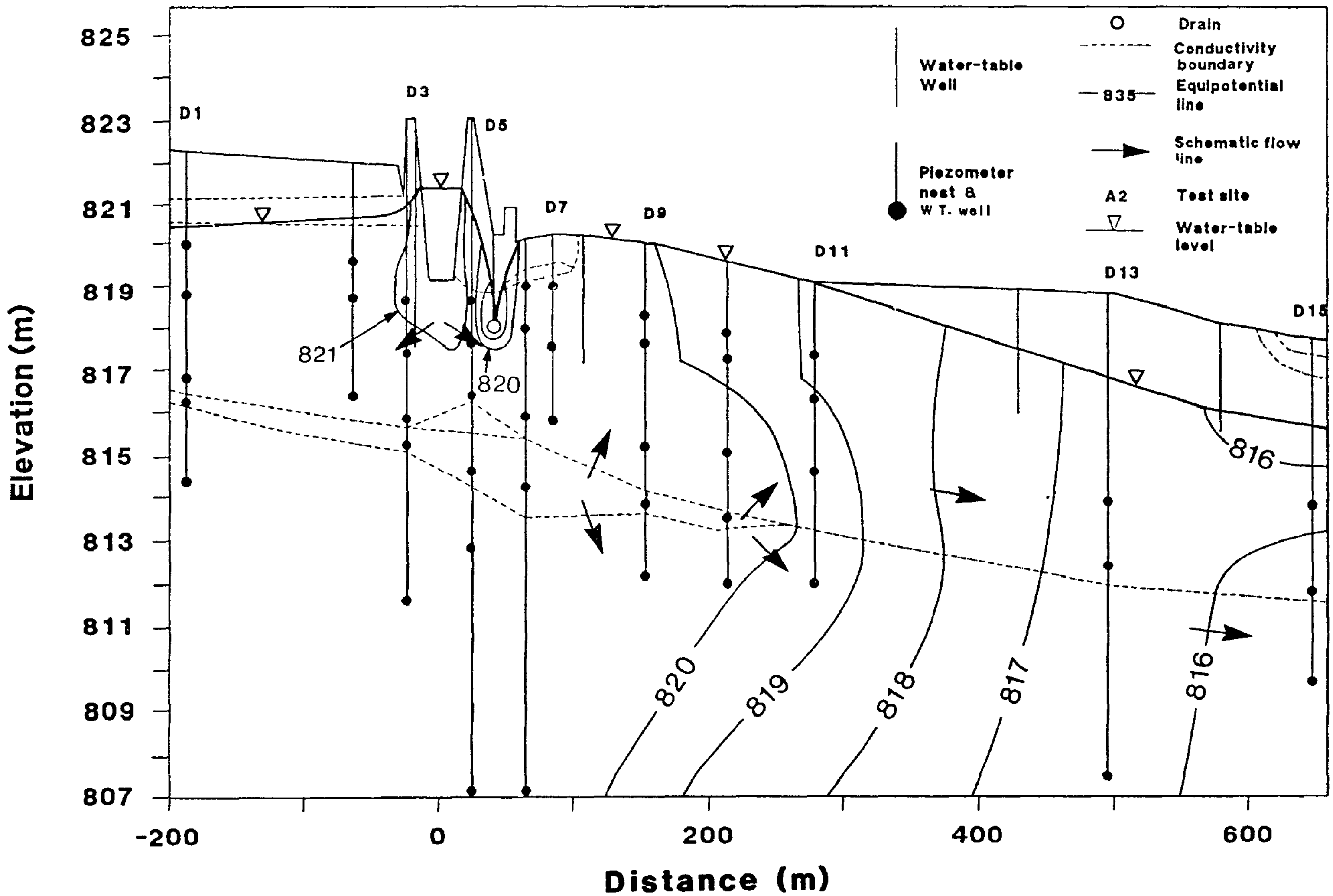

Fig. B2. Simulated groundwater flow with deep interceptor drainage; August 22, 1988.

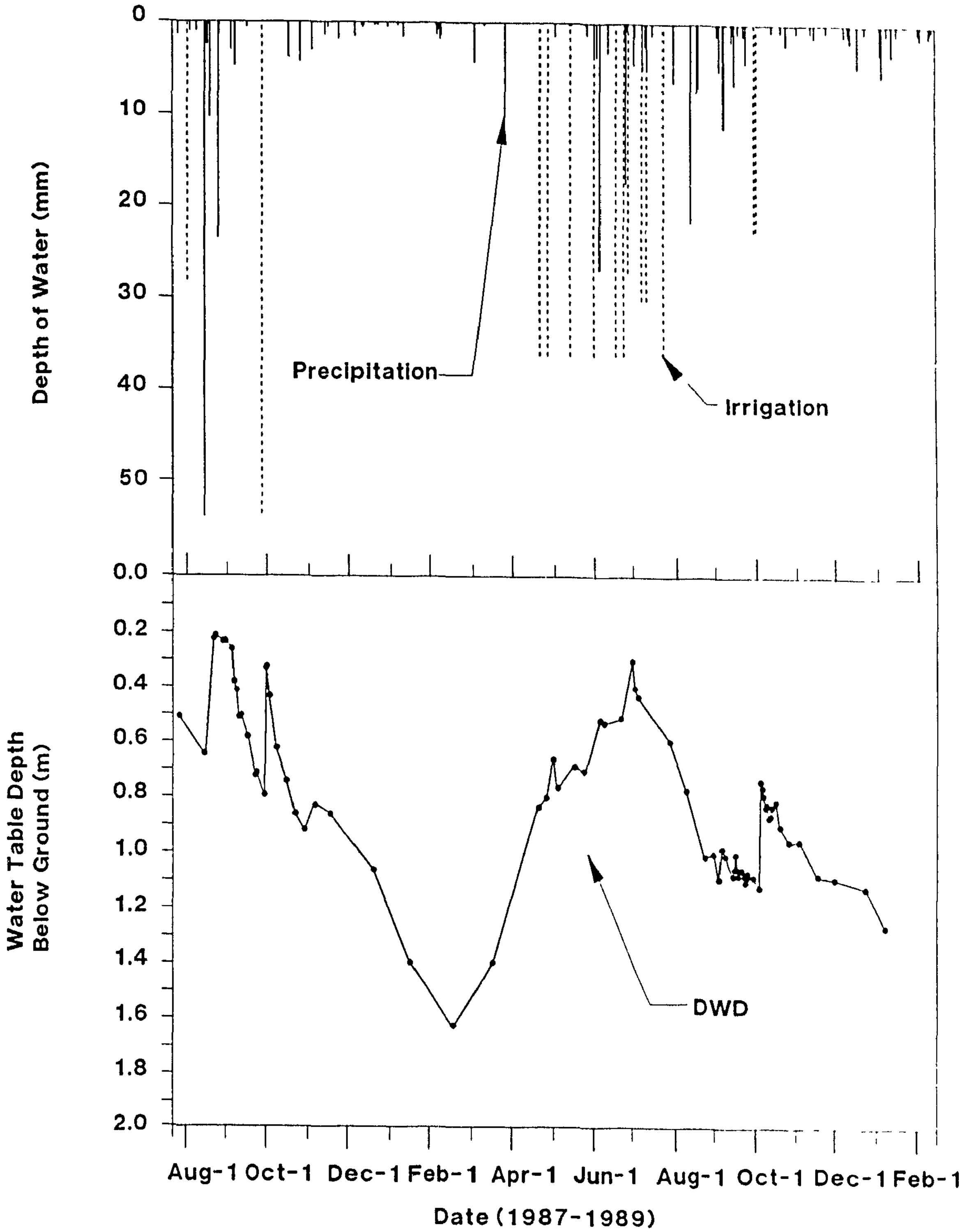

Fig. B3. Water table fluctuations as related to water applications at test plot # 1.

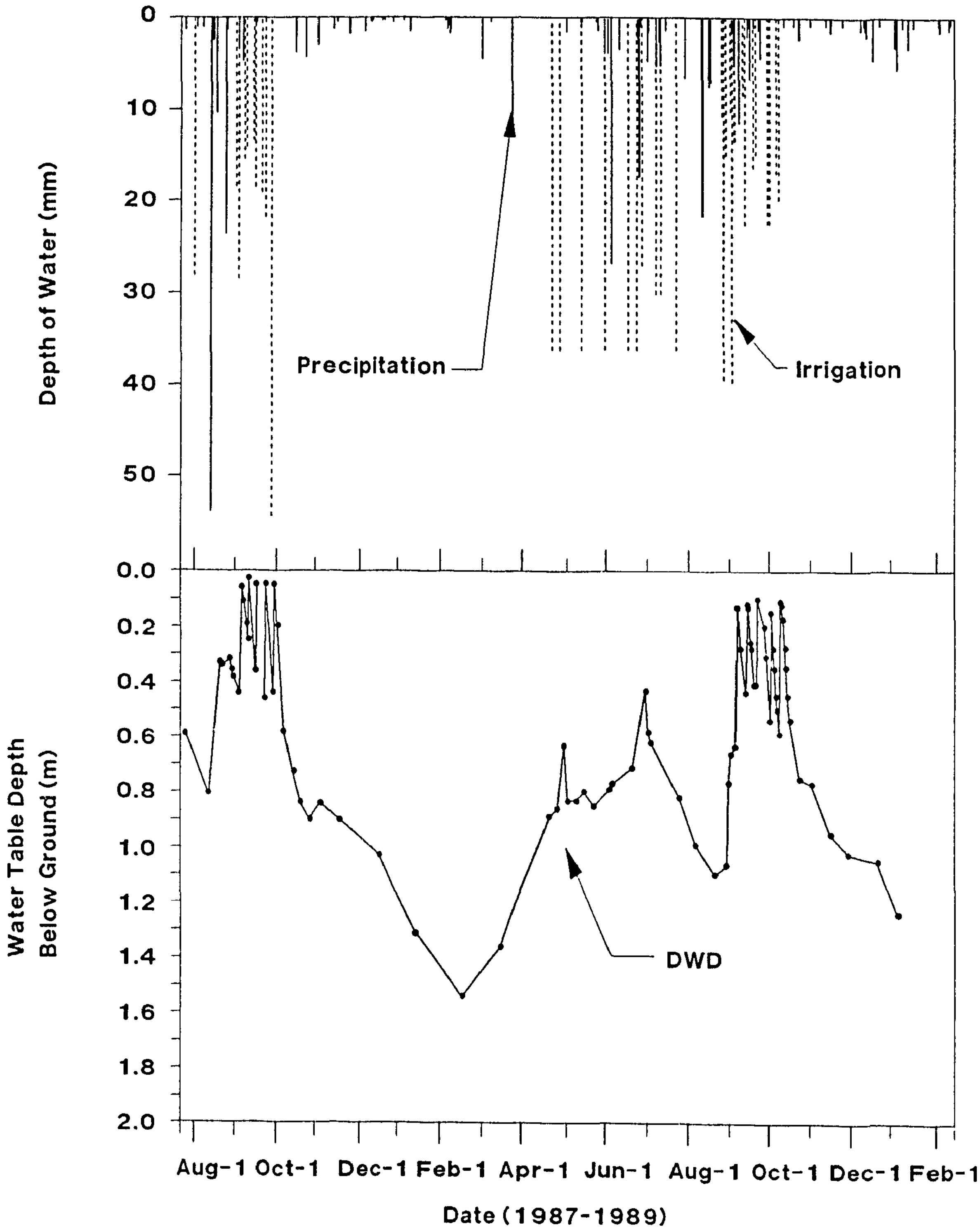

Fig. B4. Water table fluctuations as related to water applications at test plot #2.

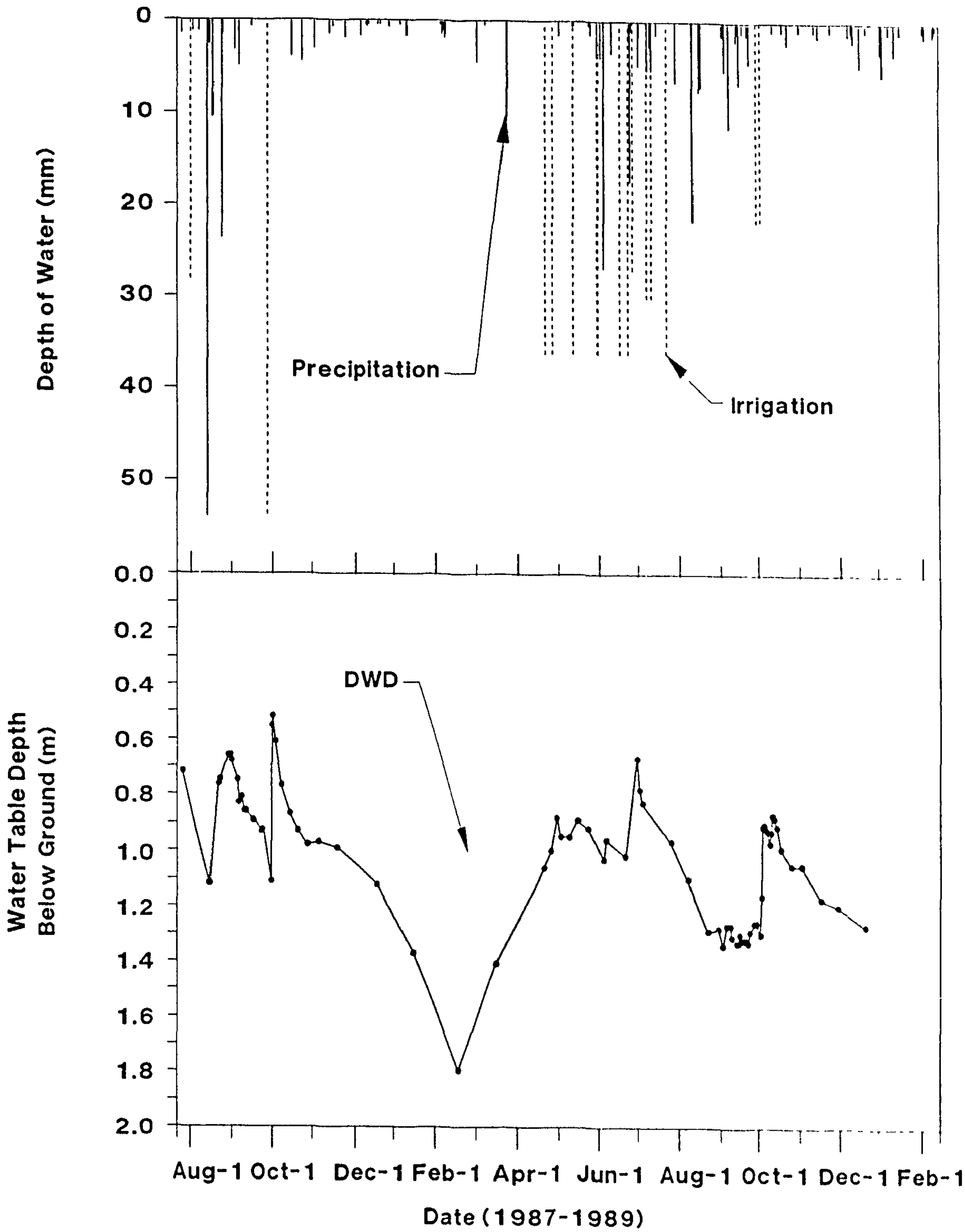

Fig. B5. Water table fluctuations as related to water applications at test plot #3.

APPENDIX C

Precipitation Data

SUMMARY OF THE BOW ISLAND CLIMATIC DATA
1961 THROUGH 1988 †

Month	Temperature (°C) Mean Max.		Mean Min.		Mean Daily		Precipitation (mm) Mean	
January	-3.6	(1.6)	-14.5	(-10.7)	-9.1	(-4.5)	15.4	(1.9)
February	0.9	(5.7)	-11.0	(-8.7)	-5.1	(-1.5)	9.2	(3.5)
March	5.6	(8.6)	-5.5	(-3.8)	0.1	(2.4)	18.1	(18.7)
April	13.0	(18.6)	0.9	(1.8)	7.0	(10.2)	29.0	(4.7)
May	20.4	(23.6)	5.7	(6.9)	13.1	(15.2)	43.7	(8.5)
June	23.9	(27.7)	10.3	(11.6)	17.1	(19.6)	56.9	(53.4)
July	27.5	(27.8)	12.1	(11.7)	19.8	(19.7)	32.8	(22.0)
August	27.1	(24.7)	11.0	(9.2)	19.1	(17.0)	33.0	(69.2)
September	19.3	(22.9)	5.5	(5.5)	12.4	(14.2)	40.5	(21.2)
October	15.1	(17.2)	0.6	(0.6)	7.9	(8.9)	13.8	(6.0)
November	4.4	(8.8)	-7.1	(-4.7)	-1.4	(2.1)	10.7	(5.3)
December	-2.4	(2.6)	-12.6	(-9.6)	-7.5	(-3.5)	13.6	(7.3)
Yearly	12.6	(15.8)	-0.4	(0.8)	6.1	(8.3)	316.7	(221.7)
Growing ‡ Season	21.9	(24.2)	7.6	(7.8)	14.8	(16.0)	235.9	(179.0)

† Source: Alberta Agriculture (1989).

( ) Average for 1987 and 1988.

‡ April to September.

BOW ISLAND TEMPERATURE AND PRECIPITATION

MARCH 1987

	TEMPERATURE (°C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	5.0	-4.0	0.5				
2.0	11.0	0.0	5.5				
3.0	16.0	3.0	9.5				
4.0	20.0	5.0	12.5				
5.0	23.0	6.0	14.5				
6.0	20.0	-2.0	9.0				
7.0	4.0	-9.0	-2.5				
8.0	0.0	-6.0	-3.0				
9.0	0.0	-5.0	-2.5				
10.0	-3.0	-7.0	-5.0			2.0	2.0
11.0	-1.0	-5.0	-3.0			T	T
12.0	13.0	-1.0	6.0				
13.0	3.0	-6.0	-1.5		5.6	3.8	9.4
14.0	3.0	-4.0	-0.5				
15.0	3.0	-3.0	0.0			2.0	2.0
16.0	3.0	-1.0	1.0				
17.0	11.0	0.0	5.5				
18.0	12.0	-3.0	4.5				
19.0	2.0	-7.0	-2.5			5.1	5.1
20.0	5.0	-9.0	-2.0				
21.0	2.0	-5.0	-1.5			4.1	4.1
22.0	5.0	-7.0	-1.0			T	T
23.0	3.0	-13.0	-5.0				
24.0	8.0	-8.0	0.0				
25.0	10.0	-1.0	4.5				
26.0	6.0	-8.0	-1.0				
27.0	-5.0	-16.0	-10.5				
28.0	-3.0	-12.0	-7.5				
29.0	8.0	2.0	5.0				
30.0	15.0	1.0	8.0				
31.0	16.0	-1.0	7.5				
MEAN T:	6.9	-4.1	1.4	TOTAL:	5.6	17.0	22.6

BOW ISLAND TEMPERATURE AND PRECIPITATION

APRIL 1987

	TEMPERATURE (^{O}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	11.0	-2.0	4.5				
2.0	18.0	3.0	10.5				
3.0	23.0	2.0	12.5				
4.0	26.0	3.0	14.5				
5.0	20.0	2.0	11.0				
6.0	19.0	1.0	10.0				
7.0	18.0	3.0	10.5				
8.0	15.0	0.0	7.5				
9.0	12.0	-6.0	3.0				
10.0	19.0	2.0	10.5				
11.0	9.0	-2.0	3.5			5.6	5.6
12.0	18.0	-2.0	8.0				
13.0	18.0	5.0	11.5				
14.0	21.0	7.0	14.0				
15.0	20.0	6.0	13.0				
16.0	20.0	6.0	13.0				
17.0	20.0	4.0	12.0				
18.0	12.0	-3.0	4.5		1.3		1.3
19.0	15.0	2.0	8.5				
20.0	16.0	4.0	10.0				
21.0	23.0	3.0	13.0				
22.0	13.0	3.0	8.0				
23.0	8.0	3.0	5.5		1.5		1.5
24.0	17.0	-2.0	7.5				
25.0	23.0	4.0	13.5				
26.0	23.0	7.0	15.0				
27.0	31.0	3.0	17.0				
28.0	31.0	10.0	20.5				
29.0	29.0	9.0	19.0				
30.0	30.0	11.0	20.5		1.0		1.0
MEAN T:	19.3	2.9	11.1	TOTAL:	3.8	5.6	9.4

06 Oct 89

BOW ISLAND TEMPERATURE AND PRECIPITATION

MAY 1987

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	23.0	5.0	14.0				
2.0	19.0	4.0	11.5				
3.0	23.0	6.0	14.5				
4.0	25.0	4.0	14.5				
5.0	24.0	8.0	16.0				
6.0	27.0	4.0	15.5				
7.0	32.0	7.0	19.5				
8.0	31.0	7.0	19.0				
9.0	29.0	6.0	17.5				
10.0	28.0	7.0	17.5				
11.0	30.0	14.0	22.0				
12.0	27.0	6.0	16.5		2.5		2.5
13.0	21.0	5.0	13.0				
14.0	28.0	9.0	18.5				
15.0	26.0	8.0	17.0		T		T
16.0	18.0	6.0	12.0				
17.0	20.0	5.0	12.5				
18.0	18.0	1.0	9.5		1.3		1.3
19.0	12.0	-2.0	5.0				
20.0	13.0	2.0	7.5				
21.0	13.0	3.0	8.0				
22.0	21.0	5.0	13.0				
23.0	25.0	8.0	16.5				
24.0	27.0	10.0	18.5		1.8		1.8
25.0	21.0	11.0	16.0		1.5		1.5
26.0	17.0	12.0	14.5		3.6		3.6
27.0	20.0	9.0	14.5		1.8		1.8
28.0	23.0	8.0	15.5		0.8		0.8
29.0	23.0	9.0	16.0				
30.0	25.0	8.0	16.5				
31.0	23.0	9.0	16.0				
MEAN T:	23.0	6.6	14.8	TOTAL:	13.3	0.0	13.3

BOW ISLAND TEMPERATURE AND PRECIPITATION

JUNE 1987

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	19.0	8.0	13.5				
2.0	18.0	4.0	11.0				
3.0	26.0	9.0	17.5				
4.0	30.0	12.0	21.0				
5.0	33.0	14.0	23.5				
6.0	31.0	6.0	18.5				
7.0	32.0	12.0	22.0				
8.0	23.0	12.0	17.5				
9.0	29.0	15.0	22.0				
10.0	28.0	10.0	19.0				
11.0	30.0	12.0	21.0				
12.0	29.0	10.0	19.5				
13.0	34.0	15.0	24.5				
14.0	37.0	20.0	28.5				
15.0	34.0	15.0	24.5				
16.0	25.0	9.0	17.0		4.6		4.6
17.0	25.0	11.0	18.0				
18.0	30.0	12.0	21.0		34.3		34.3
19.0	23.0	14.0	18.5		4.1		4.1
20.0	22.0	12.0	17.0		1.3		1.3
21.0	27.0	13.0	20.0				
22.0	23.0	9.0	16.0				
23.0	22.0	4.0	13.0				
24.0	23.0	7.0	15.0				
25.0	28.0	11.0	19.5				
26.0	30.0	11.0	20.5				
27.0	32.0	7.0	19.5		3.3		3.3
28.0	23.0	12.0	17.5				
29.0	27.0	12.0	19.5				
30.0	22.0	10.0	16.0		1.5		1.5
MEAN T:	27.2	10.9	19.1	TOTAL:	49.1	0.0	49.1

BOW ISLAND TEMPERATURE AND PRECIPITATION

JULY 1987

	TEMPERATURE (°C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	27.0	13.0	20.0				
2.0	31.0	15.0	23.0				
3.0	29.0	6.0	17.5				
4.0	26.0	10.0	18.0				
5.0	24.0	9.0	16.5		1.5		1.5
6.0	21.0	6.0	13.5				
7.0	26.0	10.0	18.0				
8.0	27.0	10.0	18.5				
9.0	23.0	10.0	16.5		4.1		4.1
10.0	18.0	4.0	11.0				
11.0	27.0	11.0	19.0				
12.0	29.0	14.0	21.5		T		T
13.0	29.0	10.0	19.5				
14.0	34.0	14.0	24.0				
15.0	30.0	10.0	20.0				
16.0	21.0	10.0	15.5				
17.0	17.0	11.0	14.0				
18.0	16.0	7.0	11.5		16.5		16.5
19.0	19.0	9.0	14.0		T		T
20.0	25.0	11.0	18.0				
21.0	26.0	13.0	19.5		0.5		0.5
22.0	21.0	8.0	14.5				
23.0	25.0	9.0	17.0				
24.0	30.0	14.0	22.0				
25.0	32.0	16.0	24.0		1.3		1.3
26.0	33.0	19.0	26.0				
27.0	36.0	18.0	27.0				
28.0	38.0	17.0	27.5		T		T
29.0	34.0	15.0	24.5				
30.0	33.0	16.0	24.5				
31.0	35.0	18.0	26.5				
MEAN T:	27.2	11.7	19.4	TOTAL:	23.9	0.0	23.9

BOW ISLAND TEMPERATURE AND PRECIPITATION

AUGUST 1987

TEMPERATURE (°C)					PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	25.0	14.0	19.5				
2.0	24.0	10.0	17.0				
3.0	23.0	10.0	16.5		1.0		1.0
4.0	31.0	11.0	21.0				
5.0	22.0	6.0	14.0				
6.0	27.0	7.0	17.0				
7.0	30.0	13.0	21.5				
8.0	27.0	12.0	19.5		1.0		1.0
9.0	31.0	14.0	22.5				
10.0	20.0	8.0	14.0				
11.0	15.0	2.0	8.5				
12.0	24.0	8.0	16.0				
13.0	22.0	9.0	15.5				
14.0	10.0	8.0	9.0		53.8		53.8
15.0	20.0	5.0	12.5		2.5		2.5
16.0	22.0	9.0	15.5		2.5		2.5
17.0	19.0	5.0	12.0		10.4		10.4
18.0	22.0	10.0	16.0				
19.0	22.0	11.0	16.5		T		T
20.0	27.0	7.0	17.0				
21.0	18.0	3.0	10.5				
22.0	23.0	10.0	16.5				
23.0	24.0	11.0	17.5				
24.0	15.0	10.0	12.5		23.6		23.6
25.0	19.0	5.0	12.0		1.3		1.3
26.0	22.0	10.0	16.0				
27.0	27.0	11.0	19.0				
28.0	27.0	5.0	16.0				
29.0	20.0	9.0	14.5		T		T
30.0	24.0	11.0	17.5				
31.0	29.0	10.0	19.5				
MEAN T:	22.9	8.8	15.9	TOTAL:	96.1	0.0	96.1

06-Oct 89

BOW ISLAND TEMPERATURE AND PRECIPITATION

SEPTEMBER 1987

TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY	RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	33.0	15.0	24.0			
2.0	28.0	11.0	19.5			
3.0	18.0	4.0	11.0	3.1		3.1
4.0	23.0	4.0	13.5			
5.0	27.0	7.0	17.0			
6.0	19.0	5.0	12.0	4.8		4.8
7.0	23.0	3.0	13.0			
8.0	23.0	9.0	16.0			
9.0	22.0	3.0	12.5	T		T
10.0	24.0	5.0	14.5			
11.0	25.0	10.0	17.5			
12.0	31.0	11.0	21.0			
13.0	24.0	6.0	15.0			
14.0	24.0	11.0	17.5			
15.0	21.0	4.0	12.5			
16.0	19.0	1.0	10.0	0.5		0.5
17.0	21.0	4.0	12.5			
18.0	23.0	2.0	12.5			
19.0	26.0	7.0	16.5			
20.0	28.0	9.0	18.5			
21.0	31.0	6.0	18.5			
22.0	31.0	4.0	17.5			
23.0	29.0	2.0	15.5			
24.0	24.0	5.0	14.5			
25.0	27.0	11.0	19.0			
26.0	18.0	5.0	11.5	T		T
27.0	19.0	-1.0	9.0			
28.0	22.0	2.0	12.0			
29.0	23.0	5.0	14.0			
30.0	28.0	4.0	16.0			
MEAN T:	24.5	5.8	15.1	TOTAL: 8.4	0.0	8.4

GROWING SEASON TOTAL (1987) 200.2

BOW ISLAND TEMPERATURE AND PRECIPITATION

OCTOBER 1987

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	23.0	8.0	15.5				
2.0	28.0	8.0	18.0				
3.0	27.0	8.0	17.5				
4.0	15.0	-2.0	6.5				
5.0	19.0	2.0	10.5				
6.0	17.0	4.0	10.5				
7.0	23.0	4.0	13.5				
8.0	6.0	-2.0	2.0				
9.0	6.0	-7.0	-0.5				
10.0	19.0	-3.0	8.0				
11.0	26.0	2.0	14.0				
12.0	23.0	-3.0	10.0				
13.0	16.0	0.0	8.0				
14.0	19.0	3.0	11.0				
15.0	12.0	-3.0	4.5		T		T
16.0	16.0	1.0	8.5				
17.0	10.0	-5.0	2.5		3.8	T	3.8
18.0	10.0	-1.0	4.5			T	T
19.0	9.0	-3.0	3.0				
20.0	12.0	1.0	6.5				
21.0	13.0	-8.0	2.5				
22.0	13.0	-6.0	3.5				
23.0	12.0	0.0	6.0				
24.0	19.0	1.0	10.0				
25.0	20.0	2.0	11.0		4.3		4.3
26.0	11.0	-5.0	3.0				
27.0	17.0	1.0	9.0				
28.0	20.0	5.0	12.5				
29.0	24.0	2.0	13.0				
30.0	23.0	5.0	14.0				
31.0	22.0	3.0	12.5				
MEAN T:	17.1	0.4	8.7	TOTAL:	8.1	0.0	8.1

BOW ISLAND TEMPERATURE AND PRECIPITATION

NOVEMBER 1987

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	13.0	-3.0	5.0				
2.0	15.0	3.0	9.0				
3.0	13.0	0.0	6.5		1.5	1.5	3.0
4.0	9.0	0.0	4.5				
5.0	14.0	0.0	7.0				
6.0	17.0	-6.0	5.5				
7.0	11.0	0.0	5.5				
8.0	13.0	-3.0	5.0				
9.0	14.0	2.0	8.0				
10.0	17.0	4.0	10.5				
11.0	17.0	4.0	10.5				
12.0	13.0	-6.0	3.5				
13.0	11.0	-5.0	3.0				
14.0	6.0	-9.0	-1.5		1.3		1.3
15.0	5.0	-7.0	-1.0				
16.0	0.0	-15.0	-7.5			0.5	0.5
17.0	0.0	-11.0	-5.5				
18.0	8.0	-5.0	1.5				
19.0	12.0	0.0	6.0				
20.0	17.0	7.0	12.0				
21.0	15.0	2.0	8.5				
22.0	10.0	-2.0	4.0				
23.0	4.0	-8.0	-2.0				
24.0	10.0	-2.0	4.0				
25.0	4.0	-9.0	-2.5			1.8	1.8
26.0	5.0	-5.0	0.0				
27.0	11.0	-9.0	1.0				
28.0	7.0	-8.0	-0.5				
29.0	7.0	-8.0	-0.5				
30.0	8.0	-5.0	1.5				
MEAN T:	10.2	-3.5	3.4	TOTAL:	2.8	3.8	6.6

BOW ISLAND TEMPERATURE AND PRECIPITATION

DECEMBER 1987

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	12.0	1.0	6.5				
2.0	10.0	-2.0	4.0				
3.0	14.0	2.0	8.0				
4.0	15.0	-5.0	5.0				
5.0	15.0	1.0	8.0				
6.0	16.0	4.0	10.0				
7.0	12.0	-2.0	5.0		1.5		1.5
8.0	8.0	-5.0	1.5				
9.0	11.0	3.0	7.0		T		T
10.0	10.0	-2.0	4.0				
11.0	5.0	-5.0	0.0			0.3	0.3
12.0	1.0	-8.0	-3.5			0.5	0.5
13.0	-3.0	-18.0	-10.5			0.3	0.3
14.0	-7.0	-13.0	-10.0				
15.0	-1.0	-17.0	-9.0				
16.0	-5.0	-10.0	-7.5				
17.0	-4.0	-15.0	-9.5				
18.0	4.0	-10.0	-3.0				
19.0	4.0	-8.0	-2.0				
20.0	2.0	-8.0	-3.0				
21.0	4.0	-17.0	-6.5			0.3	0.3
22.0	2.0	-9.0	-3.5				
23.0	-4.0	-15.0	-9.5			0.3	0.3
24.0	-3.0	-8.0	-5.5			T	T
25.0	6.0	-5.0	0.5				
26.0	4.0	-6.0	-1.0				
27.0	3.0	-7.0	-2.0				
28.0	1.0	-9.0	-4.0				
29.0	-3.0	-15.0	-9.0			T	T
30.0	-13.0	-29.0	-21.0			0.5	0.5
31.0	-9.0	-20.0	-14.5				
MEAN T:	3.5	-8.3	-2.4	TOTAL:	1.5	2.2	3.7

BOW ISLAND TEMPERATURE AND PRECIPITATION

JANUARY 1988

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	-1.0	-14.0	-7.5				
2.0	-5.0	-23.0	-14.0				
3.0	-13.0	-31.0	-22.0				
4.0	-10.0	-25.0	-17.5				
5.0	-11.0	-26.0	-18.5				
6.0	-11.0	-17.0	-14.0				
7.0	-12.0	-23.0	-17.5			0.3	0.3
8.0	-16.0	-24.0	-20.0				
9.0	-3.0	-19.0	-11.0				
10.0	-13.0	-22.0	-17.5				
11.0	-15.0	-23.0	-19.0			1.5	1.5
12.0	-10.0	-24.0	-17.0				
13.0	3.0	-3.0	0.0				
14.0	6.0	3.0	4.5				
15.0	7.0	-5.0	1.0				
16.0	5.0	-9.0	-2.0				
17.0	2.0	-17.0	-7.5				
18.0	3.0	-16.0	-6.5				
19.0	3.0	-9.0	-3.0				
20.0	6.0	-4.0	1.0			T	T
21.0	5.0	-10.0	-2.5				
22.0	7.0	-3.0	2.0				
23.0	7.0	1.0	4.0				
24.0	8.0	2.0	5.0				
25.0	10.0	-12.0	-1.0				
26.0	6.0	-3.0	1.5				
27.0	15.0	0.0	7.5				
28.0	15.0	-8.0	3.5				
29.0	-7.0	-22.0	-14.5				
30.0	-14.0	-29.0	-21.5			T	T
31.0	-21.0	-32.0	-26.5				
MEAN T:	-1.7	-14.4	-8.1	TOTAL:	0.0	1.8	1.8

BOW ISLAND TEMPERATURE AND PRECIPITATION

FEBRUARY 1988

DAY	MAX	MIN	DAILY	RAIN (mm)	SNOW (cm)	TOTAL (mm)
	TEMPERATURE (^{o}C)			PRECIPITATION		
1.0	-10.0	-22.0	-16.0			
2.0	-16.0	-25.0	-20.5			
3.0	-13.0	-28.0	-20.5			
4.0	-18.0	-31.0	-24.5			
5.0	-14.0	-18.0	-16.0		0.3	0.3
6.0	-3.0	-15.0	-9.0		1.3	1.3
7.0	-3.0	-15.0	-9.0		0.8	0.8
8.0	-12.0	-23.0	-17.5		1.8	1.8
9.0	-17.0	-32.0	-24.5		1.3	1.3
10.0	-10.0	-17.0	-13.5			
11.0	10.0	-4.0	3.0			
12.0	15.0	0.0	7.5			
13.0	6.0	-12.0	-3.0			
14.0	8.0	1.0	4.5			
15.0	10.0	-2.0	4.0			
16.0	8.0	-1.0	3.5			
17.0	10.0	-5.0	2.5			
18.0	10.0	-3.0	3.5			
19.0	14.0	2.0	8.0			
20.0	19.0	6.0	12.5			
21.0	12.0	-11.0	0.5			
22.0	0.0	-12.0	-6.0			
23.0	0.0	-13.0	-6.5			
24.0	16.0	-3.0	6.5			
25.0	20.0	-6.0	7.0			
26.0	21.0	-2.0	9.5			
27.0	12.0	-10.0	1.0			
28.0	14.0	-3.0	5.5			
29.0	13.0	-2.0	5.5			
MEAN T:	3.5	-10.6	-3.5	TOTAL: 0.0	5.5	5.5

06 Oct 89

BOW ISLAND TEMPERATURE AND PRECIPITATION

MARCH 1988

TEMPERATURE (°C)					PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	5.0	-10.0	-2.5				
2.0	9.0	-1.0	4.0				
3.0	7.0	0.0	3.5				
4.0	12.0	-1.0	5.5		4.3		4.3
5.0	20.0	0.0	10.0				
6.0	13.0	-1.0	6.0			T	T
7.0	11.0	-4.0	3.5				
8.0	15.0	1.0	8.0				
9.0	11.0	0.0	5.5				
10.0	4.0	-3.0	0.5			T	T
11.0	5.0	-8.0	-1.5			0.3	0.3
12.0	4.0	-10.0	-3.0				
13.0	11.0	-4.0	3.5				
14.0	8.0	-3.0	2.5				
15.0	6.0	-7.0	-0.5				
16.0	6.0	-13.0	-3.5				
17.0	11.0	-6.0	2.5				
18.0	15.0	2.0	8.5				
19.0	21.0	3.0	12.0				
20.0	17.0	5.0	11.0				
21.0	15.0	2.0	8.5				
22.0	12.0	-1.0	5.5				
23.0	16.0	0.0	8.0				
24.0	13.0	-5.0	4.0				
25.0	17.0	0.0	8.5				
26.0	14.0	-1.0	6.5				
27.0	-2.0	-7.0	-4.5			10.2	10.2
28.0	-1.0	-16.0	-8.5				
29.0	3.0	-16.0	-6.5				
30.0	5.0	-5.0	0.0				
31.0	16.0	2.0	9.0				
MEAN T:	10.3	-3.5	3.4	TOTAL:	4.3	10.5	14.8

BOW ISLAND TEMPERATURE AND PRECIPITATION

APRIL 1988

	TEMPERATURE (^oC)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	20.0	0.0	10.0				
2.0	26.0	7.0	16.5				
3.0	16.0	0.0	8.0				
4.0	14.0	-4.0	5.0				
5.0	14.0	6.0	10.0				
6.0	23.0	4.0	13.5				
7.0	14.0	-3.0	5.5				
8.0	9.0	-9.0	0.0				
9.0	13.0	-5.0	4.0				
10.0	25.0	6.0	15.5				
11.0	23.0	1.0	12.0				
12.0	16.0	-2.0	7.0				
13.0	19.0	4.0	11.5				
14.0	22.0	6.0	14.0				
15.0	28.0	3.0	15.5				
16.0	24.0	-2.0	11.0				
17.0	20.0	-2.0	9.0				
18.0	19.0	4.0	11.5				
19.0	15.0	-5.0	5.0				
20.0	17.0	0.0	8.5				
21.0	16.0	-3.0	6.5				
22.0	16.0	2.0	9.0				
23.0	19.0	-4.0	7.5				
24.0	7.0	2.0	4.5				
25.0	7.0	-7.0	0.0				
26.0	16.0	-3.0	6.5				
27.0	21.0	1.0	11.0				
28.0	21.0	13.0	17.0				
29.0	22.0	5.0	13.5				
30.0	16.0	5.0	10.5				
MEAN T:	17.9	0.7	9.3	TOTAL:	0.0	0.0	0.0

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BOW ISLAND TEMPERATURE AND PRECIPITATION

MAY 1988

DAY	TEMPERATURE (°C) MAX	MIN	DAILY		PRECIPITATION RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	16.0	-2.0	7.0				
2.0	17.0	-2.0	7.5				
3.0	18.0	7.0	12.5				
4.0	22.0	8.0	15.0		T		T
5.0	23.0	7.0	15.0		1.5		1.5
6.0	19.0	0.0	9.5				
7.0	21.0	3.0	12.0				
8.0	24.0	4.0	14.0				
9.0	27.0	12.0	19.5				
10.0	23.0	10.0	16.5				
11.0	27.0	8.0	17.5				
12.0	27.0	12.0	19.5				
13.0	27.0	13.0	20.0		T		T
14.0	29.0	4.0	16.5				
15.0	24.0	5.0	14.5				
16.0	34.0	12.0	23.0		0.3		0.3
17.0	21.0	8.0	14.5		0.3		0.3
18.0	21.0	7.0	14.0				
18.0	22.0	5.0	13.5				
20.0	22.0	3.0	12.5				
21.0	30.0	9.0	19.5				
22.0	32.0	14.0	23.0				
23.0	31.0	9.0	20.0				
24.0	21.0	2.0	11.5				
25.0	29.0	11.0	20.0				
26.0	27.0	10.0	18.5				
27.0	26.0	8.0	17.0				
28.0	30.0	12.0	21.0		0.3		0.3
29.0	26.0	10.0	18.0		1.3		1.3
30.0	15.0	8.0	11.5				
31.0	20.0	6.0	13.0				
MEAN T:	24.2	7.2	15.7	TOTAL:	3.7	0.0	3.7

BOW ISLAND TEMPERATURE AND PRECIPITATION

JUNE 1988

	TEMPERATURE (^oC)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	24.0	5.0	14.5				
2.0	28.0	9.0	18.5				
3.0	33.0	12.0	22.5		3.8		3.8
4.0	32.0	15.0	23.5				
5.0	29.0	15.0	22.0		3.8		3.8
6.0	29.0	15.0	22.0				
7.0	27.0	13.0	20.0		T		T
8.0	16.0	9.0	12.5		26.7		26.7
9.0	25.0	10.0	17.5				
10.0	28.0	13.0	20.5				
11.0	25.0	6.0	15.5				
12.0	18.0	6.0	12.0				
13.0	20.0	6.0	13.0		3.3		3.3
14.0	23.0	7.0	15.0				
15.0	29.0	12.0	20.5				
16.0	34.0	15.0	24.5				
17.0	33.0	16.0	24.5				
18.0	30.0	11.0	20.5				
19.0	33.0	16.0	24.5				
20.0	34.0	14.0	24.0		T		T
21.0	28.0	14.0	21.0				
22.0	34.0	19.0	26.5				
23.0	32.0	12.0	22.0				
24.0	29.0	13.0	21.0				
25.0	33.0	20.0	26.5				
26.0	33.0	16.0	24.5				
27.0	32.0	15.0	23.5		2.0		2.0
28.0	32.0	15.0	23.5		17.3		17.3
29.0	19.0	8.0	13.5		0.8		0.8
30.0	22.0	9.0	15.5				
MEAN T:	28.1	12.2	20.2	TOTAL:	57.7	0.0	57.7

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BOW ISLAND TEMPERATURE AND PRECIPITATION

JULY 1988

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	29.0	12.0	20.5				
2.0	26.0	14.0	20.0				
3.0	26.0	13.0	19.5				
4.0	26.0	12.0	19.0		4.6		4.6
5.0	23.0	9.0	16.0		1.5		1.5
6.0	20.0	10.0	15.0				
7.0	25.0	7.0	16.0				
8.0	28.0	9.0	18.5				
9.0	29.0	14.0	21.5				
10.0	29.0	14.0	21.5				
11.0	31.0	12.0	21.5		5.1		5.1
12.0	23.0	9.0	16.0				
13.0	26.0	12.0	19.0		2.5		2.5
14.0	22.0	7.0	14.5		5.1		5.1
15.0	26.0	12.0	19.0				
16.0	26.0	12.0	19.0				
17.0	22.0	6.0	14.0				
18.0	23.0	9.0	16.0		1.3		1.3
19.0	28.0	10.0	19.0				
20.0	32.0	13.0	22.5				
21.0	35.0	14.0	24.5				
22.0	35.0	10.0	22.5				
23.0	32.0	14.0	23.0				
24.0	33.0	13.0	23.0				
25.0	35.0	13.0	24.0				
26.0	35.0	14.0	24.5				
27.0	33.0	16.0	24.5				
28.0	30.0	10.0	20.0				
29.0	31.0	14.0	22.5				
30.0	32.0	15.0	23.5				
31.0	31.0	11.0	21.0				
MEAN T:	28.5	11.6	20.0	TOTAL:	20.1	0.0	20.1

BOW ISLAND TEMPERATURE AND PRECIPITATION

AUGUST 1988

	TEMPERATURE (^oC)			PRECIPITATION		
DAY	MAX	MIN	DAILY	RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	21.0	9.0	15.0			
2.0	20.0	6.0	13.0	6.4		6.4
3.0	28.0	9.0	18.5			
4.0	31.0	11.0	21.0			
5.0	30.0	8.0	19.0			
6.0	23.0	6.0	14.5			
7.0	22.0	8.0	15.0			
8.0	29.0	11.0	20.0			
9.0	31.0	11.0	21.0			
10.0	27.0	11.0	19.0			
11.0	29.0	12.0	20.5			
12.0	31.0	9.0	20.0			
13.0	30.0	10.0	20.0			
14.0	28.0	9.0	18.5	T		T
15.0	28.0	14.0	21.0	21.6		21.6
16.0	22.0	11.0	16.5	T		T
17.0	29.0	14.0	21.5			
18.0	28.0	6.0	17.0			
19.0	27.0	13.0	20.0			
20.0	19.0	11.0	15.0	7.4		7.4
21.0	22.0	11.0	16.5	6.9		6.9
22.0	24.0	7.0	15.5			
23.0	29.0	12.0	20.5			
24.0	28.0	10.0	19.0			
25.0	30.0	12.0	21.0	T		T
26.0	21.0	6.0	13.5			
27.0	22.0	7.0	14.5			
28.0	30.0	11.0	20.5			
29.0	34.0	11.0	22.5			
30.0	25.0	5.0	15.0			
31.0	25.0	5.0	15.0			
MEAN T:	26.5	9.5	18.0	TOTAL: 42.3	0.0	42.3

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BOW ISLAND TEMPERATURE AND PRECIPITATION

SEPTEMBER 1988

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	29.0	7.0	18.0				
2.0	32.0	10.0	21.0				
3.0	33.0	10.0	21.5				
4.0	32.0	10.0	21.0				
5.0	30.0	10.0	20.0				
6.0	33.0	11.0	22.0		1.3		1.3
7.0	18.0	-1.0	8.5		5.1		5.1
8.0	21.0	3.0	12.0				
9.0	23.0	7.0	15.0				
10.0	16.0	3.0	9.5		11.4		11.4
11.0	16.0	2.0	9.0				
12.0	25.0	5.0	15.0				
13.0	25.0	8.0	16.5				
14.0	28.0	10.0	19.0				
15.0	29.0	11.0	20.0				
16.0	15.0	6.0	10.5		2.0		2.0
17.0	10.0	2.0	6.0		1.0		1.0
18.0	12.0	4.0	8.0		6.6		6.6
19.0	13.0	4.0	8.5				
20.0	9.0	3.0	6.0		1.0		1.0
21.0	18.0	-1.0	8.5				
22.0	18.0	2.0	10.0				
23.0	18.0	3.0	10.5				
24.0	17.0	5.0	11.0				
25.0	21.0	2.0	11.5		1.3		1.3
26.0	15.0	2.0	8.5				
27.0	15.0	2.0	8.5		4.3		4.3
28.0	18.0	3.0	10.5				
29.0	29.0	7.0	18.0				
30.0	21.0	6.0	13.5				
MEAN T:	21.3	5.2	13.3	TOTAL:	34.0	0.0	34.0

GROWING SEASON TOTAL (1988) 157.8

BOW ISLAND TEMPERATURE AND PRECIPITATION

OCTOBER 1988

DAY	TEMPERATURE (^{o}C) MAX	MIN	DAILY		PRECIPITATION RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	20.0	7.0	13.5				
2.0	19.0	5.0	12.0				
3.0	16.0	2.0	9.0				
4.0	19.0	2.0	10.5				
5.0	23.0	2.0	12.5				
6.0	24.0	2.0	13.0				
7.0	28.0	0.0	14.0				
8.0	24.0	4.0	14.0				
9.0	23.0	4.0	13.5				
10.0	24.0	4.0	14.0				
11.0	25.0	2.0	13.5				
12.0	27.0	3.0	15.0				
13.0	27.0	8.0	17.5				
14.0	22.0	4.0	13.0				
15.0	11.0	5.0	8.0		0.8		0.8
16.0	12.0	4.0	8.0				
17.0	13.0	-6.0	3.5				
18.0	14.0	-1.0	6.5				
19.0	19.0	-1.0	9.0				
20.0	16.0	-1.0	7.5				
21.0	23.0	6.0	14.5				
22.0	13.0	-3.0	5.0		0.8		0.8
23.0	17.0	-2.0	7.5				
24.0	12.0	0.0	6.0				
25.0	16.0	3.0	9.5				
26.0	5.0	-7.0	-1.0		2.3		2.3
27.0	0.0	-14.0	-7.0				
28.0	1.0	-12.0	-5.5				
29.0	7.0	-3.0	2.0				
30.0	18.0	-1.0	8.5				
31.0	19.0	6.0	12.5				
MEAN T:	17.3	0.7	9.0	TOTAL:	3.9	0.0	3.9

BOW ISLAND TEMPERATURE AND PRECIPITATION

NOVEMBER 1988

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	17.0	-2.0	7.5				
2.0	16.0	2.0	9.0				
3.0	16.0	1.0	8.5		0.8		0.8
4.0	16.0	-6.0	5.0				
5.0	14.0	3.0	8.5				
6.0	14.0	2.0	8.0				
7.0	10.0	-7.0	1.5				
8.0	6.0	-6.0	0.0				
9.0	7.0	-7.0	0.0				
10.0	10.0	-3.0	3.5				
11.0	11.0	0.0	5.5				
12.0	12.0	-4.0	4.0				
13.0	4.0	-8.0	-2.0				
14.0	-3.0	-14.0	-8.5			0.8	0.8
15.0	-2.0	-14.0	-8.0				
16.0	5.0	-9.0	-2.0				
17.0	2.0	-14.0	-6.0			1.5	1.5
18.0	-5.0	-11.0	-8.0				
19.0	5.0	-6.0	-0.5				
20.0	10.0	-7.0	1.5				
21.0	5.0	-1.0	2.0				
22.0	11.0	0.0	5.5				
23.0	10.0	-4.0	3.0				
24.0	3.0	-10.0	-3.5				
25.0	2.0	-15.0	-6.5				
26.0	-4.0	-23.0	-13.5			0.8	0.8
27.0	3.0	-6.0	-1.5				
28.0	7.0	-5.0	1.0				
29.0	8.0	-5.0	1.5				
30.0	12.0	4.0	8.0				
MEAN T:	7.4	-5.8	0.8	TOTAL:	0.8	3.1	3.9

BOW ISLAND TEMPERATURE AND PRECIPITATION

DECEMBER 1988

	TEMPERATURE (°C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	13.0	4.0	8.5				
2.0	14.0	-8.0	3.0				
3.0	10.0	4.0	7.0				
4.0	19.0	-1.0	9.0				
5.0	14.0	-5.0	4.5				
6.0	3.0	-7.0	-2.0				
7.0	-2.0	-12.0	-7.0				
8.0	6.0	-11.0	-2.5				
9.0	5.0	-3.0	1.0				
10.0	6.0	-8.0	-1.0			1.3	1.3
11.0	10.0	1.0	5.5				
12.0	12.0	1.0	6.5		0.8		0.8
13.0	7.0	-7.0	0.0			1.3	1.3
14.0	-4.0	-14.0	-9.0			2.0	2.0
15.0	4.0	-10.0	-3.0				
16.0	5.0	-10.0	-2.5				
17.0	12.0	0.0	6.0				
18.0	7.0	-2.0	2.5				
19.0	1.0	-15.0	-7.0			4.6	4.6
20.0	-4.0	-13.0	-8.5				
21.0	-4.0	-17.0	-10.5				
22.0	-9.0	-15.0	-12.0			T	T
23.0	-7.0	-18.0	-12.5			T	T
24.0	-15.0	-23.0	-19.0			0.8	0.8
25.0	-17.0	-31.0	-24.0				
26.0	-17.0	-27.0	-22.0				
27.0	-11.0	-25.0	-18.0				
28.0	-12.0	-15.0	-13.5				
29.0	1.0	-10.0	-4.5				
30.0	1.0	-16.0	-7.5			T	T
31.0	3.0	-26.0	-11.5			T	T
MEAN T:	1.6	-10.9	-4.6	TOTAL:	0.8	10.0	10.8

BOW ISLAND TEMPERATURE AND PRECIPITATION

JANUARY 1989

DAY	TEMPERATURE (°C) MAX	MIN	DAILY		PRECIPITATION RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	-6.0	-14.0	-10.0				
2.0	3.0	-14.0	-5.5				
3.0	7.0	-6.0	0.5				
4.0	3.0	-5.0	-1.0				
5.0	-1.0	-16.0	-8.5			3.1	3.1
6.0	-15.0	-25.0	-20.0			5.6	5.6
7.0	-23.0	-32.0	-27.5				
8.0	-18.0	-33.0	-25.5				
9.0	-15.0	-27.0	-21.0				
10.0	-10.0	-20.0	-15.0			1.0	1.0
11.0	-5.0	-23.0	-14.0				
12.0	4.0	-7.0	-1.5				
13.0	4.0	-9.0	-2.5				
14.0	-2.0	-19.0	-10.5			3.3	3.3
15.0	4.0	-8.0	-2.0				
16.0	7.0	0.0	3.5				
17.0	7.0	0.0	3.5				
18.0	8.0	-14.0	-3.0			1.0	1.0
19.0	5.0	-2.0	1.5				
20.0	9.0	0.0	4.5				
21.0	7.0	-11.0	-2.0				
22.0	-2.0	-15.0	-8.5				
23.0	-5.0	-13.0	-9.0				
24.0	-6.0	-14.0	-10.0				
25.0	3.0	-3.0	0.0				
26.0	8.0	-1.0	3.5				
27.0	9.0	-5.0	2.0				
28.0	7.0	-3.0	2.0				
29.0	12.0	4.0	8.0				
30.0	13.0	-27.0	-7.0			T	T
31.0	-25.0	-33.0	-29.0				
MEAN T:	-0.4	-12.7	-6.6	TOTAL:	0.0	14.0	14.0

06-Oct-89

BOW ISLAND TEMPERATURE AND PRECIPITATION

FEBRUARY 1989

	TEMPERATURE (^{o}C)				PRECIPITATION		
DAY	MAX	MIN	DAILY		RAIN (mm)	SNOW (cm)	TOTAL (mm)
1.0	-30 0	-35.0	-32.5				
2.0	-29.0	-33.0	-31.0				
3.0	-24.0	-33.0	-28.5				
4.0	-13.0	-16.0	-14.5			0.8	0.8
5.0	-7.0	-10.0	-8.5			1.5	1.5
6.0	-3.0	-13.0	-8.0				
7.0	-6.0	-27.0	-16.5				
8.0	-5.0	-17.0	-11.0				
9.0	-2.0	-14.0	-8.0				
10.0	-4.0	-18.0	-11.0				
11.0	-2.0	-8.0	-5.0				
12.0	2.0	-9.0	-3.5			1.3	1.3
13.0	-4.0	-17.0	-10.5			0.8	0.8
14.0	-9.0	-21.0	-15.0			0.5	0.5
15.0	-17.0	-26.0	-21.5			0.3	0.3
16.0	-20.0	-28.0	-24.0			0.3	0.3
17.0	-20.0	-27.0	-23.5				
18.0	-17.0	-23.0	-20.0				
19.0	-9.0	-19.0	-14.0				
20.0	0.0	-14.0	-7.0				
21.0	1.0	-15.0	-7.0				
22.0	7.0	0.0	3.5				
23.0	7.0	-6.0	0.5				
24.0	5.0	-7.0	-1.0				
25.0	-5.0	-15.0	-10.0			T	T
26.0	3.0	-9.0	-3.0				
27.0	-6.0	-20.0	-13.0			0.8	0.8
28.0	-16.0	-27.0	-21.5				
MEAN T:	-8.0	-18.1	-13.0	TOTAL:	0.0	6.1	6 3

06 Oct 89

APPENDIX D

Irrigation Schedule

IRRIGATION SCHEDULE

Type of Irrigation: Upslope = None

Downslope and
Test Plots #1 and 3 = Centre Pivot

Test Plot #2 = Centre Pivot
and Solid Set

Irrigation Dates and Depths:

1987			1988		
Date	Type of Irrigation		Date	Type of Irrigation	
	Centre Pivot[+] (mm)	Solid Set (mm)		Centre Pivot[+] (mm)	Solid Set (mm)
May 14	36		April 24	36	
May 16	36		April 29	36	
June 16	36		May 16	36	
June 27	36		June 3	36	
July 3	36		June 20	36	
July 17	36		June 26	36	
August 1	28		June 29	27	
September 2		18	July 11	30	
September 3		29	July 14	30	
September 8		16	July 26	36	
September 9		14	August 30		11
September 14		13	August 31		39
September 15		18	September 1		15
September 21		19	September 5		10
September 22		21	September 6		40
September 28	53		September 7		13
			September 13		8
			September 14		22
			September 21		16
			September 22		15
			October 2	22	
			October 3	23	
			October 9		17
					20
TOTAL	297	148		384	226

[+] Irrigation depths derived from measurements taken on September 28, 1987 and October 2, 1988. Values were then adjusted according to the speed of the pivot recorded by the farmer at each irrigation. Data applies to the eastern half of the quarter section.

APPENDIX E

Photographs

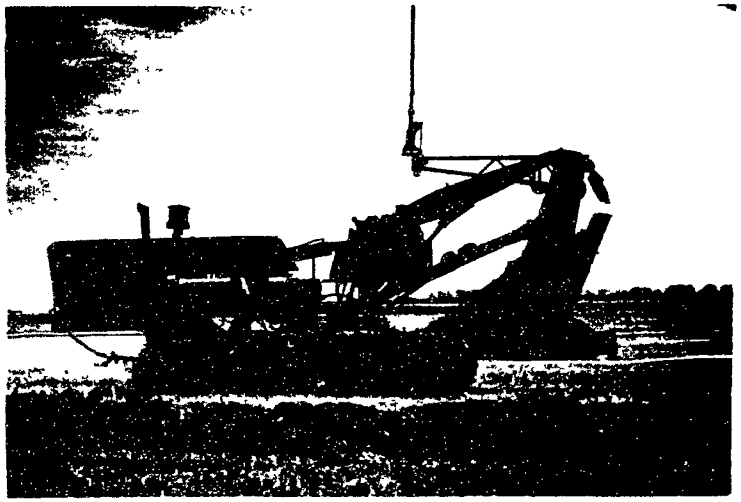

Plate E1. Wolfe Model 250 drain plow.

Plate E2. Pivot and solid set irrigation treatment at test plot #2.

Plate E3. Test plot area; August 1987.

Plate E4. Test plot area; August 1988.

Plate E5. Measurement of surface runoff at test plot #2.

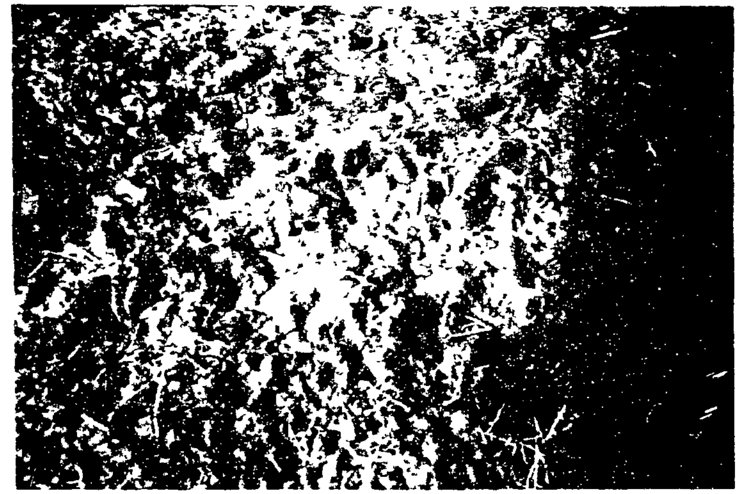

Plate E6. Dispersed soil surface.

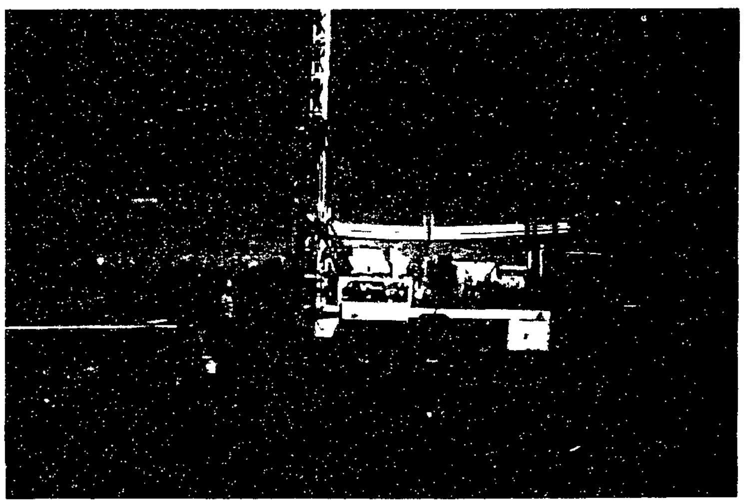

Plate E7. Installation of piezometers.

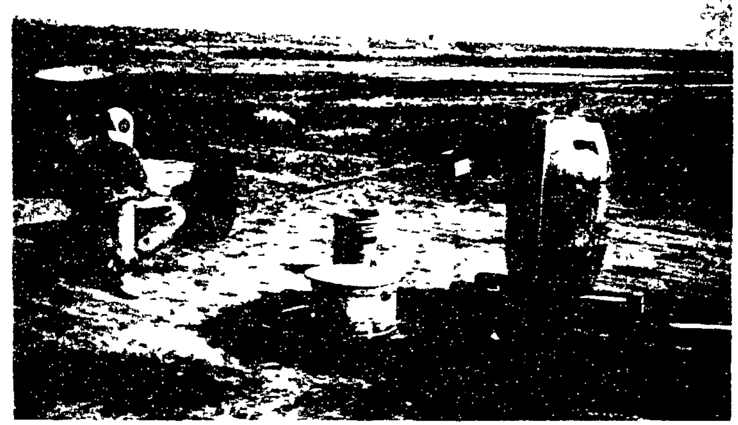

Plate E8. Measurement of soil infiltration rate.