Groundwater-flow modeling of deep interceptor and grid drainage for interception of canal seepage and groundwater

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[1]CH2M Hill Engineering Ltd., 11th Floor, 815-8 Ave. S.W., Calgary, AB, Canada, T2P 3P2; [2]Land Evaluation and Reclamation Branch, Alberta Agriculture, Lethbridge, AB, Canada, T1J 4C7; and [3]Macdonald College of McGill University, Montreal, PQ, Canada, H9X 1C0. *Received 1 October 1990; accepted 20 June 1991.*

Millette, D., Buckland, G.D., Galatiuk, W.R. and Madramootoo, C. 1992. **Groundwater-flow modeling of deep interceptor and grid drainage for interception of canal seepage and groundwater.** Can. Agric. Eng. 34:007-015. A groundwater-flow study was initiated to compare the relative effectiveness of deep interceptor and grid drainage to intercept seepage from irrigation canals. Four experimental sites, representing different hydrogeological conditions, were selected for this study. Evaluation methods included test drilling, the installation, testing and monitoring of piezometers and watertable wells and mathematical modeling of groundwater flow. Results of a one year groundwater monitoring program were used to calibrate the groundwater-flow model, MODFLOW. Subsequent simulations indicated that grid drainage and deep-interceptor drainage would provide equal control of the watertable where land downslope of the irrigation canal was affected mainly by canal seepage. Where seepage and groundwater influenced downslope land, grid drainage provided better watertable control than deep-interceptor drainage. Flow simulations using an irrigation recharge to enhance leaching of excess soil salts, indicated that grid drainage would provide better watertable control than a deep-interceptor drain regardless of the nature of the waterlogging conditions.

Une étude hydrogéologique a été réalisée afin de comparer l'efficacité des drains intercepteurs profonds à celle d'un système de drainage conventionnel, pour le contrôle du suintement des canaux d'irrigation. Quatre sites expérimentaux représentant diverses conditions hydrogéologiques ont été sélectionnés. Des piézomètres et des puits d'eau ont été installés pour mesurer la hauteur piézométrique de chaque couche stratigraphique, et le niveau de la nappe phréatique. Les piézomètres ont aussi été utilisés pour déterminer la conductivité hydraulique de chaque horizon géologique. La prise de données au terrain s'est échelonnée sur une année. Les résultats obtenus au terrain ont été utilisés pour calibrer le modèle mathématique MODFLOW. L'exercice de modélisation a indiqué que les deux types de drains intercepteurs offraient une efficacité comparable moyennant que le problème de drainage en aval du canal soit causé uniquement par le suintement du canal d'irrigation. Lorsque le suintement naturel en aval du canal est considérable, il a été démontré qu'un système de drainage conventionnel assure une meilleure interception du suintement du canal et résulte en un meilleur contrôle de la nappe phréatique. Dans l'éventualité où une quantité additionnelle d'eau d'irrigation serait ajoutée pour lessiver les sels accumulés à la surface des sols, le modèle montre qu'un système de drainage conventionnel assurerait un meilleur contrôle de la nappe phréatique indépendamment de la source du suintement.

INTRODUCTION

About 70% of saline and/or waterlogged land within the irrigation districts of southern Alberta results from or is associated with canal seepage (Chang et al. 1985; Sommerfeldt and Rapp 1982), although groundwater which originates from sources other than canal seepage may also contribute to soil salinity and waterlogging problems (Hendry and Buckland 1990; Paterson and Harker 1980). Control of canal seepage, without the simultaneous control of groundwater, may not result in the reclamation of saline land following the rehabilitation of irrigation canals (Bennett 1990). Thus, the selection of an appropriate canal-seepage control measure may require an assessment of groundwater as well as canal seepage.

Seepage from irrigation canals is usually prevented using membrane liners or cutoff curtains, or is intercepted using deep-interceptor drains or on-farm grid drains. In large irrigation canals, membrane lining is frequently cost prohibitive. The effectiveness of cutoff curtains is dependant on specific geologic conditions which normally are not present. Thus, deep-interceptor drainage and on-farm grid drainage are frequently used to intercept seepage where other methods are inappropriate.

Deep-interceptor drainage is the most common method used to intercept canal seepage. 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. A gravel chimney is placed above the drain to prevent seepage water from flowing over the drain. If salinity/waterlogging is caused primarily by canal seepage, then correct placement of the drain should reduce the downslope water table to the level of the drain (USDA 1973) and salinity/waterlogging problems will decrease. However, if a shallow water table results partially from natural groundwater and partially from canal seepage, simple hydraulics suggest that grid drainage may be more beneficial.

Grid drainage is a series of parallel, regularly spaced, 100-mm diameter, perforated polyethylene drain tubes installed throughout saline/waterlogged areas adjacent to leaking canals. Drain depth varies from 1.0 to 1.8 m. The grid drains may intercept both canal seepage and natural groundwater and may provide the added advantage of removing excess water applied by irrigation, thereby allowing the flushing of soil salts.

While deep-interceptor drains and grid drains are known to be effective in controlling canal seepage, their relative effectiveness to reclaim saline soils under southern Alberta climatic and geologic conditions has not been established. This study was initiated to determine the relative effectiveness of deep

interceptor and grid drains to control canal and groundwater seepage and reclaim saline/waterlogged soils.

MATERIALS AND METHODS

Site description

Four sites where the St. Mary River Irrigation District Main Canal in Alberta had recently been upgraded with seepage-control measures were selected for this study. A deep-interceptor drain was present at two sites near Taber, AB while grid drainage was present at two sites near Bow Island, AB. Table I summarizes the main features at each study site.

Depth of the deep-interceptor drain below ground surface was 1.6 m at site I1 and 3.0 to 4.6 m at site I2. The deep interceptor at site I1 was shallower than the usual 2 to 4-m depth because the site was located at the end of the interceptor line. The interceptor drain was located 12 m downslope of the toe of the canal at site I1 and at the toe of the canal at site I2. The average depth of the grid drains at sites G1 and G3 was 1.4 m and drain spacing was 15 m near the canal and 30 m thereafter. Grid drains extended to a distance of 690 and 360 m downslope of the canal at sites G1 and G3, respectively.

Groundwater investigations and monitoring

Test drilling was conducted at each site in transects perpendicular to the irrigation canal (i.e. roughly perpendicular to the direction of groundwater flow) to define the stratigraphy of the area. Transects extended from about 200 m upslope of the canal to a maximum distance of 600 m downslope. At least one transect, consisting of 10 to 14 watertable wells and 4 to 11 piezometer nests, was installed at each site.

Piezometers were constructed of 50-mm inside diameter PVC pipe with a 0.5-m length of plastic-wound well screen. A sand pack and bentonite seal were placed around and above the screen, respectively. The remainder of the testhole was backfilled with drill cuttings. Watertable wells were constructed of 50-mm inside diameter PVC slotted at 100-mm intervals through their entire length. Testholes were backfilled with drill cuttings and a bentonite seal was placed at ground surface. Piezometers and watertable wells were developed by hand bailing.

Single-well response tests (Hvorslev 1951) were performed on the piezometers to determine the insitu horizontal hydraulic conductivity of the various geologic units. Water levels in the piezometers and watertable wells were monitored weekly or every second week, from December 1987 to February 1989, using an electronic contact meter with an accuracy of about 25 mm.

Drain outflow at the deep-interceptor sites was monitored in observation manholes, located along the interceptor line, using a bucket and stopwatch. Drain outflow from the grid-drainage systems was measured using calibrated 20 degree V-notch weirs and continuous recorders. Water levels in the canal were measured at the times when groundwater monitoring was conducted.

Groundwater-flow modeling

The groundwater-flow modeling was designed to compare the relative effectiveness of the deep interceptor and grid drains to control the water table under similar hydrogeological conditions. The use of a groundwater-flow model was necessary because the different drainage systems were installed in different fields with known hydrogeologic differences. Saturated steady-state flow simulations were conducted with the modular, three dimensional, finite-difference groundwater-flow model, MODFLOW (McDonald and Harbaugh 1988). The model allows for recharge, evapotranspiration, rivers (canals), surface and subsurface drains, constant-head sources and wells.

One representative transect at each site was selected for groundwater-flow modeling. Each transect was divided into three rows, each 20 m in length, and from 41 to 70 columns

Table I. Decription of the experimental sites

Site and designation	Legal location	Type of drains+	Predominent surficial geology	Land slope
Taber - I1	W1/2 14-9-17-W4	Deep interceptor (0.6m)	Shallow fluvial (1.0 - 3.0 m) over bedrock	2.0%
Taber - I2	SW 7-9-16-W4	Deep interceptor (0.8 - 2.3 m)	Deep till (35 m) Scattered pockets of fluvial material	0.3% - 0.5%
Bow Island - G1	NE 9-9-11-W4	Grid (-0.4 - 0.0m)	Till (5.0 - 6.0 m) over coal (0.5 m to 2.0 m) or bedrock; Pockets of fluv. or lac. (1.0 m to 1.4 m) over till	0.5%
Bow Island - G3	SW 15-9-11-W4	Grid (-1.0 - 0.0 m)	Lacustrine (0.0 - 2.0 m) over till (2.0 - 4.0 m) over bedrock over coal	0.6%

+ Values in brackets give depth of first drain below canal invert. Negative numbers indicate that the drain was above canal invert.

(Fig. 1). Column widths were 7.5 or 15 m for grid drain spacings of 15 and 30 m, respectively. The number of vertical layers in the model varied from 6 to 12. Thickness of each layer was set to agree with local geology.

Input data required by the model included ground elevation, canal water elevations, thickness of each geological unit and horizontal (K_y) and vertical (K_z) saturated hydraulic conductivities. Ground elevation, canal levels, and thicknesses of the geologic layers were determined from ground surveys, monitoring and test drilling, respectively. Results of single-well response tests were used for K_y. An anisotropy of $K_y/K_z = 10$ was assumed for fluvial and lacustrine materials (Freeze and Cherry 1979), weathered (oxidized) and nonweathered (reduced) bedrock (Hendry and Buckland 1990) and nonweathered till (Robertson and Hendry 1985). Weathered till and coal were considered isotropic (Robertson and Hendry 1985).

The river package of the model was used to simulate the effects of the canal. Hydraulic conductivity of the canal bed was set higher than the hydraulic conductivity of the material surrounding the canal to ensure the native materials controlled seepage from the canal. The K_y and K_z of the gravel chimney above the interceptor drain was set at 10^{-3} m•s^{-1} (Cedergren 1977) to ensure seepage water did not bridge over the interceptor drain. General-head boundaries (GHB) were set at the first and last column of each row to allow for constant recharge and discharge at both ends of the cross section. A GHB consists of a source outside the modeled area which allows for flow in and out of the modeled area at a rate proportional to the head difference between the source and the cell (McDonald and Harbaugh 1988). At sites I2 and G1 GHB's were also placed along some cells to allow for flow transverse to the cross section. Water-table gradients determined between the different transects at each of sites I2 and G1 were used to determine the transverse GHB requirements. The lower boundary was set as a no-flow boundary because of the relatively low conductivity of the lower geologic unit at each site (Table II).

It was assumed that evapotranspiration was balanced by irrigation, except on the downslope portion of the transect at site I1, and the upslope section of the transect at site I2 which were under dryland management. This assumption is quite valid considering that under normal irrigation management, 70% to 100% of the crop consumptive use is satisfied by irrigation (McKenzie 1982) and that the area experiences an annual moisture deficit in the order of 300 mm (Government of Alberta 1969). An evapotranspiration component was also included for the upslope portion of the transect at site G3 because of the presence of an under-irrigated alfalfa crop upslope of the canal. This is consistent with data presented in McKenzie (1982) which indicates that a 2-line wheel-roll system cannot meet the annual consumptive use of an alfalfa crop.

Drain outflow predictions of the model were calibrated against values calculated with Hooghoudt's equation (Wesseling 1983) for grid drainage and the U. S. Bureau of Reclamation's equation (USBR 1978) for interceptor drains. The procedure involved running the model to determine the predicted drain outflow, comparing the predicted drain outflow to the theoretical drain outflow and then applying a matching factor to match the drain outflows.

The model was calibrated at each site to the existing conditions by adjusting the model parameters of K_y, K_z and evapotranspiration in a trial and error process until the steady-state model predictions for summer conditions during canal operation were in close agreement with measured hydraulic head and watertable levels. The calibration was then checked by running the model for winter conditions with the canal off and checking the model predictions against measured data.

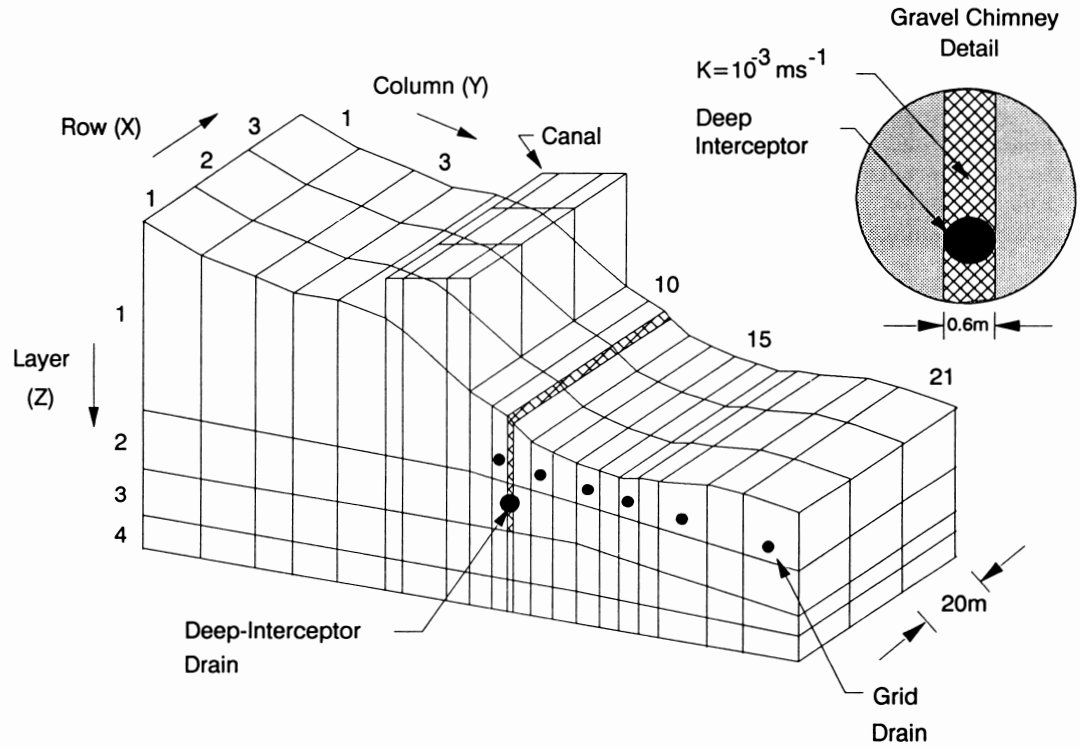

Fig. 1. Schematic cross section of groundwater-flow modeling grid.

Table II. Summary of measured K_y values used for the groundwater modeling.[+]

Site	Geologic unit [++]	Geometric mean ($m \cdot s^{-1}$)	Standard deviation factor	Range of K_y used in modeling ($m \cdot s^{-1}$)	n
I1	Fluvial	–	–	2.4×10^{-7} to 2.4×10^{-6}	Assumed
	Till	4.1×10^{-10}	0.316	4.1×10^{-10}	2
	Bedrock (1)	4.2×10^{-9}	0.906	4.2×10^{-8} to 4.2×10^{-9}	6
	Bedrock (2)	4.2×10^{-9}	0.906	4.2×10^{-9}	6
I2	Fluvial	2.1×10^{-8}	0.860	2.4×10^{-8}	9
	Till (oxidized)	2.4×10^{-8}	0.608	2.4×10^{-8}	16
	Till (reduced)	5.5×10^{-9}	0.580	5.5×10^{-9}	13
G1	Fluvial	2.5×10^{-6}	0.236	2.5×10^{-6}	6
	Lacustrine	2.3×10^{-6}	–	2.3×10^{-6}	6
	Till (3)	6.6×10^{-8}	0.958	1.9×10^{-8} to 6.4×10^{-7}	15
	Till (4)	5.8×10^{-9}	0.857	1.1×10^{-9} to 1.0×10^{-8}	4
	Till (5)	2.2×10^{-9}	0.595	7.1×10^{-10} to 5.8×10^{-9}	10
	Coal	1.6×10^{-6}	0.863	5.0×10^{-5}	6
	Bedrock	1.9×10^{-9}	0.606	8.9×10^{-10} to 4.2×10^{-9}	10
G3	Fluvial	2.4×10^{-6}	0.172	2.4×10^{-6}	10
	Lacustrine	2.4×10^{-6}	–	2.4×10^{-6}	10
	Till (2)	2.1×10^{-7}	0.780	1.2×10^{-8} to 2.1×10^{-7}	10
	Till (3)	2.2×10^{-9}	0.570	2.2×10^{-9}	11
	Coal	3.6×10^{-6}	1.111	4.3×10^{-7} to 1.0×10^{-5}	5
	Bedrock (4)	1.7×10^{-10}	0.480	1.7×10^{-9} to 1.7×10^{-10}	2
	Bedrock (6)	6.6×10^{-7}	0.780	6.6×10^{-7}	3

+ The ratio of K_y/K_z was assumed to 10 for fluvial, lacustrine, reduced till and bedrock units and 1 for oxidized tills and coal. See text for explanation.

++ Numbers in parentheses refer to model layer.

Calibration data are presented later in the paper.

Once the model was calibrated, additional simulations were conducted by varying the type of drainage system (interceptor or grid) and for a no drainage situation. Simulations were also conducted for both types of drainage using a steady-state irrigation recharge of 0.26 $mm \cdot day^{-1}$ (35 $mm \cdot yr^{-1}$). This recharge rate approximates the leaching fraction required to maintain a steady-state salt balance of an alfalfa crop on non-saline soils in the region (Robertson 1988).

RESULTS AND DISCUSSION

Site hydrogeology

Site I1 was characterized by thin (1 m) clay loam to sandy clay loam fluvial deposits which overlay shale and sandstone bedrock (Fig. 2a). Upslope of the canal, weathered, clay loam till, about 3 m thick, was present between the fluvial and bedrock units.

Equipotential distributions and schematic-flow paths for the summer of 1988 (Fig. 2b) indicated recharge upslope of the canal and from the canal. Ponded water in a stagnant surface drain located 200 m downslope of the canal also contributed to groundwater recharge. Groundwater travelled laterally downslope throughout the transect to discharge in the lower portion of the transect and beyond. During winter months groundwater discharged in the lower 200 to 400 m of the transect (data not shown). The watertable downslope of the canal during canal operation was about 1 m below the surface.

Bedrock was not encountered during drilling at site I2. Surficial materials consist of thick (10-30 m) clay loam weathered till which overlies clay loam to clay nonweathered till (Fig. 3a). Lenses of glaciofluvial and fluvial materials, 4 to 7 m thick, are interspersed throughout both till units.

Recharge water from upslope of the canal and from the canal discharged downslope of the canal (Fig. 3b) but the hydraulic gradients were small. The interceptor drain appeared to be intercepting canal seepage as indicated by the deflection of the watertable in the vicinity of the drain. Equipotential distributions and schematic-flow paths during the winter months were similar to those shown in Fig. 3b except hydraulic gradients downslope of the canal were slightly higher (data not shown). The watertable downslope of the canal during the summer months averaged about 2 m in depth but was nearer the surface immediately following irrigation events.

The geology at site G1 (Fig. 4a) was similar to that at site G3 (Fig. 5a) because the two sites were located in the same

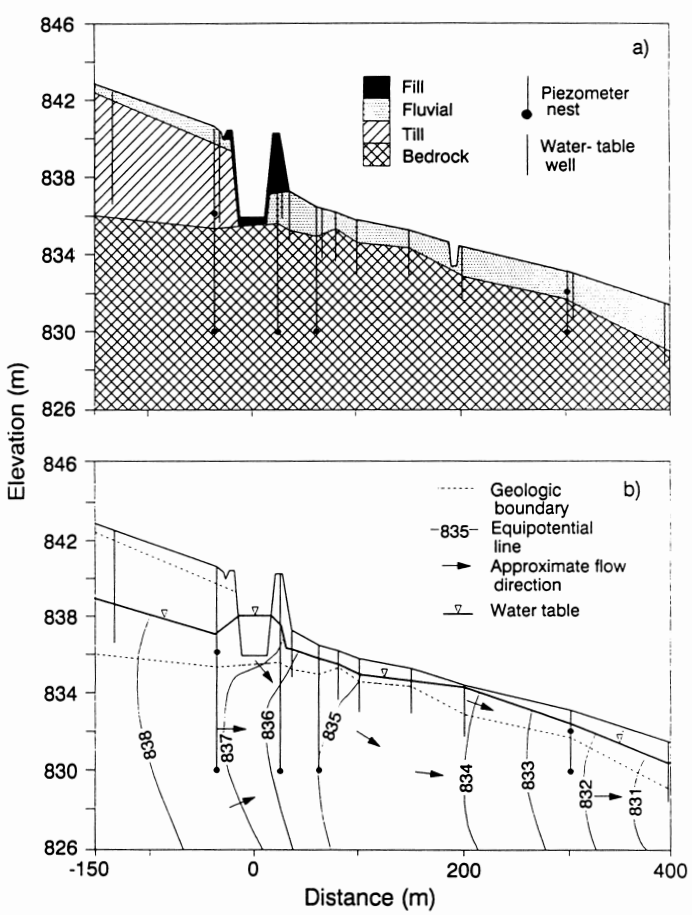

Fig. 2. a) Geology and b) groundwater flow for site I1.

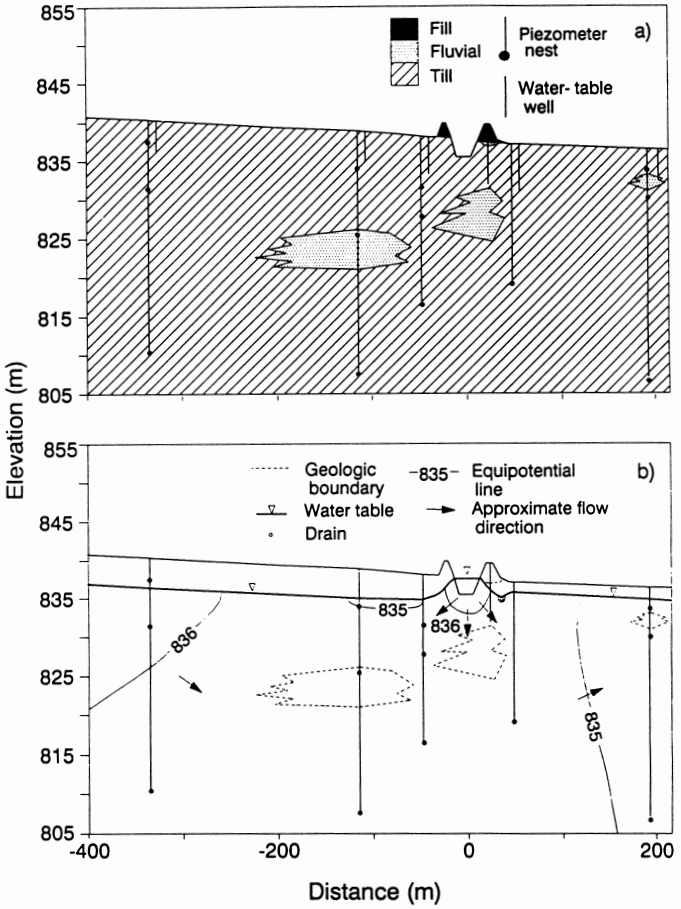

Fig. 3. a) Geology and b) groundwater flow for site I2.

area. The overburden at site G1 was predominantly weathered clay loam till with areas of surficial sandy clay loam to clay lacustrine or fluvial veneer, particularly near the canal. Similar overburden was encountered at site G3 with the exception that surficial glacial till was limited to the first 180 m downslope of the canal. At both sites, the underlying bedrock consisted of interbedded layers of claystone, mudstone and shale. A coal seam was present at both sites at depths of 5 to 6 m. The coal seam at site G3 was continuous and was capped by bedrock but at site G1 the coal seam pinched out downslope of the canal and was directly overlain by till.

At site G1 equipotential distributions (Fig. 4b) suggested that groundwater and seepage influenced water-table levels downslope of the canal. Recharge from the canal and from upslope of the canal appeared to enter the coal seam, and this water subsequently discharged into the overlying till and underlying bedrock downslope of the canal.

There was a direct relationship between the canal operation level and piezometric heads in the coal seam (Fig. 6). During canal operation, both piezometers upslope of the canal (dryland) and the piezometer downslope of the canal (centre pivot) indicated a gradual increase in the piezometric head of the coal seam. After canal closure, all three piezometers indicated a general drop in piezometric head. Lateral seepage from the canal and upward seepage from the coal seam were the major causes of waterlogging near the canal but the contribution of the coal seam to waterlogging appeared to become more predominant with increasing distance downslope of the canal. The average watertable depth downslope of the canal during summer was about 1 m, but increased to 3 to 4 m in depth at a distance of 400 m or more downslope of the canal.

Equipotential distributions at site G3 (Fig. 5b) indicated canal seepage recharged the groundwater both upslope and downslope of the canal. Groundwater in the coal seam discharged into the overlying bedrock and till downslope of the canal. Groundwater within the till unit generally travelled laterally towards the downslope end of the transect. The effect of the coal seam on the watertable was not as pronounced as was observed at site G1 because of the presence of bedrock overlying the coal seam. The average depth to watertable downslope of the canal during the summer was about 1 m.

Groundwater-flow modeling

The K_y values measured for different geologic units are given in Table II. Most values were measured from single-well response tests of piezometers installed during this study. Data for site I2 were determined from single-well response tests conducted by Robertson and Hendry (1985) while data for the lacustrine and fluvial units at sites G1 and G3 were obtained from auger-hole tests (Buckland et al. 1987). K_y for the fluvial unit at site I1 was estimated. Measured K_y values were used as a basis to calibrate the model. Values were then adjusted

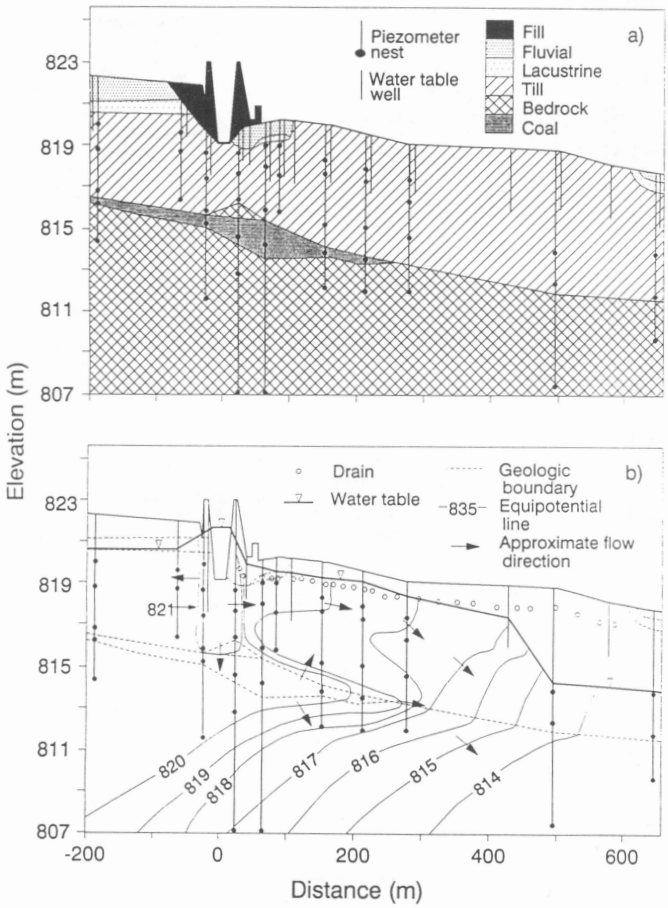

Fig. 4. a) Geology and b) groundwater flow for site G1.

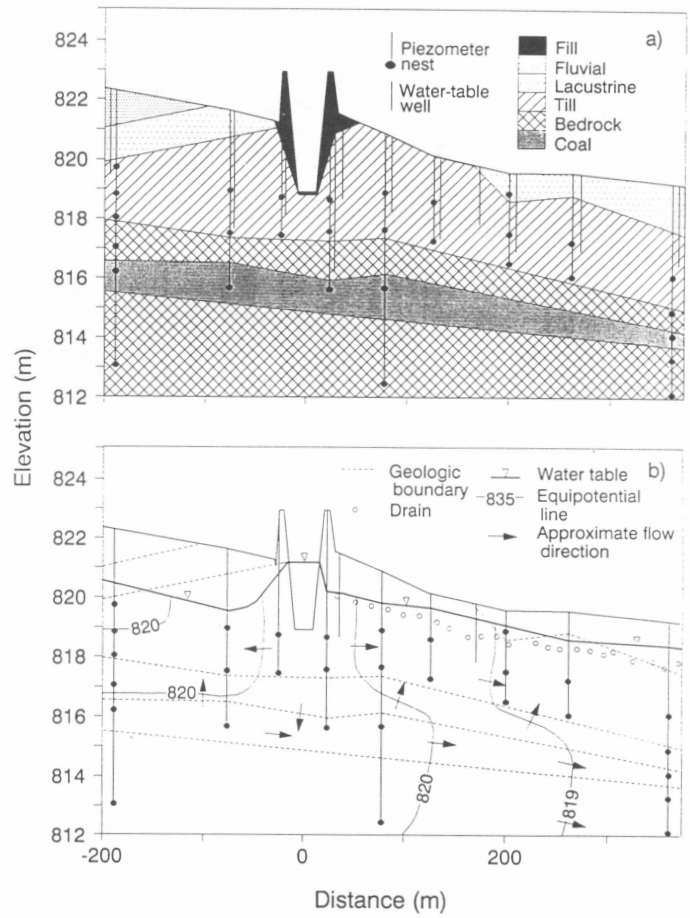

Fig. 5. a) Geology and b) groundwater flow for site G3.

(Table II) to obtain an acceptable calibration of the model. Data in Table II suggest that the adjusted K_y values used in the modeling were in close agreement with measured values except for the coal seam where significant adjustment was required. The measured K_y for the coal seam was generally lower than the K_y used for modeling because of the experimental error associated with the single-well response method (Hvorslev 1951) in highly conductive layers. The ratio of K_y/K_z was established according to discussions outlined previously.

The model was calibrated for a deep-interceptor drain at site I2 and grid drainage at sites G1 and G3. Although a deep-interceptor drain was present at site I1, the modeled transect was located 110 m upslope of the end of the drain and therefore this site was calibrated for the no drainage condition. The initial calibration was done using measured hydraulic-head data from July 28 (sites I1 and I2), August 22 (site G1) or September 14 (site G3), 1988. Different calibration dates were used for different sites to ensure groundwater levels measured at each site were representative of relatively static conditions, thereby approximating the steady-state conditions required by the model. The mean absolute deviation between measured and predicted heads was about 200 mm or less for all sites (Table III). The calibration was then checked by simulating for winter conditions (canal off) and comparing simulated heads to those measured on February 14 or 15, 1989. Again, the model

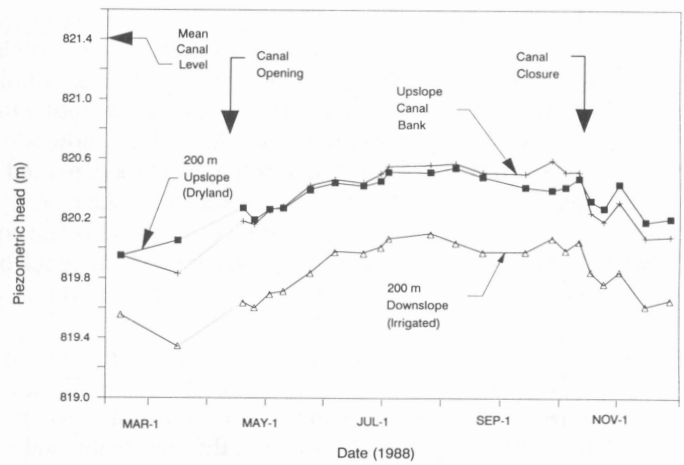

Fig. 6. Relationship between canal operation and piezometric head in the coal seam at site G1.

matched the overall flow characteristics of the sites. The mean absolute deviations between simulated and measured heads were less than 250 mm (Table III).

Figure 7 gives simulated watertable profiles at each site for conditions of no drainage and deep-interceptor and grid drainage. The predicted effect of grid or interceptor drainage, relative to no drainage, is limited at site I1 (Fig. 7a). Watertable levels upslope of the canal were not affected by drainage

Table III. Mean absolute deviation between measured and simulated hydraulic heads

Site	Summer		Winter	
	Mean deviation (m)	n	Mean deviation (m)	n
I1	0.21	14	0.21	15
I2	0.14	13	0 21	13
G1	0.16	39	0.24	39
G3	0.13	26	0.20	35

downslope of the canal. A deep-interceptor drain would lower the watertable in the first 200 m downslope of the canal to a greater extent than grid drainage. The opposite is predicted for distances greater than 200 m. The model predicted greater drain outflow from grid drains compared to the deep-interceptor drain, and flows from both types of drains were predicted to exceed canal seepage (Table IV). The greater predicted drain outflow and superior watertable control in the lower portion of the transect as provided by grid drainage, compared to deep-interceptor drainage, is attributed to the grid drainage intercepting groundwater in the downslope portion of the transect. With either type of drainage, however, this land is unlikely to reclaim because the watertable would remain at a relatively shallow depth of about 1.5 m or less. This depth is generally believed to be too shallow to prevent continued capillary rise of saline groundwater under dryland crop management. Deepening of the grid drains to further reduce the watertable depth is impractical because of shallow bedrock. Model predictions also indicated that placing the deep-interceptor drain deeper into bedrock had minimal effect on lowering the watertable (data not shown). Thus, the shallow depth of the deep interceptor at site I1 should not adversely affect its effectiveness.

At site I2, the deep-interceptor drain and grid drains would provide approximately equal and adequate control of the watertable (Fig. 7b). The depth of the watertable was predicted to be about 1.7 m which is greater than the approximate 1-m depth required for control of salinity under irrigation (van Schaik and Milne 1962). A portion of the predicted seepage water would bypass both drain types (Table IV). This is attributed to adequate vertical drainage at this site. Seepage would be accentuated by a deep-interceptor drain because a deep interceptor drain induces a stronger hydraulic gradient near the canal (Fig. 7b). A greater proportion of the canal seepage would be recovered by a deep interceptor (Table IV), probably because of greater vertical drainage below the grid drains.

At site G1 a deep-interceptor drain would lower the water-

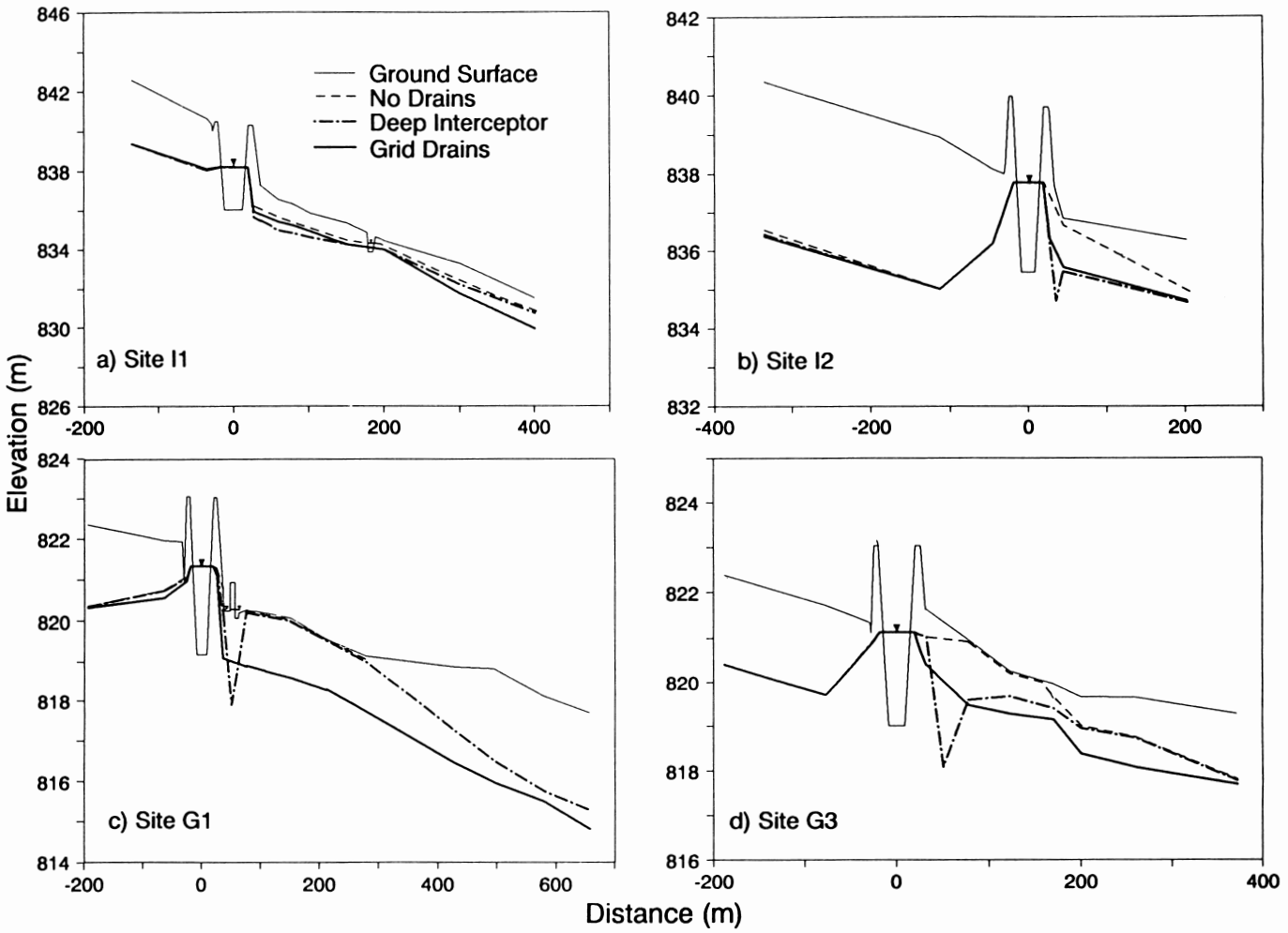

Fig. 7. Simulated watertable profiles for different types of drainage under the existing land management.

table only within 50 m of the canal (Fig. 7c) while grid drains would lower the watertable throughout the monitored transect. Similar results were observed at site G3 (Fig. 7d) although the influence of the deep interceptor would extend to about 200 m. At both sites, the simulated watertable depth is about 1 m or more for grid drains but is usually shallower than 1 m for the interceptor drains. Groundwater discharge from the coal seam, which underlies both sites, is thought to be largely responsible for the poor performance of the interceptor drain. The predicted better performance of the deep-interceptor drain at site G3 compared to site G1 likely results from the low hydraulic conductivity of the bedrock cap at site G3 which restricts groundwater discharge from the coal seam. Predicted canal seepage rates for the grid-drainage simulations at sites G1 and G3 were higher than those for the deep interceptor drains (Table IV) because of the higher hydraulic gradient at the canal bank induced by the grid drainage. For the grid drains, drain flows exceeded canal seepage and this is attributed to interception of groundwater discharge. Drain flows for the deep interceptor drains were about 30-40 percent of predicted canal seepage. It is believed that this results from vertical drainage from the canal into the underlying coal seam and subsequent discharge of water from the coal seam downslope of the deep-interceptor drain.

Steady-state flow 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). Data presented in Fig. 8 indicate that at all sites grid drainage would result in a deeper watertable than a deep-interceptor drain. This would provide greater opportunity to leach salts and reclaim the soil. It is likely the soils examined had insufficient internal drainage

Table IV. Simulated canal seepage and drain flow in (L• min^{-1}•km^{-1} of canal) under the existing land management

Site	Type	Simulation	
		Deep interceptor	Grid drainage
I1	Canal seepage	0.15	0.17
	Drain flow	0.19	8.02
I2	Canal seepage	1.92	1.65
	Drain flow	1.13	0.81
G1	Canal seepage	3.77	6.53
	Drain flow	1.14	7.72
G3	Canal seepage	0.35	0.81
	Drain flow	0.15	1.18

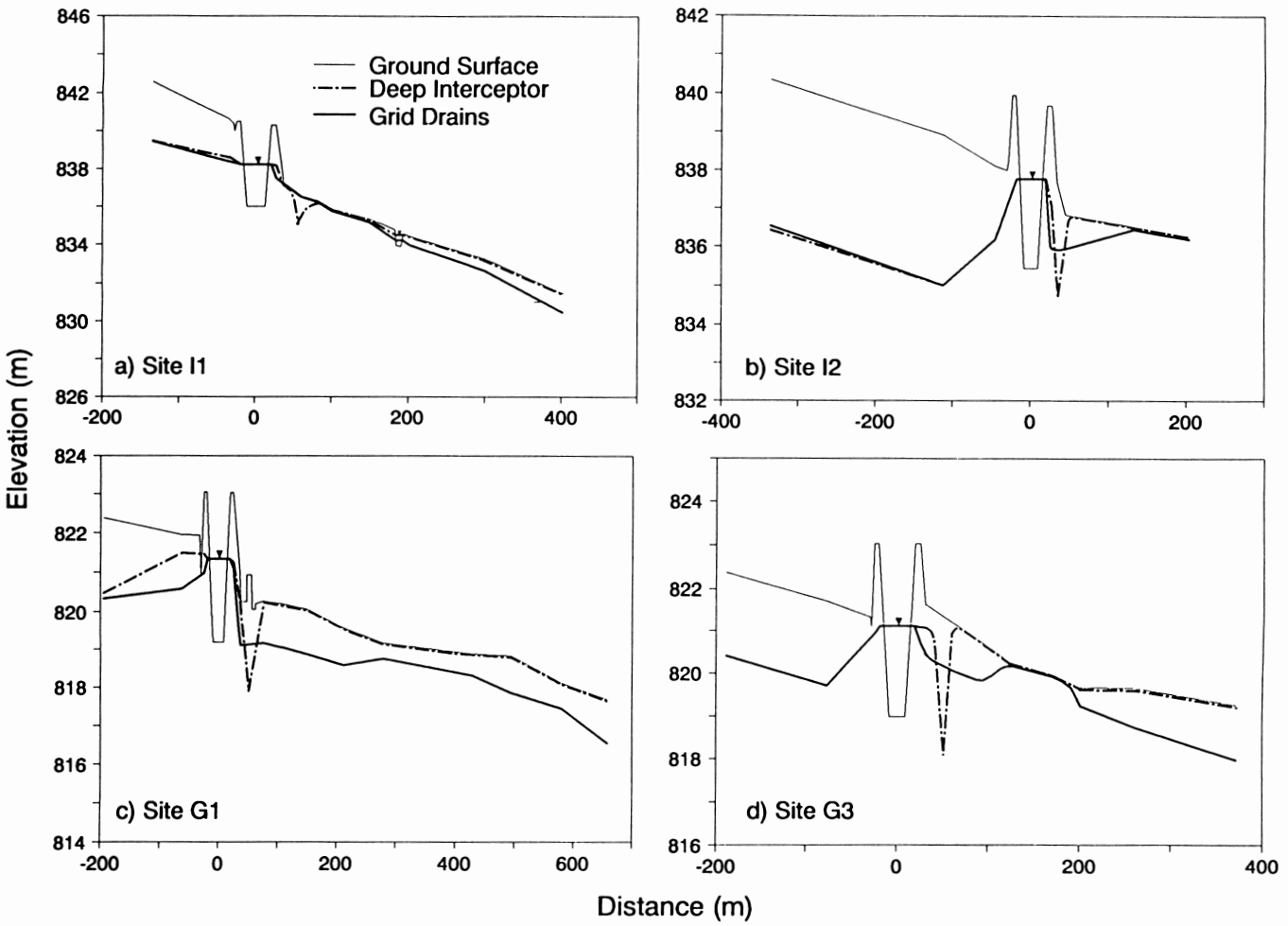

Fig. 8. Simulated watertable profiles for different types of drainage under irrigation recharge.

to provide for leaching. This was also postulated by Bennett (1990) who found persistent shallow watertables and limited salt removal from soils adjacent to several rehabilitated canals.

CONCLUSIONS

A study was conducted to examine the relative effectiveness of deep-interceptor drainage and grid drainage for controlling canal seepage and reclaiming salinized land. Mathematical modeling of canal seepage and groundwater indicated that grid drainage would result in a deeper watertable than deep-interceptor drainage when groundwater partially contributes to seepage, or when excess irrigation water is applied to leach salts from the soil. Where affected lands resulted primarily from canal seepage, grid and deep-interceptor drainage were equally effective in controlling seepage.

The study demonstrated that a rather simple groundwater modeling exercise can assist in defining and understanding the groundwater-flow regime of a groundwater system affected by irrigation canal seepage, and can help select the most appropriate type of interceptor drain. The model used for this study (MODFLOW) proved to be very versatile and well adapted to the particular needs of this project, particularly in the case of deep-interceptor drainage. It would be advantageous to incorporate Hooghoudt's equation (Wesseling 1983) directly into the drain package of the model for simulating grid drainage. This would eliminate the need to calibrate for grid-drain outflow.

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REFERENCES

Bennett, D.R. 1990. Reclamation of saline soils adjacent to rehabilitated irrigation canals. *Canadian Agricultural Engineering* 32:1-9.

Buckland, G.D., W.U. Ulmer and B.A. Paterson. 1987. On-farm subsurface drainage analysis and design for Forty Mile to Sauder Reach, km 8 to km 11, St. Mary River Irrigation District. Alberta Agriculture, Lethbridge, AB.

Cedergren, H.R. 1977. *Seepage, Drainage and Flow Nets*, 2nd ed. New York, NY: John Wiley and Sons.

Chang, C., G.C. Kozub and D.C. Mackay. 1985. Soil salinity status and its relation to some of the soil and land properties of three irrigation districts in southern Alberta. *Canadian Journal of Soil Science* 65:187-193.

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice Hall Inc.

Government of Alberta. 1969. *Atlas of Alberta*. Edmonton, AB: University of Alberta Press Ltd.

Hendry, M.J. and G.D. Buckland. 1990. Causes of soil salinization: 1. A basin in southern Alberta, Canada. *Ground Water* 28:385-393.

Hvorslev, M. J. 1951. Time lag and soil permeability in groundwater observations. US Corps Engineers, Water Experiment Station Bulletin No. 36. Washington, DC: GPO.

McDonald, M.G. and A.W. Harbaugh. 1988. *A Modular Three-dimensional Finite Difference Ground-water Flow Model*. Washington, DC: United States Geological Survey.

McKenzie, R.C. 1982. Soil moisture and water management in irrigated crop production. In *First Annual Western Provincial Conference-Rationalization of Water and Soil Research and Management "Soil Salinity"*. Alberta Agriculture, Lethbridge, AB.

Paterson, B.A. and D.B. Harker. 1980. Tile drainage of irrigated till soils in Alberta. *Proceedings American Society of Civil Engineers Specialty Conference, Irrigation and Drainage - Today's Challenges*, 263-273. New York, NY: ASCE.

Robertson, C. 1988. Potential impact of subsurface irrigation return flow on a portion of the Milk River and Milk River aquifer in southern Alberta. Unpublished M.Sc. thesis, University of Alberta, Edmonton, AB.

Robertson, C. and M.J. Hendry. 1985. Jensen farm groundwater study. Alberta Agriculture, Lethbridge, AB.

Sommerfeldt, T.G. and E. Rapp. 1982. Management of saline soils. Agriculture Canada Publication 1624E. Supply and Services Canada, Ottawa, ON.

USBR. 1978. *Drainage Manual*. Washington, DC: US Department of the Interior, Bureau of Reclamation.

USDA. 1973. *Drainage of Agricultural Land*. Syosset, NY: Water Information Center Inc.

van Schaik, J.C. and R.A. Milne. 1962. Reclamation of a saline-sodic soil with shallow tile drainage. *Canadian Journal of Soil Science* 42:43-48.

Wesseling, J. 1983. Subsurface flow into drains. In *Drainage Principles and Applications*, publ. 16, 2:3-56. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.