Dryland salinity: A Multidisciplinary Conceptual Model Designed for On-farm Salinity Control.

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INTRODUCTION

The hydrology and chemistry of dryland salinity has been described for different areas in the northern Great Plains of Canada and the United States (Benz et al., 1967, Greenlee et al., 1968; Eilers, 1973 and Henry et al., 1985).

Causes of soil salinization are related to various conceptual hydrogeological models such as those associated with sidehill seeps (Doering and Sandoval, 1976), aquifer seeps (Henry et al., 1985) and bathtub-ring seeps (Moran et al., 1986).

Various agronomic practices are used to control and reclaim saline soils (Brown and Miller, 1978, Van der Pluym, 1978). In Saskatchewan, Henry et al., (1985) suggested that aquifer seeps may be managed by draining, and irrigating the salt affected land with good quality water from the aquifer.

Practical and economic success of implementing the foregoing methods requires a multidisciplinary approach. Integration of knowledge acquired in hydrogeology and agricultural sciences is essential for successful control of soil salinization processes.

Within this context, the objectives of this article are to:

a) report on soil salinization mechanisms affecting cultivated land in Southwest Saskatchewan and

b) present an integrated hydrogeologic-plant water use model to analyze alternative management strategies for the prevention, control or reclamation of dryland salinity.

MATERIALS AND METHODS

Field Investigations

Salinity investigations were conducted between 1985 and 1988 at 133 quarter section sites throughout Southwest Saskatchewan. Site selection was based on farmers request for salinity diagnostic services provided by the Prairie Farm Rehabilitation Administration and Wheatland Conservation Area Inc.

Investigated land was within the Brown and Dark Brown soil zones. Soil parent materials encompassed glacial till, shale modified glacial till, glacio-lacustrine and fluvial materials. Salinized soils formed on aeolian and alluvial parent materials occurred less frequently. Field investigations were designed to test various hydrogeological hypotheses causing soil salinization. A hypothesis was prepared for each site after analyzing soils, geological, topographic and crop management information. Other sources of information included piezometric surface maps and drillers logs available from the Saskatchewan Water Corporation.

Hydrogeology

Test holes were drilled to install observation water wells and piezometers and to determine physical and chemical characteristics of the soils and geological formation. Observation water table wells (plastic PVC pipe, 3.8 cm diameter) were installed at every site to monitor the dynamics of the phreatic surface. Test holes for observation water wells and shallow piezometers (<12 m deep) were completed using a solid stem dry auger of 0.13 m diameter with 1.5 m long auger sections. Four composite soil samples were taken from the first 1.2 m of soil and one or two composite samples were taken per auger stem below 1.2 m.

Piezometers consisting of PVC and steel pipe of 3.8 and 5 cm diameter were installed at 30 sites to estimate the hydraulic gradients and conductivities of aquifers and aquitards. Test holes for the installation of deep piezometer were completed with a churn drill (10 cm diameter) to an average depth of 20 m. Hydraulic conductivity values for various geological stratum were estimated by the recovery test method (Theis, 1935).

Soil Salinity

Salinized areas were mapped with Geonics EM-31 and EM-38 electromagnetic survey instruments. Soil samples were analyzed for salinity by the Saskatchewan Soil Testing Laboratory. The ionic composition and electrical conductivity (E.C.) of soil samples were determined by the saturated soil paste extract method. Water samples were obtained from observation wells and piezometers immediately after drilling or weeks later after pumping. E.C. measurements were made on clear, free suspension samples at ambient temperatures.

INDRYSAM: an integrated dryland salinity model

Model Development

Indrysam is a conceptual model designed for the control of dryland salinity at the farm level. Two steps were taken to design Indrysam:

The first step was to develop a conceptual model that identified and integrated the variables and processes observed to cause dryland salinity in Southwest Saskatchewan. The conceptual model of Figure 1 indicated that groundwater has an inflow and outflow component. At the soil landscape level, inflow is represented by recharge and outflow by discharge.

The model assumes that groundwater flows under saturated conditions as described by Darcy's Law:

$$Q = K * i * A$$

where K = hydraulic conductivity

i = hydraulic gradient

A = cross-sectional area of flow path

The following equations are used to describe the hydrogeology of recharge-discharge flow in Figure 1:

$$Qr = Qi - Qsm - Qp \quad (1)$$

$$Qi = Qt - Qrun - Qe \quad (2)$$

$$Qd = Qsm + Qp + Qe \quad (3)$$

Where: Qr = actual amount of recharge water

Qi = amount of water infiltrating into the soil

Qsm = soil moisture storage at 1/3 kPa

Qp = amount of water taken up by plants

Qt = total precipitation

Qrun = amount of water that runs off-site

Qe = amount of water evaporation from soil surface

Qd = actual amount of discharge = Qc = actual capillary rise from groundwater

Qr for the Prairies has been found to range between 2 and 7% of the total annual precipitation (Meyboom, 1966). Qr in the latter case can be estimated as follows:

$$Qr = Ar * Qt * 0.07 \quad (4)$$

Where: Qr = annual recharge (m^3y^{-1})

Ar = area of recharge (m^2)

Qt = total annual precipitation (my^{-1})

The size of the recharge area (Ar) in (4) can be estimated from drillers log information, geologic and topographic survey maps and water level data from available piezometer nests. The model then allows the calculation of the area of cropping required to control the recharge into the system. The amount of annual recharge (Qr) is related to the annual crop water use (Qp) to estimate the size of the recharge area to be treated (Acrop). Hence, Acrop > Qr/Qp and the crop would be established immediately upslope from the seep, in order to control excess recharge.

The second step of modeling involved the use of a modified hydrogeological model. The basic two-dimensional model analyzes the transient changes in hydraulic heads of an heterogeneous, anisotropic confined aquifer (Pinder and Frind, 1972).

The program was modified to allow inputs of aquifer transmissivity and storage, leakance, recharge and discharge (as estimated in 1), and variables of time and space. Such inputs may be obtained from permeability measurements made during the field investigations and/or from published literature values.

Model Validation

The model simulated hydraulic head (obtained in step 2) and capillary rise (Qc) (determined in Step 1) are compared to field measurements of hydraulic head and phreatic surface. The effects of mitigative management practices on the water table can be tested by simulating the effects of groundwater withdrawal (either agronomic or mechanical) on the phreatic surface over specific areas or selected points within the model.

The simulated hydraulic head and phreatic surface in the saline area is integrated with critical depth (CD) to water table values to determine effective control practices, monitor the effectiveness of implemented remedies and/or design preventive salinity control plans at a local or regional level.

Indrysam and Salinity Investigations

Indrysam not only helps to simulate hydrological processes and potential salinity controls but also contributes to make field investigation more efficient. The model theoretical basis permits the investigator to test salinization hypothesis by collecting field information in a systematic rather than in a random fashion.

The following is some of the basic field information needed by Indrysam to assess the hydrogeology of affected land:

- Location and size of recharge area
- Identify the sources of groundwater recharge and estimate recharge flow rates (Qr)
- Location and size of discharge area
- Estimate discharge flow rates (Qd) and the groundwater sources contributing to such discharge by measuring hydraulic heads, conductivities and gradients in stratas driving the groundwater flow. Also, cross sectional areas of flow path need to be known.
- Critical depth to water table and water table dynamics especially in discharge areas.
- Plant water use under saline or non-saline groundwater conditions.

Other information that needs to be integrated with the foregoing is:

- Soil electrical conductivity
- Plant salt tolerance at germination, seedling and adult stages.
- Soil pH>8.5 may be important to assess the potential nutrient deficiencies or toxicities by elements such as Aluminum, phosphates and of trace elements such as Mo, Co, Se and B which are typical to some seep areas (Bohn et al., 1985).
- Economic and physical viability of engineering control solutions such as drainage or controlled dewatering schemes for aquifers.

Salinity control plans that integrate the foregoing information with the type of farm operation may influence directly the success of salinity control programs.

RESULTS AND DISCUSSION

Soil Salinization and Hydrogeology

The following section reports and discusses the prevailing hydrogeological mechanisms causing soil salinity in Southwest Saskatchewan. This information was the basis for designing the conceptual model of Figure 1. The hydrological variables and processes for the model were identified from the ensuing information.

Four major salinization models were found to prevail in Southwest Saskatchewan:

(1) aquifer seeps

(2) sidehill seeps

(3) bathtub ring seeps and

(4) combinations of 1, 2 and 3 (Table 1)

Artesian salinity is associated with regional groundwater flow systems. In this model, the groundwater has the potential to move from deeper aquifers towards the soil surface through leaky aquitards and capillary rise to induce salt accumulation in soil profiles (Henry et al., 1985).

Hydraulic heads measured in piezometers installed during investigations indicate that potential groundwater discharge from aquifers may affect 38% of the salinized land that was studied (Table 1). Such aquifers were found to consist of interglacial sands and preglacial materials such as sand and gravels of the Cypress Hill formation. Most of the aquifers were found to lie within 25 m of the ground surface (Table 2). Alluvial complexes represented by Swinton and Wymark Soil Associations were related to the aquifer seep model.

In comparison, sidehill seepage affects 33% of the salinized investigated areas (Table 1). The most common flow media for groundwater in the sidehill seeps are weathered till (CL to SCL) over unweathered till (SC), till over shale, sand and silt veneers over till or clay, and sand veneers truncated or sandwiched between till layers. Haverhill, Ardill, Hatton and Swinton were some of the soil associations found under the sidehill seep model. In general, no relation was found between soil association and the type of hydrogeological model causing soil salinity was obvious.

The bathtub-ring seep model which is related to local surface runoff and groundwater flow systems affected 6% of the salinized land.

Complex systems involving groundwater discharge from more than one source was found to induce salinity in 23% of the affected land (Table 1). Soil salinity mechanisms affecting 35 ha at W1/2 19-16-16W3M is an example of a complex hydrogeologic system. A series of piezometers and water table wells indicate that soil salinity may be related to three groundwater flow systems. The stratigraphy at this site consists of alternating layers of sand and clay overlying glacial till (Figure 2).

The first flow system appears to be contained within the surficial loamy sand stratum draping the southern portion of the studied area. The second appears in the middle sand exposed at piezometer C-20 and the third flow system appears in the lower sand layer exposed at piezometer C-38.

Hydraulic conductivity and gradient values indicates that the estimated groundwater flow discharging from the surficial sand is 0.4 l sec $^{-1}$ (Table 3). In comparison, the hydraulic head within the lower sand is 0.61 m [Note change from 0.4 m] below the ground surface and as such indicates potential groundwater discharge from the deep aquifer. The potential flow contributions estimated from the deep sand stratum is 4.7 l sec^{-1} (Table 3).

Electrical conductivity values for the groundwater in the upper sand and deep sand strata are 17 mS cm^{-1} and 0.7 mS cm^{-1}, respectively. The latter value strongly suggests that these goundwater flow systems are independent. Consequently the potential for direct groundwater discharge from the deep aquifer into the soil profile may be negligible. Management of local surface and groundwater flows would take priority in the control of salinity at this site.

The previous combination seep model is an example of the analytical capabilities of Indrysam to point out th type of information that needs to be collected by the field investigator.

Critical Depth to Water Table

Critical depth to water table is defined as the depth of the water table below ground surface where upward movement of water by capillarity induces a net salt accumulation in soil profiles. This concept was introduced by Szalbocs (1979) who documented a relationship between critical depth and salinity of the groundwater. Indrysam compares critical depth to water table with hydraulic head and phreatic surface information to analyze the hydrogeological characteristics of saline seeps.

Soil profiles can accumulate soluble salts if two conditions are met: exfiltration (loss of water from soil) exceeds infiltration and the water table is above a critical depth. Climate conditions in the Brown and Dark Brown soil zones provide a net moisture deficit, satisfying the first condition. In the Southern parts of the Canadian Prairies, soil salinization has been reported in areas of shallow water tables, however, no relation has been established to define critical depth to water table.

Water table records obtained during the past 4 years from various soil landscapes, and from fields with different crop management histories, has permitted us to define a two dimensional function that separates salinized soil profiles (average E.C.> 4 mS cm^{-1} in top 90 cm) from non-salinized soils. For each water table piezometer the boundary condition is a function of the shallowest depth to water table recorded over time and the respective electrical conductivity of the groundwater at the time of sampling (Figure 3). Figure 3 consists of 230 observations, 202 of which were recorded on medium textured soils and 14 on each of fine and coarse textured soils. This relation is similar to that reported by Szalbocs (1979).

The boundary function of Figure 3 becomes asymptotic at a water table depth of approximately 3.5 m and groundwater E.C.>9 mS cm^{-1}. Such depth to water table becomes the threshold depth for the concentration of salts in the topsoil.

Four soil profiles (Solonetzic and sodic) and two other salinized Orthic soil profiles showed E.C.>4 in spite of having the water table below the critical depth (5 m on average). No definit explanations can be offered for these results, although unsaturated flows transferring soluable salts from salt enriched parent material into the profile may be responsible for such observations. The solonetic conditions may reflect soil development resulting from previous groundwater conditions.

The function of Figure 3 does not explain and define the effects of time and other factors and processes involved with critical depth under field conditions. It is suggestss however, that critical depth may be the result of the combined effects of soil texture and structure, hydraulic conductivities of discontinuous soil textural layers, fractures in the parent material, evapo-transpiration demands, and groundwater and soil temperature. Anthropogenic factors such as the number of years of soil cultivation, type of crop rotation and soil fertilization may also contribute to the relation. Further research is warranted to define the factors and interactive processes controlling the depth to water table.

The critical depth boundary defined under field conditions has important implications for the prevention, control and reclamation of saline soils in dryland agriculture, i.e. effective salt leaching requires that the water table be dropped below the critical depth. Hence, adequate reclamation strategies can only be prepared if such depth is known. Monitoring water table changes in relation to critical depth will be useful to evaluate changes in soil quality after remedies are implemented at the farm level. Management practices such as growing alfalfa or grasses in soils having shallow water tables with high groundwater E.C. values can prevent the accumulation of salts even under the presence of potential artesian conditions such as found at W1/2 6-18-18W3M (Figure 3).

Critical Depth to Water Table and Hydraulic Heads

Critical depth to water table and hydraulic head values measured in the seep areas are used to assess the potential contribution to soil salinity by groundwater discharged from an aquifer.

Under the aquifer-seep model, soil salinization by potential groundwater flow from aquifers to the soil surface may only be possible if the hydraulic head (HH) is above the critical depth (CD) to water table or CD-HH≥0 (Table 2). In comparison, when CD-HH<0, the aquifer's hydraulic head may only have the potential to restrict the vertical drainage of shallow groundwater and as such would not be responsible for the transport of salts to the soil profile. In the latter case, the contributions of local groundwater flows to soil salinity would predominate over regional flows. Under such conditions, remedial plans must concentrate on management of local flows.

If the CD-HH relation holds true, 45% of the land initially classified under the aquifer-seep model in Table 1 would not be affected by direct groundwater discharge from aquifers.

In summary, Indrysam compares critical depth to water table with hydraulic head and phreatic surface information to analyze the hydrogeological characteristics of saline seeps. Critical depth to water table has been defined as a function of the shallow groundwater conditions including depth below surface and electrical conductivity. The relation may be used as an analytical tool during the preparation of plans to prevent, control or reclaim dryland salinity. The critical depth boundary and its relation to hydraulic head may also be used to assess the potential contribution of regional aquifers to soil salinization.

The relation of CD and HH is a simple analytical tool and may be used together with or as an alternative to the use natural isotopes as in Hendry and Cherry (1988) to assess the potential contributions to dryland salinity by groundwater discharge from aquifers.

Indrysam: results from an integrated dryland salinity model.

Indrysam integrates the hydrogeology of saline seeps with alternate management practices designed to increase productivity of the affected land.

The Indrysam model has been used with data obtained from sites having different hydrogeologic conditions. Two field cases are presented as examples of model behaviour.

Case 1

Soil salinity affects 60 acres of land located at NW20-14-14W3M. Auger and undisturbed core samples revealed the site stratigraphy (Figure 4). The investigation showed that salinity is associated with groundwater discharge from a shallow aquifer of the Cypress Hills formation. The hydraulic head measured in a piezometer completed into the aquifer was 1.7 m below the soil surface and the critical depth to water table 2.1 m.

Analysis of the recorded hydrogeological information suggested three alternate plans to relieve the aquifer's hydraulic head:

(a) Establish alfalfa or extend the rotation in the recharge area to reduce the net acquifer recharge.

(b) Establish a crop in the discharge area to use an amount of water > aquifers Qd.

(c) Drain the aquifer by syphoning the effluent (EC=1.2 $mScm^{-1}$) at a rate of 1.51 sec^{-1} into an adjacent coulee.

Plans a) and b) could not be implemented because the area of recharge is controlled by a different landowner and the high salinity level (E.C.>12$mScm^{-1}$) in the discharge area inhibited crop growth. Plan c) was then implemented.

Model output indicates that after 120 days of drainage, the simulated drawdown follows very closely the drawdown observed in a piezometer completed into the aquifer and placed 15 m away from the main drainage well (Figure 5).

Digital simulation also suggests that 2 years of continuous drainage may lower the phreatic surface by 25 cm in a radius of 100 m away from the drainage well. Such prediction and the model behavior under recharge conditions require further testing. According to the critical depth model, the aquifers hydraulic head in the seep area needs to drop 2.1 m below ground surface before effective leaching can take place. Such depth was achieved 10 d after drainage started.

Case 2

In this case Indrysam is used as an analytical tool to propose an agronomic strategy to control salinity. Forty acres of land were found to be salinized at NE 35-13-13W3M. The stratigraphy at the site showed that Wymark soils are underlain by alternate layers of shale and sandstone (Figure 5).

Two groundwater flow systems were identified as affecting the site. The first system appears to be contained within a 2 m thick stratum of sand found 2 m below the soil surface. The second flow system appears to be contained in a 2.3 m thick sandstone stratum found at 14.7 m. The hydraulic head from the sandstone and shallow sand were 1.7 m and 1.1 m below the soil surface, respectively (Table 2). At the same time, the phreatic surface and the critical depth to water table, in the seep area, were 1.7 m and 1.9 m below ground surface, respectively.

Analysis of the latter hydrogeological information suggest the following:

(a) Both groundwater flow systems have the potential to contribute to soil salinization since both hydraulic heads are above the critical depth.

(b) The difference in hydraulic head between the surficial sand and the sandstone suggests that water from the upper sand has the potential to drain into the sandstone.

(c) Amounts of groundwater discharge contributed by the sand and sandstone were estimated at 0.1 l/sec and $4x10^{-4}$l/sec, respectively.

Model simulation suggests that an alfalfa interceptor strip (biodrain 1200 m x 300 m) established upslope from the seep area would use the groundwater flowing through the upper sand at a rate >Qd. Consequently, the predicted drawdown on the water table in the alfalfa seeded area is about 1 m after 2 years of establishment (Figure 7).

The model also predicts a concomitant drop of the water table in the salinized areas. The recovery of the water table predicted during the winter months would not compensate for the water use by alfalfa during the growing season. The model predicts that given enough time, the alfalfa intercepts strip helps to drop the water table below the critical depth in the seep area.

Alfalfa interceptor strips have been found to improve land productivity by lowering the water table in discharge areas of a Solonetzic soil near Gull Lake and of saline soils in the Vulcan area in Alberta (Steppuhn and Wood, personal communications).

In Summary, Indrysam is an integrated model that simulates hydrogeological processes inducing soil salinity under saturated flow conditions and permits the analysis of alternate salinity management plans under dryland conditions.

Conclusions

Results obtained from salinity investigations conducted between 1985 and 1988 in Southwest Saskatchewan permits us to conclude that sidehill seeps, aquifer seeps and a combination model are the prevailing soil salinization models. Groundwater discharge from aquifers induce soil salinization in less than 20% of the affected studied areas.

Data obtained from field studies helped us to establish a function that defines the critical depth to water table. The function is dependent on the groundwater electrical conductivity and is an important tool in the management of soil salinity.

In addition, the systematic collection and modeling of hydrogeochemical data and its subsequent integration with agronomic and engineering principles and practices facilitates the preparation of effective plans to control soil salinization at the farm level.

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Table 1. Total salinized area affected by different types of saline seep models.

SEEP MODEL	Number of ha 1986	1987	1988	1986 - 1988
Aquifer	409	158	270	837
Sidehill	167	173	377	717
Bathtub-ring	46	29	50	125
Combination	157	187	174	518
Total Affected	779	547	871	2197

1. Salinized area = average soil E.C. > 4mS cm^{-1} in top 90 cm.

Table 2. Relation between critical depth to water table and the hydraulic head of various aquifers.

LOCATION (W3M)	STRATUM	Depth to (m) PIEZOMETER TIP	WATER LEVEL IN PIEZOM.	CRITICAL DEPTH	CD-HH[1]
NW 20-14-14	Till CL	2.3	Dry	2.1	
	Gravel	5.5	1.9		0.2
W1/2 19-16-16	Lac S	12.0	1.9	3.5	1.6
	Lac S	29.0	0.4		3.1
SE 21-7-6	Lac SiCL	2.7	2.4	1.7	-0.7
	Lac SiC	5.4	3.3		-1.6
	Lac LS	7.6	3.3		-1.6
SW 22-7-6	Lac SiCL	1.9	2.3	3.5	1.2
	Lac LS	4.2	2.5		1.0
	Lac SL	8.9	1.1		2.4
SE 31-16-18	Lac SiC	1.8	Dry	0.8	
	Lac SiC	5.3	3.5		-2.7
	Till SCL	8.0	3.0		-2.2
	Lac S	10.8	2.7		-1.9
SW 32-16-16	Lac SiC	3.4	Dry	2.3	
	Till SC	6.5	4.0		-1.7
	Lac S	15.6	3.7		-1.4
NE 35-13-13	Lac S	2.5	1.1	2.9	1.8
	Sandstone	16.0	1.7		1.2

1 CD=critical depth to water table.
HH=depth to piezometric surface.

Table 3. Estimated groundwater flow rates (Qd) at various locations in Southwest Saskatchewan.

LOCATION (W3M)	AQUIFER TYPE	K ($m\ sec^{-1}$)	A (m^2)	i	Qd ($l\ sec^{-1}$)
NW 20-14-14	Gravel	8×10^{-5}	7,200	0.0027	1.5
NE 35-13-13	Lac. Sand	2×10^{-5}	1,675	0.0030	0.1
	Sandstone[1]	1×10^{-10}	160,000	0.030	4×10^{-4}
W1/2 19-16-16	Lac. Sand	1×10^{-5}	10,000	0.0037	0.4
	Lac. Sand[2]	1×10^{-7}	780,000	0.060	4.7

1. K value corresponds to the overlying unweathered shale layer because it is the sratum that restricts the groundwater flow from the sandstone.
2. K value corresponds to the overlying lacustrine clay layer because it is the stratum that restricts the groundaer flow from the deeper sand.

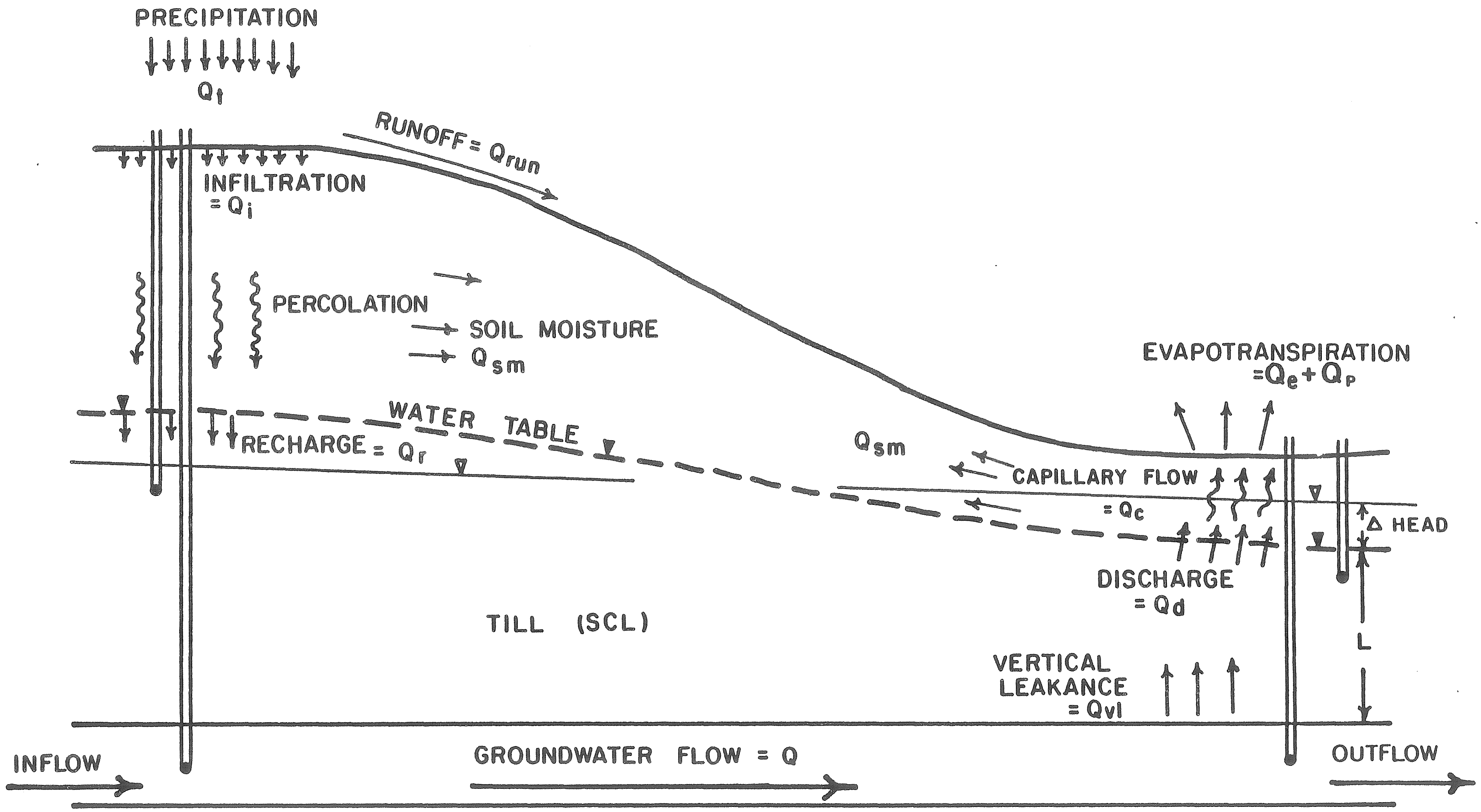

Figure 1. A conceptual model describing hydrogeologic variables and processes associated with dryland salinity.

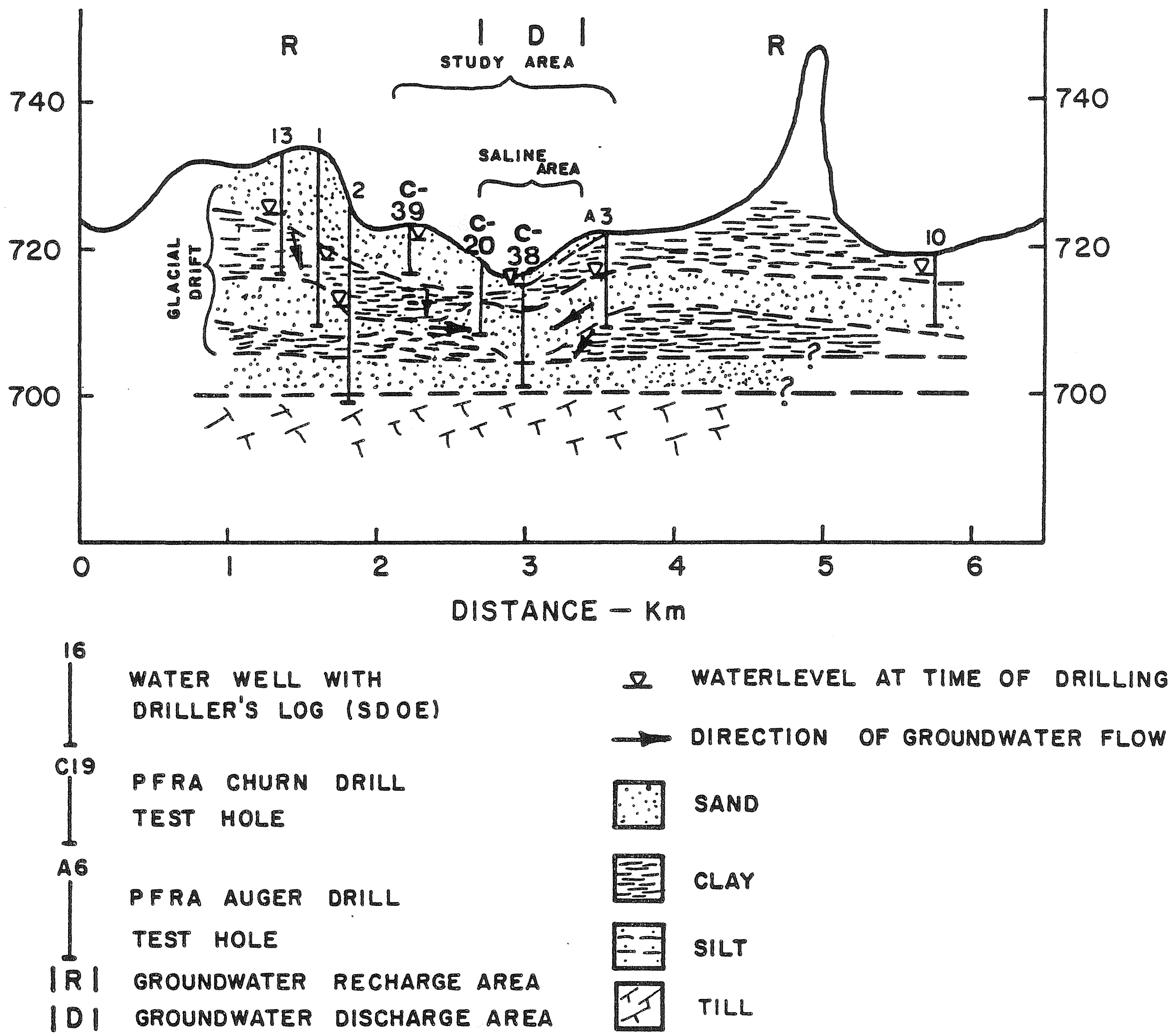

Figure 2. Hydrogeologic cross-section at W½ 19-16-16W3M.

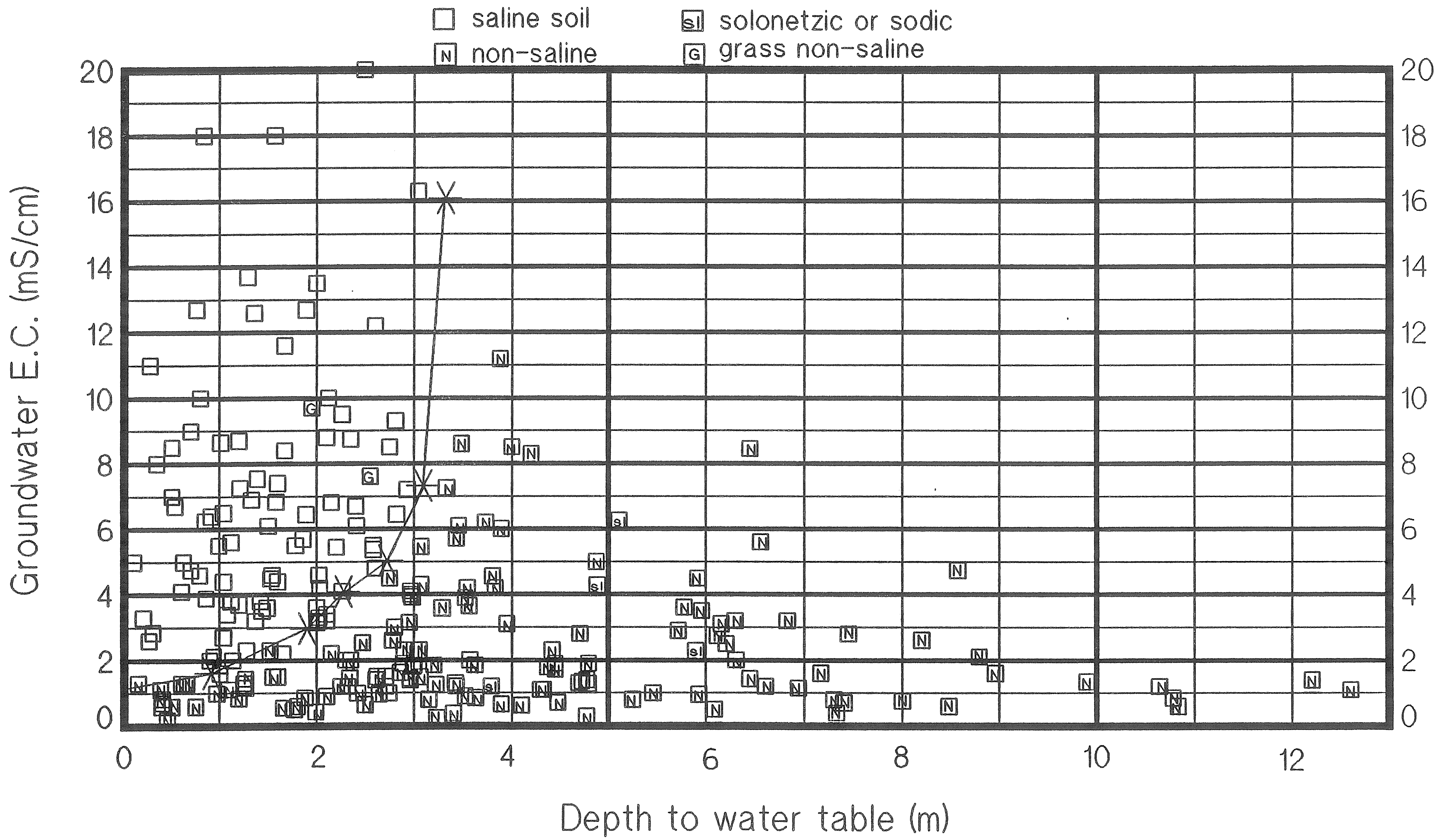

Figure 3. Critical depth to water table.

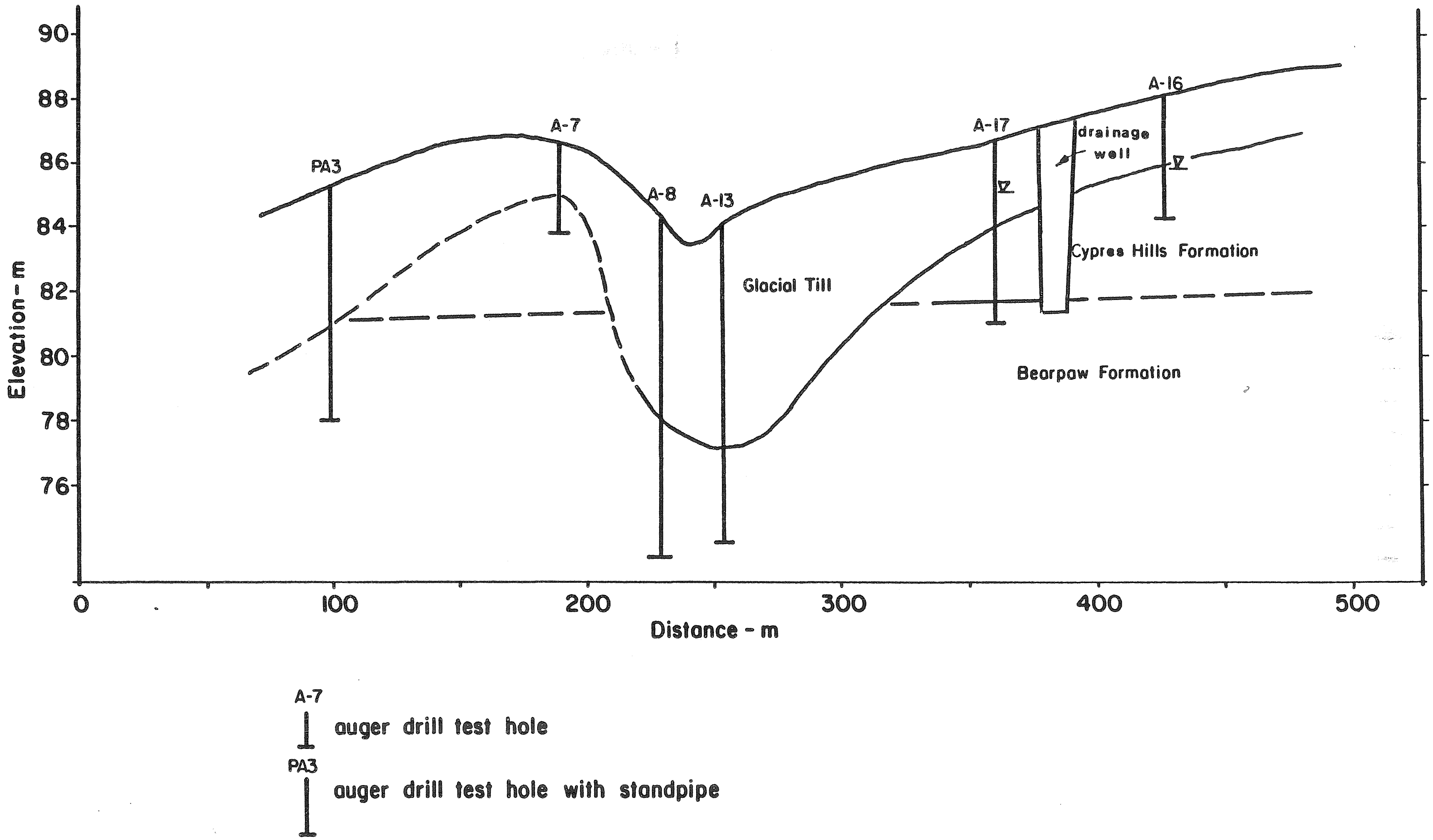

Figure 4. Hydrogeologic cross-section at NW20-14-14W3M.

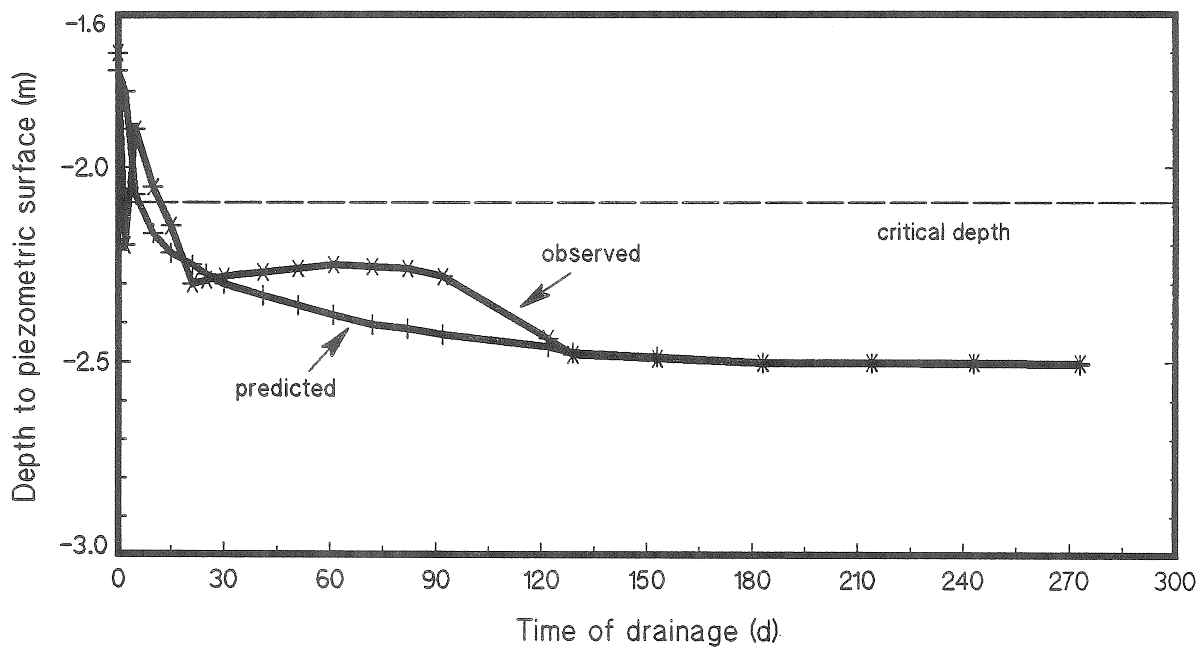

Figure 5. The effect of drainage on the hydraulic head of an aquifer of the Cypress Hills formation. Observations were made in a piezometer placed 15 m away from the drainage well.

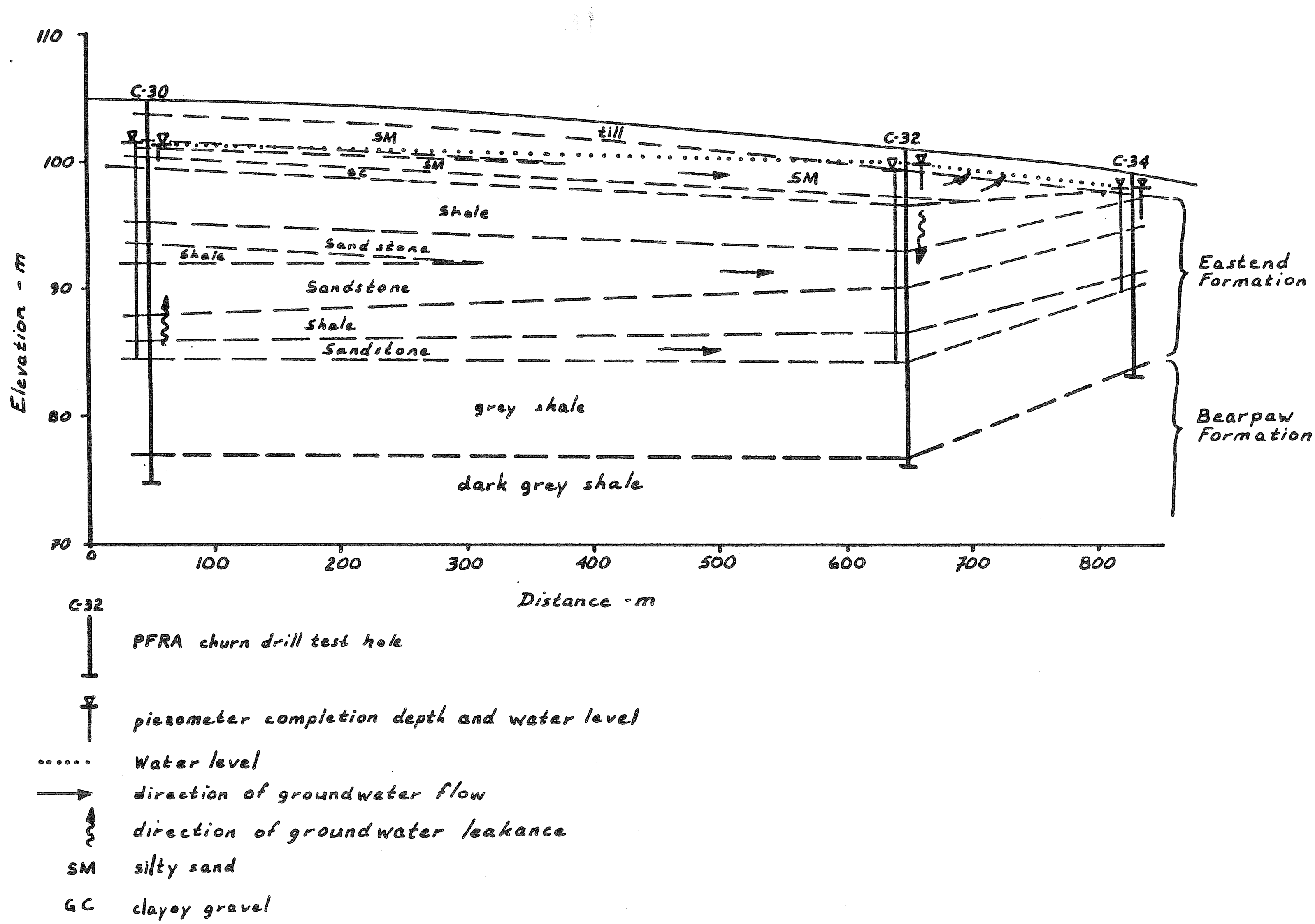

Figure 6. Hydrogeologic cross-section at NE35-13-13W3M.

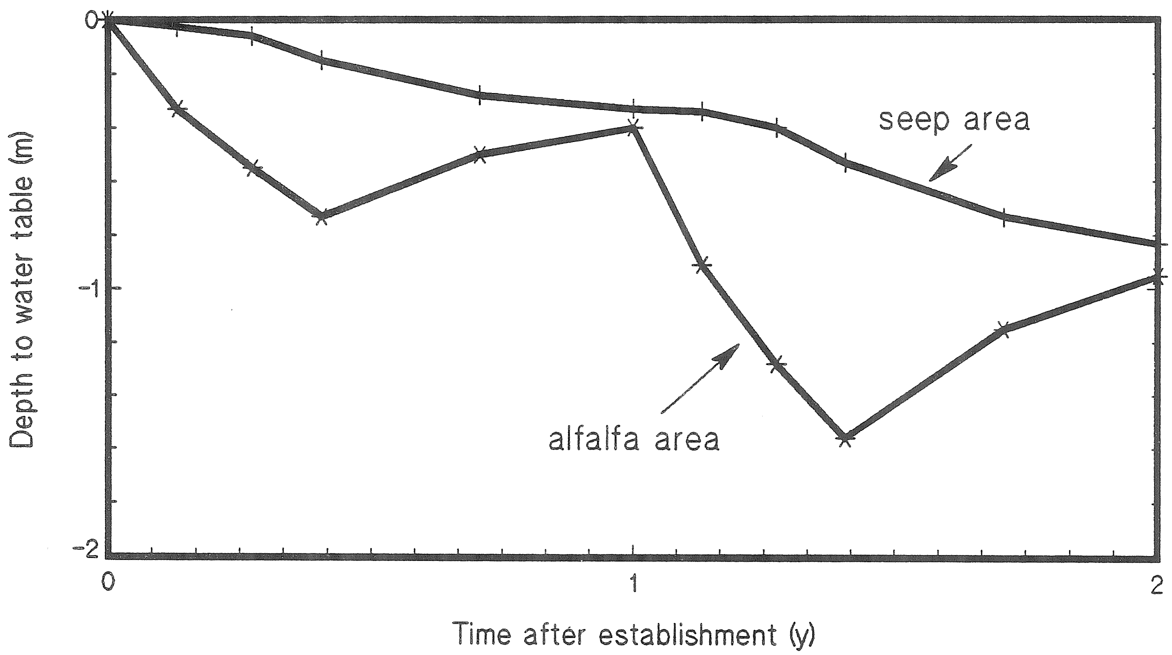

Figure 7. The simulated effect of an alfalfa interceptor strip on water table dynamics under the seep and alfalfa planted areas.