REPORT #
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PHYSICAL AND HYDROLOGICAL CHARACTERISTICS OF PONDS IN RECLAIMED UPLAND LANDSCAPE SETTINGS AND THEIR IMPACT ON AGRICULTURAL CAPABILITY

by

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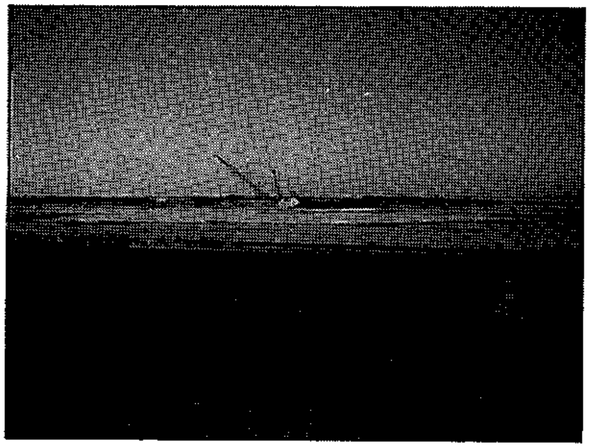
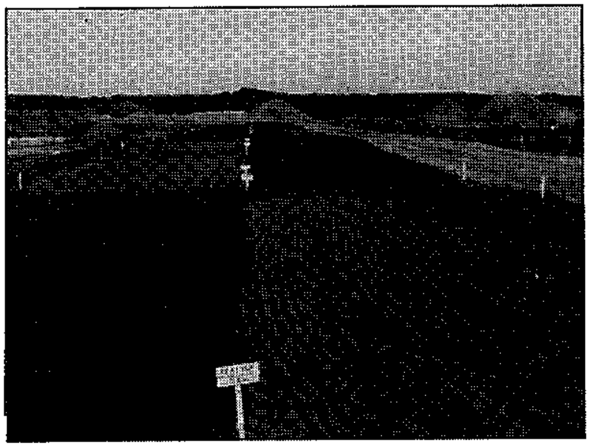
Plains Coal Reclamation Research Program





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DISCLAIMER

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

The opinions, findings, conclusions, and recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of government or industry. Mention of trade names or commercial products does not constitute endorsement, or recommendation for use, by government or industry.

REVIEWS

This report has been reviewed by members of the Reclamation Research Technical Advisory Committee and by the members of the Plains Coal Reclamation Research Program.

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ABSTRACT

In 1985, a one hectare pond developed in the upland reclaimed landscape at Vesta Mine in an area where extensive ponding had not previously been observed. Because of the thickness of the spoil, about 20 to 25 m, and the proximity to the active pit, a few hundred metres, it was inferred that the pond was perched above the water table. This pond was instrumented in September 1987 to monitor the subsurface water and salinity regime. Observations that continued throughout 1988 and 1989 provide the basis of this report.

The closed basin responsible for the existence of pond S195 was formed by construction of a low berm transverse to a long southward draining slope. The resulting drainage basin collects and channels runoff water during spring snow melt into a series of subsidence depressions in the lowest part of the basin. Compaction during placement and grading of the lower subsoil and upper spoil produced a hydraulic barrier with sufficiently high density and low hydraulic conductivity that rapid downward drainage of the ponded water was prevented. The hydraulic conductivity was further reduced by sealing of the upper surface of the spoil as a result of structural collapse of sodic clay in response to wetting.

Perched ponds impact the agricultural capability of reclaimed landscapes in three ways. (1) Perched ponds reduce the amount of farmable land within upland reclaimed landscapes and disturb field patterns as compared to upland reclaimed sites without such ponds. To put this in perspective, the area occupied by ponding in upland settings in the reclaimed sites studied is less than half that in unmined sites in the same area. (2) Perched ponds, such as S195, result in progressive development of saline and potentially sodic soils in the area adjacent to the pond. The saturated or nearly saturated conditions in the soil surrounding the pond result in upward movement of subsurface water, which is lost by evaporation and evapotranspiration, and accumulation of salts in the soil zone over time. (3) Perched ponds result in accelerated groundwater recharge, at least early in their life. On the basis of evidence from our study, however, a single isolated pond does not produce sufficient recharge to cause the water table to approach the surface in areas of thick spoil. The recharge rate at pond S195 during the period of observation was considerably lower than during the early period of ponding. It is not clear whether this diminished recharge rate resulted from a decrease in hydraulic conductivity or from a series of drier than normal years.

It appears unlikely that the size of perched ponds will increase significantly over time. It is considered more likely that the size of such ponds is limited by the interaction between the size of the contributing drainage basin, the depth of the central depression, and the rates of precipitation and evaporation.

ACKNOWLEDGEMENTS

This study was sponsored by the Reclamation Research Technical Advisory Committee and partly supported by funds from the Alberta Heritage Savings Trust Fund, administered through the Alberta Land Conservation and Reclamation Council. We would like to thank Manalta Coal Ltd. and Luscar Ltd. for allowing access to their mining properties. Gordon Jean conducted the majority of the monitoring work. Gordon and Grant Sjostrom did the surveying; Michael Huemmert conducted the hydraulic conductivity testing; Zdenek Widtman monitored the soil moisture and density access tubes. Daphne Cheel assisted in the completion of the final manuscript.

1. INTRODUCTION

1.1 OBJECTIVES

The overall objective of this project was to determine the potential effects on agricultural capability of perched ponds in reclaimed landscapes in the plains region of Alberta. The term "perched ponds" refers to semi-permanent ephemeral ponds in hydrological upland settings that are not connected to the water table. We are concerned primarily with larger ponds that occupy thousands of square metres for at least part of the year.

In order to accomplish the overall project objective, three questions must be answered:

1. Why and how do perched ponds develop in reclaimed landscapes?
2. In what ways do perched ponds alter the agricultural capability of hydrologic upland sites in reclaimed landscapes? and
3. Are perched ponds likely to expand in area over time?

1.2 BACKGROUND

Between 1979 and 1988, the Plains Hydrology and Reclamation Project (PHRP) investigated interactions of groundwater, soils, and geology and reclamation success in surface coal mines in the plains of Alberta. One of the objectives of the study was to document the processes by which a steady-state hydrologic regime was re-established following reclamation and to determine the relationship between steady-state hydrologic conditions and agricultural capability. Instrumentation was installed in spoil at two study areas: the Battle River area (Figure 1), which included Diplomat, Vesta and Paintearth Mines, and the Lake Wabamun area, which included the Highvale and Whitewood Mines.

Two distinctly different hydrologic regimes were recognized in reclaimed surface-mined landscapes: (1) upland settings and (2) lowland settings (Figure 2). Upland settings, which constitute the majority of reclaimed areas, are generally situated above the premining landscape grade and are characterized by flat to undulating terrain. Numerous small oval depressions, which are about 10 to 20 m wide by 20 to 50 m long and as much as 0.5 m deep, dot the landscape. These depressions, which typically occupy from five to ten percent of the reclaimed surface, form by differential subsidence, which accompanies resaturation of the spoil (Dusseault et al. 1983; 1984a,b,c; 1985). During spring melt and heavy summer rain storms these depressions capture water to produce ponds. Ponding is generally ephemeral and tends to be of limited areal extent, with the ponds perched above and not connected to the water table (Figure 2).

Lowland settings, which constitute more restricted areas within reclaimed landscapes, are generally situated at or below the premining landscape grade. These settings generally occupy a greater proportion of the reclaimed landscape in older mining areas than in modern mine sites. Lowland settings develop wherever the premining overburden was thin, generally less than about 4 to 5 times the thickness of the removed coal, and in the vicinity of final cuts. Lowland settings are characterized by deep depressions that result from mining operations, such as final cuts, access ramps and haul roads. Shallow, broad depressions form in areas of thinner spoil that result where pit orientation changed such that the spoil was cast over an area that was larger than the cut from which it was excavated. In addition, small depressions form through differential subsidence. Considerable ponding of surface water occurs in lowland settings with ponds tending to be permanent or semi-permanent and connected to the water table (Figure 2).

Very little upland reclaimed area was available in 1979, when PHRP was initiated, and consequently, the majority of the instrumentation that was installed focussed on lowland settings. By 1984 upland areas became available at Vesta and Paintearth Mines and three areas

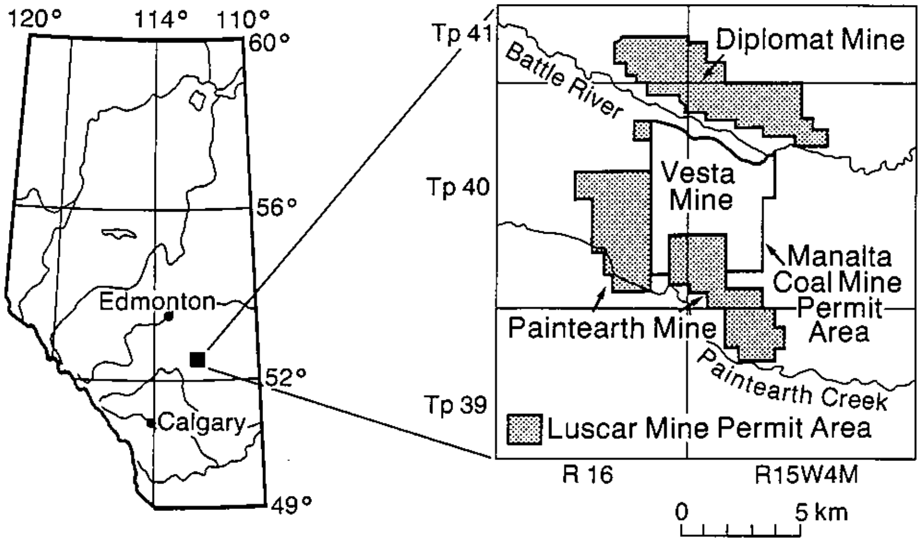


Figure 1. Map showing the location of the Battle River study area in east-central Alberta.

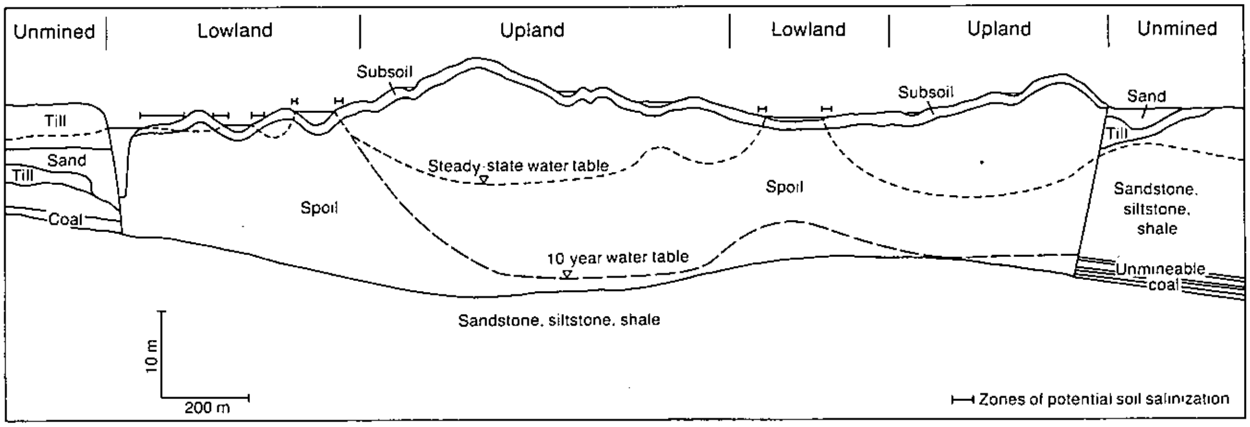


Figure 2. Schematic diagram showing hydrologic regimes in reclaimed landscapes.

were instrumented, one at Paintearth Mine (Figure 3) and two at Vesta Mine (Figures 4 and 5). Although a few small, ephemerally ponded depressions were present at Paintearth Mine and in the western portion of Vesta Mine, upland sites are typically characterized by the absence of surface water. In 1985, a relatively large pond developed around a series of isolated subsidence depressions that first appeared in 1984 (Figures 4 and 6). The pond, which was very shallow and fluctuated over a wide area, covered about 8500 m^2 in July,1985 (Figures 4 and 7). During the next two years, this pond expanded in the spring to cover large areas, then contracted by middle to late summer to cover only a few hundred square metres in the original subsidence depressions.

1.3 METHODS OF STUDY

The fundamental approach that we have followed was largely descriptive. We have collected and interpreted a body of observational data on the physical and hydrological characteristics of the prominent perched pond at Vesta Mine, S195. This report presents and discusses this accumulated information base and provides a conceptual model of the origin and implications of this type of pond in reclaimed settings in east central Alberta.

1.3.1 Instrumentation of Study Sites.

In the fall of 1987, instrumentation was installed at Pond S195 to monitor the fluctuations in pond level and to determine the effects of the pond on groundwater conditions. A staff gauge was placed in the deepest part of the pond. In the spring of 1989, a stage recorder was placed on the pond. Two nests of piezometers were installed in the fall of 1987; BR195 was within the area covered by the pond earlier in the year, and BR196 was about 60 m to the south, outside the pond (Figure 4). Five piezometers were installed in each nest, one at the base of the spoil, one at the interface between the subsoil and the spoil, and the remaining three within the spoil at about five metre intervals upward from the base. An access tube for a gamma/neutron-density/moisture probe was installed at each piezometer nest. Precipitation and evaporation were monitored at four and three sites, respectively, within the Battle River study area (Table 1).

1.3.2 Monitoring and Testing.

Monitoring activities were carried out between April and November in 1988 and 1989. The outline of the pond was staked periodically throughout the monitoring period in both years. The location of the stakes was subsequently determined by surveying. Soil samples were collected at the sites of the two instrumented nests in the fall of 1987 and 1989 to evaluate the salinity status of the reconstructed soil profile. In addition to the monitoring and testing activities around the upland pond, periodic monitoring of previously installed instrumentation in

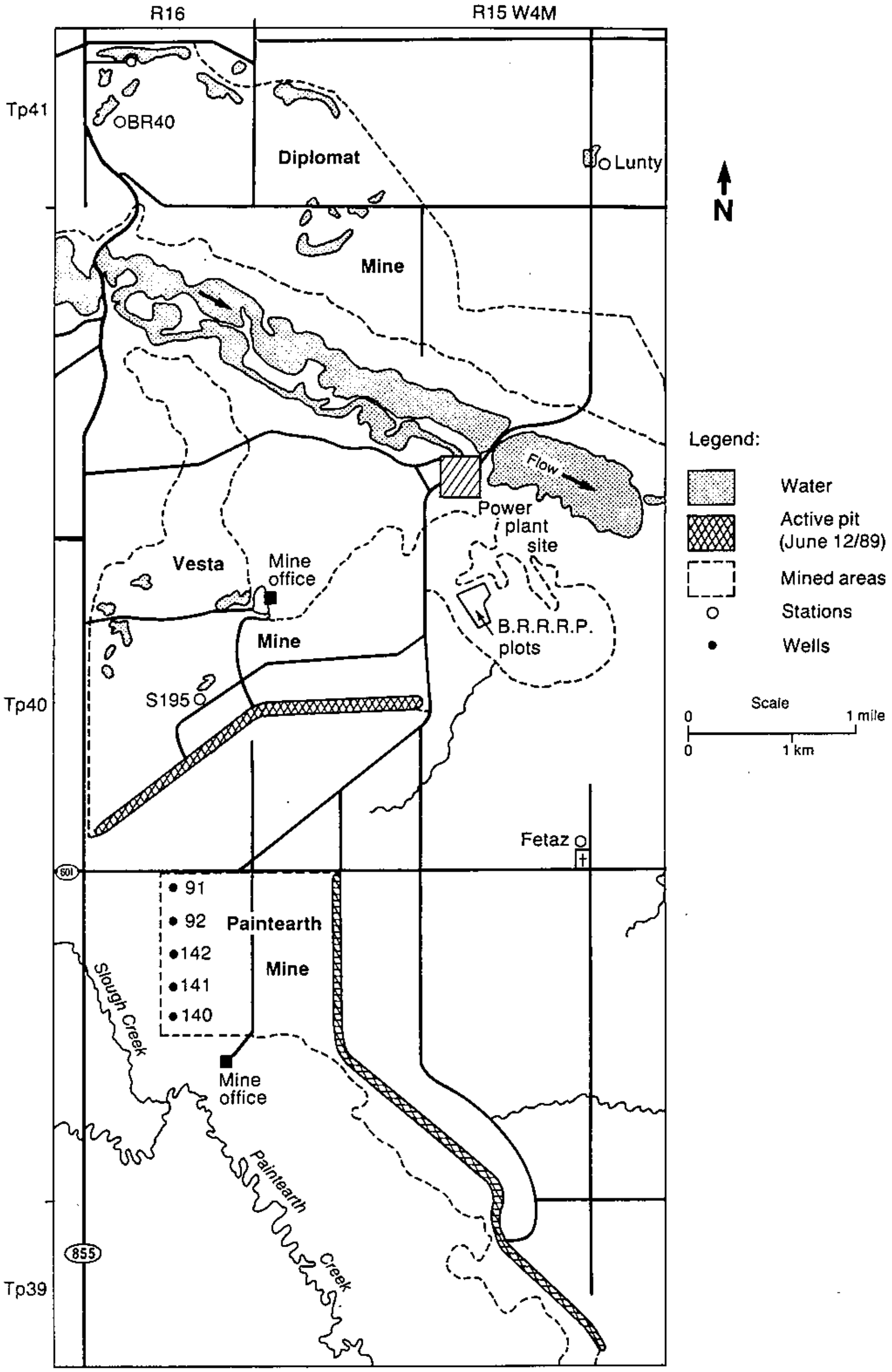


Figure 3. Map of the Battle River study area showing locations of pond S195 and precipitation monitoring stations.

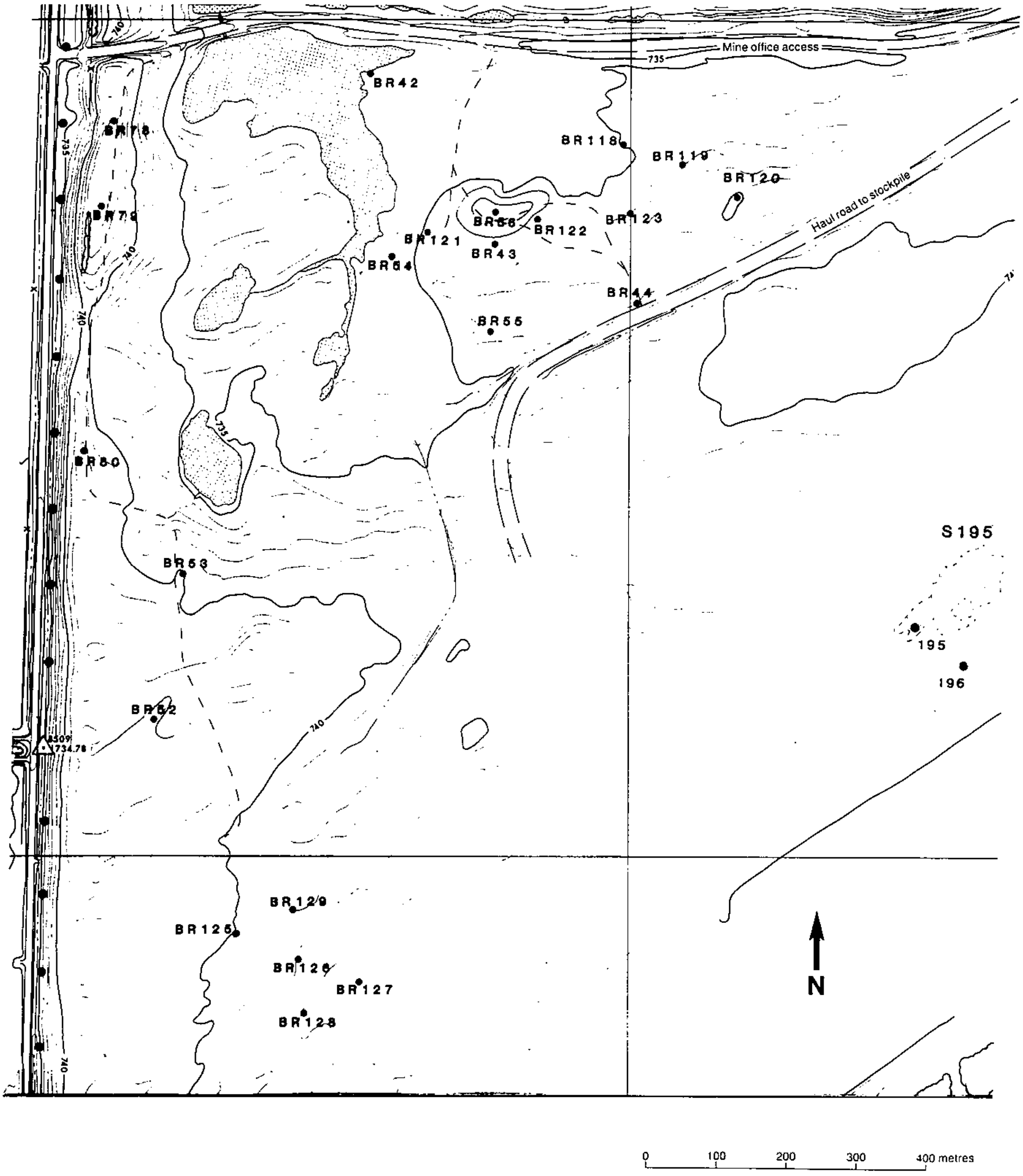


Figure 4. Map of western end of Vesta Mine showing location of monitoring instrumentation.

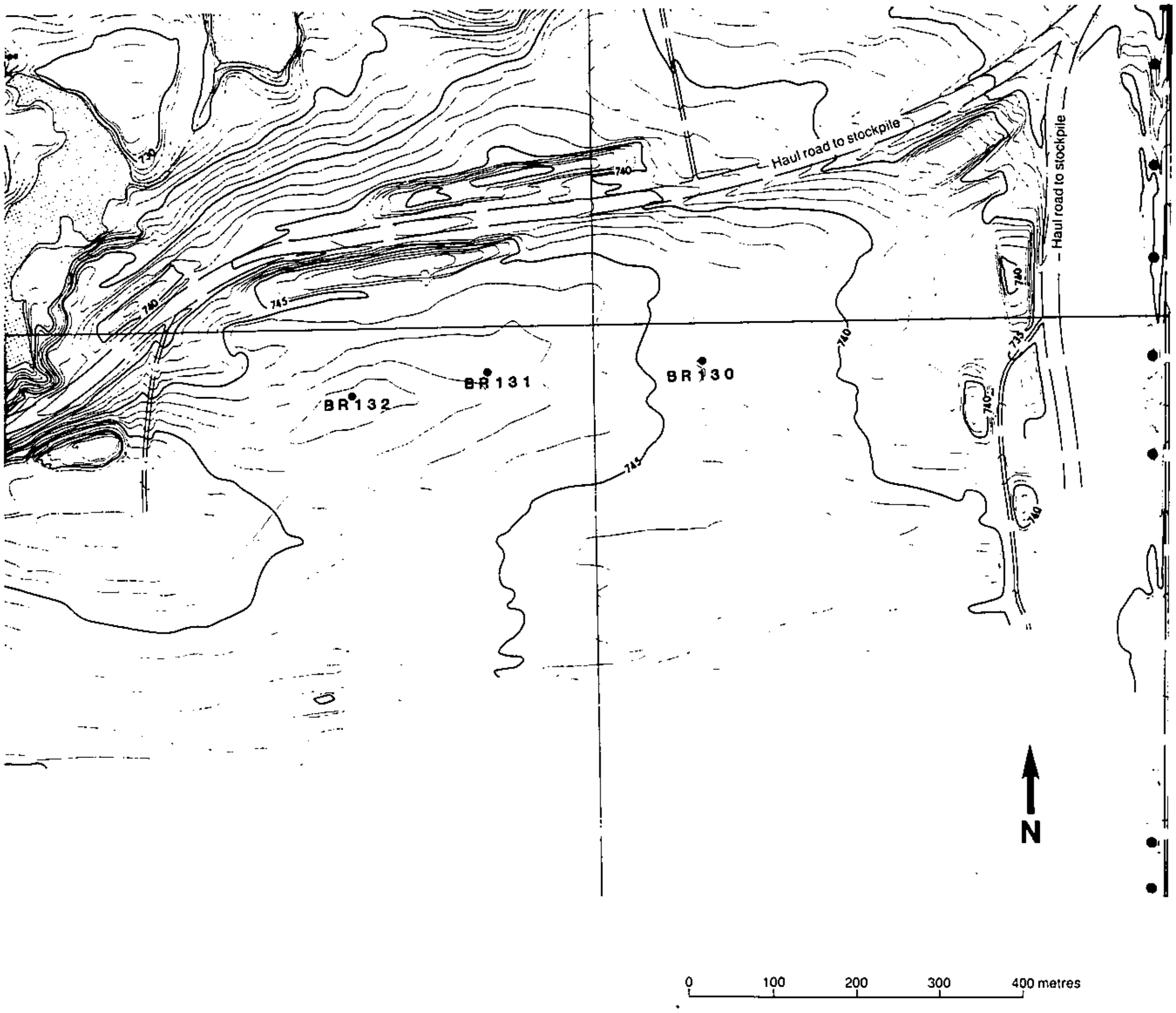


Figure 5. Map of eastern end of Vesta Mine showing location of monitoring instrumentation.

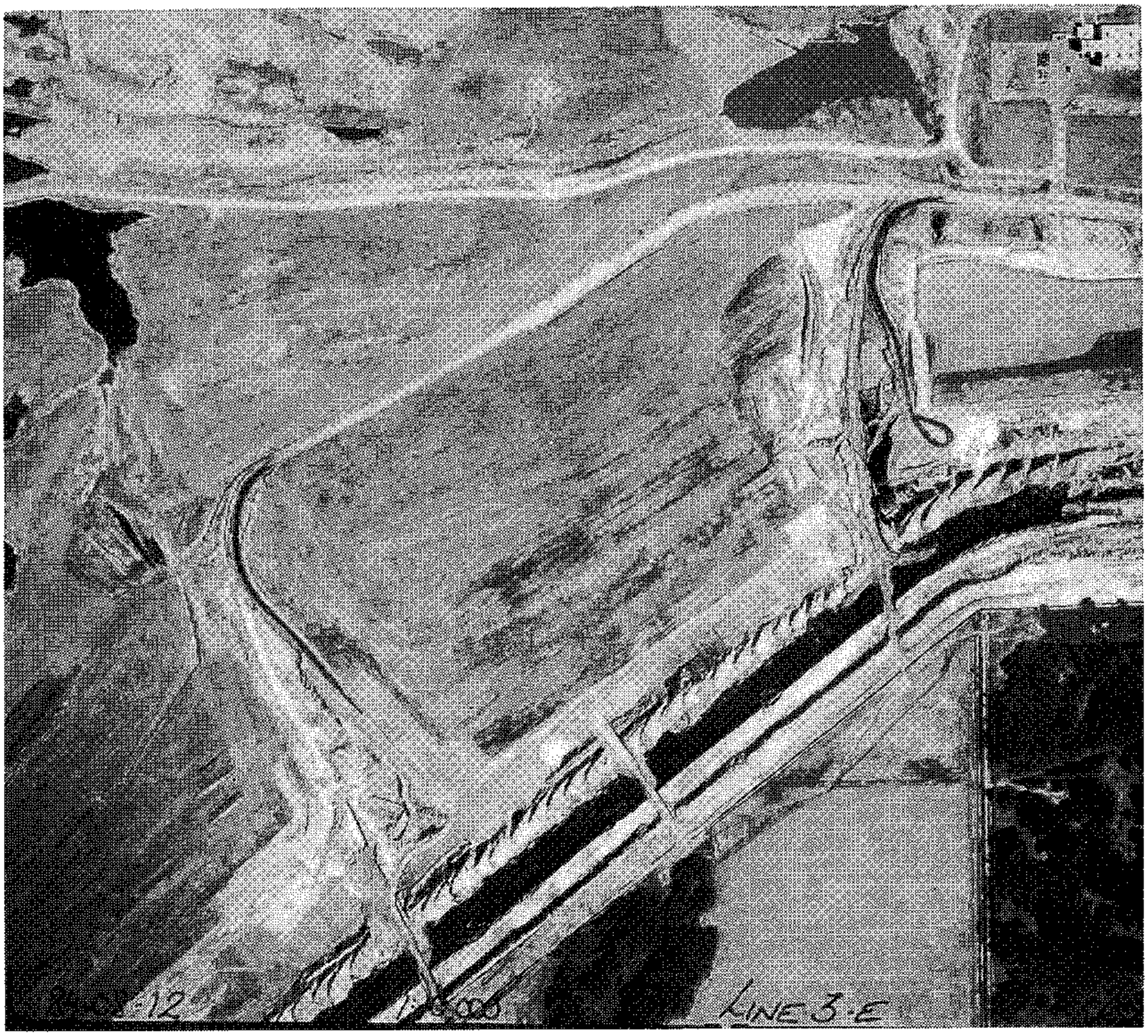


Figure 6. False-color infrared aerial photograph showing western end of Vesta Mine on August 12, 1984.

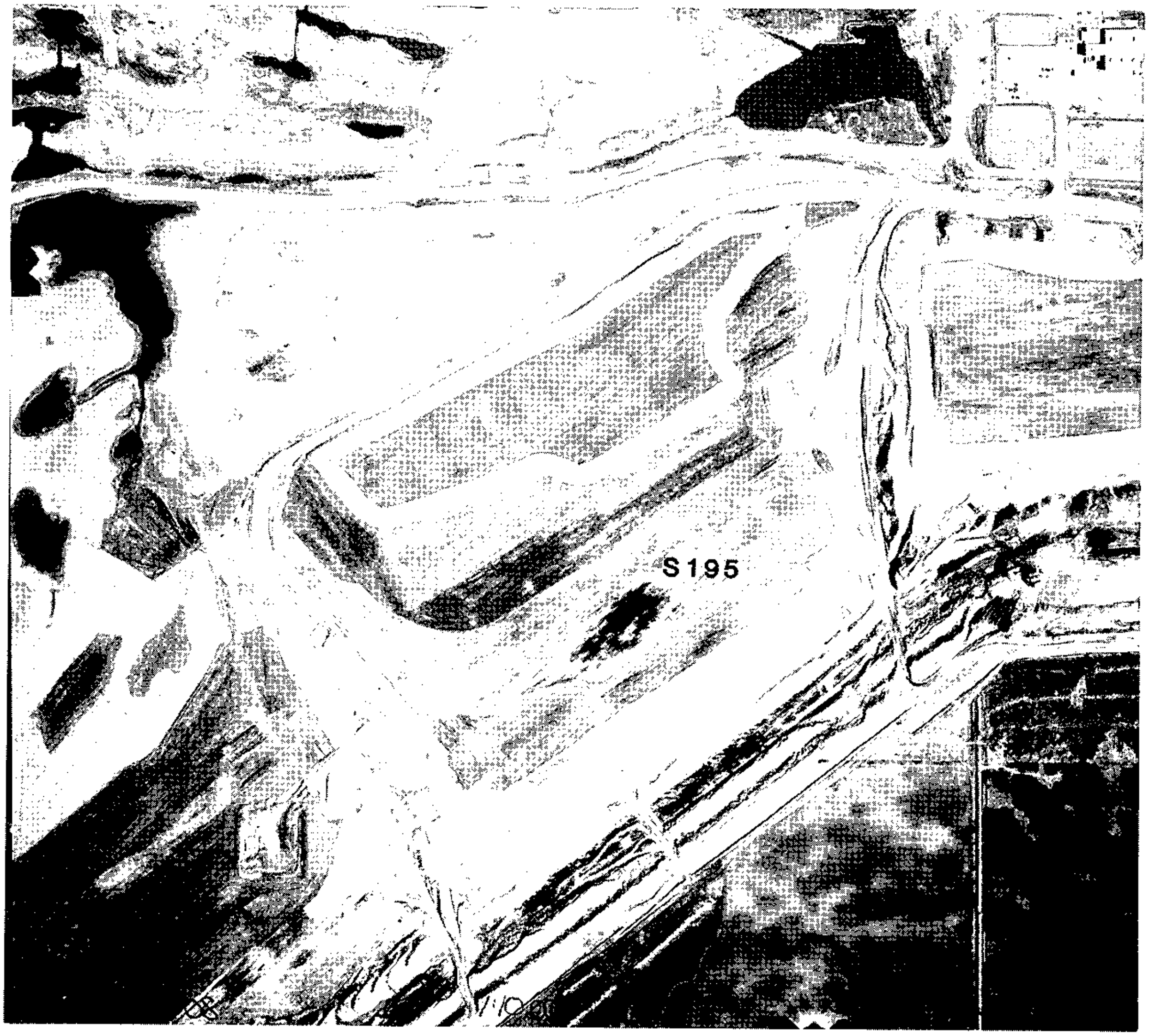


Figure 7. False-color infrared aerial photograph showing western end of Vesta Mine on July 8, 1985.

upland sites was continued throughout the period. The instrumentation monitored included piezometers at sites BR52, BR53, BR54, BR56, BR125, BR126, BR127, BR128, BR129, BR130, BR131, BR132, BR195, and BR196, at Vesta Mine, and gamma/neutron-density/moisture probe access tubes at sites BR 56, BR126, BR128, BR130, BR132, BR195, and BR196 (Figures 4 and 5).

1.3.3 Field Activities During 1989

1.3.3.1 Surface Water Monitoring. Staff gauge readings on pond S195 (Figures 3 and 4) were maintained on a weekly to biweekly basis between April and October 1989. A Stevens recorder was installed in July and continuous records of pond levels were obtained between July 17 and October 31. Pond margins were staked on a regular basis at the time that staff gauge readings were obtained. In addition, the high water mark, which was reached between monitoring events, was also staked.

1.3.3.2 Meteorological Monitoring. Evaporation pans, which were monitored on a weekly basis, and continuous recording rain gauges were maintained at or in the vicinity of pond S195 between April 1 and October 31, 1989 (Figure 3; Table 1).

Table 1. Location of meteorological monitoring stations during 1989.

Site	Instrumentation	Distance from S 195	Direction	Start of Monitoring	End of Monitoring
BRSRP	rain gauge	2.7 km	east	1/4/89	31/07/89
S195	rain gauge	on site	on site	1/8/89	31/10/89
BR 40	rain gauge and evaporation pan	6.1 km	north	1/4/89	31/10/89
Lunty site	rain gauge and evaporation pan	6.3 km	northeast	1/4/89	31/10/89
Fetaz site	rain gauge and evaporation pan	3.6 km	east-southeast	1/4/89	31/10/89

1.3.3.3 Subsurface Water Monitoring. Soil moisture determinations were made at sites BR56, BR126, BR128, BR130, BR132, BR195, and BR196 on five occasions during the year, May 2, June 6, July 11, August 9, and September 13. These readings were made using a neutron moisture metre, generally to a depth of 3.9 m.

Groundwater levels were monitored in piezometers at sites BR52, BR53, BR54, BR125, BR126, BR127, BR128, BR129, BR130, BR131, BR132, BR195, and BR196, at Vesta Mine. Sites BR195 and BR196 were monitored on a monthly basis and after rainfall events. The remainder of the sites were monitored twice during 1989.

1.3.3.4 Soil Sampling. Soil samples were collected from sites BR195, and BR196 on September 12, 1989. Samples were collected at 15 cm intervals to a depth of 1.5 m and at 30 cm intervals from 1.5 m to 2.10 m. Analyses of saturation-paste extract for EC and soluable ions were completed.

1.3.3.5 Physical Property Determinations. Soil density determinations were made at sites BR126, BR128, BR130, BR132, BR195, and BR196 on five occasions during the year, May 2, June 6, July 11, August 9, and September 13. These readings were made using a gamma-ray density meter, generally to a depth of 3.9 m.

Nineteen determinations of hydraulic conductivity of the subsoil and spoil were made to a depth of 2.70 m at sites BR195 (10) and BR196 (9). Hydraulic conductivity was determined using a Guelph permeameter device (Reynolds and Elrich 1986). In this method, a constant head test is used to determine the field saturated hydraulic conductivity (K_{fs}) over a relatively short interval (e.g., 5 to 30 cm) in an open borehole. K_{fs} is generally somewhat less than the true saturated hydraulic conductivity, due to the presence of entrapped air. However, K_{fs} is probably the preferred value because fully saturated conditions are not likely to be reached in a soil during either natural or man-induced infiltration events (Reynolds et al. 1983).

The Guelph permeameter uses the Mariotte Principle to maintain a constant head in the borehole. As a bulb of saturated soil develops around the test interval, approximately steady-state conditions are eventually reached. For steady flow from an open hole (Elrich et al. 1989):

$$Q = \left(\frac{2\pi H^2}{C} + \pi a^2\right) K_{fs} + \frac{2\pi H}{C} \phi_m \qquad (1)$$

where Q = steady rate of water outflow (L^3T^{-1}), H is the constant height of ponded water (L), a is the radius of the borehole (L), K_{fs} is the field saturated hydraulic conductivity (LT^{-1}), C is a dimensionless shape factor that depends primarily on H/a (Reynolds and Elrich 1986), and ϕ_m is the matric flux potential, which characterizes the soil's ability to take up water by capillarity (Elrich et al. 1989). In order to solve this equation with two unknowns (K_{fs}, ϕ_m) we substitute the relationship:

$$\alpha^* = \frac{K_{fs}}{\phi_m} \qquad (2)$$

where the capillarity factor, $\alpha^*(L^{-1})$, can be estimated from the soil texture and structure. Values of α^* range from 1 to 36 m^{-1} (Elrich et al. 1989):

$\alpha^* = 1\ m^{-1}$ Compacted clays (e.g., landfill caps and liners, lacustrine or marine sediments, etc.);

$\alpha^* = 4\ m^{-1}$ Primarily unstructured, fine-textured soils;

$\alpha^* = 12\ m^{-1}$ Most structured soils from clays through clay loams; also includes unstructured medium and fine sands and sandy loams. The first choice for most soils;

$\alpha^* = 36\ m^{-1}$ Coarse and gravelly sands; may also include some highly structured soils with large cracks and macropores.

The above analysis is not particularly sensitive to the value of α^* used. As reported by Elrich et al. (1989) the error introduced by using an α^* value of 36 versus an α^* of 4, corresponds to overestimating K_{fs} by a factor of 1.9 (for $H = 0.25$ m) to 3.6 (for $H = 0.05$ m). In terms of single-well field measurements of hydraulic conductivity, the error introduced by incorrectly estimating α^* will probably be much smaller than the above extremes, and will likely not be significant relative to the variability in K_{fs} due to material heterogeneity, borehole smearing, etc. Consequently, the above method (Elrich et al. 1989) employing a one-head test and estimated α^* of 12 m^{-1} was used to analyze the permeameter test data from Vesta Mine, and produce a 'best estimate' value of K_{fs} (W.D. Reynolds, Agriculture Canada, Land Resource Research Center, Central Experimental Farm, Ottawa, Canada, K1A 0L6; personal communication, 1989).

2. RESULTS

2.1 METEOROLOGICAL RECORDS

Precipitation data from the four project gauging stations are summarized in Table 2 and Figure 8. Data for the 1951 to 1980 climate normals from the Atmospheric Environment Service stations at the Forestburg Generating Station and Alliance are included for comparative purposes. Both 1988 and 1989 were drier than the normals for this area, April and May were dry in both years. July, 1988 was dry, whereas August, and September, were dry in 1989. August and September, 1988 and June and July, 1989 were somewhat wetter than the normals.

Monthly pond evaporation data for 1988 and 1989 are summarized in Table 3 and Figure 9. These data were obtained by correcting water loss from a standard class A-pan for precipitation measured at the same site and then multiplied by a pan coefficient of 0.7 to estimate pond evaporation (Linsley, Kohler and Paulhus 1975). Total evaporation during 1989 of 627 mm, was somewhat greater than the 561 mm which occurred during 1988; evaporation was greater during April and May, 1988 and June and July, 1989. In both years, the amount of water lost by evaporation from ponds was almost exactly twice as great as the amount that fell as precipitation.

2.2 DESCRIPTION OF POND S195

Pond S195 is irregularly oval in shape with the long axis aligned NE/SW, parallel to the orientation of the mine pit (Figures 3, 4, and 7). At lower levels, the pond separates into a series of smaller regularly oval shaped depressions (Figure 10). The area of the pond fluctuated considerably between April and November (Figures 11 and 12). In 1988 the minimum area was 760 m^2 on June 1; the maximum recorded area was 10 700 m^2 on June 9 (Figure 11). In 1989, the maximum area on April 5 was 13 850 m^2 with a minimum area on September 26 of 200 m^2 (Figure 11). The relationship between stage and area was described by two different equations (Figure 13). At pond stages above 735.42 m, the area increased at a rate of 450 m^2 per cm rise in stage; below this level, the area increased about 115 m^2 per cm of rise (Figure 13). This change in the shape of the pond is clearly evident in bottom profiles across the pond (Figure 14).

2.2.1 Water-level Behavior.

Water level records are available for pond S195 for the period April through October in both 1988 and 1989 (Figure 15). The pond reached high levels in the spring in response to snow melt and again in early summer in response to major rainstorms.

Table 2. Monthly precipitation (mm) data summary for the Battle River area. Standard deviation for 1988 and 1989 refers to spatial variability among the four project gauging stations. Standard deviation for Forestburg Generating Station and Alliance stations refers to temporal variability during 1951 to 1980.

	April	May	June	July	Aug	Sept	Oct	Total
1988	1.8	6.8	77.5	39.5	77.5	53.5	6.5	263.5
(STDEV)	1.5	1.9	5.4	5.7	4.4	4.1	1.7	10.5
1989	7.9	17.8	93.2	80.8	49.8	14.0	19.5	286.2
(STDEV)	1.18	3.6	21.7	14.1	21.1	9.7	3.0	35.4
Forestburg	19.4	37.6	78.9	74.3	59.0	33.2	14.5	316.9
(STDEV)	13.8	30.3	43.5	29.6	37.3	31.2	11.5	-
Alliance	24.1	42.4	76.4	75.4	63.3	41.1	17.4	340.1
(STDEV)	18.5	30	38.5	40.9	42.2	33.8	12.7	-

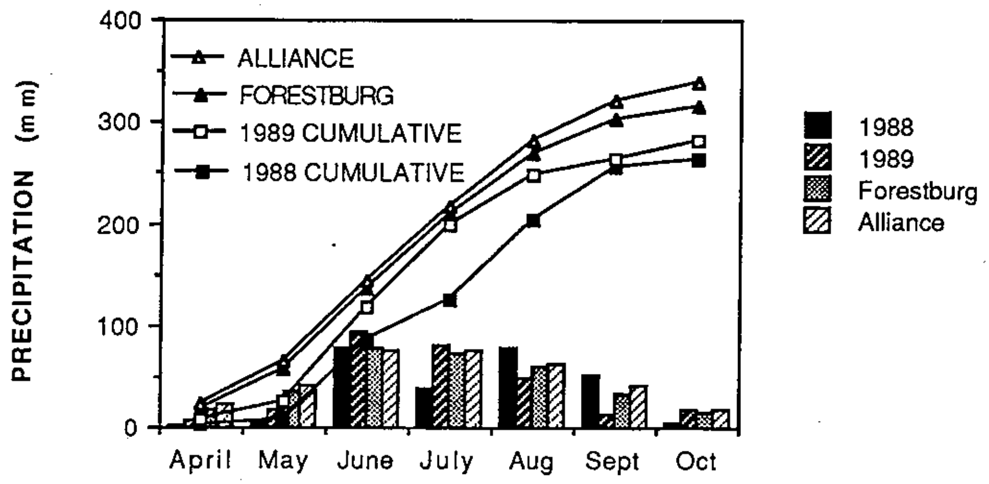


Figure 8. Monthly precipitation (mm) summary for the Battle River area, April to October.

Table 3. Summary of monthly pond evaporation (mm) for 1988 and 1989 in the Battle River area.

Month	1988	1989
April	97	78
May	137	105
June	96	136
July	81	144
August	75	58
September	13	42
October	23	21
TOTAL	523	585

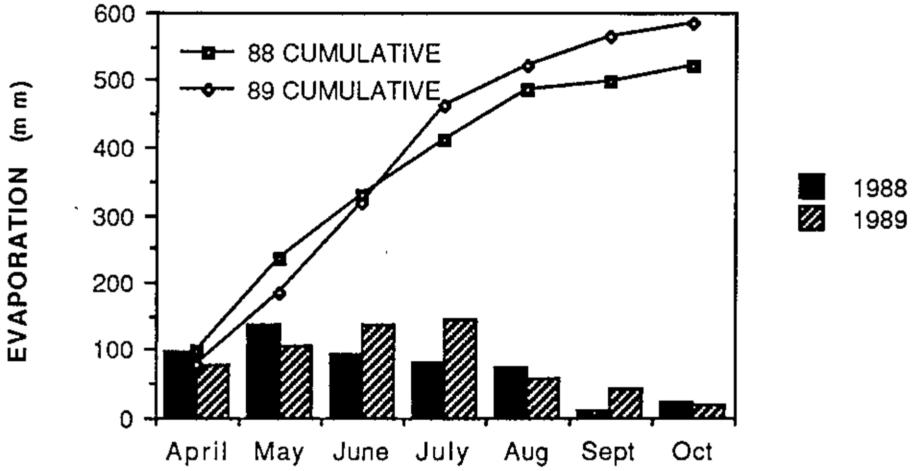
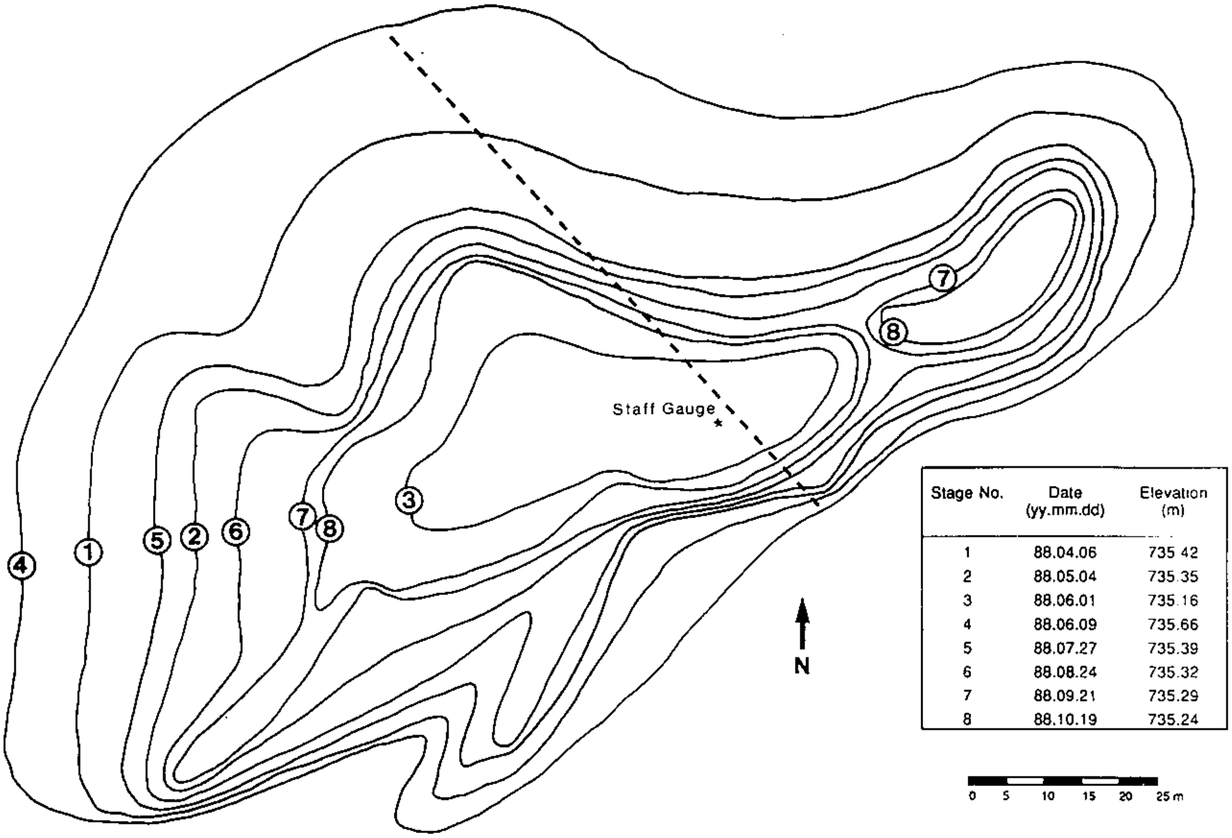


Figure 9. Summary of monthly pond evaporation (mm) data for the Battle River area for 1988 and 1989.



Stage No.	Date (yy.mm.dd)	Elevation (m)
1	88.04.06	735.42
2	88.05.04	735.35
3	88.06.01	735.16
4	88.06.09	735.66
5	88.07.27	735.39
6	88.08.24	735.32
7	88.09.21	735.29
8	88.10.19	735.24

Figure 10. Diagram of pond S195 showing position of shoreline at monitoring events during 1988. The dashed line shows the location of the profile in Figure 14.

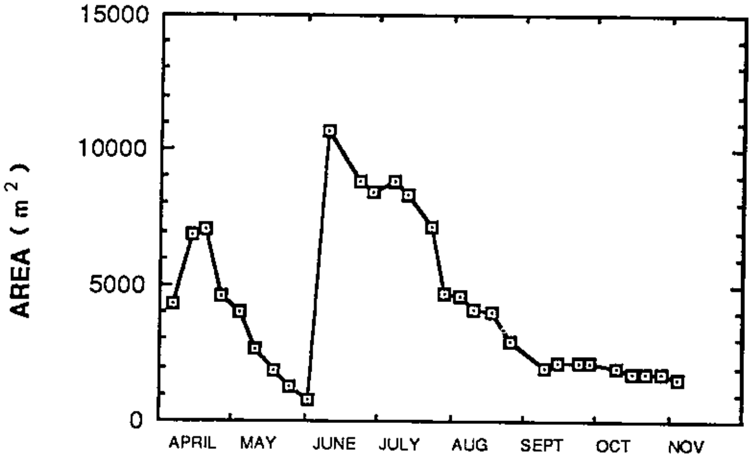


Figure 11. Variation in the area of pond S195 during 1988.

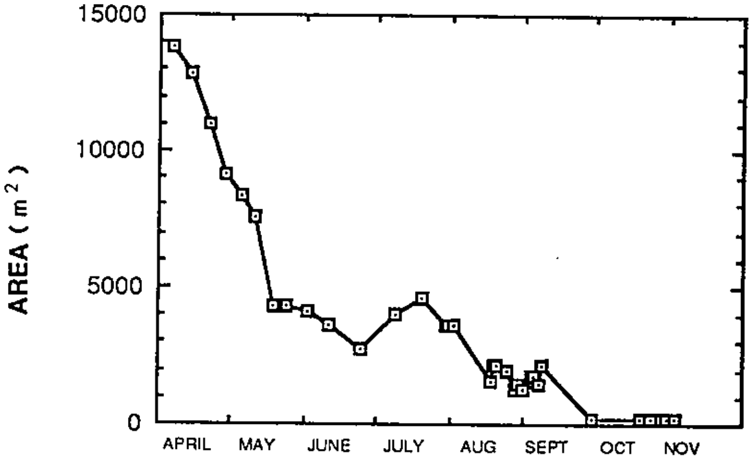


Figure 12. Variation in the area of pond S195 during 1989.

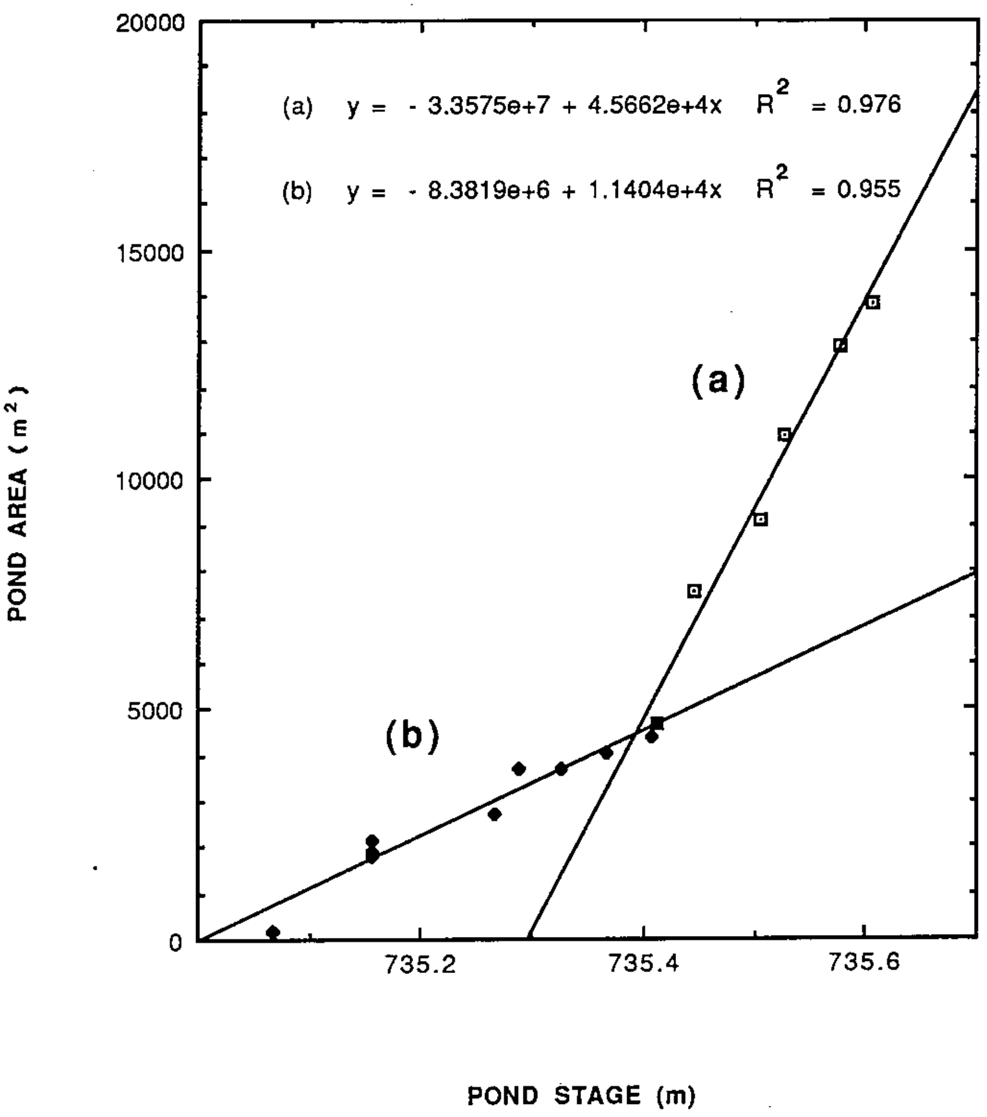


Figure 13. Graph showing large change in area of pond S195 at high stage (a), and smaller change in area at lower stage (b) during 1989 at Vesta Mine.

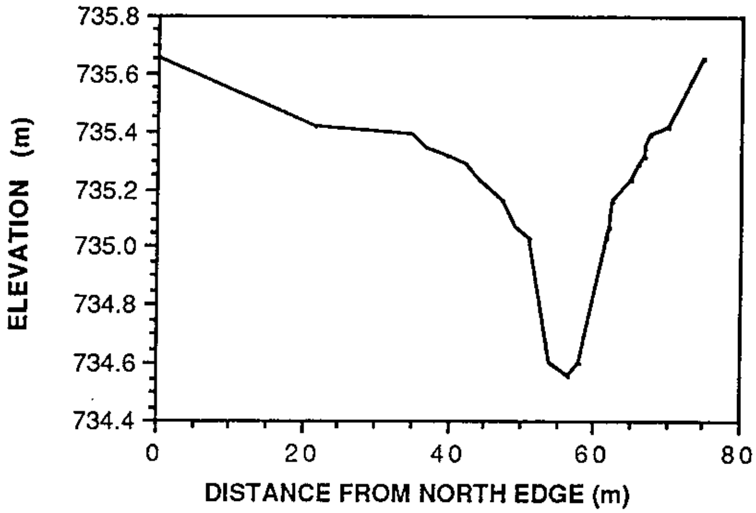


Figure 14. Profile across pond S195 showing broad outer basin and more steep-sided inner subsidence depression. Location of profile is shown by the dashed line in Figure 10.

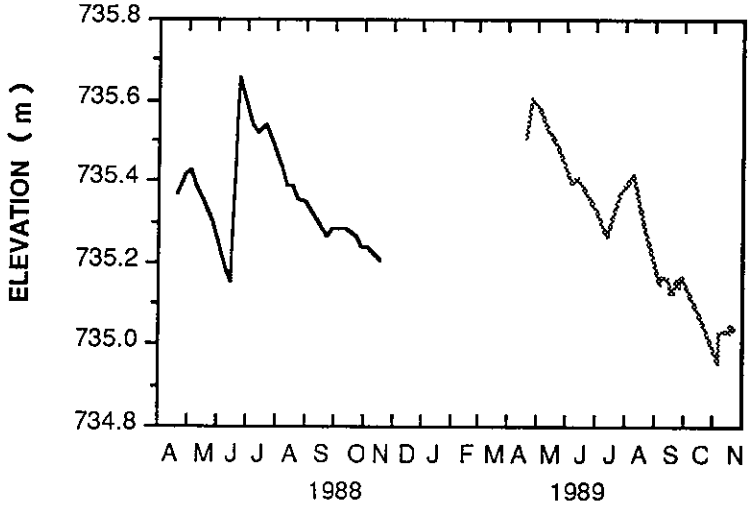


Figure 15. Variation in the level of pond S195 over time.

May and June were a period of rapidly declining water levels, with July, August and September being periods of steady but slower decline.

In 1988, the high stage caused by the spring melt occurred on April 20, 1988 when the pond was at 735.43 m. By June 1, 1988, the pond level had dropped by 0.27 m to stand at 735.16 m. A rain storm that produced 34 mm of precipitation caused the pond to rise 0.50 m to its highest level of the year, 735.66 m, by June 9, 1988. Rainfall of 110 mm during June, 1988 held the level of the pond above 735.5 m until early July when it began to fall. The pond level declined steadily, (with only one minor reversal in late August), from early July until early September, when it stood at 735.27 m. There was no precipitation in July, but between the end of July and September 7, 1988, 175 mm of rain fell. After a brief rise of about 0.02 m in middle September, the pond continued to fall until it froze in early November at 735.2 m.

In 1989, the highest stage during the entire year was 735.61 m, which occurred during April of 1989. The pond level declined steadily by 0.24 m to stand at 735.27 m on June 22, 1989. The only interruption in this trend was a rise of 0.01 m in response to 14 mm of rain between May 19 and 23, 1989. Between June 24 and July 17, 106 mm of rain produced a rise in pond stage of 0.14 m to a level of 735.41 m on July 18, 1989. The pond then dropped for about a month to stabilize at 735.15 m on August 15, 1989. About 70 mm of rain that fell between August 16 and September 5, held the pond at this level. The pond declined another 0.1 m during September and then stabilized at about 735.05 m until it froze in November.

2.3 CHARACTERISTICS OF HYDROLOGIC UPLAND SETTINGS

2.3.1 Soil Moisture Behavior

Two aspects of the soil moisture records are of interest from a hydrological perspective: the degree of saturation, and the depth to which water content fluctuations occur on an annual basis. Percent saturation was calculated by dividing the volumetric moisture content by the porosity, which was calculated by dividing the bulk density by the assumed specific gravity of solids, 2.65 g/cm^3. Because of the uncertainties in the measurement of both density and moisture content, and the assumption about specific gravity of solids, percentage values greater than 90% were considered to be fully saturated. The depth of annual fluctuation in soil water content was estimated by calculating the standard deviation of saturation values for the five monthly readings. The depth to which standard deviation values exceeded 0.05 was arbitrarily considered to be the depth of annual change in water content.

Four sites, BR126, BR128, BR195, and BR196, showed evidence of saturated or near-saturated conditions during 1989 (Figure 16, Table 4). At site BR195, the zone between 105 cm and 150 cm, in the upper part of the spoil, was saturated. At site BR196, the interval

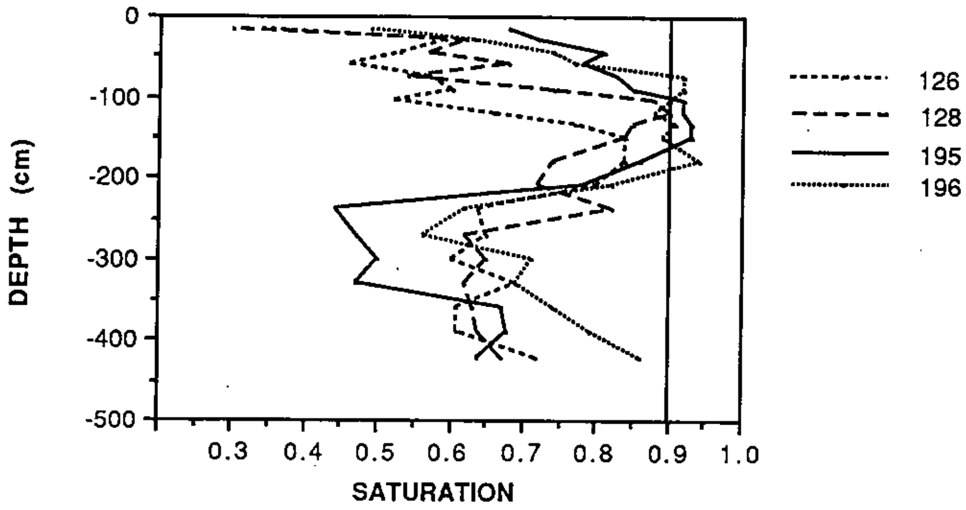


Figure 16. Profiles of nearly saturated upland sites at Vesta Mine showing proportion saturation as a function of depth.

Table 4. Mean percent saturation and (standard deviation) for Vesta sites during 1989.

Depth	Site						
(cm)	VE56(n=5)	VE126(n=5)	VE128(n=5)	VE130(n=5)	VE132(n=5)	VE195(n=5)	VE196(n=5)
15	0.43 (0.19)	0.34 (0.14)	0.34 (0.19)	0.34 (0.19)	0.32 (0.16)	0.68 (0.17)	0.49 (0.21)
30	0.55 (0.12)	0.59 (0.14)	0.62 (0.13)	0.43 (0.16)	0.33 (0.05)	0.72 (0.12)	0.63 (0.16)
45	0.69 (0.09)	0.53 (0.07)	0.57 (0.02)	0.54 (0.08)	0.31 (0.01)	0.81 (0.08)	0.74 (0.06)
60	0.67 (0.05)	0.46 (0.02)	0.68 (0.01)	0.47 (0.06)	0.30 (0.01)	0.78 (0.09)	0.77 (0.02)
75	0.65 (0.01)	0.57 (0.02)	0.54 (0.01)	0.51 (0.08)	0.29 (0.01)	0.83 (0.04)	0.92 (0.01)
90	0.64 (0.02)	0.60 (0.02)	0.74 (0.00)	0.61 (0.06)	0.30 (0.01)	0.85 (0.02)	0.92 (0.01)
105	0.56 (0.01)	0.52 (0.01)	0.88 (0.01)	0.68 (0.02)	0.47 (0.01)	0.92 (0.02)	0.90 (0.00)
120	0.57 (0.01)	0.66 (0.01)	0.90 (0.01)	0.69 (0.01)	0.66 (0.01)	0.92 (0.02)	0.88 (0.01)
135	0.61 (0.02)	0.77 (0.03)	0.85 (0.01)	0.64 (0.01)	0.61 (0.01)	0.93 (0.01)	0.91 (0.01)
150	0.70 (0.01)	0.84 (0.01)	0.84 (0.01)	0.51 (0.01)	0.61 (0.01	0.93 (0.01)	0.89 (0.01)
180	0.60 (0.01)	0.84 (0.01)	0.74 (0.01)	0.45 (0.00)	0.59 (0.01)	0.86 (0.01)	0.94 (0.00)
210	0.60 (0.00)	0.80 (0.01)	0.72 (0.01)	0.43 (0.00)	0.43 (0.00)	0.78 (0.01)	0.82 (0.01)
240	0.59 (0.01)	0.64 (0.00)	0.82 (0.00)	0.30 (0.00)	0.48 (0.01)	0.44 (0.01)	0.62 (0.01)
270	0.59 (0.01)	0.65 (0.01)	0.62 (0.01)	0.55 (0.00)	0.30 (0.01)	0.47 (0.01)	0.56 (0.00)
300	0.58 (0.01)	0.60 (0.01)	0.65 (0.01)	0.69 (0.01)	0.51 (0.01)	0.50 (0.01)	0.71 (0.06)
330	0.56 (0.01)	0.69 (0.01)	0.62 (0.03)	0.56 (0.00)	0.49 (0.01)	0.47 (0.00)	0.69 (0.01)
360	0.67 (0.01)	0.61 (0.01)	0.63 (0.01)	0.56 (0.01)	0.54 (0.10)	0.67 (0.01)	0.74 (0.01)
390	0.67 (0.00)	0.61 (0.01)	0.64 (0.01)	0.69 (0.00)	0.59 (0.00)	0.68 (0.00)	0.79 (0.01)
420	0.54 (0.01)	0.72 (0.01)	0.67 (0.01)	0.71 (0.01)	0.71 (0.00)	0.64 (0.00)	0.86 (0.01)

between 75 cm and 180 cm, in the lower part of the subsoil and the upper part of the spoil, was at or near saturation. At site BR126, the zone between 150 cm and 210 cm, in the upper part of the spoil, was nearly saturated. At site BR128, the zone between 105 cm and 150 cm, in the lower part of the subsoil and the top of the spoil, was also nearly saturated. The interface between the subsoil and spoil was above saturation throughout the year. At sites BR195 and BR196 the zone of saturated conditions is related to the ponding in adjacent pond S195. At both sites BR126 and BR128, the zone of nearly saturated conditions corresponds to the presence of sand in the profile.

Three sites, BR56, BR130, and BR132, were appreciably drier than the other four sites. Saturation at these dry sites never exceeded 75% of the porosity and was generally considerably lower (Figure 17). Site BR56 is on an elevated knoll. The micro-topography at sites BR130 and BR132 is similar to sites BR126 and BR128. Apparently the drier conditions at the former sites result from the absence of discrete sand layers in the profile.

The depth to which moisture content fluctuates on an annual basis varied between sites. Four sites, BR126, BR128, BR132, and BR196, were characterized by very shallow penetration of moisture changes (Figure 18). In contrast to these sites, BR56, BR130, and BR195 were characterized by deeper penetration of seasonal changes in moisture content (Figure 19). At BR128 and BR132, the moisture content did not vary significantly below a depth of 30 cm (Figure 20). At BR126 and BR196, the moisture content did not vary significantly below 45 cm (Figure 21). It should be noted that at site BR196 evidence of moisture change deeper into the profile was absent because nearly saturated conditions were encountered at 60 cm (Figure 21). At site BR195, seasonal fluctuation was evident to 60 cm (Figure 22). At site BR130, appreciable changes in moisture content were evident to 90 cm (Figure 22).

The moisture regime is important from the standpoint of agricultural capability because of the impact of moisture on crop growth. In the Battle River area, wilting point in most reconstructed profiles is about 15% to 17% (by volume) for the topsoil and about 19% to 22% for the subsoil (personal communication, 1990, T.M. Macyk, Manager Landscape Quality, Environmental Research and Engineering, Alberta Research Council, Edmonton, AB).

At the five upland sites, BR126, BR128, BR130, and BR132 soil moisture in the topsoil, (0 to 15 cm), was above wilting point only on July 11, 1989, following a heavy rain. The only exception to this was the September 13 measurement at site BR130. At site BR195 the topsoil was above wilting point on all monitoring dates. At site BR196, the topsoil was above wilting point in May, July, and September.

Soil moisture conditions in the subsoil were more variable in the upland sites. Two sites, BR126 and BR132, were very dry on all monitoring dates. The moisture content at site

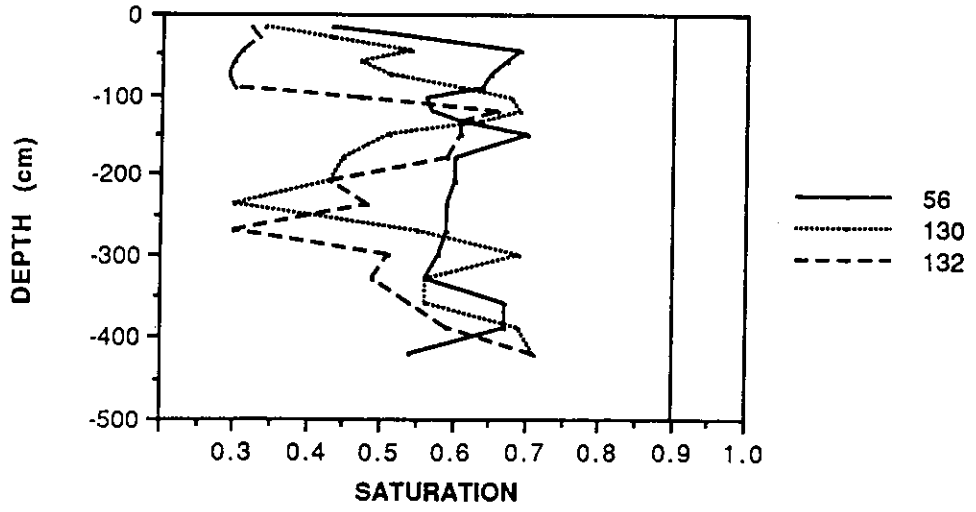


Figure 17. Profiles of dry upland sites at Vesta Mine showing proportion saturation as a function of depth.

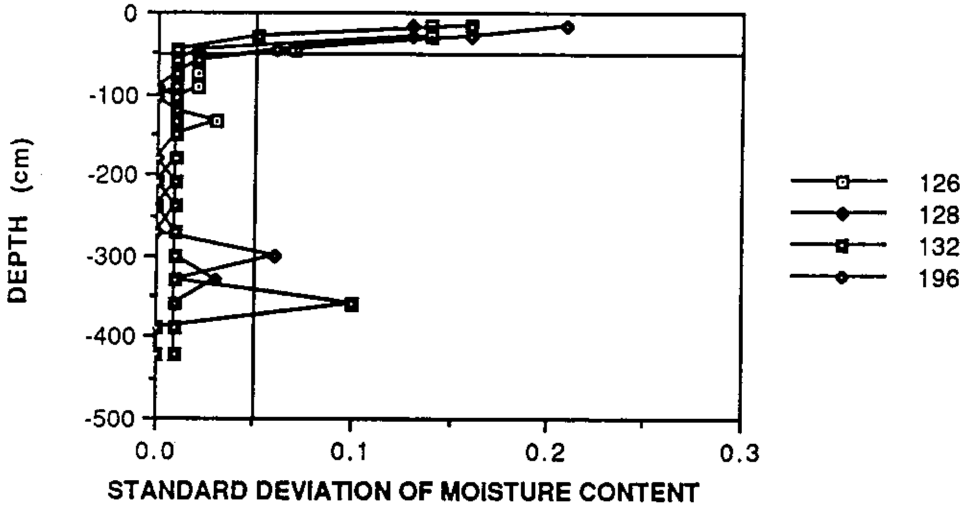


Figure 18. Profiles of inactive upland sites Vesta Mine showing standard deviation of water content as a function of depth. Inactive sites are those at which annual fluctuations in soil water content extend to less than 45 cm.

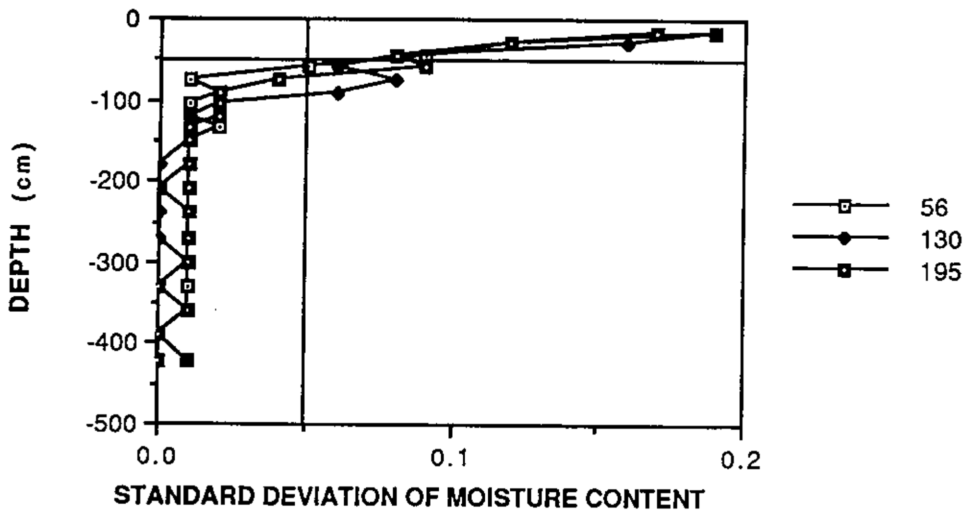


Figure 19. Profiles of active upland sites Vesta Mine showing standard deviation of water content as a function of depth. Active sites are those at which annual fluctuations in soil water content extend deeper than 45 cm.

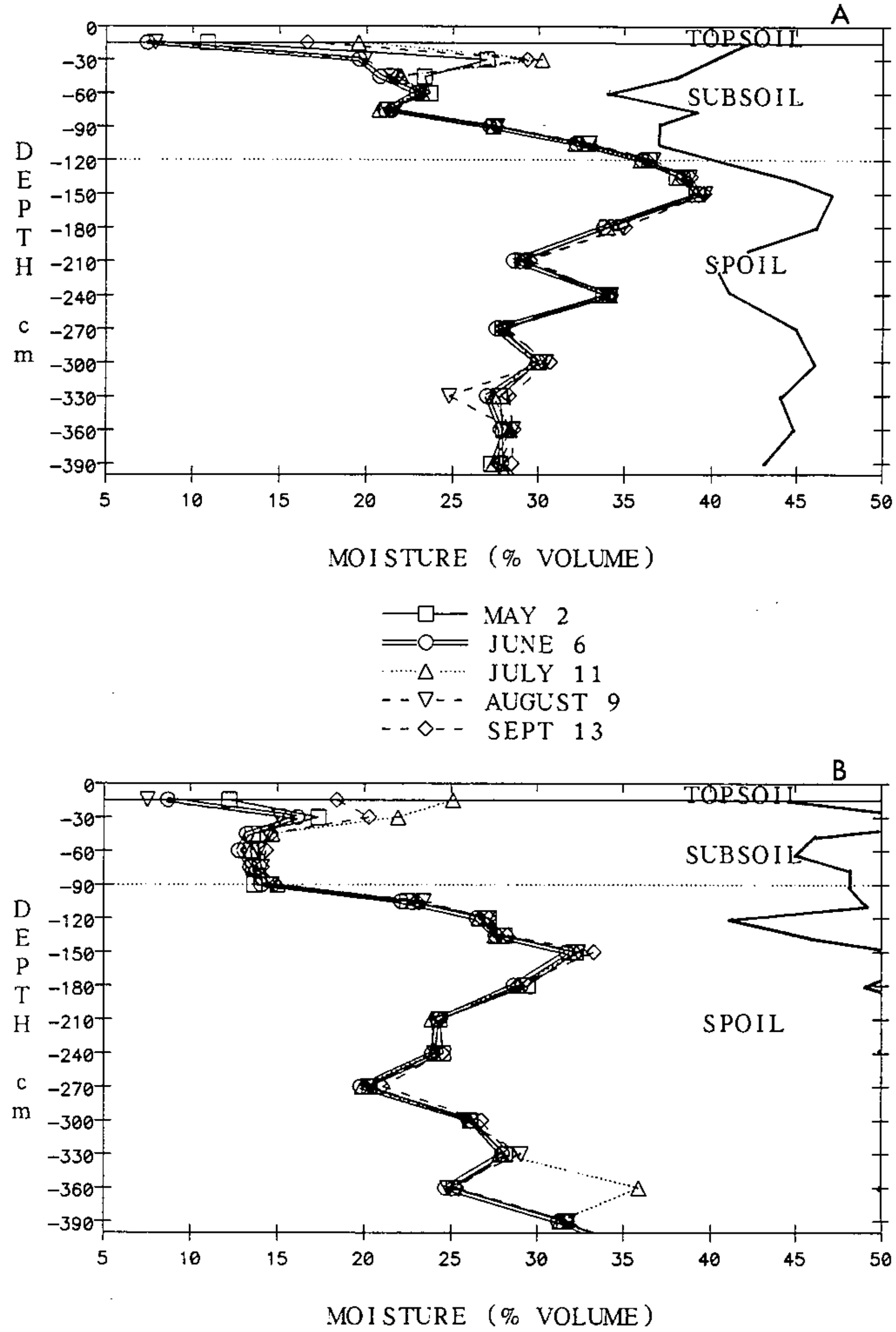


Figure 20. Soil moisture profiles for sites A) BR128 and B) BR132 at Vesta Mine showing volumetric moisture content as a function of depth. Solid line represents moisture at saturation.

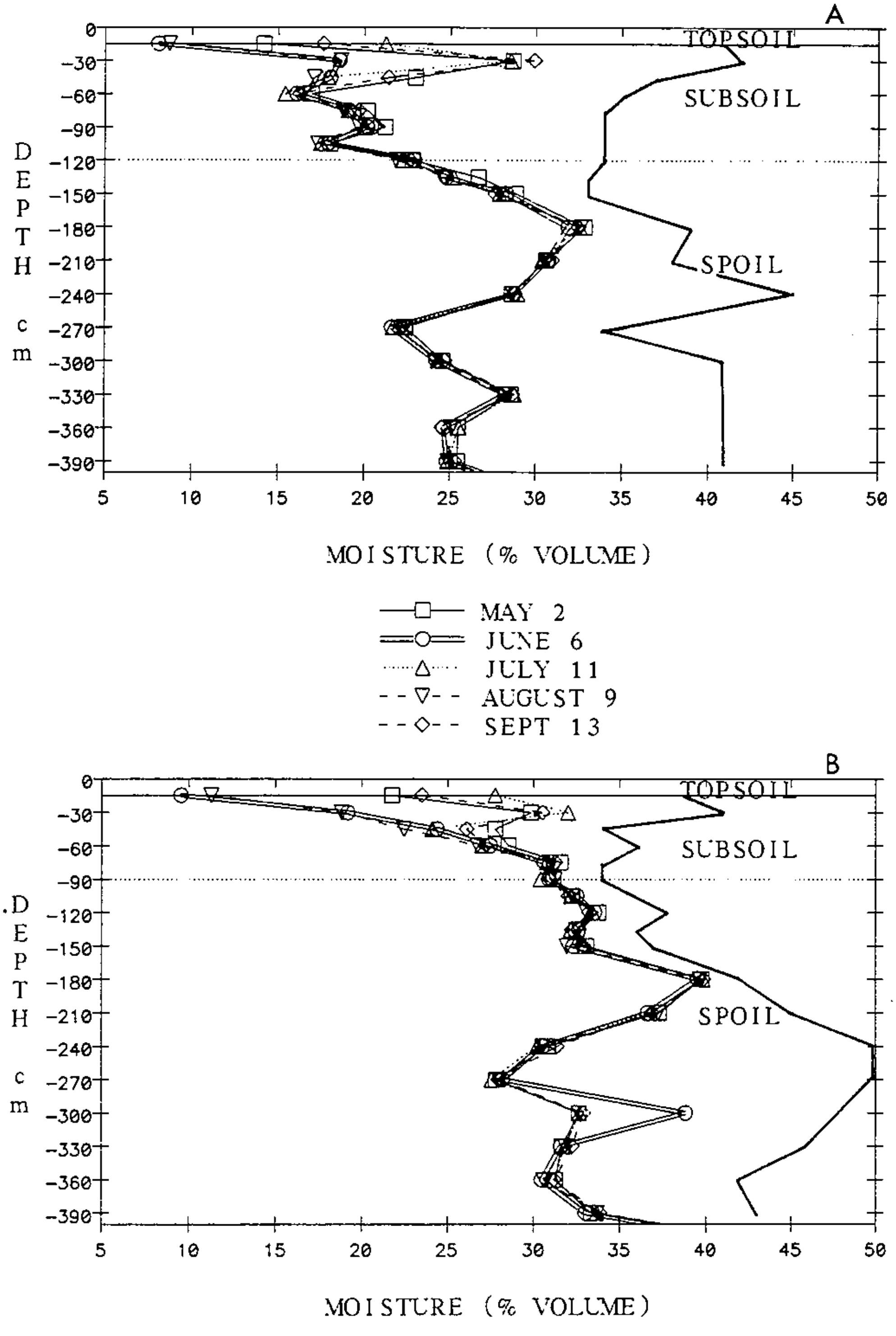


Figure 21. Soil moisture profiles for sites A) BR126 and B) BR196 at Vesta Mine showing volumetric moisture content as a function of depth. Solid line represents moisture at saturation.

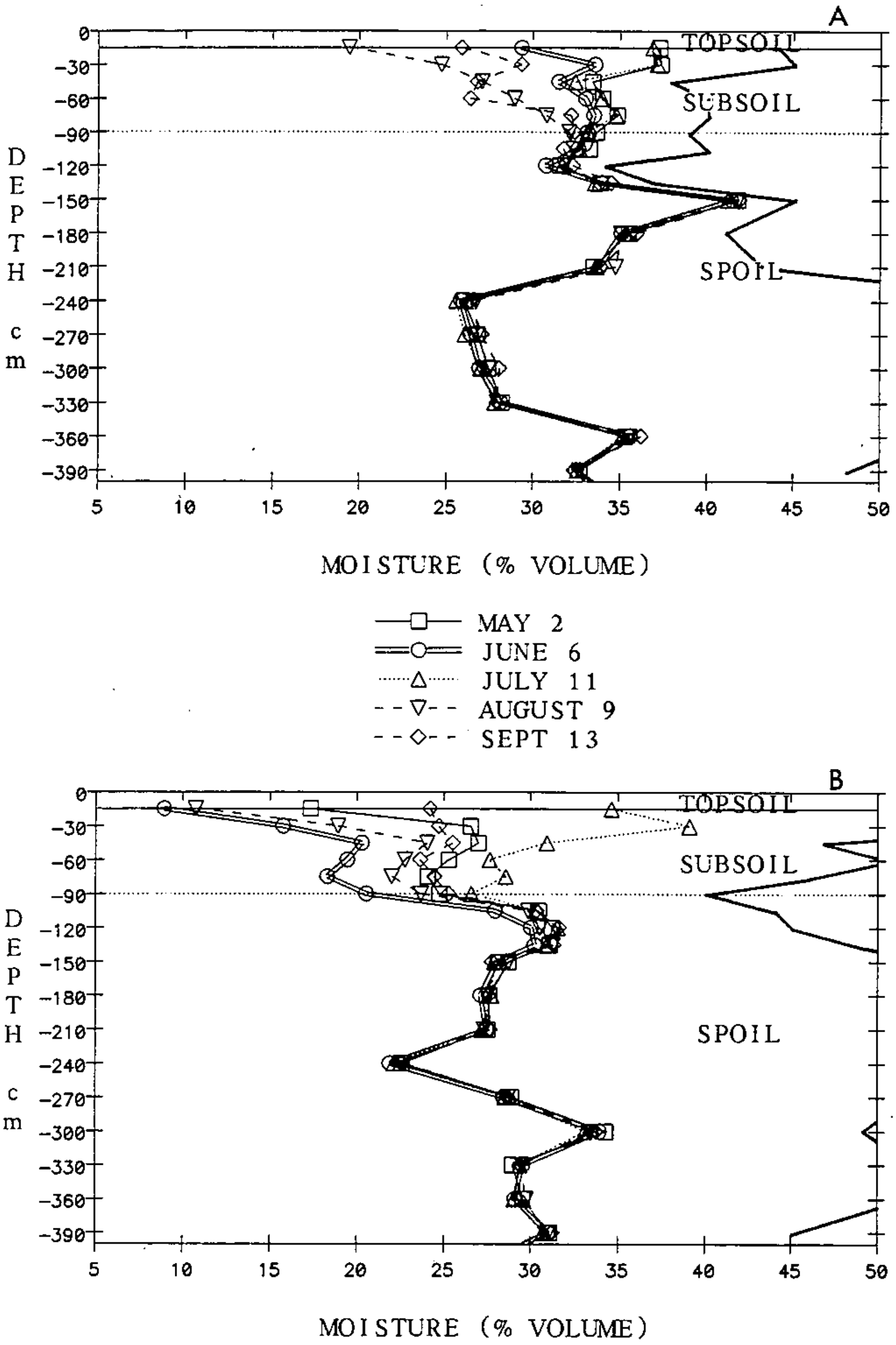


Figure 22. Soil moisture profiles for sites A) BR195 and B) BR130 at Vesta Mine showing volumetric moisture content as a function of depth. Solid line represents moisture at saturation.

BR126 was below wilting point throughout the entire thickness of subsoil; only at the base of the subsoil, at a depth of 120 cm, did the moisture content reach wilting point (Figure 21). The only exception to this was the 30 cm sample, which was above wilting point in May, July, and September. Site BR132 was below wilting point throughout the entire thickness of subsoil to a depth of 90 cm (Figure 20). At sites BR128, and BR130 the entire profile was above wilting point in May and July. At BR128, the profile was at or above wilting point from 45 cm and 60 cm downward, respectively, in June, August and September. BR130 dried to below wilting point to a depth of 90 cm in June, but was at or above wilting point below a depth of 45 cm in August. In September this site was above wilting point throughout the profile.

At site BR195, the entire profile was above wilting point on all monitoring dates (Figure 22). At BR196, the same was true, except for the 30 cm interval, which dried to wilting point in June and August (Figure 21).

2.3.2 Groundwater Conditions.

Piezometer nests monitored groundwater conditions in five separate upland settings. This section presents water-level data from monitoring of these sites. The interpretation of these data is discussed in section 3.2.3.

2.3.2.1 East Vesta Site. Nests BR130, BR131, and BR132 are in the eastern part of Vesta Mine, which was completely dry with no surface ponding (Figure 5). All piezometers at nests BR130, BR131, and BR132 have been dry since their installation in the fall of 1984.

2.3.2.2 West Vesta Site. Nests BR125, BR126, BR127, BR128, and BR129 are in the western part of Vesta Mine, which contains limited, small, ephemerally-ponded, subsidence depressions. These five nests are about 750 m south of the large lowland pond S20 (Figure 4). The five piezometer nests in this site behaved quite differently, even though they are relatively close together (Figure 4). At nests BR125 and BR129, the deepest well indicated saturated conditions with a rising head throughout the monitoring period (Figures 23 and 24). At nest BR127, the two deepest wells indicated saturated conditions with a rising head throughout the monitoring period (Figure 25). The head difference between the two wells suggests upward flow. At these three nests, the head was relatively consistent, ranging between 721.42 m at BR129-1 and 722.1 m at BR127-1. At nest BR128 the two deepest wells indicated saturated conditions with a rising head in the deeper well and a falling head in the shallower well throughout the monitoring period (Figure 26). The head at this nest was from 1 m to 3 m above that at the previous three nests. The deepest well at BR126, was dry at a level about 5 m lower

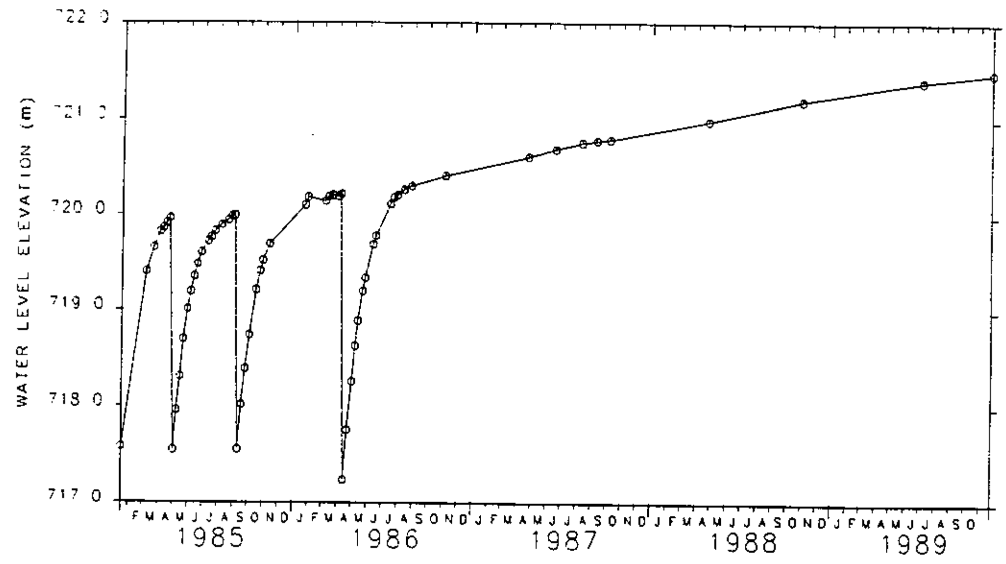


Figure 23. Water-level hydrograph for well BR125-1 at Vesta Mine showing rising head at the base of the spoil. The abrupt drops in head represent collection of water samples or hydraulic conductivity testing.

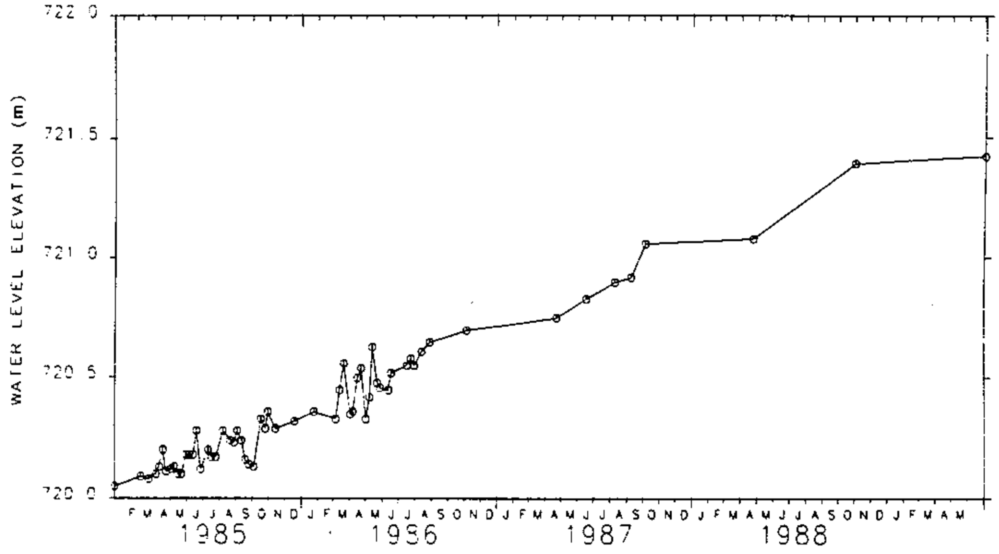


Figure 24. Water-level hydrograph for well BR129-1 at Vesta Mine showing rising head at the base of the spoil.

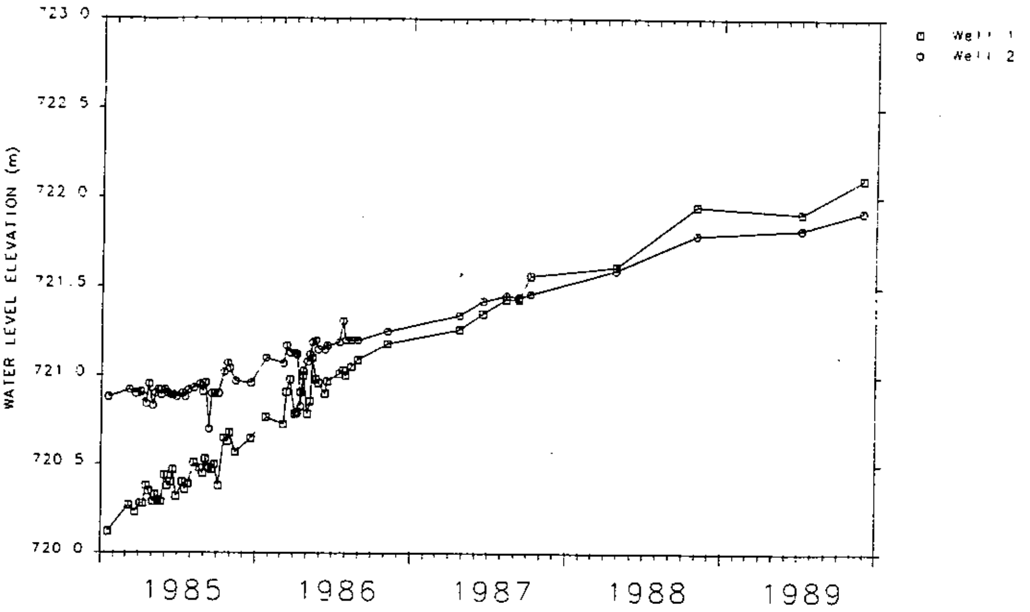


Figure 25. Water-level hydrograph for wells at BR127 at Vesta Mine showing rising head at the lower part of the spoil.

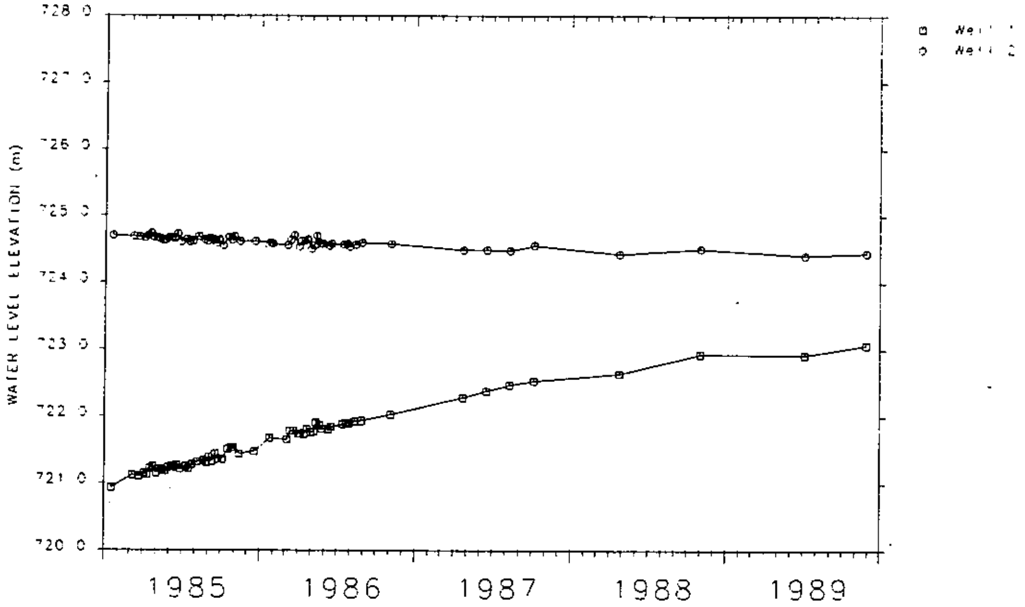


Figure 26. Water-level hydrograph for wells at BR128 at Vesta Mine showing rising head at the base of the spoil and declining head higher in the spoil.

than the other wells in the nest. The middle well indicates saturated conditions with a stable head at a level 2.25 m to 5.5 m higher than at the other wells in this site. The deepest well was initially saturated, but the level declined steadily over a period of 2 years until the well became dry in April, 1987 (Figure 27).

The piezometer nests at the west Vesta site do not present a coherent, interpretable pattern. The changes in head at sites BR125, BR127, and BR129 over time are consistent with an interpretation that the primary source of saturation of the spoil is by lateral flow southward from pond S20 (Figure 4). Nest BR128 suggests downward flow, but with saturated conditions considerably higher in the spoil than at the other three sites. Nest BR126 indicates perched saturated conditions about 10 m above the base of the spoil, which is unsaturated. Numerous zones of saturated sand were encountered during the drilling of these sites, and likely the variability in the hydrologic conditions in this area is a reflection of these sand bodies.

2.3.2.3 Vesta Berm Site. Nests BR52 and BR53 are situated on the elevated berm along the western edge of Vesta Mine, about 500 m southwest of pond S20 (Figure 4). The two piezometer nests in this site exhibited behavior that was different from the other sites. At both BR52 and BR53 the head at the base of the spoil rose throughout the monitoring period (Figures 28 and 29). The shallower wells that indicated saturated conditions, indicated declining heads during the monitoring period. At both nests, the hydraulic gradient was consistently downward.

These data have been interpreted to reflect strong leakage from the ponds to the north of these sites (Figure 4) during the first few years following reclamation (Moran et al. 1989a). Over time, the hydraulic conductivity of the spoil is believed to have decreased resulting in a decrease in the rate of pond leakage and groundwater recharge.

2.3.2.4 Perched Pond Site. Nests BR195 and BR196 are located adjacent to the large upland perched pond, S195 (Figure 4). Nest BR196 exhibited behavior like the nests at the east Vesta site; all wells were dry throughout the monitoring period. At nest BR195, the middle three wells, which were completed at 4.0 m, 9.5 m, and 14.5 m were dry throughout the monitoring period. The head in the deepest well, which was completed at the base of the spoil at 20.5 m, declined steadily from about 719.2 m in September and October, 1987 to about 718.5 m at the end of December, 1989 (Figure 30). The shallowest well in this nest, which was completed in the uppermost part of the spoil at a depth of 1.1 m to 1.4 m, displayed seasonal fluctuation in head values (Figure 31). In both 1988 and 1989, the spring melt was marked by head values very close to the land surface (Figure 31). Recession from these annual maximum values was

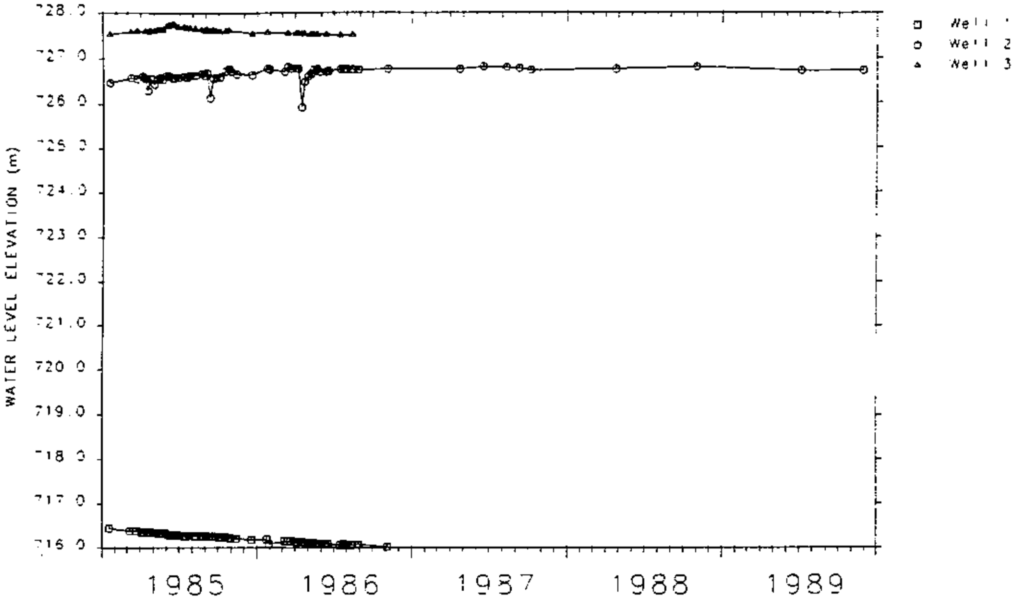


Figure 27. Water-level hydrograph for wells at BR126 at Vesta Mine showing declining head at the base of the spoil and rising head higher in the spoil.

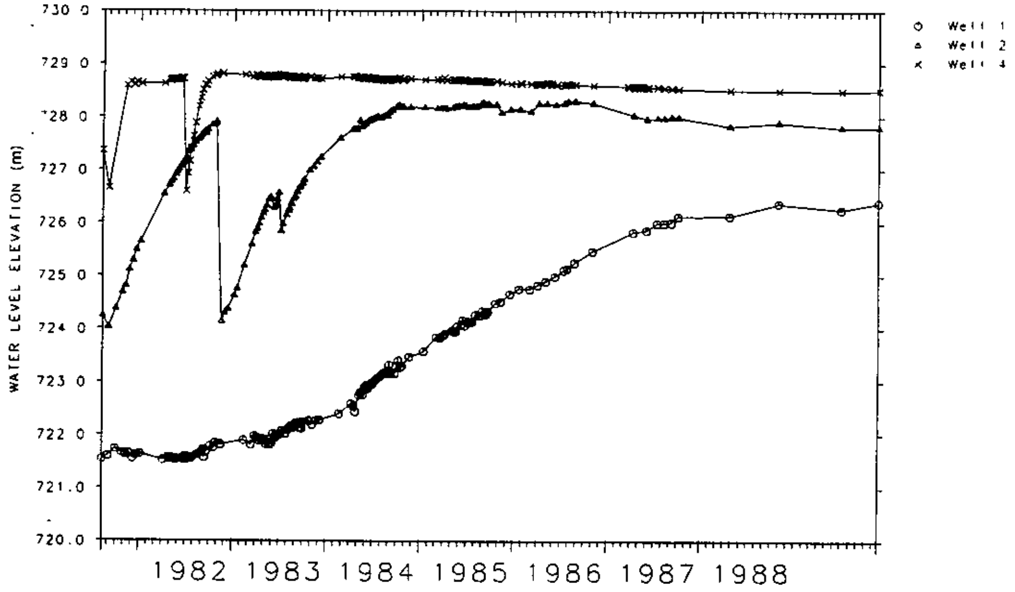


Figure 28. Water-level hydrograph for wells at BR52 at Vesta Mine showing rising head at the base of the spoil and declining heads higher in the spoil. The abrupt drops in head represent collection of water samples or hydraulic conductivity testing.

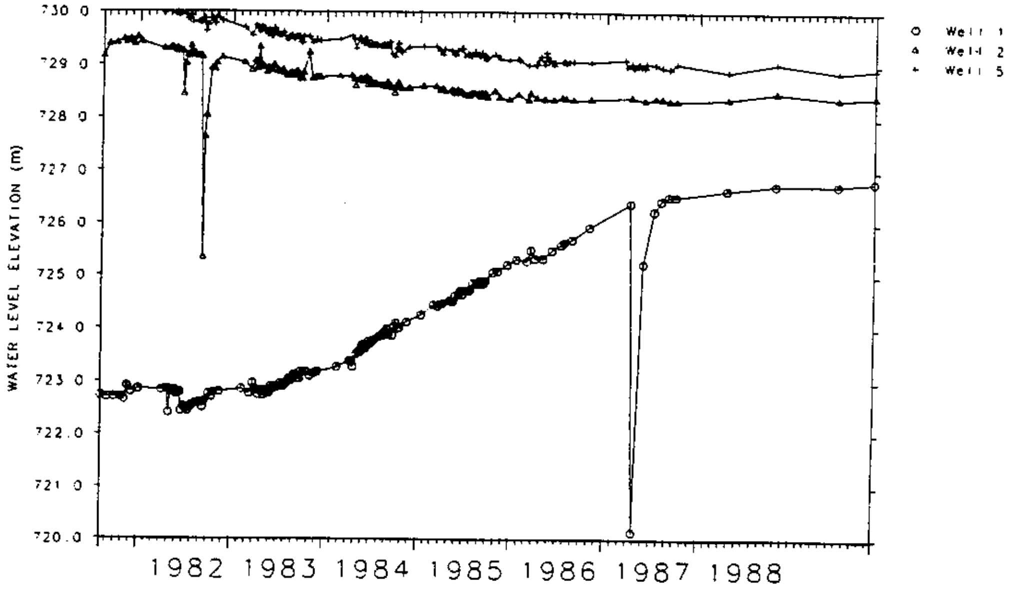


Figure 29. Water-level hydrograph for wells at BR53 at Vesta Mine showing rising head at the base of the spoil and declining heads higher in the spoil. The abrupt drops in head represent collection of water samples or hydraulic conductivity testing.

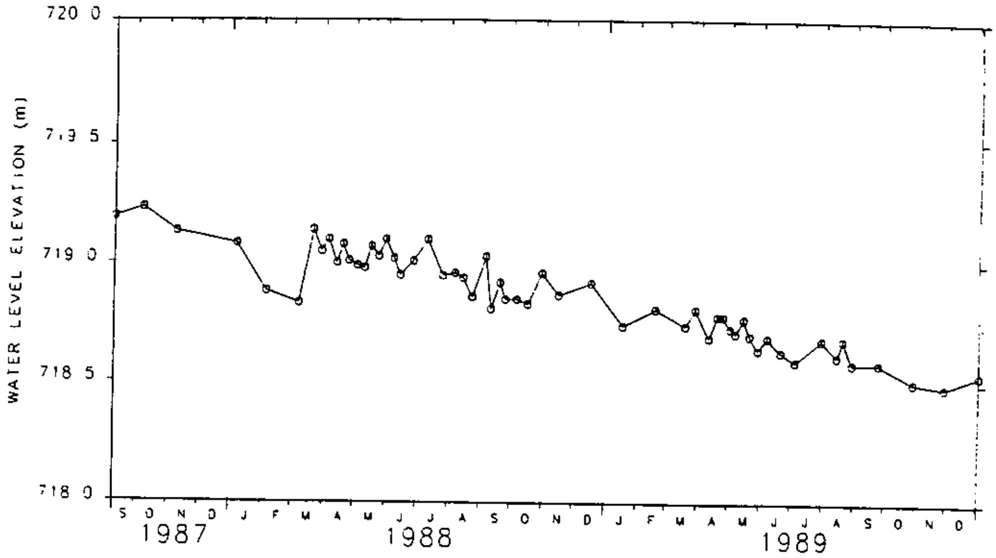


Figure 30. Water-level hydrograph for well BR195-1 at Vesta Mine showing declining head at the base of the spoil.

interrupted by heavy rain storms in June and July, 1988 and in May and July, 1989. By January of both years the head had dropped below the screened interval.

2.3.2.5 Paintearth Mine Site. Nests BR91, BR92, BR140, BR141, and BR142 are located in Paintearth Mine (Figure 3) in a setting very similar to the east Vesta Site. With the exception of a single nest, BR141, all the piezometer nests at Paintearth Mine exhibited behavior like the wells at the east Vesta site, being dry throughout the period of observation. The deepest well at nest BR141, which was completed at a depth of 16.5 m, indicated that the lower three metres of the spoil have been saturated since early 1987.

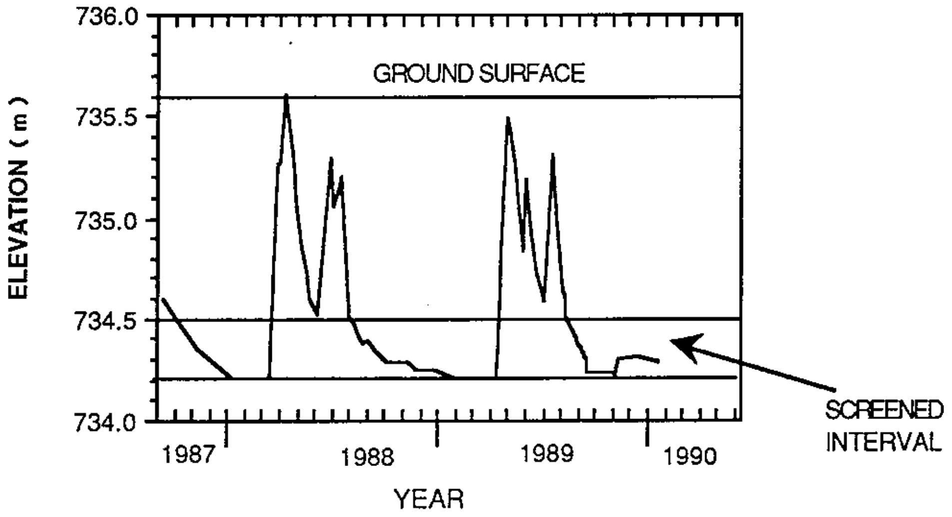


Figure 31. Hydrograph of piezometer BR195-5, which is completed in the upper part of the spoil.

2.4 PHYSICAL PROPERTIES OF SUBSOIL AND SPOIL

2.4.1 Description

Numerous soil pits and hydraulic probe samples in the vicinity of pond S195 have been examined in the course of this investigation. On the basis of these observations the following generalizations can be drawn regarding the physical characteristics of topsoil, subsoil, and spoil materials at the site.

The topsoil layer had a remarkably consistent 15 cm thickness (Figure 32). The subsoil was a mixture of till-derived and sand-derived material. So much sand was encountered in the preliminary drilling for installation of nest BR196 on the north side of the pond that the initial design was altered and the nest was moved to its present location on the south side of the pond. Although in some places the composition of the subsoil was entirely sand, in the majority of sites investigated the subsoil consisted entirely of till or till overlying sand (Figure 32). The composition of the subsoil changed abruptly and unpredictably over lateral distances of a few metres. On the basis of data that are reported below, the sand had hydraulic conductivity values that were characteristic of till. It appears that the sand occurred as discontinuous pods and lenses contained within a matrix of till. The till was very dense and generally strongly laminated, with the laminations parallel to the land surface. The material generally had the visual appearance of compacted fill.

The top of the spoil was highly compacted and generally appeared saturated with water. Beneath this upper, compacted appearing crust, the spoil was loose and dry. These visual observations of the characteristics of the material in the vicinity of pond S195 are consistent with the data on density and hydraulic conductivity.

2.4.2 Density

Conclusions regarding density of reclaimed landscapes in east-central Alberta were based on data from 9 unmined sites in the Battle River area and 10 reclaimed sites, 7 at Vesta Mine and 3 at Diplomat Mine. The majority of the density profiles from Vesta Mine indicate the presence of zones of higher density within the subsoil and upper spoil. At sites BR126, BR132, and BR195 the zone of highest density occurred in the upper 15 to 45 cm of the spoil, at depths of 120 to 150 cm beneath the surface (Figure 33). At sites BR130 and BR196, the maximum density occurred at the interface between the spoil and subsoil, about 90 cm beneath the surface (Figure 34). More compacted zones occurred within the subsoil at depths of 75 cm at BR56 (Figure 35), 60 cm and 90 to 105 cm at BR128 (Figure 35), 45 to 60 cm at BR132 (Figure 33), and 45 cm at BR195 and BR196 (Figures 33 and 34). These higher density zones were

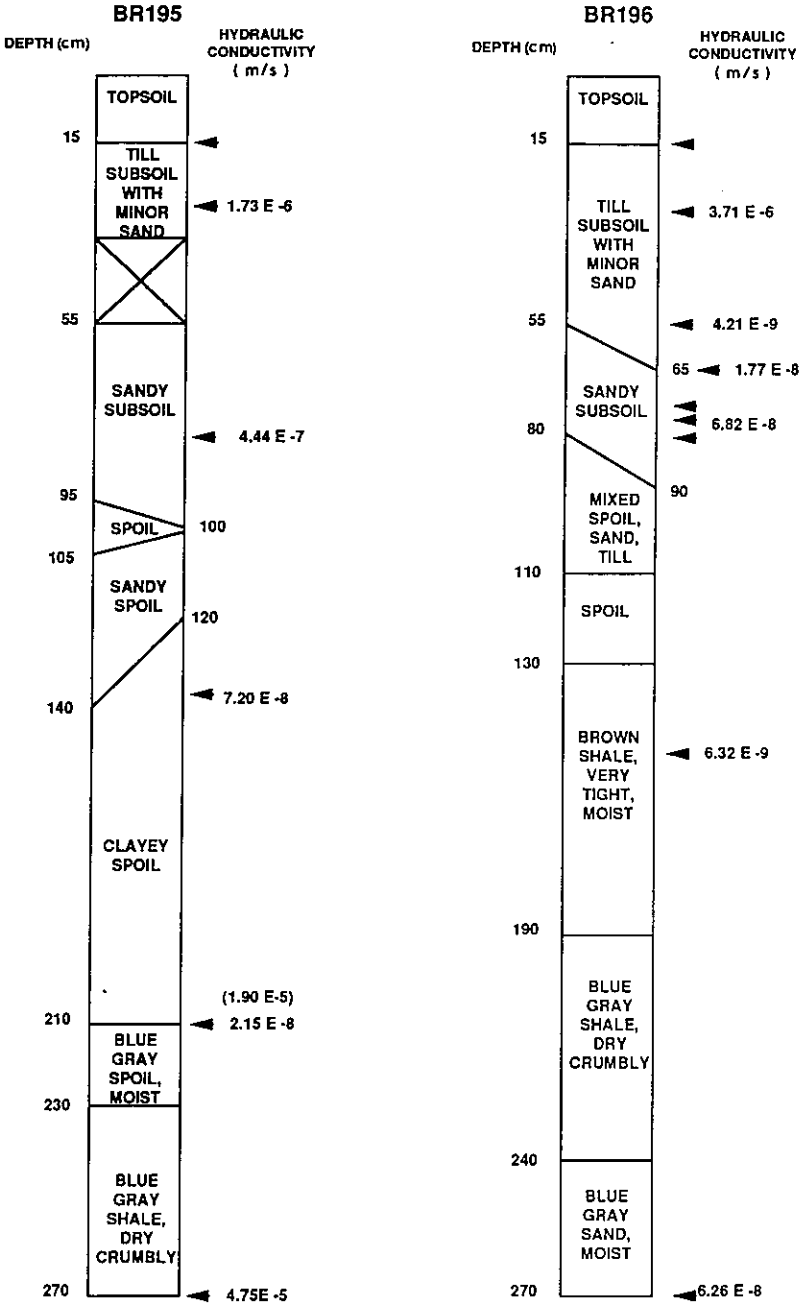


Figure 32. Profile descriptions of material encountered in borings used for hydraulic conductivity testing. Hydraulic conductivity value in parentheses is initial test result at that depth. Each column summarizes three borings

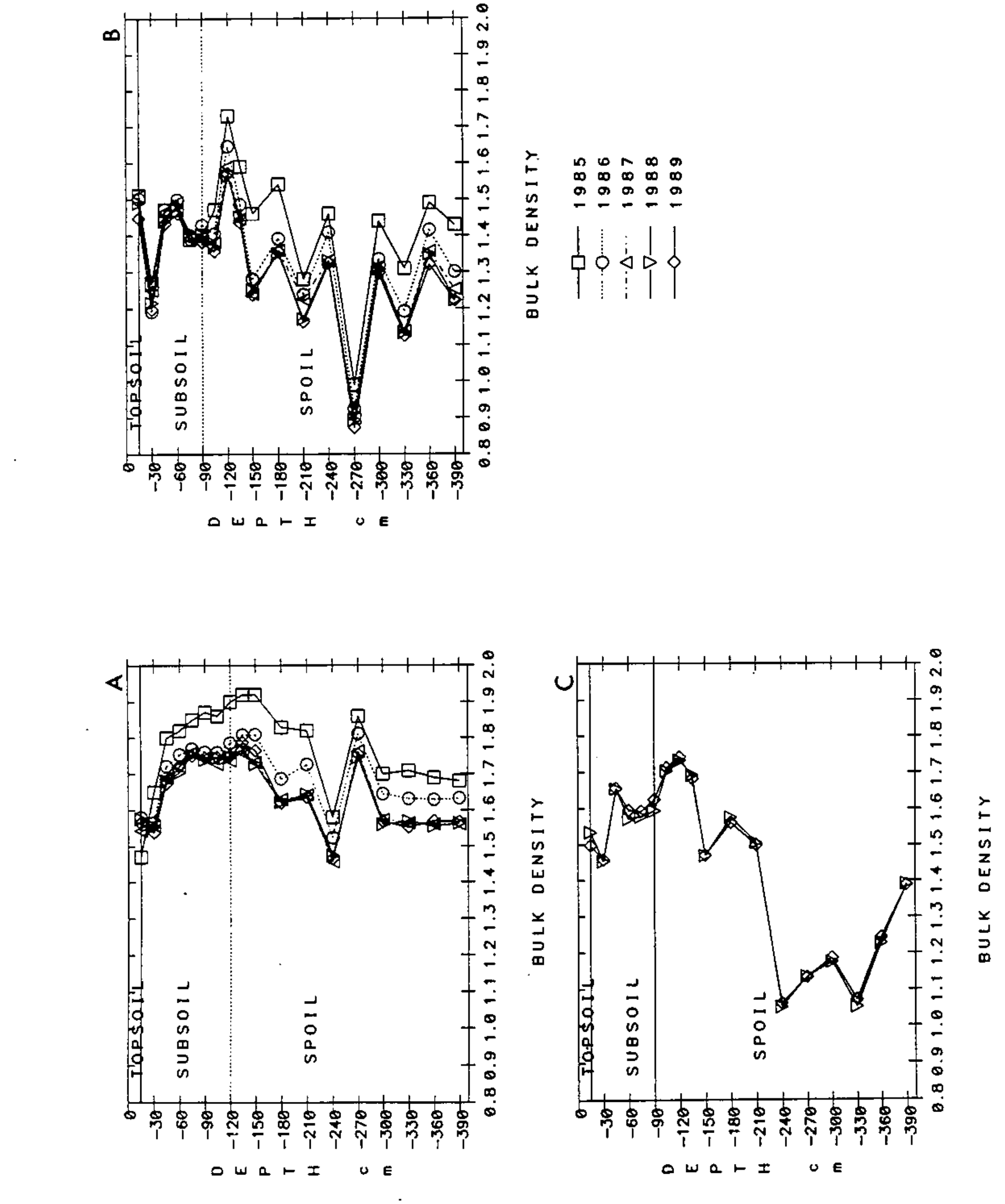


Figure 33. Bulk density profiles for sites A) BR126, B) BR132 and C) BR195 at Vesta Mine showing density as a function of depth. Values are the mean of all determinations each year.

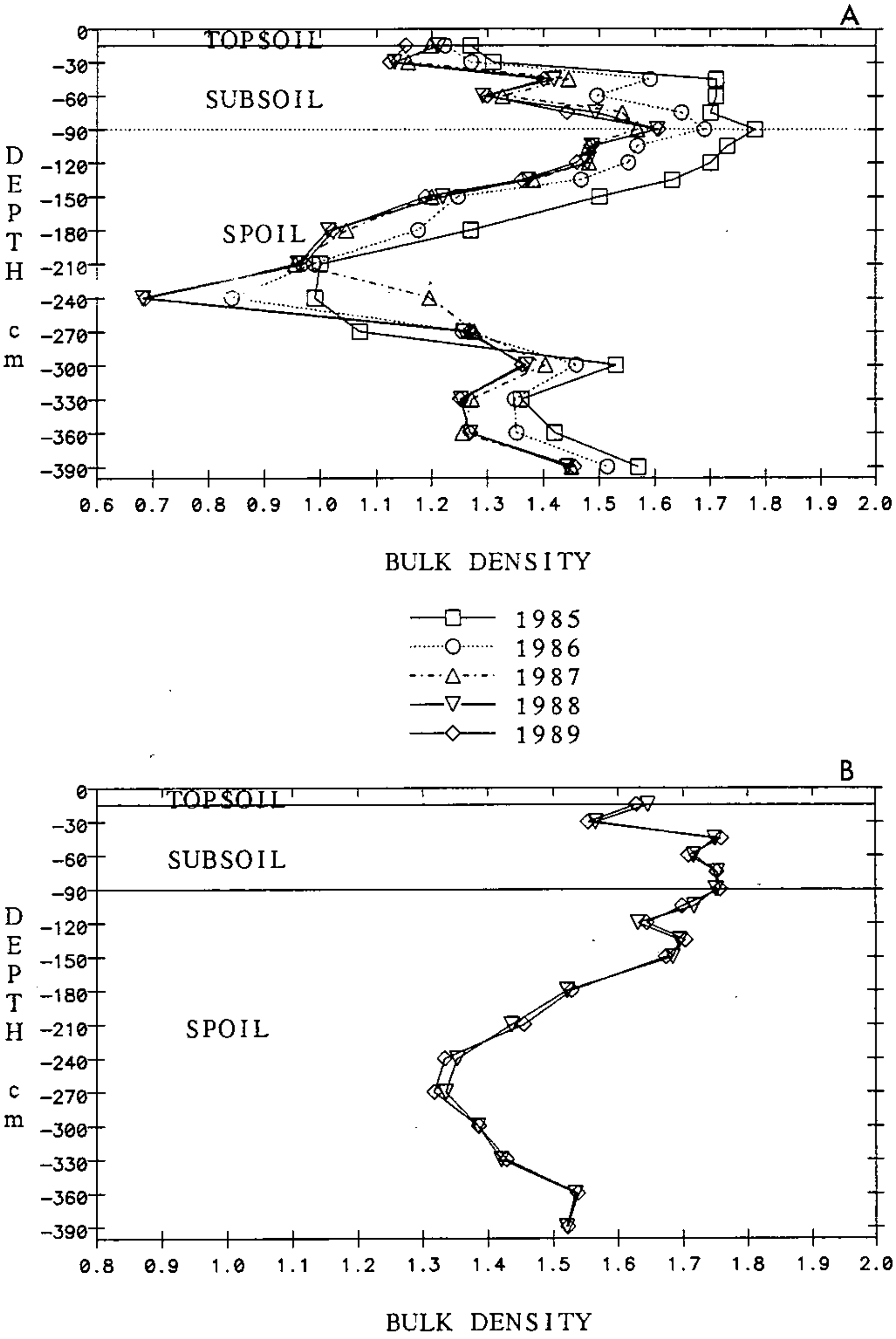


Figure 34. Bulk density profiles for sites A) BR130 and B) BR196 at Vesta Mine showing density as a function of depth. Values are the mean of all determinations each year.

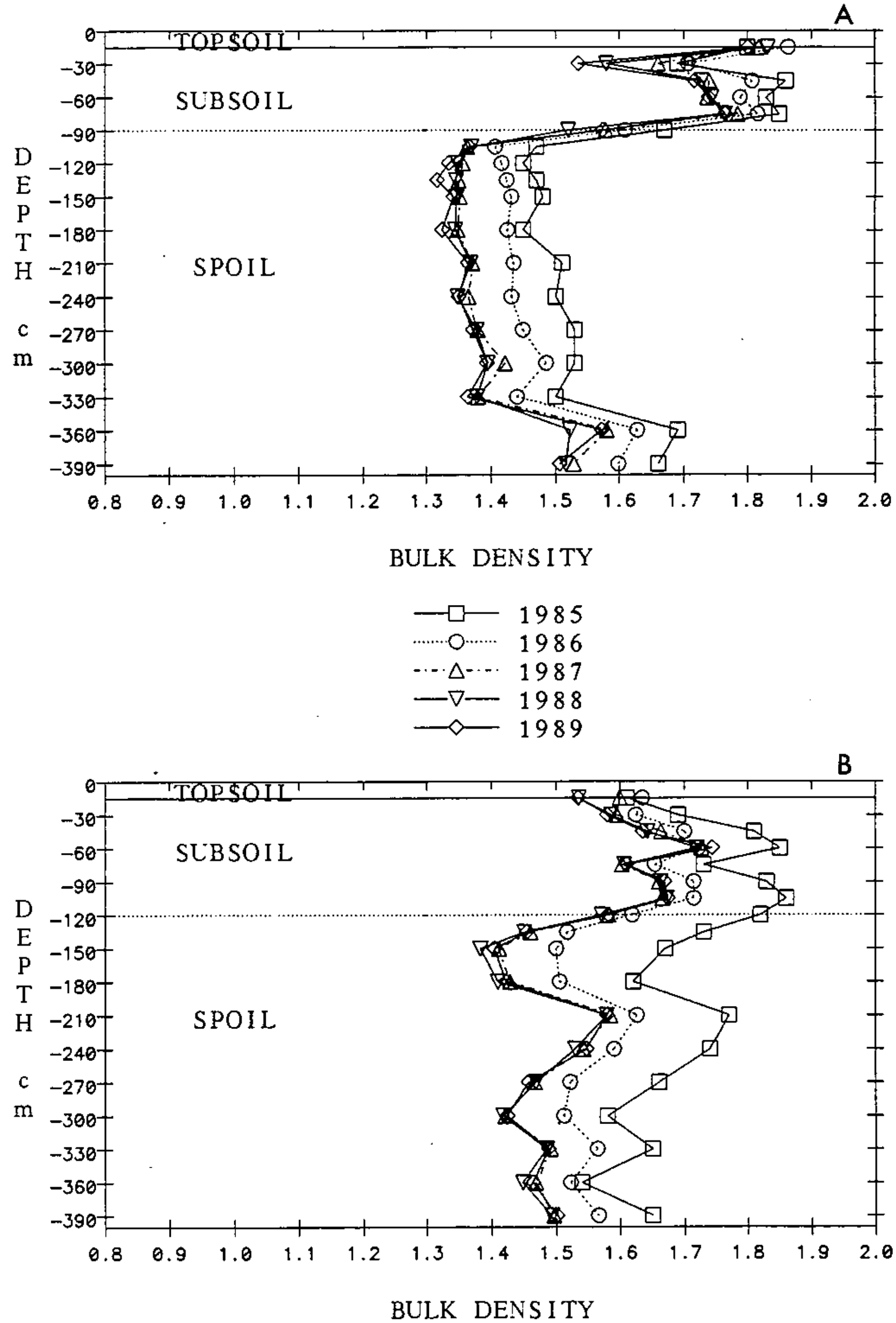


Figure 35. Bulk density profiles for sites A) BR56 and B) BR128 at Vesta Mine showing density as a function of depth. Values are the mean of all determinations each year.

believed to reflect compaction during the grading process. The zone of annual fluctuation in soil moisture at several sites corresponded to the interval above one of these density barriers. At sites BR128 and BR132, changes in soil moisture extended to a depth of 45 cm, just above zones of higher density at 60 cm.

2.4.3 Hydraulic Conductivity

The hydraulic conductivity of subsoil and the uppermost part of the spoil at two locations near pond S195 was remarkably consistent (Table 5). At nest BR195, six determinations of hydraulic conductivity of the predominantly till-derived subsoil at a depth of 30 cm were made in three separate boreholes. The values ranged from 3.3×10^{-6} to 5.5×10^{-7} m/s with a mean of 1.73×10^{-6} m/s (Figure 32, Table 5). At 80 cm, the sandy subsoil material was even less variable in six determinations from three boreholes. Hydraulic conductivity ranged from 2.4×10^{-7} to 7.3×10^{-7} m/s with a mean of 4.44×10^{-7} m/s (Figure 32, Table 5). Dense clayey spoil at 135 cm had a hydraulic conductivity of 7.2×10^{-8} m/s. The loose, low density spoil at 270 cm had the highest hydraulic conductivity values at the site of 4.75×10^{-5} m/s. The moderately dense spoil at 210 cm had an initial hydraulic conductivity value of 1.9×10^{-5} m/s but after being saturated for a period of time, yielded the lowest values at the site, 3.3×10^{-8} m/s (Figure 29).

Nest BR196 gave similar results but values were generally lower at this nest than at BR195 (Figure 32, Table 6). Till-derived subsoil was sampled at three depths, 30 cm, 55 cm, and 65 cm. Hydraulic conductivity values of 3.71×10^{-6} m/s at 30 cm were appreciably greater than the values deeper in the profile. The till derived subsoil at 55 cm gave values of 4.21×10^{-9} m/s. Till derived subsoil with a minor admixture of sand at 65 cm yielded values about one order of magnitude larger at 1.77×10^{-8} m/s. Sandy subsoil material, which contained only minor amounts of till, was sampled in three tests that yielded hydraulic conductivity values between 1.21×10^{-7} m/s at 75 cm and 3.16×10^{-8} m/s at 80 cm. Two tests in spoil yielded values of 6.32×10^{-9} m/s at 150 cm and 6.26×10^{-8} m/s at 270 cm.

2.5 SALT AND SODIUM STATUS OF SUBSOIL AND SPOIL

Saturation extract analyses are available for sites BR195 and BR196 from 1987 and 1989. We first describe the characteristics of the data for BR195 and BR196 in 1989 in reference to soil quality standards. Changes in characteristics of these two sites between 1987 and 1989 are then discussed.

Table 5. Summary of hydraulic conductivity test data for site BR195 during 1989.

			BR195		
DEPTH (cm)	MATERIAL	K VALUE	MEAN	LOG MEAN	STDEV
15	TOPSOIL	3.20E-7			
15	TOPSOIL	5.20E-6	1.29E-6	-5.889	0.856
30		3.30E-6			
30		1.70E-6			
30	TILL	5.50E-7			
30	SUBSOIL	3.00E-6			
30		1.90E-6			
30		1.50E-6	1.73E-6	-5.763	0.279
80		3.20E-7			
80		4.90E-7			
80	SANDY	4.30E-7			
80	SUBSOIL	2.40E-7			
80		6.50E-7			
80		7.30E-7	4.44E-7	-6.352	0.183
135	CLAYEY	7.20E-8			
135	SPOIL	2.00E-6			
210		1.90E-5			
210	CLAYEY	3.30E-8			
210	SPOIL	1.40E-8	2.15E-8	-7.668	0.263
270	CLAYEY	6.10E-5			
270	SPOIL	3.70E-5	4.75E-5	-4.323	0.154

Table 6. Summary of hydraulic conductivity test data for site BR196 during 1989.

		BR196			
DEPTH (cm)	MATERIAL	K VALUE	MEAN	LOG MEAN	STDEV
15	TOPSOIL	5.50E-7			
15	TOPSOIL	2.60E-6	1.20E-6	-5.922	0.477
30	TILL	3.20E-6			
30	SUBSOIL	4.30E-6	3.71E-6	-5.431	0.091
55	TILL	7.10E-9			
55	SUBSOIL	2.50E-9	4.21E-9	-8.375	0.321
65		1.30E-7			
65		5.30E-9			
65	SANDY	3.00E-8			
65	SUBSOIL	4.40E-9			
65		1.90E-8	1.77E-8	-7.752	0.601
73	SANDY	1.20E-7			
73	SUBSOIL	5.80E-8	8.34E-8	-7.079	0.223
75	SANDY	1.50E-7			
75	SUBSOIL	9.70E-8	1.21E-7	-6.919	0.134
80	SANDY	7.70E-8			
80	SUBSOIL	1.30E-8	3.16E-8	-7.500	0.546
150	CLAYEY	2.50E-8			
150	SPOIL	1.60E-9	6.32E-9	-8.199	0.844
270	SANDY	5.30E-8			
270	SPOIL	7.40E-8	6.26E-8	-7.203	0.102

The soil quality standards for disturbance and reclamation that have been proposed for Alberta, include EC and SAR among the parameters to be measured (Soil Quality Criteria Working Group 1987) (Table 7). The upper bounds of EC and SAR that are recognized for the various suitability classes are listed below. Suitability of Fair is defined as: moderate soil limitations that affect use but which can be overcome by proper planning and good management. Suitability of Poor is defined as: severe soil limitations that make use questionable; careful planning and very good management are required. Unsuitable is defined as: chemical or physical properties of the soil are so severe reclamation would not be economically feasible or in some cases impossible.

Table 7. Suitablility ratings for topsoil and subsoil.

Suitability Rating	Fair	Poor	Unsuitable
Topsoil			
Salinity (EC) dS/m	4	8	>8
Sodicity (SAR)	8	12	>12
Subsoil			
Salinity (EC) dS/m	5	10	>10
Sodicity (SAR)	8	12	>12

Similar standards have been incorporated into the agricultural capability rating system proposed for reconstructed soils by Macyk (1987). Table 8 indicates the lower bounds for EC and SAR for a series of capability classes. Soils in Capability Class R3 are defined as having moderately severe limitations that restrict the range of crops or require special conservation practices. Soils in Capability Class R4 are defined as having severe limitations that restrict the range of crops that can be grown or require special conservation practices to overcome, or both. Soils in Capability Class R5 are defined as having very severe limitations that restrict their capability for producing perennial forage crops, but improvement practices are feasible. Soils in Capability Class R6 are defined as being only capable of producing perennial forage crops and improvement practices are not feasible (Macyk 1987).

Table 8. Agricultural capability for reconstructed soils.

Capability Class	Salinity (EC) dS/m	Sodicity (SAR)
R3	2 to 4	8 to 12
R4	4 to 8	12 to 20
R5	4 to 8	12 to 20
R6	8 to 12	20 to 50

Using these criteria as a guideline, we conclude that an EC value of about 4 and an SAR value of about 10 or 12 provide useful thresholds to evaluate the important chemical properties of reconstructed soils.

At nest BR195 four sets of samples were collected through the subsoil. The mean EC values for the entire topsoil and subsoil interval were less than 4.0 dS/m (Figure 36). Only three individual samples met or exceeded this value: one at 4.16 dS/m in the topsoil, and two at 4.0 dS/m and 4.17 dS/m at 30 cm. The SAR in the topsoil ranged from 9.7 to 13.6 with a mean value of 11.5. The maximum SAR values in the subsoil, which occured in the 30 cm sample, range from 12.3 to 17.6. Mean SAR values in the subsoil ranged from about 11 near the base to 15.4 at the top (Figure 36).

The upper 30 cm of the spoil was a mixture of subsoil and spoil material. Mean EC values ranged from 2.56 dS/m to 6.01 dS/m (Figure 36). Mean SAR values ranged from 13.1 to 15.8 (Figure 36). Below 135 cm the spoil material consisted of bedrock derived material that was less saline but highly sodic. The mean EC ranged from 2.04 dS/m to 2.95 dS/m and the SAR ranged from 34.1 to 42.1 (Figure 36).

At nest BR196 the topsoil was characterized by low EC and SAR; mean EC was 0.73 dS/m, mean SAR was 1.1 (Figure 37). The upper part of the subsoil, which included the 30 cm, 45 cm, and 60 cm samples, was characterized by EC values in excess of 4.0 dS/m, with means ranging from 4.19 dS/m at 30 cm to 6.26 dS/m at 45 cm (Figure 37). Mean SAR values ranged from 10.2 to 13.4 (Figure 37). The mean EC values for the lower subsoil interval were less than 4.0 dS/m, with no values at 75 cm or 90 cm in excess of this value (Figure 37). Mean SAR values in the lower subsoil ranged from 13.1 to 14.0 (Figure 37).

The upper part of the spoil from 105 cm to 180 cm was characterized by slightly higher EC values and lower SAR values than below that depth. Mean EC values ranged from 2.66 dS/m to 5.53 dS/m (Figure 37). Mean SAR values ranged from 13.1 to 18.2 (Figure 37).

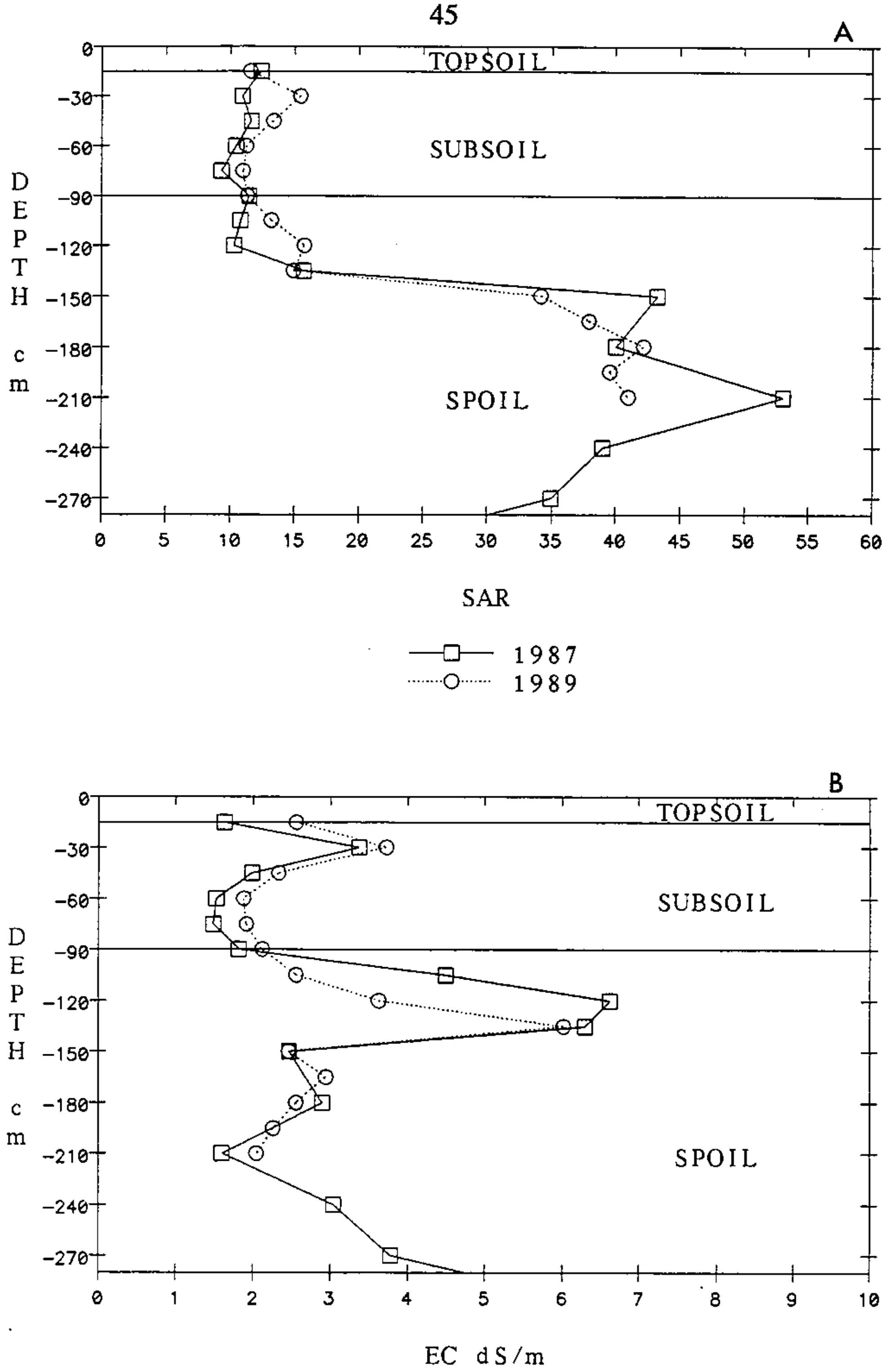


Figure 36. A) Sodium Adsorption Ratio (SAR) and B) Electrical Conductivity (EC) as a function of depth, for site BR195 at Vesta Mine. Values are the mean of all determinations each year.

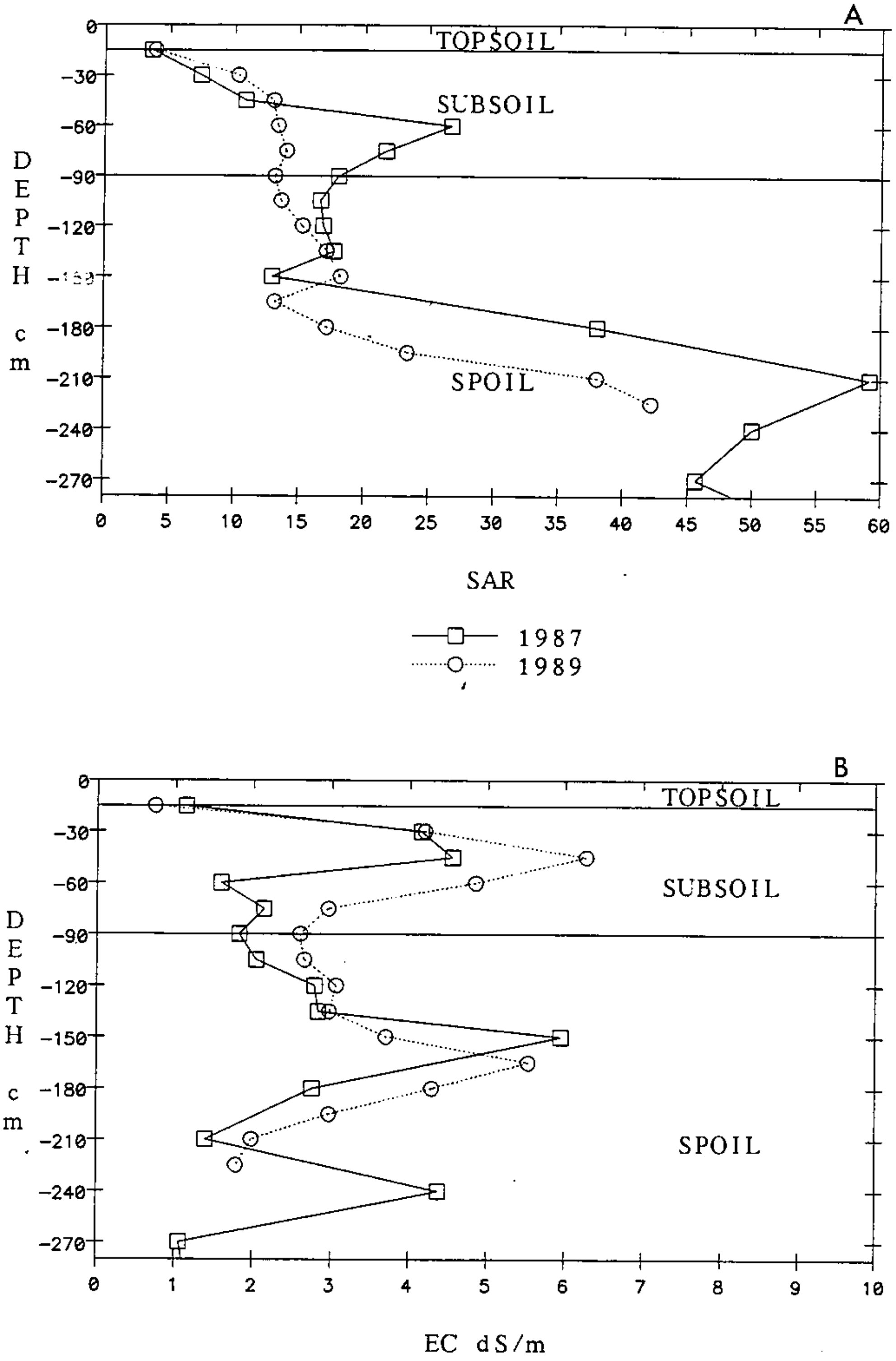


Figure 37. A) Sodium Adsorption Ratio (SAR) and B) Electrical Conductivity (EC) as a function of depth, for site BR196 at Vesta Mine. Values are the mean of all determinations each year.

Below 180 cm, the spoil material consisted of bedrock derived material that was less saline but highly sodic. The mean EC ranged from 1.79 dS/m to 2.98 dS/m and the SAR ranged from 23.3 to 42.1 (Figure 37).

Between 1987 and 1989 the EC value at BR195 increased at every sampling location in the topsoil and subsoil and decreased in the upper part of the spoil at 105 cm, 120 cm, and 135 cm (Figure 38). Similarly, the SAR increased at most levels in the subsoil and the upper part of the spoil (Figure 39). At BR196 the EC value declined in the topsoil at 15 cm and in the spoil at 150 cm. It increased in the lower part of the subsoil, at 45 cm, 60 cm, 75 cm, and 90 cm, and in the upper part of the spoil at 105 cm and 120 cm (Figure 38). The SAR increased in the 30 cm, 45 cm, and 150 cm intervals; SAR decreased in the base of the subsoil, at 60 cm, 75 cm, and 90 cm, and the upper part of the spoil, at 105 cm and 120 cm (Figure 39).

At nest BR195, which is located at the edge of the pond, the increased electrical conductivity (EC) of the topsoil and subsoil combined with the decrease in EC in the upper part of the spoil is indicates upward migration of salt (Figure 36 and 38). The increased SAR in this interval was consistent with this interpretation (Figure 36 and 39). At nest BR196, which is situated about 60 m south of the pond and about 0.40 m higher, the decrease in EC of the topsoil and marked increase in the subsoil reflects leaching at the top of the profile and accumulation at greater depth in the profile (Figure 37 and 39).

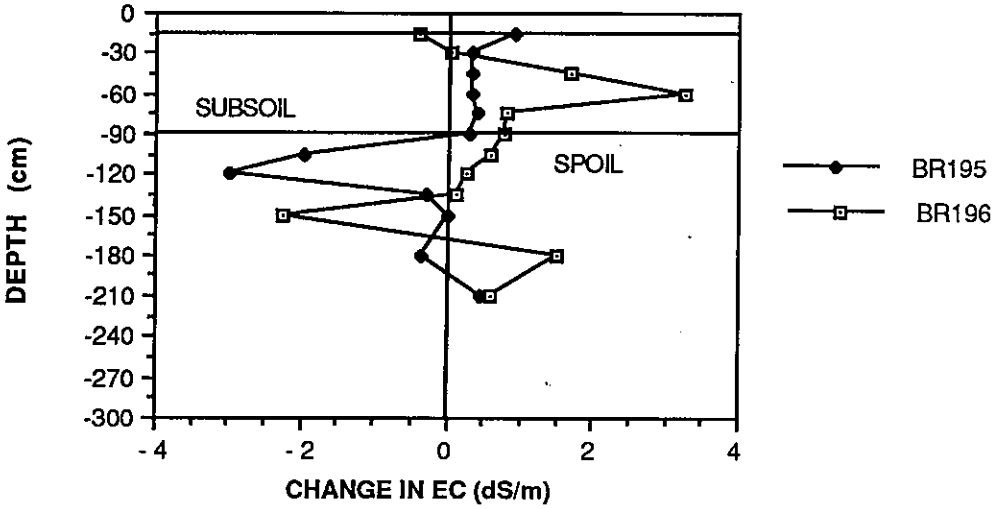


Figure 38. Depth profiles showing change in electrical conductivity (EC) between 1987 and 1989 at sites BR195 and BR196.

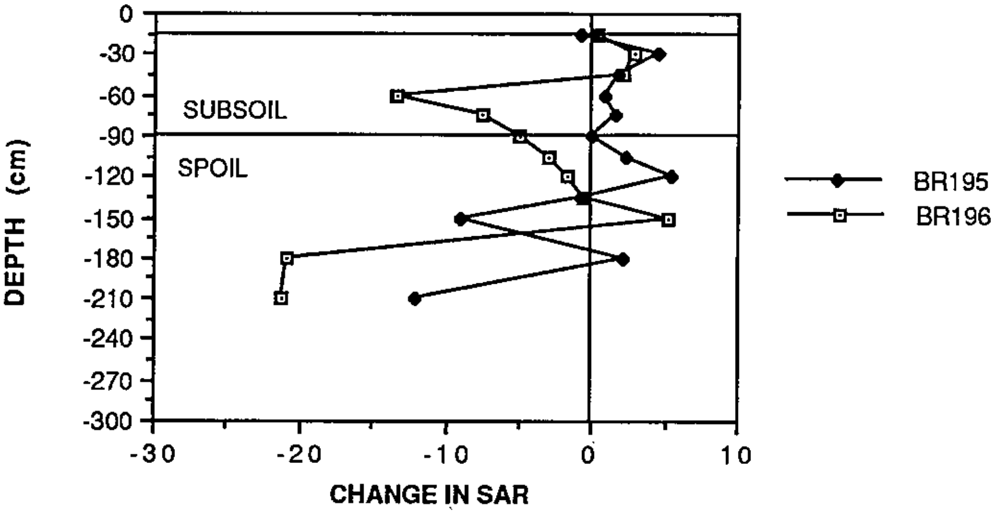


Figure 39. Depth profiles showing change in sodium adsorption ratio (SAR) between 1987 and 1989 at sites BR195 and BR196.

3. DISCUSSION

In this section we address the three questions posed as part of the Objective of the project:

1. Why and how do perched ponds develop in reclaimed landscapes?
2. In what ways do perched ponds alter the agricultural capability of hydrologic upland sites in reclaimed landscapes? and
3. How do perched ponds change in size and character with time?

3.1 FORMATION OF UPLAND PERCHED PONDS

The first factor in the formation of perched ponds is the presence of a low area within the reclaimed landscape. Pond S195 is located in an elongated trough between a 5 m high NE-SW trending ridge to the north and a low, 1 to 2 m high berm along a haul road to the south (Figures 4 and 40). Once the site was reclaimed, this trough began to collect a substantial amount of snowmelt runoff in the spring. In the spring of 1985 and 1986, the area of ponded water was apparently 3 to 5 times larger than the maximum size of the pond in 1988 or 1989. This initial spring ponding was very shallow and as a consequence, was short lived. Water was lost by evaporation and by infiltration.

The lowest part of this original shallow trough was deepened by differential subsidence caused by the infiltrating water. Newly placed and graded cast overburden, which was considerably less dense than the pre-mining overburden, had a loose structure with an initial secondary porosity of about 25 percent of the total volume. As infiltrating water came into contact with the spoil material, the structure of individual fragments collapsed and the spoil quickly lost strength (Dusseault et al. 1988). Through this process, the entire spoil mass compacted, resulting in subsidence of the land surface (Dusseault et al. 1983; 1984a,b,c; 1985). Where this wetting process was concentrated beneath ponded areas, the area-wide subsidence was accelerated and a general lowering of the land surface occurred beneath the broad lowland. Further, differential subsidence resulted in the formation of numerous oval depressions about 10 m by 20 m and as much as 0.5 m deep. These depressions, which typically occupied from five to ten percent of the reclaimed surface, increased infiltration and accelerated differential subsidence by ponding water during spring melt and heavy summer rain storms. As the original low area was deepened through this positive feedback process, the pond that formed each spring became deeper and occupied less area. In 1984, the site was a temporarily ponded portion of a cultivated field (Figure 6). By 1985, the pond had deepened enough to become semi-permanent (Figure 7).

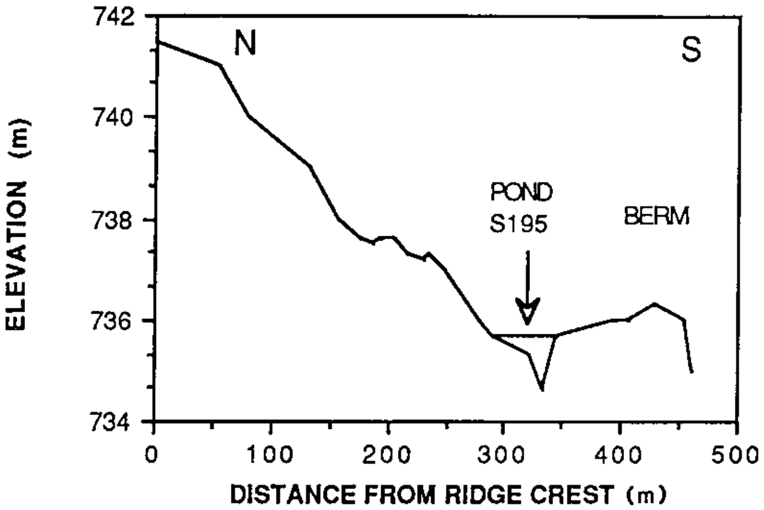


Figure 40. North-south topographic profile across basin that contains pond S195.

The second factor in the formation of a perched pond is the presence of a barrier to prevent rapid loss of water through infiltration. If the base of the depression were sufficiently permeable, any water that accumulated would infiltrate. Thus, the material at shallow depth beneath the depression must be sufficiently low in permeability to prevent rapid infiltration. The data in Table 9 summarize the relationship between hydraulic conductivity and infiltration rates under perched conditions at pond S195, where the hydraulic gradient is 1.0. On the basis of this analysis, it appears that a barrier with hydraulic conductivity values of about 3.0×10^{-8} m/s or less is required to form a semi-permanent perched pond.

Table 9. Infiltration rates from pond S195 as a function of hydraulic conductivity.

Hydraulic Conductivity (m/s)	Infiltration per Year (m)	Days to Infiltrate 0.3 m of Water
2.53×10^{-6}	79.60	1.37
3.16×10^{-8}	0.99	110.00
6.32×10^{-9}	0.20	550.00

Two possibilities have been suggested to account for the low permeability of the subsoil and spoil beneath the perched pond S195: (1) compaction of the material during placement and grading, and (2) sealing of the upper portion of the spoil in response to wetting. As discussed in section 2.4.1, the subsoil and upper spoil at both nests BR195 and BR196 displayed visual evidence of extensive compaction. Comparison of hydraulic conductivity and density values for the same intervals from sites BR195 and BR196 suggests that this compaction of the upper spoil and subsoil may account for the presence of the barrier. For till-derived subsoil, sand-derived subsoil, and spoil, the hydraulic conductivity appears to be inversely related to the density (Figures 41, 42, 43). On the basis of the regression relationship, we estimate that the threshold hydraulic conductivity for barrier formation, 3×10^{-8} m/s, is related to density of 1.68 g/cm^3 for till-derived subsoil (Figure 41), 1.81 g/cm^3 for sandy subsoil (Figure 42), and 1.55 g/cm^3 for clayey spoil (Figure 43). Using these values as the threshold for barrier formation, we estimate that three of five upland sites at Vesta Mine would have a hydrologic barrier in the subsoil (BR56, BR126, and BR128) and three of five in the spoil (BR126, BR128, and BR132). Because this analysis reflects a small number of determinations from only two sites, caution must be used in generalization of these results.

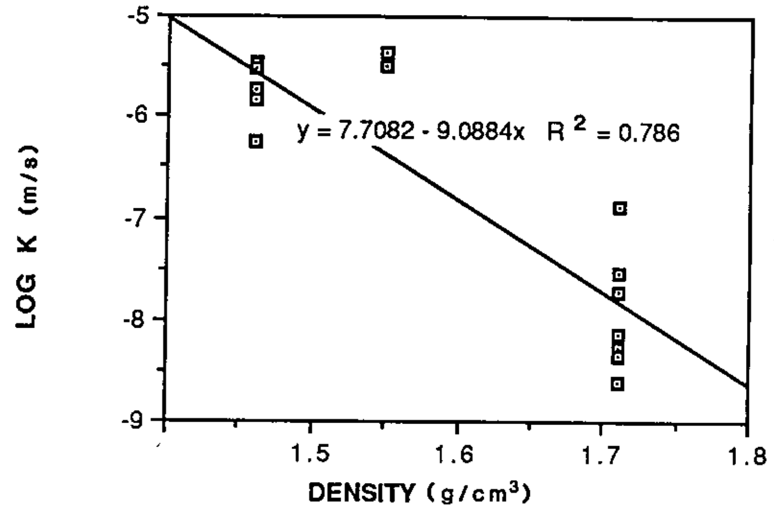


Figure 41. Relationship between density and hydraulic conductivity for till derived subsoil at sites BR195 and BR196.

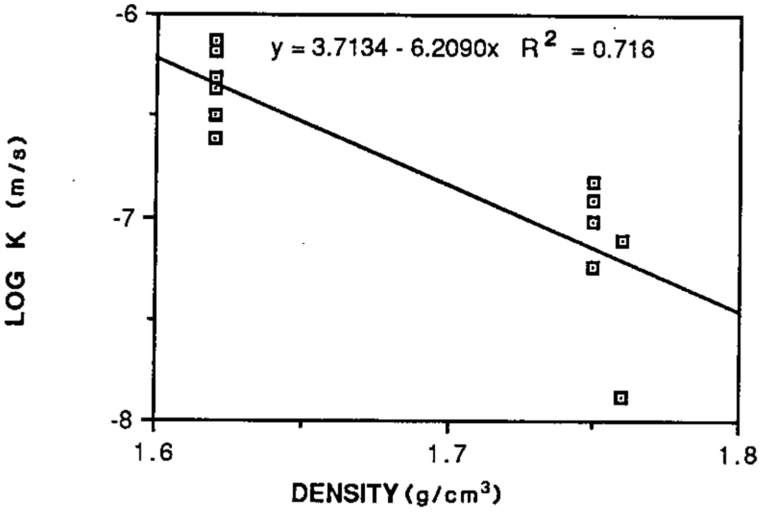


Figure 42. Relationship between density and hydraulic conductivity for sandy subsoil at sites BR195 and BR196.

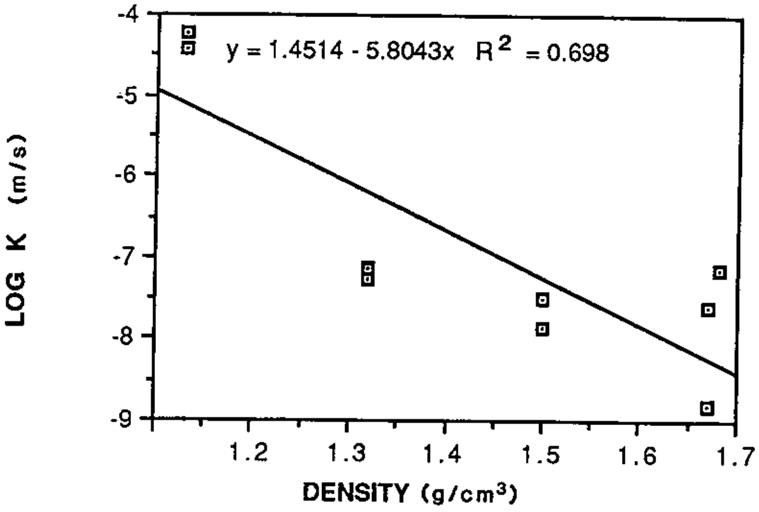


Figure 43. Relationship between density and hydraulic conductivity for clayey, bedrock-derived spoil at sites BR195 and BR196.

Sodic clayey spoil slakes and swells upon wetting (Dusseault et al. 1988). This characteristic commonly contributes to surface crusting of sodic spoil. It has been suggested that such swelling, slaking, and crusting might reduce hydraulic conductivity sufficiently to produce a barrier beneath an ephemeral pond (Moran et al. 1989a,b; in press; in prep).

Evidence from PHRP strongly suggests that the hydraulic conductivity of spoil has decreased over time (Moran et al. in press; in prep). Data from the hydraulic conductivity testing at site BR195 suggests that this process may contribute to the formation of a barrier. Three tests that were conducted at a depth of 2.10 m gave values of 1.90 x 10^{-5} m/s, 3.30 x 10^{-8} m/s and 1.40 x 10^{-8} m/s (Table 5). The initial test indicated that the spoil was highly permeable. After wetting, the conductivity dropped 3 orders of magnitude to values sufficiently low to constitute a barrier.

On the basis of our studies, we conclude that both (1) high density resulting from compaction during grading of the spoil and placement of the subsoil and (2) structural collapse of the spoil in response to wetting have contributed to the formation of a hydraulic barrier beneath pond S195. It is not possible to identify the relative importance of these two processes on the basis of the data available.

3.2 IMPACT OF UPLAND PERCHED PONDS ON AGRICULTURAL CAPABILITY

3.2.1 Disruption of Farming Operations

The most obvious implication of perched ponds is that they occupy land that otherwise might be farmed and decrease efficiency of farming operations by disrupting field patterns. Pond S195 occupied somewhat more than a hectare at its maximum stage in 1988 and 1989. The wet soil conditions in the surrounding fringe area further precluded farming, making the area affected by the pond about 1.5 ha. To put this loss of farmable land in perspective, unmined fields in the Battle River area typically contain from 5% to 10% ponded areas, or 3.25 to 6.5 ha per quarter section.

3.2.2 Development of saline and sodic soils

A potentially important negative impact of perched ponds is the development of saline sodic soil conditions in the fringe area around the pond. Small white salt patches were observed on the soil at various places around pond S195 in May, 1988 (Figure 44). Unlike lowland reclaimed areas, where the saline areas are the same from one year to the next, the location and intensity of the salinity at this upland site varies from year to year. Because pond S195 is ephemeral, its margins fluctuate over a considerable distance during the year. In addition, the land surface is continuing to subside and as a result the configuration of the depression changes from year to year. It is expected however, that once the subsidence ceases, the pond will become much more stable from year to year and the concentration of salt will be localized in the same area and therefore is expected to increase in severity with time.

The saline fringe results from radial outward flow from the pond itself. The upper surface of the sodic spoil acts as a barrier to rapid infiltration and forces lateral flow from beneath the pond outward toward discharge areas in the fringe area (Figure 45). The severity of salinity in this setting is not expected to be as great as in lowland settings because the total amount of salt available in upland settings is limited to the amount of salt in the subsoil beneath the pond; in lowland settings, salt is contributed from beneath the neighboring uplands as well. In addition to this, perched ponds are groundwater recharge sites in which the tendency is for salt to be redissolved from the saline fringe and carried downward. The initial precipitation of salt results only because the rate of recharge is much slower than the rate at which water is supplied to the pond. In upland settings, where sodic spoil is encountered at depths of 1.0 m to 1.5 m beneath the surface, the salinity problem is expected to be exacerbated by sodium salts that are carried upward from the spoil and precipitated in the saline fringe around pond margins.

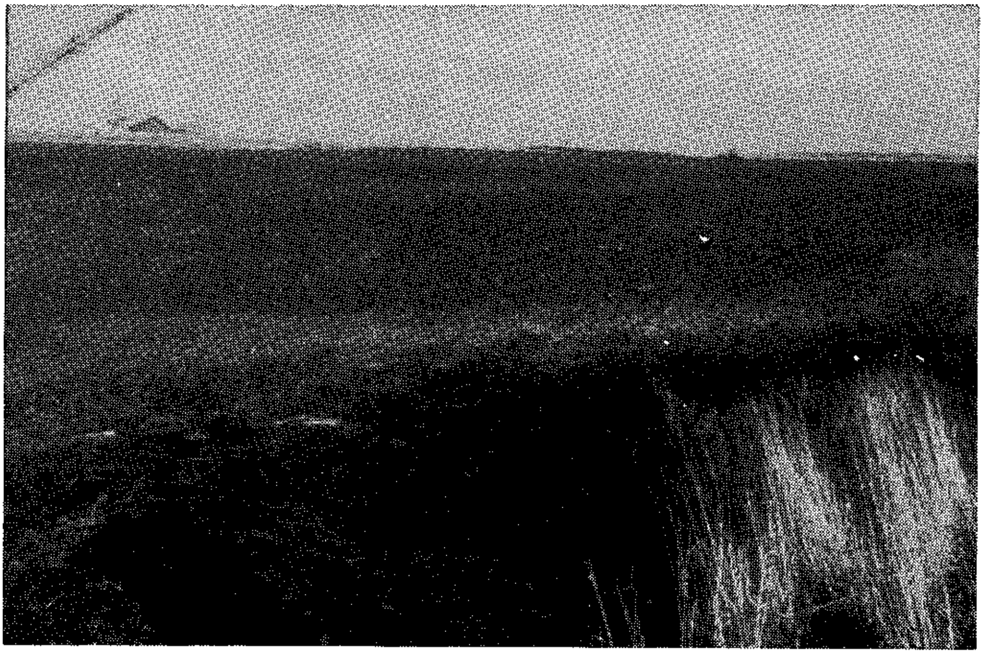


Figure 44. Photograph showing salt accumulations on soil around pond S195 in Vesta Mine in May 1988.

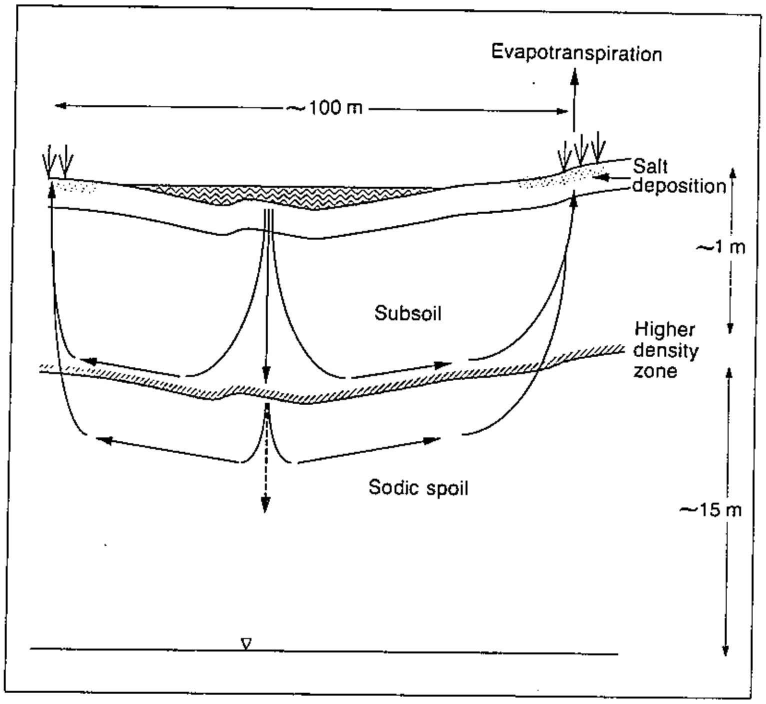


Figure 45. Schematic drawing showing formation of saline and sodic conditions in soil bordering a perched pond such as S195 as a result of lateral groundwater flow induced by a barrier in the top of the spoil.

Data on overburden EC and SAR from BR195 and BR196, which were described in section 2.5, indicate that this salinization process is proceeding as described in the theoretical discussion above. At nest BR195, the increased EC of the topsoil and subsoil combined with the decrease in EC in the upper part of the spoil is interpreted to indicate upward migration of salt in the zone around the edge of the pond (Figures 36 and 38). At nest BR196, which is situated about 60 m south of the pond and about 0.40 m higher, the decrease in EC in the topsoil and marked increase in the subsoil reflects leaching at the top of the profile and accumulation at greater depth within the profile (Figures 37 and 39). This site appears to be sufficiently far away from the pond and higher enough that it is beyond the range of pond margin salinization.

3.2.3 Influence of perched ponds on upland groundwater recharge

Groundwater recharge appears to be a very slow process in upland reclaimed areas where ponds are absent. One of the purposes of this project was to assess whether, and to what degree, the presence of a semi-permanent perched pond altered this situation.

The piezometer nests in the eastern part of Vesta Mine, BR130, BR131, and BR132, and in Paintearth Mine, BR91, BR92, BR140, BR141, and BR142, are typical of upland reclaimed sites with very little to no ponding of surface water. At only one of these eight nests, BR141 at Paintearth Mine, has there been any evidence of resaturation of the spoil. At all the other sites, all the wells in the nest have been dry for the entire monitoring period, six years at Paintearth Mine and five years at Vesta Mine. In both the west Vesta and Vesta Berm sites, the deepest well at each nest indicates saturated conditions. Although these nests are located in an upland setting, the data strongly suggest that the principal source of spoil resaturation is the large lowland pond to the north (Figure 4). In addition, the wells in the west Vesta site encountered a significant thickness of saturated sand within the spoil that appeared to have been saturated when the area was originally leveled.

We conclude from the preceding discussion, that where upland sites are sufficiently distant from the large ponds that characterize lowland settings, groundwater recharge either is not occurring or is occurring very slowly. Data from piezometer nest BR195 suggest that a perched pond, such as S195, can produce appreciable groundwater recharge, at least initially. In September 1987, when this nest was installed, the well at the base of the spoil indicated saturated conditions. The potentiometric head was 719.2 m, about 5 m above the screen. The head has steadily declined since that time, indicating that the recharge rate has decreased. Fifty metres to the south, the base of the spoil at nest BR196 has been dry throughout the period of observation.

On the basis of the observations of piezometric head beneath pond S195, we conclude that infiltration from the pond resulted in saturation of at least 5 m of spoil between initiation of the pond during snow melt in the spring of 1985 and the initiation of monitoring in September, 1987. The fact that the head has been steadily declining since September, 1987 indicates a decline in the rate of recharge from the pond. This decline is likely a combined effect of decreasing hydraulic conductivity over time and a period of several years during which precipitation has been somewhat lower than normal. Data from wells near Forestburg, about 15 km north of the site, indicate a steady decline in groundwater levels throughout this period. Clearly this decline in regional water levels is caused by the series of drier than normal years since about 1984. We consider it likely that the decrease in recharge rate beneath pond BR195 reflects a decrease in hydraulic conductivity over time in addition to this climatically controlled decline in the supply of water. Moran et al. (1989a) reached a similar conclusion regarding decreased recharge rates from the ponds in the west Vesta instrumented site.

Comparing the spoil density with the density of unmined overburden suggests that the unsaturated porosity of the newly placed spoil was about 20% to 25%. In order to saturate this amount of pore space to a depth of 5 m in the 2.5 years between initiation of the pond and installation of the wells at BR195, the average recharge rate must have been about 0.4 to 0.5 m^3/m^2 each year. On the basis of water level changes in pond S195 during 1988, Moran et al. (1989a) calculated that the recharge rate beneath pond S195 was about 0.11 m^3/m^2 per year. We estimate, therefore, that the recharge rate has decreased by at least a factor of 4 since the pond was first created. To place this in perspective, the recharge rate beneath non-ponded uplands was calculated as 0.0035 m^3/m^2 per year (Moran et al. 1989a). The estimated original recharge rate beneath the pond is thus about 120 times that beneath non-ponded upland sites; this had been reduced to about 30 times by 1988. Because the area covered by the perched pond S195 is only about 1.5% of the upland reclaimed area, the volume of recharge beneath the pond comprises about 27% of the calculated recharge in the upland area.

3.3 EXPANSION OF UPLAND PERCHED PONDS OVER TIME

At the outset of this study, we postulated that if the principal mechanism of formation of the hydraulic barrier beneath a perched pond was the sealing of sodic spoil in response to wetting, the area of such a pond would tend to expand. A positive feed-back mechanism would be established by which the formation of the seal would retard infiltration and cause the water to spread radially from the pond. This wetted fringe area would seal a larger area around the pond. The next spring, when the basin refilled, the area of reduced hydraulic conductivity would be larger and the pond would stand at a higher level, and cover a larger area for a longer period. This larger pond would then result in in expanded sealed area and the cycle would repeat itself.

It is evident from the discussion in the preceding section that there has been a decrease in the hydraulic conductivity over time as the spoil has become wetted. There is no evidence that the pond has increased in size over time. On the contrary, examination of a series of aerial photographs taken in 1985, 1986, and 1989 suggests that the maximum area of the pond has remained relatively constant. It is unlikely, however, that if such a process of expansion of the pond were occurring, that the period of record has been long enough or the measurements precise enough to detect the effect.

We consider that a more likely scenario for changes in the size of the pond over time is an initial decrease in area followed relatively rapidly by a stabilization. The pond initially would be very shallow, cover a large area, and be short lived as the shallow water rapidly evaporated and infiltrated. As the major subsidence depressions formed and deepened, the pond would become smaller but deeper and, consequently, longer lived. The ultimate size of the pond is more likely to be determined by the interaction between climatic and topographic features than by the area of the sealed barrier. The size of the contributing drainage area, combined with the amount of snow and the rate of melt, will determine the amount of water in the basin. The balance between precipitation and evaporation and evapotranspiration during the open water season are major factors in determining the rate of recession of the pond from its early spring level.

Given the climate of east central Alberta and the topography of reclaimed landscapes, we consider it unlikely that the area of perched ponds, such as S195, will increase significantly over time. In east central Alberta, evaporation is significantly greater than precipitation; about 2 times during 1988 and 1989 (Table 3). Slopes in reclaimed upland settings are generally very gentle and as a consequence small changes in the pond level result in large changes in area. Thus, even if the area of the sealed barrier were to increase, the rapid evaporation from the shallow fringe areas of the pond should limit its growth.

It is worth pointing out that repeated development of saturated conditions in the soil surrounding the margins of perched ponds could lead to salinization and development of sodic soils as appears to be occurring at BR195. It is not known how far out from the pond such conditions could develop. At site BR196, about 60 m south and 0.40 m higher than BR195, conditions of near saturation above a permeability barrier appear to be leading to development of more saline and sodic subsoil.

3.4 CREATION OR PREVENTION OF UPLAND PERCHED PONDS

In this section of the report we briefly address the question of how to design the post-mining landscape to either create or avoid the creation of a pond. The fundamental mechanism lies in adjusting material handling methods in such a way that a depression is either created, prevented or drained. We first examine the construction of a pond, whether for wildlife habitat or watering stock.

In construction of an upland pond, we must focus on three elements of the landscape:

1. development of adequate contributing drainage area,
2. creation of a depression, and
3. creation of a sufficiently impermeable seal that the depression will retain water.

The first element, the contributing drainage area, is controlled by large scale variations in the surface topography of the reclaimed surface. It is the factor that is controlled to the greatest degree by the intrinsic characteristics of the site, and over which the least control can be exercised. The second factor, creation of a closed depression, can be managed through adjustments in initial material placement and through leveling and grading. The final factor, creation of a low permeability seal, is controlled by the leveling and grading procedure.

3.4.1 Creation of adequate contributing drainage area

The first step in creation of a pond is to select an area where the final reclaimed grade will be lower than its surroundings because of inherent characteristics of the overburden. The area that drains water toward a pond must be considerably larger than the pond itself to assure adequate water to support the pond. At Vesta Mine, the drainage area of pond S195 is about 250 000 m^2, about 25 times the size of the pond itself. Although, other depressions in this basin capture water and prevent the entire basin from contributing to the master pond, we have used this 25:1 ratio as a rough design guideline.

The final post-reclamation topography can be estimated from the projected thickness of overburden and the structure of the base of the coal. The mining process disturbs the overburden and creates an additional 25 to 30% pore space. This bulking of the overburden causes the initial thickness of reclaimed spoil to be greater than the unmined overburden by about 25 to 30%. The newly reclaimed surface is therefore higher than it would be if there were no disturbance. As water begins to enter the newly created pore spaces, the physical structure of individual fragments of spoil collapses causing the overall spoil mass to compact (Dusseault et al. 1985; 1988). This compaction results in a lowering of the reclaimed surface, both by area-wide subsidence and by differential subsidence, which creates pits and depressions. The final bulking factor for mine spoil in the plains of Alberta appears to be on the order of 20%. Thus, the final spoil thickness is about 20% greater than the original thickness of the undisturbed overburden.

On the basis of the discussion in the previous paragraph we conclude that it is possible to predict in advance of mining, lower areas within the final post-mining landscape. These areas will tend to become closed depressions in the reclaimed landscape within which ponds can be developed.

The expression, $T_S = (1 + B) * T_O$, describes how the overburden thickness (T_O) and the bulking factor (B) relate to spoil thickness (T_S) (Moran et al. in press; in prep). Using data from the mine development drilling program, the thickness of spoil is computed for all locations. These thickness values are then added to the elevation of the floor of the coal seam to give an estimate of the elevation of the post-reclamation surface. These points can then be contoured and low areas identified. The exact configuration of the low area may vary somewhat depending on the direction of pit progression, but because the material is replaced within 50 m to 75 m of where it was mined, this effect is minor.

Ponds can be developed where depressional areas occur naturally or where a long slope could be interrupted with a low berm to create a basin, as is the case at pond S195. Where the natural depression is not large enough, it may be possible to expand the contributing drainage area for a pond by designing in-field surface drainage into the final grading plan to link higher, smaller basins to a lower basin.

3.4.2 Creation of a depression

Once a broad depressional area has been identified to serve as the collecting basin for a pond, the next step is to create a locally thinner zone of spoil at the low point of the basin. To accomplish this with the least disruption to existing mining operations, the spoil leveling process can be modified to convert a section of the trough between two spoil ridges into a shallow basin. It may prove feasible and more cost effective to make a slight modification in the placement of materials by the dragline to create a larger than normal trough at the location of the proposed pond. During the spoil leveling phase of the operation, the incipient depression is left as a depressed area toward which the spoil surface is graded. Where the pond is being developed for stock watering, the sides of the depression can be graded to a somewhat steeper angle, with a smaller, deeper depression than when the pond is created for wildlife habitat. During spoil leveling, a rough level survey should be conducted to ensure that the surface is graded toward the depression.

3.4.3 Placement and grading of subsoil and topsoil

To ensure that the depression will retain water, the upper part of the spoil and the lower part of the subsoil should be compacted sufficiently to reduce the hydraulic conductivity to about 1 x 10^{-9} m/s. Clayey subsoil material should be selected for placement in the depression; glacial till is the best material for this purpose, where it is available. Samples of the subsoil material should be tested to determine the relationship between moisture content, compactive effort, and density. The base of the subsoil should be placed and compacted at the optimum water content to achieve the desired density. As discussed above, limited data from BR195 and BR196 suggest that density of about 1.63 g/cm^3 for clayey spoil and 1.73 g/cm^3 for till-derived subsoil results in sufficiently low hydraulic conductivity to support a pond. A compacted thickness of 0.30 m should be adequate to provide an initial barrier beneath the pond, although a greater thickness of compacted material would further decrease the rate of water loss from the pond.

It is important that the upper portion of the subsoil is left uncompacted to assure that vegetation can become established in and around the pond. Assuming that 0.90 m of less compacted subsoil is adequate to support vegetation, we recommend a minimum thickness of subsoil of 1.20 m beneath a planned pond. Once the compacted lower portion of the subsoil has been completed, the remainder of the subsoil is placed over the entire area following the procedures normally used in the reclamation process. During subsoil grading, a rough level survey should again be conducted to ascertain that the surface is graded toward the depression.

It is recognized that topsoil is a valuable resource in reclamation of surface mined sites. Although, it has been argued that use of topsoil in areas that are to be ponded represents unwise use of that resource, we conclude that in many cases, the benefits of placing topsoil beneath potential ponds outweigh the disadvantages. Depending on the purpose and design of the pond, it may or may not be appropriate to place topsoil over the entire area. Where the pond is a broad, shallow basin such as S195, which is designed primarily as natural habitat, topsoil should be spread over the entire basin. In this type of pond, the pond margin fluctuates widely during any given year and between one year and the next. As a result extensive areas that were ponded at high stages are left exposed throughout much of the year. Topsoil is required in these areas to facilitate establishment of vegetation and to render the surface traversable to livestock and vehicles. In addition, the topsoil in the marginal zone and beneath the pond provides a source of seed, rootstock, and organic nutrients to facilitate establishment of the emergent littoral vegetation necessary to make the pond a positive element of the landscape. If the pond is constructed primarily for watering stock, and therefore has sufficiently steep sides that variations in water level will result in only minor movement of the shoreline, it may be appropriate to leave the basin without a lining of topsoil. Even in this case, however, turbidity produced by suspended sediment may be more of a problem if no topsoil lining is used.

3.4.4 Maintenance of a pond

During the first several years following completion of reclamation, the pond and surrounding area should be monitored to determine where water is accumulating in the basin. As the surface subsides and depressions develop in the surface, it may be necessary to carry out some additional leveling operations. If large depressions develop upslope of the pond and intercept appreciable amounts of the drainage water, it may become necessary to drain them to allow water to reach the designed pond.

3.4.5 Preventing formation of a pond

To prevent the formation of a pond it is first necessary to identify places within a mine site where broad, closed depressions can form. The procedure outlined in section 3.4.1 is used to project the location of closed low areas in the final reclaimed landscape. Where such low areas are projected, ponding can be minimized or prevented by altering the final configuration of the landscape. Where a large closed low area is projected, it may not be possible to remove the depression by modification of material handling procedures. In this case, it may be feasible to design the landscape such that the depression can be drained. This may be accomplished with drainage ways between spoil ridges, where the pit orientation coincides with the overall slope. Where the pit is oriented across the final slope, drainage for a closed depression may be developed using a pit access ramp. In this case, the depression would be graded toward the ramp, which would be filled to a level slightly lower than the surrounding reclaimed surface. By designing the details of the mining operation in concert with the desired final reclaimed landscape in this way, it should be possible to minimize the extent of undesirable ponding.

If it is not possible to remove or drain a depression, ponding can be minimized by ensuring that the base of the depression is as permeable as possible. Where sandy subsoil material is available, selective placement of this material within the depression will maximize the potential for subsurface drainage. Care should be taken in leveling the spoil and placement and grading of the subsoil to minimize compaction.

4. CONCLUSIONS

Perched ponds can be expected to form in reclaimed landscapes wherever these two conditions are present:

1. A large closed drainage basin to collect and channel runoff water during spring snow melt; and
2. A low permeability barrier in the lower subsoil or upper spoil that impedes downward flow of subsurface water .

The closed basin that is responsible for the existence of pond S195 was formed by construction of a low berm transverse to a long southward draining slope. Compaction during placement and grading of the lower subsoil and upper spoil produced sufficiently high density and low hydraulic conductivity that rapid downward drainage of the ponded water was prevented. The formation of a broad depression is largely related to the original thickness of overburden, although pit orientation and location of haul roads and ramps can play a contributing role. Hydrologic barriers result from highly compacted zones of dense subsoil or spoil or from sealing of the upper surface of the spoil as a result of structural collapse of sodic clay in response to wetting.

Perched ponds reduce the amount of farmable land within upland reclaimed landscapes and disturb field patterns as compared to upland reclaimed sites without such ponds. In the reclaimed sites studied, the area occupied by ponding in upland settings is less than half that in unmined sites in the same area.

Perched ponds, such as S195, result in progressive development of saline and potentially sodic soils in the peripheral area. The saturated or nearly saturated conditions in the soil surrounding the pond result in upward movement of subsurface water, which is lost by evaporation and evapotranspiration, and accumulation of salts in the soil zone over time.

Perched ponds result in accelerated groundwater recharge, at least early in their life. On the basis of evidence from our study, however, a single isolated pond does not produce sufficient recharge to cause the water table to approach the surface in areas of thick spoil. It is not clear whether the diminished recharge rate that has been observed at pond S195 results from a decrease in hydraulic conductivity or from a series of drier than normal years.

It appears unlikely that the size of perched ponds in reclaimed surface mines in east-central Alberta will increase significantly over time. It is considered more likely that the size of such ponds is limited by the interaction between the size of the contributing drainage basin, the depth of the central depression, and the rates of precipitation and evaporation.

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