GROUNDWATER HYDROLOGIC REGIMES WITHIN RECLAIMED SURFACE COAL MINED LANDSCAPES IN ALBERTA[1]

by

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Abstract. Between 1979 and 1988, the Plains Hydrology and Reclamation Project (PHRP) investigated interactions of groundwater, soils, and geology and successful reclamation of surface coal mines in the plains of Alberta. Among 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 rate at which steady-state conditions were attained. Instrumentation was installed in spoil at two study areas: the Battle River area, which included Diplomat, Vesta and Paintearth Mines, and the Wabamun area, which included the Highvale and Whitewood Mines. Our work demonstrated that the processes by which water enters the spoil and the rate at which the post-reclamation steady-state equilibrium hydrologic regime is established differ both within and between mine sites depending on the hydraulic conductivity of the spoil and the landscape setting within the reclaimed terrain. In lowland settings at mines characterized by high permeability spoil, steady-state equilibrium conditions are established within 5 to 10 years of regrading. In upland settings at mines characterized by low permeability spoil, on the other hand, many decades are required to establish steady-state equilibrium conditions.

Introduction

Between 1979 and 1988, the Plains Hydrology and Reclamation Project (PHRP) investigated interactions of groundwater, soils, and geology and successful reclamation of surface coal mines in the plains of Alberta. Among 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 rate at which steady-state conditions were attained. Instrumentation was installed in spoil at two study areas: the Battle River area, which included Diplomat, Vesta and Paintearth Mines, and the Wabamun area, which included Highvale and Whitewood Mines (Figure 1). The major focus of our work was at the Battle River area with minor input from the Wabamun area.

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[1] Paper presented at "Reclamation, A Global Perspective", Calgary, Alberta, Canada, August 27-31, 1989.

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Proceedings America Society of Mining and Reclamation, 1989 pp 209-218
DOI: 10.21000/JASMR89010209

https://doi.org/10.21000/JASMR89010209

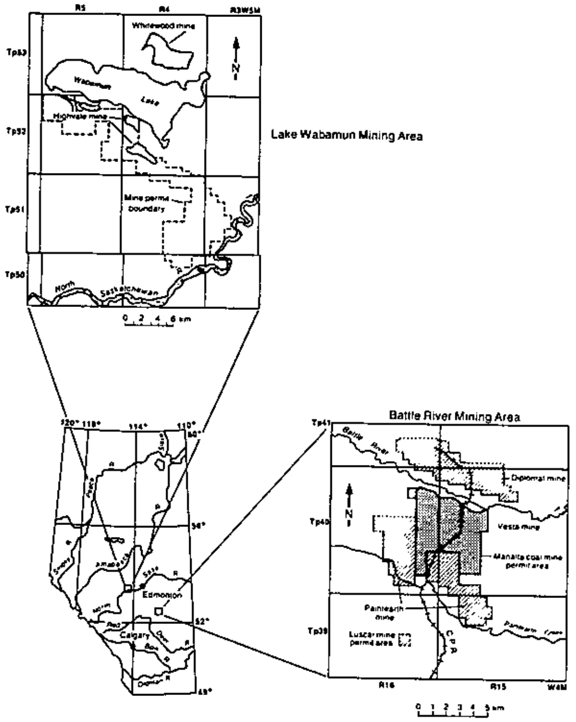

Figure 1. Location of Battle River and Wabamun study areas of the Plains Hydrology and Reclamation Project.

At Vesta Mine, 27 sites were instrumented with nests of multiple standpipe piezometers. Piezometers were installed in individual holes that were drilled to the desired depth, generally with a truck-mounted, solid-stem auger. Piezometers were generally a 5-cm PVC riser pipe with a tip consisting of a length of commercially slotted pipe. The piezometer tip was covered with frac sand, then capped with about 0.5 m of bentonite pellets. In most cases, the hole was then backfilled with drill cuttings. Neutron-probe access tubes were installed at 14 of the instrumented sites and infiltration tests were conducted at one site. In addition, three ponds were instrumented to monitor pond level and seepage. At Diplomat Mine, 32 sites were instrumented with multiple piezometer nests; neutron-probe access tubes were installed at 14 of these sites, and infiltration tests were conducted at three sites. Five ponds were instrumented to monitor pond level and seepage. At both mine sites, the majority of the instrumentation is in lowland settings but upland settings are well represented.

Our work demonstrated that the processes by which water enters the spoil and the rate at which the post-reclamation steady-state equilibrium hydrologic regime is established differ both within and between mine sites depending on the hydraulic conductivity of the spoil and the landscape setting within the reclaimed terrain. This paper presents the spoil resaturation model that was developed from the PHRP project work. The two major controlling factors, hydraulic conductivity and landscape setting, are discussed first. The majority of the paper is devoted to quantification of groundwater recharge from various sources in the two major landscape settings and in the two types of spoil. Finally, we present a brief discussion of the implications of the post-mining hydrologic regime for agricultural use of reclaimed landscapes.

Acknowledgements

This research was sponsored in part by the Reclamation Research Technical Advisory Committee (RRTAC) of the Alberta Land Reclamation Council with financial support from the Heritage Savings Trust Fund. The assistance and support of Luscar Ltd., Manalta Coal Ltd., Alberta Power Ltd., and TransAlta Utilities Corporation Ltd., without which the study would not have been possible, is gratefully acknowledged. We would like to thank Daphne B. Cheel for her assistance throughout the

project and in preparation of this paper.

Parameters Controlling Hydrologic Processes in Reclaimed Terrain

Hydraulic Conductivity of Mine Spoil

Hydraulic conductivity was determined using single-well response tests following the method of Cooper and others (1967) and Hvorslev (1951). Hydraulic conductivity of mine spoil is highly variable, ranging over as much as six orders of magnitude within individual mines (Figure 2). Hydraulic conductivity of mine spoil is generally low, with the higher values that do occur located either at the base of the spoil or where sandier or more cemented overburden material is concentrated in the spoil. Spoil derived from glacial till, such as at Diplomat and Whitewood Mines, has hydraulic conductivity values that are about 1.0 to 1.5 orders of magnitude higher than those of spoil derived from bedrock, such as at Vesta, Paintearth, and Highvale Mines (Figure 2). Spoil derived from overburden in the Ardley Coal Zone (Highvale and Whitewood Mines), has hydraulic conductivity values that are from 2.0 to 3.0 orders of magnitude higher than those of the in the Lower Horseshoe Canyon Coal Zone (Vesta, Diplomat, and Paintearth Mines) [Figure 2].

The spoil at Vesta and Paintearth Mines consists largely of sodic shale, claystone, and siltstone with a minor admixture of glacial till. Initially, the spoil has a high secondary porosity of as much as 20 to 30% and a relatively high hydraulic conductivity. As the spoil becomes resaturated, however, the sodic bedrock material begins to swell and slake (Dusseault and others, 1988) causing the hydraulic conductivity to decrease dramatically to the low values indicated in Figure 2. At Diplomat Mine, on the other hand, the spoil consists almost entirely of glacial till with minor admixtures of sodic bedrock in places. Although the spoil compacts readily and relatively rapidly assumes density values very similar to the premining state (Pauls and others, in preparation), the hydraulic conductivity of the spoil is considerably higher than at Vesta Mine (Figure 2).

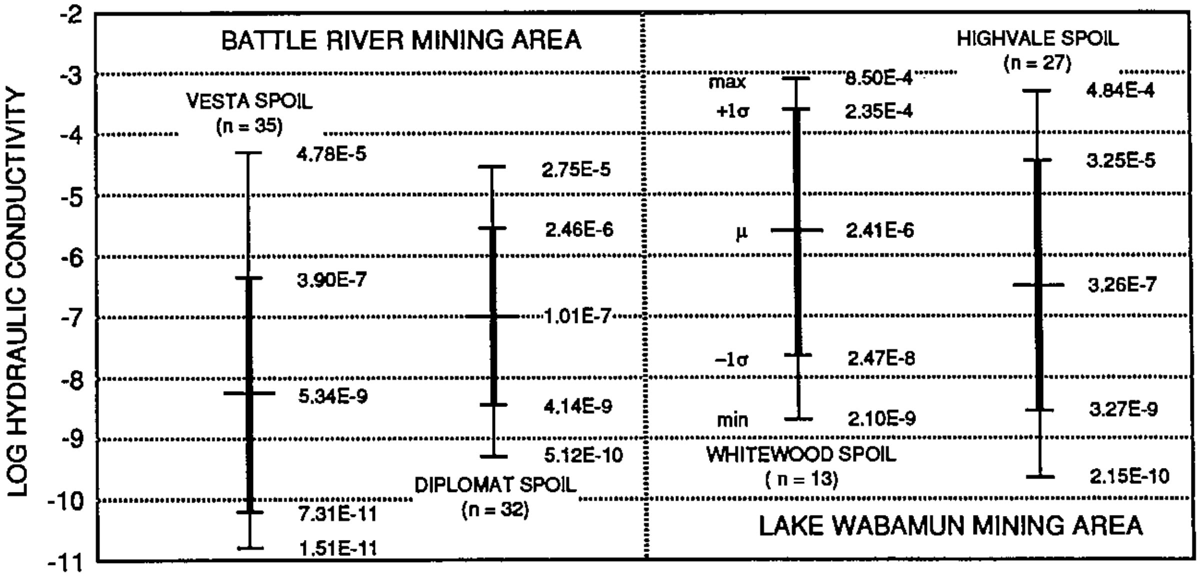

Figure 2. Hydrologic Conductivity (m/s) of Mine Spoil in Central Alberta.

Landscape Settings in Reclaimed Terrain

Two distinctly different hydrologic regimes have been recognized in reclaimed surface-mined landscapes, (1) upland settings and (2) lowland settings (Figure 3). 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 and others, 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 3).

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 is 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 3).

Model of Spoil Resaturation

The model presented in this paper is an interpretive conceptual framework based on our observations. We have measured hydraulic properties of the spoil and monitored water level recovery and response to recharge events for as much as 8 years in a variety of settings within reclaimed landscapes. The hydrologic conditions at these sites

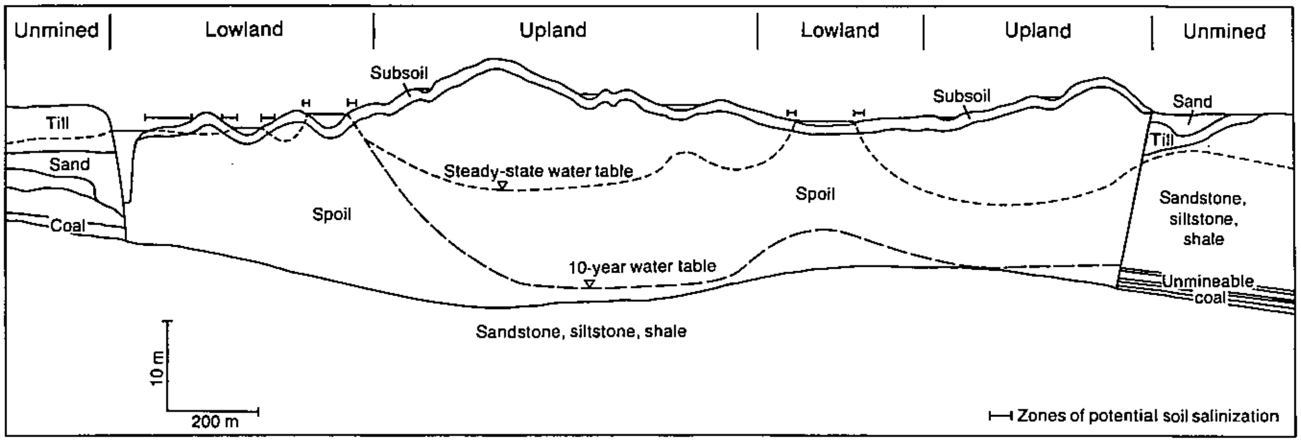

Figure 3. Schematic Diagram Showing Hydrologic Regimes in Reclaimed Landscape.

ranged from immediate post-reclamation conditions to a stable steady-state post-mining regime.

Initial Post-Mining Hydrologic Regime

During surface mining of coal in the plains of Alberta, the bedrock and unconsolidated sediment that comprise the overburden is removed by draglines or shovels and cast backward into the previous pit from which the coal has been removed. In most areas, all but the uppermost several metres of the overburden was saturated with groundwater prior to disturbance. The coal itself and overburden sandstones are commonly sufficiently permeable to meet the water supply needs of the largely rural population of the region. In the mining process, the overburden material is broken into fragments of various sizes that are replaced as spoil. As a result of the space between individual fragments, the spoil mass has a lower density than unmined overburden. This "bulking" of the spoil results in the surface of reclaimed areas being elevated above adjacent unmined areas. Depending on the type of material involved and its initial water content, the secondary porosity created by the spaces between spoil fragments ranges from 10 to 30 %. Immediately following placement of the spoil, this secondary porosity is occupied by air, but as organic matter in the spoil is oxidized the air is replaced by CO_2 (Wallick, 1983). As soon as the spoil is reclaimed, and in some cases even before reclamation is complete, water begins to infiltrate the spoil from ponded rainfall and snowmelt. In the early stages of spoil resaturation, lateral inflow from adjacent unmined aquifers makes a significant contribution to spoil resaturation in all landscape settings because of the large hydraulic gradient. With time, the gas in the secondary pore space is displaced by the rising groundwater as the spoil mass once again becomes saturated.

Spoil Resaturation

The process of spoil resaturation is fundamentally different in lowland and upland settings. The rate of spoil resaturation and the rate at which stable steady-state equilibrium conditions are established are governed by the hydraulic conductivity of the spoil. Combining these two factors gives a four component model of spoil resaturation.

Recharge in Lowland Settings with High Permeability Spoil. During the early stages of spoil resaturation, all spoil regardless of composition appears to be characterized by relatively large values of hydraulic conductivity. Groundwater recharge in lowland settings occurs more or less continuously by leakage from both deep and shallow permanent ponds (Schwartz and Crowe, 1987). Ephemerally ponded depressions and infiltration beneath unponded sites also contribute to the recharge in lowland settings (Trudell and others, 1986). Leakage of water from ponds is initially very rapid resulting in rising water levels that saturate the spoil at rates as great as 1 m/year. In spoil consisting largely of till or non-sodic bedrock, the hydraulic conductivity remains high. Rapid resaturation of the spoil continues until the rising groundwater level causes the hydraulic gradient to decrease and pond leakage slows. In mine sites with high permeability spoil, recovery of groundwater levels to the stable post-mining steady-state configuration is rapid, generally requiring no more than 5 to 10 years.

At the western end of Diplomat Mine, the PHRP project instrumented an area of about 1 490 000 m^2 of which about 807 500 m^2, or about 54% comprises lowland. Within the lowland, about 20% of the area is ponded. One large, deep pond occupies about 67 300 m^2 (8.3% of the area); small, shallow ponds occupy about 50 000 m^2 (6 % of the area); and about 5% of the area is occupied by ephemeral ponds during snowmelt and after heavy rain. Total recharge in this instrumented site is calculated as about 15 265 m^3 per year, which is equivalent to a recharge rate of 1.89 x 10^{-2} m^3/m^2 (Table 1). Large, deep ponds account for 57% of the recharge with non-ponded areas second most important, accounting for 20% of the recharge.

Recharge in Lowland Settings with Low Permeability Spoil. In lowland settings where the spoil contains abundant sodic bedrock, slaking and swelling of the spoil reduces the initially large hydraulic conductivity to much lower values. This results in a significant reduction in the rate of pond leakage and spoil resaturation. Recovery of groundwater levels to the stable post-mining steady-state configuration is slow, requiring at least several decades in mine sites with spoil having low hydraulic conductivity values.

At the western end of Vesta Mine, the PHRP project instrumented an area of about 942 500 m^2 of which about 180 000 m^2, or about 20% comprises lowland. Within the lowland, about 28% of the area is ponded. One large, deep pond occupies about 30 500 m^2 (17% of the area); two small, shallow ponds occupy about 12 850 m^2 (7.1% of the area); and about 5% of the area is occupied by ephemeral ponds during snowmelt and after heavy rain.

Table 1.

	Area		Seepage Rate	Recharge	
	(m^2)	%	(m^3/m^2)	(m^3)	%
VESTA LOWLAND					
SMALL PONDS	12,850	7.1	0.1096	1408	61.1
NON-PONDED	127,735	71.0	0.0035	447	19.4
LARGE POND	30,425	16.9	0.0083	252	10.9
EPHEMERAL PONDS	9,000	5.0	0.0220	198	8.6
TOTAL	180,000		0.0128	2305	
DIPLOMAT LOWLAND					
LARGE POND	67,300	8.3	0.1285	8645	56.6
NON-PONDED	649,825	80.5	0.0047	3054	20.0
EPHEMERAL PONDS	40,375	5.0	0.0583	2352	15.4
SMALL PONDS	50,000	6.2	0.0243	1215	8.0
TOTAL	807,500		0.0189	15266	
VESTA UPLAND					
NON-PONDED	712,875	93.5	0.0035	2495	54.3
SMALL PONDS	11,500	1.5	0.1096	1261	27.4
EPHEMERAL PONDS	38,125	5.0	0.0220	839	18.3
TOTAL	762,500		0.0060	4594	
DIPLOMAT UPLAND					
NON-PONDED	614,250	90.0	0.0047	2887	50.6
EPHEMERAL PONDS	34,125	5.0	0.0583	1988	34.9
SMALL PONDS	34,125	5.0	0.0243	829	14.5
TOTAL	682,500		0.0084	5704	

The spoil in the lowland area, which was mined and reclaimed between 1970 to 1975, ranges in thickness from about 12 m to 22 m. By 1981, when the site was instrumented, the groundwater level in the area was about 8 m above the base of the spoil, indicating an average water-table rise of about 1 m/year. Comparison of the density of the spoil in this area with that of unmined overburden indicates that secondary porosity is about 15% to 20%. On this basis we conclude that average total recharge in this area was between 0.15 and 0.20 m^3/m^2/year for the first 8 years following reclamation. Because the water table has generally been constant or has declined slightly since 1981, we conclude that the rate of spoil resaturation has decreased significantly from its initial value. The

PHRP project studied leakage from permanent ponds in this area in 1984 and 1985 and from ephemerally ponded depressions in 1986. We calculated a total recharge flux was about 1.275×10^{-2} m^3/m^2 (Table 1). We conclude from this that the average recharge rate between 1973 and 1980 was about 10 to 15 times as great as it was between 1981 and 1988. Small permanent ponds account for 61% of the recharge, with non-ponded areas second most important, accounting for 19% of the recharge.

Upland Settings with High Permeability Spoil. In upland settings, groundwater recharge occurs almost entirely by infiltration beneath unponded sites over the entire landscape and beneath ephemerally ponded depressions and the few shallow permanent ponds that form in larger subsidence depressions. Where the hydraulic conductivity of the spoil is high, steady-state equilibrium is achieved in 10 to 15 years depending on the thickness of spoil and climatic conditions.

Upland settings were instrumented in two areas of Diplomat Mine. About 682 500 m^2, or 46% of the instrumented study area at the west end of the mine consists of upland areas. Three small instrumented sites in the eastern part of Diplomat Mine also characterize upland settings. About 5% of the instrumented upland area at the western end of Diplomat Mine is occupied by permanently ponded depressions. Another 5% of the entire upland area is characterized by depressions that are ponded during snow melt and after heavy rain storms. Total recharge in the instrumented upland setting at Diplomat Mine is calculated at 5704 m^3 per year, which is equivalent to a recharge rate of 8.36×10^{-3} m^3/m^2 (Table 1). Non-ponded sites account for 51% of the recharge with ephemeral ponds accounting for 35% of the recharge.

Upland Settings with Low Permeability Spoil. In upland settings where the hydraulic conductivity of the spoil is low, a much longer period is required to reach steady-state conditions, at least several decades. As in lowland settings, the hydraulic conductivity of the spoil is initially high and water infiltrates rapidly beneath small depressions. As the spoil becomes saturated, slaking and swelling cause hydraulic conductivity to decrease. Small depressions that initially drained rapidly become the site of larger perched ponds as the rate of seepage declines and as a result of increased differential subsidence resulting from the seepage. Recharge from these depressions declines as a greater proportion of the water they contain is returned to the atmosphere by evaporation and evapotranspiration.

Upland settings were instrumented in two areas of Vesta Mine and at Paintearth Mine. About 762 500 m^2, or 80% of the instrumented study area at the west end of Vesta Mine consists of upland areas. An upland area of about 300 000 m^2 in the eastern part of Vesta Mine was instrumented with three piezometer nests and two neutron-probe access tubes. An upland area of about 500 000 m^2 at Paintearth Mine was instrumented with three piezometer nests and six neutron-probe access tubes. About 5% of these instrumented upland areas are occupied by depressions that are ponded during snow melt and after heavy rain storms. Permanently ponded depressions are present but occupy no more than about another 1.5% of the entire upland area. Total recharge in the instrumented upland setting at Vesta Mine is calculated at 4594 m^3 per year, which is equivalent to a recharge rate of 6.0 x 10^{-3} m^3/m^2 (Table 1). Non-ponded sites account for 54% of the recharge with small permanent ponds second most important, accounting for 27% of the recharge.

Steady State Equilibrium Hydrologic Regime

The significance of the model of spoil resaturation that is presented in this paper does not lie in the quantitative estimates of recharge rates. Rather, it lies in the importance of relative differences in recharge in various settings in determining the post-mining hydrologic regime. The model suggests that recharge in lowland settings is about twice that in upland settings, regardless of hydraulic conductivity. Furthermore, the model indicates that in east-central Alberta, this difference in recharge rate is sufficient to produce differences in the post-mining hydrologic regime. Where recharge is less than about 1.5 to 2.0% of the total annual precipitation, groundwater flow is able to remove the water supplied and the water table does not interact with the land surface. Where recharge is about 3.0 to 4.5% of the total annual precipitation, however, groundwater flow is not able to remove the water supplied and the water table rises to the land surface.

The steady-state hydrologic regime in reclaimed landscapes is essentially the same as that prior to mining and in adjacent undisturbed settings. The principal difference lies in the dynamics of ephemerally ponded upland depressions. In reclaimed landscapes, these depressions are expected to be subject to more severe seasonally wet conditions than in unmined landscapes. Water infiltrating beneath small depressions generally moves downward until it encounters a zone of lower hydraulic conductivity. The greater the depth to such a barrier, the more water can be drained away from the pond in the depression and the quicker the ponding dissipates. Sodic bedrock, which underlies surficial deposits and constitutes a significant hydraulic barrier in most mining areas in the plains of Alberta, is encountered at variable depths but in places is quite deep. In the Battle River mining area, for example, as much as 10 m of glacial till overlies sodic bedrock in parts of the unmined landscape. Subsequent to mining, only 1.0 to 1.5 m of till is generally replaced over the dominantly bedrock-derived spoil. The decrease in permeability at the top of the spoil is expected to impede downward infiltration and result in perching of ponds above the regional water table.

The steady-state water table in lowland settings is close to the land surface over much of the area, generally being no more than 1 m to 3 m deep (Figure 3). Once the post-mining equilibrium is established, the large ponds are sites of groundwater discharge, at least during part of the year. In upland settings, the steady state water table is at considerable depth below the land surface, at least 5 m to 10 m metres below the surface in most areas. The water table approaches the land surface only beneath larger permanent and semi-permanent upland ponds (Figure 3).

On the basis of observations within the reclaimed study sites and in adjacent unmined sites, it is expected that soil salinization will develop in lowland settings where the steady-state water table is within about 1.0 m of the land surface (Moran and others, 1986). The combination of seasonally wet conditions and saline soils is expected to significantly restrict the agricultural capability of a relatively large proportion of lowland settings in reclaimed landscapes. At Diplomat Mine, about 139 000 m^2 (13.9 ha), which represents 17% of the total lowland area, is expected to develop seasonally wet conditions and saline soils. This area, combined with areas of permanent ponds results in about 30% of the lowland area having appreciably reduced capability for agriculture relative to the remainder of the reclaimed area. Limited areas of saline soils have also been observed to be developing around larger depressions in upland settings.

At both Diplomat and Vesta Mines, ponds or sloughs were present in the premining landscape. At Diplomat Mine, the premining landscape was characterized by numerous small sloughs scattered across the area, reflecting the overall poorly-integrated drainage pattern. In some cases, ponds in the reclaimed landscape are in approximately the same location as the larger premining sloughs. In most cases, however, the location of post-mining ponds has been controlled by the mining process or by differential subsidence. At Vesta mine, the situation is similar, but with fewer ponds in both premining and reclaimed settings. Although the area of ponding at both mine sites was generally similar before and after mining, the ponds in the post-mining landscape are generally fewer, larger, deeper, and tend to be more permanent, than ponds in the premining setting. The net result is that the surface hydrology and distribution of sites of groundwater recharge and of soil salinity in reclaimed land should be more or less similar to the natural landscape.

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