REPORT #
RRTAC OF-10

A Summary of Land Resource and Groundwater Resource Issues Related to Plains Coal Mine Reclamation in Alberta

Alberta

CONSERVATION AND RECLAMATION MANAGEMENT GROUP
Reclamation Research Technical Advisory Committee

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A Summary of Land Resource and Groundwater Resource Issues Related to Plains Coal Mine Reclamation In Alberta

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Prepared for

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ALBERTA CONSERVATION AND RECLAMATION MANAGEMENT GROUP
(Reclamation Research Technical Advisory Committee)

1996

Alberta's Reclamation Research Program

Regulating surface disturbances in Alberta is the responsibility of the Conservation and Reclamation Management Group. The Chairman is from Alberta Environmental Protection. The Group oversaw a reclamation research program, established in 1978, to identify the most efficient methods for achieving acceptable reclamation in the province. Funding for the research program was provided by Alberta's Heritage Savings Trust Fund, Land Reclamation Program. Funding ended in March of 1994.

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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 Conservation 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 authors 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 was reviewed by RRTAC and the Plains Coal Reclamation Research Program Committee.

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This project was funded by the Alberta Heritage Savings Trust Fund, Land Reclamation Program through the Alberta Conservation and Reclamation Management Group.

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ABSTRACT

Development and extraction of coal resources in Alberta disrupts the landscape and alters two other important resources, land and groundwater. In order to support coal resource development that was economically and environmentally responsible, the Reclamation Research Technical Advisory Committee (RRTAC) of the Alberta Land Conservation and Reclamation Council, in consultation with the coal industry, since the late 1970's, guided research into plains coal reclamation. The results of this research program are published in 36+ RRTAC reports and numerous other papers in scientific journals and proceedings of scientific meetings.

This report synthesizes and summarizes this body of research in a manner that is designed to provide the user with a unified source of information on reclamation research in the plains of Alberta. The body of the report is separated into two main sections. The first section addresses questions that apply to the land resource, such as soil reconstruction, compaction, subsidence, and salinity. The second section addresses questions that apply to the groundwater resource, such as local and regional groundwater impacts, landscape impacts, and surface and groundwater contamination potential.

ACKNOWLEDGEMENTS

This project and report were sponsored by the Reclamation Research Technical Advisory Committee (RRTAC) of the Alberta Land Conservation and Reclamation Council, with financial support from the Alberta Heritage Savings Trust Fund. The guidance and support of the Plains Coal subcommittee of RRTAC is also gratefully acknowledged. Thanks are also given to the government and industry reclamation personnel who participated in the interview stage of the project and contributed their time and ideas.

1.0 INTRODUCTION

It is a given that the process of mining disrupts the landscape. Specifically, the two components of the landscape that are altered by mining are the groundwater resources and the land resources. As indicated in the accompanying Figure 1.1, the mining process alters the original (initial) equilibrium state of the landscape and leaves a changed state, which is not in equilibrium. Natural processes work on the changed state to bring it back to a state of equilibrium. Such processes include recharge, subsidence, salinization, and chemical and physical changes to the soil. The questions "What will be the final equilibrium state after mining?" and "How will the final landscape compare to the original landscape?" have directed much of the research in Alberta around surface mining over the last two decades.

In the middle 1970's, several vexing uncertainties about the impacts of large-scale surface mining of coal in agricultural areas of the plains of Alberta stood in the way of coal resource development. These uncertainties were sufficiently great that government was not prepared to finalize definitive reclamation guidelines and standards covering surface mining without further research. The following questions are typical of those that plagued the regulatory process at that time:

- Can surface mined areas be successfully reclaimed to support agricultural operations at all?
- Will surface mining of prime agricultural land permanently destroy the capability of the land to grow crops?
- Can solonetzic soils be reclaimed?
- How much subsoil buffer material is required to achieve successful reclamation?
- Are there amendments that can be added to reclaimed soil to enhance its agricultural potential?
- Even if the surface can be returned to productivity immediately following reclamation, will capability degrade over time?
- Can this possible degradation in capability be prevented with sufficient thickness of subsoil buffer material?
- What was the best way to compare pre- and post-mining landscapes, productivity or capability?
- Will mining destroy regional groundwater supplies?
- Will groundwater levels recover within mined out areas?
- Can aquifers be reconstructed within mined out areas?
- Will the degraded chemical quality of groundwater within mined out areas significantly degrade groundwater quality in adjacent unmined areas?

- Can the chemical quality of groundwater in mined out areas be prevented from degrading through selective materials placement?

Beginning in 1977, with the formation of the Reclamation Research Technical Advisory Committee (RRTAC), the Alberta Government began to work with the mining companies to address these questions. RRTAC invested in three major projects: the Battle River Reclamation Research Project (BRRRP), Plains Hydrology and Reclamation Project (PHRP), and Highvale Soil Reconstruction Project (HVSRP), and numerous smaller projects to determine the answers necessary to support a regulatory framework that was both environmentally and economically responsible. The results of this research program are published in 36 RRTAC reports and numerous other papers in scientific journals and proceedings of scientific meetings.

This report synthesizes and summarizes this body of research results in the form of a series of questions and answers that is designed to provide the user with a single, unified information source for information on reclamation research in the plains of Alberta. The questions are separated into two main sections: Section 2.0 addresses questions that apply to the land resource, while Section 3.0 addresses questions that apply to the groundwater resource. Appropriate references for the interested reader are included at the end of each section.

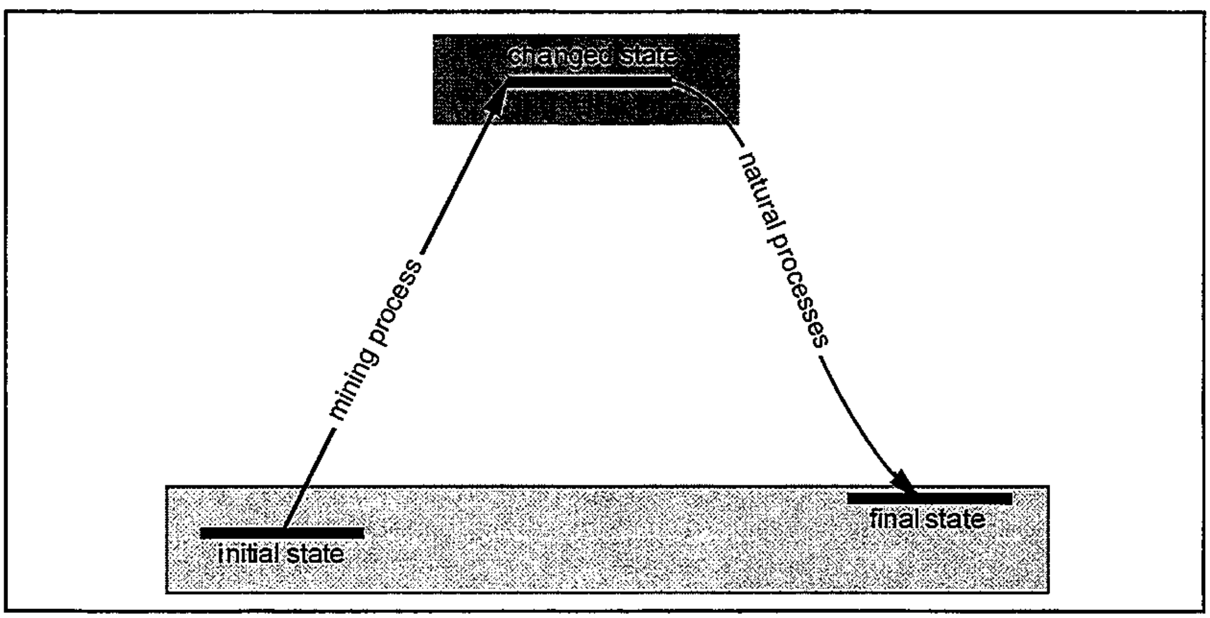

Figure 1.1 The final equilibrium state of a landscape after mining has occurred will be equivalent to a pre-mining landscape of equivalent characteristics. The two major controls on the landscape are climate and geology. The time required to reach equilibrium is variable and is still difficult to predict.

What Are The Land Resource Issues Related To Surface Mining?

Capability is the overriding issue around the land resource. In the plains of Alberta the type of capability in question is more often than not agricultural. Most of the questions asked in the past, and currently asked, revolve around the capability of the land surface or landscape. In this document, the discussion of the land resource issues related to surface mining is tailored and organized around capability. Section 2.1 discusses the concept of capability, what is meant by capability and how it is measured. The next four sections discuss the influence of a variety of landscape and management processes on the capability of reclaimed landscapes, specifically:

- Section 2.2, the soil reconstruction process;
- Section 2.3, compaction;
- Section 2.4, subsidence; and
- Section 2.5, soil salinization.

Finally, Section 2.6 provides a list of references for more in-depth information about plains coal mining, capability, and landscape and management processes.

The discussions in this document are based on a wealth of studies done over the last two decades in Alberta by both government (under the auspices of RRTAC) and industry. These studies, and years of operational experience by industry, represent a considerable body of knowledge and have increased the general understanding of reclaimed landscapes and the processes acting within them. However, there still remains considerable uncertainty and a lack of consensus in a number of key areas.

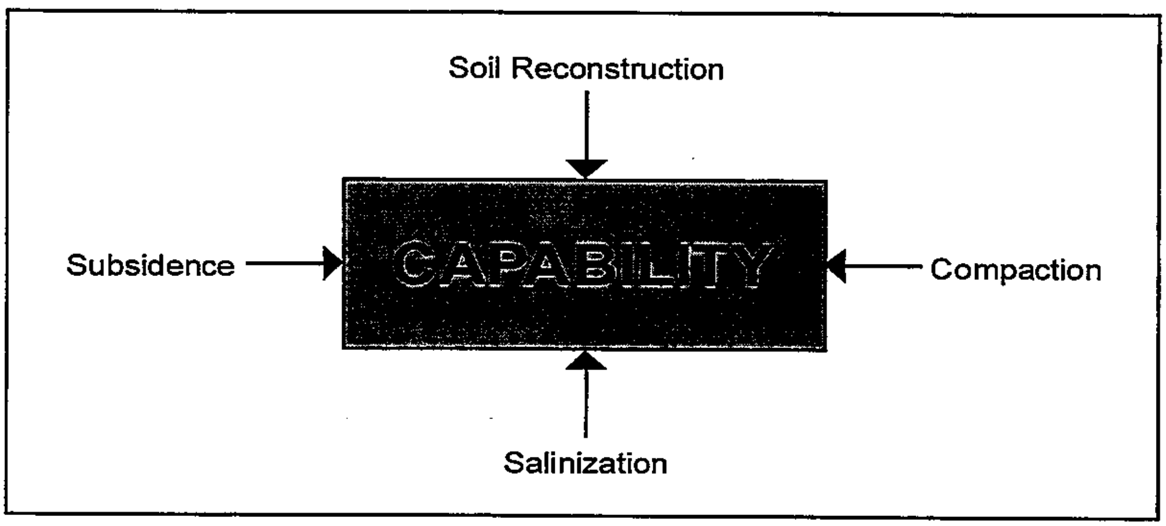

Figure 2.1 Some processes acting in the reconstructed landscape that affect the capability of the reconstructed landscape.

Q2.1 WHAT IS MEANT BY "CAPABILITY"?

A. Land capability, as defined in the Alberta Environmental Protection and Enhancement Act (1992), Conservation and Reclamation Regulation (AR 115/93) is:

> "the ability of land to support a given land use, based on an evaluation of the physical, chemical and biological characteristics of the land, including topography, drainage, hydrology, soils and vegetation."

The same regulation also defines the term "equivalent land capability" as:

> "the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical."

Capability is not productivity. As discussed in a paper by Macyk (1990):

> "Capability for agriculture was chosen as the basis for evaluating the product of reclamation rather than productivity primarily because **capability considers intrinsic properties of the landscape**. Productivity, on the other hand, addresses a parameter that is very much subject to alteration by management practices. In simple terms, a given level of productivity can be achieved from either good land with minimal management input or poorer land with greater management input. The significance of this is that in the latter case, removal of management input results in deterioration of productivity. Therefore, using productivity as a measure of reclamation performance does not allow for separation of the relative contributions of the land itself and management inputs."

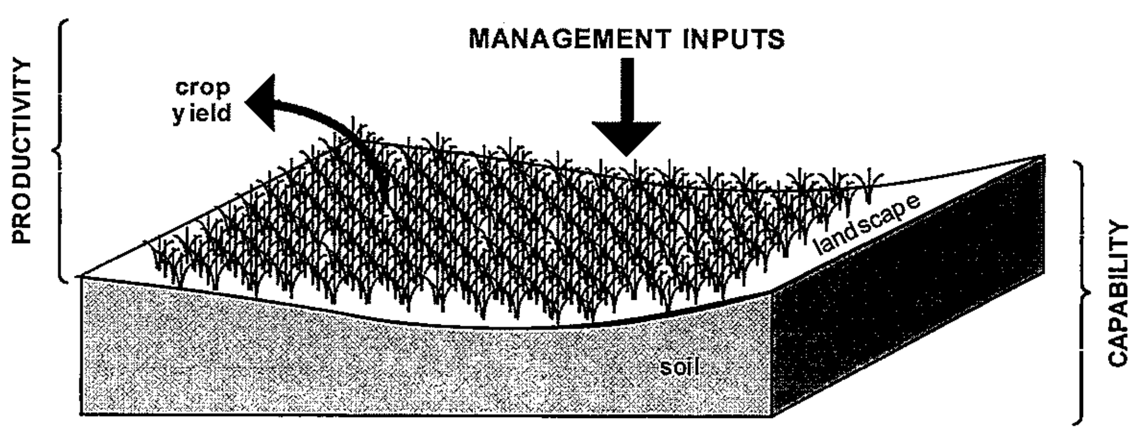

Figure 2.2 Capability considers intrinsic properties of the landscape, whereas productivity includes consideration of land management practices.

Q. How is capability measured?

A. Capability is measured on the basis of climate, landscape, and soil parameters. In Alberta, three methods exist for assessing capability (primarily agricultural) :

1. Land Capability Classification for Arable Agriculture,
2. Agricultural Capability Classification for Reclamation, and
3. Soil Quality Criteria.

The **Land Capability Classification for Arable Agriculture** (LCC) system is based on land and environmental factors as they affect dryland agriculture (Alberta Soils Advisory Committee 1987). In can be used to assess the agricultural capability of the post-, as well as the pre-disturbed condition. The component factors are all measurable climate, soil, or landscape features that affect plant growth and which are not dependent on undisturbed sites or traditional taxonomic classifications (Macyk, 1990). This system retains a close similarity to the previously used CLI – Soil Capability for Agriculture system, but tends to be more quantitative.

The **Agricultural Capability Classification for Reclamation** (ACCR) system parallels the LCC system. It uses the same land and environmental factors and the same rating scheme. As such it allows general comparisons to be made between reclaimed and adjoining undisturbed lands. The difference between the two systems is that the ACCR system explicitly defines the reconstructed soil profile and limits the rating to a depth of one metre.

The **Soil Quality Criteria** (SQC) is not a complete capability assessment method as it only considers the soil component of capability. Rather, SQC provides physical and chemical criteria for evaluating the suitability of soils and supports the other, previously mentioned, capability assessment methods. SQC is most often used to select soil handling options.

METHODS FOR ASSESSING CAPABILITY

- **LAND CAPABILITY CLASSIFICATION FOR ARABLE AGRICULTURE IN ALBERTA**
  Alberta Soils Advisory Committee, 1987. Edited by W.W. Pettapiece. Alberta Agriculture, Edmonton, Alberta. 103 pp., 5 maps.
- **AGRICULTURAL CAPABILITY CLASSIFICATION FOR RECLAMATION**
  L.A. Leskiw, 1993. Alberta Conservation and Reclamation Council Report No. RRTAC 93-13. ISBN 0-7732-6039-0. 97 pp.
- **SOIL QUALITY CRITERIA RELATIVE TO DISTURBANCE AND RECLAMATION**
  Alberta Soils Advisory Committee, 1987. Alberta Agriculture, Edmonton, Alberta. 56 pp.

Figure 2.3. Methods of assessing capability of reconstructed landscapes.

Q. What is the relationship between soil quality and capability?

A. The short answer is that soil quality is a component of capability. Soil quality embraces the quantification of specific soil parameters whereas capability is a holistic ranking of soil, landscape, and climate factors (Macyk, 1992). Soil capability is a synthesis of quality and quantity ratings.

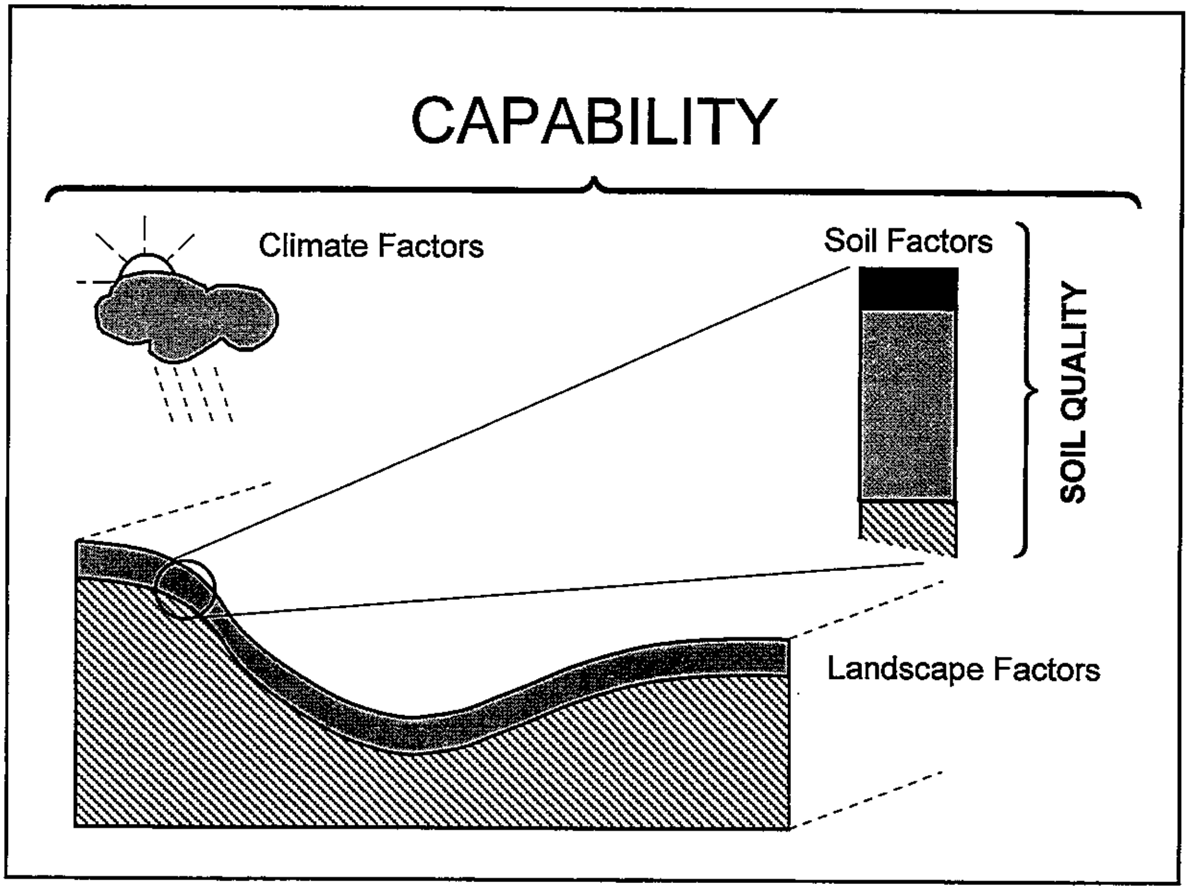

Figure 2.4. Components (factors) that are used to assess capability, and the relationship between capability and soil quality.

Q. Can reclaimed landscapes support the same range of land use as the pre-mining landscape?

A. Research and operational experience has shown that in the majority of situations, reclaimed landscapes can support the same/similar land use as that which existed prior to mining. In fact, disturbed land in Alberta has a legislative requirement to be returned to an equivalent land capability. This means that overall, the reclaimed land capability will be equivalent to the pre-disturbance capability, but that the ability to support individual land uses will not necessarily be identical after reclamation. Generally, the capability ratings (by %), for a given land area, are assessed prior to disturbance; the reclamation plan is then designed to replace similar percentages of each land capability class.

It's important to note that TIME is probably the most important factor in evaluating the impact of land disturbances. Climate remains the same prior to, and subsequent to mining. Topography following mining is generally similar to that which existed prior to mining, particularly if agriculture is the main land use. The soil materials that existed prior to mining are used in the reconstruction process. Good materials handling procedures (salvage and replacement) will minimize the effect of the disruption on a variety of soil parameters (i.e., pH, salinity, structure, porosity), so that the disturbed land is returned to an equivalent land-use state.

Q2.2 HOW DOES SOIL RECONSTRUCTION AFFECT CAPABILITY?

A. **Soil handling techniques during soil salvage and reconstruction strongly influences the resulting capability of the reconstructed landscape.** Soil reconstruction is a multi-stage process that begins with topsoil removal and ends with topsoil replacement.

As part of the mining process, topsoil and subsoil are removed as discrete layers in the area to be mined and either used immediately in soil reconstruction or stockpiled for use later in the reclamation process (see Thurber Consultants, et.al., 1990 for a discussion on the effects of topsoil storage). After mining has been completed and the spoil material graded, the soil mantle is reconstructed. In practice, up to 1.5 m of subsoil material has been placed on the spoil using scrapers, trucks, or graders. A layer of topsoil has then been spread over the subsoil to a depth of 15 cm.

As a consequence of the removal and reconstruction processes, the pre-existing soil mantle is mixed. Mixing results in the blurring of the abrupt distinction between different soil types that characterized the unmined landscape, resulting in a reconstructed soil mantle that is more uniform in its characteristics over larger areas than is the unmined landscape. Surface mining alters the scale over which variability in physical and chemical properties of soil occurs within the landscape. Reconstructed soils are heterogeneous on a local scale, but relatively homogeneous over larger areas (Macyk 1986). There is greater variability in chemical and physical properties within the reconstructed soil profile and within distances of a few metres than occurs in soil profiles in the unmined landscape.

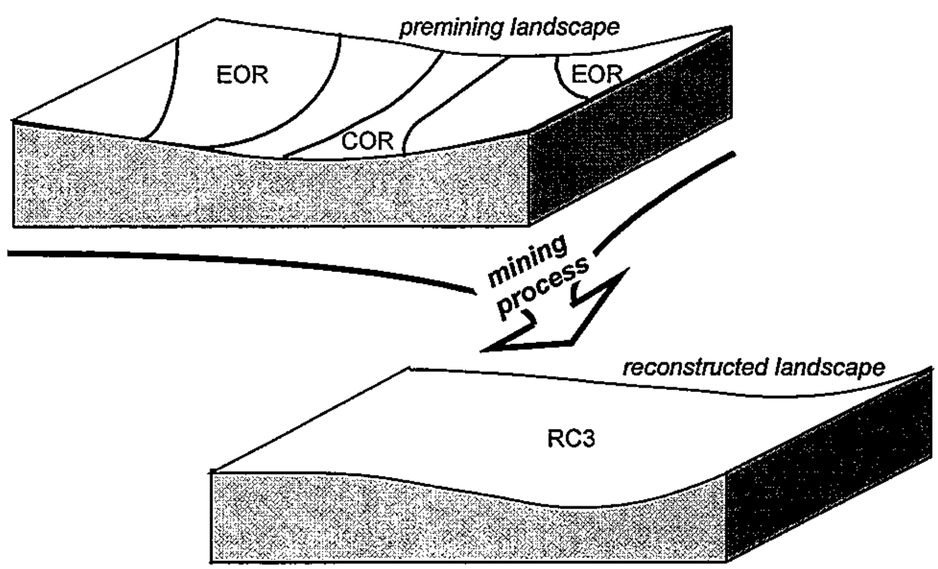

Figure 2.5 Mixing of the soil mantle during the removal and reconstruction processes blurs the abrupt distinction between the different soil types that characterize the undisturbed landscape.

Q. What are suitable replacement depths for topsoil and subsoil?

A. Suitable replacement depths are a function of site-specific characteristics. What occurs in the natural undisturbed landscape should be used as a guide or template for suitable replacement depths in the reconstructed landscape. Replaced soil thickness should be no more limiting to plant growth than it was in the undisturbed state. It must be emphasized that thickness replaced depends not only upon soil quality but the quality of the overburden and other factors such as mean annual precipitation, topography, slope angle and water-table position (Macyk, 1992).

Q. Can replacement depth vary?

A. The replacement depths for topsoil and subsoil may vary from site-to-site, as is the case for soils in the undisturbed state. The established practice in Alberta has been replacement of approximately 15 cm of topsoil over at least 1.0 m of subsoil. These replacement depths have evolved largely because development of surface coal mines has occurred in areas of Alberta that generally had natural topsoil and subsoil depths in these ranges. If development occurs in areas of Alberta that have different undisturbed topsoil and subsoil depths, equivalent replacement depths should be used. Essentially, one works with the site specific characteristics at a given location.

There is no question that replacement of the soil mantle – as subsoil and topsoil – is essential for a productive reconstructed landscape. Two RRTAC studies, The Battle River Soil Reconstruction Project (Leskiw, 1989) and The Highvale Soil Reconstruction Project (Graveland, 1988) demonstrated the benefit of placing subsoil over spoil, then replacing the topsoil. Results from these studies also suggest that replacement depths of subsoil may vary (within a certain range) without significantly impacting plant growth.

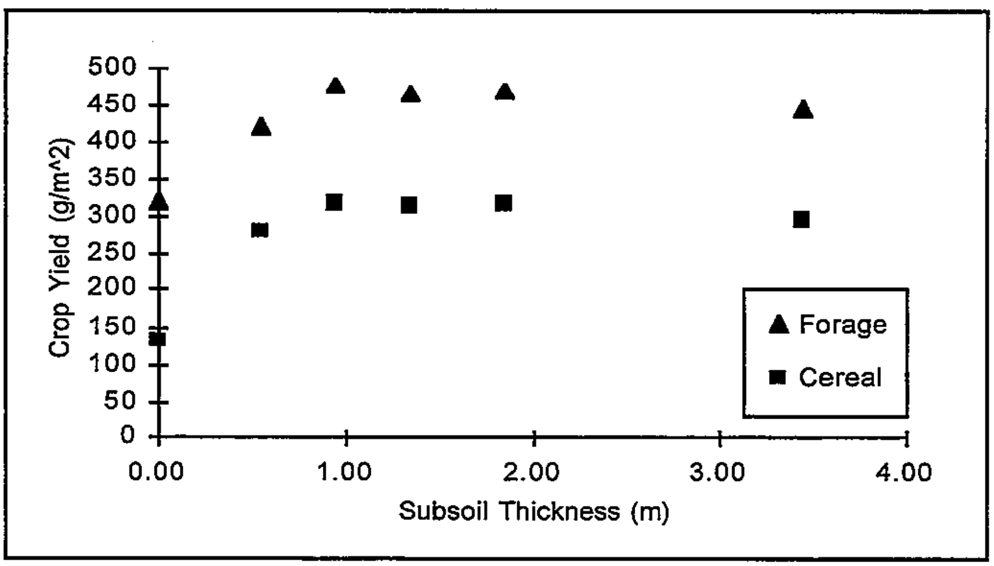

Figure 2.6 Variation in crop yields (5-year means) as a result of changes in subsoil thickness (adapted from Graveland et al., 1988).

Q. What variability in thickness is allowable?

A. The undisturbed landscape should be used as a guide for what variability is reasonable within a given site. Some variability within a site is only realistic, and will occur naturally as the landscape evolves. As an operational practice, variability within original replacement in an area has been low. When assessing variability one should keep in mind the purpose of the soil layer. Sufficient material should be replaced to allow the re-creation of a medium that supports good plant root development. Too shallow a soil layer will impact the capability of the site, by affecting key soil parameters that influence crop growth, such as water-holding capacity.

Data from the Highvale Soil Reconstruction Project, as indicated in Figure 2.6, are in agreement with this position. Over the subsoil thickness range of 0.55 m to 3.45 m there were no significant differences in crop yields. Unfortunately, the data do not provide an indication of which subsoil thickness would significantly reduce crop yields.

The characteristics of the underlying spoil or overburden material will have a bearing on effects of different subsoil thicknesses. For example, in an area where < 0.5 m subsoil has been replaced, it is likely that crop yields will be better where the underlying spoil is of fair to good quality than where underlying spoil is poor to unsuitable. In other words, spoil characteristics will have a greater effect on crop yields, etc., in areas of more shallow subsoil replacement.

Q. What constitutes suitable subsoil?

A. Generally speaking, suitable subsoil at a given site is determined by the nature of the subsoil in the undisturbed setting.

The optimum subsoil is considered to be non-saline, non-sodic, have a neutral to slightly acid pH, a bulk density of 1.3, with a friable, granular structure. However, optimum subsoil, may not exist naturally in a given location. Therefore, the suitable subsoil in a reconstructed landscape should parallel what is found in the undisturbed setting.

Q. How is suitability assessed?

A. The suitability of topsoil and subsoil for use in reclamation is assessed primarily on the basis of chemical criteria, using the method outlined in the document: Soil Quality Criteria Relative to Disturbance and Reclamation. There has been some inclusion of key physical properties in the evaluation by some mining companies to improve the suitability evaluation.

The Soil Quality Criteria (SQC) system does not account for climate or landscape considerations and is designed strictly for rating soil quality, based on soil characteristics. It divides Alberta into three regions: Plains, Eastern Slopes, and Northern Forests. In the Plains region it is assumed that the intended land use is agriculture, and this is reflected in the soil criteria. For example, pH ranges for the various classes in the Plains are generally higher than for the Northern Forests.

In the SQC system, soil properties (mostly chemical properties) in each soil horizon or depth interval are rated as good, fair, poor, or unsuitable (Figure 2.7, Tables 2.1 and 2.2). Separate criteria are used for topsoil and subsoil layers. Each soil horizon or layer is given a rating based on its most limiting property. For example, if the pH is classified as poor but all other properties are rated as good, the horizon is given an overall rating of poor to reflect the pH limitation.

The SQC system directs considerable attention to appropriate survey techniques, mapping, soil sampling, and soil analytical methods. It recommends sampling to five metres depth because some of the deeper material may be used in place of subsoil. The criteria are used to assess soil material quality prior to disturbance to plan soil salvage and subsequent to soil reconstruction to determine reclamation success.

Category	Interpretation/Limitations
Good (G)	● **NONE TO SLIGHT** soil limitations that affect use as a plant growth medium.
Fair (F)	● **MODERATE** soil limitations that affect use but which can be overcome by proper planning and good management.
Poor (P)	● **SEVERE** soil limitations that make use questionable. This does not mean the soil cannot be used, but careful planning and very good management are required.
Unsuitable (U)	● **VERY SEVERE**; chemical or physical properties of the soil are so severe that reclamation would not be economically feasible or in some cases impossible.

Figure 2.7 Categories of soil suitability (Alberta Soils Advisory Committee, 1987).

Table 2.1. Criteria for evaluating suitability of **subsoil** in the Plains Region (Alberta Soils Advisory Committee 1987).

Rating/Property	Good (G)	Fair (F)	Poor (P)	Unsuitable (U)
Reaction (pH)	6.5 to 7.5	5.5 to 6.4 & 7.6 to 8.5	4.5 to 5.4 & 8.6 to 9.0	< 4.5 & > 9.0
Salinity (EC) (dS/m)	< 3	3 to 5	5 to 10	> 10
Sodicity (SAR)	< 4	4 to 8	8 to 12	> 12[1]
Saturation (%)	30 to 60	20 to 30 60 to 80	15 to 20 80 to 120	<15 & >120
Stone Content (% Vol.)	< 3	3 to 25	25 to 50	> 50
Texture	FSL, VFSL, L, SiL, SL	CL, SCL, SiCL	S, LS, SiC, C, HC	Bedrock
Moist Consistency	very friable, friable	loose, firm	very firm	extremely firm
Gypsum $CaC0_3$ Equivalent (%)	The suitability criteria for sodicity (SAR) may be altered by the presence of high levels of either lime ($CaCO_3$) or gypsum ($CaS0_4$) in excess of other soluble salts.			

1 Materials characterized by an SAR of 12 to 20 may be rated as poor if texture is sandy loam or coarser and saturation % is less than 100.

Table 2.2 Criteria for evaluating suitability of **topsoil** in the Plains Region (Alberta Soils Advisory Committee 1987).

Rating/Property	Good (G)	Fair (F)	Poor (P)	Unsuitable (U)
Reaction (pH)	6.5 to 7.5	5.5 to 6.4 & 7.6 to 8.4	4.5 to 5.4 & 8.5 to 9.0	< 4.5 & > 9.0
Salinity (EC) (dS/m)	< 2	2 to 4	4 to 8	> 8
Sodicity (SAR)	< 4	4 to 8	8 to 12	> 12[1]
Saturation (%)	30 to 60	20 to 30 60 to 80	15 to 20 80 to 120	< 15 & > 120
Stoniness Class	S0, S1	S2	S3, S4	S5
Texture	FSL, VFSL, L, SL, SiL	CL, SCL, SiCL	LS, SiC, C[2], S, HC[3]	
Moist Consistency	very friable, friable	loose	firm, very firm	extremely firm
Organic Carbon (%)	> 2	1 to 2	< 1	
$CaC0_3$ Equivalent (%)	< 2	2 to 20	20 to 70	> 70

1 Materials characterized by an SAR of 12 to 20 may be rated as poor if texture is sandy loam or coarser and saturation % is less than 100.

2 C – May be upgraded to fair or good in some arid areas.

3 HC – May be upgraded to fair or good in some arid areas.

Q. When should suitability be assessed?

A. Suitability of subsoil should be assessed during two phases of the mining process: (1) as part of the baseline assessment prior to land disturbance, at a reasonable time prior to development; and (2) after landscape reconstruction, from several days to as much as a year after the process has been completed.

Undertaking soil quality assessments one or two or more years following completion of work at a site can result in a change in ratings compared to an assessment completed shortly after the reconstruction process has been completed (Macyk, 1992). Several parameters, such as bulk density, SAR, and EC, could be changed due to natural processes acting on the soil column over time. As a result, soil quality will change with time, either favourably or unfavourably.

Q. Can anything be done to improve subsoil quality?

A. Generally speaking, if good soil handling procedures are followed, there will likely not be the need to adjust subsoil quality. The best way to maintain or enhance subsoil quality is to minimize impact on the physical properties of the material. This means salvage and replacement of materials at, or as near to, optimum soil moisture as possible to preserve adequate porosity, water movement, and plant rooting capability.

Amendments such as fly ash or bottom ash could be added to potentially improve subsoil structure, however, this addition potentially would limit the types of amendments that could be used in the topsoil.

Q2.3 IS CAPABILITY OF RECONSTRUCTED SOILS ADVERSELY AFFECTED BY COMPACTION?

A. Capability of reconstructed soils in the Plains Region of Alberta generally has not been adversely affected by compaction. Compaction of reconstructed soils in the Plains Region of Alberta has tended to be restricted to surface soil layers. This makes the compaction that has occurred amenable to corrective measures, thus minimizing the affect of compaction on capability.

Soil compaction is not, of course, unique to industrial activities. There are many natural processes that also compact soil. Natural processes that may result in soil compaction include, for example, animal trampling, tree root pressure, and soil forming processes. The compaction resulting from these natural processes tends to either affect shallow soil layers and/or be of limited thickness. Standard tillage is generally sufficient to loosen soil compacted by natural processes. However, compaction arising from soil reconstruction activities at a mine site can be extensive and affect a deep layer of soil. If soil conditions are conducive to compaction during soil reconstruction, there is a risk of deep compaction extending throughout the depth of soil replacement. Although the risk exists, evidence collected to date in the Plains Region of Alberta shows that compaction in reconstructed soils has been restricted to the surface soil layers (Figure 2.8)

The responses to questions posed in this section of the report have as their primary source two RRTAC documents:

RRTAC 91-4, Soil Physical Properties in Reclamation; and

RRTAC OF-9, The Effect of Soil Compaction on Root Penetration, Mechanical Impedance, and Moisture-Density Relationships of Selected Soils of Alberta.

The responses also draw on observational results from several projects conducted by RRTAC during the 1980's, some of which has been reported in the following documents:

RRTAC 88-11, Highvale Soil Reconstruction Project: Five Year Summary;

RRTAC 89-5, Battle River Soil Reconstruction Project Five Year Summary; and

RRTAC 90-8, Plains Hydrology and Reclamation Project: Summary Report

For more a more in-depth treatment of this topic, the interested reader is referred to these documents.

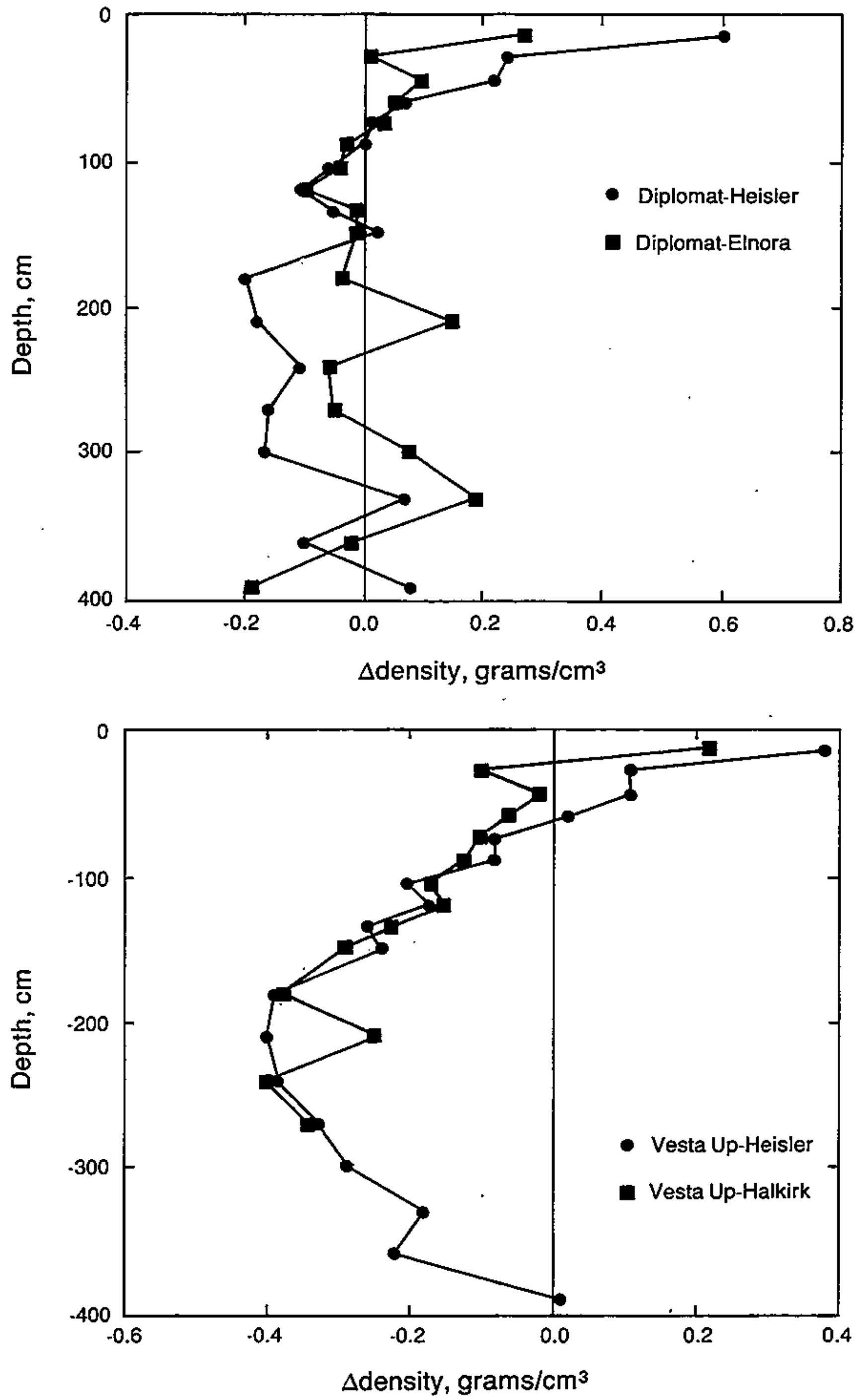

Figure 2.8 Density differences between reconstructed soils at Diplomat and Vesta Mines with comparable unmined soils (Heisler, Halkirk, and Elnora soils). Positive values indicate compaction of the reconstructed soil. Source: RRTAC 90-8.

Q. What effect does compaction have on crop growth in the reclaimed setting?

A. Soil compaction affects plant growth directly by retarding root development and indirectly by altering soil properties that influence the soil's aeration and water movement.

As plant roots grow they must push aside soil particles ahead of the root tip and beside the roots. The greater the resistance of the soil to deformation, the slower the roots are able to grow and the less developed the root system will be. A poorly developed root system makes it difficult for the plant to obtain an adequate supply of moisture and nutrients, and plant growth and yield may be adversely affected. To maximize root growth, plants exploit the path of least resistance such as soil pores and zones of looser material. In a compacted soil, pore size and total porosity are reduced, leaving little for the plant to exploit, thus reducing the rate of root growth.

A penetration resistance of 3.0 MPa for soil, measured with a soil penetrometer, is often cited as causing severe root growth restriction. Although this is generally true, plants vary in their sensitivity to compacted soils. Perennial plants often do better than annuals on compacted soils because the longer growing season of perennials allows them to exploit periods when the soil is moist and of relatively low strength (i.e., early in the growing season). Another factor in their favour is that the root systems of perennials maintain live tissue through the winter and so do not have to develop an entirely new root system each year.

Penetration resistance measurements are highly dependent on soil moisture, so interpretation of data can sometimes be difficult. Bulk density is the other common measure of soil compaction. It has its own set of interpretation problems, because plant response to bulk density is highly dependent on soil texture. Table 2.3 shows an attempt by one soil capability assessment scheme to quantify the effect of bulk density and texture on capability for agriculture in Alberta (Pettapiece, 1987). Figure 2.9 is another proposed scheme for establishing a set of threshold values so that field personnel could determine whether or not a 'problem' existed from a physical perspective, considering plant growth as the overall concern (Naeth, et.al., 1991). In this case bulk density and penetration resistance where chosen as the two indicator parameters because of their relative ease of measurement and the generally universal understanding of their interpretive value (Naeth, et.al., 1991)

Table 2.3 Point deductions for soil capability rating system based on bulk density/soil texture combinations. The point system is scaled 0 to 100. The system is based on soil capability for agriculture and includes factors such as type of crops that can be grown; therefore, the values in the table do not indicate a percent reduction of yield, rather they represent the relative capability for agriculture (Adapted from Pettapiece, 1987).

	Texture					
Bulk Density	S, LS	SL	L	SiL, CL	SiC – C	HC
1.20	0	0	0	0	0	0
1.30	0	0	0	0	0	5
1.35	0	0	0	0	5	10
1.40	0	0	0	5	10	20
1.45	0	0	5	10	20	40
1.50	0	5	10	20	40	50
1.60	10	20	30	40	55	70
1.70	30	40	50	60	70	90
1.80	50	60	70	80	90	—

Notes: S = sand; L = loamy; Si = silt; C = clay; HC = heavy clay

		Rating / Threshold Values			
Property	Texture	Good	Fair	Poor	Limiting
Bulk Density (Mg/m^3)	Sandy Loam	≤ 1.50	> 1.50 and ≤ 1.60	> 1.60 and ≤ 1.70	> 1.70
	Loam	≤ 1.40	> 1.40 and ≤ 1.50	> 1.50 and ≤ 1.60	> 1.60
	Clay Loam	≤ 1.30	> 1.30 and ≤ 1.40	> 1.40 and ≤ 1.50	> 1.50
Penetration Resistance (MPa)		≤ 2.0	> 2.0 and ≤ 3.0	> 3.0 and ≤ 4.0	> 4.0

Notes:

- Measurements should be made under average antecedent soil water conditions (neither extremely dry nor exceedingly wet).
- It is recommended that these measurements be made at a depth of 15 cm.
- It is recommended that ASAE standards be followed in use of the penetrometer (ASAE standard 30° cone, manually pushed, with either 0.5 or 0.2 sq. inch cone).

Figure 2.9 Proposed threshold values for soil physical properties related to plant growth (after Naeth et al., 1991).

Q. Will compaction always develop?

A. Although soil compaction is always possible, it won't necessarily develop in reconstructed soils. In mine reclamation situations, the potential for compaction is substantial because of two factors: (1) the use of large, heavy equipment for earth moving operations; and (2) the disruption of soil strength due to materials handling. However, when proper materials handling procedures are used for soil reconstruction, compaction tends to be minimal.

Q. Can compaction be alleviated?

A. Compaction may be alleviated through natural processes and/or mechanical methods, with the most widely used method being subsoil ripping.

The natural processes that work to loosen compacted soils are: plant root growth, wet/dry cycles, and freeze/thaw cycles. None of these processes are very effective in the Plains, except perhaps in a thin surface layer. As a result soil compaction can often be measured decades after the land was disturbed.

Plant roots penetrate pores and other zones of soil weakness and help fracture the soil as their roots expand. Thick-rooted plants that develop extensive root systems, such as alfalfa, are most effective but even they will take several years to cause any measurable change. Because roots are only able to penetrate if there are initial planes or zones of weakness, plants are ineffective at loosening seriously compacted soils.

As soils go through **wet/dry cycles** they swell and shrink, which creates physical stresses in the soil that gradually loosen a compacted layer. Because many areas in Alberta have smectite clays which are noted for their shrink/swell properties, wet/dry cycles have good potential to loosen compacted soil. However frequent wet/dry cycling is limited to a thin surface layer and the effect decreases rapidly with depth. While wet/dry cycling may loosen surface compaction, it has little effect on most of the root zone.

Freeze/thaw cycles loosen compacted soils through stresses associated with the freezing of water in water-filled soil pores (volume expansion) and by ice lens formation. The volume expansion effect is most pronounced in the thin surface layer that undergoes numerous freeze/thaw cycles; ice lens formation is most pronounced at depth where the freezing front remains stationary for extended periods. Both these processes require a considerable amount of moisture in the soil. If soil pores are not saturated with water, the ice merely expands into the empty pore space and does not fracture the soil. If there is little soil moisture at depth, water does not move to the freezing front to form ice lenses.

In the Plains region of Alberta the months before freeze-up are generally dry and so there is often little soil moisture to freeze. Freeze/thaw may be a factor in moister regions (Mountains and Foothills, for example) but has little, if any, effect on compacted soils in the Plains.

The most widely used **mechanical method** of ameliorating compaction is **subsoil ripping** (Naeth, et. al., 1991). A ripper, the most commonly used piece of equipment for these operations, consists of a number of steel shanks that deeply penetrate and shatter the soil. A ripper usually has three or five shanks, the spacing between them approximately equal to the depth of penetration. Depth of penetration usually varies from about 30 cm to almost 100 cm. The size of equipment needed to pull rippers ranges from farm tractors to large D-8 or D-9 caterpillar tractors, depending on the depth of ripping and severity of compaction. Ideally, the ripper shanks should extend beyond the wheels of the equipment used to pull the ripper, otherwise the wheels of the equipment may cause further compaction. In addition, ripping must be done under the proper moisture conditions to be effective (i.e., dry enough to shatter the soil).

Q. What are the optimum conditions for placing subsoil?

A. In theory, preventing compaction is simple: stay off susceptible soils with heavy loads (Thacker et. al., 1994). The susceptibility of soils to compaction varies with a soil's structural development, organic matter content, soluble salt concentration, and most of all, water content (Thacker, et al. 1994). In turn, each of these parameters are related to a soil's texture and clay mineralogy. One method for obtaining the information required to assess the susceptibility of a soil to compaction is the Proctor engineering test. A Proctor test assesses the maximum density obtainable for a soil under varying moisture contents. An example of the output of a Proctor test is given as Figure 2.10, which shows the moisture density relationship for seven different soil materials.

A common guideline for minimizing soil compaction is to restrict machine operations/traffic when the soil water content equals or surpasses the "optimal moisture content"; ideally moisture content should not exceed 75% of this value when compactive forces are introduced. Thacker et al., 1994, recommend that this value (75% of optimum moisture content from the Proctor test) be used as the standard to avoid compaction.

Soil susceptibility to compaction can also be evaluated by considering the maximum bulk density obtained from the moisture-density curves. The most susceptible soils are those that exhibit the highest "maximum density" during the Proctor test.

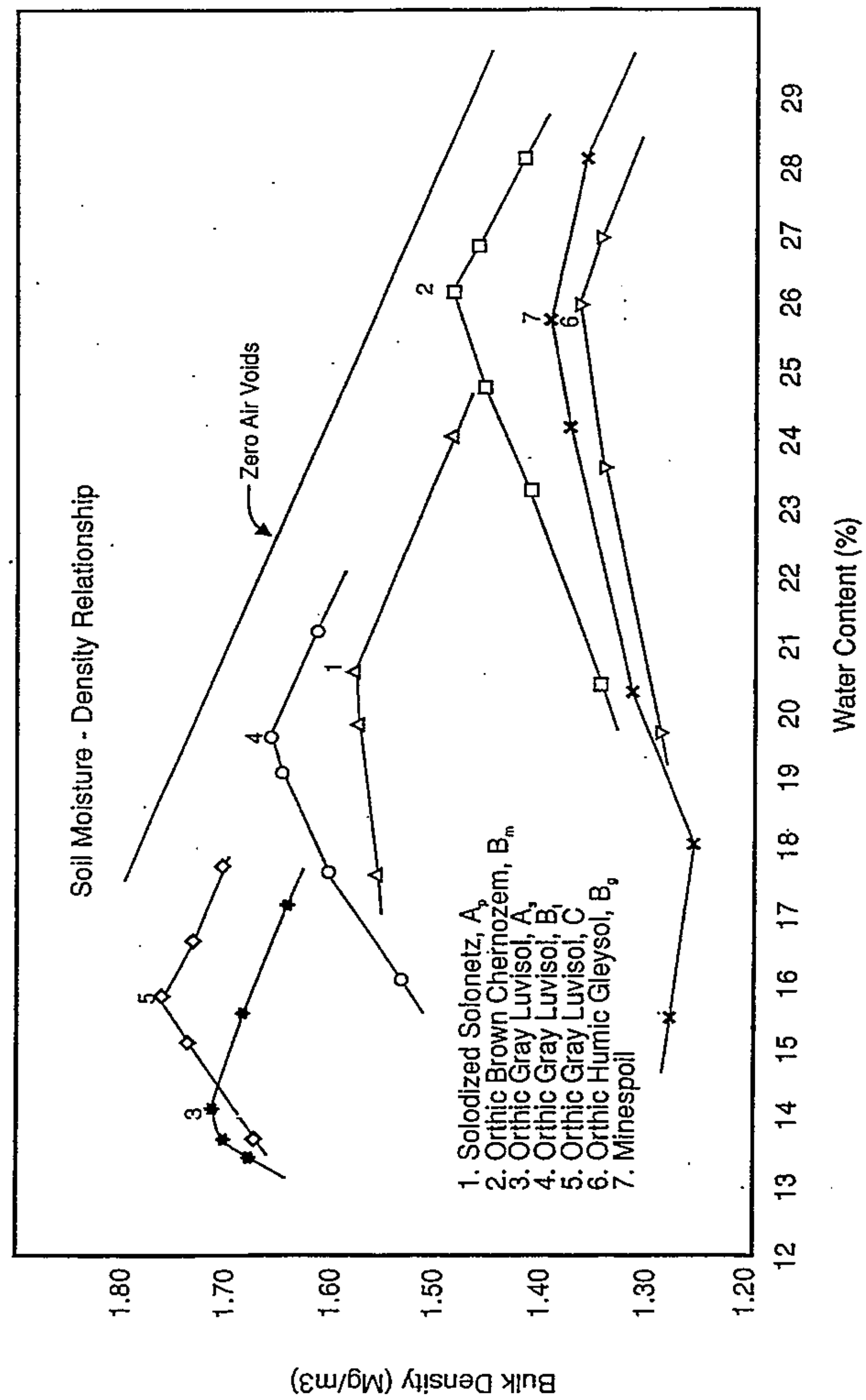

Figure 2.10 Moisture-density curves for seven Alberta soils derived from Proctor tests (after Thacker et al., 1994). The water content at the peak density is termed the "optimal moisture content".

Q2.4 IS CAPABILITY OF RECONSTRUCTED LANDSCAPES ADVERSELY AFFECTED BY SUBSIDENCE?

A. The simple answer is yes, but not in a very significant way. Settlement behavior of reclaimed mine spoil was the subject of a series of studies that were carried out by a geotechnical engineering team from the University of Alberta between 1979 and 1987. Studies were conducted at Diplomat, Vesta, and Paintearth Mines in the Battle River mining area as part of PHRP and at Highvale Mine in the Lake Wabamun mining area as part of a separate study conducted for TransAlta Utilities Ltd. The results of these studies were reported in a series of papers that were published in conference proceedings and in scientific journals, and in a series of RRTAC reports, which are listed at the end of this section. The key findings of these studies are presented here as they relate to the question posed as the title of this section.

The discussion that follows expands on the simple answer by examining a series of questions that follow from the initial question:

1. Is mine spoil unique in its subsidence behavior?
2. In what ways can subsidence adversely effect agricultural capability?
3. How is subsidence manifested in a reclaimed landscape?
4. What causes mine spoil subsidence to occur?
5. Why does spoil subside differentially?
6. Is the subsidence behavior of all mine spoil the same?
7. What magnitude of subsidence can be expected in mine spoil?
8. How long after mining is completed will subsidence continue?
9. Are there techniques for preventing or managing spoil subsidence?
10. How does a field inspector cope with certification of land that is continuing to subside?

It's important to note that subsidence can complicate the certification process. This is because the potential for subsidence creates uncertainty regarding the stable steady-state topography and the resulting potential for reduction in capability for agriculture. This uncertainty may cause inspectors to delay certification, while awaiting development of subsidence to allow greater confidence in their decisions.

Q. Is mine spoil unique in its subsidence behavior?

A. Mine spoil is not unique in its subsidence behaviour, rather it behaves like any other uncompacted fill in exhibiting surface subsidence. When soil or rock rubble is dumped or dozed into place without being compacted, the resulting fill constitutes uncompacted fill. Settlement, or subsidence, of the land surface is a characteristic of all uncompacted fills, not just mine spoil. Some subsidence occurs even in dry spoil material in response to its own weight (SELF-LOAD COMPACTION). The loose structure of the lower part of the fill is compressed by the weight of the overlying material. The addition of water increases both the rate and magnitude of subsidence (HYDROCOMPACTION).

Q. In what ways can subsidence adversely affect agricultural capability?

A. Surface subsidence can adversely affect agricultural capability by altering the designed end land use and posing a hazard to equipment and livestock.

The first way that subsidence can adversely agricultural capability, **alteration of designed end land use**, is accomplished through the creation of depressions. Subsidence depressions commonly result in ponding, which has a number of effects, including:

- reduction in the arable acreage relative to the original reclamation plan,
- creation of obstructions that alter field pattern and reduce "farmability", and
- creation of unplanned water-fowl habitat.

Subsidence can also disrupt post-reclamation drainage patterns by altering gradients or creating closed depressions. As a result, drainage may be rerouted or disrupted.

Subsidence can also disrupt structures such as roads and buildings. Roads across spoil commonly require extraordinarily high maintenance. For example, repeated re-surfacing of Highway 855 is required where it crosses Diplomat Mine. In addition, construction of buildings may not be possible without extraordinary foundation treatment.

The second way that subsidence can adversely agricultural capability is by **posing a hazard to agricultural operations** in the form of equipment damage and injury to livestock. Under certain conditions, subsidence on farm land can produce relatively uncommon and short-lived sinkholes, which are generally a few metres in diameter. These features, which form under particular conditions, create voids that are capable of causing equipment damage or injury to livestock.

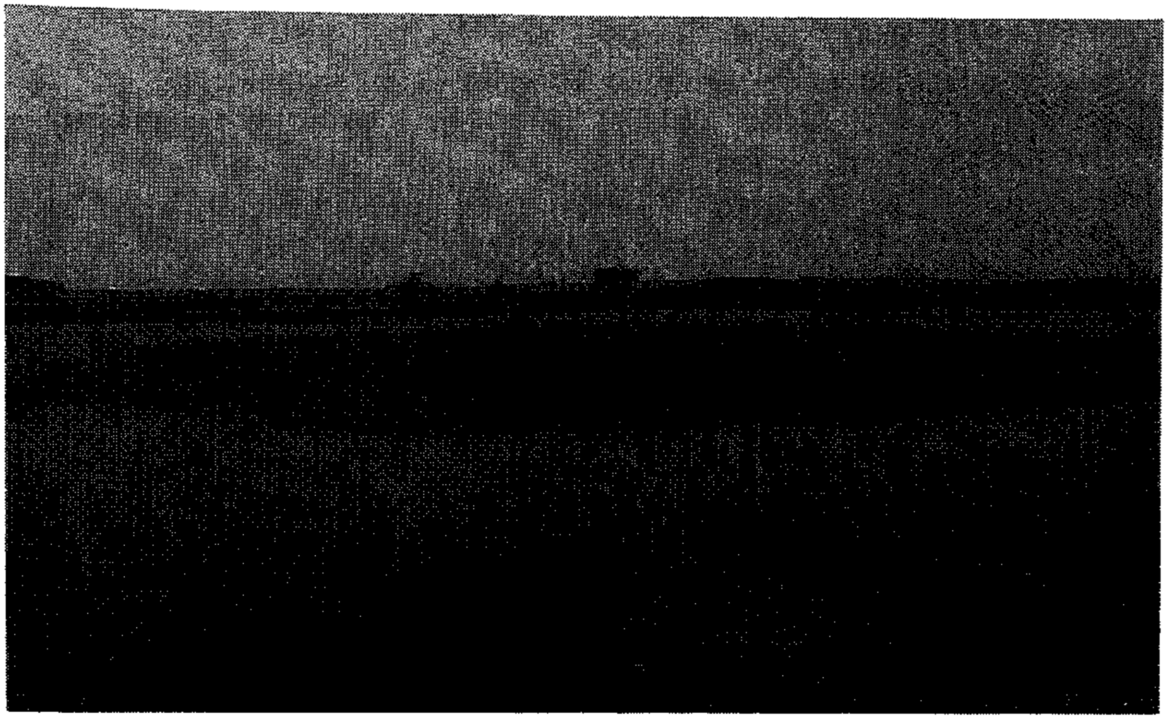

Figure 2.11 Subsidence depression in the eastern part of Diplomat Mine. Ponding in the depression has resulted in drowning out of crops.

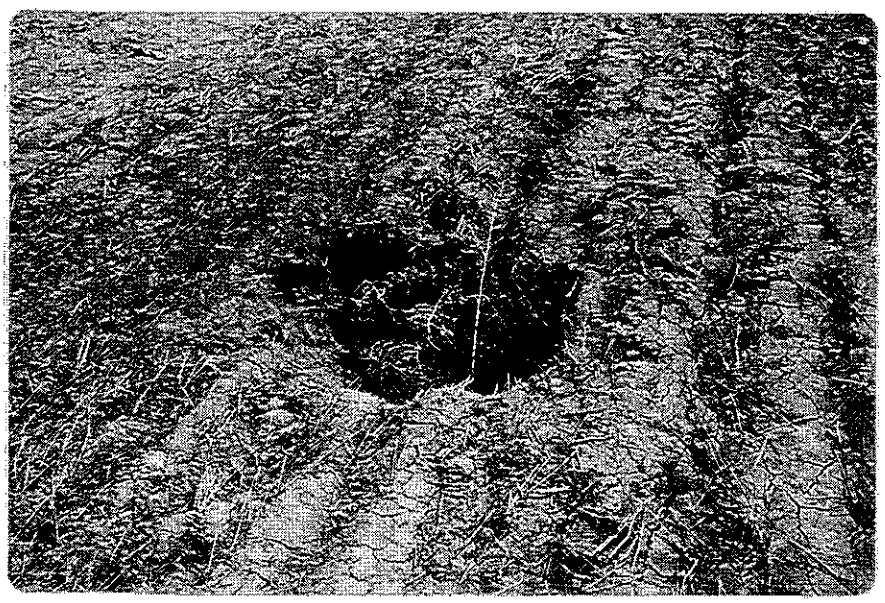

Figure 2.12 Sinkholes such as this one, form where voids migrate upward through thin, till-derived spoil, early in the post-reclamation period. Cattle or farm equipment moving over such a void that has not yet broken the surface run the risk of dropping a leg or wheel into the void.

Q. How is subsidence manifested in a reclaimed landscape?

A. The subsidence of surface mined spoil manifests itself in two ways:

- **area-wide subsidence**, which requires an elevation survey to detect; and
- **differential subsidence**, which is seen in most reclaimed landscapes in the form of surface pits and depressions.

Reclaimed landscapes are characterized by two types of topographic feature that are formed by differential subsidence: elliptical depressions and sinkholes. Elliptical depressions are by far the most common and can develop over as much as 5% to 10% of the surface. In contrast, sinkholes are rarely observed.

Depressions generated by differential subsidence are elliptical in plan view, generally symmetrical, with the long axis of the ellipse about twice the length of the short axis. The depth of the depression is commonly about 1/40th of the length of the long axis. These depressions generally occur in sub-parallel, approximately linear trends that parallel the crests of spoil windrows prior to leveling. The long axis of the depressions are generally aligned along the trend. The depressions generally occur over the pre-leveling troughs between spoil windrows.

In the larger depressions ephemeral ponding generally develops during spring melt and following major summer and fall rain storms. In some cases the ponds can become semi-permanent or permanent. Water ponded in these depressions infiltrates into the underlying spoil and induces subsidence (source of water for rewetting of the spoil mass).

Sinkholes have been observed to form near the centres of some elliptical depressions. Typically, the hole itself is 0.5 to 0.6 m in diameter, with side slopes inclined outward at about 70°. The central debris pile is commonly about 0.3 to 0.6 m below the surface.

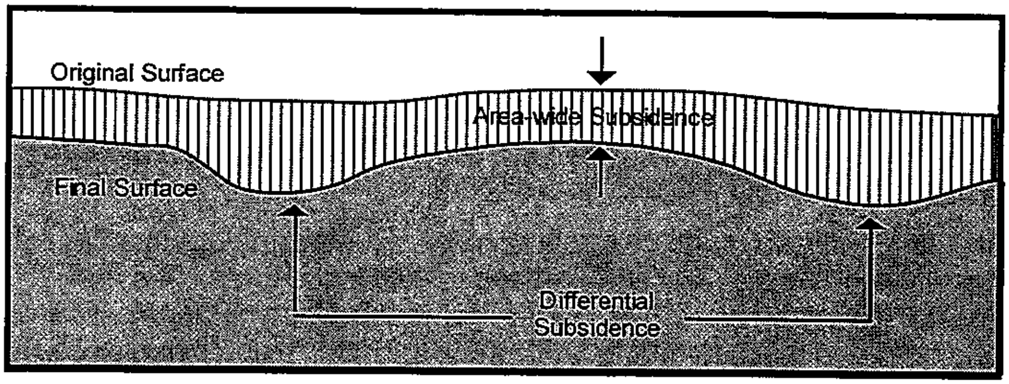

Figure 2.13 Schematic diagram showing relationship between area-wide settlement and differential subsidence. The entire mine spoil mass compresses to produce area-wide settlement . Some locations experience greater than average compression resulting in differential subsidence.

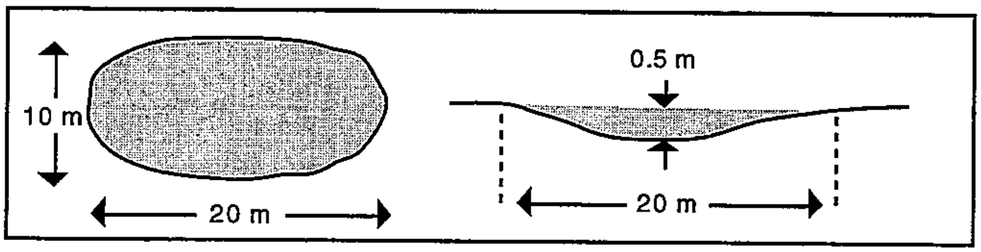

Figure 2.14 The long axis of settlement depressions is commonly about 20 m across, although in thicker spoil, depressions as much as 100 m across are not uncommon.

Figure 2.15 The linear trend of ponded depressions just to the right of the road indicates alignment of subsidence depressions along the trend of the trough between two spoil windrows. The parallel lines of wetter (darker) soil mark this and neighboring troughs.

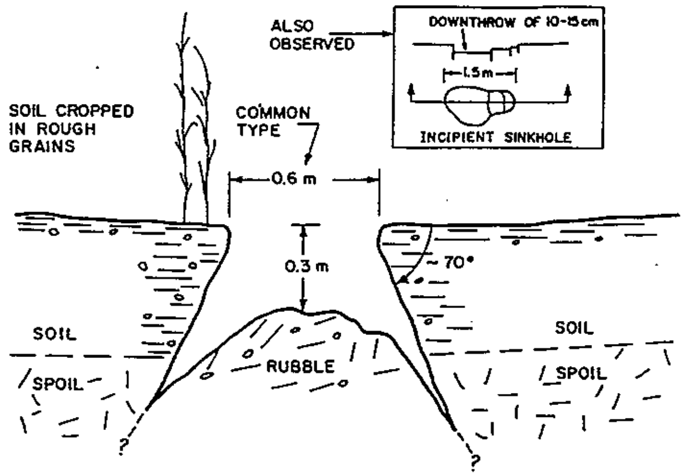

Figure 2.16 This schematic diagram illustrates the geometry of typical sinkhole features observed in thin, till-derived spoil.

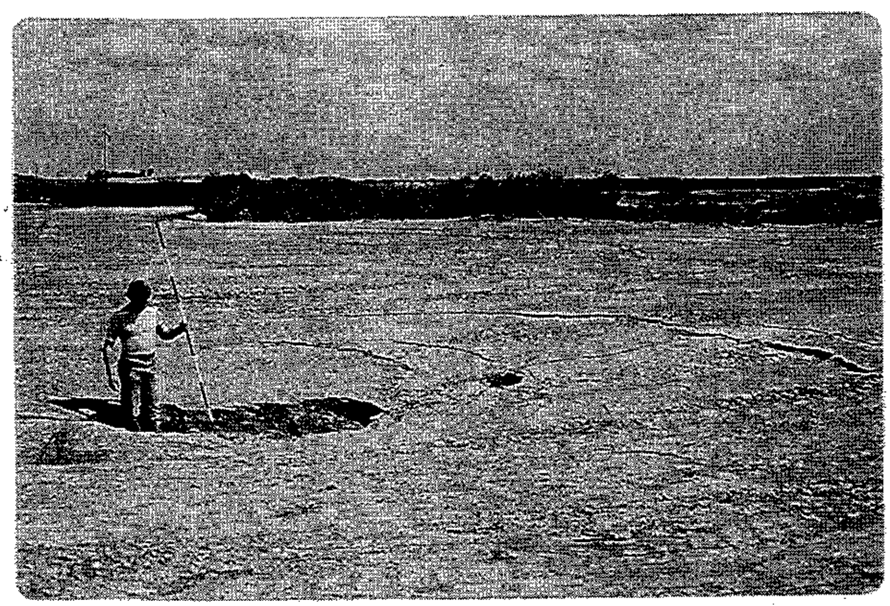

Figure 2.17 Subsidence depression and sinkhole formed during initial subsidence of graded spoil at Diplomat Mine.

Q. What causes mine spoil subsidence to occur?

A. Subsidence of mine spoil occurs as a result of a combination of three processes: self-load compression, hydro-compaction and macro-void migration.

- **Self-Load Compression begins immediately on an area-wide basis**

Spoil settles through compression from the weight of overlying spoil. At a micro level this compression occurs by (1) crushing of fragments and (2) rotational reorientation of individual fragments in response to loading.

- **"Hydro-Compaction" results from rewetting of spoil**

All overburden material in the plains region of Alberta exhibits the property of losing strength in response to rewetting. When fragments of spoil material are originally disturbed, they expand slightly in response to the release of stress. This slight expansion places the pore water under tension and the fragments become quite hard and strong. When these fragments are rewetted, they imbibe water, swell to a greater or lesser degree, and disintegrate. Where the disintegrating fragment is buried within the spoil mass, the weight of the overlying spoil loads the fragment resulting in volume reduction through crushing. In addition, particles that are shed from the disintegrating fragment move downward, in response to gravity, to fill voids between larger fragments. This reduction in volume within the spoil mass results in subsidence of the overlying surface.

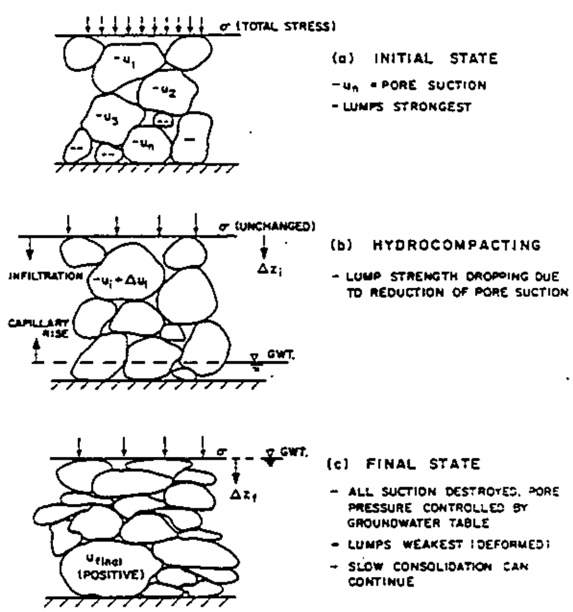

Figure 2.18 Diagrammatic explanation of volume reduction resulting from hydrocompaction of loose, blocky spoil.

- **Upward Migration of Macro-Voids produces sinkholes**

Formation of sinkholes in spoil involves a particular interaction of large voids, which form under certain conditions, with the two processes of self-load compaction and hydrocompaction. Large voids in spoil are formed around large, angular blocks of spoil, by melting of frozen blocks, or by hydrocompaction of loose spoil beneath a more dense layer. The spoil above such a void arches so little deflection of the ground surface is observed. The void migrates up through the spoil as the overlying spoil becomes wetted, slakes, and collapses into the void. The surface layer is commonly more compact because of the compactive effort produced by vehicle traffic. This surface commonly forms a beam-like layer spanning the growing void. When the surface layer becomes sufficiently undermined, it shears and falls in to the void leaving a distinct hole at the ground surface. **The sinkhole generally is a very short-lived feature being filled by collapse of the surrounding soil into the hole.**

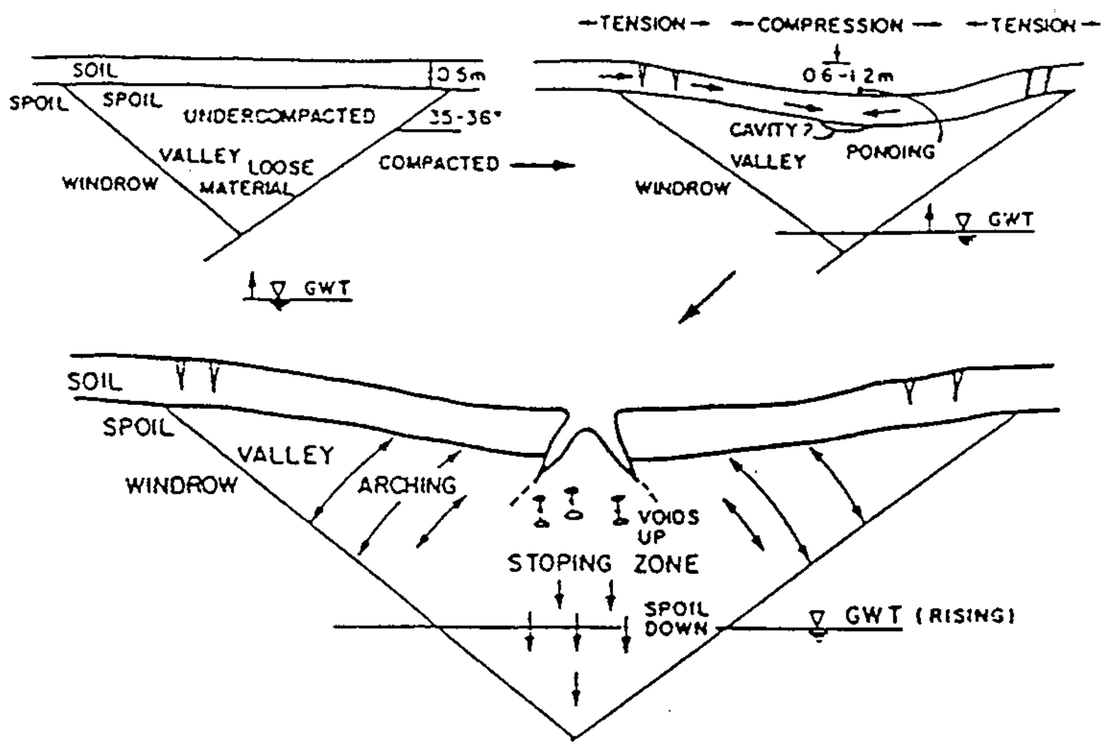

Figure 2.19 Diagrammatic explanation of formation of sink holes by upward migration of macrovoids formed between spoil windrows.

Q. Why does spoil subside differentially?

A. Differential settlement arises because dragline or shovel mining produces uncompacted spoil that contains zones of differing density. In thin spoil, the pattern of variation in density is regular and relatively simple. In thick spoil the variation in density is highly irregular and complex.

Stripping shallow overburden (less than 12 m) with large draglines creates distinct windrows of spoil with high peaks relative to the deep valleys between windrows (Figure 2.20a). The piles are generally built almost entirely on the pit floor with only minor overlap between piles. The spoil deposited in the peak location is dynamically compacted as dragline bucket loads are dropped from considerable heights (3 m to 10 m) on the growing spoil pile. The weight of the pile acts to further compact the spoil beneath the centre of the pile. The spoil in the valleys is characterized by a concentration of larger lumps and blocks. It is not dynamically compacted by being dropped nor is it loaded by being buried. The valleys are filled with loose, uncompacted material, which has been disturbed twice, initially when removed by the dragline and the second time when pushed by dozers from the peaks. Thin spoil is generally characterized by a relatively simple pattern of discrete zones of loose, compact, and dense spoil (Figure 2.20a).

Mining deep overburden results in less distinctive relief between spoil windrows than is the case in thin spoil, although the peak-to-peak spacing and relief between crest and valley is similar. Successive spoil piles are built on the flanks of preceding piles (Figure 2.20b). With windrows overlapping, the dense peak material of the second pile is deposited over the less dense material on the flank of the first pile providing some compactive effort to the loose spoil. Construction of toe piles and more complex dragline positioning and spoil placement sequences required for thick spoil further increase the complexity of the pattern of distribution of loose, compact, and dense zones within the resulting spoil (Figure 2.20b).

When spoil material is deposited, either by being dropped from the dragline bucket or by being pushed into place by a dozer, the spoil is a loose rubble consisting of angular blocks and fragments of varying size. From 20% to 35% of the volume of this original, generally loose, rubble consists of space that is filled with air. The spaces between individual blocks is roughly related to the size of the blocks. Thus, where larger blocks are concentrated, the spaces between them are correspondingly larger than where no large blocks are present. In dense zones formed where spoil is dynamically loaded by being dumped by draglines, the void space is less and the bulk density approaches values of 1.85 Mg/m^3. Where the spoil is loose, the amount of void space is greater and bulk density is lower. Density values of 1.45 Mg/m^3 are commonly observed in these loose zones, with values as low as 1.25 Mg/m^3 in some places, in bedrock-derived spoil.

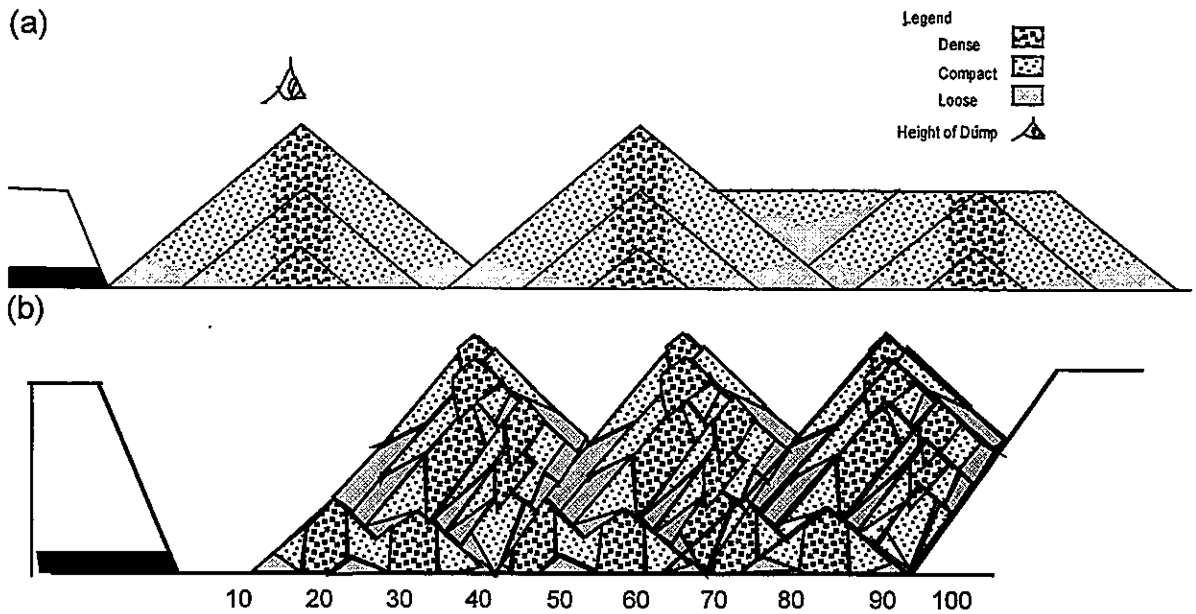

Figure 2.20 Schematic diagram showing formation of (a) simple pattern of loose, compact, and dense zones in thin spoil, and (b) complex pattern of loose, compact, and dense zones in thick spoil.

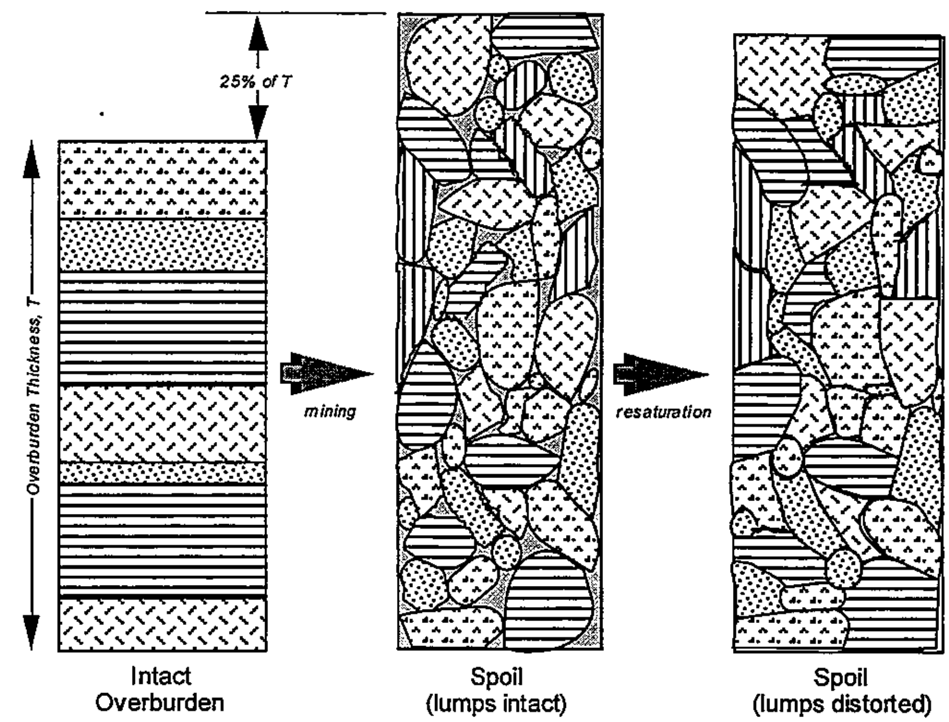

Figure 2.21 Schematic drawing showing transition from unmined overburden to initial angular blocky spoil and then to compressed less porous spoil following settlement.

Q. Is the subsidence behavior of all mine spoil the same?

A. No, the subsidence behaviour of spoil appears to be affected by differences in overburden composition and climate. Studies of subsidence have been conducted in two major climate regions with different geologic material. Data obtained from these studies allow limited generalizations about variation in subsidence behaviour as a result of changes in factors (climate and material). Subsidence appears to be controlled by behaviour of material when it is wetted under load. The overburden properties that are most strongly linked to subsidence behaviour are density, state of consolidation or cementation, and mineralogy. The climate factor of importance is availability of water to wet the spoil. The research studies conducted in the plains of Alberta provide the following examples of variation in subsidence behaviour with differing geologic material and climate setting.

Observations made at Diplomat Mine between 1980 and 1986 demonstrate subsidence behavior of spoil derived from glacial till in the Lower Horseshoe Canyon Coal Zone, within the Aspen Parkland Ecoregion. The subsidence behavior of this material under this moisture regime is characterized by rapid development of settlement depressions and rapid stability. Depressions generally appear within a few months after the surface is graded. Where spoil is less than about 10 m thick, sinkholes may develop within the first year following reclamation. The entire subsidence process is generally completed within a few years.

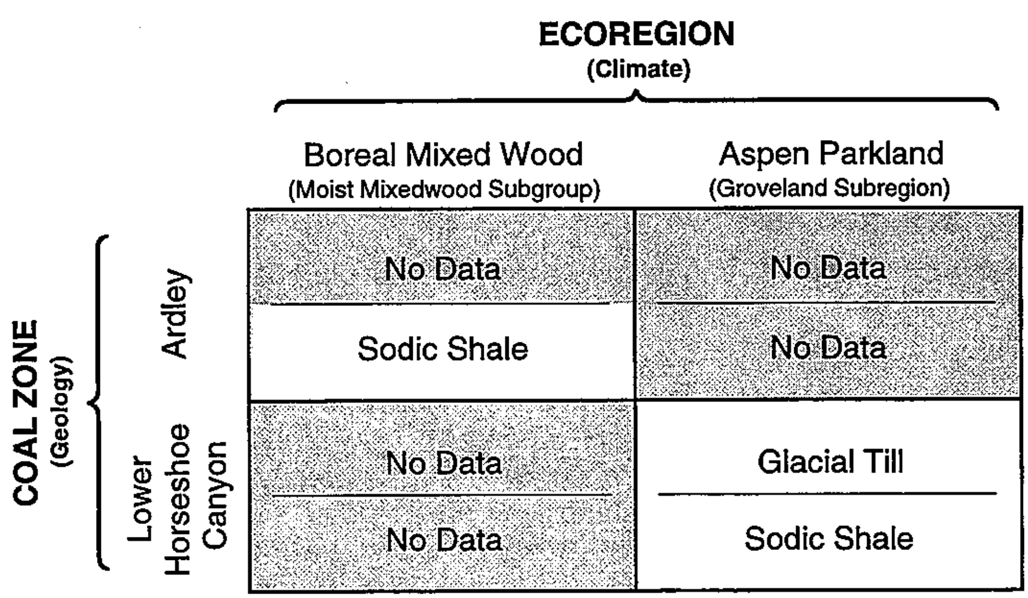

Figure 2.22 Graphic summary showing geologic, climatic and material type setting of data sets on spoil subsidence.

Subsidence behavior of spoil derived from sodic bedrock from the Lower Horseshoe Canyon Coal Zone, within the Aspen Parkland Ecoregion is characterized by slow development and extended periods of time before stability. This is demonstrated by observations made at Vesta and Paintearth Mines between 1981 and 1986. Depressions appeared months to a few years after grading. The subsidence process continued at a slow rate for many years before stability was finally achieved.

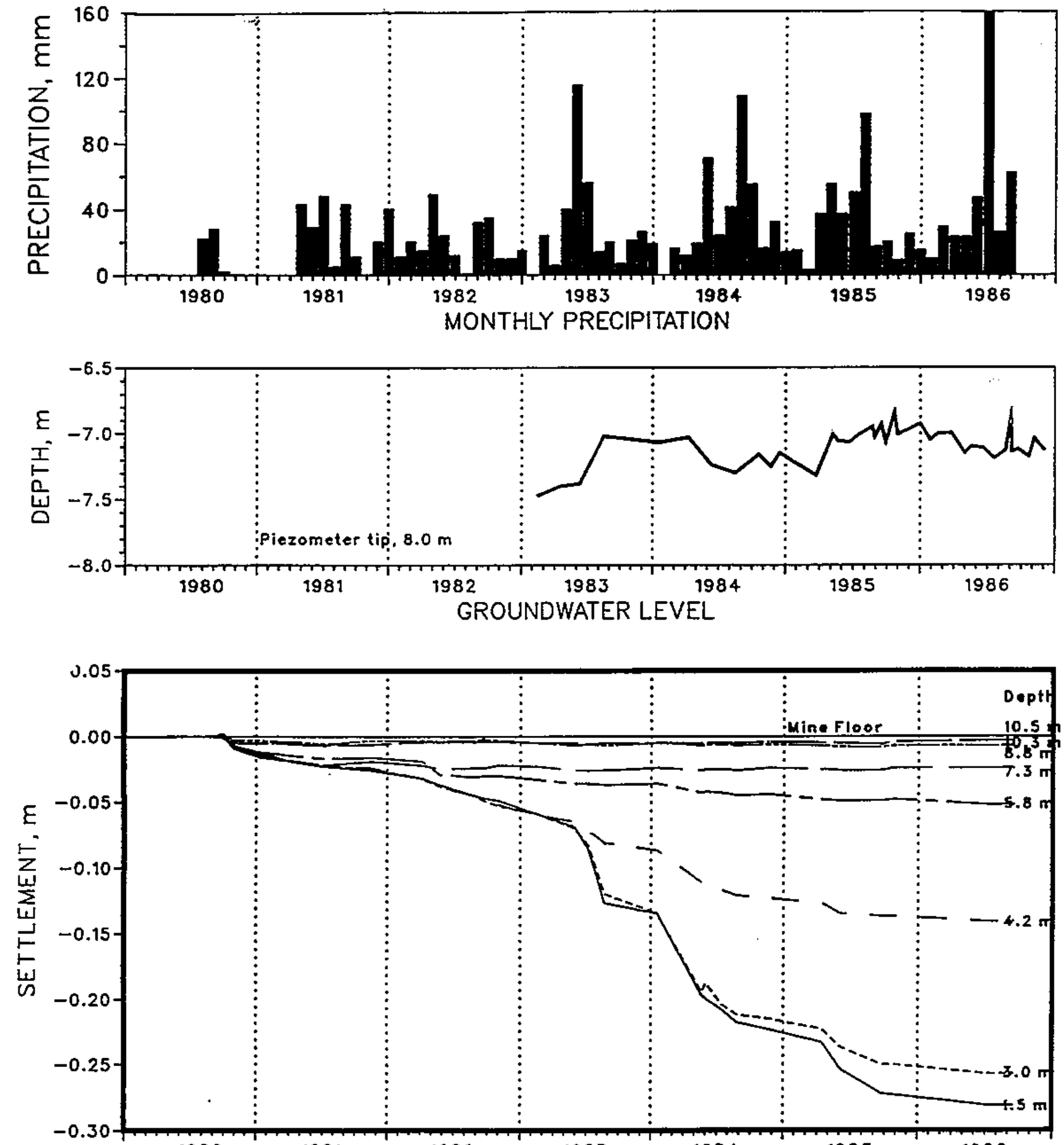

Figure 2.23 Precipitation records, groundwater levels, and subsidence behavior at Diplomat Mine showing settlement caused by rising groundwater level resulting from heavy rain.

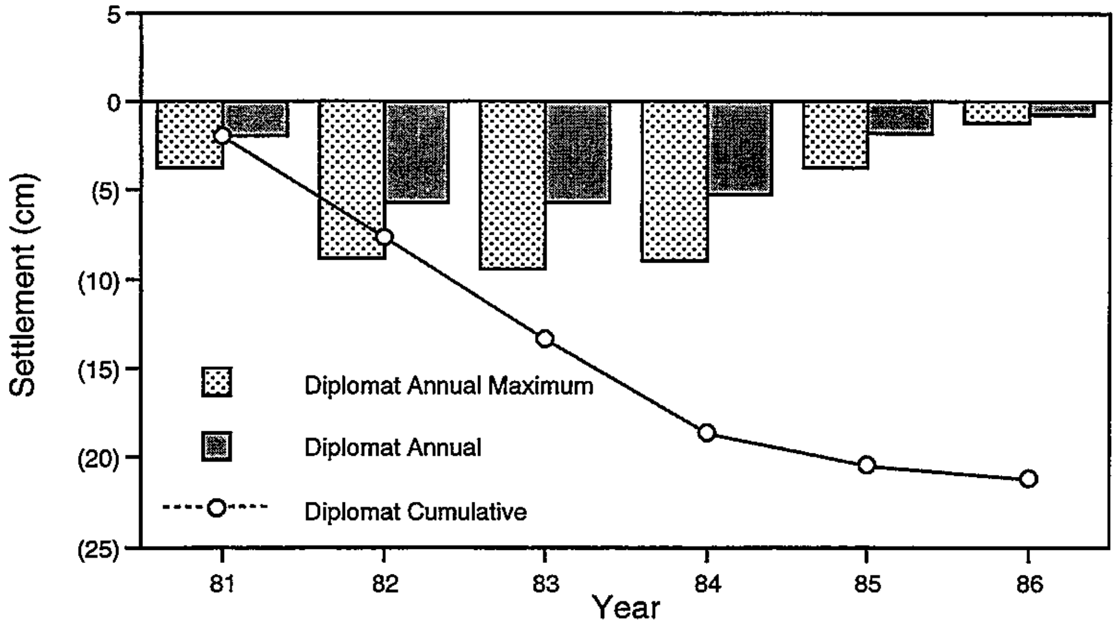

Figure 2.24 Graphic representation of measurements of surface subsidence observed at Diplomat mine between 1981 and 1986 showing rapid development of subsidence and stability.

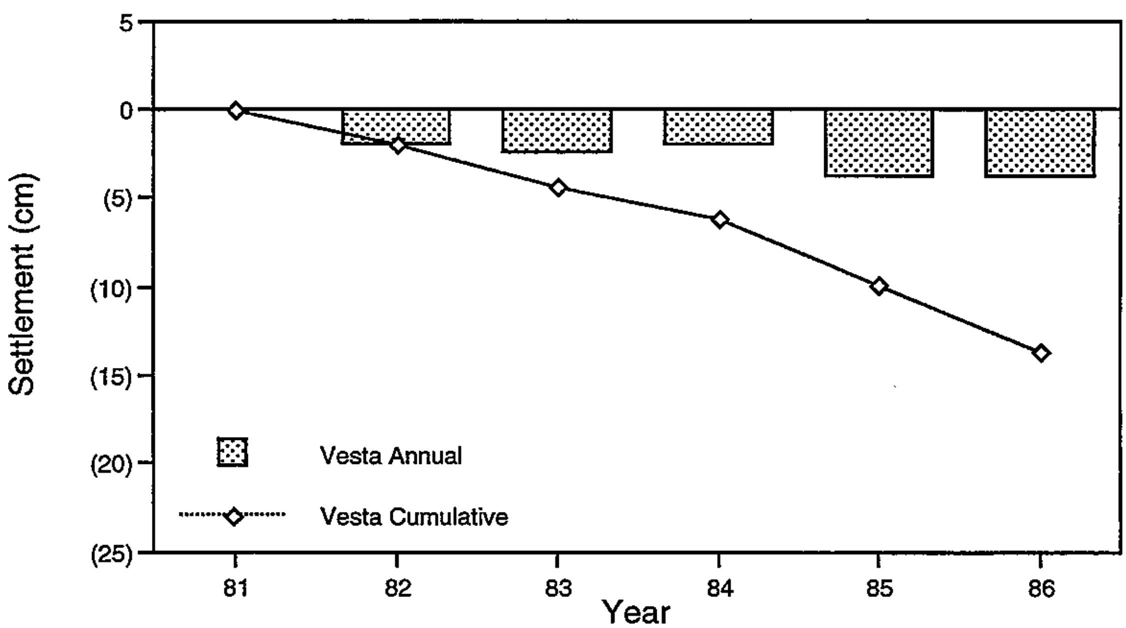

Figure 2.25 Graphic representation of measurements of surface subsidence observed at Vesta Mine between 1981 and 1986 indicate gradual development of subsidence. The rate of settlement appears to be accelerating with no evidence of stability.

Observations made at Highvale Mine demonstrate the initial subsidence behaviour of spoil derived from sodic bedrock from the Ardley Coal Zone within the Boreal Mixedwood Ecoregion. Subsidence behaviour of this material under this moisture regime is characterized by rapid settlement localized at the base of spoil, immediately above the rising water table. It is postulated that the subsidence process will be generally complete within a few years.

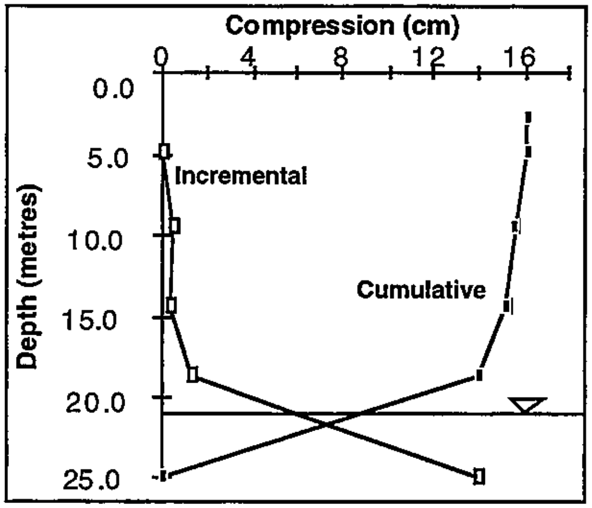

Figure 2.26 Graphic representation of measurements of surface subsidence observed at Highvale Mine after 347 days. Nearly all the subsidence was localized at the base of the spoil, immediately above the rising water table.

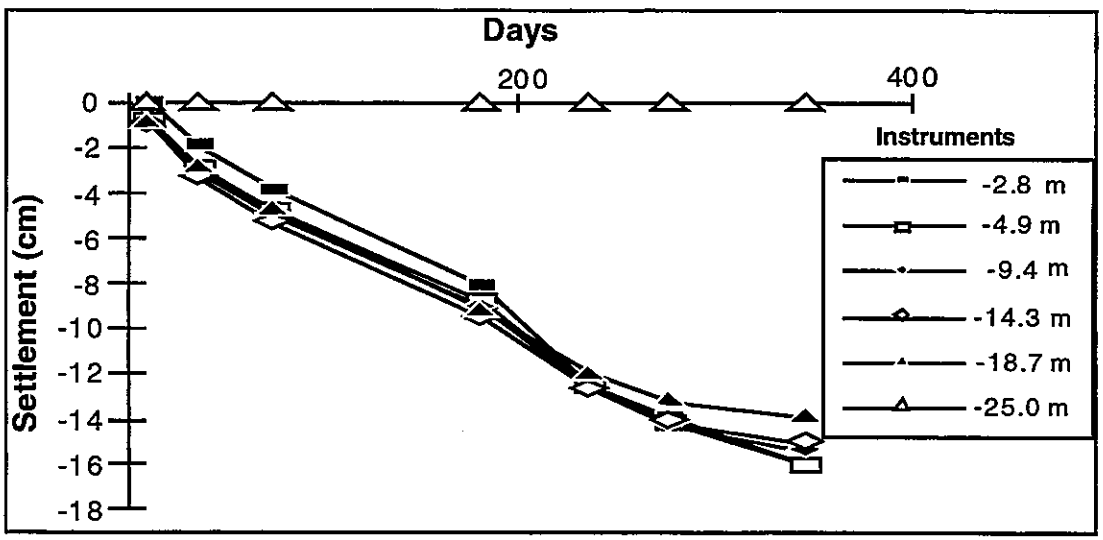

Figure 2.27 Graphic representation of measurements of surface subsidence observed at various depths in spoil at Highvale Mine. Substantial compression can be observed in the 5 m of spoil at the base of the pit as early as 11 days after monitoring began.

Q. What magnitude of subsidence can be expected in mine spoil?

A The amount of settlement is highly variable depending on the interactions between (1) spoil composition, (2) spoil thickness, (3) initial water content and bulk density of the spoil, and (4) final water table position within the spoil. Data are too sparse to develop a completely generalized understanding of the magnitude of subsidence, but anecdotal evidence from both field observation and laboratory testing provides some usable insights.

Till–Derived Spoil

- **Potential magnitude of subsidence in Till–Derived Spoil is controlled by initial density and water content of the spoil and the spoil thickness.**

In till derived spoil, the magnitude of potential subsidence can be completely described in terms of initial density and water content of the spoil, and thickness of spoil. In general terms, the potential subsidence decreases as the initial density or water content increases. We conclude on the basis of data from Diplomat Mine, that potential subsidence of till derived spoil is likely to be between 2.5% and 7.5% of initial spoil thickness. Some zones within the spoil will experience no shortening. More than 40% of 65 samples from Diplomat Mine, for example, had potential strain of zero. In other zones within the spoil, shortening of as much as 10% to 15% appears possible. Only 20% of the 65 samples from Diplomat Mine, however, indicated a potential strain of more than 5%. The amount of compression of till-derived spoil material appears to be relatively constant regardless of the depth of burial. Thus, the amount of potential subsidence can be described by the thickness of spoil multiplied by the average strain.

- **Magnitude of actual subsidence of till-derived spoil is determined by potential subsidence and final water table position.**

The potential subsidence of till-derived spoil becomes actual subsidence, when the spoil becomes wetted. Therefore, the amount of actual settlement is a function of the steady state position of the water table in the spoil. Till-derived spoil experiences maximum subsidence in the capillary fringe, about 2 to 3 m above the rising water table. We conclude that potential subsidence will be translated into actual subsidence from the base of the spoil to about 3 m above the water table. For example, if the potential subsidence of a 10 m thick column of till-derived spoil were 5%, or 0.5 m, and the water table stabilized 6 m beneath the surface, the expected subsidence would be about 70% of the potential or 0.35 m. It is important to remember that this is total subsidence, not differential subsidence, which is related to spatial variation in the amount of total subsidence.

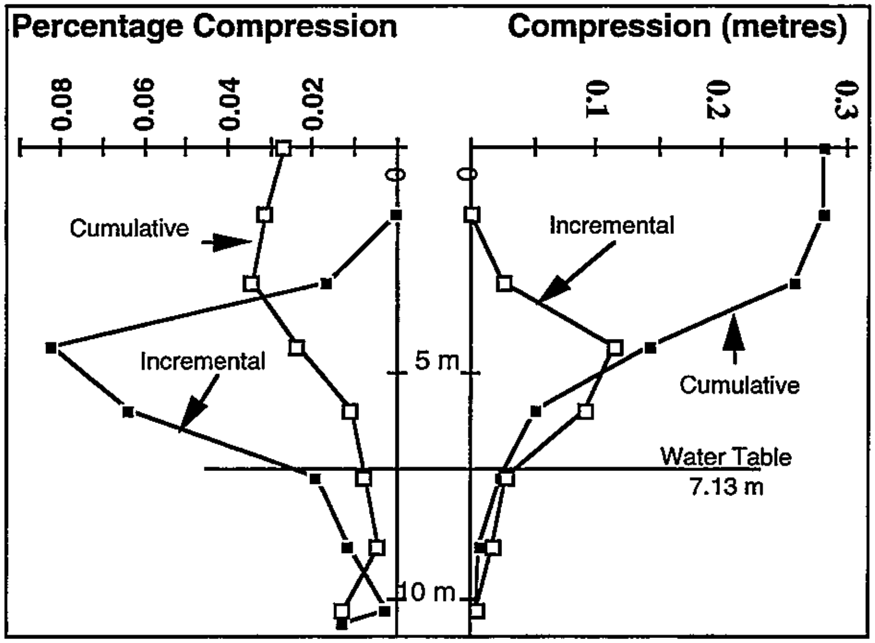

Figure 2.28 Graphic representation of measurements of surface subsidence observed at an instrumented site in Diplomat Mine between 1981 and 1986 showing total settlement of 28 cm, which represents about 2.6% of the total spoil thickness. In isolated zones immediately above the water table, as much as 8.8% compression was recorded.

Sodic Bedrock–Derived Spoil

- **Magnitude of subsidence of sodic spoil is controlled by original density, spoil thickness and depth to stable water table.**

Only limited field observations are available on which to infer the subsidence behavior of sodic spoil. Experimental data, however, provide insights into the magnitude of settlement and the importance of depth of burial in determining subsidence of sodic spoil. A set of six confined consolidation tests indicate the effects of original density, thickness of spoil, and water-table depth on subsidence of sodic spoil. Three pairs of spoil samples at field moisture content were prepared at a range of densities observed in spoil at Battle River, 1.35 Mg/m^3 to 1.55 Mg/m^3. One sample of each pair was incrementally loaded to 500 kPa or 600 kPa, equivalent to overburden thickness of 27 m or 32 m respectively, and then saturated. The other sample in each pair was first saturated and then incrementally loaded to the same maximum load. All six samples attained nearly the same density, 1.7 Mg/m^3 with a standard deviation of 0.02 Mg/m^3.

We conclude, on the basis of the test data, that subsidence of sodic spoil is strongly controlled by initial density. We expect a 30 m thick spoil having an initial density higher than about 1.5 Mg/m^3 to subside very little, less than 1.0 m (about 2.5%). We expect a 30 m thickness of spoil with initial density less than about 1.45 Mg/m^3, on the other hand, to subside as much as 2.5 m to 3.0 m (about 7.5% to 9%) depending on the final water table position (Figure 2.29).

As is the case with till-derived spoil, the potential for subsidence of sodic spoil is achieved only when the spoil is wetted by rising groundwater. The amount of subsidence of sodic spoil is expected to vary substantially as a function of depth to water table in the interval between the base of the pit and 10 m beneath the surface. We expect essentially no change in the amount of subsidence once the water table depth is within 10 m of the surface (Figure 2.29).

Unlike till-derived spoil, which displays constant strain regardless of load, the amount of compression of sodic spoil appears to vary with the applied load, i.e. with the depth of burial. Under loads less than 150 kPa to 200 kPa, which is equivalent to burial of 8 m to 11 m, sodic spoil absorbed water and swelled. At loads greater than 200 kPa, sodic spoil samples underwent compression.

The load-dependent subsidence character of sodic spoil is particularly evident when we examine the effect of spoil thickness on amount of potential subsidence (Figure 2.30). The data indicate that for spoil thickness less than about 15 m, potential subsidence of sodic spoil is less than 0.5 m regardless of density. At thicknesses greater than about 15 m, the amount of potential subsidence increases markedly with increasing depth, especially in low density spoil. In contrast, the amount of potential subsidence of till-derived spoil is directly related to depth.

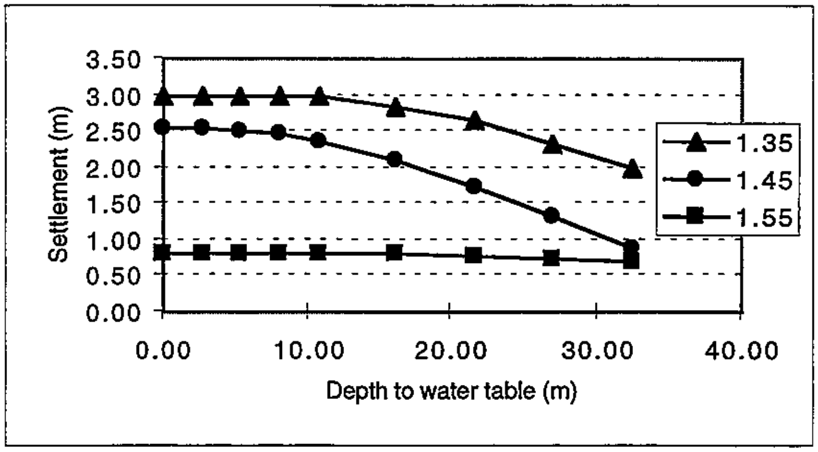

Figure 2.29 Graph showing relationship between stable water-table position and total subsidence as a function of the density of spoil (derived from laboratory consolidation tests). For low and medium density spoil, the amount of subsidence increases markedly as the stable water table rises above the base of the pit. Where the water table is within 10 m of the surface, little change in subsidence is expected with change in water-table position. Refers to total subsidence. Surface depressions result from differential subsidence, i.e., differences in total subsidence in neighboring locations.

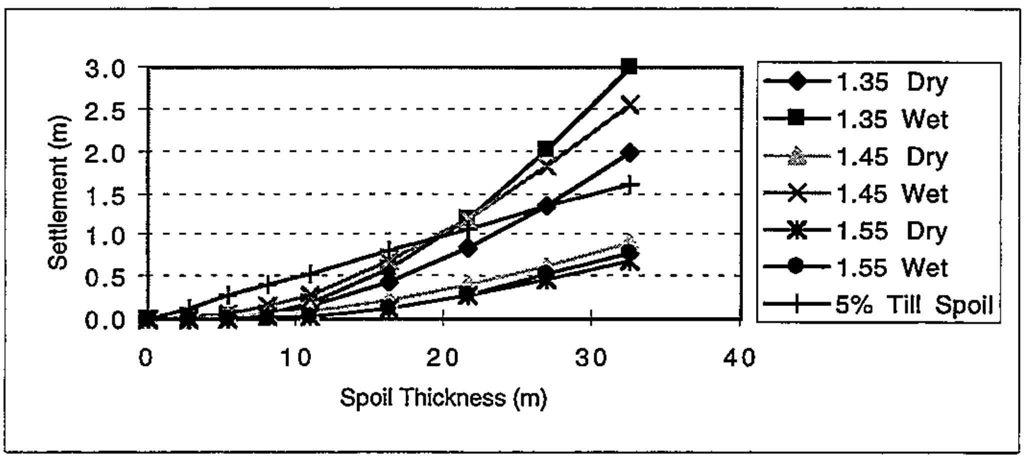

Figure 2.30 Graphic representation of potential subsidence of sodic spoil as a function of spoil depth (derived from laboratory consolidation tests). The data indicate that for spoil thickness less than about 15 m, potential subsidence of sodic spoil is less than 0.5 m regardless of density. At thicknesses greater than about 15 m, the amount of potential subsidence increases markedly with increasing depth, especially in low density spoil. In contrast, the amount of potential subsidence of till-derived spoil is directly related to depth. Refers to total subsidence. Surface depressions result from differential subsidence, i.e., differences in total subsidence in neighboring locations.

Q. How long after mining is completed will subsidence continue?

A. The answer to this question is dependent on the composition of the spoil material and the period of time required for establishment of steady-state groundwater conditions in the reclaimed materials. Field observations indicate that till-derived spoil can achieve stability within three to five years in settings that exhibit rapid groundwater recharge. Spoil derived from sodic spoil was still undergoing subsidence at the completion of the nine-year PHRP study. Comparison of experimental data for Diplomat and Vesta Mines provides further insight into the differences in the rates at which the two types of material undergo settlement.

At loads greater than 200 kPa, which is equivalent to about 11 m of overburden, sodic spoil samples underwent compression. Under loads of 500 kPa to 600 kPa, which is equivalent to burial of 27 m to 32 m, this compression caused the hydraulic conductivity of samples to decrease to the degree that periods of several weeks were required to completely wet the sample. These results support the field observation that sodic spoil experiences very slow subsidence relative to till-derived spoil. Comparison of results of consolidation tests on till-derived spoil and sodic spoil graphically demonstrate this difference. The test illustrated in Figure 2.31 involved loading the sample to equilibrium and then introducing water into the sample. A 7 cm thick sample of till-derived spoil from Diplomat Mine experienced a compression of 5%, which was 90% complete after 300 minutes. This was atypically long for samples from Diplomat Mine, which typically achieved full equilibrium in as little as 30 minutes. In contrast, a 1.5 cm thick sample of the sodic spoil from Vesta Mine required 5000 minutes to achieve 90% of its 9.9% compression. Thus, the sodic spoil required about two orders of magnitude longer to realize its full settlement potential than did the till-derived spoil. Although it is impossible to translate these results quantitatively to the field because of the variability in materials and porosity, it is clear that **subsidence of sodic spoil requires much longer to achieve equilibrium than does till-derived spoil.**

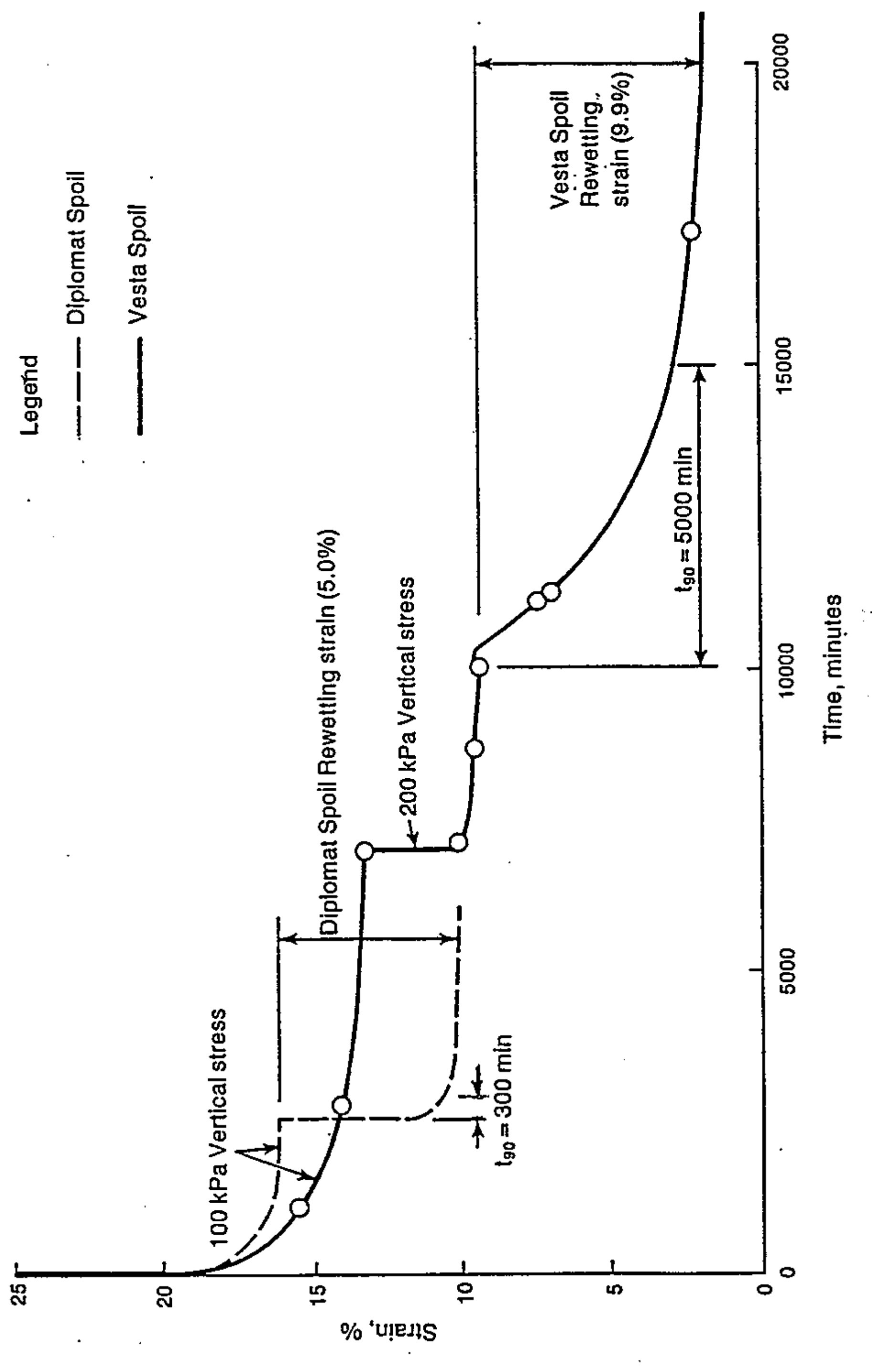

Figure 2.31 Graph comparing consolidation behavior of a spoil sample derived from sodic bedrock with a sample of till-derived spoil. These data demonstrate that spoil derived from sodic bedrock requires very much longer to achieve stability.

Q. Are there techniques for preventing or managing spoil subsidence?

A. Spoil subsidence may be minimized through materials handling and/or landscape design, or prevented through systematic compaction. Various companies have adapted operational material handling techniques and sequences to minimize subsidence in response to reclamation observations. For example, in the middle 1970's it was noted that burial of snow, ice and frozen aggregates of spoil material during grading operations led to development of excessive subsidence. At a number of mines in North Dakota, grading operations were suspended during the winter to minimize this effect. Subsequent operational experience in Alberta suggests that the decrease in compaction of spoil and subsoil associated with grading in the winter far out weighs any increased susceptibility to subsidence. While mining an area of thin, glacial till overburden at Diplomat Mine during the early 1980's, Luscar Ltd. encountered a situation of rapidly developing, severe subsidence. The company adjusted their material handling sequence to involve an initial grading process, followed by a one year delay prior to final grading and topsoil placement. By allowing the majority of the subsidence to occur prior to placement of topsoil, both disruption of the field by subsidence and costs of remedial work were minimized, and the effective use of the scarce topsoil resource was maximized.

Landscape design can minimize negative effects of subsidence, by predetermining where in the landscape water will accumulate. Slopes in reclaimed landscapes encourage precipitation and snow melt to run off and minimize ponding and the resulting subsidence. Where subsidence depressions do develop on sloping surfaces, their capacity is significantly reduced by even very low slopes. As a result, the area covered by standing water and the duration of such ponding is reduced producing less disruption to agricultural operations. Examination of the dimensions of numerous subsidence depressions as part of PHRP indicated that by far the majority would be completely drained on slopes of 3% to 5%. By using pit orientation and limited selective material handling procedures and working with the pre-mining topography and spoil thickness, considerable portions of mines could be designed with a series of open slopes that connect to form an integrated drainage pattern. Where the combination of distance to drainage and limited relief prevent drainage from traversing the entire reclaimed area, larger ponds can be incorporated into the landscape to receive the drainage from the upslope area. The enhanced subsidence beneath these ponds will deepen the basin over time and can create sustainable wetlands.

Settlement can be prevented only by a method of **systematic compaction.** Where it is absolutely necessary that spoil subsidence be prevented, it is possible to achieve this by compacting the spoil as it is emplaced. This would involve placing the spoil with dozers and or scrapers and using packers and compactors to increase density to the desired level. This type of practice has been used on occasion in Great Britain, where highway right-of-way was required to traverse a reclaimed site. Compaction of spoil to prevent subsidence is extremely expensive and can be justified only where structures such as large buildings or important highways must be constructed on the reclaimed landscape.

Q. How should a field inspector cope with certification of land that is continuing to subside?

A. **Certification requires comparison of ponding in unmined landscape with estimated potential subsidence-induced ponding.** It is important to remember that subsidence limits agricultural capability only in so far as it results in ponding that disrupts cultivation. Subsidence depressions will not degrade capability where the depressions are sufficiently small that ponding is short lived, or where the reclaimed landscape slopes enough to allow drainage of depressions, or where the precipitation is low enough that ponding seldom, if ever, occurs.

The full development of subsidence depressions on a reclaimed landscape can require periods of many years, especially in thicker spoil and during periods of lower than normal precipitation. The rate of development of subsidence depressions is not related to time, but rather is controlled by the occurrence of infiltration events that cause the spoil to be rewetted. As a result, there is no simple function that allows the use of preliminary data obtained after a few years of subsidence to project the degree to which a given area will be affected, once the depressions are fully developed. The inspector can rarely, if ever, expect to have the luxury of waiting until the potential subsidence on a given quarter section of reclaimed land is fully developed. Thus, the challenge facing the inspector is to develop an estimate of the influence of subsidence on the capability of the reclaimed landscape before the subsidence is fully developed.

In considering the reclamation objective of equivalent capability, it is important to view ponding on the reclaimed landscape in comparison with ponding on the unmined landscape in the same area. There are very few areas in the Parkland region of Alberta where either ephemeral or permanent ponding does not occur in the unmined landscape. During spring melt, the area covered by standing water increases markedly as numerous small depressions host ephemeral ponds. The inspector should become familiar with the ponding in the area surrounding the mine site. What proportion of the unmined landscape in the area surrounding the mine site is arable and what proportion is occupied by permanent ponds? To what degree does ephemeral ponding during spring melt increase the area of ponding? How often do some of these ephemeral ponds remain until seeding or reappear following heavy summer rain storms? These observations should be used as a benchmark against which to compare the reclaimed landscape to evaluate the impact of subsidence on capability. Our observations suggest that in even the most severely affected, flat reclaimed landscapes, ponded subsidence depressions occupy no more than 5% of the landscape during spring melt. Because of the small size and shallowness of many of these depressions, many are dry prior to seeding. On many reclaimed surfaces, especially in sloping landscapes, the amount and duration of ponding is less. Given this rule of thumb, it is expected that no more than 3 to 5 ha of ponding would develop in a given quarter section as a result of the most severe, fully developed subsidence. How does this figure compare with the coverage of ponds in the unmined landscape? Observations in earlier areas of the same mine or older mines in the same area can be used as guides for estimating the performance of a newly reclaimed area, and modifying this general maximum estimate to local conditions. Walking the landscape in the spring provides an excellent basis to evaluate the importance of subsidence caused ponding. It is especially important to note the persistence of ponding later in the spring.

Q2.5 WILL CAPABILITY OF RECONSTRUCTED LANDSCAPES BE ADVERSELY AFFECTED, OVER TIME, BY SOIL SALINIZATION?

One of the principle objectives of the Plains Hydrology and Reclamation Project (PHRP) was to determine the origin of soil salinity that was observed to be occurring at Diplomat Mine in 1977.

Studies directed at understanding the formation of soil salinity in reclaimed landscapes included determination of the process and rates of spoil resaturation, groundwater flow patterns in reclaimed landscapes, and study of the distribution and temporal changes in a band of saline soils adjacent to a pond in Diplomat Mine. The results of these studies were reported in a series of papers that were published in conference proceedings, scientific journals, and in a series of RRTAC reports. A list of these reports and papers is provided at the end of this section. This section presents the key findings of these studies as they relate to the question– will salinization degrade the capability of reclaimed landscapes over time?

In order to fully answer the general question, a series of secondary questions must be answered first:

1. How does soil salinity develop in reclaimed landscapes?
2. Where does soil salinity develop in reclaimed landscapes?
3. Is salinity development in reclaimed landscapes different than in adjacent unmined landscapes?
4. Will soil salinity develop at all reclaimed mines within the plains of Alberta?
5. How can salinization in reclaimed landscapes be minimized?
6. How can pond formation and development be controlled?
7. What factors lead to the development of hydrologic conditions conducive to salinization?

Q. How does salinity develop in reclaimed landscapes?

A. Salinity develops in a landscape as the net result of competing rates of salt accumulation in response to evaporation and evapotranspiration, and of salt leaching in response to infiltration. For salinization to occur, evaporation and evapotranspiration must exceed precipitation. That dryland salinity is commonly observed in much of the agricultural region of east-central and southern Alberta is evidence that this condition is met in most of the region.

In addition to the requirement that evaporation and evapotranspiration must exceed precipitation, there also needs to be a source of water to drive the salt accumulation process. This source is typically groundwater. Therefore, the groundwater hydrologic regime of the reclaimed landscape is another fundamental determinant of whether salinity will develop. The elements of the hydrologic regime that control the development of salinity are the depth to water table and the balance between groundwater recharge and discharge within the site.

In order for dryland soil salinity to develop, the water table must persist within a certain critical depth range beneath the surface for an extended period during the growing season. The net flux of groundwater over time needs to be toward the site of potential salt accumulation. Specifically, salinity develops where groundwater flow is directed upward or laterally into an area where the water table lies within about 2.0 m of the surface. The principal mechanism by which shallow, lateral groundwater flow develops is the presence of a hydraulic barrier at depth, such as a marked decrease in hydraulic conductivity caused by a change in material. This condition has been observed at two intervals within reclaimed landscapes: (1) at the pit floor where spoil material rests on undisturbed bedrock, and (2) at the interface between sodic spoil material and the non-sodic subsoil.

Salinization is a natural phenomenon whose conditions for formation are met in lowland reclaimed settings where ponding occurs, particularly if there is also ponding in the adjacent upland. Ponds in the lowland area cause the water table to persist near the surface. Where there is sufficient ponding in the adjacent upland to maintain the water table at levels above that in the lowland, groundwater will flow toward the lowland. In this setting, the fringe area around lowland ponds will become salinized. The flatter the lowland landscape, the larger the salinized area will be.

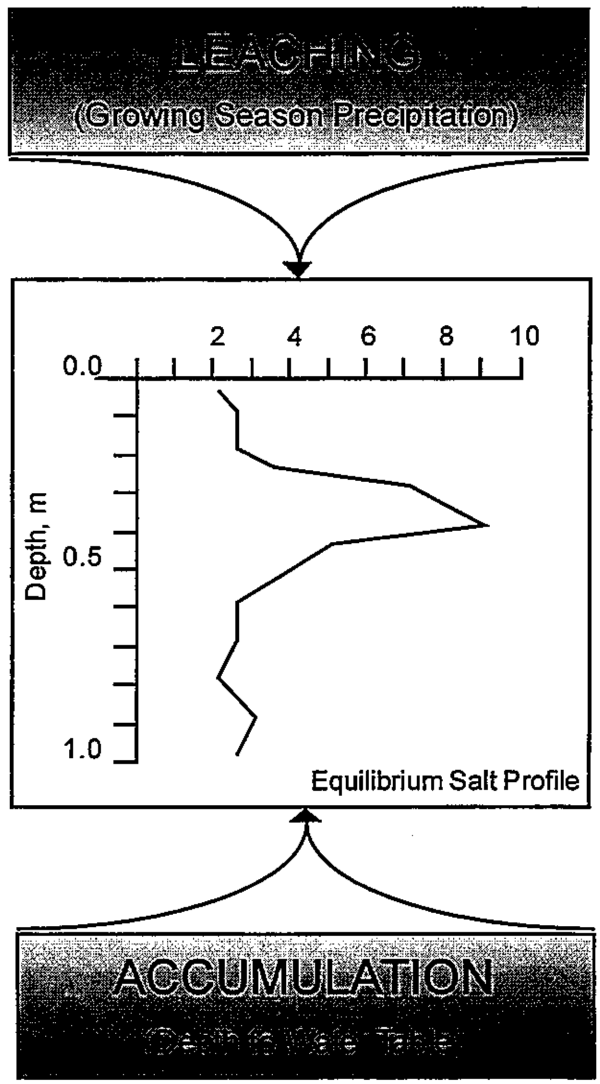

Figure 2.32 Competing processes in salinity development. Accumulation results from evapotranspiration, the rate of which is controlled by the "Depth to Water Table". Leaching results from precipitation and is controlled by "Growing Season Precipitation".

Q. Where in reclaimed landscapes does soil salinity develop?

A. **Salinity in reclaimed landscapes occurs in both upland and lowland settings.** In lowland settings, conditions favorable for the formation of soil salinity are sufficiently common that 20 to 30 percent of the land area may become either wet or saline. In upland settings, salinity is a rare occurrence, when present occupying less than 5% of the landscape.

In **lowland settings** in reclaimed landscapes, salinity has been observed to develop in the fringe area adjacent to ponds . This salinity is interpreted to reflect discharge of groundwater flowing laterally toward the pond from adjacent uplands combined with groundwater flowing outward from the ponds themselves. This type of salinity develops where depressions in the adjacent upland are sufficiently large and numerous to produce substantial groundwater recharge. The downward movement of groundwater recharging beneath the upland is blocked by the shale and sandstone barrier that comprises the pit floor beneath the spoil. Groundwater is thus forced to flow laterally toward the lowland area throughout the year. During spring melt and heavy rain storms, surface runoff augments direct precipitation in the lowland and large lowland ponds become sites of groundwater recharge as well. The water table in the fringe area of the lowland depression is thus held within one to two metres of the surface throughout the growing season allowing formation of a saline fringe.

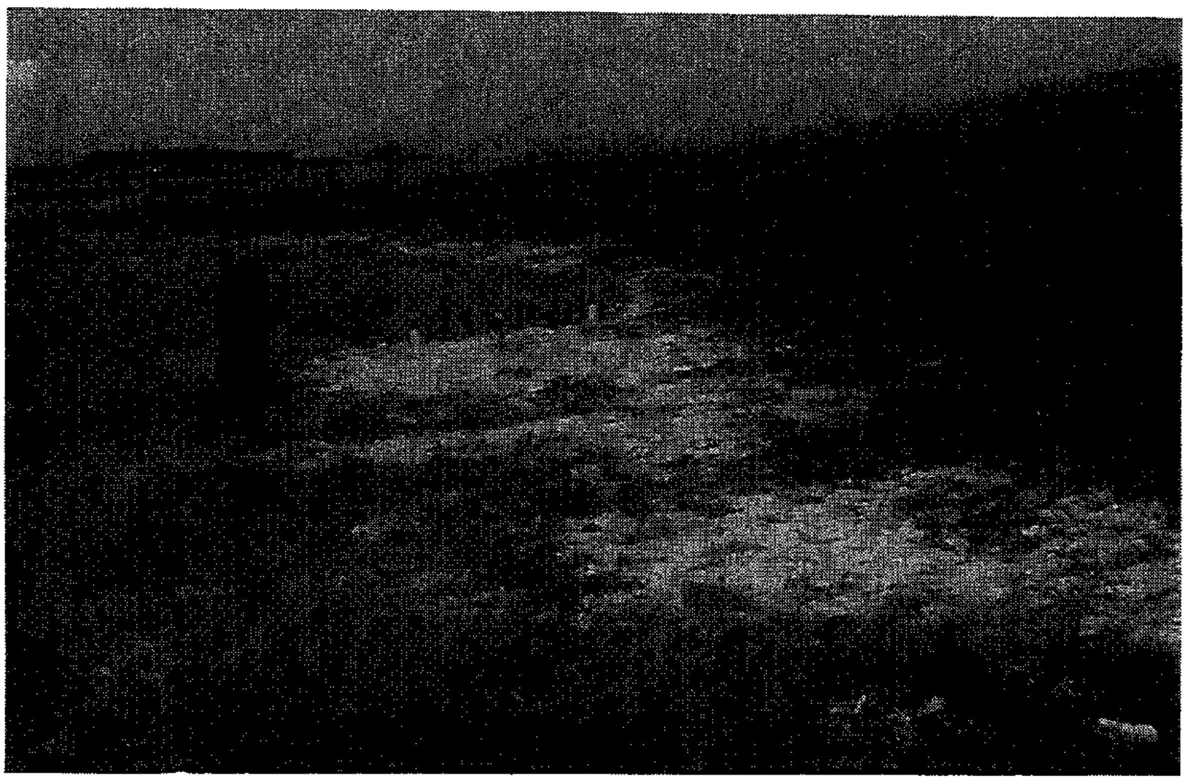

Figure 2.33 Pond in lowland setting at Diplomat Mine, showing salinity development in fringe area adjacent to the pond.

In **upland reclaimed landscape settings**, ponds can produce salinization given the right hydrologic conditions. In rare cases where an upland depression is fed by a sufficiently large drainage area, and where the subsoil or upper spoil has exceptionally low hydraulic conductivity, semi-permanent ponds can develop. Surface salinity has been observed to develop around the margins of such ponds. The formation of this salinity differs from the process in lowland settings in two important respects. First, the pond is not connected to the regional water table within the reclaimed area. Rather it is perched above the water table. Second, the saline fringe results entirely from radial flow outward from the pond itself. There is no component of upland groundwater flow toward the site in the upland setting.

Not uncommonly, more highly compacted layers of subsoil or spoil are encountered in the immediate vicinity of the interface between these two materials. Spoil placement and grading by scrapers and dozers results in compaction of the material. The higher density, and therefore reduced hydraulic conductivity, of the compacted subsoil and the upper surface of the sodic spoil acts as a barrier to rapid infiltration. Groundwater, which is perched above the water table is forced to flow laterally from beneath the pond. Evaporation from the saturated soil surface and transpiration from plants around the edge of these depressions induces flow outward from the pond and upward from the upper surface of the spoil. Where the spoil is highly sodic, the salinity problem is expected to be exacerbated by sodium salts that are carried upward from the spoil and precipitated in the saline fringe. Salt and sodium levels in the soil surrounding these depressions are expected to increase over time to levels that are detrimental to vegetation.

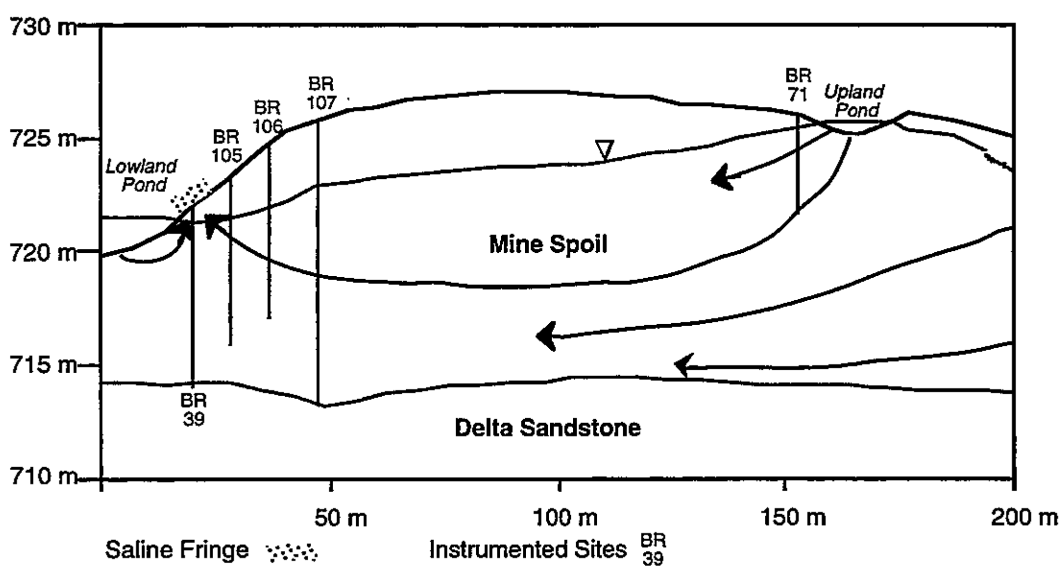

Figure 2.34 Cross-section of pond and adjacent upland in reclaimed spoil at Diplomat Mine. Salt is accumulating at the pond margin where lateral flow from beneath the upland encounters flow moving radially out from the pond.

The severity of salinity in upland settings 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 upland as well. In addition, upland ponds are groundwater recharge sites where the tendency is for salt to be re-dissolved from the saline fringe and carried downward. The initial precipitation of salt results only because the rate of recharge is very much slower than the rate at which water is supplied to the pond. In the restricted portion of upland settings around semi-permanent ponded upland depressions, typically less than 5 percent of the landscape, capability may be permanently decreased.

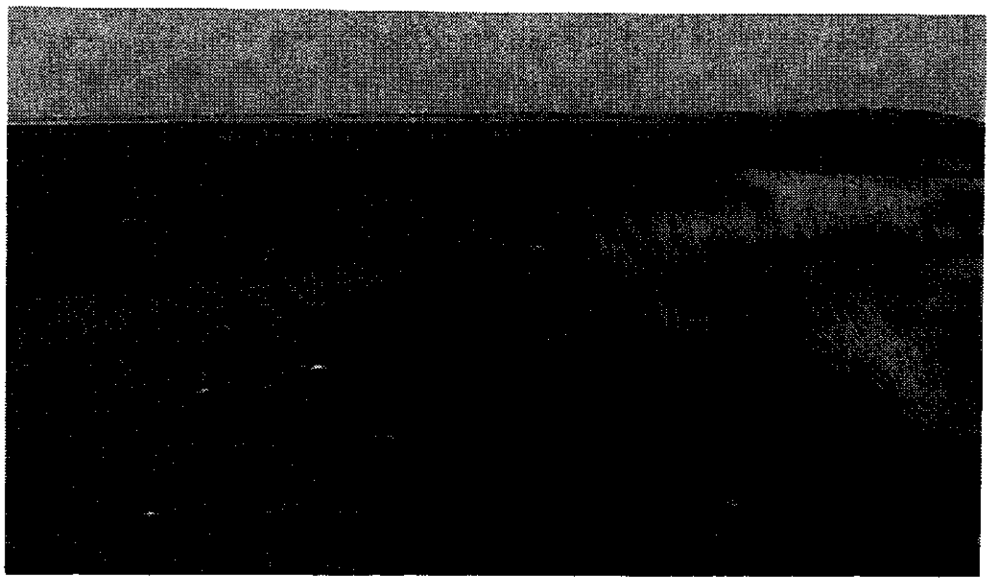

Figure 2.35 Pond in upland setting at Vesta Mine showing saline fringe.

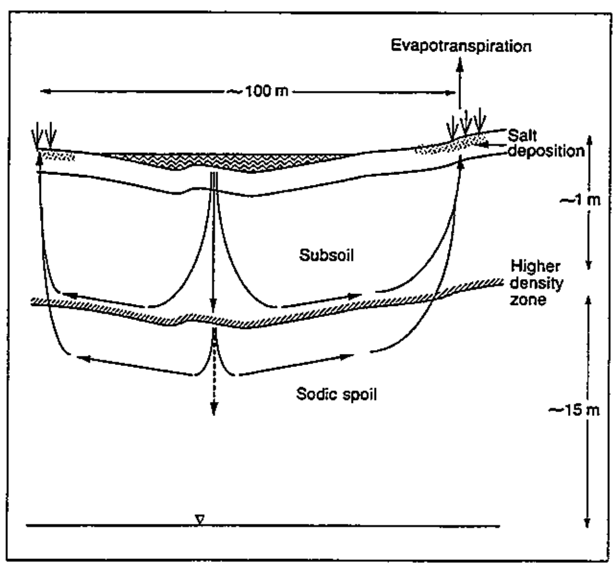

Figure 2.36 Schematic drawing showing groundwater flow around a perched upland pond.

Q. Is salinity development in reclaimed landscapes different than in adjacent unmined landscapes?

A. The simple answer to this question is no, the steady-state hydrologic regime and salinization potential in lowland settings in reclaimed landscapes is essentially the same as that prior to mining and in adjacent undisturbed settings. The origin of saline fringes around lowland ponds in reclaimed sites appears to be analogous in every respect to that of the saline fringes around ponds in unmined sites. The same pattern of extensive recharge through numerous depressions in the upland combined with low hydraulic conductivity of the till maintains the upland water table level above that in the adjacent lowland throughout the year. Radial flow from the lowland pond toward its upland margin combines with the flow from the upland to hold the water table within one to two metres of the surface throughout the growing season, allowing formation of a saline fringe.

The principal difference between reclaimed and unmined upland landscapes 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 and salinity 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, enhancing the development of salinization around the margin of upland ponds.

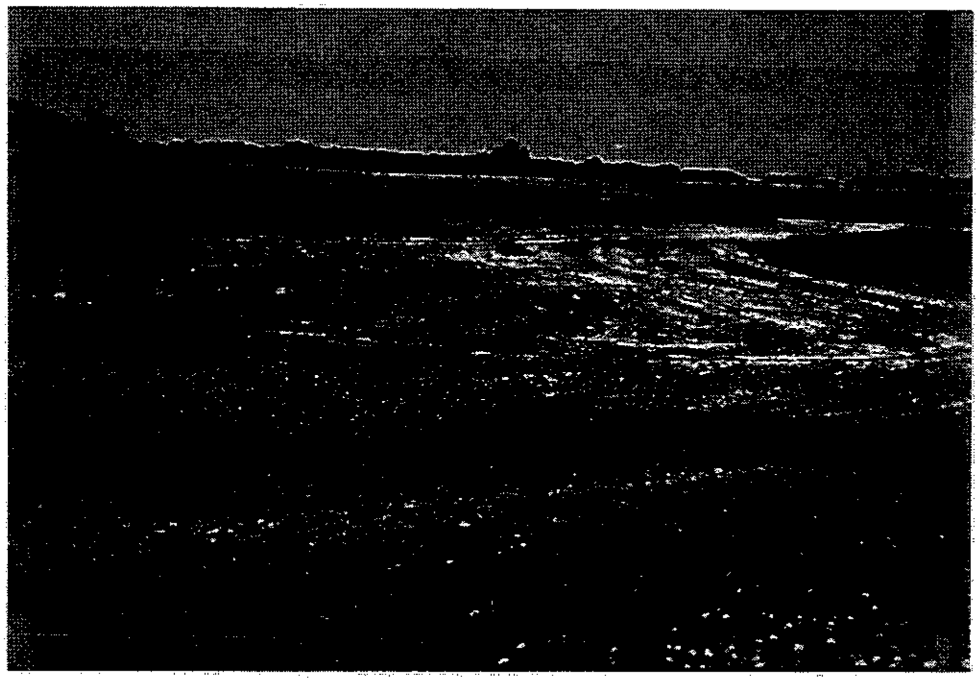

Figure 2.37 Salinity development in an unmined landscape adjacent to a mined area.

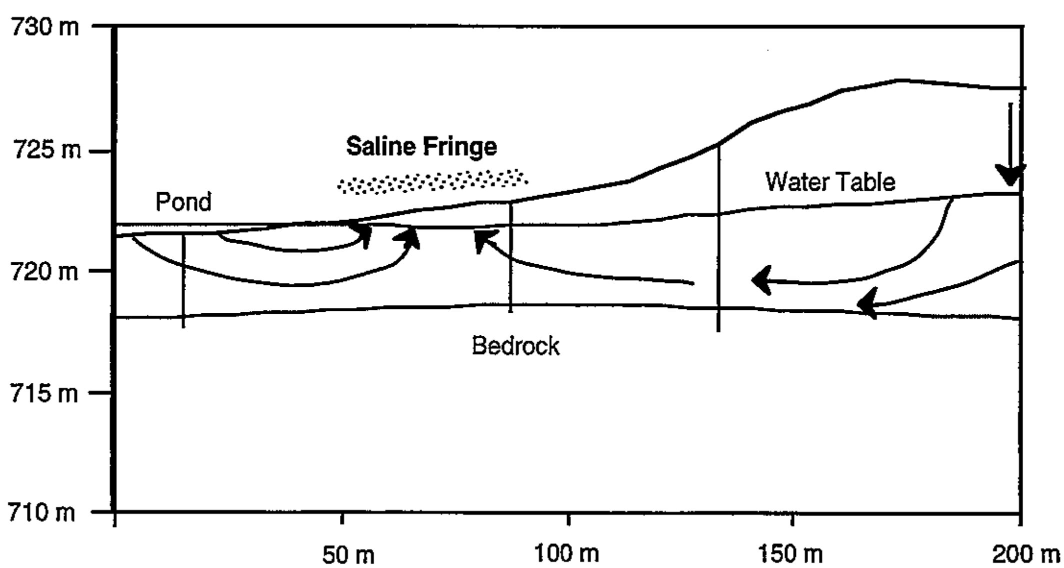

Figure 2.38 East-west cross-section of the unmined study site (Lunty). Salt is accumulating at the pond margin where lateral flow from beneath the upland encounters flow moving radially out from the pond.

Q. Will soil salinity develop at all reclaimed mines within the plains of Alberta?

A. Soil salinity can develop in reclaimed landscapes in areas where salinity occurs in unmined sites.

Dryland salinity, although more of a problem in southern and southwestern parts of Alberta, is of concern for surface mines throughout the grassland and parkland ecoregions of the province. In these regions sufficient salt is generally available within overburden materials to produce problem salinity almost everywhere that the necessary hydrologic and climatic conditions are met. The map on the facing page shows those areas in the plains of Alberta where reclaimed areas have the potential for salinity to develop. This map was derived from a regional map of soil salinity by Pettapiece and Eilers (1990). The potential salinity classes represent a reinterpretation of data on abundance of surface salinity combined with abundance of solonetzic soils.

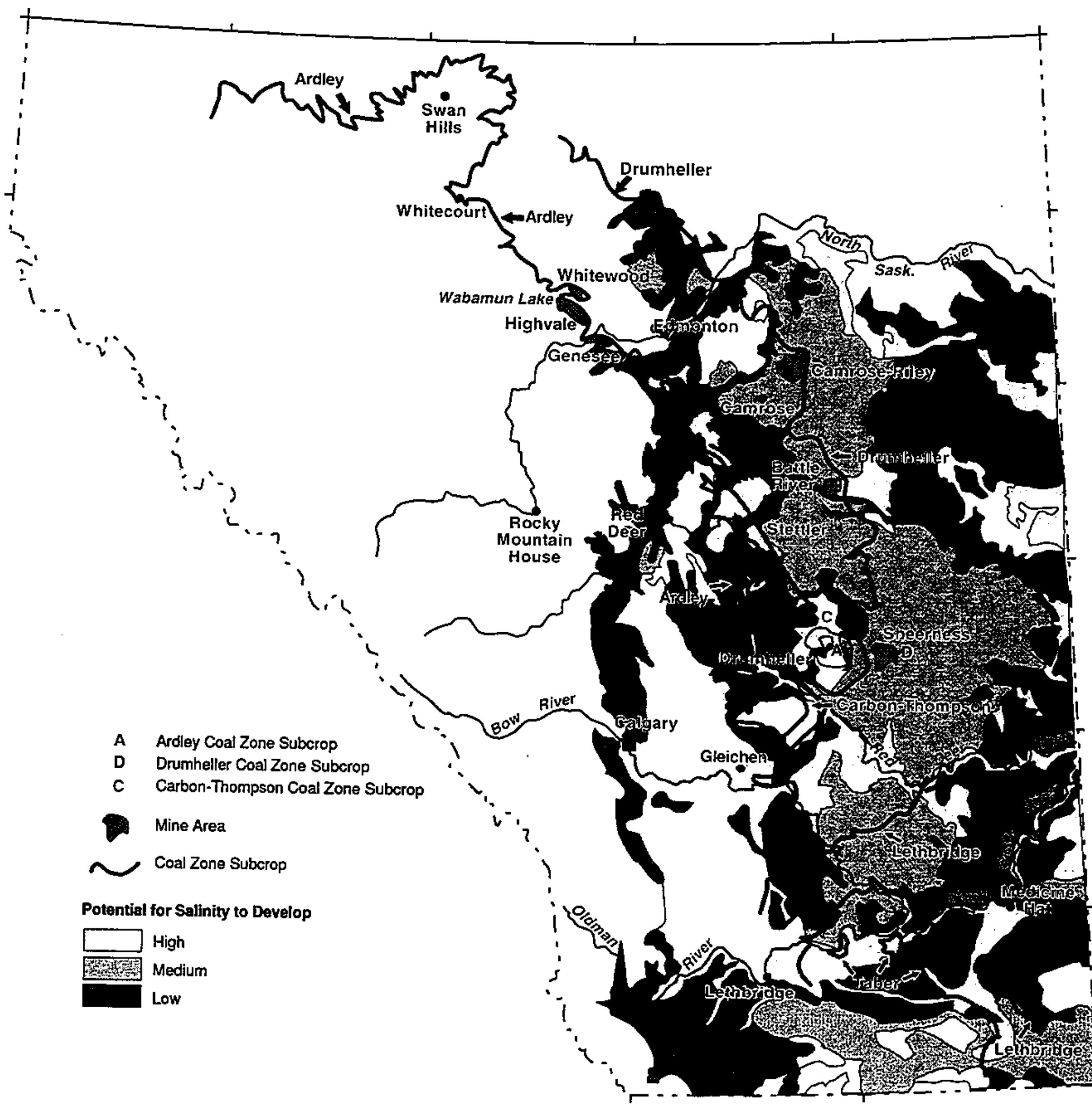

Figure 2.39 Map showing potential for development of salinity in reclaimed sites in the plains region of Alberta (based on mapping by Pettapiece and Eilers, 1990).

Q. How can salinization in reclaimed landscapes be minimized?

A. The development of salinity within a reclaimed landscape can be minimized by controlling the formation and development of ponds, which can be done through modification of materials placement and grading within existing operations. Construction of a landscape that contains moderately sloping, integrated drainage interspersed with a smaller number of larger ponds is probably the optimal approach to minimize the loss of agricultural capability through water-logging and development of salinity. The entire well-drained upland area can be intensively farmed during most years rather than being disrupted by numerous, scattered, seasonally wet, and potentially saline depressions. If properly constructed, the ponded areas can be developed as productive wildlife habitat and managed so that a minimum of land area is subject to salinization.

Grading the upland portion of the reclaimed landscape into open slopes with integrated drainage can minimize ponding. Unpublished work that was done as part of PHRP by Pauls and others, concluded that slopes in the range of 1.5 to 3 percent along the long axis of subsidence depressions are sufficient to drain more than 95 percent of the water that is ponded on existing reclaimed surfaces.

There is no known method to prevent the formation of lowland areas where overburden is less than 4 to 5 times the thickness of the coal mined, other than the expensive process of transporting material from other areas in the mine. Within lowland areas, the extent of salinization can be minimized by grading to an undulating to rolling landscape with slopes of 3 percent to 5 percent. This will result in narrower zones around the lowland ponds where the water table is within the critical depth of the surface than when the terrain is more nearly level. These lowland areas can be managed as productive hay land, pasture, or wildlife habitat, which adds variety to the reclaimed landscape. For a more extensive discussion on this topic, the interested reader is referred to a report by Moran et. al., 1990 (RRTAC 90-4).

Q. How can pond formation and development be controlled?

A. The fundamental mechanism to either create or avoid the creation of a pond lies in adjusting the material handling methods in such a way that a depression is either created, prevented or drained. Three elements of the landscape are important in creation of a pond:

1. the size of the contributing drainage area,
2. the presence of a closed depression, and
3. presence 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 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, as well as the nature of the spoil and subsoil material.

To prevent the formation of a pond it is first necessary to identify places within a mine site where broad, closed depressions can form. It is possible to predict in advance of mining where lower areas will occur within the final post-mining landscape. These low areas will tend to become closed depressions in the reclaimed landscape within which ponds can develop. The thickness of spoil can be computed using the expression, $T_s = (1 + B) * T_o$, where:

T_o = overburden thickness

B = bulking factor , and

T_s = spoil thickness.

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. Where such low areas are projected, ponding can be minimized or prevented by altering the final configuration of the landscape. It may be feasible to design the landscape such that the low area can be drained. This may be accomplished with drainage channels 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, especially in upland areas.

In some mines, extensive lowland areas that can not be drained are likely to develop. The recommended approach to minimizing salinity in these areas is to minimize the area of ponding, by designing ponds that are relatively deep and steep sided.

Q. What factors lead to the development of hydrologic conditions conducive to salinization?

A. Five factors lead to or contribute to hydrologic conditions conducive to salinization: the original topography of the mine site; the thickness of overburden relative to the thickness of the coal removed; the handling and placement of overburden during the mining operation; the climate; and the hydraulic conductivity of the spoil. (Figure 2.41).

The first three factors, (1) the original topography of the mine site, (2) the thickness of the overburden relative to the thickness of coal removed, and (3) the handling and placement of overburden during the mining operation, govern the configuration of the reclaimed landscape. The configuration of the reclaimed landscape, the climate, and the hydraulic conductivity of the spoil interact to determine the number, depth, and area of surface ponds within the reclaimed landscape. The degree of surface ponding in the reclaimed landscape determines the proximity of the water table to the land surface.

Within this model, two of the elements, the climate and hydraulic conductivity of the spoil, are fixed for any particular mine site. The original topography and overburden thickness vary throughout a mine site, but are fixed at each location within the site. The only element of the model over which the miner or regulator can exercise control is the material handling and placement. In this section, we briefly discuss generalizations of PHRP results as they concern the four relatively fixed elements of the model.

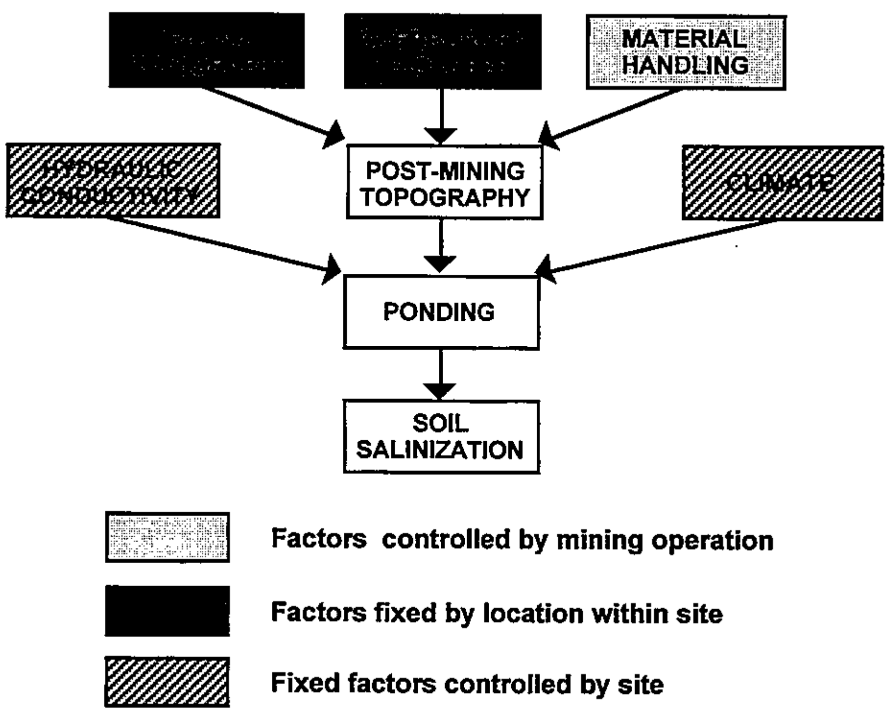

Figure 2.40 Factors that control the hydrologic regime and thus the salinization potential of reclaimed landscapes.

Original topography, overburden thickness, and material handling interact to create low areas in the reclaimed landscape. Areas in the pre-mining landscape that are topographically low are generally expected to be lower than the surrounding landscape following reclamation. The only exception to this generalization is where a low area in the landscape is only partly disturbed, and the coal seam being mined is considered thin. In this case, the reconstructed landscape could be higher than the adjacent undisturbed low area.

If coal could be removed without disturbing the overburden, the post-mining landscape would be simply lowered by an amount equivalent to the thickness of the removed coal. In reality, however, the mining process disturbs the overburden and creates an additional 25 to 30 percent of pore space, which produces an initial spoil thickness of 1.25 to 1.3 times the unmined thickness. As water begins to enter the newly created pore spaces, the physical structure of individual fragments of spoil either collapses, or swells and collapses, causing the overall spoil mass to compress (See earlier discussion of settlement). This compression 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 percent. Thus, the final spoil thickness is about 20 percent greater than the original thickness of the undisturbed overburden.

On the basis of the discussion in the previous paragraph, it is possible to predict in advance of mining, areas where the final post-mining landscape will be lower than the pre-mining landscape, and therefore lower than the surrounding unmined landscape. These areas will tend to become hydrologic lowland sites in the reclaimed landscape, which accumulate surface water and become the locus of discharge for groundwater flow systems. In some instances, the landscape configuration can be designed to minimize, or even eliminate lowland sites. In most cases, however, lowland sites will persist with certain inherent limitations to post-mining capability. The following expression describes the relationship between the thickness of coal to be mined (T_C), overburden thickness (T_O) and bulking factor (B) required for lowland conditions to develop:

$$T_O B < T_C$$

Upland settings develop when $T_O B > T_C$. Using this relationship, with bulking factors of 20 and 25 percent, lowland conditions will result when the overburden thickness is less than 5 and 4 times the thickness of the coal, respectively.

The hydraulic conductivity of the spoil is the primary control on the rate at which the post-mining steady-state equilibrium situation is established. Decades to centuries will be required for steady-state conditions to be attained in Lower Horseshoe Canyon mine sites, where overburden is dominantly fine textured bedrock. In the Ardley Coal Zone it is anticipated that the majority of mines developed will have mine spoil characterized by hydraulic conductivity similar to Highvale Mine (about 10^{-7} m/s). Ten to twenty years will be required for steady-state conditions to be attained in these mine sites.

In general terms, in an area of equivalent climatic conditions, surface depressions of similar size and contributing area would be expected to support larger, longer-lived ponds on mine sites in the Lower Horseshoe Canyon Coal Zone than in the Ardley Coal Zone.

Climate interacts with hydraulic conductivity of spoil to control the size and permanence of surface ponds. The most important aspect of climate as it influences the hydrologic regime in reclaimed landscapes is the availability of water to produce ponds. The availability of water is a function of the magnitude and timing of precipitation and the potential for evaporation and evapotranspiration. In general terms, as one moves from the Lake Wabamun mining area southeastward across the plains of Alberta, the availability of water decreases, precipitation decreases, and evaporative losses increase. The zonation of the plains region into a series of ecoregions reflects this trend. Thus, for a depression of a given size, the potential for ponding, and the frequency and duration of ponding decreases to the southeast. Hence, in order to form a pond of the same size at Sheerness as one at Highvale, the contributing drainage area must be much larger at the former site than at the latter. The implication for this decrease in potential for ponding toward the southeast is that there is much less likelihood for shallow water table conditions to develop at Sheerness than at Camrose-Ryley or Genesee. In the event that permanent or semi-permanent ponding should develop at a mine in the Short Grass or Mixed Grass Ecoregion, however, the potential for salinization is much greater than it is farther to the northwest.

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3.0 THE GROUNDWATER RESOURCE

What Are the Groundwater Resource Issues Related to Surface Mining?

The potential impact on groundwater due to surface mining and reclamation was a principal focus of the Plains Hydrology and Reclamation Project. Studies were done at Diplomat, Vesta and Paintearth mines in the Battle River study area, and at Highvale mine in the Lake Wabamun study area.

The groundwater issues related to surface mining fall into two general categories: (1) effects on groundwater resources, in terms of groundwater supply, and (2) interactions between groundwater and the land surface, related to the long-term capability of reclaimed lands.

Groundwater resources can be impacted by mining either directly, for example by the removal of overburden aquifers within the area of mining, or indirectly, from the influence of mining on water levels or groundwater quality outside of the mine area. In either case the concern is over the quantity of groundwater available for domestic or agricultural use, and the quality of that groundwater, both during mining and after reclamation. Sections 3.1, 3.2 and 3.3 discuss the nature of the groundwater resource in surface mining areas in Alberta, groundwater impacts within the mine area, and groundwater impacts outside the mine area, respectively.

In reclaimed lands, re-establishment of a water table can aggravate surface subsidence. Ponds in reclaimed landscapes can be either groundwater recharge or discharge features, and the corresponding groundwater flow systems that develop can contribute to soil salinization in low-lying areas. These processes can all affect the long-term capability of reclaimed lands. Section 3.4 provides a discussion of these groundwater–landscape interactions. Section 3.5 looks at environmental contamination issues associated with spoil groundwater. To conclude this discussion on the groundwater resource, Section 3.6 gives the reader some guidance with respect to consideration of groundwater within the mining process, and Section 3.7 provides a list of references for more in-depth information on Plains coal mining and groundwater.

Q3.1 WHAT IS THE NATURE OF THE GROUNDWATER RESOURCE IN SURFACE MINING AREAS IN ALBERTA?

A. **In most mining areas, groundwater useable for domestic or agricultural purposes occurs in coal beds or aquifers present above the lowest coal.** In fact, water supplies for the rural population living on the plains are derived almost entirely from groundwater. Surface mining of coal disrupts these supplies. However, wells are generally few and far between, averaging 1 to 3 wells per section. In the plains, the depth of approximately two-thirds of the wells is at or above the base of mining (typically less than 50 metres deep) and therefore these wells will be disturbed by mining.

The wells tap aquifers that occur in thin sheets separated by thick aquitards. Aquifers may be in surficial sand and gravel, sandstone or coal (Figure 3.1). For example in the Battle River mining area, 75 per cent of the 28 domestic wells surveyed as part of PHRP, were completed in the two coal beds that are being mined. In the Lake Wabamun mining area, 18 per cent of 196 wells potentially affected by the mining were completed within the Ardley Coal Zone, 62 percent in sandstone overlying the coal, and 17 percent in glacial drift overburden. Hydraulic conductivity of the aquifers commonly decreases with depth, as does the water quality.

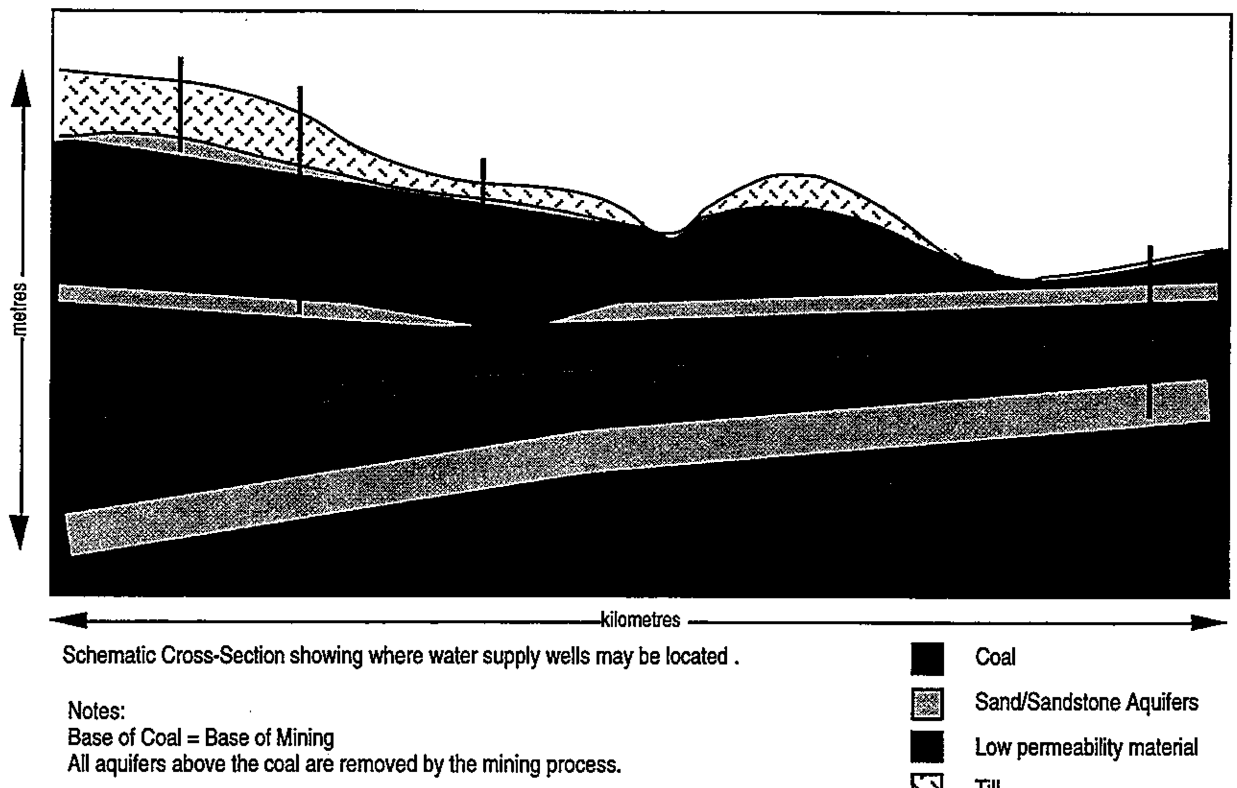


Figure 3.1 Schematic cross section showing where water supply wells (vertical lines) may be completed. Most wells are usually shallow and completed within the zone disturbed by mining.

Q3.2 WHAT GROUNDWATER IMPACTS OCCUR WITHIN MINING AREAS?

A. Mining reduces groundwater supply potential by removing primary aquifers within the mining area. Surface mining irrevocably alters the groundwater regime. It removes the fractured coal bed or sandstone aquifers and replaces them with spoil, thereby decreasing the capability of the area to supply groundwater. The resulting spoil mass is made up of disconnected blocks of aquifer-like material in a matrix of aquitard material (Figure 3.2). It behaves like an aquitard.

Mine spoil from plains coal mining has a low hydraulic conductivity – from 10^{-7} to 10^{-9} m/s – significantly lower than the pre-mining aquifers. Only in very rare cases can the hydraulic conductivity of these mine spoils be altered.

The hydraulic conductivity of mine spoil is also much more variable (ranging over six orders of magnitude within individual mines) than the pre-mining overburden (Figure 3.3). Sandstone beds, coal beds and glacial drift all range in hydraulic conductivity over slightly less than three orders of magnitude; silt and clay beds in the pre-mining overburden are even less variable, ranging over slightly more then one order of magnitude. Therefore, the hydraulic conductivity of spoil can vary over the full range of premining overburden values. However, because the individual blocks of material in spoil are small, there is no lateral continuity to any single range of hydraulic conductivity.

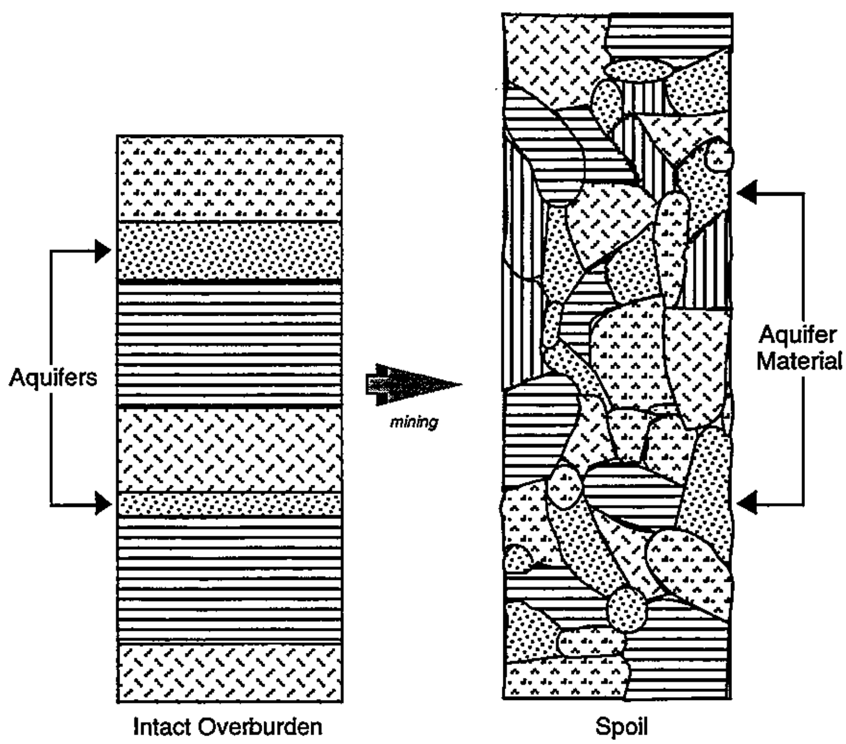


Figure 3.2 Mining replaces horizontally continuous aquifers with spoil: disconnected blocks of aquifer material in a clayey matrix.

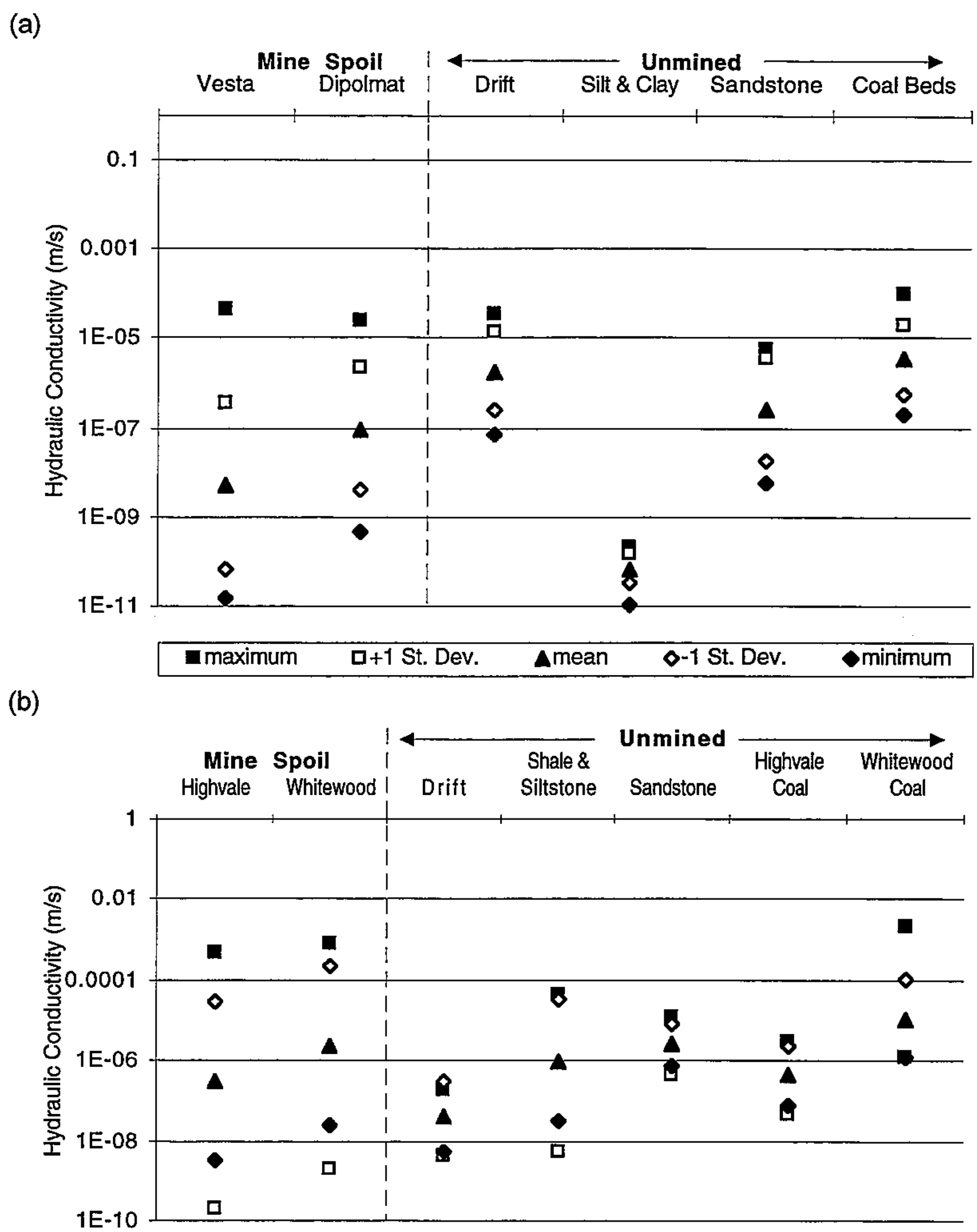


Figure 3.3 The hydraulic conductivity of mine spoil is lower and more variable than that of pre-mining aquifers: (a) example from the Battle River mining area, (b) example from the Lake Wabamun mining area.

Q. Will groundwater levels within reclaimed areas return to pre-mining levels?

A. Groundwater levels within reclaimed areas will recover over time. Although the time it takes to resaturate spoil varies from mine to mine, it is important to note that the water table in spoil does re-establish. The proximity of the water table to the land surface is the most critical aspect of the hydrologic regime that determines the success of reclamation, because of its potential impact on soil.

The rate of spoil resaturation depends on the landscape setting (climate and topography) and the hydraulic conductivity of the spoil material. Initial resaturation rates tend to be rapid as water rushes in to fill the spaces in the spoil. The water that resaturates the spoil material comes from both groundwater (at the base of the spoil) and surface water (ponds). As the spoil becomes wet it slakes and swells, thus slowing the rate of resaturation until a steady state is reached (Figure 3.4). The entire resaturation process can take anywhere from 10 to 100 years.

The process of spoil resaturation is fundamentally different in lowland and upland settings within a mined area. Data collected by PHRP suggest that the recharge rate in lowlands is about twice that in uplands, regardless of hydraulic conductivity. For example in lowland mine sites with high permeability spoil, recovery of groundwater levels to steady state generally requires no more than five to 10 years. In contrast, upland sites with similar high permeability may take 10 to 15 years to achieve steady state conditions.

Hydraulic conductivity is the second major factor controlling rate of resaturation. The effect can be seen in a comparison of two upland sites, one with high hydraulic conductivity and the other with low hydraulic conductivity (Figure 3.5). Whereas the site with high hydraulic conductivity may achieve steady state in less than 10 years, the one with low hydraulic conductivity may take at least several decades.

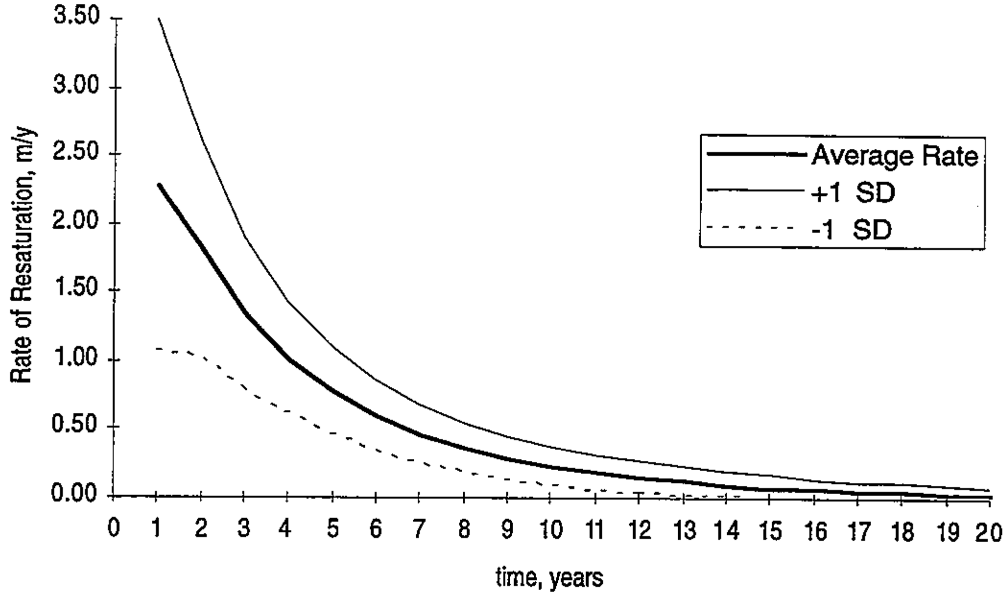


Figure 3.4 The rate of spoil resaturation is initially high, but decreases over time until steady state is reached. The curves presented are based on data obtained by PHRP at Diplomat Mine.

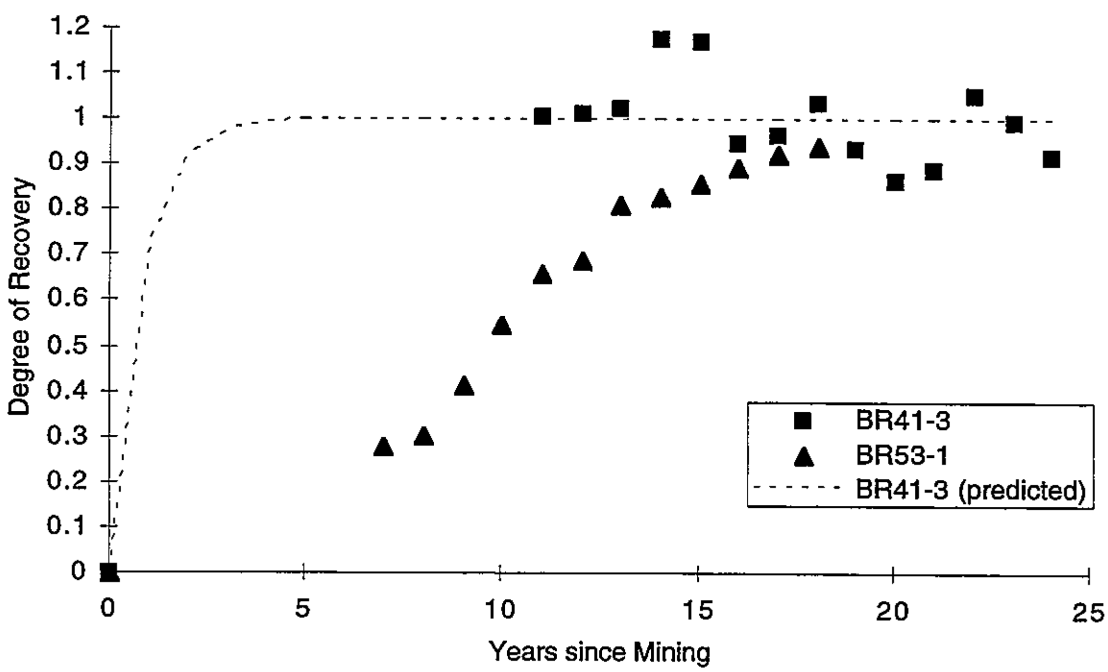


Figure 3.5 Comparison of groundwater recovery at sites with differing hydraulic conductivity (K). Site BR41-3 represents a high K, while BR53-1 represents a low K.

Q. What is the chemical quality of groundwater in mine spoil?

A. Groundwater in spoil is almost everywhere more saline and has a substantially different chemical composition than the water in pre-mining aquifers. It is generally unsuitable for consumption by humans or livestock because of excessive concentrations of dissolved solids, particularly sulfate.

Chemistry of groundwater varies among mining areas and individual mines (Figure 3.6). Spoil groundwater in the Battle River mining area is considerably more saline than water in the Lake Wabamun mining area. It is not known whether this difference is a function of differences in overburden, climate, or both. Differences in groundwater chemistry among mines in the same area reflect differences in overburden material. For example, in the Lake Wabamun mining area, groundwater in Highvale Mine spoil, which is primarily bedrock, has a mean TDS of 3668 mg/L; whereas groundwater in Whitewood mine spoil, which is primarily sand and gravel, has a mean TDS of 1395 mg/L.

At most of the PHRP study sites, groundwater chemistry in spoil remained essentially constant over time. However changes over time were observed in the chemistry of spoil-derived groundwater to the west of Vesta Mine. The initial flush of water through the mine spoil had an appreciably greater TDS concentration than the concentrations subsequently recorded.

On the basis of groundwater chemistry studies and experimental weathering of overburden, it appears that much, if not most, of the dissolved salt in spoil groundwater results from dissolution of secondary salts that had accumulated in the soil zone of pre-mining overburden. An additional, although less important source of salt is rock material that was originally beneath the water table and is exposed to atmospheric weathering processes as a result of mining.

The brackish nature of groundwater in mine spoil appears to be an inevitable consequence of mining on the plains. Salinity increases range from 2.4 to 5.9 times the pre-mining levels (Figure 3.7). There is no known method of material handling that would alter the chemical make-up of the groundwater in mine spoil in this region.

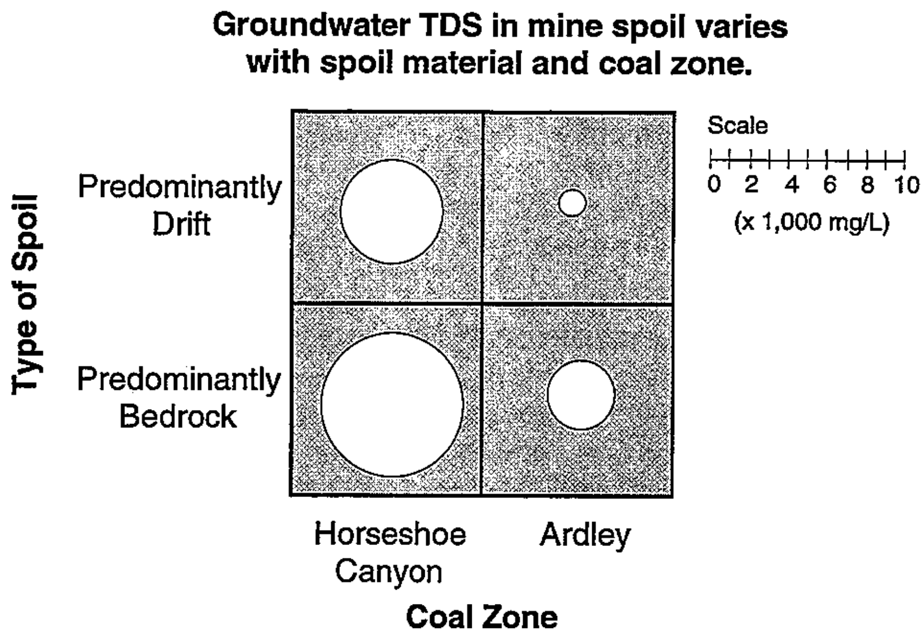


Figure 3.6 Schematic diagram showing the difference in groundwater salinity depending on geology (coal zone) and make-up of spoil. Diameter of circle reflects the TDS of spoil groundwater, as given by the scale.

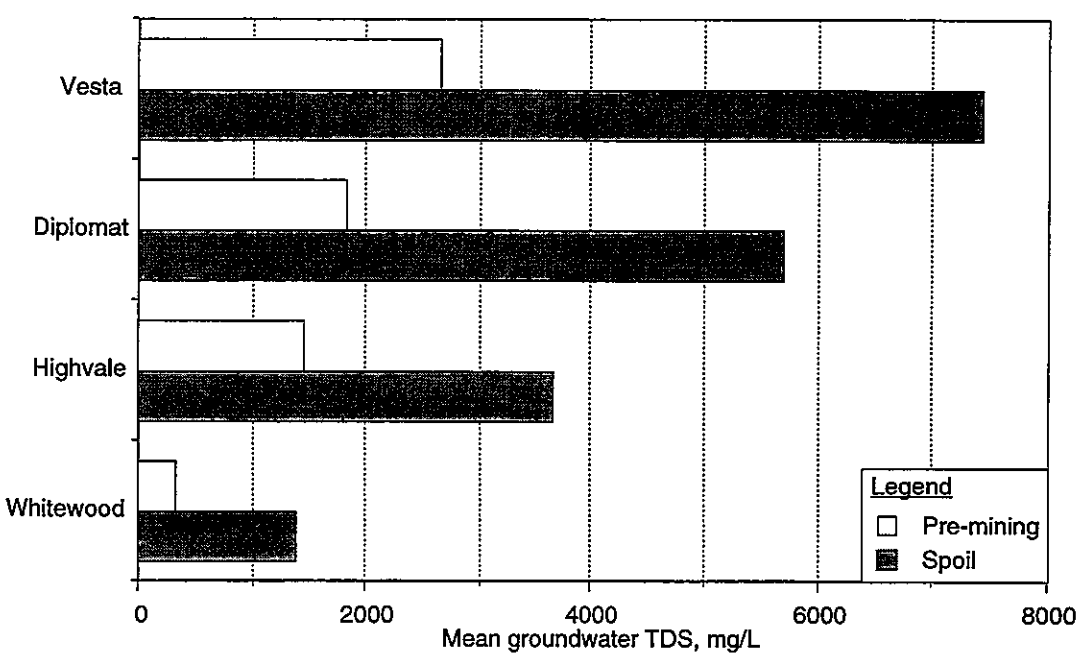


Figure 3.7 Comparison of total dissolved solids concentration of groundwater in pre-mining aquifers and mine spoil in the plains of Alberta.

Q. Are there replacement groundwater supplies where surface mining has occurred?

A. There is limited potential to replace the shallow groundwater supplies disrupted by mining with either the mine spoil or other deeper aquifers. The low hydraulic conductivity of the spoil renders it incapable of supplying water to wells. There are no aquifers in mine spoil. In addition, the brackish nature of the water in spoil makes it unfit for consumption by humans and livestock.

It is highly unlikely that an aquifer could be successfully constructed in mine spoil. One exception may be the rare case where large volumes of sand or gravel are present within the overburden to reconstruct an aquifer. The design and construction of such an aquifer would be costly and justified only if there was no viable alternative to providing an adequate water supply. As well, the groundwater from these reconstructed aquifers may not be suitable for human consumption.

There is limited potential to replace the shallow groundwater supplies disrupted by mining with deeper aquifers. However, these deeper aquifers occur in only a few places depending on the geology of the area. For example in the Lake Wabamun mining area, discontinuous channel sandstones underlie the coal zone but their location is very difficult to predict without detailed geological investigations.

Deeper aquifers also tend to have lower hydraulic conductivity and/or poorer water quality. Although the sheet-like sandstones below the coal in the Horseshoe Canyon Formation can produce an adequate water supply, the water is usually too saline for human consumption. The deep sandstone beds in the eastern part of PHRP's Battle River study area tend to have better water quality, as a result of receiving local recharge. In general, where the water quality is acceptable, these sandstone beds offer the best naturally occurring option to replace groundwater supplies lost as a result of mining.

It is extremely important to note that the possible absence of groundwater supply in the post-mining environment is not an "unnatural" condition. Extensive areas of the plains of Alberta are underlain by marine shale in which there are no sandstone or coal aquifers at all. In these areas, potable groundwater is rarely available. It is also important to note that surface water supplies (i.e., ponds and dugouts) could also be used as a replacement option for agricultural water supply needs.

Q3.3 WHAT IMPACT DOES MINING HAVE ON GROUNDWATER OUTSIDE THE MINE AREA?

A. **The significance of impacts beyond the mine area depends on "scale".** The scales of concern are "regional" and "local". Mining may sometimes impact regional groundwater levels, given the right hydrologic conditions. On the local scale, there is nearly always an impact on groundwater levels. These impacts (regional and local) are discussed in detail in the following sections.

Q. What regional impacts occur?

A. The effect of mining on regional water levels depends on the hydrologic setting of the mine. The effect of the mine is different depending on whether it is situated in a regional recharge or discharge area. In the regional recharge setting, mine dewatering results in only local effects on water levels, generally less than 1.5 km from the mine. Once the mine has been completed, water levels generally recover within a few years. In the regional discharge setting, however, mine dewatering can reduce water levels at distances of many kilometres from the mine. Upon completion of mining, water levels recover slowly. Each of these settings are portrayed schematically in the accompanying figure.

All existing surface mines in the Plains region of Alberta are located in regional groundwater recharge areas. This is because the mining areas are situated in regionally elevated topographic settings, and the vertical hydraulic gradient is everywhere directed downward. In addition no potential mines in the Plains region of Alberta are known to be located in areas of regional groundwater discharge. As a result, it is unlikely that any mines in the Plains region of the province will result in groundwater impacts beyond the immediate vicinity of the mining operation.

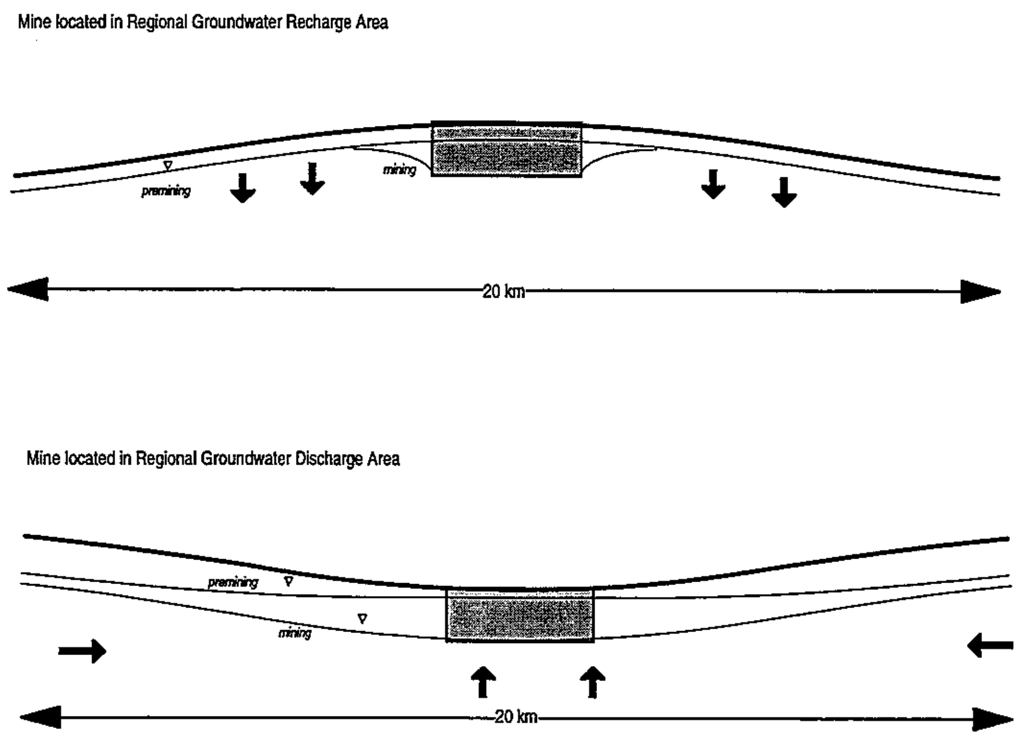


Figure 3.8 Schematic diagram showing the effect of mining on groundwater in different regional settings. The thick, black arrows indicate direction of regional groundwater flow.

Q. What local impacts occur?

A. Given the right hydrologic and physical conditions, water level declines of many metres can occur in wells within 1.5 km of active mine pits. These conditions are:

- **hydrologic:** the well completed in an aquifer connected to (with) the active mine pit; and
- **physical:** the well in close proximity to the active mine pit (i.e., less than 1.5 km).

It's important to note that drawdown effects of mine pits do not propagate uniformly in all directions. This differential drawdown is believed to be related to the higher hydraulic conductivity in the direction of jointing (or cleat direction) in the coal. In Figure 3.9 the decline in water level in a well 1350 m from Vesta Mine did not begin until the mine pit aligned with the well site, along the major cleat direction of the coal.

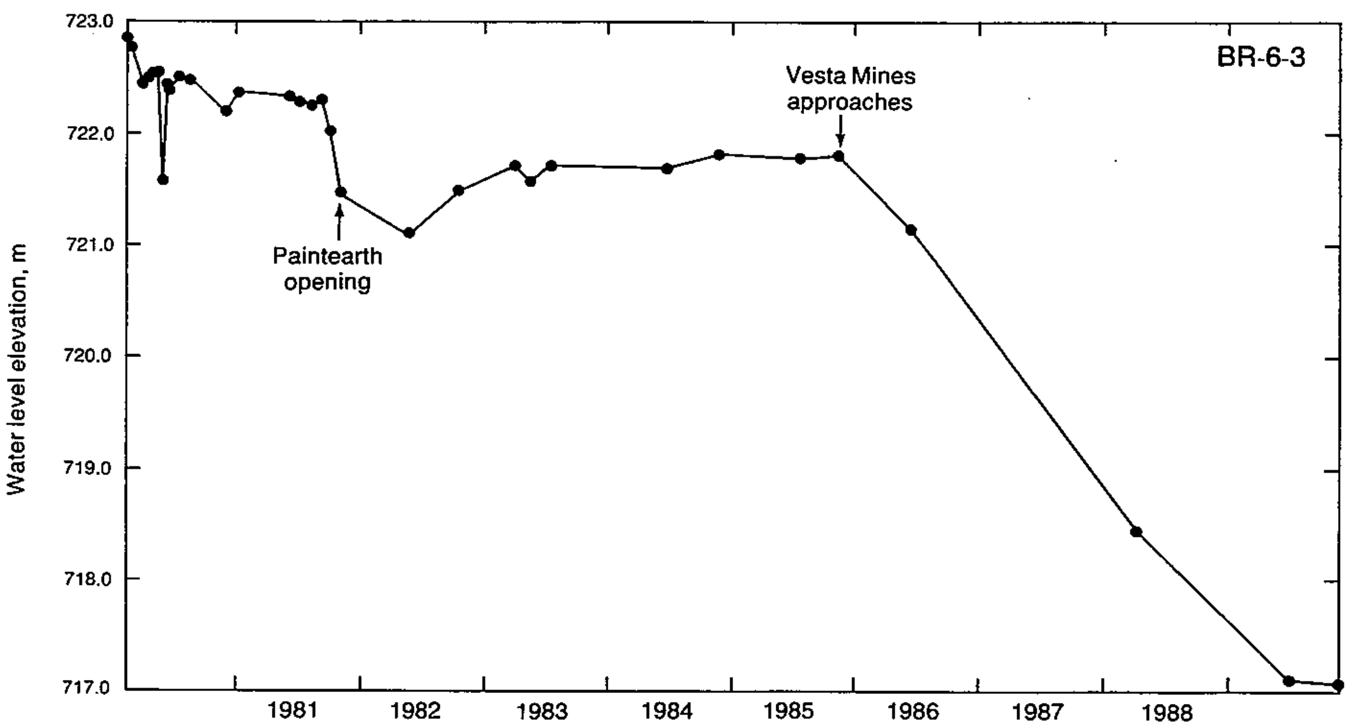


Figure 3.9 Water level declines in the well did not occur until the well site and the highwall were in line with the major cleat direction of the coal.

Q3.4 HOW DOES GROUNDWATER INTERACT WITH THE LAND SURFACE WITHIN A RECLAIMED MINE AREA?

A. **Four elements of the reclaimed landscape (groundwater, ponds, subsidence, and salinity) dynamically interact at the landscape scale in a unified model**, as represented by Figure 3.10. The result of the interactions between these elements is the observed, steady-state reclaimed landscape. The nature and magnitude of the interactions between the elements varies over the evolution of the reclaimed landscape. Specifically, research conducted under the RRTAC Plains Coal program (primarily PHRP) has shown that:

- Contribution to groundwater recharge by ponds is greatest in the early stages of reconstructed landscape recovery;
- Subsidence driven by ponded water is greatest in early times;
- Subsidence driven by groundwater is delayed and episodic; and
- Salinity and groundwater discharge to ponds are longer term phenomena.

The following discussion covers the following interactions in more detail: (1) groundwater and ponds, (2) water (surface and ground) and subsidence, (3) groundwater and salinity. It then looks at the changes in the interactions, as mentioned above, as time progresses.

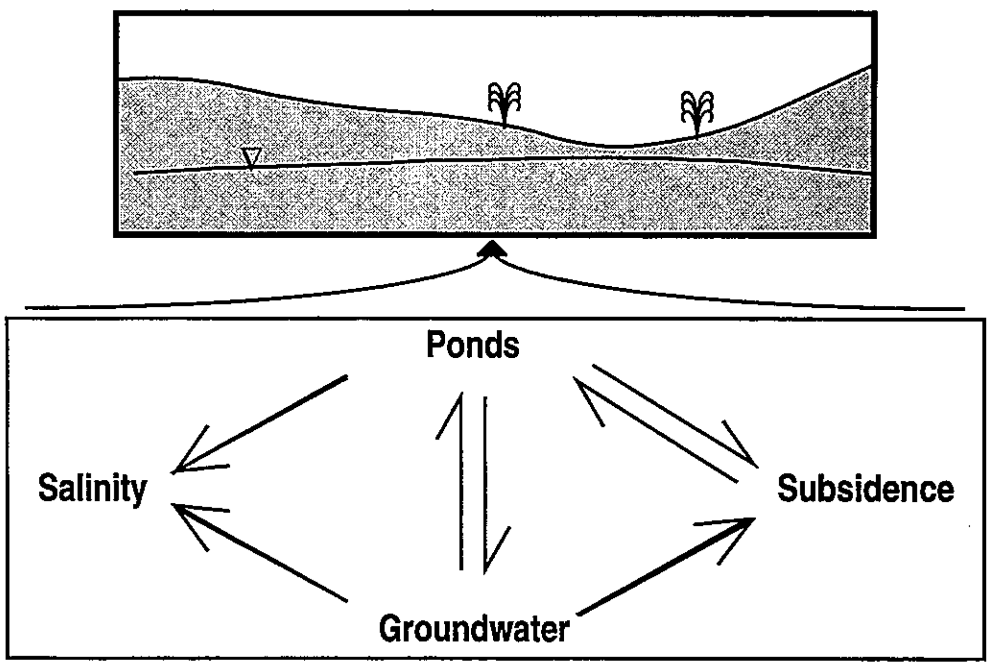
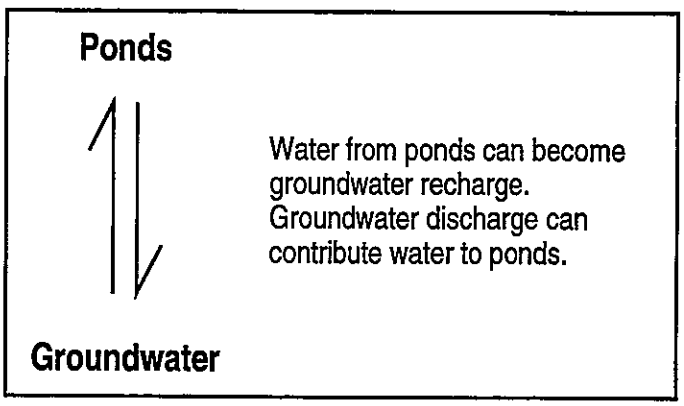


Figure 3.10 Groundwater, ponds, subsidence, and salinity interact in a reclaimed landscape, influencing both the evolution and the final state of the reclaimed land.

Q. How do ponds affect groundwater and vice versa?

A. Groundwater and ponds are dynamically interlinked in reclaimed landscapes, or put another way, ponds cause groundwater which in turn causes ponds.

Ponds in reclaimed landscapes occur in two hydrologic settings. Some ponds are not connected to the water table. Unsaturated spoil occurs between the pond and the water table. This is commonly the case in upland reclaimed areas. Other ponds are connected to the groundwater regime in the spoil. This is most likely to occur in lowland reclaimed settings. One of the important roles of ponds in reclaimed landscapes is as a major source of groundwater recharge. All ponds that are not connected to the groundwater regime (i.e. those that are "perched" above the water table) lose water by downward percolation to the groundwater. The same is true for many, if not most, ponds that are connected to the groundwater, at least during the spring. Ponds that are low in the landscape and are connected to the groundwater are commonly partly fed by groundwater discharge.



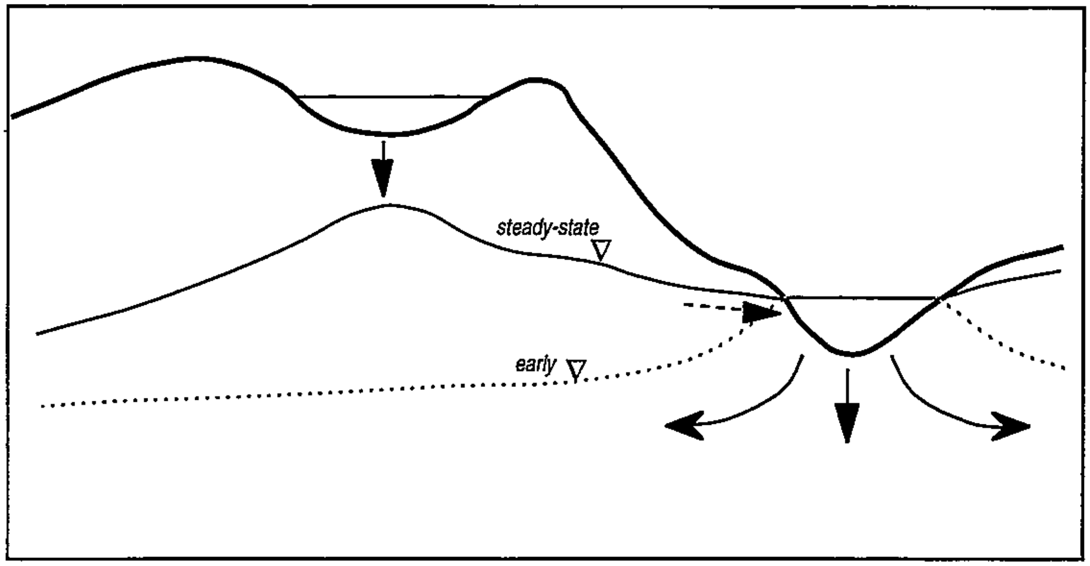


Figure 3.11 Ponds in lowland settings may receive some groundwater discharge under steady-state conditions. Otherwise, ponds are groundwater recharge sources

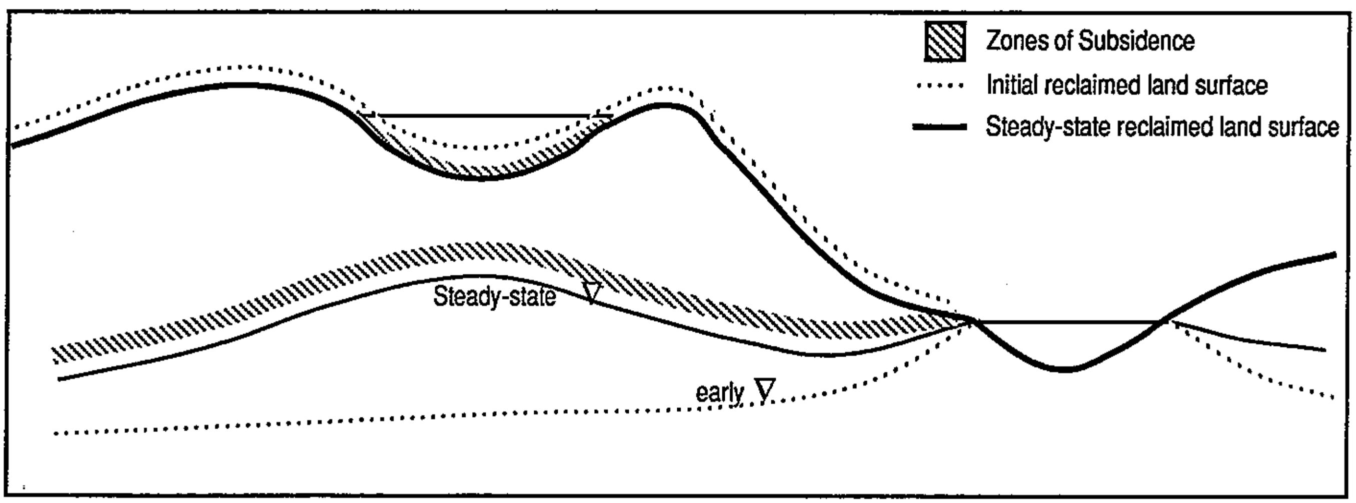


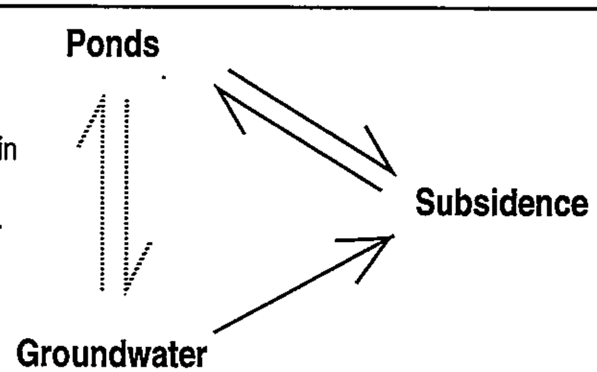
Figure 3.12 Subsidence in reclaimed landscapes is triggered by water from ponds and/or groundwater.

Q. What is the relationship between water and subsidence?

A. Subsidence in reclaimed landscapes is triggered by infiltrating water from perched ponds and by rising groundwater.

Upland ponds in reclaimed landscapes contribute to surface subsidence in two ways. Direct infiltration from the pond results in subsidence of the pond itself. Groundwater recharge from the pond raises the water table, which produces more wide-spread subsidence. Once a site has been reclaimed, low areas begin to collect snowmelt runoff in the spring. The original shallow depression is deepened by differential subsidence caused by the infiltrating water. As infiltrating water comes into contact with the spoil material, the structure of individual fragments collapse and the spoil loses strength and compacts. This differential subsidence results in the formation of numerous oval depressions about 10 m by 20 m and as much as 0.5 m deep. These depressions increase infiltration and accelerate differential subsidence by ponding water during spring melt and heavy summer rain storms. As the original low area deepens through this positive feedback process, the pond that forms each spring becomes deeper and more persistent. As the pond becomes more persistent, it plays a greater role in recharging groundwater.

Groundwater recharge causes the water table to rise. As the zone immediately above the rising water table becomes wetted through capillary action, the spoil consolidates resulting in further surface subsidence.



Water from ponds can trigger subsidence, which in turn can cause ponds to grow larger and/or deeper. A rising water table is also a trigger for subsidence.

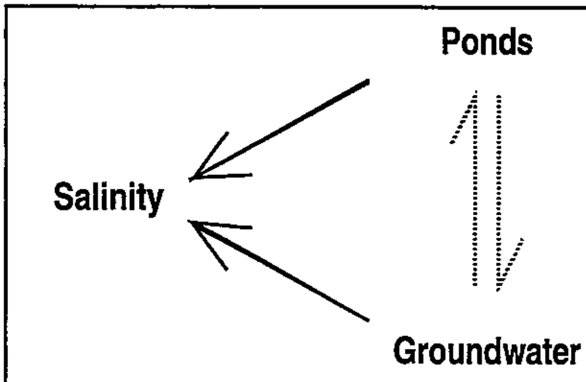
Q. What role does groundwater play in soil salinization?

A. Salinization of reclaimed soils is caused by water moving outward from ponds and/or upward from a shallow water table.

Dryland salinity, although more of a problem in southern and southwestern parts of Alberta, is of concern for potential surface mines throughout the grassland and parkland ecoregions of the province. In these regions of Alberta, sufficient salt is generally available within overburden materials to produce problem salinity almost everywhere that the necessary hydrologic and climatic conditions are met.

Soil salinization is caused by removal of water from the capillary fringe above a shallow water table by direct evaporation and by evapotranspiration through plants. The salt is left as a precipitate when the water is removed. It is evident that the equilibrium salt status of a given profile is the net result of competing rates of salt accumulation in response to evaporation and evapotranspiration, and of salt leaching in response to infiltration. In order for salinization to develop evaporation and evapotranspiration must exceed precipitation. These conditions are met in most of the agricultural region of east-central and southern Alberta.

Two hydrologic conditions are necessary for the development of dryland soil salinity. The first requirement is that the water table persists within a certain critical depth range beneath the surface for an extended period during the growing season. The second requirement is that the net flux of groundwater over time is toward the site of potential salt accumulation. Specifically, salinity develops where groundwater flow is directed upward or laterally into an area where the water table lies within about 2.0 m of the surface. The principal mechanism by which shallow, lateral groundwater flow develops in reclaimed terrain is the presence of a barrier at depth, such as a marked decrease in hydraulic conductivity caused by a change in material. This condition occurs at two intervals within reclaimed landscapes: (1) the hydraulic conductivity of the undisturbed rock beneath the pit floor is, in general, significantly lower than the overlying spoil; and (2) the hydraulic conductivity of till-derived subsoil is, in general, significantly greater than the underlying spoil, which is derived from sodic bedrock.



Water moving outward from ponds and/or upwards from a shallow water table can produce salinization in reclaimed soils.

Ponds in reclaimed landscapes, even where not connected to the water table, have the potential to produce sodic, saline soils. The change in hydraulic conductivity between subsoil and spoil acts as a barrier to the downward infiltration of water. Evaporation from the saturated soil surface and transpiration from plants around the edge of these depressions induces flow outward from the pond and upward from the upper surface of the spoil. Salt and sodium levels in the soil surrounding these depressions are expected to increase over time to levels that are detrimental to vegetation so that the agricultural capability of these areas is permanently decreased.

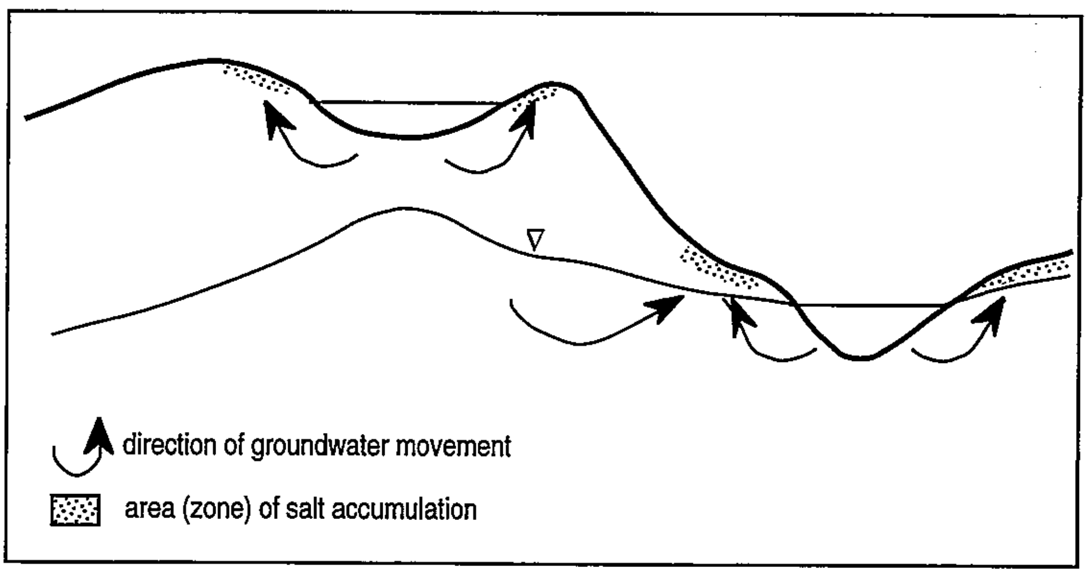


Figure 3.13 Water moving outward from ponds and/or upwards from a shallow water table can produce salinization in reclaimed soils.

Q. Are these interactions between groundwater, ponds, subsidence and salinity constant in time?

A. The nature and magnitude of the interactions between these four elements varies over the evolution of the reclaimed landscape. The following discusses the importance of each element in the evolution of the reclaimed landscape.

Contribution to groundwater recharge by ponds is greatest in the early stages. Immediately after reclamation in upland areas, the surface is generally flat to very gently undulating with only limited areas of very subtle, shallow depressions. During snow melt and after heavy rain storms, the minor depressions on this surface collect water, which infiltrates into the spoil. Because of the loose, open structure of the spoil, the water infiltrates deeply into the spoil mass to recharge the groundwater. At this stage in the hydrologic evolution of reclaimed landscapes, all ponds are perched above the water table and contribute to spoil resaturation by downward leakage. As the infiltrating water wets the spoil material, it swells, slakes, and is compressed under the weight of the overlying spoil causing the loose, open structure to be lost. As a result, the hydraulic conductivity decreases allowing less downward percolation of ponded water and the rate of groundwater recharge from ephemerally ponded upland depressions slows.

Depressions in lowland settings collect surface runoff to form ponds. Early in the post-mining period these ponds, like the upland ponds, are almost entirely sources of groundwater recharge. These ponded depressions quickly become connected to the water table. As the water table rises beneath the higher landscape bordering these lowland depressions, the rate of outflow from the ponds slows. As steady-state conditions are reached, the groundwater may periodically discharge into lowland ponds.

Subsidence driven by ponded water is greatest in early times. As the water infiltrates downward from ponded depressions, it wets the spoil material, which loses strength and is compressed under the weight of the overlying spoil. This causes the land surface to subside and results in a broadening and deepening of the incipient depressions. As a result, the growing depressions capture more water and support larger ephemeral ponds. Depending on the size of the drainage area of the depression, this positive feedback mechanism can produce many small, ephemeral ponds, or few, larger semi-permanent to permanent ponds. This increase in subsidence is countered by the decreasing infiltration caused by closing of the open, loose structure of the spoil material. As a result, the rate of subsidence caused by downward infiltration from ponds diminishes with time.

Subsidence driven by rising groundwater is delayed and episodic. The water table marks the upper boundary of completely saturated spoil. In a capillary fringe, which is from 0.5m to 1.5 m thick above the water table, the spoil is partly saturated, becoming progressively more saturated as the water table is approached. As the water table rises in spoil in response to groundwater recharge, the capillary fringe precedes the rising groundwater causing the spoil to become wetted. This wetting results in a loss of strength by the spoil material, which is compressed under the weight of the overlying spoil causing the land surface to subside. This type of groundwater induced subsidence is a one-time event that occurs the first time that the water table moves upward through the spoil. The rate at which the water table rises, therefore controls the rate and magnitude of surface subsidence.

Salinity and groundwater discharge to ponds are longer term phenomena. Once recharge from ponds is sufficient to cause the water table to rise to within one to two metres of the land surface in the area peripheral to the pond, salinization will become increasingly evident. Where recharge beneath an adjacent upland is sufficiently great to cause the water table to rise above the level of the ponds in the lowland, groundwater flow is reversed. During at least part of the year, and around at least part of the pond periphery, groundwater flow is directed toward, not away from the pond. In those zones permanent salinization can begin to develop. The conditions necessary for the development of permanent salinity require that the groundwater regime be well established. For this reason, development of salinity is a phenomenon that occurs late in the evolution of the post-mining landscape toward its stable, steady-state condition.

Q3.5 WILL SURFACE MINING IN THE PLAINS RESULT IN CONTAMINATED SURFACE WATER OR GROUNDWATER?

This unit examines questions regarding the environmental effect of surface-mining beyond that of the immediate reclaimed landscape. These concerns are generally associated with the movement of groundwater from the reclaimed mine area into areas that are unmined.

The potential for contamination to occur involves three factors that must be evaluated (Figure 3.14):

1. is there a source for the contaminant or contamination?
2. is there a pathway between the source and receptor? and
3. is there a receptor?

In addition to these three factors, the relative magnitude of the release from the mined area must be weighed in light of the impact on the receptor (i.e., hazard evaluation).

In the case of reclaimed surface mine areas, the potential source of the contamination is the spoil groundwater. It's movement can result in off-site subsurface migration into adjacent aquifers, discharge into surface water bodies, and/or dissolution of other contaminants from waste disposal areas in the spoil material, in particular, ash. Each of these scenarios will be explored further in the following sections.

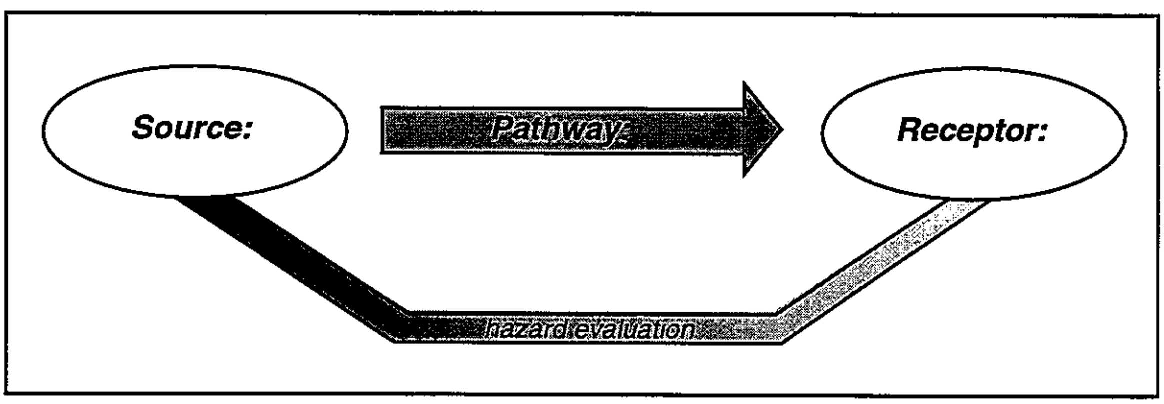


Figure 3.14 Components required to evaluate the risk associated with any potential environmental contamination.

Q. Will the spoil groundwater contaminate unmined aquifers?

A. Spoil groundwater can migrate into adjacent unmined aquifers under rare circumstances. Any offsite effects on groundwater or soil due to mining are likely to be minor. The chemical compounds released from mine spoil are all naturally-occurring, largely innocuous compounds that are already present in the soils or groundwater in unmined areas, although at lower concentrations. Because mine spoil has very low hydraulic conductivity, only a small amount of spoil-derived compounds can be released. Any release, therefore, is readily diluted in the surrounding environment. A possible exception to this general conclusions is due to the in-pit burial of ash, which can be more problematic, and is discussed in a later section.

Movement of groundwater from mine spoil into adjacent unmined land is considered to be an exceptional event related to specific geological and hydrological circumstances. In general, the potential for migration of spoil groundwater into unmined aquifers exists wherever hydraulic head in the spoil is greater than in the surrounding unmined area. In order to cause migration into bedrock aquifers, a reclaimed landscape must include deep ponds that recharge the base of spoil resulting in relatively high hydraulic heads at depth. In the case of migration into shallow surficial aquifers, the elevation of the reclaimed landscape needs to be significantly higher than the surrounding unmined area for the migration to occur. The direction of spoil groundwater migration is influenced not only by the distribution of hydraulic head, but also by the preferred directions in horizontal hydraulic conductivity. In coal aquifers these preferred directions are related to the fracture orientation of the coal, and are probably the characteristics that control the direction of plume migration. In unconsolidated sand aquifers the rate and direction of plume movement appears to be controlled by zones or lenses of higher than average permeability.

The implications of off-site migration of spoil groundwater are two-fold. First, and most obvious is the deterioration of potential water supply as a result of

Off-Site Subsurface Migration

Source:	*Spoil Groundwater*
Pathway:	*Hydraulic Head and Connection*
Receptor:	*Unmined aquifers*

degradation of water quality in the aquifers affected. The loss of the groundwater resource may or may not have a significant negative impact on a local scale, depending on the usage or ability of the aquifer to supply water. Any effect will be smallest, due to dilution, where natural groundwater flow rates are high and water quality is good.

A less obvious, but potentially more significant consequence of the presence of degraded water in unmined aquifers adjacent to reclaimed areas is soil salinization. Two areas are potential sites for salinization to occur. The first is immediately adjacent to the mine where the water table is close to the surface. The second is where a permeable bed crops out and the affected groundwater is discharged to the surface.

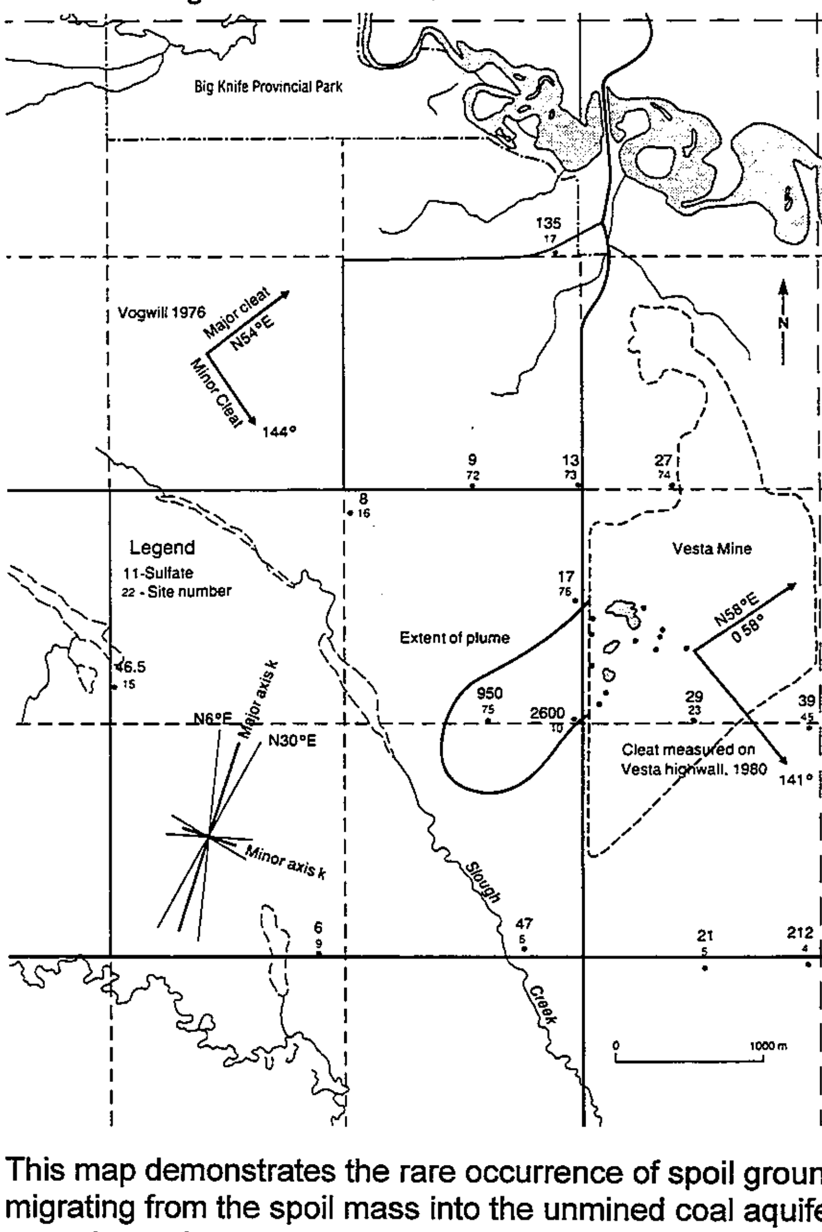


Figure 3.15 This map demonstrates the rare occurrence of spoil groundwater migrating from the spoil mass into the unmined coal aquifer. The map shows the concentration of sulfate in groundwater from the Battle River Bed near Vesta Mine.

Q. Will spoil groundwater contaminate surface streams?

A. **Impact of the small amount of spoil groundwater that discharges into surface streams is negligible.** Groundwater discharging from mine spoil does not appear to pose a significant threat to the chemical quality of surface water. Although elevated in concentration, spoil groundwater contains the same dissolved chemicals that naturally occurring surface water. Along the 10 km reach of the Battle River valley, where it traverses Diplomat and Vesta Mines in the Battle River mining area, i25 springs and seeps were identified in a study by Trudell (1988). Fourteen of these springs discharged spoil-derived groundwater and the remainder represented groundwater discharge from unmined aquifers. The volume of discharge from the spoil-derived springs and seeps constituted about twice that of the unmined aquifers (103 vs. 50 m^3/d), but the salt loading was more than four times as great (449 kg/d vs. 106 kg/d). The impact of this discharge on the Battle River, however, is almost undetectable, due to dilution. The worst case scenario would involve low flow in the river late in the summer. The natural salt load of the river under these conditions is calculated at 23 600 kg/d, based on the minimum long-term average daily flow recorded by the Water Survey of Canada. Under these conditions, the addition of the entire salt loading from spoil-derived springs represents an insignificant increase of only 2 percent compared to the natural salt load in the river (Trudell 1988).

Surface Water Contamination

Source:	*Spoil Groundwater*
Pathway:	*Spoil groundwater seepagefrom springs*
Receptor:	*Stream, surface water*

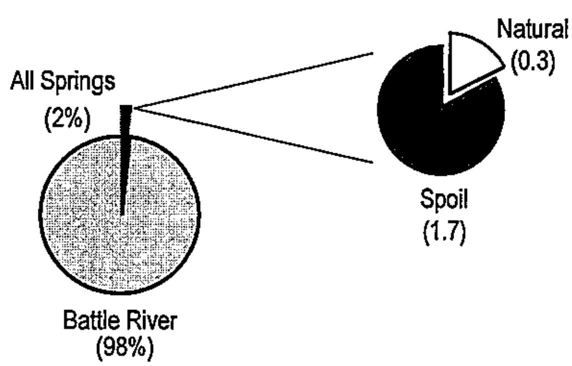


Figure 3.16 Salt load from the discharge of spoil groundwater from springs along 10 km of the Battle River valley makes up 2% of the total salt load in the river.

Q. Will buried coal ash contaminate groundwater?

A. Careful placement of coal ash within mine spoil can prevent or minimize potential groundwater contamination

Coal ash, the residue from the combustion of coal, is often disposed of in pits at surface coal mines. The chemical characteristics of the ash are generally such that the potential for groundwater contamination by either heavy metals and/or salts can occur. For example, in a study by Trudell and others (1984) found that as a result of leaching and modeling experiments of coal ash from the Battle River mining area, spoil groundwater in contact with buried ash was expected to have TDS concentrations from 4000 to 5000 mg/L above the background levels. The potential also exists for elevated levels of boron, selenium, and possibly arsenic to be released from the ash leachate.

The most important factor in preventing groundwater contamination from ash waste sites is keeping the wastes dry as suggested by Beaver and others (1991). With water absent, there is no mechanism present to leach or transport contaminants. The following criteria could be used to optimally place an ash disposal site in mine spoil. These criteria are also portrayed schematically in Figure 3.17. Application of these criteria will prevent or minimize the movement of water vertically or laterally through the waste mass.

In – Pit Ash Disposal

Source:	*Spoil Groundwater in contact with buried ash*
Pathway:	*Appropriate saturated hydraulic conditions for migration*
Receptor:	*Reclaimed soils, and/or other on- or off- site landscape features*

Groundwater Protection Criteria for locating ash disposal site in mine spoil

An ash disposal site should be located:

- above the capillary zone of the re-established, steady state groundwater table
- subjected to minimal-to-no recharge (i.e., free-draining uplands)

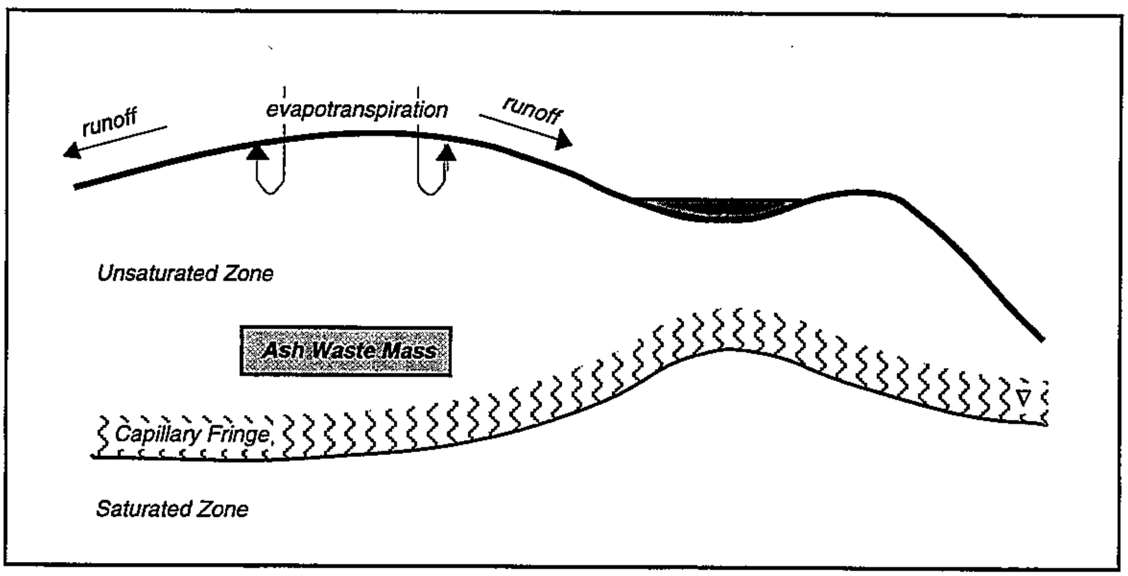


Figure 3.17 Ash disposal sites should be located above the capillary fringe, under a dry upland area where recharge is minimal.

Q3.6 AT WHAT STAGE(S) IN THE SURFACE MINING PROCESS SHOULD GROUNDWATER BE CONSIDERED?

A. Groundwater issues should be considered as part of mine planning, reclamation planning, and post-mining land-use planning.

The timing of dewatering effects on domestic water wells can be included in mine planning. The replacement of domestic wells that are completed in or above the coal and dewatered by mining can be expected as mining progresses within about 1.5 km of a well. Dewatering is likely to be greatest in the direction of the major cleat in the coal. If deeper aquifers are not available to supply replacement wells, then more expensive alternative water supplies, such as trucked-in water, may be required. If large numbers of such wells occur in an area, there may be cost savings if mining near such areas was planned to occur later rather than sooner.

Because groundwater and surface water are closely linked in the landscape, the effect of ponds in reclaimed areas should be carefully considered in reclamation planning. Depending on the goals of reclamation, ponds can be located to enhance or inhibit groundwater recharge. Similarly, the design of slopes and drainage patterns should consider the influence on groundwater recharge of flat versus sloping land. Ponds can be located to minimize salinization in reclaimed land, and slopes adjacent to ponds can be increased to minimize the area susceptible to shallow water table conditions. Since differential subsidence is likely to create depressions, the reclamation plan can incorporate slopes to minimize the ponding of water in subsidence depressions. This has the advantage of both minimizing obstacles to mechanized agriculture in the spring, and minimizing infiltration accompanied by further subsidence.

Land-use planning for reclaimed lands should consider the availability of groundwater supply in identifying reclaimed areas for residential use. Depending on the intended post-mining land use, the influence of surface ponds on groundwater, and the importance of salinization may in part determine the suitability of reclaimed land for agricultural use (livestock, grain or forage production) or wildlife habitat.

Q3.7 WHERE CAN I FIND OUT MORE INFORMATION?

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