

**Macro-Scale Cover Design  
and Performance  
Monitoring Manual**

**MEND Report 2.21.5**

**This work was done on behalf of MEND and sponsored by:  
The Mining Association of Canada (MAC) and MEND**

**July 2007**





Natural Resources Canada  
Ressources naturelles Canada

# MACRO-SCALE COVER DESIGN AND PERFORMANCE MONITORING MANUAL

## MEND Report 2.21.5

Prepared for MEND

Sponsored by The Mining Association of Canada (MAC) and MEND

Edited by:



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## EXECUTIVE SUMMARY

MEND 2.21.4 (Design, Construction, and Performance Monitoring of Cover Systems for Waste Rock and Tailings, 2004) is comprised of basic theory, laboratory site and field characterization methods, conceptual design and approach to numerical modelling, and field performance monitoring of test-scale and full-scale cover systems. Understanding the dynamics of the cover system is an important concept to grasp because it is the interface between the waste material and the environment. However, to evaluate the success of reclamation of an entire area, evaluation criteria need to be expanded on a larger scale, which leads to the development of the current manual, MEND 2.21.5.

The primary objective of this manual is to introduce design and monitoring guidelines for mine waste soil cover systems on a macro-scale, i.e. a watershed and landform-scale, and the challenges that arise due to the increased size and complexity. Design guidelines for covers on a macro-scale are largely governed by the same guidelines as for landform design (landform engineering). A key design issue for a newly reclaimed landscape is to create an initial condition so that the landscape follows a suitable trajectory of evolution both in terms of rate of change and end point. Background on the need for landform design and some general guidelines for landform design that also apply for cover design on a macro-scale are given in Section 2 of this manual.

One of the greatest challenges is the ability to predict and quantify what changes may occur that can potentially affect the integrity of a soil cover system. In order to meet or design for the expectations set, an understanding for the long-term behaviour of the system is necessary which lies in understanding the processes that lead to change. Macro-scale cover evolution, which is discussed in Section 3 of this manual, follows many of the same guidelines and is governed by the same processes as landform evolution. Long-term field performance monitoring of reclaimed sites becomes an important element to defining the critical trajectory by determining the associated mechanisms and processes that cause the landscape to evolve. Syncrude Canada Ltd. is introduced at the beginning of Section 3 as a case study to illustrate the challenges and lessons learned in terms of tracking the evolution / performance of some of their reclamation covers.

Macro-scale monitoring is a tool that is used to characterize conditions, processes, and interactions within a watershed to provide a systematic method to understand and organize ecosystem information. In so doing, watershed analysis enhances the ability to estimate direct, indirect, and cumulative effects of management activities and guide the general type, location, and sequence of appropriate future management activities. The majority of the monitoring methods presented in Section 4 of this manual were 'fine-tuned' years ago at a micro-scale level, and can be easily applied in the scope of a macro-scale cover monitoring program. Monitoring challenges are highlighted throughout Section 4 with examples from Syncrude Canada Ltd.

Detailed information related to the various surface and sub-surface hydrologic monitoring methods and instruments can be found in Appendix A.

The application of hillslope hydrology for design of watersheds to reclaim large mine waste storage facilities is relatively new. Hence, the information presented in this document should be viewed as a report on a "work in progress". Research in this area is on-going with design methods yet to be fully developed and proven, which will allow them to be put into practice with confidence that a reclaimed watershed design will be sustainable over the long term.



## RÉSUMÉ

Le manuel 2.21.4 (Design, Construction, and Performance Monitoring of Cover Systems for Waste Rock and Tailings, 2004) du NEDEM porte sur les systèmes de couverture de résidus miniers d'échelles expérimentale et réelle et présente des concepts fondamentaux, des méthodes de caractérisation en laboratoire et sur le terrain, une définition et une approche conceptuelles en matière de modélisation numérique, ainsi que des activités de suivi du rendement des couvertures. Il est important de comprendre la nature des systèmes de couverture, car ces derniers constituent l'interface entre les rejets miniers et l'environnement. Toutefois, pour évaluer l'efficacité de la remise en état d'un site dans son ensemble, il faut étendre la portée des critères d'évaluation, ce qui est objet du présent manuel.

Ce manuel a pour principal objectif de présenter des lignes directrices en matière de conception et du suivi des systèmes de couverture de rejets miniers à grande échelle, c'est-à-dire à l'échelle des bassins versants, ainsi que les défis posés par la dimension et la complexité plus grandes de ces systèmes. Les lignes directrices relatives à la conception de systèmes à l'échelle des bassins versants reposent en grande partie sur celles qui régissent la conception touchant le relief. Un de principaux problèmes de conception de paysages nouvellement remis en état est l'établissement de conditions initiales qui permettront une évolution appropriée du paysage, tant sur le plan du taux de changement que sur celui du résultat final. La section 2 du manuel renseigne sur la nécessité de la conception du relief et présente des lignes directrices générales en conception du relief, mais qui s'appliquent également aux systèmes de couverture à l'échelle des bassins versants.

Un des principaux défis consiste à prévoir et à quantifier les changements qui peuvent influencer sur l'intégrité d'un système de couverture du sol. Pour répondre aux attentes ou axer la conception sur celles-ci, il faut comprendre le comportement à long terme du système, ce qui implique une compréhension des processus menant à des changements. L'évolution d'un système de couverture à l'échelle des bassins versants, sur laquelle porte la section 3 du manuel, fait l'objet de nombreuses lignes directrices ayant trait à l'évolution du relief et suit les mêmes processus que cette dernière. Le suivi sur le terrain du rendement à long terme des sites remis en état s'avère particulièrement importante puisqu'il faut déterminer comment le relief évoluera en identifiant les mécanismes et les processus à l'origine de son évolution. Au début de la section 3, on présente une étude de cas montrant les défis relevés et les leçons tirées par Syncrude Canada Ltd. pendant le suivi de l'évolution et du rendement de certains systèmes de couverture mis en place à des fins de remise en état.

Le suivi à l'échelle réelle sert à caractériser les conditions, les processus et les interactions dans un bassin versant, dans le but d'élaborer une méthode systématique de compréhension et d'organisation des données sur les écosystèmes. L'analyse des bassins versants permet ainsi une meilleure estimation des effets directs, indirects et cumulatifs des activités de gestion et une

meilleure détermination de la nature, de l'emplacement et du déroulement en général des activités de gestion à venir. La plupart des méthodes de suivi figurant à la section 4 du manuel ont été « perfectionnées » à l'échelle du site par le passé et peuvent être facilement mises en œuvre dans le cadre d'un programme de suivi des systèmes de couverture à l'échelle des bassins versants. Tout au long de la section 4, on souligne les défis posés par les activités de suivi et donne des exemples rapportés par Syncrude Canada Ltd.

L'annexe A comprend des renseignements détaillés sur les divers instruments et méthodes de suivi hydrologique de surface et de subsurface.

Cela fait assez peu de temps que l'on applique l'hydrologie des versants à la conception de bassins versants aux fins de la remise en état d'importantes installations de stockage de rejets miniers. Par conséquent, les renseignements figurant dans le présent document doivent être considérées comme un rapport sur les « travaux en cours ». La recherche en la matière se poursuit, et les méthodes de conception de bassins versants remis en état sont encore en voie d'élaboration et n'ont pas été parfaitement éprouvées, ce qui permettrait de les appliquer avec confiance et d'assurer ainsi la durabilité à long terme des bassins versants remis en état.

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## **1 INTRODUCTION**

In recent years, reclamation standards for mining have become more stringent and as a result, mine closure has become a crucial part of the planning process. Reclamation and closure planning has evolved so that the mine's closure activities have become directly part of the mine's operating decisions and practises (Robertson and Shaw, 2005). Successful closure outcomes need to be determined on a site-specific basis by examining a number of regional factors such as climate, land capability, water resources, and ongoing land use and how these interact with one another.

MEND 2.21.4 (Design, Construction, and Performance Monitoring of Cover Systems for Waste Rock and Tailings, 2004) is a document developed for the design and construction of cover systems over mine waste. The objective of this document was to compile the best available technology and practises from a wide variety of sources. The manual is to be used as a resource for mining personnel to understand the background and scope of work that is required for the design of a cover system. MEND 2.21.4 (2004) is comprised of basic theory, laboratory site and field characterization methods, conceptual cover design and approach to numerical modelling, field performance monitoring of test-scale, and full-scale cover systems. Understanding the dynamics of the cover system is an important concept to grasp because it is the interface between the waste material and the environment. However, to evaluate the success of reclamation of an entire area, evaluation criteria need to be expanded on a larger scale, which leads to the development of the current manual, MEND 2.21.5 (Macro-scale Cover Design and Performance Manual).

For the purposes of this manual, 'micro-scale' refers to design and monitoring performance of a cover system, while 'macro-scale' refers to design and monitoring on a watershed-scale. Macro-scale monitoring is a tool that is used to characterize conditions, processes, and interactions within a watershed to provide a systematic method to understand and organize ecosystem information. In so doing, watershed analysis enhances the ability to estimate direct, indirect, and cumulative effects of management activities and guide the general type, location, and sequence of appropriate future management activities.

### **1.1 Objectives of Manual**

The primary objective of this manual is to introduce design and monitoring guidelines for mine waste soil cover systems on a macro-scale. This manual expands upon the information presented in MEND 2.21.4 to include the state-of-the-art technology, which is for cover design and monitoring on a macro-scale. This includes both watershed and landform-scale and the challenges that arise due to the increased size and complexity.

The focus of this manual in terms of detail and case studies presented is on macro-scale cover performance monitoring. The majority of the monitoring methods presented in this manual were 'fine-tuned' years ago at a micro-scale level, and can be easily applied in the scope of a macro-scale cover monitoring program. The application of hillslope hydrology for design of watersheds to reclaim large mine waste storage facilities is relatively new. Hence, the information presented in this document should be viewed as a report on a "work in progress". Research in this area is on-going with design methods yet to be fully developed and proven, which will allow them to be put into practice with confidence that a reclaimed watershed design will be sustainable over the long term.

## **1.2 Scope and Organization of Manual**

This manual describes methods for designing and monitoring soil covers (also referred to as "dry" covers) on a macro-scale. The design and monitoring of water covers (or "wet" covers) are outside the scope of this manual and are not discussed. The fundamentals of soil cover design are not included in this manual as these can be found in detail in other publications such as MEND 5.4.2 (MEND Manual) and MEND 2.21.4.

Design guidelines for covers on a macro-scale are largely governed by the same guidelines as for landform design (landform engineering); therefore, Section 2 of this manual gives a background on the need for landform design and some general guidelines for landform design that also apply for cover design on a macro-scale. A watershed is then introduced as the ideal unit size for evaluating performance of a cover system on a macro-scale. At the end of this section, the design, construction and performance monitoring of a cover system and final landform for the backfilled pit at Whistle Mine near Sudbury, ON is presented as a case study.

Section 3 of this manual introduces cover evolution with time and long-term performance monitoring. Macro-scale cover evolution, as with macro-scale cover design, follows many of the same guidelines and is governed by the same processes as landform evolution. The scope of this section limits the discussion to issues of landform evolution that pertains to cover evolution. Syncrude Canada Ltd. is introduced at the beginning of Section 3 as a case study to illustrate the challenges and lessons learned in terms of tracking the evolution / performance of some of their reclamation covers.

Section 4 of the manual discusses watershed-scale monitoring methods. This manual highlights those monitoring methods and associated instrumentation that become increasingly important and challenging for evaluating covers (and landforms) on a watershed-scale as compared to small-scale. Monitoring challenges are highlighted throughout Section 4 with examples from Syncrude Canada Ltd. Detailed information related to the various surface and sub-surface hydrologic monitoring methods and instruments can be found in Appendix A.

A glossary of terms is included following some concluding remarks in Section 5.

## **2 MACRO-SCALE COVER DESIGN (LANDFORM DESIGN)**

In general, macro-scale cover design is not greatly different than cover design on a small-scale. The guidelines for choosing appropriate soil layers to support vegetation, store and release meteoric water, restrict infiltration, or maintain tension-saturated conditions, are largely the same and are not discussed in detail in this manual. The fundamental difference is observed when the cover design is evaluated in the field. Small test plots are not exposed to all the processes that will influence performance of a full-scale cover system. Heterogeneity in the cover properties after placement occur based on which parts of the cover are upslope or downslope, facing south or north, sloped or flat, subject to runoff or run-on, etc. (MEND, 2004). As time passes and soil horizons develop, vegetation matures, and local hydrology establishes itself; the cover continues to evolve and heterogeneity becomes even more apparent. Therefore, the true challenge in macro-scale cover design is to incorporate the evolution of the cover system in the design.

Historic construction and reclamation practices for mine waste landforms are briefly discussed prior to reviewing the state-of-the-art practices. The objective for the design of final landforms for waste storage facilities is then described, followed by a recommended design approach and guidelines. A case study is provided at the end of this section to further illustrate some of the key macro-scale cover design principles presented in this manual. Note that the terms ‘reclamation’ and ‘rehabilitation’ are used interchangeably throughout this manual.

### **2.1 Historical Construction and Reclamation of Mine Waste Landforms**

Waste material at most historic mining operations was generally stockpiled or placed in the most cost-effective method, with no concern for rehabilitation. Haigh (2000) discusses historical reclamation methods and outlines the “cosmetic” approach where temporary measures such as thin topsoil layers and temporary erosion controls were used to mask the disturbance. The landscapes created were still fragile and would often succumb to extreme erosion, or biological and chemical processes such as those producing acid rock drainage. Revegetation was frequently used synonymously with successful reclamation.

Historically, final landforms for waste rock or overburden stockpiles consist of linear (in plan), planar slope surfaces with unvarying gradients and angular slope intersections. The slopes of many historic stockpiles remain at angle-of-repose (typically 37° or ~1.3H:1V), making them susceptible to excessive gully erosion and nearly impossible to revegetate. In general, most reclaimed stockpiles slopes are not steeper than 20° (2.75H:1V), because this is often viewed as the maximum angle for safe operation on the contour by a dozer. Flattening steep slopes by dozing from the top downwards can also result in slopes with a convex profile unless closely supervised.

Final landforms for tailings facilities generally consist of large areas with relatively low relief compared to waste rock or overburden stockpiles; therefore, landform engineering is not as critical for closure of these facilities. However, some tailings facilities are relatively large and although the majority of the surface possesses gentle slopes, the downstream embankment of the facility generally possesses a steep slope that requires special consideration at closure. Similar issues of landform engineering apply to these embankments as were noted for waste rock or overburden stockpiles; therefore, these issues will be included in the remainder of this discussion in the context of landform engineering for “waste material stockpiles”.

Following a tour of 57 abandoned and partially reclaimed operating mines, McKenna and Dawson (1997) created an inventory of mine closure practices, the physical performance of reclaimed areas, and the environmental impacts of reclaimed and abandoned mines. The inventory shows that the greatest physical risk to the landscapes is associated with gully erosion and re-established surface water drainage courses. Gully erosion poses the greatest environmental threat to covered waste storage facilities containing acid-generating or radioactive materials. In addition, methods to reduce and control infiltration and the subsequent leaching of contaminants often work against measures to reduce erosion, which tend to promote infiltration and reduce runoff.

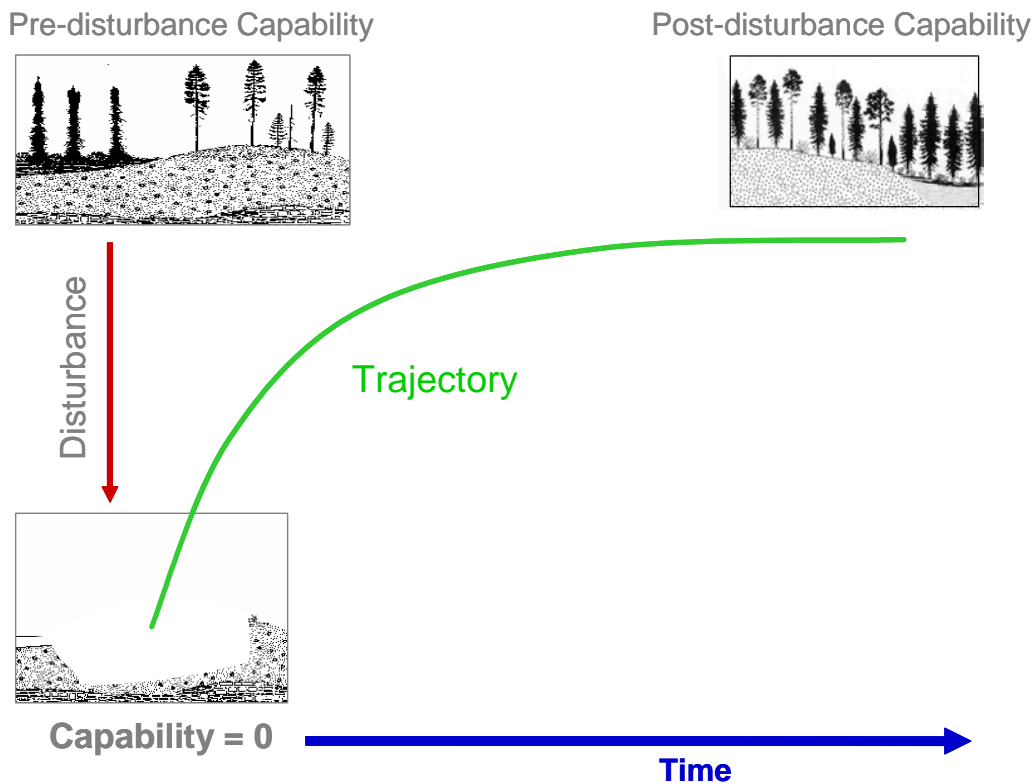
It is well known that steep unarmoured slopes will flatten, planar slopes will gully, straight drainage courses will start to meander, and linear or convex slopes will become concave. Unplanned, rapid changes in the reclaimed landscape could result in unacceptable high sediment loading of streams, gully scarring, and landslides (Keys *et al.*, 1995). The incorporation of natural slope features into the final landform design for stockpiles not only improves aesthetics, but also emulates slopes that are in equilibrium with local conditions of rainfall, soil type, and vegetation cover (Ayres *et al.*, 2006). The relatively small increase in costs for engineering and constructing natural landforms are more than offset by improved aesthetic impact, decreased slope maintenance costs, and improved long-term stability. Schor and Gray (1995) state that the design and engineering costs associated with landform grading increase by approximately 1 to 3%, and surveying 1 to 5% over conventional methods.

Rehabilitation practices of the mining industry need to become increasingly sophisticated as new methods emerge and as the environmental impacts of mining become better understood (Hancock *et al.*, 2003). This requires that post-mining landforms be designed according to best practice technology. With the time and resources now available, mining companies are able to develop more sophisticated plans to restore the landscapes they disturb, and to meld this process into their mining activities such that the resource requirement is minimized. In addition, the ability to demonstrate successful reclamation has become a competitive advantage in the mining industry (e.g. see Barbour *et al.*, 2004).

## 2.2 Landform Design Objective – Land Capability

An essential feature of the current expectations for rehabilitation is that the reclaimed landscape must be returned to some productive end use, whether this is forestry, agriculture, recreation, or urbanization. In the oil sands industry, for example, this end use is often focused on forestry and the ability of the reclaimed landscapes to support this end use is defined by its ‘land capability’ (Leskiw, 1998). Mining creates a disturbance that removes the capability of the land to support a productive forest. The goal of reclamation is to create conditions in which the landscape can evolve to a new, “post-disturbance” capability, equivalent, albeit different, from that which existed prior to mining. Figure 2.1 illustrates this concept.

Successful reclamation is not *restoring* a landscape, but rather providing conditions such that the landscape can *redevelop* towards an equivalent capability to that which existed prior to mining. There are two key features of this view of reclamation. First, the specific features of the reclaimed landscape may be different than those that existed prior to mining, but they should produce an ‘equivalent capability’ to that which existed prior to mining. Secondly, the performance of these new landscapes will evolve over time. The goal of reclamation is to establish the basic building blocks for this new landscape and to ensure that the trajectory of evolution for this new landscape is correct, both in terms of the rate of evolution and end point.



**Figure 2.1** The effect of mining and reclamation on land capability (Qualizza, 2003).

The design of a new landscape is often referred to as landform engineering or landscape design. Landform engineering is not a new concept for mining reclamation; however, it requires one significant resource *time*. To design and create a new landscape, time must be taken to coordinate all the mining activities to allow for the progressive evolution of a new landscape. An optimal starting condition for this landscape can be established but only time and natural processes can ultimately bring the landscape to its final capability.

## **2.3 Landform Design**

### *2.3.1 General Background*

The forces that act on landforms include climate (precipitation, evaporation, wind), gravitational forces causing mass land movements, and weathering processes that cause chemical and biological changes to the materials. The resistance of the material derives from the physical properties of soils and the added structural stability contributed from biomass such as roots and surface debris (Toy and Hadley, 1987).

The result of the application of force and resistance to a landform over time is a reshaping of the landform. Generally, a dynamic equilibrium is reached, although to say a landform is unchanging is incorrect. A landform is never static – evolution is constant – but the degree of change is typically slow for a landform in “equilibrium”. However, there is always the potential for an extreme event such as an earthquake, a flood, or major storm to dramatically change a landform that was previously relatively unchanged for hundreds or thousands of years.

The combination of forces and resistance for a given landform result in processes that change the shape of the landform. Geomorphic processes can be generally divided into two categories: physical and chemical. Physical processes include the effects of gravitational forces such as mass movements and erosion, and physical weathering such as wet/dry and freeze/thaw cycling. Chemical processes include geochemical processes such as oxidation, dissolution and precipitation (Toy and Hadley, 1987).

There are a number of issues at stake in designing a reclaimed landform besides that of creating an aesthetically pleasing and stable landform. Regulations of allowable contaminant releases and the requirements for post-mining land capability usually create requirements for isolating or treating the site-specific waste materials. For example, potentially acid generating tailings or waste rock generally must be isolated from air and/or water to control oxidation and/or weathering rates to minimize contamination of groundwater and surface water receptors. These requirements can dictate certain design aspects of the landform such as the location of drainage swales and the type and thickness of various soil layers. The priorities in general landform design are to create a stable landform and have the landform meet specific criteria for slope and shape as defined by the land capability requirement. For example, if the post-mining land



capability were to be agricultural, then gentle slopes would be preferred over steep ones. After these two criteria have been met, then additional details such as soil covers designed to limit the entry of oxygen and/or water can be incorporated into the final landform design.

### 2.3.2 Geomorphic Principles for Landform Design

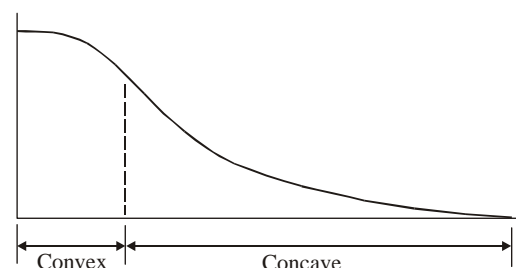
The consideration of geomorphic principles is fundamental when designing a stable landform. Reclamation failure can usually be traced to violation of geomorphic principles, such as having too great a disparity between force and resistance (Toy and Hadley, 1987). Examples of this are having a hillslope that is too steep or too long, channel gradients that are too steep, drainage courses with sharp angles (in plan), or drainage basins that are too large.

Geomorphologists study natural systems to examine patterns and trends in hillslopes, drainage channels, drainage density and drainage patterns. For example, Toy (1977) examined the relationship between hillslope form and climate and found that hillslopes tended to be longer and less steep as climates became more humid. Other researchers such as Carson and Kirkby (1972) compiled data on a large number of hillslopes, and determined that the majority of hillslopes possess rounded convex summits and have shallow concave elements at the base separating them from stream channels. Based on research such as this, it is possible to determine some fundamental guidelines when designing a landform. Toy and Hadley (1987) describe the following guidelines for hillslope design, channel design, and the design of drainage basins.

- The most preferable hillslope design is a spur-end hillslope plan with a concave or complex (convex-concave) profile as shown in Figure 2.2. Natural hillslopes show that in arid regions, hillslopes may be steeper, shorter, and have a smaller radius of curvature in their convex segments than hillslopes in more humid regions.



(a)



(b)

**Figure 2.2** a) Photograph showing key features of a natural hillslope (near Salt Lake City, Utah) and b) profile view showing complex (convex-concave) hillslope shape (from Ayres *et al.*, 2006).

- The design of channels should be based on the discharge and sediment load of the stream. Therefore, it is important to estimate these factors prior to designing the drainage channels.
- The design of drainage basins based on physical laws governing their development can be complex and often requires the use of computer simulations. For the conceptual design, the dendritic drainage pattern is generally the most appropriate for reclaimed lands because disturbance often removes any underlying geologic control over drainage patterns. However, in some instances, waste material may be placed in such a way as to create layers or other geologic structures that may influence the drainage pattern (e.g. long linear spoil banks from area surface mining). A description of alternative drainage patterns and how they form can be found in Way (1973). A rule of thumb for the drainage density is that the density should be greater than the surrounding undisturbed areas because infiltration rates on reclaimed areas are typically lower than undisturbed areas. It is also beneficial to design numerous, smaller drainage basins because the total sediment yield increases with the drainage basin area.

In general, a good starting point for landscape design is to examine the surrounding undisturbed landscape. A similar landscape that is exposed to the same climate is a good natural analogue for the design landscape (Keys *et al.*, 1995). The reclaimed landscape can be no more stable than the adjacent undisturbed landscape (Toy and Hadley, 1987); therefore, the designer can assume that the reclaimed area will be less stable and design accordingly, with gentler slopes, higher drainage density and smaller drainage basins.

The basic geomorphic principles dictate the slope angles, the drainage density, and the size of the drainage basin, but many different landscape designs can satisfy these criteria. The designer is required to use creativity to develop an aesthetically pleasing landscape that not only satisfies the criteria for physical stability, but also contributes to the land capability and satisfies the quantitative and qualitative criteria described by the stakeholders.

Visual appeal is key in designing reclaimed landscapes. Attention should be given to visually softening steeper areas by avoiding straight "engineered" ridges and sharp changes of angle. Possible methods for creating visual appeal include constructing small mounds (2 – 4 m high) or planting trees at the visual edge of the landscape, which act as a type of "false front" on the rest of the landscape (McKenna, 2002). On a smaller scale, it is difficult to contour a landscape to exactly defined topographical contours. In this respect, it is best to let the operators use their own creativity and skill to sculpt the topography on a meso-scale within the established macro-scale guidelines.

### 2.3.3 Landform Design Approach

Landform design for reclamation requires a holistic view of mining operations, where each operational stage and each component of the mine is part of a plan that considers the end use of the site as much as the immediate need (Environment Australia, 1998). This plan, which needs to be flexible to accommodate changes in methods and/or technology, is about optimizing post-mining land capability, minimizing the costs in achieving optimal land use, and limiting long-term maintenance liabilities.

Ayres *et al.* (2006) proposed the following generalized approach for developing a sustainable final landform design for future waste material or overburden stockpiles:

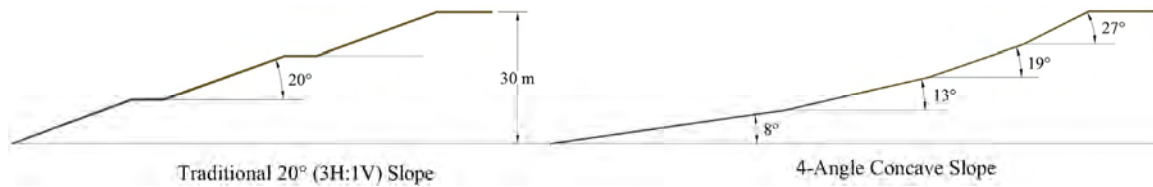
- 1) Determine the final land use for the rehabilitated site through consultation with all stakeholders, and an assessment of potential geologic or structural control elements for the landform;
- 2) Observe and collect data on the natural landscape prior to mining, such as hillslope forms and gradients, soil and vegetation types, drainage density, and watershed characteristics;
- 3) Determine the long-term eroded profile for the various slopes of the future final landform through erosion and landform evolution numerical modelling, to aid in the design/construction of the stockpile during mine operation;
- 4) Determine a suitable footprint design for construction of the stockpile based on the contours of natural landforms for post-mining visual blending and consideration for potential enlargement of the footprint following construction of the final landform;
- 5) Design a surface water management system to safely convey meteoric water off the final landform, and ensure runoff reaches final discharge points in volumes and at velocities that will not cause unacceptable erosion or sedimentation;
- 6) Develop a waste management plan/stockpile design that takes into consideration the storage of reactive and non-reactive waste materials (e.g. encapsulation of reactive materials with inert waste as described in Waters and O’Kane (2003)), and the findings from completing Steps 3 to 5 inclusive;
- 7) Develop a revegetation plan suitable for the swales and ridges in the final landform based on data collected in Step 2; and
- 8) Review the final landform design with key stakeholders for general acceptance prior to implementation.

The above design approach can be applied to existing waste material or overburden stockpiles with modifications to steps 2, 3, 4, and 6 as follows (from Ayres *et al.*, 2006):

- 2) Observe and collect data on a nearby natural landscape (a natural analogue) to determine hillslope forms and gradients, soil and vegetation types, drainage density, and watershed characteristics;
- 3) Determine the long-term eroded profile for the various slopes of the existing stockpile through erosion and landform evolution numerical modelling;
- 4) Based on the maximum slope length and gradient as determined from Steps 2 and 3, design a methodology for reshaping the existing stockpile to conform to these requirements (a horseshoe-shaped landform, which creates a small, well-defined catchment, can be effective in reducing slope length and gradients without changing the footprint of an existing stockpile); and
- 6) Develop a final landform design following completion of Steps 2 to 5 inclusive, taking into consideration the long-term safe storage of reactive materials (a suitable cover design would be included in this step).

The most appropriate design for a final landform will vary from site to site, depending on a range of factors including climate, geology, soils, local hydrological patterns, topography, and the adopted final land use (Environment Australia, 1998). The following should be considered when developing a sustainable final landform design for waste material or overburden stockpiles (from Ayres *et al.*, 2006).

- It is very difficult in practice, particularly for stockpiles with long slopes, to construct concave slopes with continual curvature on a waste rock stockpile. However, hillslope curvature can be obtained using a series of linear slopes or slope facets as shown in Figure 2.3. Hancock *et al.* (2003) demonstrated through simulations with a landform evolution model that there is minimal difference in sediment loss between a hillslope constructed of linear facets and that constructed from continual curvature.
- Erosion and subsequent evolution of the proposed final landform design(s) should be predicted over a period of at least 100 years using state-of-the-art software packages (see Section 2.3.4).
- The thickness of earthen covers designed to minimize the entry of atmospheric oxygen and/or meteoric water to reactive or radioactive material should not only be based on soil-atmosphere numeric simulations, but should also take into consideration the predicted long-term erosion of the final landform.



**Figure 2.3** Schematic showing traditional and concave slope designs for reclaimed waste rock stockpiles (from Ayres *et al.*, 2006).

- The design of surface water drainage courses should be based on the discharge and sediment load of the receiving stream(s). Drainage channels used to convey surface water off the top of the landform should follow the slope gradient of the final landform as much as possible. The use of imported substrate as well as man-made materials such as pipes, gabions, and concrete should be avoided whenever possible.
- Design conservatively to account for excessive erosion resulting from extreme climatic events and differential settlement in the reclaimed landform.
- Reclamation of large waste storage facilities should include the construction of small catchment areas and wetlands upstream of final surface water discharge points, provided they are geomorphically compatible and stable. Such features will attenuate surface runoff to reduce peak flows and increase sedimentation prior to reaching receiving streams (Sawatsky, 2004).

#### 2.3.4 Numerical Analyses of Erosion/Landform Evolution

Numerical analyses of erosion/landform evolution allow an assessment of current and future landscape designs without the problems associated with field studies. Much of the available literature investigates erosion on long flat slopes (e.g. agricultural sites), with little information available for steeper slopes common to waste rock stockpiles or tailings embankments. Steeper slopes tend to rill dramatically, something that traditional erosion models (e.g. Universal Soil Loss Equation, USLE) have not been able to satisfactorily address. The development of the Water Erosion Prediction Project (WEPP) (Laflen *et al.*, 1991; Flanagan and Livingston, 1995) and SIBERIA (Willgoose *et al.*, 1991; Willgoose, 2000) models have begun to address this analytical deficiency.

The WEPP model is a process-based program that was developed in the late 1980's and early 1990's by the United States Department of Agriculture (USDA). It is best suited for detailed consideration of short-term (up to 100 years) impacts of slope length, gradient, and management on erosion rates. The appropriate scales for application are tens of metres for hillslope profiles, and up to hundreds of metres for small watersheds (Flanagan and Livingston, 1995). The model explicitly considers rill and interrill erosion and is therefore better able to consider interactions of

slope length and gradient than other models. Interrill erosion, also known as sheet erosion, consists of soil particle detachment from the soil matrix by raindrop impact and particle transport by splash and shallow overland sheet flow (Grosch and Jarrett, 1994). Rill erosion involves the concentration of runoff flow often caused on natural hillslopes by microtopography or vegetation (Bryan, 2000). The development of rills on a land area can greatly increase the soil erosion rate by concentrating runoff flow resulting in increased flow velocity and turbulence producing more energy to detach and transport material (Gatto, 2000). While similar in shape to rills, gullies are much larger erosional features often created by extreme erosion events involving large mass movements of soil.

WEPP estimates net soil loss for an entire hillslope or for each point on a slope profile on a daily, monthly, or average annual basis. Basic inputs required for the WEPP model include climate data, slope configuration, soil properties, and soil management (vegetation) properties. The WEPP model provides a detailed description of the susceptibility of soils and spoils to rill initiation and transport. This aspect makes the model especially applicable to situations where soil erodibility is measured in the laboratory, and to consideration of materials (such as rocky spoils) for which erosion responses to slope length and gradient differ greatly from those of agricultural soils. However, as it is an agriculturally-based model, WEPP does not consider potential effects of erosion and deposition on landform development, nor does it deal specifically with gully development.

SIBERIA is a physically-based model for simulating the evolution of landforms over geomorphic timescales and was developed by Dr. Garry Willgoose at the University of Newcastle, Australia. It simulates runoff and erosion from a landform that evolves in response to predicted erosion and deposition. It is a three-dimensional topographic evolution model, which predicts the long-term evolution of channels and hillslopes in a catchment on the basis of runoff and erosion. The location and speed with which gullies develop are controlled by a channelization function that is related to runoff and soil erodibility (Willgoose *et al.*, 1991). The model solves for two variables; elevation, from which slope geometries are determined, and an indicator function that determines where channels exist. An activation threshold governs channel growth. A surface may commence with no gullies, but when the activation threshold, which depends on discharge and slope gradient, is exceeded, a channel develops.

The SIBERIA model needs to be calibrated before evaluating whether it correctly models the observed evolution of rehabilitated mine landforms. The model has been calibrated to rainfall and runoff data from the ERA Ranger Mine (ERARM) in the Northern Territory, Australia, and used to predict the possible erosion over 1,000 years for the ERARM rehabilitation proposals (Evans and Willgoose, 2000). Hancock *et al.* (2000) demonstrated that SIBERIA is an appropriate model for assessment of erosional stability of rehabilitated mine sites over time spans of around 50 years. The following methods can be used for obtaining erosion parameters required for input to the SIBERIA model:

- Collect erosion data from rainfall and runoff testing using rainfall simulators as described by Loch *et al.* (2001), and subsequently use a model such as WEPP to determine erosion rates for each soil type;
- Measure controlled flow through a series of flumes constructed on the hillslope. This method does not simulate rainfall/runoff but allows assessment of the impact of high flow rates on a range of armouring methods; and
- Determine erosion rates from periodic digital mapping of actively eroding slopes.

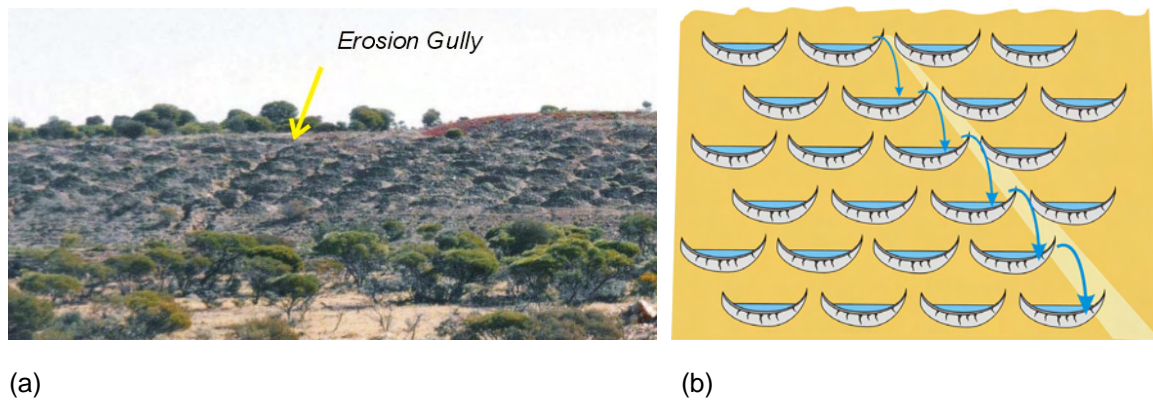
### 2.3.5 Short-term versus Long-term Landform Stability

The following is taken from Ayres *et al.* (2006).

Various measures can be, and have been, used in the reclamation of waste rock stockpiles that provide short-term stability, but these methods are not generally suitable for long-term landform stability. These include terracing or contour banks, cross-slope or contour ripping of the surface, dozer basins or “moonscaping” (Figure 2.4), and placement of erosion control blankets in drainage channels. Provided these measures are properly implemented, they reduce erosion rates by producing higher infiltration (i.e. lower runoff) and/or greater roughness on the surface (i.e. surface resistance). These techniques are prone to failure over the short term (i.e. 1 to 10 years), which explains why none of these measures are found on natural slopes. However, this time frame may be sufficient to allow a good stand of grasses and legumes to establish, thereby aiding in the long-term stability of a reclaimed slope.

Moonscaping has been implemented on a number of waste rock pile slopes in Australia as a potential method of slope stabilization; however, it has been of limited success and is not recommended as a long-term surface treatment. Moonscaping is where the slopes are formed into rows of basins intended to contain all water within their individual catchments. Each row of basins is offset half a basin width from the rows above and below to ensure all water is intercepted (Figure 2.4a). The limiting factors to moonscaping are:

- Cost – it requires very precise earthmoving to create;
- Sizing of basins to contain all water;
- Leaking from basins downslope through the uncompacted outer edge;
- Slumping and failure of the outer edge leading to a cascading failure;
- Overtopping of basins leading to cascading failure (Figure 2.4b);
- Basins filling up with sediment over time and losing storage capacity; and
- High visual impact.



**Figure 2.4** (a) Photograph showing a moonscaped surface on the side of waste rock stockpile with evidence of gully erosion and (b) schematic of the failure mode for most moonscaped surfaces (from Ayres *et al.*, 2006).

## 2.4 Evaluation of Landform Design – Watershed

Landform engineering is not an exact science. Many of the tools in designing a landform involve assessment of the performance of the landscape. This is an iterative process where feedback from the landscape performance is used to adjust the landscape design, which is then evaluated further prior to a final design being chosen (McKenna, 2002). To evaluate a landform design, a landform must be constructed, instrumented, and monitored. To fully evaluate the behaviour of a landscape, all the topographic variations and landform types must be included. So, the question becomes, what is the minimum size of landform required to evaluate the behaviour of an entire landscape?

By definition, a watershed is an area of land that contributes runoff to a single outlet location (McCuen, 1989). While the definition itself appears simple, a watershed consists of a network of inherent complex drainage pathways located both on the surface and underground. A watershed is ideal as the unit element of a landscape. It contains most of the topographical variations that will be in the final landform including; highlands, lowlands, slopes, drainage areas, swales, and a collection of slopes that face different directions (and therefore receive varying degrees of solar radiation). By monitoring a watershed, most of the questions that will be asked by stakeholders and regulators regarding the behaviour of the landscape can be answered (Barbour *et al.*, 2004). The watershed also reveals the processes that will control the evolution of landscapes. Fundamentally, a landscape is diverse, and a watershed is the smallest unit size of a landscape that encompasses most of the diversity.

Various methods and instrumentation for monitoring the performance of a cover system at the macro- or landform-scale are reviewed in Section 4.



## 2.5 Case Study – Whistle Mine, Ontario

Approximately seven million tonnes of acid-generating waste rock remained on surface following cessation of open pit mining at CVRD Inco's Whistle Mine near Sudbury, ON. In light of the environmental and economic liabilities associated with release of acid rock drainage (ARD) to the surrounding ecosystem, CVRD Inco elected to relocate the waste rock to the open pit as a means of mitigating environmental damage post-closure. However, because a portion of the backfilled waste rock will remain above the water table, an engineered cover system is required to further reduce the production of ARD. The following is taken from Ayres *et al.* (2005, 2007), and is a synopsis of the design, construction and performance monitoring of a soil cover and final landform for the backfilled pit at Whistle Mine.

Whistle Mine is surrounded by undeveloped wilderness and is situated in the Post Creek watershed, an area of approximately 5,400 ha that drains into Lake Wanapitei, 3 km east of the mine. The climate in the area is semi-humid, characterized by wetter conditions in the fall, winter, and spring and drier conditions during the hot summer months. The site has a mean annual precipitation and potential evaporation of 900 mm and 520 mm, respectively. Approximately 30% of the annual precipitation occurs as snow.

Geochemical modelling was conducted to assess the effectiveness of various cover options on the long-term water quality of the backfilled pit. Based on these modelling results, the primary design objective of the pit cover is to limit the ingress of atmospheric oxygen to the underlying waste rock. A multi-layer soil cover incorporating a compacted layer of fine-textured soil (i.e. a barrier layer) was selected as the preferred type of cover system for the Whistle Mine backfilled pit. Cover system trials were constructed at the site in 2000 to obtain site-specific information on the construction feasibility and potential performance of various soil cover designs incorporating different barrier layers (compacted clay, compacted sand-bentonite mixture, and a geosynthetic clay liner (GCL)). Based on estimated construction costs for the entire backfilled pit and the requirement for an adequate oxygen barrier, a source of local clay was chosen as the material for the pit cover barrier layer.

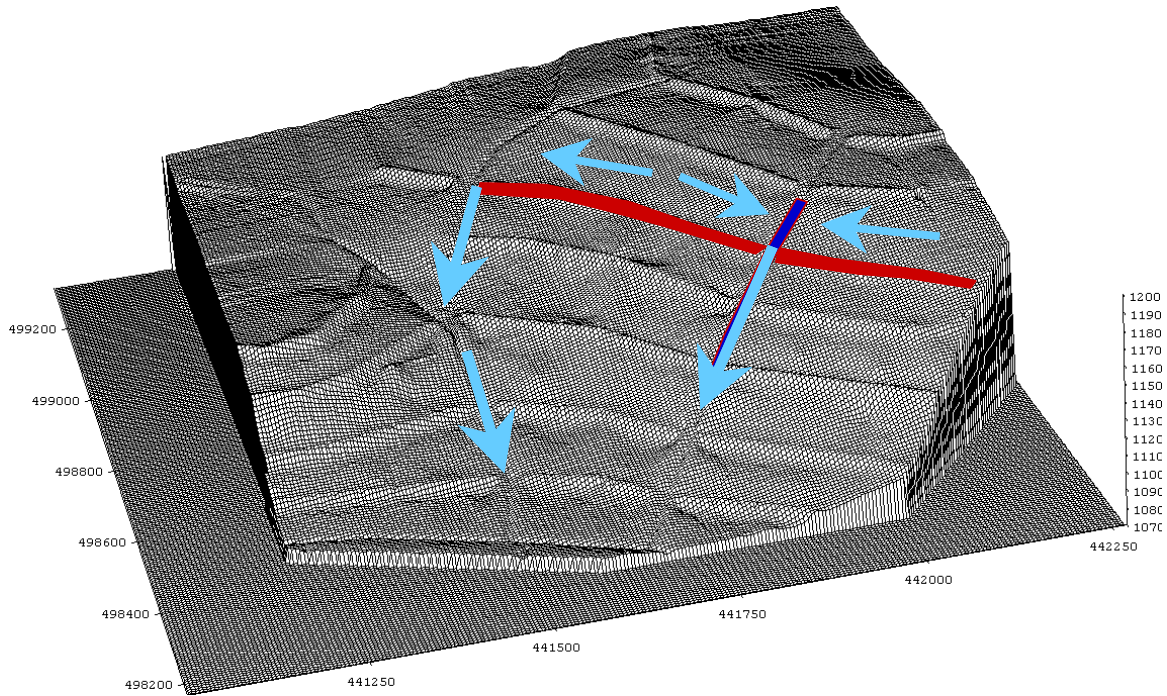
One- and two-dimensional soil-atmosphere numerical modelling was conducted to design a multi-layer soil cover with acceptable rates of oxygen ingress and water infiltration. The final cover system design for the backfilled pit consisted of a 0.1 m sand and gravel levelling course, a geosynthetic separation fabric (geotextile), a 0.45 m barrier layer comprised of compacted clay, and a minimum of 1.2 m of sand and gravel for a protective / growth medium layer. The primary purpose of the levelling course is to provide a suitable foundation for the geotextile, but it also acts as a capillary break layer. A thin layer of topsoil was admixed to the pit cover surface to assist with growth of a seeded mixture of native grass and legume species. Construction of the pit cover system was completed during the snow-free periods of 2004 and 2005.

Erosion and landform evolution numerical modelling was conducted to design a runoff management system and final landform for the backfilled pit. The WEPP model was used to estimate erosion rates from the cover surface, while the SIBERIA model was used to predict the evolution of the final landforms. A 100-year climate database was developed for the site based on historical data collected from a nearby meteorological station. The surface of the cover system was assumed to be bare of vegetation for all WEPP simulations. This is a reasonable assumption for the short term, and probably somewhat conservative for long-term predictions of erosion rates. WEPP output data were used to generate parameters for the SIBERIA model.

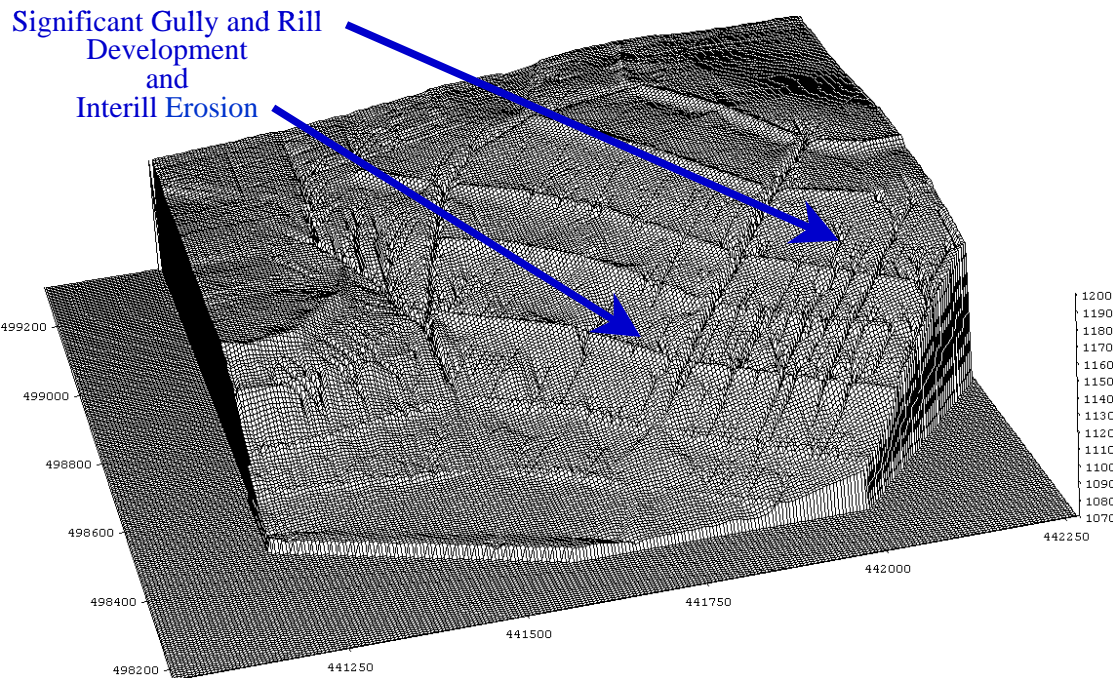
The first landform alternative examined consists of a highly engineered system to manage runoff generated from spring snowmelt and rainfall events. The landform has contour banks to capture runoff water and divert it laterally to one of two collection channels oriented parallel to the slope. A perspective view of this landform design is shown in Figure 2.5. Output from the SIBERIA model showing the evolved nature of this landform design after running the 100-year climate file is presented in Figure 2.6. The model output shows breaching of the contour banks, development of gullies and rills, and in general, failure of the landform over a 100-year period, where the term “failure” is used to indicate when the contour banks are not functioning as designed. The gullies may armour over the longer term, but acting against this possibility is the relatively large contributing area that will feed some of the gullies.

The second alternative and ultimate landform design implemented for the backfilled pit cover system consists of a number of catchments oriented parallel to the slope with a “swale and ridge” pattern (Figure 2.7). This micro-topography is beneficial for revegetation efforts because snow accumulates in the troughs, thereby increasing soil moisture levels, and wind velocities are reduced across the ground surface, thus reducing potential wind erosion of topsoil and grass seeds. The size and geometry of the catchments are based on the results of WEPP modelling, which takes into consideration acceptable erosion rates for the cover system and sediment loading that will be delivered to the runoff collection system. The SIBERIA model was not used to predict the long-term evolution of the second landform design.

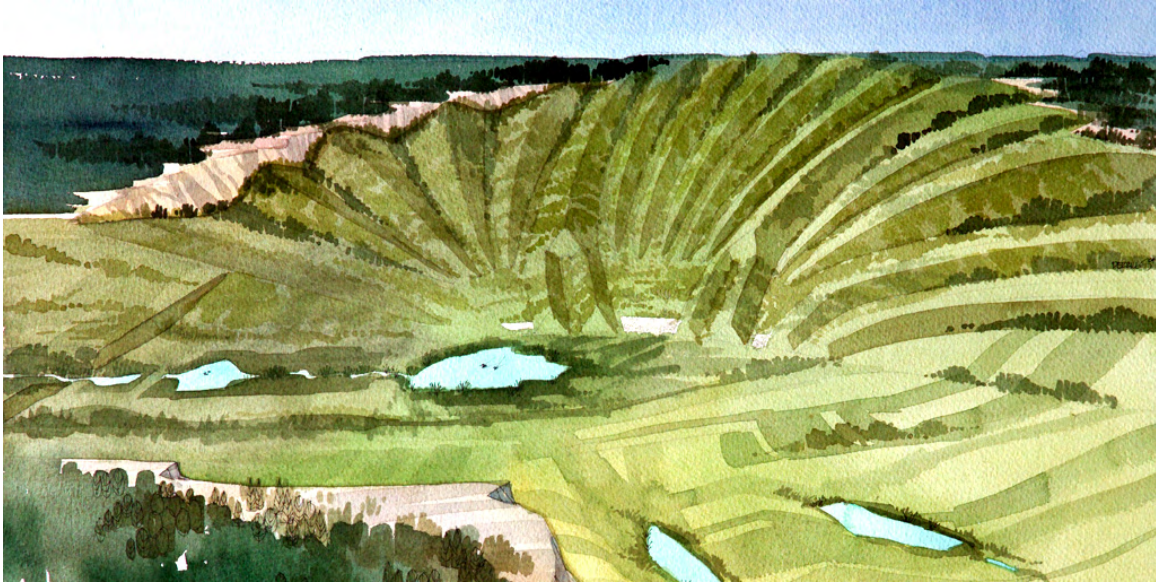
In conjunction with the design of a sustainable final landform, a system was required to minimize fluvial erosion on the pit cover and manage suspended sediment in runoff waters over the short and long term. Progressively higher levels of erosion protection were used in the hillslope channels as the contributing area and associated design flow velocities increased towards the south. This included the use of temporary erosion control blankets, a 150 mm thick layer of 60 mm diameter riprap, and finally, a 300 mm thick layer of 125 mm diameter riprap. A series of three containment ponds were designed at the south end of the backfilled pit for management of suspended sediments in the pit cover runoff water. The base of each pond consists of a minimum 0.6 m layer of compacted clay and slopes gradually east to west, towards individual hydraulic control structures (overshot gates) and the final discharge point (Post Creek wetlands).



**Figure 2.5** Surface contours (vertically enhanced) for the first landform alternative evaluated for the Whistle Mine backfilled pit cover system (from Ayres *et al.*, 2005).



**Figure 2.6** Predicted landform evolution of the first landform alternative for the Whistle Mine backfilled pit cover system after 100 years (from Ayres *et al.*, 2005).



**Figure 2.7** Second alternative and ultimate landform design implemented for the Whistle Mine backfilled pit cover system (from Ayres *et al.*, 2005).

Minimal erosion as a result of runoff has occurred on the Whistle Mine pit cover, and although the vegetation cover has developed slower than anticipated, considerable growth occurred during the summers of 2006 and 2007. Figure 2.8 shows the condition of the pit cover and landform as of July 2007.



**Figure 2.8** The Whistle Mine pit cover as of July 2007 (looking north) with the runoff collection and sedimentation ponds in the foreground.

Performance monitoring has been on-going at the site since the fall of 2005. A performance monitoring system was installed to achieve the following objectives:

- 1) obtain a water balance for the site;
- 2) develop confidence with all stakeholders with respect to cover system performance from a micro- and macro-scale perspective;
- 3) enhance understanding of the key characteristics and processes that control cover system performance at this site; and
- 4) track the evolution of the cover system and landform in response to various site-specific physical, chemical, and biological processes.

The monitoring system includes a meteorological station, two weirs for measuring runoff flows, two automated stations for monitoring net percolation rates and *in situ* moisture and gas concentrations within and below the cover system, 13 secondary stations to monitor spatial performance, and four groundwater monitoring wells.

The Whistle Mine pit cover system is performing as expected in its first full year since construction, based on field data collected up to December 2006. Based on *in situ* volumetric water content measurements, the average oxygen diffusion coefficient for the barrier layer in 2006 was  $4.6 \times 10^{-11} \text{ m}^2/\text{s}$ , which is nearly two orders of magnitude lower than the minimum required for closure. The net infiltration measured through the pit cover in 2006 was 21 mm, which is equal to 2.7% of the total precipitation measured at the site during the monitoring period. This compares well with the annual net infiltration of 2.2 % of precipitation that was predicted for a normal climate year during the cover design modelling program. It is anticipated that net infiltration rates for the pit cover will decrease over time as vegetation develops and removes additional water stored in the growth medium layer. In summary, the influx of atmospheric oxygen and meteoric water to the waste rock backfill has been substantially reduced since construction of the cover system.

### 3 EVOLUTION OF COVER SYSTEMS WITH TIME

*“Another challenge is to provide estimates of reliability and longevity of the landforms to meet the stated goals. Unlike virtually all other engineering disciplines, the timeframes for landscape engineering performance are often unbounded, and that geomorphic change, perhaps in perpetuity, must be considered. Moreover, the goals may change during this timeframe.”* (McKenna, 2002).

The final measure of successful reclamation has been defined as “the degree to which reclaimed land can look after itself” (Sawatsky, 2004). Natural soils are extremely complex and have developed as a result of a variety of factors: parent material, physical and chemical weathering, microbiology, climate, drainage, topography, and land use. In a natural system, the physical, chemical, and biological processes have come into “dynamic” equilibrium in such a way that they have the ability to self regulate a nutrient supply, provide chemical buffering, preserve soil density, porosity, aeration, and water holding capacity. In contrast, newly placed soils, as in the case of a soil cover system, are a fragile system that is at the beginning of a long process of adaptation.

As introduced in Section 2.2, the goal is to reconstruct a reclaimed site in a manner that will maximize the reclamation development over time. Moreover, the final landform should be stable requiring no maintenance over several millennia (Shukla *et al.*, 2004; Bozkurt *et al.*, 2001). Once reclamation specifications and criteria have been determined, the underlying question remains: “*How can we design for change?*”. Reclamation planning must include a well-established strategy with goals and objectives with success criteria clearly defined. The plan must be implemented with the realization that it may have to be altered in the future due to the direction taken by the progression of the reclamation (Cooke and Johnson, 2001).

A case study is introduced in Section 3.2, and examples from the case study are given throughout Sections 3 and 4 to illustrate challenges and lessons learned in terms of tracking the evolution / performance monitoring of cover systems at a macro-scale.

#### 3.1 Long-term Behaviour and Trajectory

One of the greatest challenges is the ability to predict and quantify what changes may occur that can potentially affect the integrity of a soil cover system. In order to meet or design for the expectations set, an understanding for the long-term behaviour of the system is necessary which lies in understanding the processes that lead to change. The timeframe of interest to evaluate the long-term behaviour in most cases is in the order of hundreds, even thousands of years. A typical boreal forest in the Athabasca region of northern Alberta takes between 50 and 100 years to mature (Barbour *et al.*, 2004). In terms of a landscape, a wide range and large amount of data

are required to evaluate the processes that determine how a landscape will evolve. The source of these data has chiefly been experiments conducted in a laboratory or in some cases at a field-scale. Specific processes may be studied; however, the complexity and time required to fully understand all aspects in the development of a landform cannot be simulated in a laboratory-scale experiment even when undertaken with utmost accuracy under representative conditions. The conception of what will happen thousands of years from now at a landfill is often based on extrapolations and speculations, emphasizing the need to systematize, understand, and quantify the long-term processes (Bozkurt *et al.*, 2001).

Mine operators are interested in obtaining certification for closure long before the reclaimed landscape has reached final maturity, and therefore a “trajectory” for the area is defined. The trajectory of evolution, as introduced in Section 2.2, is a conceptual model or the overall pattern of change that a cover system, or even an entire reclaimed landscape may follow (SER, 2004). The period of liability for mine operators varies, normally regulated by governing bodies. The “liable” time period generally only represents a small point in the succession of a mature reclaimed area. In the case of the Athabasca oil sands region of northeastern Alberta, the oil sands industry has implemented a 15-year timeframe as a standard for certification evaluation because after this period of time, the trees are considered to have overcome the potential challenges of the site and are considered “free to grow”. This period of time is early in the overall establishment of a mature boreal forest so operators have implemented the landscape trajectory concept as a tool to demonstrate that the landform is on course toward a thriving, sustainable landscape (Barbour *et al.*, 2004). In the Appalachian region of southwest Virginia’s coal mining area, successful reclamation is normally evaluated five years following soil placement based on the criteria of 90% vegetation ground cover and the liability period can be as short as two years when further mining is conducted on an abandoned mine site. A short time frame of liability can cause reclamation efforts to focus primarily on bond releases based on short-term results (Holl *et al.*, 2001). Cover materials will evolve over time in response to site-specific physical, chemical, and biological processes such that as-built performance, and performance after two or three years may not represent long-term performance.

A trajectory becomes a useful tool in the concept of landform planning, but the final reclamation goal may become somewhat of a moving target; and the question that arises is “*Should the final landscape be an exact replica or an ecologically superior one to the previously existing one?*” (Cooke and Johnson, 2001). Historical conditions of the area, if known, can be invaluable in providing a basis for reclamation design and planning, establishing boundaries, and setting the general direction of the trajectory; however, the reclaimed landscape will likely follow an altered trajectory compared to the historic landscape due to differing constraints and conditions compared to what previously existed. Long-term field performance monitoring of reclaimed sites becomes an important element to defining the critical trajectory by determining the associated mechanisms and processes that cause the landscape to evolve. By quantifying and

understanding the processes involved, operators can then use this information to optimize design and techniques used in reclamation.

### **3.2 Syncrude Canada Ltd. – Case Study**

The following overview of reclamation activities at Syncrude Canada Ltd. (Syncrude) is adapted from Barbour *et al.* (2004) and Chapman (2006).

#### *3.2.1 General*

The Athabasca Oil Sands, located in the Athabasca basin of northeastern Alberta, Canada, is one of the most extensive shallow ore deposits in the world. This deposit covers approximately 40,000 square kilometres and contains over a trillion barrels of bitumen. Surface mining is the primary method of recovering the oil sand when it is located under no more than approximately 75 m of overburden (Industry Canada, 2005). This region will produce more than 50% of Canada's oil supply within the next 10 years with Syncrude alone supplying 20% of the nation's oil.

The Syncrude Mildred Lake Mine is one of the world's largest operating mines. Large tracts of land are disturbed through these operations. Reclamation of Syncrude's Base Mine alone will involve the reconstruction of 21,000 ha of boreal forest. One of the major concerns limiting development is the time frame to successfully reclaim these disturbances. The ability to demonstrate successful reclamation has, in fact, become a competitive advantage in a region where limitations on development due to cumulative environmental impacts are a reality.

Syncrude has targeted much of its sponsored research at defining the critical "trajectory" (see Section 3.1) and the particular mechanisms and processes that are critical in landscape evolution. The research has tried to focus on studies that encompass at least one complete watershed within the landform. There are several reasons for selecting a watershed:

- It is the primary unit for mine planning, particularly as it relates to routing of surface water;
- It is of sufficient size to address central questions about landscape performance and risk;
- It encompasses a range of target ecosites for a particular parent material;
- It allows for realistic measurements and estimates of essential fluxes and balances (e.g. water, salt, nutrients);
- It includes sufficient complexity so that the interactions between these fluxes are represented; and
- It keeps monitoring and analyses manageable.



Research has shown that rapid changes in the hydraulic characteristics of a cover system occur within the first three to five years. Consequently, the watershed level research is targeted for a minimum period of five years.

Synchrude commenced its instrumented watershed research work with the University of Saskatchewan in 1998 on one of the saline sodic overburden areas – the South Bison Hill. Following from the example set there, the program was expanded to a tailings sand slope watershed in 2001 and a petroleum coke-based landform in 2003. Over the next 10 years instrumented watersheds will be established on other major material types including soft tailings, buried sulphur, lean oil sand, and coarse-textured overburden. These watersheds will be part of an 8 to 10-year program of research focussed on gaining insight on the following subjects:

- 1) Water and energy balances (total and circulation rates);
- 2) Salt balances, including inorganics, organics, ions, nutrients, metals (total and circulation rates);
- 3) Plant and ecological responses to 1) and 2); and
- 4) Optimal management of these balances.

### *3.2.2 Description of the Wood Bison Hills Research Program*

Saline sodic overburden will comprise about one-third of the 80 km<sup>2</sup> area comprising Synchrude's final landscape. These soils are Cretaceous marine shales consisting of swelling clays (illite and montmorillonite) that are highly saline (10-20 dS/m) and sodium saturated (Sodium Absorption Ratio (SAR) >20). The initial question asked of the research group was simply "what is the correct soil cover depth to place over saline sodic shales to ensure establishment of a productive boreal ecosystem while minimizing percolation of meteoric water through the shale pile?".

An initial three-year study, which began in 1998, was developed to address this question with the following specific objectives:

- 1) Evaluate the long-term performance and effectiveness of soil covers for reclamation of sodic waste overburden;
- 2) Characterize the impact of weathering within the overburden shale so that the long-term physical stability, chemical, and hydraulic behaviour of the spoil piles can be defined; and
- 3) Develop a fully monitored watershed within the reclaimed sodic waste from which the evolution of the hydrologic and hydrogeologic behaviour of the reclaimed dumps and associated wetlands can be studied.

The overall objective of this integrated study is to define the basic mechanisms controlling moisture movement within the reclaimed landscape. Mechanisms were characterized by the installation, verification and continuous monitoring of field instrumentation on three prototype

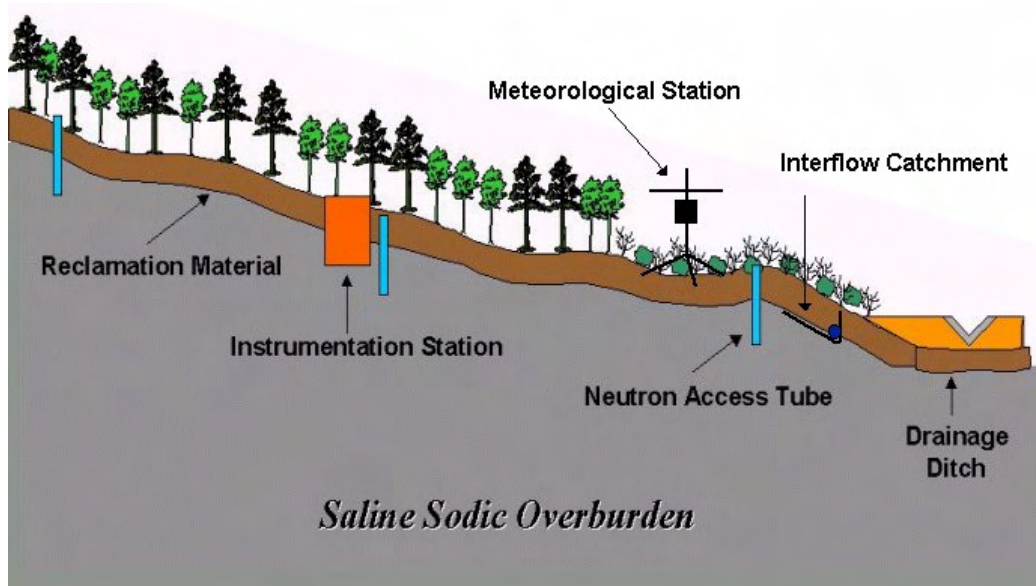
covers. Once these mechanisms were characterized, their subsequent impact on salt migration and revegetation were addressed. Numerical models were modified and verified to allow Syncrude a means of undertaking preliminary design of cover alternatives and reclamation strategies for the remainder of the mine site. The monitored study site also provided a valuable field site to track the long-term hydrologic evolution of a reclaimed landscape and provided insight into the hydrologic processes occurring within soil covers on reclaimed overburden, thus aiding in optimizing cover design.

These study objectives focused on the long-term performance of reclamation cover sites located on the South Bison Hill (see Figure 3.1). The study area included three new alternative prototype layered covers along with an older, previously reclaimed cover located adjacent to a voluntary wetland known as Bill's Lake. The prototype covers drain into a single swale running along their base while the cover surrounding Bill's Lake drains directly into the Bill's Lake wetland. Bison Lake is a small lake located downstream from Bill's Lake. Any runoff collected from the top of the dump, which was reclaimed in 2001, is collected along a swale and is drained into two wetlands situated in series and known as Peat Pond and Golden Pond.



**Figure 3.1** Aerial photograph of the South Bison Hill study locations at Syncrude (from Barbour *et al.*, 2004).

The prototype covers were constructed in 1999 with three different thicknesses of peat over a till-secondary material, sufficient to provide the "available water holding capacity" required for the development of a sustainable vegetative soil cover. The Bill's Lake cover, also part of the study, was placed in 1996. Each of the three prototype covers is approximately 1 ha in size (200 m long and 50 m wide) and is placed on a 5H:1V slope. The prototype covers were constructed side by side, west to east, as follows: D1, 20 cm of peat overlying 30 cm of till-secondary; D2, 15 cm of peat overlying 20 cm of till-secondary; and D3, 20 cm of peat over 80 cm of till-secondary. The cover at Bill's Lake consists of 100 cm of mixed peat/till-secondary. The D3 cover is the control plot, with a cover thickness corresponding to the requirements of Alberta Environment. Figure 3.2 shows a representative cross-section of the performance monitoring instrumentation installed on the prototype covers. The Bill's Lake monitoring location has a similar monitoring system design but does not include a meteorological station or a surface runoff measurement system.



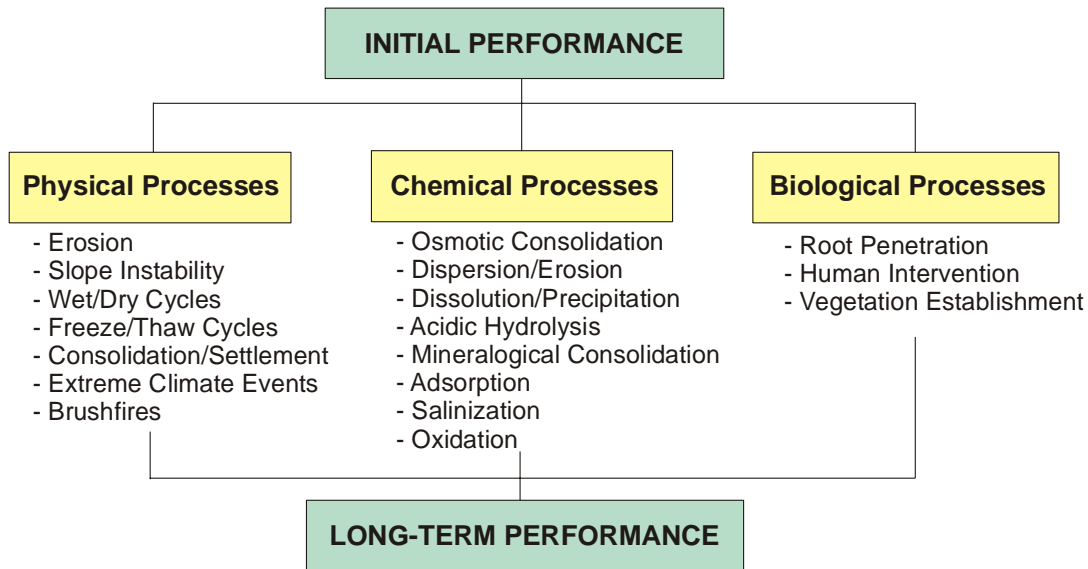
**Figure 3.2** Representative cross-section of the instrumented D1, D2 and D3 prototype covers at the South Bison Hill research area at Syncrude (from Barbour *et al.*, 2004).

### 3.3 Processes that Affect Cover System Evolution

The processes that affect a mine waste cover system are the same processes that initiate change in the overall landscape. This manual focuses on design and monitoring on a macro-scale. This section provides an overview of the main processes that influence the evolution of the smaller, soil cover systems because there is limited research focused on evolution on landscape scale. Marcucci (2000) identifies "keystone processes" as formative processes that influence the trajectory of landscape change. Any change or cessation of these processes may result in a

completely altered trajectory. For the purpose of the design of a cover system, keystone processes can generally be put into three main categories (see Figure 3.3): physical, chemical, and biological and each of these key processes will affect performance of cover systems differently, either separately or in combination with one another.

A mine waste cover system design is influenced by the climate of the area, the type and reactivity of the underlying waste, and the hydrogeologic setting (MEND 2.21.4). The integrity of a soil cover is a key property because long-term performance is based on the physical dimensions of the specific cover design. If the natural environment changes the physical limits of the cover, then predictions based on the original cover design cannot be considered valid (INAP, 2003). Characterization and monitoring programs must gather data necessary to describe ongoing physical, hydrological, geochemical, and microbiological processes and to determine the properties controlling these processes (Lefebvre *et al.*, 2001).



**Figure 3.3** Processes that could potentially affect long-term performance of a soil cover on a macro-scale level (adapted from INAP, 2003).

### 3.3.1 Physical Processes

Physical processes, and associated properties, affect the success of a soil cover by controlling moisture dynamics. Physical processes involve the response of the cover materials to changes in climatic conditions, which include erosion, wet/dry cycles, freeze/thaw cycles, consolidation and settlement. Extreme climate events, or events that do not fall within recorded historic normals such as floods or droughts, are also processes that alter the physical properties of a cover system. Not all changes in soil physical properties result from occurrences in nature. Material handling operations during the process of reclamation such as spreading topsoil and landform construction may cause soil compaction and alter physical and structural characteristics

that control root development (Shukla *et al.*, 2004). In current restoration practises, much attention and research has been devoted to each stage of materials handling, both removal and placement, to protect soil properties and to keep, as much as possible the physical, chemical, and biological characteristics of the soil intact. After placement, the rate of soil development in reclaimed soils is not fully quantified; however, it is agreed that the initial high rate of soil weathering decreases rapidly with time (Shukla *et al.*, 2005).

#### 3.3.1.1 Erosion

Soil erosion is one of the most common causes of deterioration in cover systems. It is generally agreed that the three main erosion processes are interrill, rill, and gully erosion. The loss of topsoil due to erosion can result in deterioration of a soil cover or even total loss of a thin cover system in just a few years. Severe loss of soil organic carbon required for proper vegetative establishment is directly related to the loss of topsoil. Erosion is progressive and is normally initiated by sporadic extreme hydrologic events. The long-term liability is determined by the erosion rate, the amount of produced sediment, and the impact on the overall landscape.

Slope instability is the mass movement of an entire slope that may destroy the integrity of the cover and expose the underlying waste. Three driving forces behind slope instability include gravitational, seepage, and seismic forces (INAP, 2003). Many studies have shown that changes in the saturated hydraulic conductivity of materials within a hillslope can elevate pore-water pressures, generally at the base of slopes, and lead to hillslope failure (Reid, 1997). Both the gravitational and seepage forces act to increase the shear stress of the cover materials and seismic forces are created by earthquakes or large-scale movement of the earth's tectonic plates.

Table 3.1 outlines the most important factors believed to affect erosion of soil cover layers (INAP, 2003). All factors outlined in Table 3.1 should be taken into consideration when determining the potential impact that erosion might have on a soil cover system.

#### 3.3.1.2 Wet/Dry Cycles

Wet/dry cycles cause shrinking and swelling of fine-textured materials that contain clay minerals, which attract and absorb water. Shrinking and swelling of soils can significantly alter the hydrogeologic and diffusion characteristics of the soil cover. Shrinkage cracks occur when the capillary pressures exceed the cohesion or the tensile strength of the soil. Swelling occurs when water molecules are absorbed into gaps between clay plates. As more water is absorbed, the plates are pushed further apart causing an increase in soil pressure resulting in an increased soil volume. Shrinkage of the soil occurs rapidly, while swelling is a slow process that can take up to months or even years to complete. Shrinkage occurs in climates where evaporation occurs on the surface in dry climates and by the desiccation caused by vegetation during periods of water

stress. A soil that undergoes the process of shrinking and swelling as a result of wet/dry cycling develops a “memory” and will not return to its original state. Fracturing as a result of wet/dry cycling results in an unfavourable increase in hydraulic conductivity.

**Table 3.1**  
Factors affecting the erosion of cover systems (from INAP, 2003).

Factor	Comments
Slope Angle	Erosion rate increases with increased slope angle
Slope Length	Erosion rate increases with increased slope length
Material Properties	Materials with low cohesion, and small particle size (lower mass) are more easily detached and entrained into water flow
Rainfall Intensity	Storm intensity defines the amount of runoff flow available for erosion; increased storm size will bring more erosion. It is not a linear relationship; a single large storm event has the ability to produce the majority of erosion experienced at a site over a long period of time.
Vegetation	Vegetation increases the strength of the soil and reduces the energy of runoff flow by creating barriers to flow
Base Flow (Antecedent Moisture Condition)	Increased erosion occurs at seepage faces due to the lower strength of the saturated material as compared to the unsaturated material

### 3.3.1.3 Freeze/Thaw Cycles

Freeze/thaw cycling causes soil cover desiccation by breaking down the cover structure through the expansion of water contained in the macropores upon freezing. Repeated freeze/thaw cycles cause frost heave, cryoturbation, and mechanical weathering. When water expands as it freezes, it can exert pressures of up to 21 MPa, often high enough to cause significant changes in the soil matrix and macropores to intensify and expand. Ice crystals that have formed in the pore spaces grow as they attract water that has not frozen from the surrounding pores. Frost desiccation occurs when soil moisture is drawn from the unfrozen soil material as the freezing front moves from the soil surface downward, and in the case of permafrost, drawn from the permafrost table as it moves upward, resulting in the formation of a granular structure in fine-textured soils.

The freezing and subsequent thaw of the material will decrease the material density as well as increase the water content and void ratio, ultimately leading to an increase in the saturated hydraulic conductivity. The greatest change in hydraulic conductivity has been found to occur within the first two freeze/thaw cycles and after which it remains relatively constant (MEND 2.21.4; Meiers *et al.*, 2003). However, the potential does exist for further damage to the

compacted layer with subsequent freeze/thaw cycles (CANMET, 2002; Wong and Haug, 1991). Silt has been identified as the material most susceptible to freeze/thaw cycling because the silt pores are small enough to induce suction gradients during freezing but still allow an adequate supply of water to the freezing front.

#### 3.3.1.4 Consolidation/Settlement

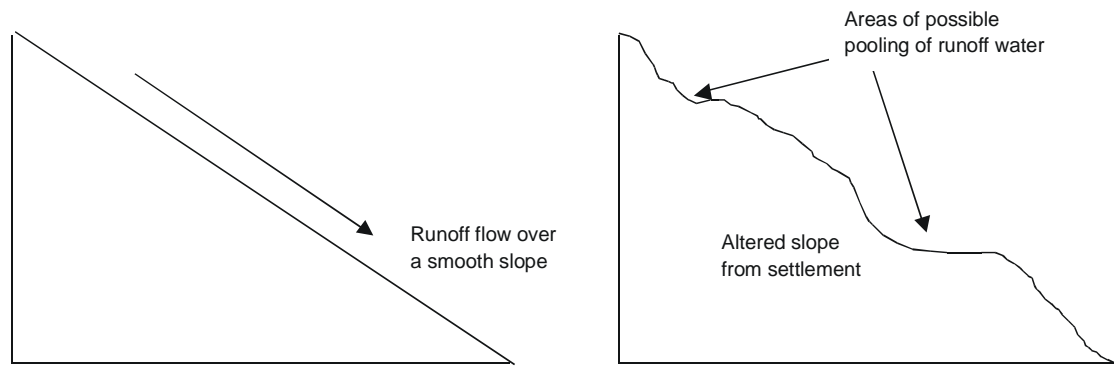
Consolidation and settlement will affect the integrity of the cover system by reducing the thickness of the cover layers. Consolidation is the process in which the cover material decreases in volume due to a decrease in the volume of voids within the material. However, with consolidation also comes an increase in the density of the soil matrix, which can alter the saturated hydraulic conductivity and moisture retention characteristics of the material. As a result of consolidation, the *in situ* moisture content is increased which subsequently changes the overburden pressure and shear strength within the cover material profile. Consolidation of “freshly placed” cover material has been shown to occur over a relatively short period in response to extreme climate events such as high intensity rainstorms.

Cover system field trials constructed on a waste rock pile at an iron ore mine located in western Australia subsided approximately 10 cm in less than 10 hrs in response to a 210 mm rainfall event (OKC, 2004). Due to the rapid subsidence, cracks developed throughout the cover profile, which functioned as preferential flow paths during high intensity rainfall events resulting in meteoric water bypassing the cover profile.

Settlement is the term used to describe the reduction in volume of the cover material. The process of settlement can change the geometry and drainage patterns of the cover system. Differential settlement, which is most likely a result of settlement of the underlying waste, can create local recharge and discharge areas on the cover system that were not accounted for in the cover design. Cover systems established on sloped surfaces utilize the slope to help shed water as runoff. This reduces the amount of water available to infiltrate the cover system and the underlying mine waste material. Figure 3.4 shows a conceptual schematic of how runoff flow may be affected by changes in the slope surface due to settlement.

### **CASE STUDY**

The evolution of the hydraulic performance of Syncrude's three prototype covers described in Section 3.2 was investigated by Meiers *et al.* (2006) through measurement of the field saturated hydraulic conductivity ( $K_{fs}$ ) over time. Changes in  $K_{fs}$  were related to field performance of the trial cover systems. Repeated field measurements of  $K_{fs}$  conducted over a five-year period (2000 – 2004) were completed using the Guelph permeameter technique (described in Section 4.3.3) at midpoint locations in the peat/mineral and glacial till cover materials and 30 cm below the interface of the glacial till and shale of the three cover systems.

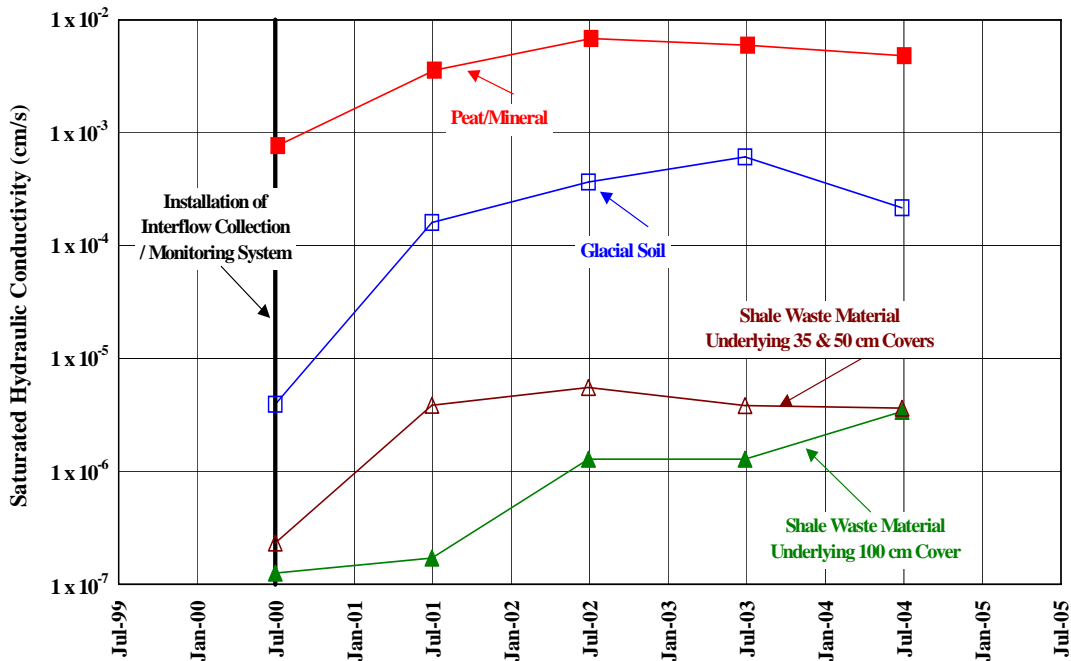


**Figure 3.4** A schematic representation of the effects of differential settlement on the surface hydrology of a slope (from INAP, 2003)

The mean  $K_{fs}$  for all tests in the peat/mineral cover layer increased from  $8 \times 10^{-4}$  cm/s to  $7 \times 10^{-3}$  cm/s from 2000 to 2002. This value remained relatively constant for each of the remaining field seasons. The  $K_{fs}$  of the glacial till cover layer increased by two orders of magnitude from  $2 \times 10^{-6}$  cm/s to  $2 \times 10^{-4}$  cm/s over the first year of monitoring and remained relatively unchanged at approximately  $4 \times 10^{-4}$  cm/s for the remaining field seasons. The geometric mean  $K_{fs}$  of the shale underlying all three covers was approximately  $2 \times 10^{-7}$  cm/s in 2000. This value increased to approximately  $4 \times 10^{-6}$  cm/s by 2004. However, the rate of change in the shale underlying the thickest 100 cm cover lagged behind that of the 35 cm and 50 cm covers. The hydraulic conductivity of the three soil types is presented in Figure 3.5.

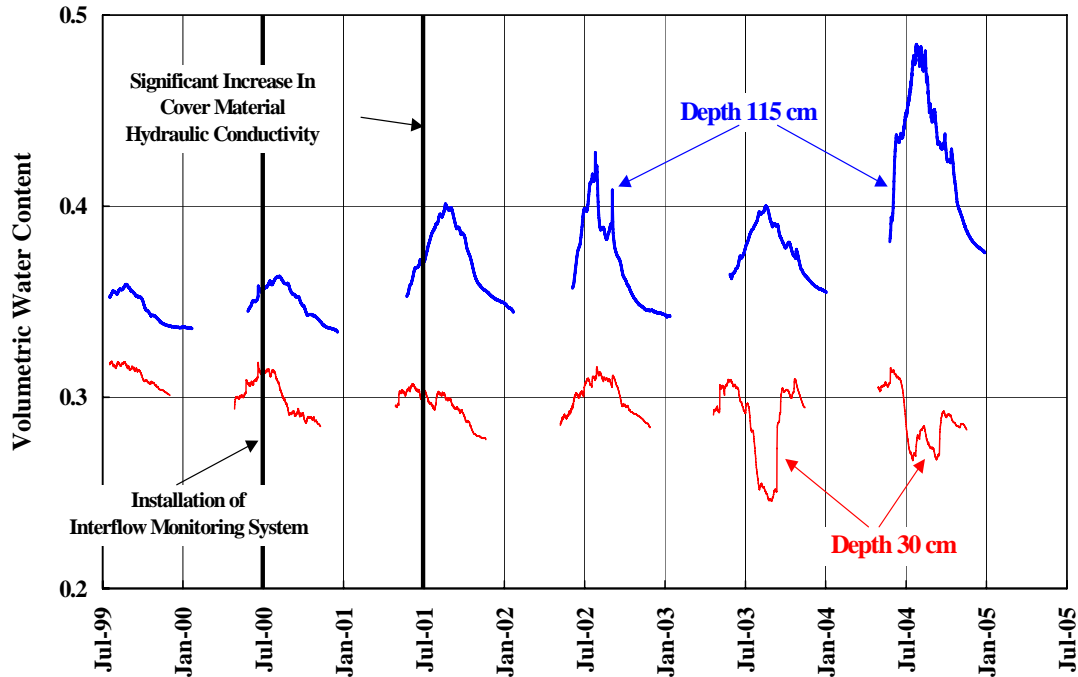
Measurements of *in situ* temperature suggest that soil temperatures did not fall below  $0^{\circ}\text{C}$  at all Guelph permeameter test locations below the 100 cm cover during the winter of 2000. However, the depth of frost did reach all sensor locations the following winter. The increase in  $K_{fs}$  measured at the deep locations in the shale following freezing conditions demonstrates that freeze/thaw cycling is the dominant process affecting changes in hydraulic conductivity. Biological processes were not deemed to be a factor because changes in  $K_{fs}$  were noted through the whole cover profile, and not just near surface where root development and biological activity was more prevalent. Results from *in situ* measurements of matric suction and volumetric water content show that wetting and drying occurred to varying degrees at various depths on each of the prototype covers. Wet/dry cycles can strongly impact the  $K_{fs}$ ; however, because the  $K_{fs}$  of similar materials on all cover systems was equivalent under different degrees and rates of wetting and drying, wet/dry cycling was not deemed to have as much of an effect on cover  $K_{fs}$  as freeze/thaw cycling.





**Figure 3.5** Geometric mean field saturated hydraulic conductivity of the cover materials and shale (from Meiers *et al.*, 2006).

Precipitation measured at the site during the first four years was well below annual average precipitation measured at the Fort McMurray station (1953-1993) of 460 mm. Contrary to the low amounts of precipitation received, the 100 cm cover experienced a steady increase in water content at the base of the cover. Figure 3.6 shows volumetric water content measured in the 100 cm cover at a depth of 30 cm, immediately below the peat/mineral – glacial till interface, and at a depth of 115 cm, immediately above the glacial till – shale interface (note that the actual cover thickness at the location of the monitoring sensors is 120 cm). An initial increase in water content early in the year is due to snowmelt, spring rain, and low potential evaporation conditions. The volumetric water content at a depth of 115 cm starts to increase as soon as temperatures rise above freezing, which may take up to two months after the surface has thawed at this site. A decrease in water content occurs around July, the peak of the growing season, in response to transpiration. This decrease is more dramatic in 2003 and 2004 as the vegetation has become more established. Volumetric water content data for the 115 cm depth shown in Figure 3.6 shows a noticeable increase in moisture content from the beginning of monitoring in 1999 to the end of 2004; this is contrary to what might be expected given the decreasing annual precipitation totals. The increase in  $K_{sat}$ , from  $2 \times 10^{-6}$  cm/s in 2000 to  $2 \times 10^{-4}$  cm/s in 2001, appears to have led to an increase in the dynamics of moisture movement near the base of the cover, even in the presence of lower precipitation.



**Figure 3.6** Monitored volumetric water contents within the 100 cm cover (from Meiers *et al.*, 2006).

The interflow monitoring system installed during the summer of 2000 at the base of the cover trials collects the total volume of water moving laterally downslope through the covers along the glacial soil/shale interface. The annual cumulative volume of interflow increased consistently from 2001 to 2004 for all covers. The volume of interflow for the 100 cm cover was consistently greater than for the other covers in 2001, 2003, and 2004. The dramatic increase in interflow volumes suggest that the changes in  $K_{sat}$  as measured by the Guelph permeameter are influencing the hydrologic performance of the covers.

### 3.3.1.5 Extreme Climate Events

Extreme climate events can be the driving force behind altering the effectiveness of a cover system. A mine waste cover system design is largely based on the climate conditions of the area. The three most noted climate events that may cause damage to the cover system are extreme precipitation events, long periods of drought, and freezing conditions.

Extreme precipitation events may be the result of high rates of precipitation or precipitation quantities that are greater than the historical average. High intensity precipitation events exceed the soils capacity for infiltration resulting in runoff, most often resulting in erosion causing high levels of damage. Precipitation quantities that are greater than the historical average, either in the form of rain or snow, can lead to high percolation rates through the cover. In addition, extreme

rainfall events can cause significant erosion of surficial cover materials and potentially cause shallow slope failures due to the build-up of pore-water pressures in a particular soil cover layer.

Drought conditions can impact the cover system by altering the cover structure. Drought conditions cause desiccation cracking, predominantly in soils with relatively high fines content, increasing soil permeability allowing higher rates of oxygen ingress and net infiltration of meteoric water. In the case of a cover system designed to limit the ingress of oxygen, long periods of drought can reduce the degree of saturation in the layer designed to remain tension saturated. Drought conditions may affect any established vegetation layer increasing the potential for erosion and net infiltration when precipitation occurs.

### 3.3.2 *Chemical Processes*

Chemical processes, in general, are more applicable to liner design rather than cover systems as covers seldom have to defend against chemical attack. It could be argued that the exception to this would be the impact of sodium migrating from the underlying waste to the overlying cover material. Exchange of cations (generally calcium) on clay particles with the sodium can lead to sodicity, and a resultant change in soil structure, causing a reduction in permeability and increase in erodibility. The effect of chemical processes in the long-term performance of a cover system is not as evident as physical and biological processes, which are generally more easily observed. Chemical processes have the potential to change the actual fabric of a cover material. Cover systems utilizing a layer of material containing clay material (generally associated with a low permeability layer), will likely need to address the potential for pore-water to “attack” the integrity of the clay mineralogical structure, or alter the hydraulic behaviour of the clay material. The poor quality pore-water may result from oxidized products moving vertically upward by diffusion as a result of atmospheric demand for moisture (i.e. evaporation), or result from acidic seepage waters emanating laterally from a sloping face. Chemical processes examined that have an affect on the integrity of a soil cover include osmotic consolidation, dispersion/erosion, acidic hydrolysis, mineralogical consolidation, and sorption.

#### 3.3.2.1 Osmotic Consolidation

Low permeable clays are strongly affected by electrolyte solutions (high salts), which can result in osmotic consolidation. Osmotic consolidation is the shrinkage (or swelling) induced in soils caused by a change in pore-water chemistry causing cracks and fissures to develop. Barbour (1987) identified two types of osmotic volume change; namely, osmotically induced consolidation and osmotic consolidation. Osmotically induced consolidation results from the release of water due to chemical gradients. Osmotic consolidation results from alterations in clay particle interactions due to changes in pore-water chemistry.

Osmosis refers to the flow through a semi-permeable membrane that separates high and low concentration solutions. In the case of a soil cover system, the pore-water surrounding the soil particles primarily consists of water and dissolved solids. Water is referred to as the “solvent” while the dissolved solids are known as the “solute”. There is extensive evidence in laboratory and field studies that clay soils have a semi-permeable nature (Barbour, 1987). The clay soil, acting as a semi-permeable membrane, allows the solvent to move from the lower concentration solution to the higher concentration fluid. The solute also has a tendency to migrate but the semi-permeable clay layer impedes solute flow. As water is removed, a decrease in pore-water pressure in the clay develops causing an increase in effective stress resulting in consolidation.

Osmotic consolidation is the alteration of clay particle interactions as a result of changes in pore-water chemistry. Barbour (1987) suggests that particle-to-particle interaction is largely controlled by long-range repulsive forces. A change in pore-water concentration can result in changes in these long-range electrostatic forces resulting in a reduced thickness of the diffuse double layer. The diffuse double layer refers to the layer of cations established around the clay particle, with increasing cation concentration towards the surface of the clay particle. If cations enter into the clay with a higher valence than the exchangeable ions currently in place (i.e.  $\text{Ca}^{++}$  for  $\text{Na}^+$ ), stronger bonds between the clay particles may develop subsequently reducing the space between the clay particles (reducing the diffuse double layer thickness).

Several methods have been formulated to limit the extent of osmotic consolidation including: minimizing the clay content of the cover material, applying a sufficient confinement to the clay so that fractures and cracks are not able to develop, and reducing the potential for volume change (i.e. chemically pre-treat the cover material) (Haug *et al.*, 1988).

### 3.3.2.2 Dispersion/Erosion

The dispersion of clay minerals and subsequent susceptibility to erosion should be considered in evaluating the long-term performance of a cover system composed of a clayey soil. Chemical processes can influence the arrangement of clay particles and may lead to the development of dispersed clay, which are prone to increased rates of erosion. The stability of clays is dependent upon the arrangement of the soil particles. Important factors in determining clay stability include pore-water ion concentration, the type of clay minerals present, and the exchangeable cations present.

Note that dispersion without confinement such as that of a soil cover surface can lead to erosion as discussed above, but also to a decrease in the saturated hydraulic conductivity. Alternatively, internal dispersion (i.e. below the surface of the cover system) may lead to clogging and a decrease in hydraulic conductivity.

### 3.3.2.3 Acidic Hydrolysis

Hydrolysis is a chemical reaction between a mineral and aqueous hydrogen ions ( $H^+$ ), which may be either a component of natural water ( $H_2O \leftrightarrow H^+ + OH^-$ ) or is associated with acids in aqueous solution. In a cover system, minerals in the cover materials may react with acids in the pore fluid from the underlying waste, thus forming new minerals. Water molecules separate into  $H^+$  and  $OH^-$  ions. In acidic hydrolysis, an acid such as sulphuric acid ( $H_2SO_4$ ) or water ( $H_2O$ ) gives up a proton ( $H^+$ ) (depending on the acid, maybe more than one proton) and obtains a cation from surrounding mineral grains. Some minerals in soil covers may be entirely (e.g. calcite) or partially (e.g. feldspars) dissolved, and new minerals (e.g. gypsum or ferrihydrite) may be formed by these reactions. The mineral transformations may or may not compromise the integrity of the soil cover.

### 3.3.2.4 Mineralogical Consolidation

Mineralogical consolidation may occur as a result of changes in the mineralogy of soil particles. This could involve a change in crystal structure or even the chemical composition of minerals. Long-term cover performance may be affected by the characteristics of the new mineral(s). If the newly formed mineral(s) causes consolidation to occur, crack or fissures may develop, thus reducing the effectiveness of the cover system.

### 3.3.2.5 Adsorption

Dissolved minerals within groundwater can be adsorbed onto the surfaces of mineral grains in the soil cover. Adsorption removes solute from the solution retarding solute movement. Adsorption is assumed to be a reversible reaction. The adsorption of ions or molecules changes the chemistry of the cover material and may affect its long-term performance. Adsorbed ions or molecules may cause osmotic volume change or dispersion/erosion in a particular cover material.

Adsorption isotherms are used to estimate the amount of adsorption for certain concentrations. All isotherms level off eventually because the capacity of the soil to store minerals is limited. Mineral surfaces have a limited amount of area to which ions can bond.

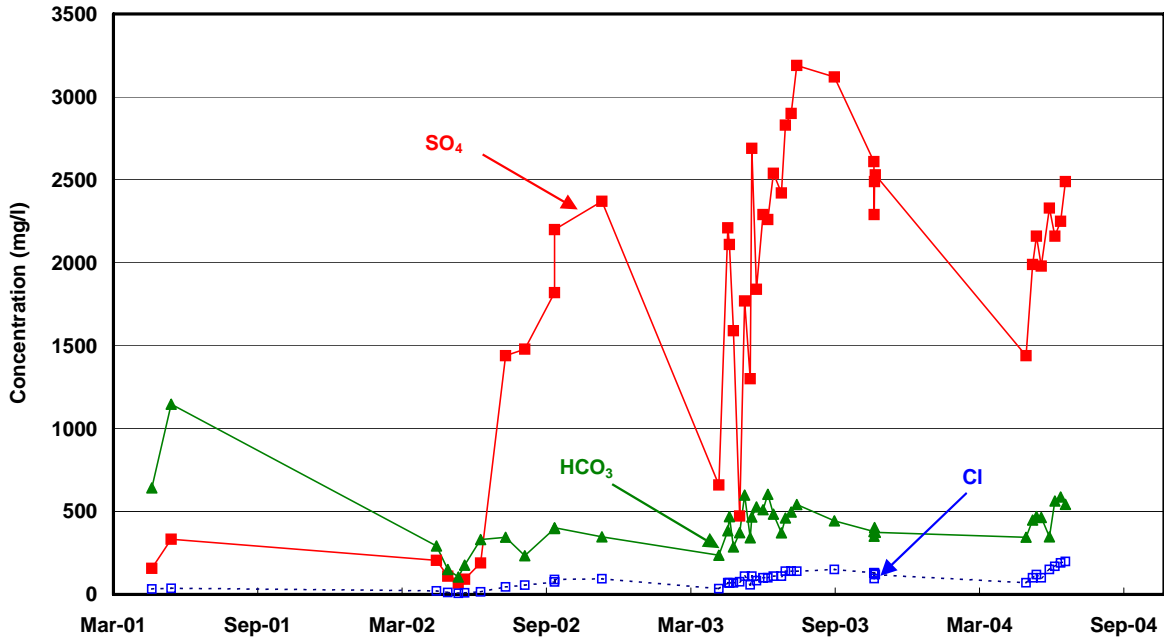
## **CASE STUDY**

Barbour *et al.* (2005) tracked the evolution of a five-year-old cover system within a small watershed on a saline sodic overburden structure at Syncrude. A full description of the site and the details of the reclamation covers and monitoring system can be found in Section 3.2. Of particular concern was migration of salts, especially sodium, into the rooting zone of the cover system from the underlying saline-sodic shale.

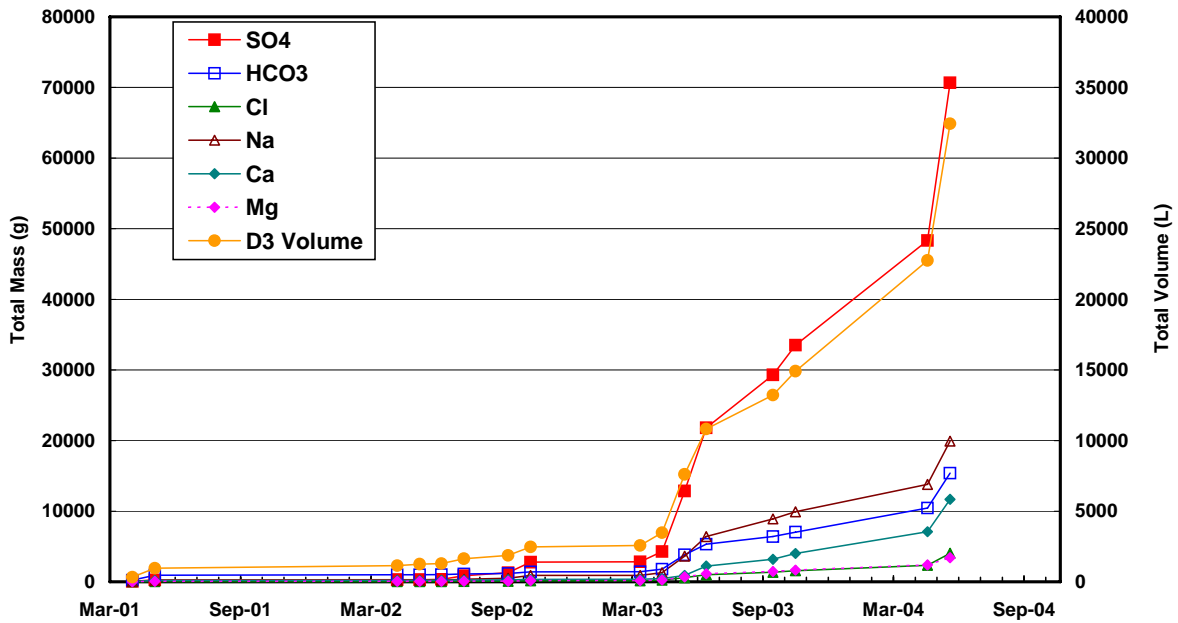
Soil geochemistry was investigated by two separate studies. Kessler (2006) investigated the chemical properties of the soil cover three to four years after placement and related these to cover thickness and slope position. The objective of this program was to determine the distribution of major salts into the landscape and to evaluate the extent of the salt transfer between the highly saline shale overburden and the cover. Ten sampling locations were designated on each of the three different layered covers to collect soil samples with depth to analyse for chemical properties. Samples were collected through the cover profile to a depth of 30 cm below the interface between the cover and shale. Chemical analysis was completed using a saturated paste extract on major properties including pH, electrical conductivity (EC), soluble cations, soluble anions, sodium absorption ratio (SAR), exchangeable cations, and cation exchange capacity (CEC). The second geochemical study conducted by Wall (2005) focused on determining the specific sulphur forms/concentrations in the overburden as well as the rate of sulphide mineral oxidation and the resulting salt loading because additional salt can be released from the shale as a result of oxidation of disseminated pyrite. A total of 44 soil gas sampling probes were installed to investigate variations in gas concentrations due to slope position and cover treatment.

Preliminary results show that oxidation of sulphide is occurring below the interface between the cover and the shale to depths of approximately 1 to 2 m below surface. Detailed measurement of oxygen concentrations suggest that the principle zone of oxygen consumption and carbon dioxide production lies within the upper region of the shale. Increased levels of EC were found approximately 15 cm above the interface between the glacial till and shale in all covers showing no clear relationship to cover thickness. Detailed chemistry results from samples collected through the cover profile and into the shale illustrate that the salinity at the shale interface is dominated by sulphate, consistent with pyrite oxidation. Total salts and SAR were shown to follow the same pattern as EC and did not show any relationship to slope position. Diffusion is thought to be the dominant mechanism of salt transport into the covers over the first four to five years resulting in elevated salinity and sodicity in the lower portion of the covers.

An interflow monitoring system installed during the summer of 2000 at the base of the cover trials collects the total volume of water moving laterally downslope through the covers along the glacial soil/shale interface. Samples from the interflow collection system for each cover were collected for chemical analysis. The cumulative total volume of interflow increased by an order of magnitude over a three-year period likely due to increasing hydraulic conductivity of the cover materials as well as wetter climatic conditions. When compared to the total water balance for this site, the total interflow volumes collected are not significant; however, Barbour *et al.* (2005) showed that interflow is an important hydraulic mechanism for salt flushing from the covers. Figure 3.7 shows the chemical concentration of interflow water collected from the 100 cm cover and Figure 3.8 shows the cumulative sulphate loading to the interflow from the 100 cm cover. Figures 3.7 and 3.8 illustrate how the increased concentration and the rate of interflow have combined to dramatically increase the rate of sulphate flushing from the covers.



**Figure 3.7** Concentration of interflow water from the 100 cm prototype cover with time (from Barbour *et al.*, 2005).



**Figure 3.8** Cumulative sulphate loading to the interflow system at the 100 cm prototype cover (from Barbour *et al.*, 2005).

The advective/diffusive transport of sulphate across the interface of the cover and the shale was simulated in a model described in Barbour *et al.* (2005). The model clearly showed that the initially high sulphate release rates will rapidly diminish as gradients begin to increase. The sulphate concentration currently captured by the interflow system only accounts for approximately 10% of the diffusive salt flux into the cover; however, the observed increasing volumes of interflow and the concentrations of sulphate collected in the interflow suggest that salt flushing through interflow may begin to equal salt release rates within the first 10 years following cover placement.

## **LESSONS LEARNED**

Findings from this study show that water and salt fluxes can evolve rapidly in the first years after placement. The thickest 100 cm cover has shown to be an effective cover design based not on water holding capacity alone. The thickest cover allows for excess water to be stored and made available for interflow to provide a mechanism for salt release downslope and as well aids in limiting oxygen diffusion due to an elevated degree of saturation. The 100 cm cover also provides a lower zone where salt can be stored until it can be released through flushing mechanisms. The secondary layer in some instances may have to be designed to be thick enough to allow for a “sacrificial layer” because it may become contaminated as a result of contaminant transport, through mechanisms such as diffusion, from underlying waste. These fluxes will eventually decrease as other mechanisms of transport such as deep percolation or interflow begin to dominate.

### *3.3.3 Biological Processes*

Biological processes affect soil formation and aggregation, organic matter breakdown, and degradation of toxic substances. The long-term evolution and sustainability of a soil cover requires a fully developed biological system capable of nutrient cycling sufficient to maintain appropriate levels of organic matter and nitrogen. Biological activity contributes to soil structure development and has the greatest impact on hydraulic conductivity near surface with the impact decreasing with depth (Meiers *et al.*, 2003). When designing a cover system, one important consideration relating to biological processes is to determine what the native species of the area are and what potential impact they may have on the cover design. The two main biological processes that may affect soil cover performance are vegetation root penetration and burrowing animals.

#### 3.3.3.1 Root Penetration

The establishment of vegetation on a reclaimed site is usually a reclamation goal and a requirement by regulators. However, if the cover design does not anticipate the type and density of the vegetation, the vegetation has the potential to affect the cover system negatively. Roots



and plant biomass create macropores within the cover structure allowing water to more easily infiltrate into the cover material to the underlying waste. Koerner and Daniel (1997) summarize the damage that plant roots may have:

- roots may penetrate the barrier layer of a cover system;
- decomposing roots leave channels for movement of water and vapours;
- roots may dry clayey layers, causing shrinking and cracking; and
- roots may enter the waste material and take salts and undesired metals upward into the cover system and the soil surface.

Grass and shrubs are often used to vegetate the surface of mine waste cover systems. In general, shrubs and grasses are quick to mature and have shallow rooting systems that do not reach the barrier layers of a cover system. However, it should be noted that the depth of root penetration is a function of species and climate, among numerous other factors.

Research on the rooting depths and biomass distribution of tree species has showed that 80% of tree roots stay within 0.6 m of the soil surface, indicating that many trees have shallow, lateral rooting systems. Active plant roots will plug the macropores of the soil structure and consolidate the ground around them, leading to a decrease in the soil hydraulic conductivity in the vicinity of vegetation.

#### 3.3.3.2 Burrowing Animals

Burrowing animals also influence the integrity of the cover system. Koerner and Daniel (1997) summarized the effects that burrowing animals can have on the long-term performance of a cover system:

- the animals may burrow through the cover, resulting in direct channels for movement of water, vapour, roots, and other animals;
- they may carry waste material directly to the surface during excavation;
- animals construct their burrows for natural ventilation which may dry the soil and decrease water intrusion; and
- by working the soil and transporting seeds, they may hasten establishment of deep-rooted plants on the cover system.

### **CASE STUDY**

A study looking at 18 year-old soil covers for waste rock at the Rum Jungle uranium and copper mine located in the Northern Territory, Australia was undertaken to investigate reported deterioration in cover performance (ACMER, 2003). Biological processes were found to be the

most significant factors affecting the performance of the cover system. Covers were constructed during 1984 – 85 with design specifications to reduce water infiltration to less than 5% of incident rainfall by water shedding and moisture store-and-release mechanisms. Regular monitoring established that the cover systems met the design criteria for a period of over 10 years. Since that time, the monitoring system has shown water infiltration into the cover has increased significantly. The decreased cover performance was investigated using field data and laboratory testing to evaluate the design, construction, type and amount of cover materials used, and physio-chemical and biological characteristics.

The cover system at this site consisted of three layers: a low-permeability clay layer placed directly on the waste rock to control infiltration; a moisture store-and-release layer to provide adequate moisture for vegetation throughout the growing season and to maintain saturation in the clay layer; and an upper layer to provide a suitable growth medium as well as erosion protection. Upon examination, the upper cover layers in some areas were not as thick as design specifications required due in large part to a shortage of suitable materials in the area. This shortage was thought to contribute to the reduced cover performance over time. To investigate cover structure evolution, thorough physical and geotechnical testing was completed. Test results indicated that an extensive system of desiccation cracks had developed in the lower clay layer.

Chemical observations noted minor formations of jarosite and expanding clay corrensite, which indicated that the upper layer of the waste rock had oxidized. A noticeable distribution of trace elements implies that capillary rise of acidic waters occurred from the waste rock into the overlying cover material. Measurement of oxygen flux into the underlying waste rock was reduced by up to 23%, which is proportional to cover thickness. Oxygen flux into the cover was observed to be approximately four times higher at the end of the dry season as a result of lower soil moisture content.

Biophysical characteristics of the soil cover were only assessed 18 years after cover placement; therefore, it was difficult to identify any changes that may have occurred. Biological processes were deemed to be one of the most significant factors affecting the cover system evolution, and were largely restricted to the near surface materials. Penetration of plant roots and colonization of native animal species were regarded to be the major factors leading to an increase of the soil cover hydraulic conductivity.

Root penetration and colonization of animal species were recognized as a vital part of reclamation that is almost certainly unavoidable. Plant roots were noted to extend through the cover profile into the underlying waste material. Root channels create a dynamic system of macropores which will last beyond the death and decay of the root. The cover vegetation was initially planted with pasture species as it was thought that tree roots would penetrate the entire cover into the underlying waste rock affecting cover performance. Volunteer tree species were

observed to have established with their roots penetrating into the compacted clay layer. The pasture grasses are not expected to remain effective as an established cover without some maintenance intervention such as fertilizer. A vegetative community composed of natural grasses and shrubs would more likely be a better alternative for a long-term vegetation establishment.

Termites and ants were found to densely inhabit the soil covers. Animal activities, in addition to plant roots, were found to alter the structure of the cover profile. Termites are most active in the surface layer where they are gathering material to line their galleries and above ground mounds. Sub-vertical galleries, as well as root channels, act as conduits for active and bypass flow of water through the cover into the underlying waste.

## **LESSONS LEARNED**

A number of recommendations have been made in regards to the design and construction of covers as a result of the findings from the Rum Jungle cover study. To ensure that design specifications are met, it was concluded that adequate supervision and quality control is essential during construction. Monitoring systems should be installed at the time of construction and observed regularly over many years to enable the performance of the cover to be quantified. The materials used in the construction of a cover system must be extensively tested to ensure that they meet the design specifications set out and that any changes in material properties be noted using testing techniques.

Plant selection has been shown to be extremely important in the longevity of the cover system and that the selection of native plant species may be the most beneficial to achieve maximum evapotranspiration. Biological changes are inevitable and are a significant indicator of successful reclamation. Allowance must be made for biological changes/colonization. Thicker cover systems may have to be incorporated into future designs to assist with the root and insect impacts on cover hydraulic conductivity.

### **3.4 Summary**

The evolution of a soil cover system occurs via physical, chemical, and biological processes from soil cover placement, to the establishment of vegetation at the disturbed site, to eventual stabilization. Disruption at any stage may hinder the development process compromising the ability of the soil cover to achieve its reclamation goal, whether it be vegetative establishment or isolating waste. Over time, the properties of the cover materials, the climate of the mine site, the vegetation cover, and the wildlife species within the mine site area will change. Prediction of the impact of these changes on the performance of the cover system is extremely difficult, yet regulating agencies often require it. Understanding the processes that affect evolution will help to

realize what the trajectory of the system is and what interventions are needed to reach the final reclamation goal.

Success of any reclamation can be interpreted over time at a watershed-scale using the correct monitoring to evaluate how physical, chemical, and biological processes are coming into equilibrium with the surrounding environment. Natural systems can be used as an analogue because they are in equilibrium with local conditions of climate, soil type, and vegetation cover. The ability to characterize and monitor these sites is vital to understanding the risks, and developing appropriate remedial approaches for progressive reclamation and long-term closure. The analysis of the long-term evolution of soil covers have shown that additional monitoring should be integrated into a set of design and construction protocols for soil covers for use by mining companies and consultants. Proper monitoring, supplemented with manual *in situ* measurements are extremely important in developing an understanding of the evolution of the cover materials and in providing a sense of the time frame required for the cover system to “come into equilibrium” with its environmental setting.

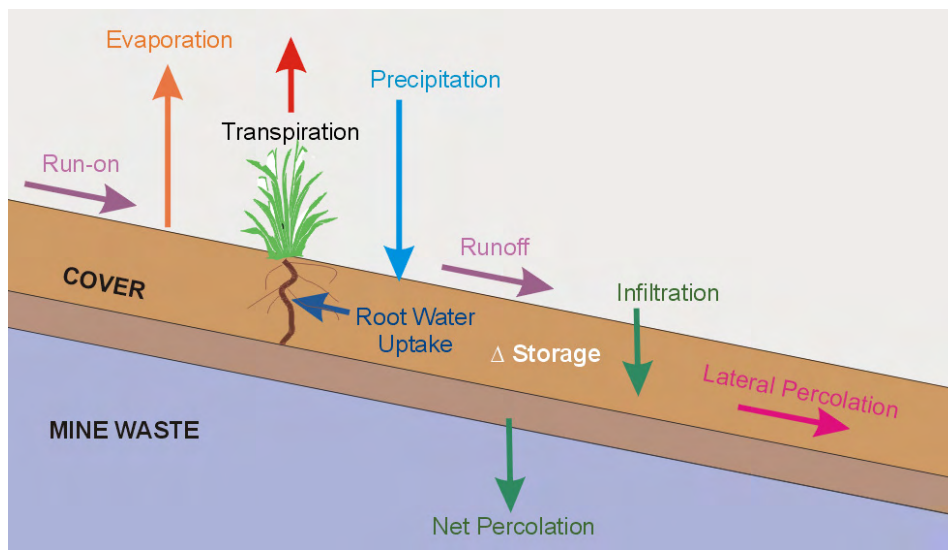
## 4 MACRO-SCALE (WATERSHED-SCALE) MONITORING METHODS

Monitoring at a watershed-scale is more challenging than monitoring at a point-scale typical of a test plot or field trial program. Whereas test plot monitoring is largely one-dimensional, watershed-scale monitoring is multi-dimensional with abundant spatial and temporal variation. Watersheds cannot be monitored on a point-scale; the type and quantity of measurements must be scaled-up to properly evaluate the performance of a reclaimed watershed. The heterogeneity inherent to the design of a reclaimed watershed means that the monitoring program must evaluate the behaviour of the entire watershed.

This section discusses methods of monitoring applicable to a watershed-scale. Although the methods outlined describe monitoring of certain points in a watershed, it should be noted that data from different parts of a watershed are required to understand how each component of the watershed is linked. The monitoring is divided into five broad categories: surface hydrologic monitoring, sub-surface hydrologic monitoring, soil characteristics and physical properties, soil and water chemistry, and biological properties.

### 4.1 Surface Hydrologic Monitoring

Hydrologic monitoring involves measuring and tracking the movement of water in the watershed. The main water source to the watershed is from precipitation, both from rainfall and snowfall. As shown in Figure 4.1, water that enters the watershed may runoff, evaporate, transpire, infiltrate and be stored as soil moisture, percolate through the cover, or move laterally as interflow. Measurement techniques for the surficial processes are discussed in this section, while measurement techniques for the subsurface processes are reviewed in Section 4.2.



**Figure 4.1** Typical watershed water balance.

#### 4.1.1 *Precipitation*

Measurement of precipitation is the most crucial of site-specific meteorological measurements as it is the primary input of the hydrologic cycle (Viessman and Lewis, 1996; Bras, 1990). Rainfall should be measured at several locations on a watershed to quantify spatial differences in rainfall depth and intensity. Snowfall should be measured with an all-season precipitation gauge and in addition, regular depth/density measurements of the snowpack should be collected with increasing frequency as spring freshet approaches.

A variety of instruments and methods have been developed for the measurement of precipitation. The three most common are: 1) non-recording gauges; 2) recording gauges; and 3) the snow survey method. Further details on these instruments and methods can be found in Appendix A.

#### 4.1.2 *Runoff*

Runoff is a complex process and therefore accurate measurement of local surface runoff from a natural soil system is challenging. Small-scale field test plots typically have runoff collection systems that divert all runoff into a lined drainage channel where flow can be measured using tipping buckets, collection barrels or weirs. For watershed-scale monitoring, this type of collection system is not practical. Geomembrane liners and collection ditches are too costly to install at a watershed-scale and are not part of the natural landscape.

Defined in Section 2.4, a watershed is an area of land that contributes runoff to a single outlet location. Therefore, runoff can be approximated by measuring streamflow from the outlet of a watershed. Streamflow can be classified as permanent, intermittent, or ephemeral (Maidment, 1993). Ephemeral streams are those that flow only after rainfall or snowmelt events. These streams provide the most direct measurement of runoff rates. Permanent or intermittent streams include water from other hydrological processes such as baseflow and interception and consequently do not provide direct measurements of runoff (Maidment, 1993).

Streamflow is typically measured using either velocity measurement or stage measurement (McCuen, 1989). Velocity measurement involves measuring the flow velocity at a number of locations along the cross-section of the stream using a velocity-measuring device such as a Pitot tube, dynamometer, or current meter (Viessman and Lewis, 1996). This method is best suited to large rivers or permanent streams in which the flow rates are more constant.

Stage measurement is where the flow rate of a stream is related to the elevation of the water. Stage measurement can either use the natural streambed, or it can involve the construction of measurement structures. For a natural streambed, a staff gauge or water level is used to determine the height of water at various known flow rates (measured using a velocity measurement device). An empirical stage-discharge curve is then determined to predict the flow rate based on water level.

Flow rate measurement structures are the most common method used for measuring flow rates in small, ephemeral streams and are therefore the most practical method for measuring runoff from small watersheds. These structures have a known stage-discharge relationship, which can be applied without detailed measurement of the streamflow. There are a variety of flow-measurement structures, but weirs and flumes are those most commonly used in runoff measurement applications. Detailed descriptions of flow rate measurement methods for open-channel flow can be found in Dodge (2001), International Standards Organization (ISO, 1983), Gray (1973), Ackers *et al.* (1978), Bos *et al.* (1991), and Montes (1998).

Weirs act like a dam in the channel and force the water to flow over an obstruction. The height of the water as it flows over the weir is directly related to the flow rate. Flumes change the area and slope of the channel to force the water to increase in velocity; the level of the water rises in the channel in relation to the increase in velocity and the water level is directly related to the flow rate. These two flow rate measurement structures are described in further detail below followed by an overview of field instrumentation available for monitoring weir water levels.

Further details on weirs, flumes, and water level monitoring instruments can be found in Appendix A.

### **CASE STUDY EXAMPLE**

A zero-height V-notch weir was installed at Syncrude to measure runoff from a reclaimed watershed area. This design is used as an example for using a weir for runoff monitoring.

The design options considered for the Syncrude runoff monitoring structure included the H-flume, the rectangular thin plate weir, the V-notch thin plate weir, and the zero-height V-notch weir. The ability of the flow structure to measure a wide range of flows and also possess the ability to pass sediments were the two key design criteria identified. The rectangular thin plate weir and V-notch thin plate weir were not selected, as they possess a crest or lip over which water must flow. This requires the build-up of a water head before the runoff is spilled into the drainage channel. The weir crest reduces the ability of the weir to measure low flow rates, and will trap sediment as runoff flows through the weir.

Investigation of the H-flume and the zero-height V-notch weir found that both had the ability to measure a wide range of flow rates, including low flows, and to pass sediments, thus preventing the build-up of material in front of the weir. The zero-height V-notch weir was chosen because of its ease of construction and because it met the two key design criteria.

Based on available information, the assumptions made in the design of the zero-height V-notch weir were:

- the design flow rate for the weir was 0.1 m<sup>3</sup>/s; and
- the gradient of the channel was approximately 3-4%.

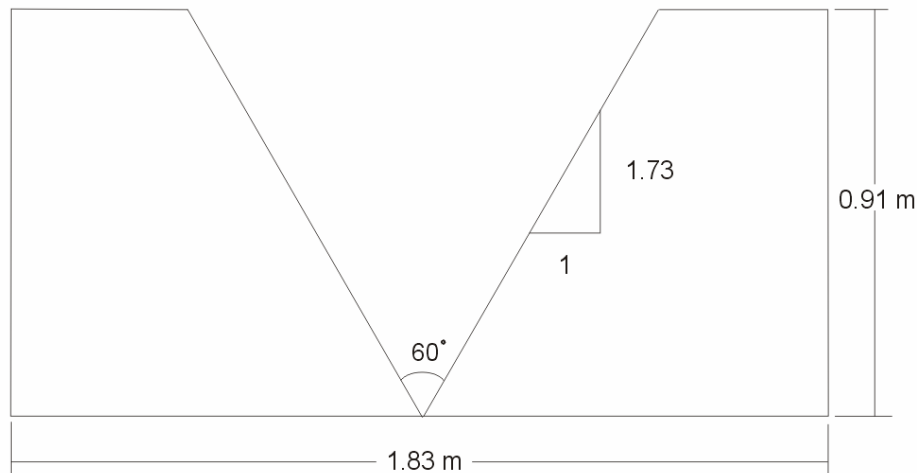
The design of the zero-height V-notch weir combined the need to accommodate the peak design flow with a requirement for a simple construction method. The weir structure was constructed from wood materials while the weir plate was manufactured from stainless steel. A weir plate with a 60° V-notch, height of 0.91 m, and width of 1.83 m was designed as shown in Figure 4.2.

The flow equation for the zero-height V-notch weir was presented by Smith (1995) as:

$$Q = C_d \cdot 8/15 \cdot (2g)^{1/2} \cdot \tan(\theta/2) \cdot h^{5/2} \quad [4.1]$$

where:

- Q = flow rate over the weir plate (m<sup>3</sup>/s);
- C<sub>d</sub> = weir coefficient of discharge;
- g = acceleration due to gravity (m/s<sup>2</sup>);
- θ = interior angle of V-notch (°); and
- h = vertical head above the V-notch (m).



**Figure 4.2** General configuration of the Syncrude zero-height 60° V-notch weir.



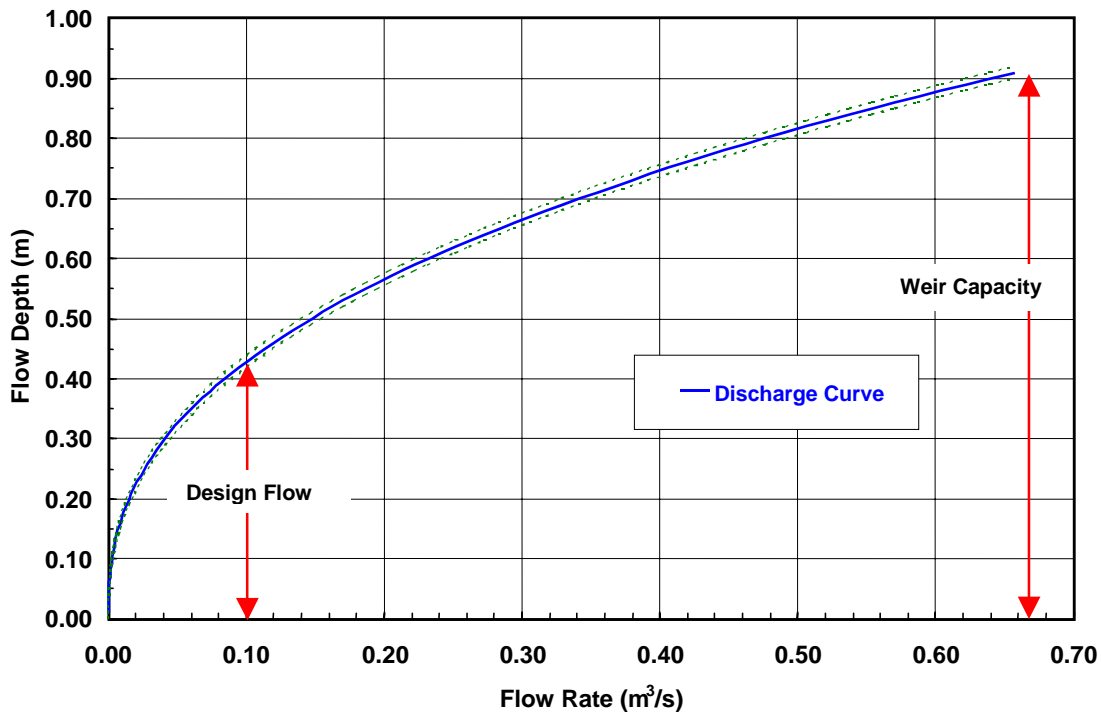
Equation [4.1] can be reduced by inserting the coefficient of discharge (0.605), the acceleration due to gravity ( $9.81 \text{ m/s}^2$ ), and the interior angle of the V-notch weir plate ( $60^\circ$ ). The coefficient of discharge was taken from Smith (1995) for a V-notch weir with a 2:1 width to height ratio. Equation [4.1] reduces to Equation [4.2]:

$$Q = 0.825169 h^{5/2} \quad [4.2]$$

Figure 4.3 shows the stage-discharge curve developed for the zero-height V-notch weir based on Equation [4.2].

The weir plate was installed inside a heated hut to minimize the formation of ice in the weir structure during spring melt, as shown in Figure 4.4. An automated flow measurement system was installed in the weir hut, comprised of an ultrasonic sensor installed above the upstream flow to measure the water depth and an air temperature probe to correct readings from the ultrasonic sensor. Measurements are collected every minute with maximum, minimum and average values output every hour. An example of the flow data from a V-notch weir at Syncrude is shown in Figure 4.5.

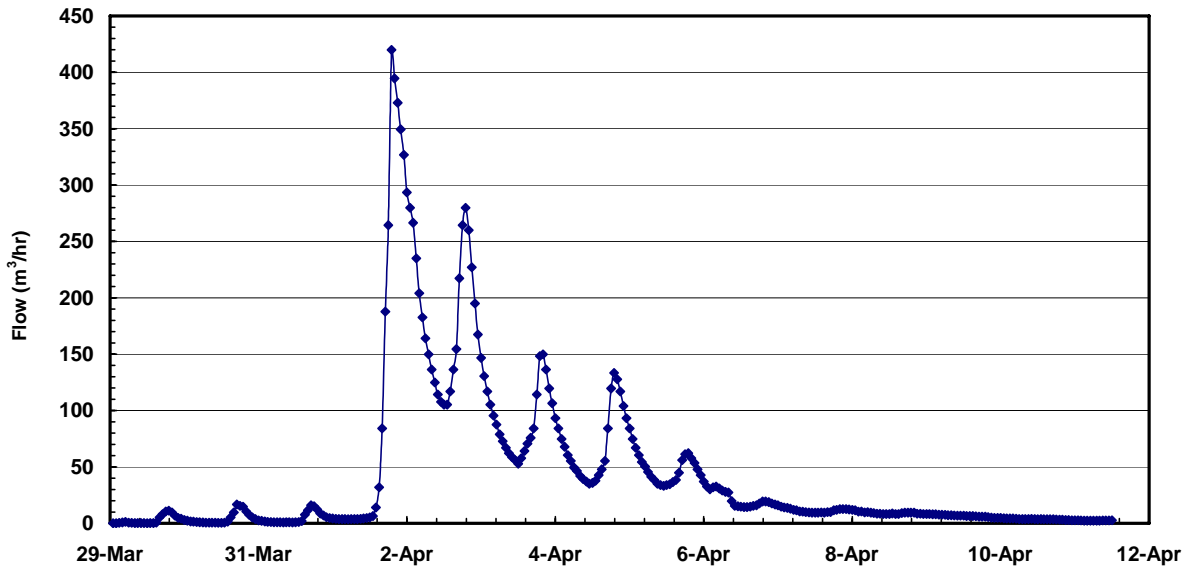
Appropriate riprap material with an underlying filter layer was placed upstream and downstream of the weir structure to prevent erosion of the channel bed.



**Figure 4.3** Stage (head) – discharge relationship for the Syncrude zero-height  $60^\circ$  V-notch weir.



**Figure 4.4** Photo of Syncrude V-notch weir during spring melt (photo provided by Syncrude).



**Figure 4.5** Flow data from 2005 spring melt at Syncrude Mildred Lake Operation measured with a zero height V-notch weir (data provided by Syncrude).

## LESSONS LEARNED

The quality of data obtained from surface runoff collection devices installed after cover construction is often questioned because the installation of such devices typically requires disturbance of the natural ground surface. As a result, it is often desirable to install a surface runoff collection and monitoring system immediately upon completion of a cover trial or full-scale cover to avoid disturbance of vegetation and the macropore structure that will eventually develop. In addition, the quantity of surface erosion should also be assessed as part of the same collection and monitoring system because of the connection between surface runoff and erosion.

Some of the greatest challenges in measuring runoff using weirs or flumes have to do with maintenance of the structure. Over the short term, the structures must be regularly inspected and maintained. During spring melt, even with heating, prevention of ice build-up is a challenge. Daily maintenance is required to prevent water from freezing and forming an ice dam at the V-notch. Sediment or debris build-up can also be a challenge, depending on the nature of the watershed. A build-up of sediment or debris must be promptly removed to ensure accuracy of the flow data. It is also beneficial to supplement the automated water level measurement system (e.g. ultrasonic sensor) with manual measurements to ensure integrity of the data.

Over the long term, erosion and flow bypassing the structure are major challenges for weir or flume structures. A combination of the changing shape of the stream channel and degradation of the structure can lead to some or all of the stream flow bypassing the weir or flume structure. Adequate quality control during construction of the weir structure and in particular, installation of the upstream cutoff and wing walls, as well as on-going maintenance and repair are required to prevent this from occurring.

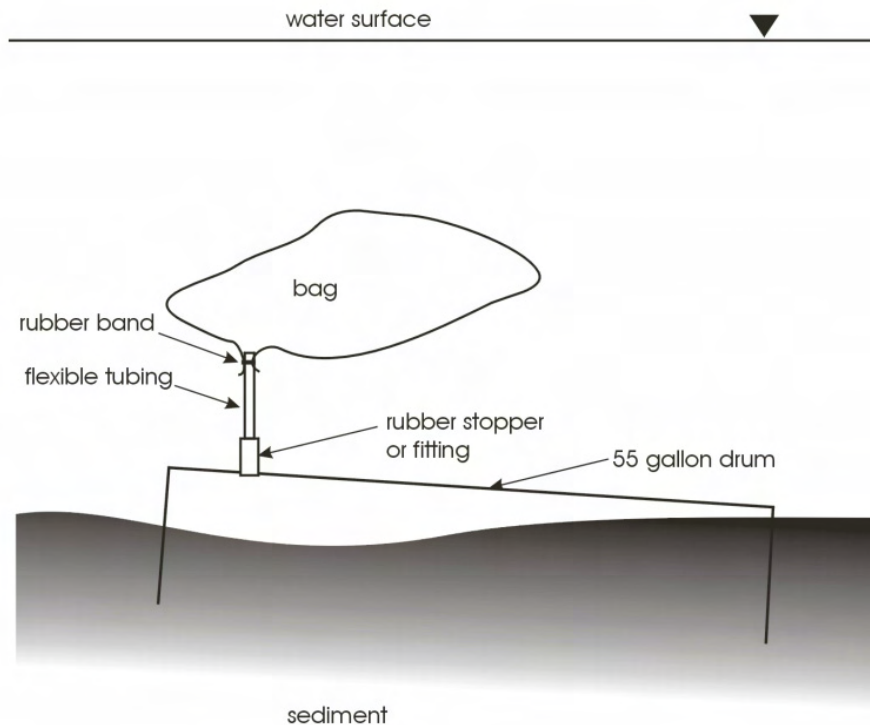
### *4.1.3 Pond Monitoring*

To understand watershed hydrology, it is important to monitor any ponds or surface water bodies that exist within the watershed. Water can be contributed to the ponds from precipitation, runoff, and seepage and can be removed from the ponds by seepage, outflow and evaporation. Typical hydrologic pond monitoring consists of water level measurement and seepage monitoring. Evaporation is usually estimated from pan evaporation rates measured as part of a meteorological monitoring program.

Water level measurement is typically done manually using a staff gauge or some other type of depth measurement. A staff gauge consists of a graduated post that is sunk into the centre of a pond to a depth that ensures that the post does not move from season to season. The depth of the water can be monitored by reading the graduation on the post that corresponds to the water level. This monitoring can often be completed from shore and should be done frequently. Automated depth measurement systems are available, although less common.

Seepage monitoring is less straightforward than water level monitoring. The goal of seepage monitoring is to measure the rate of seepage into or out of a pond. Mini-piezometers are sometimes used to track hydraulic gradients across the seepage face and then used to estimate the seepage face (Lee and Cherry, 1978). For direct measurement of seepage, seepage meters are the most commonly used method.

Seepage meters range from simplistic manual devices to complex automated devices. The most common seepage meter consists of one end of a 55-gallon drum inserted into the pond sediment (Lee, 1977), as shown in Figure 4.6. The drum is vented to a plastic bag. As seepage enters the drum from the sediments beneath, water is displaced into the plastic bag. The rate at which the plastic bag fills with water can then be used to calculate the seepage rate into the pond. If seepage is out from the pond, then the bag can be pre-filled with water and the rate at which the bag drains can be used to determine the seepage.



**Figure 4.6** Simple seepage meter (from Lee, 1977).

Although simplistic, these seepage meters require careful installation and regular monitoring to obtain good results. As shown in Figure 4.6, it is important to insert the 55-gallon drum at an angle with the vented side raised slightly. This allows any gases trapped during installation to vent prior to placing the bag on the outlet port (Lee, 1977). The bags must be sufficiently lightweight to allow the displaced water to open the bag, but must be durable enough to hold up during removal, placement, and transport. Balloons and condoms have been used with success

as well as bags. The bag volume must be chosen carefully and checked regularly to ensure that it does not reach capacity. Lee (1977), Lee and Cherry (1978), Boyle (1994), Lewis (1987), and Fellows and Brezonik (1980) give additional information on the use of this type of seepage meter.

It has been found that the barrel and bag type of seepage meters are somewhat prone to errors. Shaw and Prepas (1989) show that the rate of water displacement into the bag is not constant and is higher when the bag is empty and lower when it is close to full. They recommend that the bag be pre-filled with a small volume of water to increase accuracy of measurement. Belanger and Montgomery (1992) also discuss errors associated with bag type seepage meters based on the results of tank tests.

Complex automated seepage meters are also available. These have been developed largely for higher rate seepage fluxes or where a finer time resolution is required, such as for measuring tidal fluxes (Sholkovitz *et al.*, 2003). In general, these devices allow seepage to flow through a chamber where the flow rate is measured indirectly. Taniguchi and Fukuo (1993) and Taniguchi and Iwakawa (2001) developed a heat-pulse based instrument where flow rate is estimated by the timed transmission of heat pulses as measured by downstream thermistors in a flow tube (Sholkovitz *et al.*, 2003). An acoustic (ultrasonic) seepage meter has been developed by Paulsen *et al.* (2001), which is based on the timed perturbation of sound in a moving fluid (Sholkovitz *et al.*, 2003). Sholkovitz *et al.* (2003) use the timed dilution of dye, as measured by the change in absorbance of the fluid, to calculate the flow rate.

In typical watershed pond applications, the simple barrel and bag-type seepage meter typically give suitable results for water balance determinations.

## **CASE STUDY**

Seepage meters were installed in three ponds on a reclaimed saline-sodic overburden dump at Syncrude to obtain information about the subsurface flow patterns surrounding the wetlands. Seepage meters were used during the summers of 2000, 2001, and 2002. The seepage meter base consisted of the bottom third of a 45 gallon, thick-walled plastic drum. The seepage collection apparatus underwent a number of design changes as problems were encountered.

The original design of the seepage meter was similar to that shown in Figure 4.6. A removable stopper was placed in one of the bungholes of the barrel and a shutoff valve was inserted into the stopper. A piece of flexible plastic tubing was attached to the shutoff valve and a plastic bag partially filled with water was affixed to the tubing. The seepage barrel was pushed into the soil below the pond and air was allowed to exit the barrel before the bag attachment was added. As water infiltrated into the soil from the pond the barrel water drained from the bag. The bag, which was weighed previous to the installation, was then removed and re-weighed allowing calculation of an infiltration rate for the bottom of the pond. The main problems experienced with this design

were that the simple plastic bags were not durable and tore easily, predominantly due to the vegetation growing in the ponds.

Upon further research, it was decided to simplify the design to minimize movement or disruption that would influence the amount of water which accumulated in the collection bags. The modified design used the same base but used an HDPE barbed ¼" fitting inserted into a hole drilled into the barrel top. The barbed fitting was sealed with silicone to prevent leakage. The collection bag was a simple balloon that fit snugly over the fitting. A small known volume of water was poured into the balloon prior to placing it on the barrel base. Due to the low seepage rates of the ponds of this area, the balloon could be left for a week. The balloon was removed and replaced with a new one each week. The volume of seepage collected was measured directly in the field using a 100 ml graduated cylinder.

A total of 14 seepage meters were installed in three ponds on a single reclaimed watershed area. Meters were installed according to Lee (1977). Results showed that the general discharge/recharge behaviour was consistent; however, the exact seepage rates were quite variable.

## **LESSONS LEARNED**

One of the main lessons learned using seepage meters to determine seepage rates into and out of the ponds at the reclaimed overburden dump was that it was important that the base of the seepage meter be installed properly. This proved to be challenging at some of the installation locations due to a thick peat layer that made it difficult to obtain a proper seal. The excess material had to be cleared away to install the seepage meter into the till base to obtain an accurate reading. These instruments were also very labour intensive. Installation and collection had to be done manually, which involved wading into the soft ponds on a regular basis to take measurements.

### *4.1.4 Evapotranspiration*

Evapotranspiration is comprised of two components, evaporation and transpiration, both of which may influence the soil moisture content. Evaporation is an abiotic process occurring due to a vapour pressure gradient between the soil and the atmosphere. Transpiration is a biotic process that refers to the uptake and subsequent release of moisture into the atmosphere by plants.

A variety of methods are available for measuring evaporation and evapotranspiration rates from the ground surface. The most commonly utilized methods can be classified as direct measurement methods or micrometeorological methods. Atmometers, evaporation pans, and weighing lysimeters are the most widely used methods for direct measurement of evaporation and evapotranspiration. The most commonly used micrometeorological methods are the Bowen ratio energy balance method, the aerodynamic method, the mass transport method, and the Eddy

covariance method. These micrometeorological methods of measurement should be considered implicit as evaporative quantities are determined indirectly; that is, they are based either on principles of energy balance or mass transfer.

A review of the literature indicates that the three most popular methods of measuring evaporation and evapotranspiration rates are evaporation pans, weighing lysimeters, and the Bowen ratio energy balance method. Each of these methods is discussed in Appendix A, along with a brief discussion on the eddy covariance method.

## **CASE STUDY**

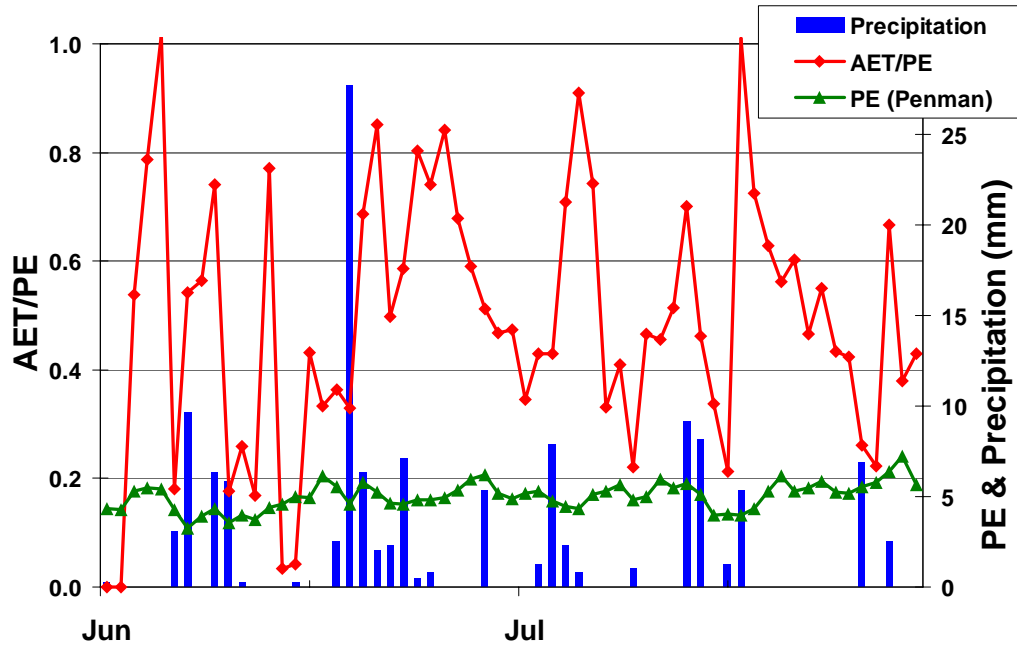
### *Bowen Ratio Energy Balance Method*

A Bowen ratio station and a Class A evaporation pan were installed as part of a field instrumentation program on reclamation soil covers over saline-sodic overburden at Syncrude (Boese, 2003). The Bowen ratio station was operational during the months of May through October and data were recorded every 20 minutes while it operated. The data set included measurements of wind speed, air temperature and vapour pressure at two heights, net radiation, soil heat flux, and soil moisture. The depth of water in the pans was measured and refilled every couple of days in the summer months of 2000 (June through September).

Routine maintenance of the Bowen ratio station equipment was extremely important to ensure the collection of accurate measurements. Every two weeks the filters in the air intakes were changed and the mirror in the hygrometer was cleaned. The level of the net radiometer was checked frequently and adjusted when needed. The fine-wire thermocouples were cleaned as necessary.

The evaporation pan also required frequent maintenance. During the summer months, the pan accumulated insects, sediment and vegetation brought by wind, and on some occasions, dead birds or mice. All of this debris will have an affect on measured evaporation rates.

The measured AET values from the Bowen ratio station were compared to PE values as calculated by the Penman (1948) method. The Penman (1948) method uses daily averages of wind speed, air temperature, and relative humidity and these were measured at the site by a meteorological station. The ratio of AET/PE was plotted for the months of June and July 2000 to verify if the Bowen ratio station responded correctly to atmospheric forcing conditions (Figure 4.7). During the monitoring period, the value of AET/PE fluctuates widely from 0 to 1.0 in response to available water. The average value of AET/PE was calculated to be 0.51, a reasonable value for a site of this nature and the Bowen ratio monitoring system was generally considered to be responding correctly.



**Figure 4.7** AET/PE ratio and precipitation for June and July 2000 (from Boese, 2003).

## 4.2 Sub-Surface Hydrologic Monitoring

Sub-surface hydrologic monitoring involves measuring and tracking the movement of water through the various soil layers of the watershed. Water that infiltrates into the ground surface may be utilized by vegetation, it may evaporate back into the atmosphere, it may move downslope as lateral drainage or interflow, or it may continue downwards as deep percolation or groundwater recharge. Measurement techniques for measuring soil moisture content, soil suction, net percolation, interflow, and groundwater are discussed in the following section. The last section (Section 4.2.6) discusses techniques for designing an efficient watershed monitoring system.

### 4.2.1 Soil Moisture Content

Measurements of soil moisture are fundamental to the development of a water balance for a watershed. Soil moisture profiles in the waste and cover layers allow the volume of water stored within the profile to be quantified, and can be interpreted to define the rates and direction of water movement in response to plant root uptake, evaporation, percolation, and interflow.

The five most common methods of measuring the *in situ* moisture content of soils are:

- 1) the gravimetric method;
- 2) the nuclear method;



- 3) time domain reflectometry (TDR);
- 4) frequency domain reflectometry (FDR); and
- 5) the electrical capacitance method.

The key details pertaining to each of these methods are summarized below, with complete details provided in Appendix A.

#### 4.2.1.1 Gravimetric Method

The gravimetric water content of a soil sample can be easily and accurately determined in the laboratory, as specified in ASTM D2216-92 (ASTM, 1992). A soil sample is dried to a constant mass in an oven at 110°C, until there is no more variation in the mass of the sample. The loss of mass due to drying is considered to be water. The gravimetric water content ( $w$ ) is computed using the mass of water ( $M_w$ ) and the mass of the dry sample ( $M_s$ ) where  $w = M_w/M_s$ . Gravimetric water content can be converted to volumetric water content by knowing the dry density of the soil.

#### 4.2.1.2 Nuclear Method

The use of the neutron moisture probe for measuring *in situ* soil water content was established in the agricultural industry (Gardner and Kirkham, 1952). However, in recent years environmental monitoring has increased the use of the neutron method to other fields. Wong (1985) successfully used a neutron moisture probe to measure the fluid content of potash tailings. O’Kane (1996) used this measurement technique to monitor the performance of an engineered soil cover system for sulphidic mine waste in terms of degree of saturation. The neutron moisture probe has gained wide acceptance because the method is non-destructive, relatively fast and can be performed at any time (Silvestri *et al.*, 1991). The disadvantage of the neutron method is that it cannot distinguish chemical species (e.g. leachate from water) (Kramer *et al.*, 1992).

Access tubes must be installed into the soil to use the neutron moisture probe. The material used for the access tube influences the results obtained from the neutron moisture probe (Keller *et al.*, 1990). Proper calibration of the neutron moisture probe is crucial to its successful use (Silvestri *et al.*, 1991). Calibration and measurement concerns arise due to the radius or sphere of influence (i.e. effective volume of measurement).

Other complications with the neutron moisture probe are related to the nuclear source. Operators of the probe must be trained to use the probe properly because there is a risk of exposure to radiation. The neutron moisture probe requires permitting and placards for transportation, and must be inspected annually to ensure that it meets all safety requirements.

#### 4.2.1.3 Time Domain Reflectometry

The early uses of time domain reflectometry (TDR) were in locating breaks in cables and transmission lines. Davis and Chudobiak (1975) moved the application of TDR to soils for the measurement of water content. Over the past 20 years, TDR has been used extensively in the fields of agriculture (Davis and Annan, 1977; Topp and Davis, 1985), geotechnical engineering (Look and Reeves, 1992; Kaya *et al.*, 1994) and environmental monitoring (St-Arnaud and Woyshner, 1992; Benson *et al.*, 1994; Ayres, 1998). This measurement technique has gained wide acceptance because it measures *volumetric* water content in a non-destructive manner, provides an immediate result, and can be automated.

TDR measures the apparent dielectric constant ( $K_a$ ) of the soil surrounding the probe.  $K_a$  is strongly dependent on the volumetric water content ( $\theta_w$ ) of the soil because of the large difference in the various components of the soil ( $K_{air} = 1$ ;  $K_{soil} \approx 5$ ; and  $K_{water} \approx 80$ ). It is important to note that TDR only gives an indication of the volumetric *liquid* water content of soils because the dielectric constant of ice is approximately 3.2 (Spaans and Baker, 1995).

Instrumentation for measuring the apparent dielectric constant of soils generally consists of a multi-wire probe connected to a TDR device via a coaxial cable. The major components of a TDR device are a pulse generator, a timing control, a sampling receiver, and an oscilloscope to display the reflected voltage pulse. A variety of TDR probes are available, such as the standard laboratory coaxial cell, the parallel two-wire probe (Topp *et al.*, 1980), and the coaxial emulating three-wire and four-wire probes (Zegelin *et al.*, 1989). Several probes may be connected to a multiplexer and datalogger system for continuous monitoring of soil moisture content (Baker and Allmaras, 1990).

TDR probes may be installed in a soil profile horizontally, vertically, or any orientation depending on the application (Zegelin *et al.*, 1992). All orientations will give the water content in the soil averaged over the length of the probe. Vertically oriented probes are the easiest to install, but preferential flow of water and heat alongside the probe wires is a concern. Horizontal probes require excavation of a pit with the probes inserted into one or more walls of the pit at required depths. The major advantage of horizontal probes is that they give water content in a horizontal plane, which allows for the accurate determination of water content profiles. The installation of all probes must be performed carefully to minimize the formation of air gaps around the wires because probe sensitivity is highest in the immediate vicinity of the probe wires (Zegelin *et al.*, 1992).

#### 4.2.1.4 Frequency Domain Reflectometry

The theory behind the measurement of *in situ* moisture content of soils and other fine-textured materials using frequency domain reflectometry (FDR) is similar to that of the TDR method. FDR systems measure the apparent dielectric constant of soils by measuring the change in a radio wave frequency as it passes through the soil (Bilskie, 1997). A factory or “universal” calibration equation supplied with the FDR sensor is used to convert the frequency readings into volumetric water content readings.

FDR measurement systems are similar to that of the TDR measurement system described above. Two-wire probes are generally installed horizontally into the soil profile and subsequently connected to a multiplexer and datalogger system for continuous monitoring of *in situ* moisture content. As with TDR measurement systems, all FDR measurement systems should be calibrated in the field to facilitate the collection of quantitative *in situ* moisture content data, in particular for high clay and organic matter soils (Veldkamp and O'Brian, 2000).

The FDR has the ability to detect bound water in fine soil particles that is still available to plants, which is ideal at a site that is primarily fine-textured. The FDR is less susceptible to soil salinity errors but can be more susceptible to changes in temperature, bulk density, and the presence of air pockets.

#### 4.2.1.5 Electrical Capacitance

Capacitance sensors use the dielectric properties of soil to measure water content. The capacitance sensor is essentially a capacitor that incorporates the soil as the dielectric medium. A high frequency electrical field, created around the sensor, extends into the soil. The magnitude of the frequency is a function of the apparent dielectric constant of the soil, which is dependant on the water content. The more water in the soil, the higher the  $K_a$  value and the lower the frequency measured by the sensor. Additional information on the theory behind the capacitance sensor can be found in Dean *et al.* (1987), Paltineau and Starr (1997), Lane and MacKenzie (2001), and Gaskin and Miller (1996).

A variety of capacitance sensors are available. Some sensors can be inserted directly into the soil, while others require the installation of a PVC access tube. Both manual and automatic data logging capabilities are available. Typically, the sensors that require an access tube are more suitable for watershed-scale monitoring, as they can monitor to greater depths and at various depths within the same location. As with TDR and FDR sensors, capacitance sensors require calibration for the given soil type (Baumhardt *et al.*, 2000; Morgan *et al.*, 1999; and Geesing *et al.* 2004). The readout of this sensor is not linear with water content and is influenced by soil type and soil temperature, therefore; calibration of the instrument is extremely important. Because

careful calibration is needed, the long-term stability of the calibration is questionable (Zazueta and Xin, 1994).

Some types of capacitance sensors can be used as a portable moisture sensor, similar to the nuclear moisture probe. The benefits of the capacitance method compared to the nuclear probe are that the sensor does not use a radioactive source and measurements can be taken very quickly with good reliability.

#### 4.2.2 *Soil Suction*

The three most common methods used to measure soil suction in the field are tensiometers, thermal conductivity sensors, and electrical resistance sensors (i.e. gypsum blocks). All three methods provide a field measurement of matric suction, which along with osmotic suction (reduced chemical energy in the water due to the presence of dissolved salts (Barbour and Fredlund, 1989)) are the two components of total suction. The key details pertaining to each of these methods are summarized below, with complete details provided in Appendix A.

##### 4.2.2.1 Tensiometers

Tensiometers provide a direct measurement of the negative pore-water pressure (or matric suction, assuming the pore-air pressure is atmospheric) in a soil. The tensiometer consists of a porous ceramic, high air-entry cup connected to a pressure measuring device through a small bore capillary tube. The pressure sensor may be a manometer, vacuum gauge, or pressure transducer (Stannard, 1992). The tube and the cup are filled with de-aired water. The cup is inserted into a pre-drilled hole to provide intimate contact with the soil. After equilibrium has been achieved, the water in the tensiometer has the same negative pressure as the pore-water in the soil. The suction that can be measured at the tip of the tensiometer is limited to a maximum value of 80 or 90 kPa due to the onset of cavitation in the water (Fredlund and Rahardjo, 1993).

##### 4.2.2.2 Thermal Conductivity Sensors

Thermal conductivity sensors were developed in the agricultural field some years ago (Phene *et al.*, 1971a and 1971b), and were primarily used to assist in irrigation scheduling (Phene *et al.*, 1989). The application of this soil suction measurement technique in geotechnical engineering was recognized nearly two decades ago. Sattler and Fredlund (1989) describe the use of thermal conductivity sensors in the laboratory for measuring matric suction of Shelby tube samples. O’Kane (1996) successfully used this measurement technique to monitor the performance of an engineered soil cover system for sulphidic mine waste.

A thermal conductivity sensor generally consists of a porous ceramic block containing a temperature sensing element and a heater. The porous ceramic block has a wide pore-size

distribution that allows water from the surrounding soil to flow in and out of the sensor until equilibrium is reached. The soil matric suction is determined by first measuring the temperature of the ceramic block, then heating the ceramic block for a specified period with a small constant current, and measuring the temperature after heating. Essentially, this procedure measures the rate at which the heat pulse is dissipated into the ceramic block by measuring the difference in temperature before and after heating. The amount of water in the ceramic block affects the heat capacity and heat dissipation within the block such that the rate of heat dissipation increases with water content.

A relationship also exists between the water content in the porous block and matric suction. Hence, the temperature difference in the ceramic block is calibrated in the laboratory against applied levels of matric suction. In general, a laboratory developed soil-water characteristic curve should be obtained for each thermal conductivity sensor installed in the field because of the uniqueness of each ceramic block. Thermal conductivity sensors are most accurate in the range of approximately 10 to 1,000 kPa (Scanlon *et al.*, 2002).

#### 4.2.2.3 Electrical Resistance

Electrical resistance methods have been used for many years in the agricultural industry to provide an indirect measurement of the matric suction in soils. The most common electrical resistance sensor is a gypsum block sensor where two electrodes are embedded in a porous block of gypsum plaster. The measured electrical resistance between the two electrodes is a function of the water content in the gypsum block, which can be converted to matric suction through laboratory calibration. Gypsum blocks are relatively inexpensive and can be connected to an automated data acquisition system for continuous monitoring of matric suction.

There are; however, a number of problems commonly encountered when using gypsum blocks, especially in saline (Phene *et al.*, 1971a) or acidic environments. Each block possesses slightly different characteristics and must be individually calibrated. Eventually the gypsum will dissolve into the soil. As well, the presence of dissolved salts in the pore-water affects electrical conductivity independently of water content. The gypsum, used to mask variations in soil salinity, eventually dissolves, resulting in an unstable matrix for the sensor. Acidic pore-waters also dissolve the gypsum block. Gypsum blocks also exhibit hysteresis that can significantly reduce sensitivity to sudden wetting and drying conditions. Gawande *et al.* (2003) provide a comparison of electrical resistance methods to other methods of water content measurement. As the sensor degrades, the calibration changes with time, which may result in inaccurate readings over time.

### 4.2.3 Net Percolation

Net percolation is a critical facet to understanding the water balance of a watershed. Often, net percolation is required to evaluate the effectiveness of a soil cover over reactive waste. Despite the importance of this parameter, it is often not given due consideration when planning for an instrumented watershed.

Detailed analyses of the hydraulic gradients within the cover layers and underlying waste material can be used to determine the net percolation through a cover system. Hydraulic head measurements in the cover and waste materials can be obtained by one of the methods described in this manual for measuring *in situ* soil suction (Section 4.2.2). Suction data can be combined with soil hydraulic conductivity data and the respective soil-water characteristic curve to calculate a value of net percolation.

The preferred method is the installation of a lysimeter, often placed below the reclamation cover layer. This instrument should not be confused with a weighing lysimeter, which is described in Appendix A for measuring actual evapotranspiration. In general, the design and installation of lysimeters to monitor evaporative fluxes as well as net infiltration is well understood and implemented in the soil science discipline; however, the design of lysimeters for field monitoring programs in the mining industry have typically not included fundamental aspects of lysimeter design as established in the soil science literature. The key elements for designing a field lysimeter are outlined in Appendix A based on information in Bews *et al.* (1997) and O’Kane and Barbour (2003).

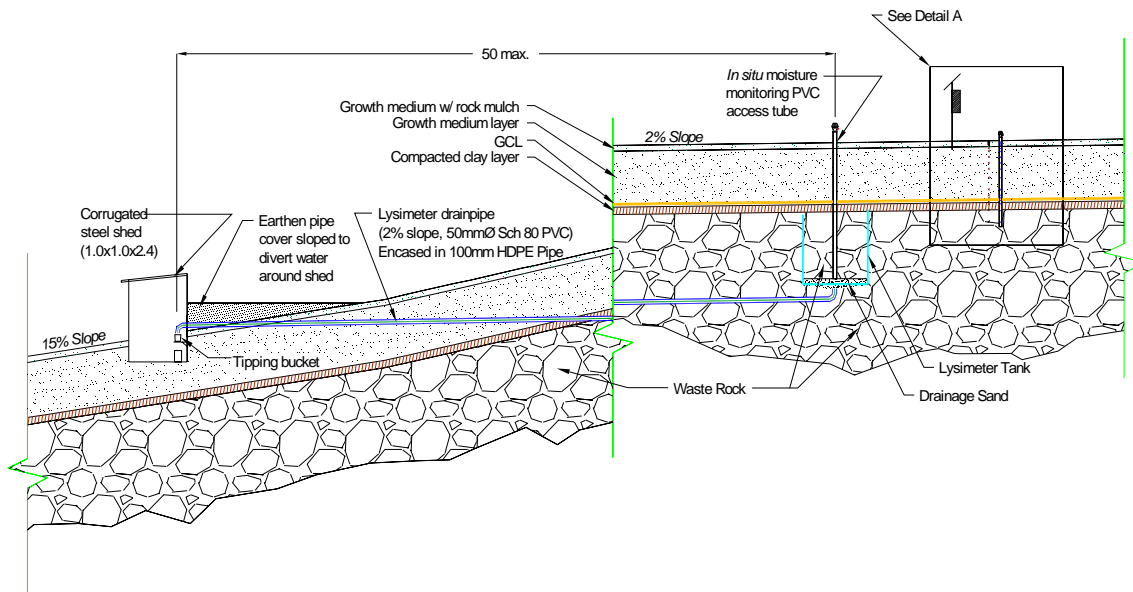
A state-of-the-art field lysimeter, shown schematically in Figure 4.8, is typically comprised of the following components:

- Net percolation collection tank;
- *In situ* moisture monitoring system;
- Underdrain system; and
- Net percolation monitoring system.

Further details on each of the above lysimeter components can be found in Appendix A.

Field lysimeters should be installed prior to placement of the cover or reclamation layers on the watershed. In general, lysimeter tanks are installed at or a short distance below the cover/waste material interface. The lysimeter tanks should also be installed in representative areas of the watershed (i.e. locations where the potential inflow of meteoric waters will be representative of the watershed). For example, if a lysimeter is being installed on a slope, one could argue that, in general, the lysimeter should be located somewhere between the toe and mid-point. Installation of a lysimeter near the crest of a sloping cover system may underestimate the net percolation

because a smaller volume of water may be transmitted down-slope to this location. The desired or optimum locations for the lysimeters should be determined following a two-dimensional saturated-unsaturated flow modelling exercise.



**Figure 4.8** A state-of-the-art field lysimeter for measuring net percolation. Note: tank depth and dimensions must be tailored to each specific site.

## CASE STUDY

Two net percolation collection and monitoring systems (i.e. tank lysimeters) were installed on a Syncrude watershed investigation site for evaluating the quantity and quality of percolating water as well as the gas concentrations through two cover system field trials. Each system is comprised of the following components:

- Net percolation collection tank;
- *In situ* moisture and gas monitoring; and
- Piezometer for water level measurement, sample collection, and water removal.

The net percolation collection tank, which is the main component of the lysimeter, consists of a circular plastic storage tank. These prefabricated plastic tanks, which have a diameter of 2.4 m and a height ranging from 2.5 m to 3.0 m, were modified by local contractors by removing the top dome-shaped portion of the tank.

The base of the tank of each lysimeter was installed 2.5 m below the waste/cover material interface. A tracked backhoe was used to create the excavations in the waste material. As the

material was being excavated, *in situ* density and moisture conditions were measured at approximately 0.5 m lifts using a nuclear densometer.

Both the tank and the excavation around the tank were backfilled simultaneously. The waste material was placed in 0.5 m lifts and compacted with a plate tamper. A nuclear densometer was used to measure the density and moisture content after compaction of each lift to ensure that the conditions were similar to *in situ* conditions. The objective of the tank backfilling exercise was to create a material profile inside the tank similar to the material profile outside the tank.

A piezometer and an *in situ* monitoring system were installed within both net percolation collection tanks. The piezometer allows for measuring the net percolation rate by monitoring the depth of water that collects in the bottom of the tank, and removing the water as needed. Water samples can also be obtained. An access tube for soil moisture monitoring was installed along with a series of gas ports for *in situ* monitoring of temporal and spatial changes in O<sub>2</sub>/CO<sub>2</sub> gas concentrations in the tank backfill. Once the first 0.5 m lift was placed, shovels were used to excavate two holes to the bottom of the tank, one at the centre and one between the centre and the wall. The piezometer was placed in the excavation in the centre of the tank, and the deep moisture monitoring pipe was placed in the excavation between the piezometer hole and the edge of the tank. The purpose of re-excavating the holes was to provide an anchor for the bottom of the pipes to ensure they were not shifted during the backfilling process. A shallow excavation near the wall was made to place the deepest gas sampling port. As the remainder of the tank was backfilled, the material was carefully compacted around the instrumentation and the gas sampling ports were placed at various depths.

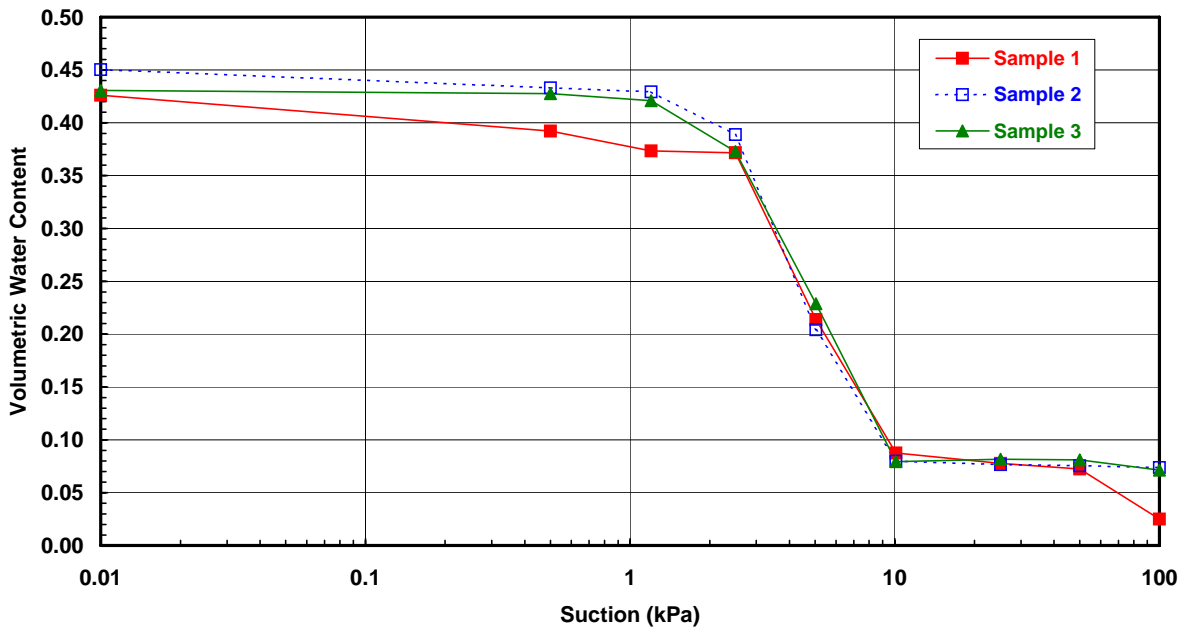
The piezometer consisted of 50 mm PVC pipe with a 30 cm slotted section at the bottom. The slots were covered with a filter sock to prevent particulates from entering the piezometer. As water percolates through the cover and the underlying material, it eventually reaches a zero pressure condition and starts to pool at the base of the lysimeter tank. The pooled water can then be monitored inside the piezometer to determine the volume of water that has percolated over a given time period. Typically, a water level indicator is used to measure the depth of water in the tank. Once the water level has been determined, the water is removed using either a manual bailer or a pump. At this point, samples of the water can be taken for laboratory analysis.

A numerical analysis was completed to determine the optimum depth of the lysimeter over a range of potential net percolation conditions. The numerical analysis was based on determining the depth of lysimeter required to ensure that the pressure head at the top of the lysimeter tank was the same as the surrounding material to prevent water from bypassing around, or preferentially flowing into, the lysimeter. To calculate the pressure head for various percolation rates, the soil-water characteristic curve and the saturated hydraulic conductivity of the waste material and cover materials were required. Using the soil-water characteristic curve and the saturated hydraulic conductivity, it was possible to estimate the hydraulic conductivity function



using the Fredlund and Xing method as utilized by the program SEEP/W (Krahn, 2004). The measured soil-water characteristic curve of the waste material is shown in Figure 4.9, the measured saturated hydraulic conductivity values are provided in Table 4.1, and the estimated hydraulic conductivity function is presented in Figure 4.10.

A range of percolation rates was used in the analysis to represent the maximum and minimum percolation rates that might occur at the watershed. The maximum percolation rate was assumed to be the saturated hydraulic conductivity of the cover material ( $1.3 \times 10^{-5}$  cm/s), because this is the maximum rate at which the cover can transport water. The minimum percolation was calculated assuming that 2% of precipitation would infiltrate through the cover, assuming annual precipitation of approximately 500 mm; the minimum percolation rate is  $3.2 \times 10^{-8}$  cm/s.

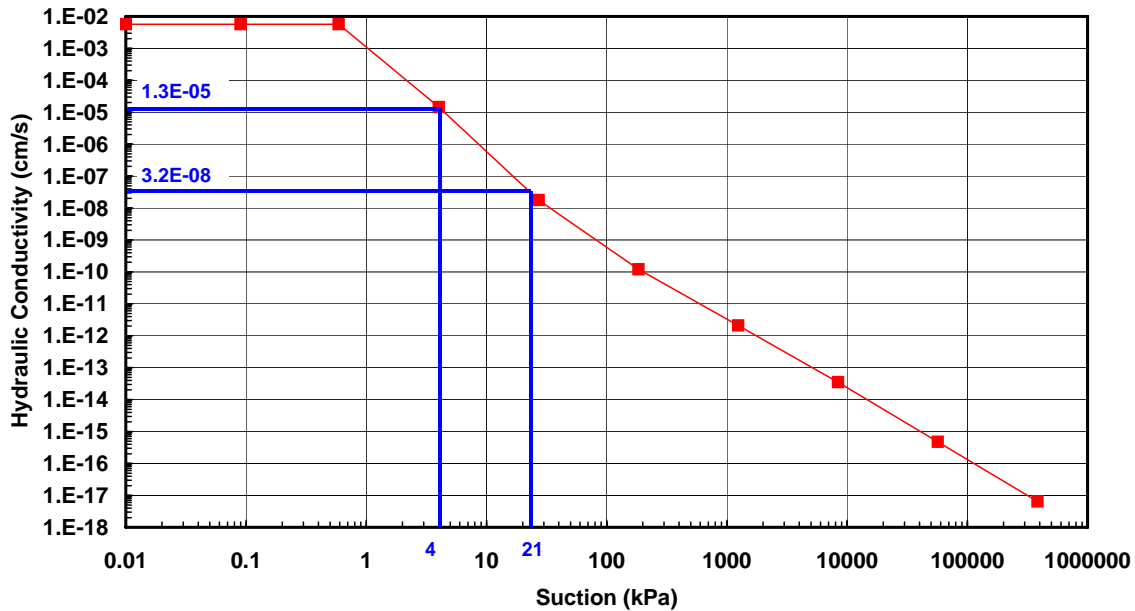


**Figure 4.9** Soil-water characteristic curve for the Syncrude waste material.

**Table 4.1**

Measured saturated hydraulic conductivity (cm/s) for the Syncrude waste material.

Sample 1	Sample 2	Sample 3
$7.85 \times 10^{-3}$	$8.26 \times 10^{-3}$	$1.96 \times 10^{-3}$
$7.99 \times 10^{-3}$	$6.21 \times 10^{-3}$	$2.43 \times 10^{-3}$
$8.08 \times 10^{-3}$	$5.75 \times 10^{-3}$	$2.98 \times 10^{-3}$
	$5.77 \times 10^{-3}$	
$7.97 \times 10^{-3}$	$6.74 \times 10^{-3}$	$2.46 \times 10^{-3}$



**Figure 4.10** Estimated hydraulic conductivity function for the Syncrude waste material using the program SoilCover.

The vertical portion of the pressure head profile occurs when the hydraulic gradient is equal to 1.0. Using Darcy's Law for flow:

$$q = -ki \quad [4.3]$$

where  $q$  is the flow rate (cm/s),  $k$  is the hydraulic conductivity (cm/s), and  $i$  is the hydraulic gradient, it can be seen that if  $i$  is equal to 1.0, then  $q$  is equal to  $-k$ . Therefore, when the pressure head profile is vertical, the hydraulic conductivity is equal to the flow rate (net percolation rate). This allows the suction to be estimated at the point at which the pressure head profile is vertical by using the hydraulic conductivity function. The net percolation (or flow) rate is found on the y-axis and, from the curve, suction can be estimated. For the maximum net percolation rate ( $1.3 \times 10^{-5}$  cm/s), the suction condition is equivalent to 4 kPa. For the minimum net percolation rate ( $3.2 \times 10^{-8}$  cm/s), the suction condition is equivalent to 21 kPa. Below the vertical portion of the pressure head profile, the pressure head follows the hydrostatic line. At hydrostatic conditions, the pressure head is equal to the elevation head. By converting the suction to a pressure head, the equivalent elevation head can be determined using the following equation:

$$h_z = h_p = \frac{\psi_m}{\rho g} \quad [4.4]$$

where  $h_z$  is elevation head (m),  $h_p$  is pressure head (m),  $\psi_m$  is matric suction (Pa),  $\rho$  is the density of water ( $\text{kg/m}^3$ ), and  $g$  is acceleration due to gravity ( $\text{m/s}^2$ ). For example, as 1 m of water is equivalent to 10 kPa, a suction of 5 kPa is equivalent to approximately 0.5 m of pressure head, and therefore equivalent to 0.5 m of elevation head. Knowing the elevation head allows the location of the break to be determined, which in this case would be 0.5 m above the water table. Using the maximum percolation rate example, the break in the lysimeter tank would occur 0.5 m above the base of the tank. Therefore, to ensure that the pressure head profile is vertical at the top of the tank, the tank must be deeper than 0.5 m. For the minimum percolation rate ( $3.2 \times 10^{-8}$  cm/s), where the suction condition is 21 kPa, the break would occur 2.1 m above the water table.

A depth of 2.5 m was chosen as reasonable for the Syncrude lysimeter tanks. This depth was chosen to ensure that the pressure head profile is vertical at the top of the tank regardless of the net percolation rate. Extra height was allowed so that if ponding of water occurs in the base of the tank, the location of the break in the pressure head profile will not rise above the top of the tank. The maximum depth of water that should be allowed to collect in the bottom of the lysimeter tanks is 0.25 m.

The tank chosen for installation was 2.5 m deep by 2.5 m in diameter. The large diameter is beneficial so that the backfill material can be placed and compacted to a condition as close as possible to the *in situ* material. A large diameter also allows a greater sample of material to be placed in the tank, thus allowing for some heterogeneity in material as might be encountered outside of the tank. The diameter is considered “large” for the materials backfilled. Note that for coarser material, or one that possesses much larger particles (e.g. run-of-mine waste rock), it could be argued that the cross-sectional area of the lysimeter should be even larger than that for a 2.5 m diameter tank. However, at no point should it be considered that the lysimeter can be shallower just because it possesses a substantial cross-sectional area.

## **LESSONS LEARNED**

A number of factors are important to consider when choosing a lysimeter design. Although the design with an underdrain system gives excellent high resolution net percolation data, the design is not only more costly, but can pose potential difficulties for monitoring and maintenance due to the confined space of a manhole or shed. However, without an underdrain system, net percolation data are more difficult to collect and interpret.

For lysimeters without an underdrain system, it is important to monitor the water level regularly, especially after storm events, to increase the accuracy of the predicted net percolation rate. It is also important not to allow the tank to collect too much water. The ponded water forms an artificial phreatic surface inside the tank, which affects the suction conditions of the material profile through the tank. If the phreatic surface is too high, then the suction conditions inside and

outside the tank may be different, causing a gradient to allow water to either flow into, or out of, the tank, which will lead to net percolation rates not representative of actual conditions.

#### 4.2.4 Interflow

Water that enters the soil surface may percolate downwards until it reaches a less permeable layer, at which point it may start to move laterally down-slope. Interflow often occurs in covers where either the underlying waste or a compacted cover layer is less permeable than the soil layer above. In natural systems, interflow may occur in the more permeable topsoil layer. Quantification of the interflow is especially important for estimating percolation rates into underlying waste material, and it is also useful to understand the contribution of interflow as seepage into swales or ponds in the watershed.

Measuring interflow is typically accomplished by placing a subsurface drainage system at an appropriate location on the watershed. In small-scale interflow monitoring, a drainage channel is typically placed at the bottom of a test plot during construction. This drainage channel is placed just below the elevation of the permeable layer. The channel is often lined with a geomembrane and weeping tile to transport the water to an outlet. The outlet must daylight further down-slope, and the interflow is monitored using tipping buckets or collection barrels. For watershed-scale monitoring, interflow becomes more challenging because there are multiple locations to monitor and interflow rates may vary dramatically over the various monitoring locations on the watershed.

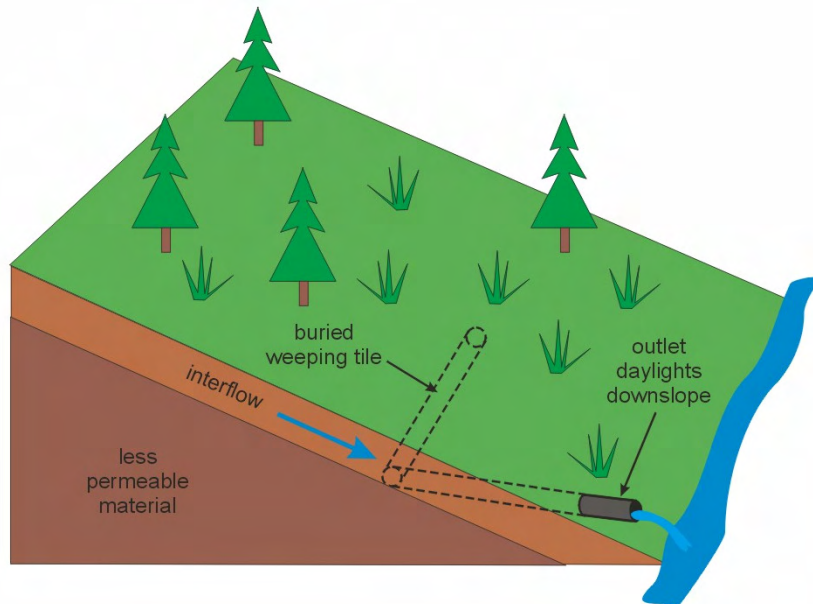
Subsurface drainage systems are common in agriculture as a method of controlling flooding and maintaining moisture conditions suitable for crop growth in humid climates (Sands, 2001). These systems are similar to interflow collection channels; the major difference is that drainage systems are put in place to *alter* the subsurface hydrology, where the goal of interflow monitoring is to measure interflow *without altering* the subsurface hydrology. Many of the methods and guidelines for subsurface drainage techniques can be applied to designing an interflow monitoring system but care must be taken that the monitoring system does not alter the natural drainage regime. Most monitoring systems have an impact on the systems they measure, despite all efforts to avoid it. As such, it is more reasonable to design a system that minimizes the impact, rather than one that has no impact at all.

Subsurface drainage systems are typically located at a number of locations over a watershed area. A typical agricultural subsurface drainage system consists of buried drainage pipes or weeping tile installed at a depth of 80 to 100 cm, with a spacing between the pipes at 6 to 25 m, depending on the soil type and drainage requirements (Zucker and Brown, 1998). Agricultural drainage attempts to maximize drainage and therefore the layout of the drainage may be in a uniform pattern over an entire field, or it may target specific areas where drainage is poor. In general, drainage systems run parallel to topographic contours so that the drains intercept the water flow (Wright and Sands, 2001).

Like a subsurface drainage system, the layout of an interflow monitoring system would be dependent on the topography and drainage patterns of the watershed. However, the goal of an interflow monitoring system is not to drain the soil, simply to monitor it; therefore, a single weeping tile drain may be installed in a given area, as opposed to a series of closely spaced drains. Like a subsurface drainage system, it is important to align the drain parallel to the topographic contour of the area, so that the drain runs perpendicular to the flow of water.

Both subsurface drainage systems and interflow collection systems require some type of outlet. Ideally, there is sufficient grade below the elevation of the interflow pipe for the pipe to daylight further down-slope (Figure 4.11). In relatively flat areas, this may not be possible, and the interflow may have to drain into a sunken collection barrel. If possible, the outflow should be directed towards the swale or pond where it can drain without collection. This lessens the impact of removing the water from the water balance of the watershed.

Monitoring the interflow rate depends largely on the quantity of interflow and the resolution of measurements required. Automated monitoring is easy to achieve for outflow pipes that daylight downslope. A tipping bucket can be used with a datalogger to collect flow data. A shed would be required to protect the automated monitoring system. If the outflow pipes do not daylight, then automated monitoring is more difficult. It is possible to install a manhole with a tipping bucket measurement system along with a pump to pump the interflow water back to the surface. This system would require a source of electrical power.



**Figure 4.11** Illustration of interflow system where outlet daylights downslope.

Manual measurements are more cost effective, and the resolution of the data is sufficient for most watershed water balances. The outflow water can be collected in a barrel located either at the outlet of the pipe or in a sunken barrel. The volume of water collected must be routinely measured and drained or pumped out of the barrel. This method allows for easy sampling but does not provide information on interflow response to short term precipitation events unless the collection barrel is monitored on a daily basis.

Similar to weirs, or other runoff flow measurement, interflow measurement systems are prone to freezing. Depending on the depth of the interflow, flow may continue into the fall/winter after the surface soils are frozen. Shallow interflow that occurs in the spring may also be susceptible to freezing when temperatures drop below zero overnight. Sunken collection barrels are insulated by the frozen soil surrounding them, and so thaw slower than the shallow soil contributing the interflow. The barrels may have to be thawed in the spring so that water entering the barrel can be measured. Automated tipping bucket measurement systems or surface collection barrels may require a heated hut to prevent freezing.

Another potential pitfall in interflow measurement is long-term maintenance of the drainage channel. As in agricultural subsurface drainage systems, the weeping tile can slowly fill with soil or become plugged with roots. These problems can often be avoided provided the drainage system is protected with an envelope or filter. Envelopes or filters are often a geotextile, granular material, organic material, or a combination of these. More information on design of envelopes and filters for drainage systems, as well as general information on agricultural drainage systems, can be found in Wright and Sands (2001), Ritzema *et al.* (1996), Zucker and Brown (1998), and Irwin (1997).

#### 4.2.5 Groundwater

The interaction of surface water and groundwater is another important component of the watershed water balance. Perched water tables and groundwater flow add complexity to large-scale water balances. Groundwater monitoring is typically well understood, and therefore, this manual will not go into great detail on groundwater monitoring methods.

The most common method of monitoring groundwater levels is with a standpipe piezometer, usually constructed of PVC pipe with a lower screened or slotted portion that allows water to flow into the pipe. Borehole drilling or augering must be used to install the piezometer at depth. Sand is placed around the slotted end and the rest of the annulus around the pipe is sealed with grout isolate the intake. Details on the design and installation of piezometers can be found in Freeze and Cherry (1979) and Maidment (1993).

The difficulties associated with groundwater monitoring for watersheds on reclamation material are similar to those for natural landscapes. Significant changes in material layers can create a

complex subsurface hydrology that is difficult to quantify. Installation of the monitoring equipment can be challenging when access is limited and soils are unstable. Some challenges, however, are unique to the mining industry. Historic practices of disposing refuse or old equipment in pits or waste rock dumps can pose a problem when trying to drill through the material.

#### 4.2.6 *Monitoring Locations and Sensor Placement Guidelines*

Reclamation landscapes, and the resulting watersheds, are topographically and geologically complex due to their very nature, and consequently can have complex hydrology. Soil moisture conditions, runoff rates, evaporation and transpiration rates, etc. may be strongly tied to slope position and aspect. The biggest challenge in watershed monitoring is determining where to monitor and how frequently to monitor.

In developing a monitoring plan, it is most helpful to first clearly define what the monitoring data will be used for. Are net percolation rates needed to determine reaction rates and total contaminant loadings? Is erosion a major concern with expected runoff rates? Is the development of sustainable vegetation the key parameter, where available water over the growing season is a critical value? Is it important to understand the groundwater regime to predict contaminant transport?

Each of these, taken individually or in combination, define the needs of the monitoring plan. Generally, the following details should be taken into consideration when installing a watershed monitoring system:

- *In situ* moisture content and soil suction sensors should be installed throughout the cover/waste profile, but should be concentrated around interfaces in the profile (e.g. cover-atmosphere interface, growth medium layer-barrier layer interface, barrier layer-waste material interface). Suction sensors located above and below a given interface allow hydraulic head gradients to be computed, thus allowing the direction of moisture flow to be determined.
- *In situ* moisture content and soil suction sensors should be installed adjacent to one another to facilitate the development of a 'field-based' soil-water characteristic curve for each layer in the cover/waste profile.
- A watershed monitoring program should have one or two detailed or primary instrumentation sites along with several secondary monitoring sites. For example, a primary instrumentation site may include automated *in situ* moisture content and suction sensors, an access tube for manual *in situ* moisture content measurements, *in situ* gas sampling ports, a lysimeter, and a fully automated meteorological station. The primary and secondary instrumentation sites should be located such that they reflect the variable conditions influencing performance of the watershed. For example, if slope orientation is thought to strongly influence evaporation and

vegetation conditions (i.e. a north facing slope will possess different performance characteristics than a south facing slope) then more than one slope aspect should be monitored. Other factors that can influence the location of a monitoring site include slope angle, runoff and run-on conditions, slope length, elevation of the monitoring location (if the site is in a mountainous terrain), reactivity of the underlying material, and texture of the underlying material. A secondary monitoring site may only consist of an access tube for manual measurement of the *in situ* moisture conditions; however, this will at least give some indication of the potential spatial variability of conditions in the watershed. In addition, incorporation of the manual measurement method at the primary site will provide some correlation/validation for the data obtained at the secondary monitoring sites.

### **4.3 Soil Characteristics and Physical Properties**

Field characterization of soil properties involves evaluating both the micro- and the macro-scale soil characteristics of the watershed. Micro-scale soil characteristics include soil temperature and pore-gas concentrations, while physical properties include field hydraulic conductivity ( $K_{fs}$ ), bulk density ( $\rho_b$ ), specific gravity ( $G_s$ ), and particle size distribution. Macro-scale soil characteristics include changes in topography due to subsidence and erosion. Measurements of most micro-scale soil properties such as bulk density, specific gravity, and particle size distribution, are well understood and are not discussed in detail in this manual. Soil temperature monitoring is often included in *in situ* soil monitoring along with moisture content and suction as discussed in the previous section. Field hydraulic conductivity and soil pore-gas concentrations, both of which are *in situ* measurements, are discussed in detail in the following section. Lastly, macro-scale soil properties relating to topography and how this varies over time due to subsidence and erosion is discussed.

#### **4.3.1 Soil Temperature**

The temperature of the soil profile defines the presence of freezing conditions, provides an indication of geochemical activity, and highlights critical temperatures for plant germination and growth.

Measurement of soil temperature is relatively straightforward. A soil temperature sensor is either permanently buried or temporarily inserted in the soil at the depth of interest and a temperature is measured. The most commonly used sensors for measuring soil temperature are thermocouples or thermistors. Thermocouples are pairs of dissimilar wires joined at one end that generate a net thermoelectric voltage depending on the temperature difference between the two ends. Thermistors are thermally sensitive resistors that exhibit a change in electrical resistance with a change in temperature (Webster, 1999). Both types of sensors are relatively inexpensive, and



can measure temperature over a range typically found in most climates. Both automated measurements and manual readouts can be used.

For standard meteorological observation, soil temperatures are monitored at depths of 10, 20, 30, 50, 100 cm, and up to 3 m (AES, 1978). For watershed temperature monitoring, the depths of the sensors depend on the information that is required and the materials and layers present in the profile. Shallow sensors are useful for evaluating biological and vegetation activity in the topsoil. Deeper sensors may be spaced according to material layers, such as in layered cover systems. The depth of the deepest sensor would most likely correspond to the average depth of frost penetration, or, if the waste is reactive, then deeper sensors may be required to monitor potential heating of the waste material.

#### 4.3.2 *Soil Pore-Gas Concentration*

Gas concentrations through the soil profile are of interest in watershed-scale cover design for a variety of reasons. Gas concentrations in the topsoil are indicative of biological activity, and can indicate whether or not vegetation will thrive. Gas concentrations also indicate biological and chemical reactions that may be taking place deeper in the profile, whether in the waste, or in the cover materials.

Monitoring of soil pore-gas concentrations requires sampling pore-gas from a specific depth within the soil profile. This is most commonly done by installing some type of gas sensor or port within the soil profile. The sensors are typically screen or mesh surrounding an air space that comes into equilibrium with the soil pore-gas. The sensor or port is connected to the surface with tubing to allow sampling from the surface.

#### 4.3.3 *Field Hydraulic Conductivity*

Field measurements of hydraulic conductivity in unsaturated soils are most often referred to as the “field-saturated” hydraulic conductivity ( $K_{fs}$ ) (Reynolds *et al.*, 1983). This is in recognition of the fact that air bubbles are usually entrapped in the porous media when it is “saturated” by downward-infiltrating water, particularly under ponded conditions. The water content of a porous medium at “field saturation” is consequently lower than at complete or true saturation. Depending on the amount of entrapped air,  $K_{fs}$  can be a factor of two or more below true saturation.

Determination of field hydraulic conductivity is fundamental for determining watershed performance because secondary structures in soil such as structural cracks, worm holes, root channels, and macropores can provide preferential flow paths in fine-textured materials. Hence, the development of a soil structure will strongly influence the hydrological properties of fine-textured cover materials (Meiers *et al.*, 2003; 2006). Freeze/thaw and wet/dry cycles, as well as biological activity all contribute to soil structure development. Vegetative and biological activities

have the greatest impact on near surface hydraulic conductivity. Wet/dry and freeze/thaw cycles can have a significant impact on the hydraulic properties of cover materials at significantly greater depths. Field hydraulic conductivity measurements are a single point measurement. To determine a representative value for a material, it is important to do a number of measurements over a representative area.

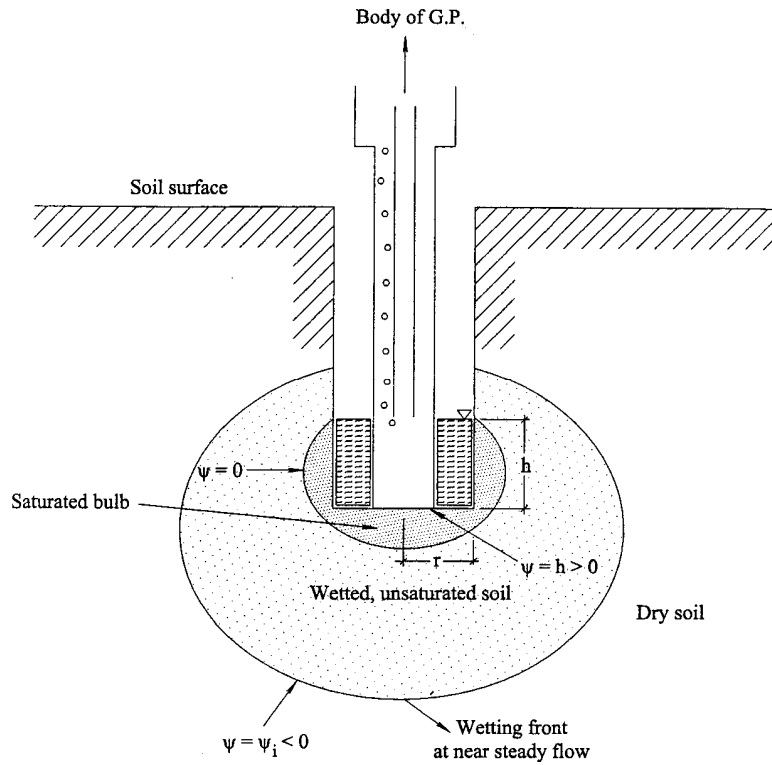
Various methods exist for measuring the  $K_{fs}$  of soil, including *in situ* and laboratory procedures. In the field, infiltration can be measured by providing water to the soil at a constant pressure, either positive or negative. The simple double ring infiltrometer can be used to estimate  $K_{fs}$  by measuring infiltration under either constant or falling heads, and mostly commonly under positive water pressures (Zeleeke and Si, 2005). Constant head well permeameter methods provide an *in situ* determination of the value of  $K_{fs}$  in the unsaturated zone. These methods involve the measurement of the steady-state infiltration rate required to maintain a steady depth of water in an uncased, cylindrical auger hole that terminates above the water table (Reynolds 1993). There are several constant head well permeameter methods, each differing based on theory, procedure, and apparatus. The constant well permeameter technique described in this section is known as the “Guelph Permeameter” (*GP*) method.

The tension infiltrometer (*TI*) has also been widely used for determining the hydraulic conductivity (Messing and Jarvis, 1993) and water conducting porosity (Watson and Luxmoore, 1986; Dunn and Phillips, 1991) of soils under near saturated conditions, as well as  $K_{fs}$  (Reynolds and Elrick 1991).

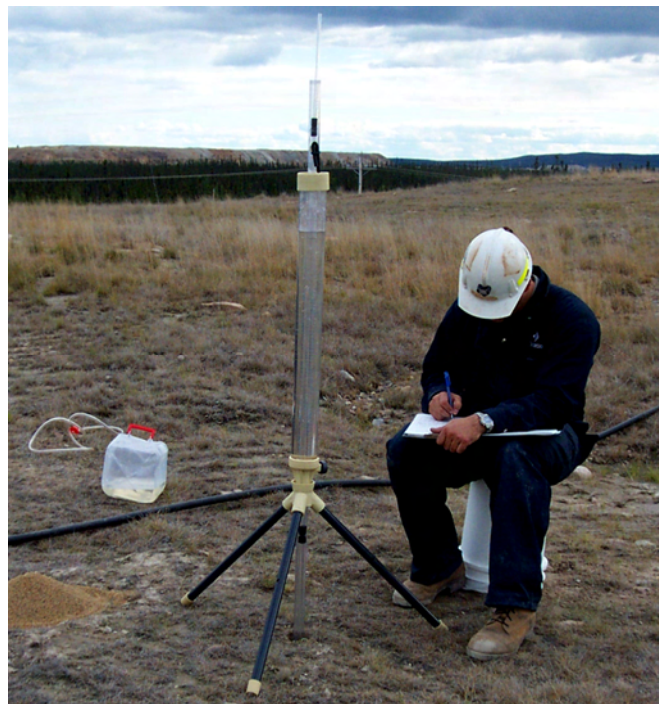
The different methods of determining  $K_{fs}$  each have particular advantages and limitations. The selection of a method, therefore, should be based on the requirements of the specific application. Factors which should be considered, in addition to those relating to accuracy and precision, are; the ease of operation, location of the measuring sites, the availability of time and other resources, and, above all, the ultimate purpose for the measured values of  $K_{fs}$  (Gupta *et al.*, 1993).

*In situ* methods for determining the  $K_{fs}$ , which incorporate a large cross-sectional area, will tend to mask regions of low hydraulic conductivity. Values of  $K_{fs}$  measured with the *GP* typically show relatively high coefficients of variation, indicating sensitivity to the heterogeneous hydraulic characteristics of soil.

Figures 4.12 and 4.13 illustrate the *GP* method of measuring field hydraulic conductivity. Reynolds *et al.* (1985) provide a complete description of the *GP* apparatus, which is essentially an in-hole Mariotte bottle constructed of concentric, transparent plastic tubes. The Guelph Permeameter is available from SoilMoisture Equipment Corp and additional details on the operation of this device can be found in their operating manual (SoilMoisture, 1986).



**Figure 4.12** GP saturated bulb and wetting front surrounding the auger hole, where:  $\psi$  is the pressure head,  $h$  is the height of ponded water,  $\psi_i$  is the initial pressure head in the soil (from Giakoumakis and Tsakiris, 1999).



**Figure 4.13** Field hydraulic conductivity testing with the Guelph Permeameter.

#### 4.3.4 *Topography Change (subsidence, erosion)*

One of the most important variations between watershed-scale cover monitoring and small-scale cover test plot monitoring is the time-scale over which the monitoring is done. Usually, small-scale test plot monitoring is done over a period of a few years, during which time the test plot is assumed to have similar physical properties as to when it was placed. In reality, cover and waste material properties evolve with time as discussed in Section 3. One of the ways that the topography of a watershed may change with time is as a result of subsidence and erosion.

##### 4.3.4.1 Monitoring Subsidence

Changes in topography occur over time in both natural and man-made watersheds. Depending on the mechanism, the topography change may be due to factors including, but not limited to, subsidence, slumping, consolidation, and freeze/thaw cycles. In natural watersheds, topography may change due to material instability, or changes in pore-water pressures may result from large-scale dewatering or flooding. In man-made watersheds, material instability is the most common mechanism leading to subsidence. Changes in pore-water pressures may change over time in constructed watersheds following dramatic changes in the local hydrology due to flooding of an open pit or draining of a tailings dam, for example. As the topography changes, drainage patterns change, which may have an impact on soil nutrients, vegetation patterns, and even the watershed water balance.

Monitoring topography change can be quantitative or qualitative. Quantitative methods most commonly use survey markers or GPS to accurately map the topography over the watershed as it changes from year to year. Another method, typically used for large-scale subsidence monitoring, is a borehole extensometer. Qualitative monitoring of topography change is usually done using a photo log. Permanent posts with a camera platform can be placed at a number of locations on the watershed. Every year photos are taken of the watershed on each of the platforms. The photos are useful not only for monitoring the topography change but also the change in vegetation.

##### 4.3.4.2 Monitoring Erosion

Watershed-scale cover systems are usually designed with the assumption that they will remain intact and that the basic physical dimensions and structure of the cover layer will not change. However, topography change occurs for a number of reasons, erosion being one of them. Erosion not only has an impact on the topography, but may have a significant effect on the long-term performance of a cover system, especially those at sites that experience short duration, high intensity rainfall events. Erosion can compromise the structural integrity of the cover system by reducing the thickness of the cover layer or removing it entirely.

Erosion occurs when soil particles are detached from the soil matrix and then transported from the area. The erosion process is driven by the energy delivered from rainfall striking the soil or due to movement of surface water (including runoff) or groundwater. It is generally agreed that the three main erosion processes are interrill, rill, and gully erosion. Erosion is usually monitored in conjunction with runoff monitoring, where sediment that is transported with the runoff is collected and measured. However, other methods are available, such as erosion troughs, erosion pins, silt fences, profile and slope measurements, and repeat photography using reference points.

Erosion usually occurs during precipitation or snowmelt runoff events. If runoff is being monitored at a given location, sediment will be carried in the runoff and can be collected or sampled at the monitoring location. However, if erosion is significant, the sediment may pose problems for runoff monitoring. The ability to pass sediment is a design feature of the zero height V-notch weir. If a traditional weir was installed, sediment would build up on the upstream side and eventually cause measurement errors. So, if erosion is measured in conjunction with runoff measurement, it must be done in a way that does not negatively impact the runoff measurement.

Sediment may be either trapped or sampled in the runoff. A sediment trap may involve an upstream settling basin where the majority of the sediment would settle out. Once the runoff event was complete, the trap would be cleaned out and the sediment weighed to determine the total material eroded during that event. Sediment can also be measured directly in runoff using sampling techniques. Standardized samplers can be lowered into the flow to collect suspended sediment manually, or automated methods can be used where samples are taken from a given location in the flow by an automated sampler. Sediment sampling methods are discussed in Maidment (1993) and Gray (1973).

A variation on sediment trapping is the erosion trough. A trough is dug into the hillslope, which collects the runoff and the associated sediment. The trough may be sloped to drain the sediment to a collection system, or it might be sufficiently large to contain the sediment that accumulates over the measurement period. At the end of the measurement period, the mass of sediment is measured to determine the erosion that occurred over the measurement period. This method works well for small-scale measurement, especially test plots, where the contributing area is well defined. To apply this method to a watershed-scale, a contributing area would have to be clearly defined either with cutoff walls, or by utilizing local topographic controls. Use of erosion troughs are described in Kapolka and Dollhopf (2000), Luk and Hamilton (1986), Gerlach (1967) and Gellis (1998).

Sediment trapping may also be accomplished using an temporary barrier known as a silt fence. A silt fence consists of geosynthetic fabric that is fine enough to collect the sediment, but is sufficiently permeable to allow water to pass through. The fabric is keyed into the hillslope perpendicular to the slope and attached to vertical fence posts. The geosynthetic fabric acts as a

filter, trapping the sediment as runoff travels downslope. Sediment that is trapped by the fabric is removed and weighed after each runoff event to estimate the erosion rate from the contributing area. As with collection troughs, silt fences require a known contributing area. A benefit of the silt fence over the erosion trough is that the silt fence does not produce as much of an interruption of the surface hydrology as the erosion trough. Some interception and resulting head loss will occur in the runoff flow, but the water is not completely diverted. Information on silt fences can be found in Robichaud and Brown (2002) and USDA (1999).

Quine *et al.* (1997) describe a method for measuring the change in slope morphology on a small agricultural watershed. At two metre intervals down the slope a measuring tape was extended across the slope to record the location, depth, and width of the existing rill network. The measurement process can be repeated after specified intervals or after large erosion events to define the change in rill geometry and estimate the amount of soil lost to erosion.

A similar measurement method involves the installation of erosion pins to form a grid across the area being monitored. This method of measuring erosion is primarily used as a reconnaissance method to get a first approximation of the amount of erosion that is occurring which then can be used as a basis for further investigation. Erosion pins often consist of a nail and a washer. The nail is pounded into the ground through the washer such that the washer and the nail head rest on the ground surface. The depth of scour can be determined by the distance the nail head emerges above the ground surface (as noted by the washer). If there is deposition, then the mass of soil that has collected on the nail and washer is measured. These measurements allow the generation of erosion contours for the area. This technique was utilized to measure erosion at the Kidston Gold Mine in Australia (Horn *et al.*, 1998).

As opposed to the detailed and quantitative techniques described above, erosion can be measured using visual observation to qualitatively determine the extent of erosion and how it changes over time. Visual observation may consist of ground surveys, where rills, channels, gullies, and sediment wedges etc. are observed and roughly measured as they change over time. Ground level surveying is common in forestry practices and details on their methods can be found in Sasich (1998) and Sturhan (1997).

Another useful method for visual observation of erosion is with the use of aerial photographs. This allows a large geographical area to be surveyed, although gullies are usually the only erosion feature visible. Areas requiring a ground survey can be determined based on the aerial photographs. The ground survey may then lead to a selection of areas that require more detailed erosion monitoring. The use of aerial photographs for erosion surveying is outlined in Beer and Johnson (1963), Seginer (1966), and Burkard and Kostachuk (1997).

## 4.4 Chemistry

The chemistry of soil and water is a critical facet of watershed-scale cover monitoring. Soil and water chemistry are often the most direct indicators of the performance of a cover system. For example, chemical indicators in the pore-water from acid-generating mine waste will indicate whether or not the cover system is acting to reduce acid generation. Other wastes may generate salinity, or leach heavy metals or other contaminants. However, it is usually difficult to directly monitor the pore-water or leachate from a watershed-scale cover system. For this reason, most performance criteria are based on the water balance, which is an indirect measure of performance. Soil and water chemistry are also important to determine the viability of vegetation and illustrate reactions taking place in the topsoil and subsoil.

### 4.4.1 Soil Chemistry

Monitoring soil chemistry largely depends on the type of waste, the potential reactions that may take place, and the information required for vegetation and biological impacts. Some mine waste oxidizes and produces some sort of waste product, such as acidity, heavy metals, or salts. To determine the effectiveness of the cover system, it is important to monitor the soils for evidence of these oxidation products or products of secondary reactions due to the oxidation of the waste. For the vegetation layer, it is also important to monitor oxidation products, as these are often detrimental to vegetation growth. Standard soil monitoring is also important to determine the viability of vegetation; this usually includes monitoring for cations, anions, cation exchange capacity, pH, nutrients, and organic carbon.

Monitoring of soil chemistry can be done through collection of soil samples or by using *in situ* methods. *In situ* methods are not as common for evaluating cover performance; therefore, this manual will only discuss soil sampling and laboratory testing.

Soil sampling requires taking representative samples of the various soils on the watershed at various depths to represent the variation in soil chemistry over the watershed. Soil sampling methods vary, but are usually tailored to the data requirements. Soil sampling may involve digging test pits and taking undisturbed samples or cores from the pit walls. Disturbed samples can also be obtained with a hand auger, which causes less disruption to the soil surface. Information on sampling methods can be found in Leskiw (1998), McKeague (1978), and in many of the MEND reports (MEND 5.4.2b, MEND 4.1.1, MEND 4.5.4).

Laboratory testing methods for soil chemistry are fairly standard and well understood. A brief description of the most common soil chemistry characteristics are described below.

#### 4.4.1.1 Salinity/Sodicity

Salinity describes the total concentration of soluble salts in the soil. An increase in salinity leads to an increase in osmotic suction and affects a plant's ability to remove water from the soil. Plant growth can be negatively affected at 4 dS/m and if soil salinity levels are high enough, a condition known as physiological drought can result (Larcher, 1995), although plant susceptibility to elevated salinity levels is species dependent. High soil salinity levels can disrupt nutritional and metabolic processes in plants, and as such, can alter the vegetation community, and therefore lead to changes in the structure, permeability and aeration of the soil.

Sodicity describes the sodium content of the soil. Sodium affects soils differently than salinity. Salinity causes soil particles to flocculate and often increases the hydraulic conductivity and aeration of the soil. Sodium ions cause soil particles to disperse and can lead to a decrease in hydraulic conductivity on exposure to fresh water and surface crusting.

Salinity is typically determined by measuring the electrical conductivity (EC) of a saturated paste solution. This method is a relatively quick and inexpensive method to estimate the salinity of a soil. An electrical conductivity meter is immersed in the solution and measures the electrical conductivity of the solution, which is directly proportional to the concentration of ions in the solution (Zhang *et al.*, 2005). Sodicity is either determined from the sodium adsorption ratio (SAR) or the exchangeable sodium percentage, both of which require measurement of the individual cation species in the soil (Sumner and Miller, 1996).

#### 4.4.1.2 Acidity/Alkalinity

Acidity and alkalinity, or the soil solution pH, can both contribute to inhibited plant growth in the vegetative layer or a cover system. Acidity is often caused by the oxidation of mine wastes where, in some cases, the acidic pore-waters dissolve metals and salts that can then leach into the soil layers above.

#### 4.4.1.3 Cation Exchange Capacity

The cation exchange capacity is an indication of a soil's ability to hold and retain cations. Soils tend to have a net negative charge due to the presence of clay and humus particles, both of which have overall negative charges. The negatively charged particles attract and retain positively charged cations in a sufficient quantity to balance the charge. The cations that may be held on the exchange sites are  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ , and  $\text{Al}^{3+}$ . The cation exchange capacity gives an indication of the ability of the soil to provide nutrients for the plants, as the cations on the exchange sites are readily available for plant uptake. Cation exchange capacity can be measured using a number of methods, but most methods involve flushing the cations off the



exchange sites using a high ionic strength solution of a single cation (usually  $\text{NH}_4^+$ ) and then measuring the individual cation concentrations of the flushed solution.

#### 4.4.1.4 Nutrients

There are sixteen essential nutrients for plant growth and development. The nutrients are divided into two categories: macro- and micronutrients. The macronutrients are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur. The micronutrients are copper, zinc, boron, manganese, iron, molybdenum, and chlorine. Of these sixteen, carbon, hydrogen and oxygen are obtained by plants from photosynthesis, the atmosphere, and water. The remaining thirteen must be obtained from the soil. The nutrients in the soil must be present in a certain amount for optimum plant health; too high and they become toxic to the plant, too low and the plant will not be able to complete the vegetative and reproductive stages of its life cycle.

Nutrients are measured either *in situ* using methods such as ion exchange membranes (Qian and Schoeneau, 2002), or are measured in the laboratory from soil samples. Ion exchange membranes use a pre-treated anion and cation exchange membrane to simulate a plant root and measure the nutrients available to a plant root at the conditions present in the soil. Laboratory methods use a chemical extracting solution to dissolve the nutrients from the soil. The solution is then measured for the concentrations of the various nutrients, which is related back to the mass of the soil sample used for the test to determine the concentration of nutrients in the soil on a mass basis.

#### 4.4.1.5 Organic Carbon

Organic carbon is an indicator of the quantity of organic matter present in the soil. Organic matter is important for good soil structure as it binds the soil particles together. Organic matter also plays an important role in adsorption of cations and improves the water holding capacity of the soil. Organic matter in the soil comes from surface litter such as leaves and plant matter as well as from root matter left in the soil. Monitoring soil organic matter is a good indicator of the impact of various remediation options on soil health as it is a key component in determining soil fertility, stability, and condition as well as estimating the overall health of the watershed. Organic carbon determination requires sampling the soils at various locations and depths, then performing a laboratory analysis involving combustion of the sample in furnace.

#### 4.4.2 Water Chemistry

The rationale for monitoring water chemistry are similar to those for soil chemistry. Some mine waste oxidizes and produces oxidation products that impact on pore-water chemistry, and can migrate and impact surface water and groundwater. Other contaminants in the waste may also

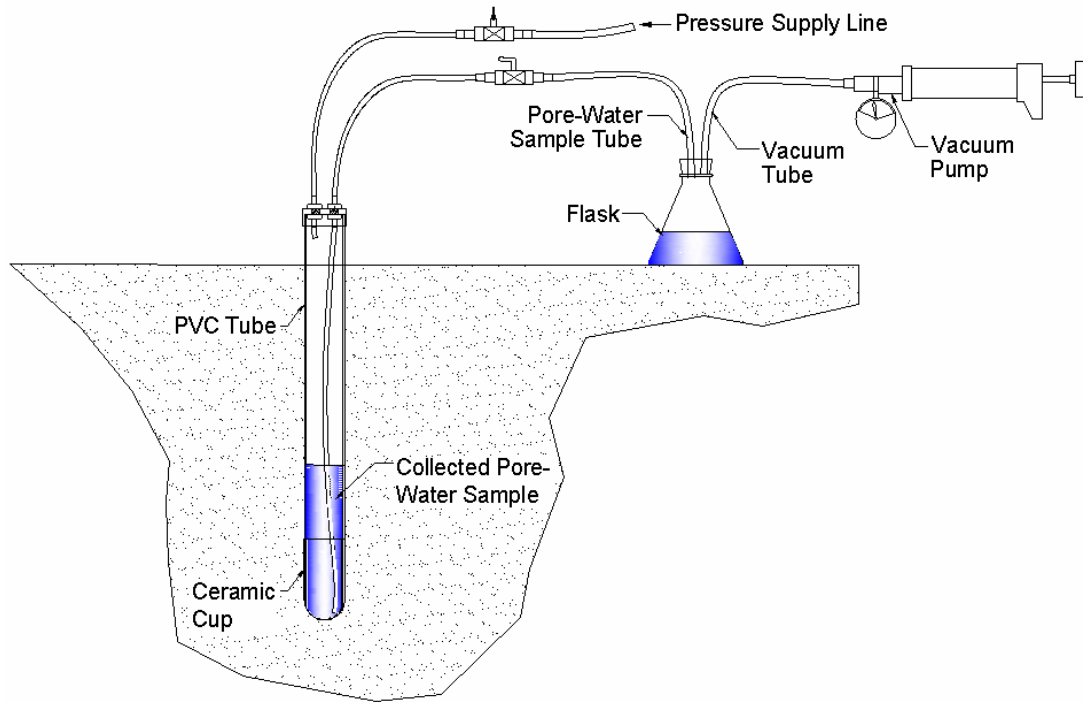
be important to quantify using water chemistry. A brief description of monitoring methods for water chemistry is given below.

#### 4.4.2.1 Pore-Water Monitoring

Pore-water is difficult to monitor because it is difficult to extract representative samples from soil pores. In unsaturated soils, pore-water can be sampled *in situ* using a suction lysimeter (Litaor, 1998; Paramasivam *et al.*, 1997). Suction lysimeters use a ceramic or Teflon cup that is attached to a length of PVC (Figure 4.14). A vacuum is applied to the inside of the cup that then draws the unsaturated pore fluid through the ceramic and into the cup where it can be sampled. This method works well in soils where the matric suction is less than 90 kPa, which is generally the maximum suction that can be applied to the suction lysimeter. The ability of the suction lysimeter to draw in a sample over a reasonable period of time is also a function of the hydraulic conductivity of the surrounding soils. For soils with very low hydraulic conductivity, the suction lysimeter must maintain the vacuum for a sufficient length of time for fluid to move into the ceramic cup.

Studies have shown that most of the fluid collected by a suction lysimeters originate from the larger macropores surrounding the porous cup, as opposed to the micro-pores (Paramasivam *et al.*, 1997). Therefore, the chemistry results from the pore-water samples may not be truly representative of all the pore fluid. However, it is generally considered to be a reliable method of monitoring soil pore-water.

In some instances, a discrete sample of pore fluid is required in saturated sediments. This is common in tailings ponds where oxidation reactions occur and are of interest to monitor the pore-water chemistry as it varies with depth in the sediment. This type of measurement would also apply to any surface water body where weathering may be taking place in the sediments. The device used to make this measurement is a peeper or dialysis sampler. This type of sampler consists of a cell or an array of cells filled with deoxygenated double distilled water and covered with a semi-permeable membrane. When the array of cells is placed in the sediments, diffusion occurs across the membrane and brings each cell into equilibrium with the pore fluid at the corresponding depth. Once the peeper is removed, the fluid from each cell can be removed and tested. Additional information on the use of peepers can be found in MEND 5.4.2b, US EPA (2001), Adams (1991), and Bufflap (1995).



**Figure 4.14** Illustration of a suction lysimeter.

#### 4.4.2.2 Surface Water Monitoring

Methods for sampling of surface water have been discussed in previous sections of this manual. Auto-samplers can be used to sample streamflow, seepage meters can be used to sample seeping water, and non-flowing surface water bodies can be sampled with grab samples.

#### 4.4.2.3 Groundwater Monitoring

Groundwater samples are usually taken from monitoring wells or piezometers. Piezometers were discussed in Section 4.2.5. A bailer or some type of pump can be used to bring a sample of the groundwater to the surface. The type of bailer used should be carefully considered in the application it is used for.

#### 4.4.2.4 Samples and Storage

Depending on what is being tested, the samples may need to be preserved and/or may have a short window in which the testing should be performed. Care must also be taken when using the methods described above as the residence time of the samples in the sampler may be long enough for secondary reactions to occur. Information regarding sample collection, storage containers, preservation methods and storage times can be found in MEND 5.4.2b and MEND 4.5.1-1.

## 4.5 Biological Properties

Biological properties provide indirect information on environmental conditions and can be compared to baseline conditions or conditions at natural sites. Biological properties can also be used to detect reactions that may be occurring in the waste or cover materials.

Characterization of the vegetation is likely the highest priority of biological monitoring in reclamation. Establishing vegetation is important for minimizing erosion, improving aesthetics, and returning the reclaimed area to a final target such as a productive forest, recreational land, or to a pre-disturbance state. Characteristics of the established vegetation such as leaf area index or rooting depth/density are critical to understanding the distribution and magnitude of moisture uptake as a result of transpiration.

Soil and water biology monitoring also provides important information regarding the performance of a reclaimed watershed. For example, a reclaimed watershed that shows failing vegetation may be storing adequate moisture in the cover system but may not be supporting the appropriate micro-organisms to maintain nutrient cycling.

Watershed-scale monitoring of biological properties largely differs from small-scale monitoring in volume as opposed to method. Larger areas with diverse hydrology create equally diverse vegetation. The heterogeneous nature of vegetation complicates monitoring and quantification of species and density. However, monitoring biological properties on a large scale is common in various disciplines and these methods can be applied to watershed-scale cover monitoring. Due to the extensive information that exists for monitoring biological properties, this manual only provides a short overview of the various biological properties measured, the characteristics that are typically measured, and an overview of methods used to monitor long-term performance.

### 4.5.1 *Vegetation*

Vegetation monitoring consists of evaluating the species types, vegetation density, vegetation frequency, the percent area coverage, and the above ground biomass production. These factors can be used to determine the viability of certain species, the impact of soil amendment options, and can help to determine the performance of various cover treatment options.

Vegetation surveys involve randomly evaluating small fixed areas of vegetation, typically called quadrats. Many methods exist for statistical accuracy, but typical methods involve evaluating plants within a quadrat along a transect. Depending on what is being measured during the survey, the occurrence and frequency of specific species may be measured, the mass of plant material within the quadrat may be determined, or the canopy cover may be measured. Detailed guidelines for vegetation surveys can be found for a number of disciplines, such as forestry or rangeland management. U.S Department of Agriculture (1999), Roberts-Pichette and Gillespie

(1999), and Barker (2001) are excellent manuals on vegetation survey methods. Other references are Bonham (1989) and Myers and Shelton (1980).

With the development of advanced measurement instruments, another form of vegetation monitoring used for cover performance evaluation is related to measurable physiological factors (Larcher, 1995). This can include measurement of factors such as photosynthesis (Jones *et al.*, 2003; Zhao *et al.*, 2005), transpiration (Tognetti *et al.*, 1998; McLeod *et al.*, 2004), stomatal conductance (Tognetti *et al.*, 1998; Ewers *et al.*, 2005; Zhao *et al.*, 2005), internal leaf CO<sub>2</sub> concentrations (Zhao *et al.*, 2005), and xylem water potential (Tognetti *et al.*, 1998; Ewers *et al.*, 2005). These measurements indicate the plant's physiological response to various environmental factors on a time dependant scale. These measurements are useful, in conjunction with the vegetation surveys, for determining the health and viability of the vegetation on watershed-scale cover systems.

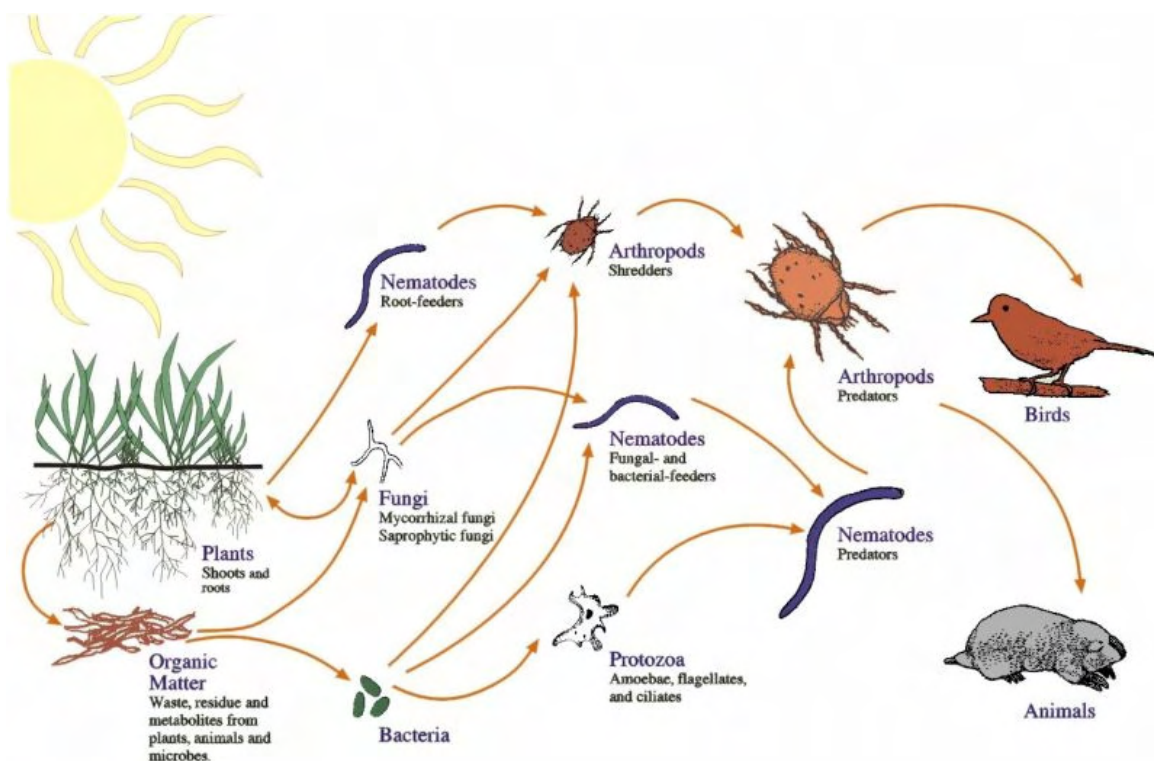
#### 4.5.2 Soil Biology

Healthy soils are intrinsic to watershed-scale cover design in that they support plant growth, store and cycle nutrients, and have an impact on overall ecosystem health. The biological component of soil is the primary constituent contributing to soil health; a complex community made up of a variety of types of organisms. The community of organisms and their reliance on each other is sometimes referred to as the soil food web (Tugel *et al.*, 2000). The soil food web, as illustrated in Figure 4.15, consists of biological crusts, soil microbiota such as fungi, bacteria, and protozoa macro fauna such as nematodes, arthropods, and earthworms and fauna such as burrowing mammals, and birds. These organisms form a complex food chain that cycles nutrients, provides habitat for plants, and changes the physical structure of the soil. Monitoring the status and behaviour of these organisms can indicate the health of the soils, and can aid in the prediction of the long term performance of reclamation activities, especially the long-term viability of vegetation. Additional information on soil biology can be found in Richards (1987), Dindal (1990), and Walker (1999).

Monitoring the biological characteristics of soil typically consist of a combination of both direct and indirect measurements. Direct measurements consist of counting organisms and measuring cellular constituents; whereas indirect measurements consist of measuring activity levels, such as measuring by-products or decomposition rates.

Quantitative estimation of soil microbial populations involves either direct or indirect counting methods. Direct counts are performed using the naked eye for larger organisms, or a microscope for smaller organisms. Indirect counts include dilution plate counts, or most-probable-number (MPN) estimates (Dandurand and Knudsen, 1997). Dilution plate counting accommodates the extremely large numbers in an environmental sample and the microscopic size of the individuals by diluting the population to countable numbers. This method involves inoculating a general

growth media with a diluted aliquot of the soil sample. Individual viable organisms can metabolize the available growth media and will grow into a colony of cells that can be counted with the naked eye and differentiated based on colour or morphology (Zuberer, 1994). Quantification estimates using either of these methods can be used to estimate the biomass of certain microbial communities in the soil.



**Figure 4.15** Soil food web (from Tugel *et al.*, 2000).

Measuring microbial metabolic activity levels include measuring respiration, nitrification, and decomposition rates. Measuring respiration rates involves measuring  $\text{CO}_2$  production (Stotzky, 1997), whereas nitrification rates involve measuring the rate at which ammonium is converted to nitrate (Myrold, 1997). Decomposition rates can be measured by monitoring the change in mass of organic matter as it is transformed over time, or by the decomposition of standardized cotton strips.

The total biomass can be measured by measuring cellular constituents such as biomass carbon, nitrogen, or phosphorus (White *et al.*, 1997). Enzymes that occur in living cells, phospholipids or other types of lipids, and DNA and RNA can also be measured to further characterize the biological community (Ogram and Feng, 1997).

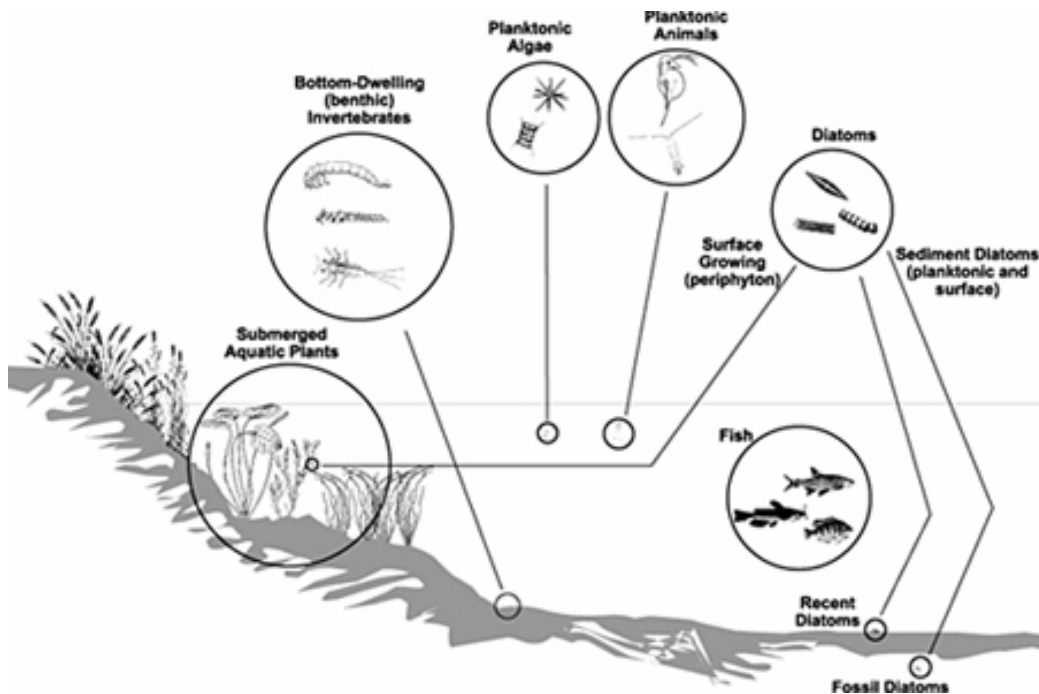
Additional information on methods of monitoring soil health, and in particular the biological components, can be found in Pankurst *et al.* (1997), Ritz *et al.*, (1994), Weaver (1994), Robertson *et al.* (1999), and Blair *et al.* (1996).

### 4.5.3 Water Biology

In a similar manner to soil biology, water biology is a fundamental indicator of the health of a watershed, and specifically the health of water bodies. Water biology is often used to determine a baseline prior to mining activities, or as a baseline prior to reclamation activities. Monitored over time, the changing biological characteristics of water bodies can indicate the relative performance of cover systems.

The biological community in surface water is made up of similar organisms to the soil biological community: bacteria, periphyton, plankton, benthic invertebrates, and fish (Figure 4.16). The biological community in groundwater is not as diverse, but is still worth monitoring as bacteria can indicate various reactions occurring in the materials at depth.

As with soil monitoring, biological monitoring of water bodies is common in other disciplines and therefore a large source of information exists on monitoring methods. The MEND Manual (MEND 5.4.2) describes biological sampling methods useful for monitoring the impacts of acidic drainage. A brief summary of the information presented in the MEND Manual is given in the following discussion.



**Figure 4.16** Biological community in a typical lake (from US EPA, 1998).

Periphyton are the primary producers in the aquatic ecosystem and therefore provide valuable information on the productivity of the ecosystem and factors that may be impacting this productivity. Changes to the productivity may occur due to changes in nutrient concentrations.

Typically, periphyton are sampled off stone or cobble substrates. Sampling involves brushing or scraping off the algae from a defined area and placing the sample in a sample bottle. The sample can then be tested for species present, chlorophyll  $\alpha$ , or biomass. If natural stones are not present, artificial substrates can be placed in the water body to collect the algae.

Plankton consist of zooplankton and phytoplankton. Monitoring of plankton is not common in monitoring for environmental impacts, but provides useful data on baseline monitoring, or in conjunction with other biological monitoring. The difficulty with plankton monitoring is that there is a lot of natural variability and therefore providing comparative data is difficult. Zooplankton are sampled using a conical fine mesh net where the net is lowered to a specified depth then slowly pulled up through the water column. The distance the net travels through the water and the volume of water that passes through the net is used to determine species density. Phytoplankton are sampled using a van Dorn bottle, which is a plexiglass container, open at both ends, with plungers on both ends that can be triggered to close. The sampler is lowered to a specified depth and the plungers are closed to obtain a sample from that depth. Laboratory testing then determines the numbers and species present.

Benthic invertebrates are good indicators of changes in water condition as they are farther up the food chain from the aquatic producers. Monitoring of benthic invertebrates is useful for both baseline characterization and for determining ongoing performance of reclamation activities. The number and location of monitoring sites depends on the size of the waterbodies and the complexity of the aquatic communities. Sampling consists of net samplers for small stream sampling or sediment grab samples for pond or lake sampling.

Fish are a fundamental aspect to biological water monitoring in that they are at the top of the food chain and fish populations are well understood by the public. However, monitoring fish is complex in that there are significant variations over the season, and due to their mobility, fish are difficult to relate to a specific area of water. There are a number of ways of monitoring fish. There are numerous methods typically used to monitor fish, which depend on the type of water body, the data requirements, and various other site specific conditions. Methods for streams can be beach seining, electro-fishing, using nets, or angling. Lakes and ponds are typically measured using nets or angling.

Additional information on biological monitoring can be found in MEND 5.4.2b, Cavanagh *et al.* (1994), Hurst (1997), AETE 2.1.2, AETE 2.3.2, AETE 2.2.3, and US EPA (1998).



## 5 CONCLUDING REMARKS

Mine owners and operators understand that reclamation and closure planning are contemporaneous requirements. The primary objective of this manual is to introduce design and monitoring guidelines for mine waste soil cover systems on a macro-scale, i.e. a watershed and landform-scale, and the challenges that arise due to the increased size and complexity. Macro-scale monitoring is a tool that is used to characterize conditions, processes, and interactions within a watershed to provide a systematic method to understand and organize ecosystem information. In so doing, watershed analysis enhances the ability to estimate direct, indirect, and cumulative effects of management activities and guide the general type, location, and sequence of appropriate future management activities.

A watershed is an ideal scale to address a majority of questions asked about landscape performance and risk – i.e. hydrogeology, surface water quality, soil performance, ecosite development and toxicology. It is recognized that interactions between landforms is an essential issue, but these should not be addressed until a composite of answers addressing questions arising from the watershed itself is developed. A watershed is the largest building block in a landscape and is the unit by which the designers reconstruct landscapes. In addition, a watershed can encompass the range of target ecosites desired for the particular parent material, it allows for calculation of water and mass balances, and it is a manageable size.

The design of a new landscape requires a significant amount of time and resources to create a suitable environment for progressive evolution to occur. A key design issue for a newly reclaimed landscape is to create an initial condition so that the landscape follows a suitable trajectory of evolution both in terms of rate of change and end point. Landscape design depends on a number of factors including climate, geology, soils, local hydrogeologic patterns, topography, and final land use. A natural analogue is an ideal starting point for landscape design as it provides an example of the end point of a similar landscape exposed to the same climate. An ideal plan for landscape design should be flexible to accommodate changes in methods/technology, optimize post-mining land capability, minimize cost, and limit long-term maintenance liabilities.

One of the most challenging aspects of landscape reclamation is how to design for changes that are inevitable in systems designed for integration into nature. Landform engineering is unique in that the timeframe of interest is in the order of hundreds to thousands of years. As well, it is extremely difficult to predict and quantify the types of changes that will occur which will affect the system. Processes that affect evolution of a system can be grouped into physical, chemical, and biological. Each type of process will affect reclaimed systems differently over time, either separately or in combination with one another.

Long-term field performance monitoring is a critical element for defining the critical trajectory by determining the associated mechanisms and processes that cause the landscape to evolve. Monitoring on a macro-scale is multi-dimensional with abundant spatial and temporal variation. Monitoring on a macro-scale must evaluate the behaviour of the entire watershed and includes surface hydrologic monitoring, sub-surface hydrologic monitoring, soil characteristics and physical properties, soil and water chemistry, and biological properties. The information obtained from macro-scale monitoring enables as-built performance to be compared to predicted performance of the new landscape, and particularly for large sites where progressive reclamation occurs, provides feedback to adjust future landform designs.

## GLOSSARY OF TERMS

*Aspect* – horizontal direction in which a slope faces; commonly expressed as degrees clockwise from north.

*Dendritic drainage pattern* – a drainage pattern resulting in regions underlain by homogeneous material. The subsurface geology has a similar resistance to weathering so there is no apparent control over the direction the tributaries take. The pattern looks like the branching pattern of tree roots.

*Gully erosion* – advanced stage of surface erosion in which rills, carved by overland flow, combine into larger channels in soil or soft rock.

*Hydraulic conductivity* – a measure of the ability of a soil or soil-like material to transmit water, and is a maximum for saturated soils or soil-like materials.

*Interrill erosion* – The removal of a fairly uniform layer of soil on a multitude of relatively small areas by splash due to raindrop impact and by sheet flow.

*Matric suction* – the difference between the pore-air pressure and the pore-water pressure in a soil or soil-like material.

*Porosity* – the ratio of the volume of voids to the total volume, and is generally presented as a percentage.

*Rill erosion* – the result of erosion that causes the removal of soil by concentrated overland flow running through small trenches.

*Sheet erosion* – removal (more or less evenly) of surface material from sloping land, as a result of broad sheets of overland flow.

*Soil water characteristic curve (SWCC)* – the relationship between matric suction and volumetric water content, which describes the moisture retention capability of a soil or soil-like material.

*Spur-end hillslope* – a hillslope that is predominantly convex in profile and located at the end of a valley.

*Swale* – a channel with gentle sloping side-slopes (concave in cross-section) constructed along the contour of a slope to intercept surface runoff.

*Volumetric water content* – the ratio of the volume of water to the total volume of the soil, and is generally presented in decimal form.

## REFERENCES

- Ackers, P., White, W.R., Perkins, J.A., and Harrison, A.J.M. 1978. Weirs and Flumes for Flow Measurement. John Wiley & Sons, New York, NY.
- ACMER (Australian Centre for Mining Environmental Research). 2003. Determination of the reasons for deterioration of the Rum Jungle waste rock cover. ISBN: 0 9577966 8 4, July.
- Adams, D.D. 1991. Sampling sediment pore-water. *In* CRC Handbook of Techniques for Sediment Sampling. Edited by A. Mudroch and S.D. MacKnight. CRC Press, Inc., Boca Raton, FL.
- AES (Atmospheric Environment Service). 1978. Soil Temperature: Manual of Standard Procedures for Obtaining Soil Temperature Data. Atmospheric Environment Service. Central Services Directorate, Canada.
- AETE 2.1.2. 1997. Optimization of field and laboratory methods for benthic invertebrate biomonitoring. Aquatic Effects Technology Evaluation (AETE) Program, Natural Resources Canada, Ottawa, ON. Available from <http://www.nrcan.gc.ca/mms/canmet-mtb/mmsl-lmsm/enviro/metals/aete.htm>. January.
- AETE 2.3.2. 1997. Technical evaluation of monitoring methods using macrophytes, phytoplankton and periphyton to assess the impacts of mine effluents on the aquatic environment. Aquatic Effects Technology Evaluation (AETE) Program, Natural Resources Canada, Ottawa, ON. Available from <http://www.nrcan.gc.ca/mms/canmet-mtb/mmsl-lmsm/enviro/metals/aete.htm>. June.
- AETE 2.2.3. 1999. Technical evaluation of fish methods in environmental monitoring. Aquatic Effects Technology Evaluation (AETE) Program, Natural Resources Canada, Ottawa, ON. Available from <http://www.nrcan.gc.ca/mms/canmet-mtb/mmsl-lmsm/enviro/metals/aete.htm>. February.
- ASTM (American Society for Testing and Materials). 1991. Standard guide for measuring matric potential in the vadose zone using tensiometers (D3404-91). *In* 1998 Annual Book of ASTM Standards, Vol. 4.08. ASTM, Philadelphia, Pa.
- ASTM (American Society for Testing and Materials). 1992. Standard test method for laboratory determination of water (moisture) content of soil and rock (D2216-92). *In* 1998 Annual Book of ASTM Standards, Vol. 4.08. ASTM, Philadelphia, Pa.
- ASTM (American Society for Testing and Materials). 2005. Standard specification for thermistor sensors for clinical laboratory temperature measurements (E879-01). *In* 2005 Annual Book of ASTM Standards, Vol. 14.03. ASTM, Philadelphia, Pa.

- Aubertin, M., Bussière, B., Barbera, J.-M., Chapuis, R.P., Monzon, M., and Aachib, M. 1997. Construction and instrumentation of *in situ* test plots to evaluate covers built with clean tailings. *In Proceedings of the 4<sup>th</sup> International Conference on Acid Rock Drainage*, Vancouver, BC, May 31-June 6, pp. 715-730.
- Ayres, B. 1998. Field monitoring of soil-atmosphere fluxes through uranium mill tailings and natural surface soils at Cluff Lake, Saskatchewan. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Ayres, B., Dobchuk, B., Christensen, D., O'Kane, M. and Fawcett, M. 2006. Incorporation of natural slope features into the design of final landforms for waste rock stockpiles. *In Proceedings of the 7<sup>th</sup> International Conference for Acid Rock Drainage*, St. Louis, MO, USA, March 26-30, pp. 59-75.
- Ayres, B., Lanteigne, L. and O'Kane, M. 2005. Design and construction of the backfilled pit cover system at Whistle Mine, Canada: A case study. *In Proceedings of Securing the Future 2005*, International Conference on Mining and the Environment, Skelleftea, Sweden, June 27-July 1.
- Ayres, B., Lanteigne, L., Smith, Q., and O'Kane, M. 2007. Closure planning and implementation at CVRD Inco's Whistle Mine, Ontario, Canada. Paper accepted to II International Seminar on Mine Closure, Santiago, Chile, October 16-19.
- Baker, J.M. and Allmaras, R.R. 1990. System for automating and multiplexing soil moisture measurement by time domain reflectometry. *Soil Science Society of America Journal*, **54**: 1-6.
- Barbour, S.L. 1987. Osmotic flow and volume change in clay soils. Ph.D. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, SK.
- Barbour, S.L. and Fredlund, D.G. 1989. Mechanics of osmotic flow and volume changes in clay soils. *Canadian Geotechnical Journal*, **26**: 551-562.
- Barbour, S.L., Chapman, D., Qualizza, C., Kessler, S., Boese, C., Shurniak, R., Meiers, G., O'Kane, M., Hendry, J., and Wall, S. 2004. Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds – A brief history of the Syncrude Southwest 30 overburden reclamation research program. *In Proceedings of the International Instrumented Watershed Symposium*, Edmonton, AB, Canada, June 22-25.
- Barbour, S.L., Qualizza, C., Kessler, S., Meiers, G., and Hendry, J. 2005. Tracking the evolution of a reclamation cover on saline sodic overburden over time. *In Proceedings of the Alberta Soil Science Workshop*, Calgary, AB, Canada, February.
- Barker, P. 2001. A technical manual for vegetation monitoring. Resource Management and Conservation, Department of Primary Industries, Water and Environment, Hobart, Tasmania. Available from <http://www.dpiwe.tas.gov.au/inter.nsf/Publications/LBUN-5L23XL?open>.

- Baumhardt, R.L., Lascano, R.J. and Evett, S.R. 2000. Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes. *Soil Science Society of America Journal*, **64**: 1940-1946.
- Beer, C.E., and Johnson, H.P. 1963. Factors in gully growth in the deep loess area of western Iowa. *Transactions of the ASAE*, **6**: 237-240.
- Belanger, T.V. and Montgomery, M.T. 1992. Seepage meter errors. *Limnology and Oceanography*, **37**: 1787-1795.
- Benson, C.H., Bosscher, P.J., Lane, D.T. and Pliska, R.J. 1994. Monitoring system for hydrologic evaluation of landfill covers. *Geotechnical Testing Journal*, **17**: 138-149.
- Bews, B.E., O'Kane, M.A., Wilson, G.W., Williams, D., and Currey, N. 1997. The design of a low flux cover system, including lysimeters, for acid generating waste rock in semi-arid environments. *In Proceedings of the 4<sup>th</sup> International Conference on Acid Rock Drainage*, Vancouver, BC, May 31-June 6, pp. 747-762.
- Bilskie, J. 1997. Using dielectric properties to measure soil water content. *Sensors Magazine*, **14**: 26-32.
- Blair, J.M., Bohlen, P.J., and Freckman, D.W. 1996. Soil invertebrates as indicators of soil quality. *In Methods of Assessing Soil Quality*, SSSA Special Publication No. 49, Soil Science Society of America, pp 283-301.
- Boese, C.D. 2003. Design and installation of a field instrumentation program for the evaluation of soil-atmosphere water fluxes in a vegetated cover over saline-sodic overburden. M.Sc. Thesis, Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Bonham, C.D. 1989. *Measurements for Terrestrial Vegetation*. John Wiley & Sons, New York.
- Bos, M.G., Replogle, J.A., and Clemmens, A.J. 1991. *Flow Measuring Flumes for Open Channel Systems*. American Society of Agricultural Engineers, Republication of book by same title, originally by John Wiley & Sons, New York 1984.
- Bowen, I.S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physics Review*, **27**: 779-787.
- Boyle, D.R. 1994. Design of a seepage meter for measuring groundwater fluxes in the nonlittoral zones of lakes – evaluation in a boreal forest lake. *Limnology and Oceanography*, **39**(3): 670-681.
- Bozkurt S., Sifvert, M., Moreno, L., and Neretnieks, I. 2001. The long-term evolution of and transport processes in a self-sustained final cover on waste deposits. *The Science of the Total Environment*, **271**: 145 – 168.

- Bras, R.L. 1990. Hydrology: An Introduction to Hydrologic Science. Addison-Wesley Publishing Company, Inc., Reading, Mass.
- British Columbia Ministry of the Environment Water Management Branch. 1981. Snow survey sampling guide, Report SS13-81, Parliament Buildings, Victoria, B.C. Available from [http://wlapwww.gov.bc.ca/rfc/river\\_forecase/snow\\_surveys\\_manual.pdf](http://wlapwww.gov.bc.ca/rfc/river_forecase/snow_surveys_manual.pdf).
- Bryan, R.B. 2000. Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, **32**: 385-415.
- Bufflap, W.E. and Allen, H.E. 1995. Sediment pore-water collection methods: A review. *Water Research*, **29**: 165-177.
- Burkard, M.B. and Kostaschuk, R.A. 1997. Patterns and controls of gully growth along the shoreline of Lake Huron. *Earth Surface Processes and Landforms*, **22**: 901-911.
- Burn, K.N. 1964. Calibration of a neutron moisture meter in Leda clay. *Canadian Geotechnical Journal*, **1**: 94 -103.
- Bussi re B. and Aubertin, M. 1999. Clean tailings as cover material for preventing acid mine drainage: An *in situ* experiment. *In Proceedings of the Sudbury '99 Conference, Mining and the Environment II, Sudbury, ON, Sept. 13-17, Vol. 1, pp. 19-28.*
- Bussi re B., Aubertin M., and Chapuis R.P. 2001. Unsaturated flow in layered cover systems: A comparison between numerical and field results. *In Proceedings of the 54<sup>th</sup> Canadian Geotechnical Conference, Calgary, AB, Sept. 16-19, Vol. 3, pp. 1612-1619.*
- CANMET. 2002. CANMET – CETEM manual on cover system design for reactive mine waste. Prepared by O'Kane Consultants, Report No. 689-01, June.
- Carson, M.A. and Kirkby, M.J. 1972. Hillslope Form and Process. Cambridge University Press, Cambridge, UK.
- Cavanagh, N., Nordin, R.N., and Warrington, P.D. 1994. Biological sampling manual. British Columbia Ministry of Environment, Lands, and Parks, Victoria B.C. Available from <http://srmwww.gov.bc.ca/risc/pubs/aquatic/freshwaterbio/index.htm>.
- Chapman, D. 2006. Hydrogeology of South Bison Hill. M.Sc. Thesis (in progress), Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Cooke, J.A. and Johnson, M.S. 2001. Ecological restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. *Environmental Review*, **10**: 41-71.
- Dalton, F.N. 1992. Development of time domain reflectometry for measuring soil water content and bulk soil electrical conductivity. *In Advances in Measurement of Soil Physical*

- Properties: Bringing Theory into Practice. Soil Science Society of America Special Publication No. 30, pp. 143-167.
- Dandurand, L.C. and Knudsen, G.R. 1997. Sampling microbes from the rhizosphere and phyllosphere. *In* Manual of Environmental Microbiology. Edited by C.J. Hurst. ASM Press, Washington, D.C., pp. 391-399.
- Davis, J.L. and Annan, A.P. 1977. Electromagnetic detection of soil moisture: Progress report 1. Canadian Journal of Remote Sensing, **3**: 76-86.
- Davis, J.L. and Chudobiak, W.J. 1975. *In situ* meter for measuring relative permittivity of soils. Paper 75-1A, Geol. Surv. Can., pp. 75-79.
- Dean, T.J., Bell, J.P. and Baty, A.J.B. 1987. Soil moisture measurement by an improved capacitance technique, part 1: Sensor design and performance. Journal of Hydrology, **93**: 67-78.
- Dindal, D.L. 1990. Soil Biology Guide. John Wiley & Sons, Inc., New York, NY.
- Dodge, R. 2001. Water measurement manual. Revised Reprint, Water Resources Technical Publication, Water Resources Research Laboratory, U.S. Department of the Interior Bureau of Reclamation.
- Dunn, G.H. and Phillips, R.E. 1991. Macroporosity of a well drained soil under no-till and conventional tillage. Soil Science Society of America Journal, **55**: 817-823.
- Environment Australia. 1998. Landform design for rehabilitation. *In* Best practice environmental management in mining, ISBN 0 642 54546 4. Available from <http://www.ea.gov.au/industry/sustainable/mining/booklets/landform/index.html>.
- Evans, K.G., M.J. Saynor, G.R. Willgoose, and S.J. Riley. 2000. Post-mining landform evolution modelling: 1. Derivation of sediment transport model and rainfall-runoff model parameters. Earth Surface Processes and Landforms, **25**: 743-763.
- Evans, K.G. and Willgoose, G.R. 2000. Post-mining landform evolution modelling: 2. Effects of vegetation and surface ripping. Earth Surface Processes and Landforms, **25**: 803-823.
- Ewers, B.E., Gower, S.T., Bond-Lamberty, B., and Wang, C.K. 2005. Effects of stand age and tree species on canopy transpiration and average stomata conductance of boreal forests. Plant Cell Environment, **28**: 660-678.
- Farnes, P.E., Peterson, N.R., Goodison, B.E., and Richards, R.P. 1982. Metrication of manual soil sampling equipment by Western Snow Conference Metrication Committee. *In* Proceedings of the 39<sup>th</sup> Eastern Snow Conference (same as Proceedings of the 50<sup>th</sup> Western Snow Conference), Reno, Nevada, pp. 120-132.



- Fellows, C.R. and Brezonik, R.L. 1980. Seepage flow into Florida lakes. *Water Resources Bulletin*, **16**: 635-641.
- Feng, M. and Fredlund, D. 1993. Calibration of thermal conductivity sensors with consideration of hysteresis. *Canadian Geotechnical Journal*. **40**: 1048-1055.
- Flanagan, D.C. and Livingston, S.J. 1995. Water Erosion Prediction Project (WEPP) Version 95.7 User Summary. *In* WEPP User Summary, NSERL Report No 11, July.
- Fredlund, D.G. and Rahardjo, H. 1993. *Soil Mechanics for Unsaturated Soils*. John Wiley & Sons, Inc., New York, NY.
- Fredlund, D.G. and Wong, D.K.H. 1989. Calibration of thermal conductivity sensors for measuring soil suction. *Geotechnical Testing Journal*, **12**: 188-194.
- Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, NJ.
- Fritschen, L.J. 1966. Evapotranspiration rates of field crops determined by the Bowen ratio method. *Agronomy Journal*, **58**: 339-342.
- Fritschen, L.J. and Qian, P. 1990. Net radiation, sensible and latent heat flux densities on slopes computed by the energy balance method. *Boundary-Layer Meteorology*, **53**: 163-171.
- Fritschen, L.J. and Simpson, J.R. 1989. Surface energy and radiation balance systems: general description and improvements. *Journal of Applied Meteorology*, **28**: 680-689.
- Fuchs, M. and Tanner, C.B. 1967. Evaporation from a drying soil. *Journal of Applied Meteorology*, **6**: 852-857.
- Gardner, W. and Kirkham, D. 1952. Determination of soil moisture by neutron scattering. *Soil Science*, **78**: 391-401.
- Gaskin, G.J., and Miller, J.D. 1996. Measurement of soil water content using a simplified impedance measuring technique. *Journal of Agricultural Engineering Research*, **63**: 153-160.
- Gatto, L.W. 2000. Soil freeze/thaw induced changes to a simulated rill: Potential impacts on soil erosion. *Geomorphology*, **32**: 147-160.
- Gawande, N.A., Reinhart, D.R., Thomas, P.A., McCreanor, P.T., and Townsend, T.G. 2003. Municipal solid waste *in situ* moisture content measurement using an electrical resistance sensor. *Waste Management*, **23**: 667-674.
- Geesing, D., Bachmaier, M. and Schmidhalter, U. 2004. Field calibration of a capacitance soil water probe in heterogeneous fields. *Australian Journal of Soil Research*, **42**: 289-299.
- Gellis, A.C. 1998. Characterization and evaluation of channel and hillslope erosion on the Zuni Reservation 1992-95. U.S. Geological Survey Water-Resources Investigation 97-4292.

- Gerlach, T. 1967. Hillslope troughs for measuring sediment movement. *Revue Geomorphologie Dynamique*, **4**: 1.
- Giakoumakis, S.G. and Tsakiris, G.P. 1999. Quick estimates of hydraulic conductivity in unsaturated sandy loam soil. *Irrigation and Drainage Systems*, **13**: 349-359.
- Goodison, B.E., Ferguson, H.L., and McKay, G.A. 1981. Measurement and data analysis. *In Handbook of snow: principles, processes, management and use. Edited by D.M. Gray and D.H. Male. Pergamon Press, Toronto, Canada, pp. 191-274.*
- Gray, D.M. 1973. *Handbook on the Principles of Hydrology*. Water Information Center, Port Washington, NY.
- Greacen, E.L., Correll, R.L., Cunningham, R.B., Johns, G.G., and Nicholls, K.D. 1981. Calibration. *In Soil water assessment by the neutron method. Edited by E.L. Greacen. CSIRO, Victoria, Australia, pp. 50-72.*
- Grosh, J.L. and Jarrett, A.R. 1994. Interrill erosion and runoff on very steep slopes. *Transactions of the ASAE*, **37**: 1127-1133.
- Gupta, R.K., Dickinson, W.T., and Patni, G.J. 1993. Comparison of saturated hydraulic conductivity measured by various field methods. *American Society of Agricultural Engineers*, **36**: 51-55.
- Haigh, M.J. 2000. The aims of land reclamation. *In Reclaimed Land: Erosion Control, Soils and Ecology. Edited by M.J. Haigh. Rotterdam: Brookfield: A.A. Balkema, pp 1-20.*
- Hancock, G.R., Evans, K.G., Willgoose, G.R., Moliere, D.R., Saynor, M.J., and Loch, R.J. 2000. Medium-term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model. *Australian Journal of Soil Research*, **38**: 249-263.
- Hancock, G.R., Loch, R.J., and Wilgoose, G.R. 2003. The design of post-mining landscapes using geomorphic principles. *Earth Surface Processes and Landforms*, **28**: 1097-1110.
- Haug, M.D., Barbour, S.L., and Longval, P. 1988. Design and construction of a prehydrated sand-bentonite liner to contain brine. *Canadian Journal of Civil Engineering*, **15**: 955-963.
- Hill, R. 1999. How good is your water measurement?. Utah State University Extension, Electronic Publishing, AG/BIE/WM/01. Available from <http://www.extension.usu.edu/files/engrpubs/biewm01.pdf>.
- Hillel, D. 1980. *Applications to Soil Physics*. Academic Press, New York, NY.
- Holl, K.D., Zipper, C.E., and Burger, J.A. 2001. Recovery of native plant communities after mining. Virginia State University – Virginia Cooperative Extension, Publication No. 460-140. Available from [www.ext.vt.edu/pubs/mines/460-140/460-140.html](http://www.ext.vt.edu/pubs/mines/460-140/460-140.html).

- Horn, C.P., So, H.B., and Mulligan, D.R. 1998. Waste rock dump rehabilitation research project: Stability of outer dump surfaces. Report prepared for Kidston Gold Mine Ltd., September.
- Hurst, C.J. 1997. Water microbiology in public health. *In* Manual of Environmental Microbiology. Edited by C.J. Hurst. ASM Press, Washington, D.C., pp. 131-242.
- INAP (International Network for Acid Prevention). 2003. Evaluation of the long-term performance of dry cover systems, final report. Prepared by O'Kane Consultants Inc., Report No. 684-02, March.
- Industry Canada. 2005. Athabasca oil sands process: Mining. Available from <http://collections.ic.gc.ca/oil/index1.htm>.
- Irwin, R.W. 1997. Handbook of Drainage Principles. Publication 73, RP-01-97-500, Ontario Ministry of Agriculture and Food.
- ISO (International Standards Organization). 1983. Liquid flow measurement in open channels. Handbook 16, International Standards Organization.
- Jones, H.G., Archer, N., Rotenberg, E., and Casa, R. 2003. Radiation measurement for plant ecophysiology. *Journal of Experimental Biology*, **54**(384): 879-889.
- Kaya, A., Lovell, C.W., and Altschaeffl, A.G. 1994. The effective use of time domain reflectometry (TDR) in geotechnical engineering. *In* Time Domain Reflectometry in Environmental, Infrastructure and Mining Applications. United States Bureau of Mines Special Publication No. 19-94, pp. 398-409.
- Kapolka, N.M. and Dollhopf, D.J. 2000. Effect of slope gradient and plant growth on soil loss on reconstructed high altitude slopes. *In* Proceedings of the 2000 Billings Land Reclamation Symposium, Billings, MT, March 20-24, pp. 75-84.
- Keller, B.R., Everett, L.G., and Marks, R.J. 1990. Effects of access tube material and grout on neutron probe measurements in the vadose zone. *Groundwater Monitoring Review*, Winter 1990, pp. 96-100.
- Kessler, S. 2006. Salinity profiles in reconstructed soils over saline-sodic waste from the oil sands industry. M.Sc. Thesis (in progress), Department of Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Keys, M.-J., McKenna, G., Sawatsky, L. and Van Meer, T. 1995. Natural analogs for sustainable reclamation landscape design at Syncrude. *In* Proceedings of Environmental Management for Mining. Edited by COGEMA Resources Inc. Saskatoon, SK, Canada, October 25-27.
- Koerner, R.M. and Daniel, D.E. 1997. Final Covers for Solid Waste Landfills and Abandoned Dumps. ASCE Press. Reston, VA.

- Koliasev, F.H. 1941. Measures for the control of evaporation of soil moisture. *Sbornik Rabot po Agronomi sheskoe Fiziki*, **3**: 67-81.
- Krahn, J. 2004. Seepage modelling with SEEP/W – An engineering methodology. GEO-SLOPE International Ltd., May.
- Kramer, J.H., Cullen, S.J. and Everett, L.G. 1992. Vadose zone monitoring with the neutron moisture probe. *Groundwater Monitoring Review*, Summer 1992, pp. 177-187.
- Lafren, J.M., Elliot, W.J., Simanton, J.R., Holzhey, C.S., and Kohl K.D. 1991. WEPP soil erodibility experiments for rangeland and cropland soils. *Journal of Soil and Water Conservation*, **46**: 39-44.
- Lane, P.N.J. and MacKenzie, D.H. 2001. Field and laboratory calibration and test of TDR and capacitance techniques for indirect measurement of soil water content. *Australian Journal of Soil Research*, **39**(6): 1371-1386.
- Larcher, W. 1995. *Physiological Plant Ecology*, Third Edition. Springer-Verlag. New York, N.Y.
- Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography*, **22**(1): 140-147.
- Lee, D.R., and Cherry, J.A. 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. *Journal of Geological Education*, **27**: 6-10.
- Lefebvre, R., Hockley, D. Smolensky J., and Gélinas, P. 2001. Multiphase transfer processes in waste rock piles producing acid mine drainage 1: Conceptual model and system characterization. *Journal of Contaminant Hydrology*, **52**: 137-164.
- Leskiw, L.A. 1998. Land capability classification for forest ecosystems in the oil sands region. Alberta Environment, available from the Information Center, Main Floor, 9820 – 106 St. Edmonton, Alberta, Canada T5K 2J6; Email: env.infocent@gov.ab.ca; Website: <http://www3.gov.ab.ca/env/info/infocentre/PubDtl.cfm?ID=1010>.
- Lewis, J.B. 1987. Measurements of groundwater seepage-flux into a coral reef: Spatial and temporal variation. *Limnology and Oceanography*, **32**: 1165-1169.
- Litaor, M.I. 1988. Review of soil solution samplers. *Water Resources Research*, **24**: 727-733.
- Loch, R.J. 2000. Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong, Queensland. *Australian Journal of Soil Research*, **38**: 299 – 312.
- Loch, R.J., Robotham, B.G., Zeller, L., Materman, N., Orange, D.N., Bridge, B.J., Sheridan, G., and Bourke, J.J. 2001. A multi-purpose rainfall simulator for field infiltration and erosion studies. *Australian Journal of Soil Research*, **39**: 599-610.

- Look, B.G. and Reeves, I.N. 1992. The application of time domain reflectometry in geotechnical instrumentation. *Geotechnical Testing Journal*, **15**: 277-283.
- Luk, S., and Hamilton, H. 1986. Experimental effects of antecedent moisture and soil strength on rainwash erosion of two luvisols, Ontario. *Geoderma*, **37**: 29-43.
- Machulla, G., Bruns, M.A., and Scow, K. M. 2005. Microbial properties of mine spoil materials in the initial stages of soil development. *Soil Science Society of America Journal*, **69**: 1069-1077.
- Maidment, D.R. (Ed.) 1993. *Handbook of Hydrology*. McGraw-Hill Inc., New York, NY.
- Marcucci, D.J. 2000. Landscape history as a planning tool. *Landscape and Urban Planning*, **49**: 67-81.
- McCuen, R.H. 1989. *Hydrologic Analysis and Design*. Prentice-Hall of Canada Inc, Toronto, ON.
- McKeague, J.A. 1978. *Manual of soil sampling and method analysis*. Second Edition, Canadian Society of Soil Science.
- McKenna, G.T. 2002. Sustainable mine reclamation and landscape engineering. Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada.
- McKenna, G.T. and Dawson, R. 1997. Closure planning practise and landscape performance at 57 Canadian and US mines. Draft, July 18.
- McLeod, M.K., Daniel, H., Faulkner, R., and Murison, R. 2004. Evaluation of an enclosed portable chamber to measure crop and pasture actual evapotranspiration at small scale. *Agricultural Water Management*, **67**: 15-34.
- Meiers, G.P. 2002. The use of field measurements of hydraulic conductivity to characterize the performance of reclamation soil covers with time. M.Eng. Report, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Meiers, G.P., Barbour, S.L., and Meiers, M.K. 2003. The use of field measurements of hydraulic conductivity to characterize the performance of reclamation soil covers with time. *In Proceedings of the 6<sup>th</sup> International Conference on Acid Rock Drainage*, Cairns, Qld, Australia, July 12-18, pp. 1085-1090.
- Meiers, G.P., Barbour, S.L., Qualizza, C.V. 2006. The use of *in situ* measurement of hydraulic conductivity to provide an understanding of cover system performance over time. *In Proceedings of the 7<sup>th</sup> International Conference for Acid Rock Drainage*, St. Louis, MO, USA, March 26-30, pp. 1259-1272.
- MEND 2.21.2. 1993. Field evaluation of the effectiveness of engineered soil covers for reactive tailings: Volume I – Laboratory and field tests. October.

- MEND 2.21.4. 2004. Design, construction and performance monitoring of cover systems for waste rock and tailings. July.
- MEND 2.22.2c. 1999. Études sur les barrières sèches construites à partir de résidus miniers. Phase II – Essais en place. November.
- MEND 4.1.1. 1989. Field sampling manual for reactive sulphide tailings. November.
- MEND 4.5.1-1. 1994. Waste Rock Sampling Techniques. June.
- MEND 4.5.4. 1997. Guideline document for monitoring acid mine drainage. October.
- MEND 5.4.2b. 2001. MEND manual Volume 2 – Sampling and analysis. January.
- MEND 5.4.2d. 2001. MEND manual Volume 4 – Prevention and control. February.
- Messing, I., and Jarvis, N.J. 1993. Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. *Journal of Soil Science*, **44**: 11-24.
- Montes, S. 1998. *Hydraulics of Open Channel Flow*. ASCE Press, Reston, VA.
- Morgan, K.T., Parsons, L.R., Wheaton, T.A., Pitts, D.J., and Obreza, T.A. 1999. Field calibration of a capacitance water content probe in fine sand soils. *Soil Science Society of America Journal*, **63**: 987-989.
- Myers, W.L. and Shelton, R.L. 1980. *Survey methods for ecosystem management*. A Wiley-Interscience Publication, John Wiley & Sons, New York, NY.
- Myrold, D.D. 1997. Quantification of nitrogen transformations. *In Manual of environmental microbiology*. Edited by C.J. Hurst. ASM Press, Washington, D.C., pp. 445-452.
- Nawrot, J. and Smout, G. 1993. The new Kathleen Mine – soil cover refuse demonstration: 20 years later. *In Proceedings of the 10<sup>th</sup> Annual National Meeting, American Society for Surface Mining and Reclamation, Spokane, WA, May 16-19*, pp. 845-864.
- Nichol, C., Beckie, R., and Smith, L. 2002. Evaluation of uncoated and coated time domain reflectometry probes for high electrical conductivity systems. *Soil Science Society of America Journal*, **66**: 1454-1465.
- Nichol, C., Smith, L., and Beckie, R. 2003. Long-term measurement of matric suction using thermal conductivity sensors. *Canadian Geotechnical Journal*, **40**: 587-597.
- Ogram, A. and Feng, X. 1997. Methods of soil microbial community analysis. *In Manual of environmental microbiology*. Edited by C.J. Hurst. ASM Press, Washington, D.C. pp. 422-430.
- Ohmura, A. 1982. Objective criteria for rejecting data for Bowen ratio flux calculations. *Journal of Applied Meteorology*, **21**: 595-598.

- OKC (O’Kane Consultants Inc.). 2004. Tom Price Operations, acid rock drainage control field test plots, monitoring report no. 2 for year one. Report #662/3-02 prepared for Rio Tinto, Hamersley Iron Pty. Ltd., October.
- O’Kane, M. 1996. Instrumentation and monitoring of an engineered soil cover system for acid generating mine waste. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- O’Kane, M. and Barbour, S.L. 2003. Field performance of lysimeters used to evaluate cover systems for mine waste. *In Proceedings of the 6<sup>th</sup> International Conference on Acid Rock Drainage*, Cairns, Qld, Australia, July 12-18, pp. 327-339.
- Oke, T.R. 1987. *Boundary Layer Climates*, Second Edition. Routledge, New York, NY.
- Paltineau, I.C. and Starr, J.L. 1997. Real-time soil water dynamics using multisensor capacitance probes: laboratory calibration. *Soil Science Society of America Journal*, **61**: 1576-1585.
- Pankurst, C.E., Doube, B.M., and Gupta, V.V.S.R. (Eds.) 1997. *Biological Indicators of Soil Health*. CAB International, Oxon, UK.
- Paramasivam, S., Alva, A.K., and Fares, A. 1997. Vadose zone soil solution sampling techniques to investigate pollutant transport on soils. *Trends Soil Science*, **2**: 115-136.
- Paulsen, R.J., Smith, C.F., O’Rourke, D., and Wong, T.-F. 2001. Development and evaluation of an ultrasonic ground water seepage meter. *Ground Water*, **39**: 904-911.
- Penman, H.L. 1948. Natural evapotranspiration from open water, bare soil and grass. *Proceedings of the Royal Society of London, Series A*. **193**: 120-146.
- Phene, C.J., Allee, C.P. and Pierro, J. 1989. Measurement of soil matric potential and real time irrigation scheduling. *Agricultural Water Management*, **16**(3): 173-185.
- Phene, C.J., Hoffman, G.J. and Rawlins, S.L. 1971a. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: I. Theory and sensor construction. *Soil Science Society of America Proceedings*, **35**: 27-33.
- Phene, C.J., Rawlins, S.L. and Hoffman, G.J. 1971b. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: II. Experimental results. *Soil Science Society of America Proceedings*, **35**: 225-229.
- Qian, P. and Schoenau, J. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. *Canadian Journal of Soil Science*, **82**: 9-21.
- Qualizza, C., 2003. Instrumented watersheds research rationale. *Watershed Research Annual Meeting*, Edmonton, AB, Canada, January 6-7.
- Quine, T.A., Govers, G., Walling, D.E., and Zhang, X. 1997. Erosion processes and landform evolution on agricultural land – New perspectives from Caesium-137 measurements and

- topographic-based erosion modelling. *Earth Surface Processes and Landforms*, **22**: 799-816.
- Reid, M.E. 1997. Slope instability caused by small variations in hydraulic conductivity. *Journal of Geotechnical and Geoenvironmental Engineering*, **123**(8): 717-725.
- Reynolds, W.D., Elrick, D.E., and Clothier, B.E. 1985. The constant head well permeameter: effect of unsaturated flow. *Soil Science*: **139**(2): 172-180.
- Reynolds, W.D. 1993. Saturated hydraulic conductivity field measurements. *In Soil sampling and methods of analysis. Edited by M. R. Carter. Canadian Society of Soil Science*, **56**: 599-605.
- Reynolds, W.D., and Elrick, D.E. 1991. Determination of hydraulic conductivity using a tension infiltrometer. *Soil Science Society of America Journal*, **55**: 633-639.
- Reynolds, W.D., Elrick, D.E., and Topp, G.E. 1983. A reexamination of the constant head well permeameter method for measuring saturated hydraulic conductivity above the water table. *Soil Science*, **136**: 250-265.
- Richards, B.N. 1987. *The Microbiology of Terrestrial Ecosystems*. John Wiley & Sons, Inc., New York, NY.
- Ritz, K., Dighton, J., and Giller, K.E. (Eds.) 1994. *Beyond the Biomass: Compositional and Functional Analysis of Soil Microbial Communities*. John Wiley & Sons, Inc., West Sussex, UK.
- Ritzema, H.P., Kselik, R.A.L. and Chanduvi, F. 1996. Irrigation water management training manual no. 9: Drainage of irrigated lands. Water Resources, Development and Management Service, Land and Water Development Division, Food and Agriculture Organization of the United Nations (FAO), Viale delle Terme di Caracalla, I-00100 Rome, Italy. Available from <http://www.fao.org/ag/aql/aglw/cropwater/training.stm>.
- Roberts-Pichette, P. and Gillespie, L. 1999. Terrestrial vegetation biodiversity monitoring protocols. EMAN Occasional Paper Series, Report No. 9. Ecological Monitoring Coordinating Office, Burlington, Ontario. Available from <http://www.eman-rese.ca/eman/ecotools/protocols/terrestrial/vegetation/intro.html>.
- Robertson, A. and Shaw, S. 2005. Mine closure – Introduction. Available from <http://technology.infomine.com/enviromine/issues/closure.html>.
- Robertson, G.P., Bledsoe, C.S., Coleman, D.C., and Sollins, P. (Eds.) 1999. *Standard Soil Methods for Long Term Ecological Research*. Oxford University Press, New York, NY.
- Robichaud, P.R. and Brown, R.E. 2002. Silt fences: An economical technique for measuring hillslope soil erosion. General Technical Report RMRS-GTR-94. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available from <http://216.48.37.142/pubs/viewpub.jsp?index=4543>.



- Ruygrok, P. 1988. Evaluation of the gamma and neutron radiation scattering and transmission methods for soil density and moisture determination. *Geotechnical Testing Journal*, **11**: 3-19.
- Sands, G. 2001. Agricultural drainage: Soil water concepts. University of Minnesota Extension Service Bulletin BU-07644. Available from <http://www.extension.umn.edu/distribution/cropsystems/DC7655.html>.
- Sasich, J. 1998. Monitoring effectiveness of forest practices and management systems: Surface erosion – Study design guidelines, procedures and methods. Prepared for the Timber/Fish/Wildlife (TFW) Monitoring Advisory Group, Cooperative Monitoring Committee of the Washington Timber/Fish/Wildlife Program. Available from <http://www.nwifc.wa.gov/TFW/documents.asp>.
- Sattler, P. and Fredlund, D.G. 1989. Use of thermal conductivity sensors to measure matric suction in the laboratory. *Canadian Geotechnical Journal*, **26**: 491-498.
- Sawatsky, L. 2004. Reclamation strategies that address mine closure drainage. *In Proceedings of The Canadian Institute Mine Reclamation Conference, Vancouver, BC, Canada, November 8-9.*
- Scanlon, B.R., Andraski, B.J., and Bilskie, J. 2002. Miscellaneous methods for measuring matric or water potential. *In J.H. Dane and G.C. Topp (ed.) Methods of Soil Analysis: Part 4 – Physical Methods. Book Ser. No. 5. SSSA, Madison, WI, pp. 643–670.*
- Schor, H.J. and Gray, D.H. 1995. Landform grading and slope evolution. *Journal of Geotechnical Engineering*, **121**: 729-734.
- Seginer, I. 1966. Gully development and sediment yield. *Journal of Hydrology*, **4**: 236-253.
- SER (Society for Ecological Restoration International). 2005. Ecological restoration – A means of conserving biodiversity and sustaining livelihoods. Available from <http://www.ser.org/content/Globalrationale.asp>.
- SER (Society for Ecological Restoration International Science & Policy Working Group). 2004. The SER international primer on ecological restoration. [www.ser.org](http://www.ser.org) & Tucson: Society for Ecological Restoration International.
- Shaw, R.D. and Prepas, E.E. 1989. Anomalous, short term influx of water into seepage meter. *Limnology and Oceanography*, **34**: 1343-1351.
- Sholkovitz, E., Herbold, C. and Charette, M. 2003. An automated dye-dilution based seepage meter for the time-series measurement of submarine groundwater discharge. *Limnology and Oceanography: Methods*. **1**: 16-28.

- Shukla, M. K., Lal, R., and Ebinger, M. 2005. Physical and chemical properties of minespoil eight years after reclamation in northeastern Ohio. *Soil Science Society of America Journal*, **69**: 1288-1297.
- Shukla, M. K., Lal, R., Underwood, J., and Ebinger, M. 2004. Physical and hydrological characteristics of reclaimed minesoils in southeastern Ohio. *Soil Science Society of America Journal*, **68**: 1352-1359.
- Silvestri, V., Sarkis, G., Bekkouche, N., Soulie, M. and Tabib, C. 1991. Laboratory and field calibration of a neutron depth moisture gauge for use in high water content soils. *Geotechnical Testing Journal*, **14**: 64-70.
- Smith, C.D. 1995. *Hydraulic Structures*. University of Saskatchewan Printing Service, Saskatoon, SK.
- SoilMoisture Equipment Corp. 1986. *Guelph Permeameter 2800KI Operating Instructions*. SoilMoisture Equipment Corporation, Santa Barbara, CA.
- Spaans, E.J. and Baker, J.M. 1995. Examining the use of time domain reflectometry for measuring liquid water content in frozen soil. *Water Resources Research*, **31**: 2917-2925.
- Stannard, D.I. 1992. Tensiometers – Theory, construction, and use. *Geotechnical Testing Journal*, **15**: 48-58.
- St-Arnaud, L.C. and Woyshner, M.R. 1992. Hydrological evaluation of the thickened tailings disposal system at Kidd Creek Division, Falconbridge Ltd. Report V2-1-T01, Centre de technologie Noranda, Pointe Claire, Quebec.
- Stotzky, G. 1997. Quantifying the metabolic activity of microbes in soil. *In Manual of environmental microbiology*. Edited by C.J. Hurst. ASM Press, Washington, D.C., pp. 453-458.
- Sturhan, N. (Ed.) 1997. *Watershed analysis manual*. Washington Forest Practice Board, Washington Department of Natural Resources, Olympia, WA. Available from <http://www.dnr.wa.gov/forestpractices/watershedanalysis/manual/>.
- Sumner, M.E. and Miller, W.P. 1996. Cation exchange capacity and exchange coefficients. *In Methods of Soil Analysis – Part 3: Chemical Methods*. Edited by D.L. Sparks. SSSA, ASA, Madison, WI.
- Swanson, D.A. 1995. Predictive modelling of moisture movement in engineered soil covers for acid generating mine waste. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Taniguchi, M. and Fukuo, Y. 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. *Ground Water*, **31**: 675-679.

- Taniguchi, M., and Iwakawa, H. 2001. Measurement of submarine groundwater discharge rates by a continuous heat-type automated seepage meter in Osaka Bay, Japan. *Journal of Groundwater Hydrology*, **42**: 271-277.
- Tanner, C.B. 1960. Energy balance approach to evapotranspiration from crops. *Soil Science Society of America Proceedings*, **24**: 1-9.
- Tognetti, R., Longobucco, A., Miglietta, F., and Raschu, A. 1998. Transpiration and stomatal behaviour of *Quercus ilex* plants during the summer in a Mediterranean carbon dioxide spring. *Plant Cell Environment*, **21**: 613-622.
- Topp, G.C. and Davis, J.L. 1985. Measurement of soil water content using time domain reflectometry (TDR): A field evaluation. *Soil Science Society of America Journal*, **49**: 19-24.
- Topp, G.C., Davis, J.L., and Annan, A.P. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, **16**: 574-582.
- Toy, T.J. 1977. Hillslope form and climate. *Geological Society of America, Bulletin*, **88**: 16-22.
- Toy, T.J. and Hadley, R.F. 1987. *Geomorphology and Reclamation of Disturbed Lands*. Academic Press, Inc., Florida, USA.
- Tugel, A.J., Lewandowski, A.M., and Happ-vonArb, D. (Eds.) 2000. *Soil Biology Primer*. Rev. Ed. Ankeny, Iowa: Soil and Water Conservation Society. Available from [http://soil.usda.gov/sqi/soil\\_biology\\_primer.htm](http://soil.usda.gov/sqi/soil_biology_primer.htm).
- USDA (United States Department of Agriculture). 1984. Snow survey sampling guide. Agriculture Handbook 169, Natural Resources Conservation. Available from <http://www.wcc.nrcs.usda.gov/factpub/ah169/ah169.htm>.
- USDA (United States Department of Agriculture). 1999. Sampling vegetation attributes. Interagency Technical Reference 1734-4, Bureau of Land Management, National Business Center, Denver, Colorado. Available from <http://www.blm.gov/nstc/library/pdf/samplveg.pdf>.
- USDA & MSU (United States Department of Agriculture and Mississippi State University). 1999. Silt fence. *In* Water Related Best Management Practices in the Landscape – Water Runoff Management, Watershed Science Institute United States Department of Agriculture and Mississippi State University, October. Available from <http://abe.msstate.edu/csd/NRCS-BMPs/water.html>.
- USDA (United States Department of Agriculture). 2000. Nuclear gauge train-the-trainer course. USDA Radiation Safety Staff, Beltsville, Massachusetts. Available from <http://www.cprl.ars.usda.gov/wmru/pdfs/gauge-1.pdf>.

- US EPA (United States Environmental Protection Agency). 1998. Lake and reservoir bioassessment and biocriteria: Technical guidance document. Washington, DC. Available from <http://www.epa.gov/owow/monitoring/tech/lakes.html>.
- US EPA (United States Environmental Protection Agency). 2001. Methods for collection, storage, and manipulation of sediments for chemical and toxicological analyses: Technical manual. EPA-823-B-01-002, Office of Water, Washington, DC. Available from <http://www.epa.gov/waterscience/cd/collection.html>.
- Veissman, W., and Lewis, G.W. 1996. Introduction to Hydrology, Fourth Edition. HarperCollins College Publishers, New York, NY.
- Veldkamp, E. and O'Brian, J. 2000. Calibration of a frequency domain reflectometry sensor for humid tropical soils of volcanic origin. *Soil Science Society of America Journal*, **64**: 1529-1553.
- Walker, L.R. (Ed.). 1999. Ecosystems of Disturbed Ground. Elsevier Press, New York, NY.
- Wall, S.N. 2005. Geochemical reactions in overburden. M. Sc. Thesis, Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Waters, P. and O'Kane, M.A. 2003. Mining and storage of reactive shale at BHP Billiton's Mt. Whaleback Mine. *In Proceedings of the 6<sup>th</sup> International Conference on Acid Rock Drainage*, Cairns, Qld, Australia, July 12-18, pp. 155-161.
- Watson, K.W. and Luxmoore, R.J. 1986. Infiltration, macroporosity, and mesoporosity distributions on two forested watersheds. *Soil Science of America Journal*, **52**: 329-335.
- Way, D.S. 1973. Terrain Analysis. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pennsylvania, USA.
- Weaver, R.W. (chair of editorial committee). 1994. Methods of soil analysis. Part 2: Microbial and biochemical properties. Soil Science Society of America, Madison, WI.
- Webster, J.G. 1999. The measurement, instrumentation, and sensors handbook. CRC Press, Boca Raton, FL.
- Whalley, W.R. 1993. Considerations on the use of time domain reflectometry (TDR) for measuring soil water content. *Journal of Soil Science*, **44**: 1-9.
- White, D.C., Pinkart, H.C., and Ringelberg, D.B. 1997. Biomass measurements: Biochemical approaches. *In Manual of environmental microbiology*. Edited by C.J. Hurst. ASM Press, Washington, D.C., pp. 91-101.
- Willgoose, G.R. 2000. User manual for SIBERIA (Version 8.10). The University of Newcastle and Landtech Landform Technologies (A Division of TUNRA), July.

- Willgoose, G.R., Bras, R.L., and Rodriguez-Iturbe, I. 1991. A physically based coupled network growth and hillslope evolution model: 1 Theory. *Water Resources Research*, **27**: 1671-1684.
- Wilson, G.W., Fredlund, D.G. and Barbour, S.L. 1994. Coupled soil-atmosphere modelling for soil evaporation. *Canadian Geotechnical Journal*, **31**: 151-161.
- Wong, D. 1985. A study of brine flow through saturated-unsaturated potash tailings. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Wong, L.C. and Haug, M.D. 1991. Cyclical closed system freeze/thaw permeability testing of soil liner and cover materials. *Canadian Geotechnical Journal*, **28**: 784-793.
- Woo, M.-K. 1997. A guide for ground-based measurement of the arctic snow cover. Report prepared for the Climate Research Branch of the Meteorological Service of Canada. Available from <http://www.msc.ec.gc.ca/crysys/education/snow/woo.pdf>.
- Woyshner, M.R. and St-Arnaud, L.C. 1994. Hydrogeological evaluation and water balance of a thickened tailings deposit near Timmins, ON, Canada. *In* Proceedings of the 3<sup>rd</sup> International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, Vol. 2, pp. 198-207.
- Wright, J. and Sands, G. 2001. Planning an agricultural subsurface drainage system. University of Minnesota Extension Service Bulletin BU-07685. Available from <http://www.extension.umn.edu/distribution/cropsystems/DC7685.html>.
- Yoder, J. 1999. Plumbing the depths of open-channel flow measurements. Control for the Process Industries. July.
- Zazueta, F. and Xin, J. 1994. Soil moisture sensors. Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, University of Florida. Bulletin 292. April.
- Zegelin, S.J., White, I. and Jenkins, D.R. 1989. Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry. *Water Resources Research*, **25**: 2367-2376.
- Zegelin, S.J., White, I. and Russell, G.F. 1992. A critique of the time domain reflectometry technique for determining field soil water content. *In* Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. Soil Science Society of America Special Publication No. 30, pp. 187-208.
- Zelege, T.B. and Si, B.C. 2005. Parameter estimation using the falling head infiltration model: Simulation and field experiment. *Water Resources Research*, **41**(2): Art. No. W02027.
- Zhang, H., Schroder, J.L., Pittman, J.J., Wang, J.J., and Payton, M.E. 2005. Soil salinity using saturated paste and 1:1 soil to water extracts. *Soil Science Society of America Journal*, **69**(4): 1146-1151.

- Zhao, D., Reddy, K.R., Kakani, V.G. and Reddy, V.R. 2005. Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. *European Journal of Agronomy*. **22**: 391-403.
- Zuberer, D.A. 1994. Recovery and enumeration of viable bacteria. *In* *Methods of Soil Analysis*. Part 2. Microbiological and biochemical properties. *Edited by* J.M. Bigham. Soil Science Society of America, Madison, WI.
- Zucker, L.A. and Brown, L.C. (Eds.) 1998. Agricultural drainage: Water quality impacts and subsurface drainage studies in the Midwest. Ohio State University Extension Bulletin 871. Available from <http://ohionline.osu.edu/b871/index.html>.

**MACRO-SCALE COVER DESIGN AND  
PERFORMANCE MONITORING  
MANUAL  
MEND 2.21.5**

**APPENDIX A**

**Details for Monitoring Methods  
and Instrumentation**





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## **A1 SURFACE HYDROLOGIC MONITORING**

### **A1.1 Precipitation**

Measurement of precipitation is the most crucial of site-specific meteorological measurements as it is the primary input of the hydrologic cycle (Viessman and Lewis, 1996; Bras, 1990). Rainfall should be measured at several locations on a watershed to quantify spatial differences in rainfall depth and intensity. Snowfall should be measured with an all-season precipitation gauge and in addition, regular depth/density measurements of the snowpack should be collected with increasing frequency as spring freshet approaches.

A variety of instruments and methods have been developed for the measurement of precipitation. The three most common are: 1) non-recording gauges; 2) recording gauges; and 3) the snow survey method. Snow surveys are discussed in detail in Section A1.1.1 (Snowmelt). Non-recording and recording gauges are discussed in Sections A1.1.2 and A1.1.3.

#### *A1.1.1 Snowmelt*

In many areas of Canada and the world, snowfall is a significant portion of the precipitation. After snow has fallen, it can be relocated by wind, sublimate back into the atmosphere, or remain on the ground until snowmelt occurs in the spring. Spring snowmelt is a critical component of the water balance for a watershed, particularly in many northern climates where it is the dominant source of runoff to streams and wetlands. The measurement of snow precipitation is also discussed in Section A1.1.2, but this section deals with predicting the amount of snowmelt that will be contributed to the surface of the watershed during spring melt.

The most accurate method of predicting snowmelt is to conduct snow surveys just prior to springmelt. Snow surveys are commonly done manually, but some large-scale snow surveys can be done using thermal infrared or passive microwave data from satellites (Veissman and Lewis, 1996). Manual snow surveys provide information on the depth, density and water equivalent of the snowpack over the area in question. A series of sampling locations (typically a grid) must first be mapped out over the watershed, with each location typically 15 to 30 m apart. At each location, the depth of snowpack is recorded and a core is obtained.

There are a number of variations of method and equipment used for snow surveys (Woo, 1997). Generally, a snow sampler of some type is used to obtain the snow cores. These can be metal or plastic tubes with a steel cutter on one end comprised of steel teeth to cut through dense snow or thick ice lenses. The snow sampler often consists of multiple lengths that can be threaded together depending on the total snow depth. Other design features that may be available are some type of handle for pushing and turning the sampler in the snow. The sampler may be

slightly wider at the top to allow the snow core to slide out easily. Depending on the manufacturer, snow samplers may vary in diameter from 4 cm to 7 cm. Farnes *et al.* (1982) found that the larger the diameter, the more accurate the snow core due to the larger volume and less compression of snow.

In addition to taking a snow core, the snowpack depth is also measured during a snow survey. Depending on the depth and density of the snow, a ruler can be used, but more commonly a steel rod is used. In some instances, the depth is read off the snow sampler itself before removal from the snowpack.

The snow core is used to determine the snow density, water equivalent, and snow quality. The snow core can either be weighed in the field or it can be bagged and taken to a laboratory to be weighed. These measurements are used to compute the snow-water equivalent (SWE) as follows:

$$\text{SWE} = 0.01 \rho_s d_s \quad [\text{A1.1}]$$

where,

SWE = snow-water equivalent (mm),

$\rho_s$  = density of the snowpack ( $\text{kg/m}^3$ ), and

$d_s$  = depth of the snowpack (cm).

Maidment (1993) reports that an average density of  $100 \text{ kg/m}^3$  for new snowfall is often assumed, which gives 1 unit of water for every 10 units of snowfall.

Snow survey methodology varies depending on the snow data needs for a particular climate and watershed. The United States Department of Agriculture Natural Resources Conservation Service (1984) and the British Columbia Ministry of the Environment Water Management Branch (1981) both provide manuals on snow survey methods. Woo (1997) also discusses snow survey techniques.

#### A1.1.2 Non-Recording Gauges

The standard rain gauge is the simplest, most accurate, and least expensive instrument for measuring rainfall. The gauge consists simply of a cylindrical container and a calibrated measuring stick, which may be a part of the gauge. The disadvantage of this instrument is that it only records total accumulated depth (i.e. the rainfall intensity is not recorded) and data collection and emptying of the gauge is undertaken manually.

All non-recording snow gauges measure SWE directly. The most common non-recording snow gauge in Canada is the MSC Nipher snow gauge (Goodison *et al.*, 1981). The gauge consists of

a cylindrical container and an inverted bell-shaped shield to reduce wind turbulence around the orifice. The gauge is mounted far enough above the snow surface to minimize the accumulation of blowing snow in the gauge. Snow caught by this gauge is melted and measured in a special graduated glass cylinder to obtain the water equivalent. Although the MSC Nipher gauge is simple to use and relatively accurate, human intervention is required at least once per day to retrieve the cylinder and determine the SWE.

### *A1.1.3 Recording Gauges*

The most popular type of recording gauge for measuring rainfall is the tipping-bucket rain gauge (Bras, 1990). In general, this gauge consists of two balanced buckets (each nominally 0.2 mm capacity) that tip back and forth as they are filled in turn by rainfall directed to them by a collection funnel. As the balance swings about its pivot, a pulse is sent through a lead wire to a datalogger where the time and quantity of bucket tips are recorded. The advantages of this gauge are that rainfall intensity is recorded and minimal human intervention is required. The disadvantage of this technique is that it is considerably more expensive than the standard rain gauge.

The tipping-bucket rain gauge can also measure SWE using a special snowfall adapter. The adapter consists of a large open cylindrical reservoir of antifreeze with a thin layer of mineral oil floating on the surface to reduce evaporation and sublimation. Above the reservoir is a shield to reduce wind turbulence. As snow falls into the reservoir, it melts and displaces the antifreeze. The displaced antifreeze flows through an overflow and is directed into the tipping-bucket rain gauge, where an equivalent water volume is measured. Regular maintenance is required on this device because the antifreeze is continuously diluted as the snow melts in the reservoir. It is also imperative that the liquid in the reservoir stay at a height just below the overflow. Mineral oil is often used to minimize evaporation from the surface of the antifreeze; however, evaporation and sublimation may still occur and can reduce the volume of liquid in the reservoir very quickly. An additional complication is that it is difficult to secure the snowfall adapter to such an extent as to control the unit from swaying due to wind. Hence, the reservoir tends to overtop the outlet during windy conditions, causing “false” bucket tips during periods of no precipitation. In addition, this prevents bucket tips from occurring during subsequent snowfall events until an equivalent volume of precipitation occurs to replace the antifreeze that had overtopped due to swaying.

The weighing-type precipitation gauge is another common type of recording gauge and is capable of measuring both rain and SWE (Goodison *et al.*, 1981). Precipitation is collected in a catch bucket mounted on a mechanical balance at the base of a cylindrical container. The weighing-type gauge is also equipped with a shield to help reduce wind turbulence over the gauge orifice. A datalogger is used to record the mass measured by the mechanical balance at specified time intervals - the smaller the time interval, the more accurate the determination of precipitation rates. Antifreeze must be added to the catch bucket in cold climates to melt falling snow and prevent freezing of precipitation in the catch bucket (Goodison *et al.*, 1981). These gauges have been left

unattended in remote locations for up to one year; however, weighing-type gauges should be serviced at least every three months to ensure reliable, continuous operation (Goodison *et al.*, 1981). The disadvantage of this device is that it is considerably more expensive than all other recording and non-recording gauges and requires AC power at the monitoring location.

## **A1.2 Runoff**

Runoff is a complex process and therefore accurate measurement of local surface runoff from a natural soil system is challenging. Small-scale field test plots typically have runoff collection systems that divert all runoff into a lined drainage channel where flow can be measured using tipping buckets, collection barrels or weirs. For watershed-scale monitoring, this type of collection system is often not practical. Geomembrane liners and collection ditches are costly to install at a watershed-scale and are not part of the natural landscape.

Runoff can be approximated by measuring streamflow from the outlet of a watershed. Streamflow can be classified as permanent, intermittent, or ephemeral (Maidment, 1993). Ephemeral streams are those that flow only after rainfall or snowmelt events. These streams provide the most direct measurement of runoff rates. Permanent or intermittent streams include water from other hydrological processes such as baseflow and interception and consequently do not provide direct measurements of runoff (Maidment, 1993).

Streamflow is typically measured using either velocity measurement or stage measurement (McCuen, 1989). Velocity measurement involves measuring the flow velocity at a number of locations along the cross-section of the stream using a velocity-measuring device such as a Pitot tube, dynamometer, or current meter (Viessman and Lewis, 1996). This method is best suited to large rivers or permanent streams in which the flow rates are more constant.

Stage measurement is where the flow rate of a stream is related to the elevation of the water. Stage measurement can either use the natural streambed, or it can involve the construction of measurement structures. For a natural streambed, a staff gauge or water level is used to determine the height of water at various known flow rates (measured using a velocity measurement device). An empirical stage-discharge curve is then determined to predict the flow rate based on water level.

Flow rate measurement structures are the most common method used for measuring flow rates in small, ephemeral streams and are therefore the most practical method for measuring runoff from small watersheds. These structures have a known stage-discharge relationship, which can be applied without detailed measurement of the streamflow. There are a variety of flow-measurement structures, but weirs and flumes are those most commonly used in runoff measurement applications. Detailed descriptions of flow rate measurement methods for open-



channel flow can be found in Dodge (2001), International Standards Organization (ISO, 1983), Gray (1973), Ackers *et al.* (1978), Bos *et al.* (1991), and Montes (1998).

Weirs act like a dam in the channel and force the water to flow over an obstruction. The height of the water as it flows over the weir is directly related to the flow rate. Flumes change the area and slope of the channel to force the water to increase in velocity; the level of the water rises in the channel in relation to the increase in velocity and the water level is directly related to the flow rate. These two flow rate measurement structures are described in further detail below followed by an overview of field instrumentation available for monitoring weir water levels.

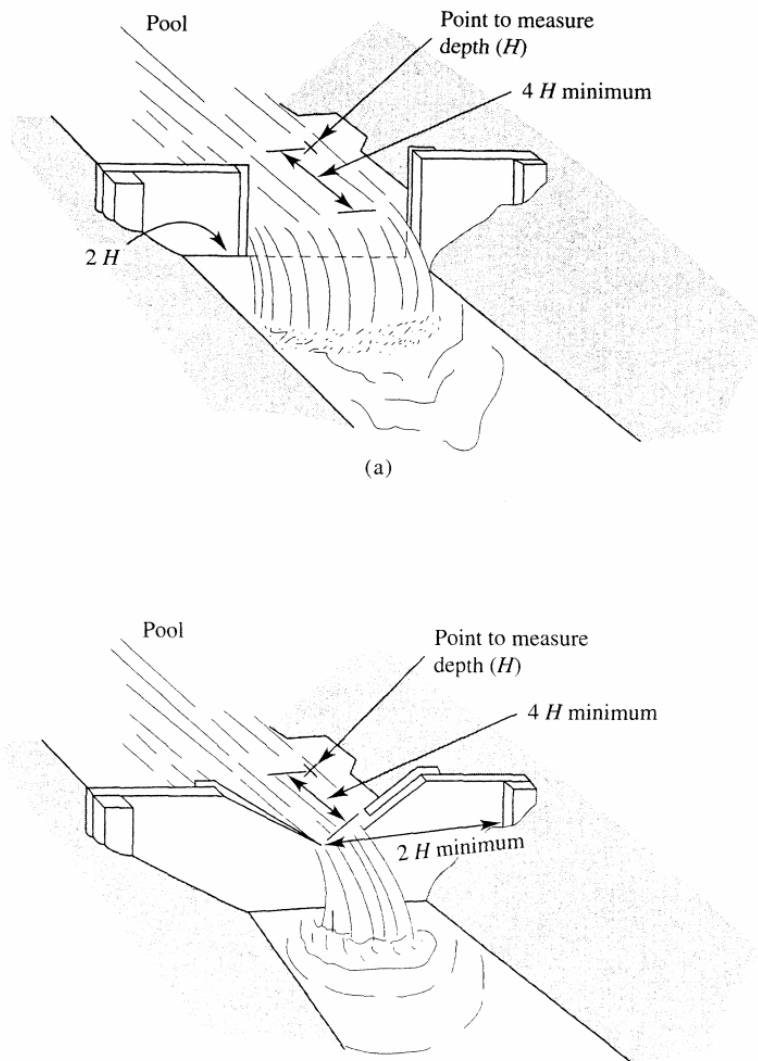
#### A1.2.1 Weirs

The most commonly used weir types are the V-notch weir and the rectangular weir (Veissman and Lewis, 1996). These two structures are illustrated in Figure A1.1. V-notch weirs provide good accuracy over a range of flow rates and the design lends itself to winter heating due to a small water surface area (Gray, 1973). The V-notch weir is limited in its capacity to pass a heavy sediment load or where surface debris can collect at the notch. The rectangular weir is better suited to passing sediment and debris, but accuracy is reduced at low flow rates. The rectangular weir is less suited to winter heating than the V-notch weir. An experimental non-dimensional coefficient of discharge, commonly denoted as  $C_d$ , is used in weir flow calculations to calculate actual flow. The  $C_d$  takes into consideration surface tension, viscosity of the liquid, approach velocity, and contraction of flow; development of this coefficient can be found in Smith (1995).

An alternative to the V-notch weir is the zero-height V-notch weir. This weir has the benefits of the V-notch weir but there is no head build-up behind the weir plate and therefore it allows some sediment to pass (Smith, 1995). With no head build-up, the zero-height V-notch weir is not a true weir, but is sometimes referred to as a lateral contraction, similar to a flume.

#### A1.2.2 Flumes

The most commonly used flume is the Parshall flume, which consists of a specially shaped open channel flow section that can be installed within a channel such as a ditch or canal to measure flow rate (Figure A1.2). The Parshall flume is used primarily for fixed flow monitoring, but for low flow applications such as runoff measurement, the H-flume is the most suitable (Dodge, 2001). The H-flume is different from the Parshall flume in that the vertical walls converge at the downstream end of the flume forming a notch that gets progressively wider with distance from the bottom. Flumes have the advantage of low head loss and the ability to pass sediments compared to weirs; however, they are more costly to fabricate and install (Hill, 1999).

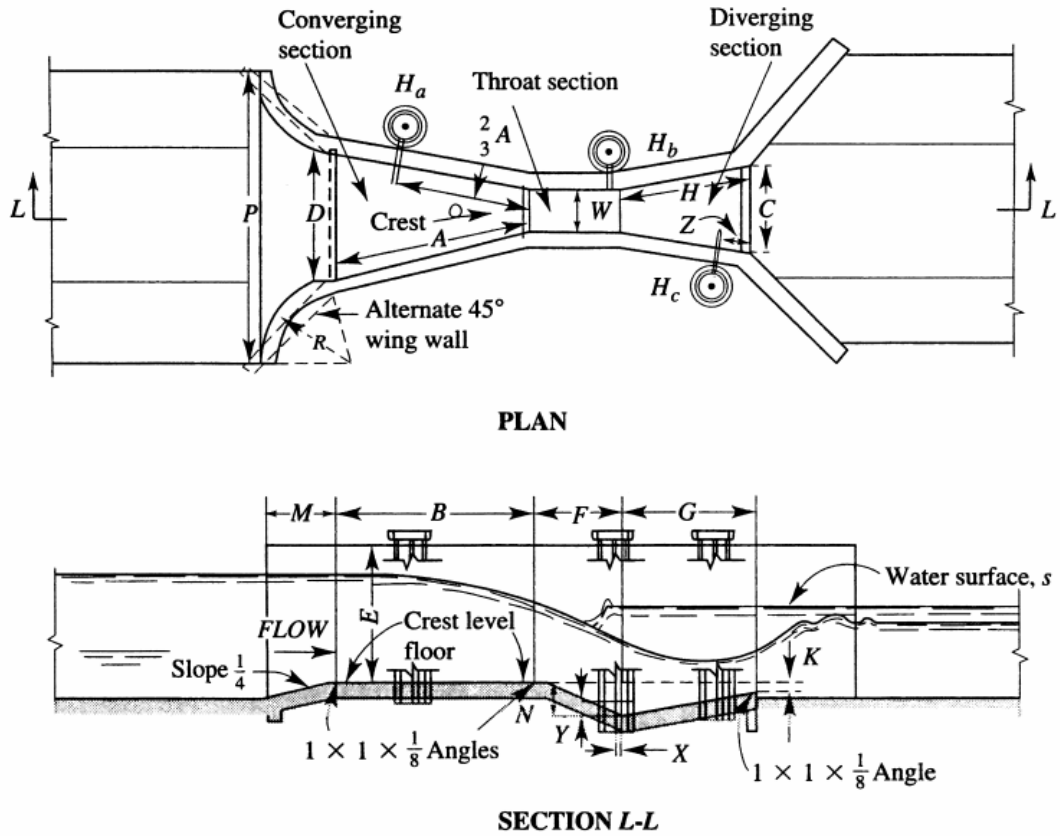


**Figure A1.1** Rectangular weir (a) and V-notch weir (b) (from Veissman and Lewis, 1996).

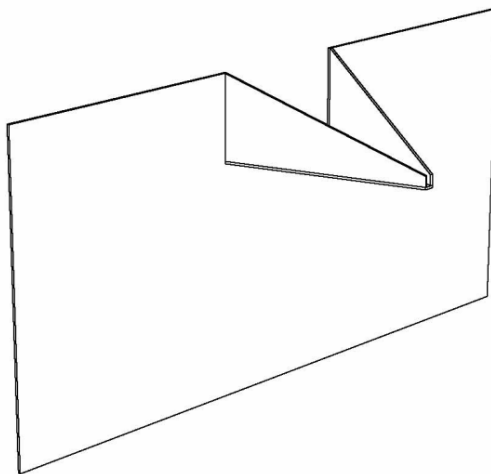
### A1.2.3 Water Level Measurement Instruments

There are a number of methods available for measuring the height of water in weirs or flumes. Manual methods such as a staff gauge or calibrated rod or ruler can be used but these require manual reading and consequently do not provide accurate results for flows that are highly variable. Ultrasonic sensors, flotation systems, pressure transducers, bubblers, and electrical methods can be controlled using dataloggers or chart recorders to provide automatic, frequent measurements (Yoder, 1999).

Ultrasonic sensors are mounted above the upstream floor of the weir or flume. The sensor sends out a sound wave that is reflected off the water surface. The time it takes for the sound wave to return to the sensor is used to accurately measure the height of water.



(a)



(b)

**Figure A1.2** (a) Parshall flume (from Veissman and Lewis, 1996) and (b) H-flume (adapted from Dodge, 2001).

Flotation systems use a float in combination with a pivoting arm or a cable and a pulley to translate the water height to a mechanical movement. These are often used with chart recorders.

Bubblers use a bubbler tube located at the bottom of the flow stream. Bubbles are released at a fixed rate and carried away by the streamflow. A pressure transducer measures the air pressure required to maintain the fixed bubble rate. The water level is proportional to this pressure.

Electrical methods use the water to complete an electrical circuit, and therefore predict the depth of water based on whether or not the circuit is complete.

The most common instruments used for measuring water levels for runoff applications are ultrasonic sensors or flotation systems. Ultrasonic sensors are rugged and suitable for use in all weather conditions. As opposed to the other sensor types, ultrasonic sensors are not in contact with the water, and therefore are not susceptible to damage from freeze/thaw, debris, or erosion. Ultrasonic sensors are also ideal for automated data collection with a datalogger.

### **A1.3 Pond Monitoring**

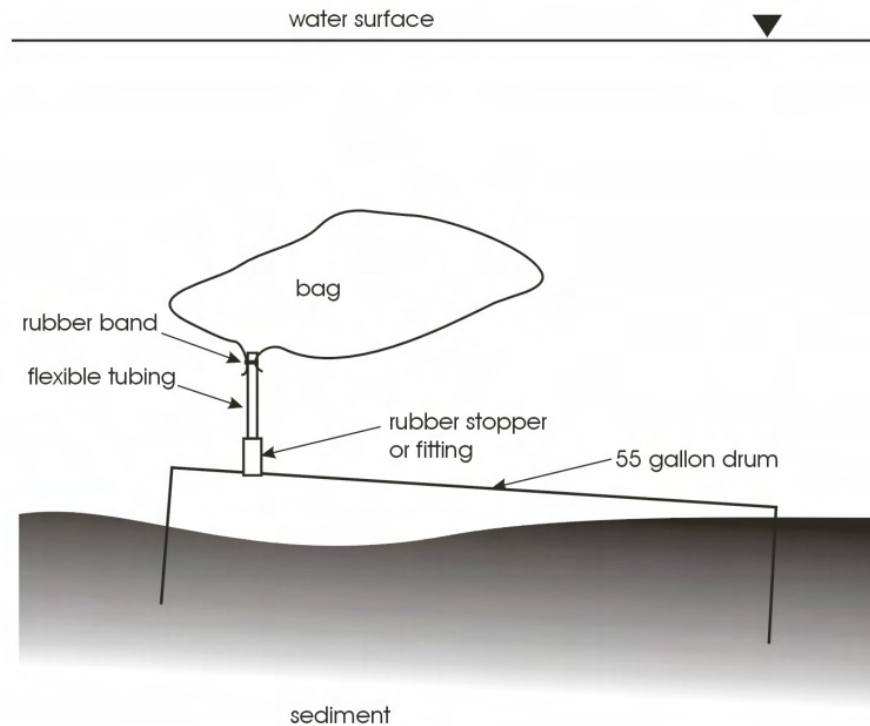
To understand watershed hydrology, it is important to monitor any ponds or surface water bodies that exist within the watershed. Water can be contributed to the ponds from precipitation, runoff, and seepage and can be removed from the ponds by seepage and evaporation. Typical hydrologic pond monitoring consists of water level measurement and seepage monitoring. Evaporation is usually estimated from pan evaporation rates measured as part of a meteorological monitoring program.

Water level measurement is typically done manually using a staff gauge or some other type of depth measurement. A staff gauge consists of a graduated post that is sunk into the centre of a pond to a depth that ensures that the post does not move from season to season. The depth of the water can be monitored by reading the graduation on the post that corresponds to the water level. This monitoring can often be completed from shore and should be done frequently. Automated depth measurement systems are available, although less common.

Seepage monitoring is less straightforward than water level monitoring. The goal of seepage monitoring is to measure the rate of seepage into or out of a pond. Mini-piezometers are sometimes used to track hydraulic gradients across the seepage face and then used to estimate the seepage face (Lee and Cherry, 1978). For direct measurement of seepage, seepage meters are the most commonly used method.

Seepage meters range from simplistic manual devices to complex automated devices. The most common seepage meter consists of one end of a 55-gallon drum inserted into the pond sediment (Lee, 1977), as shown in Figure A1.3. The drum is vented to a plastic bag. As seepage enters the drum from the sediments beneath, water is displaced into the plastic bag. The rate at which

the plastic bag fills with water can then be used to calculate the seepage rate into the pond. If seepage is out from the pond, then the bag can be pre-filled with water and the rate at which the bag drains can be used to determine the seepage.



**Figure A1.3** Simple seepage meter (from Lee, 1977).

Although simplistic, these seepage meters require careful installation and regular monitoring to obtain good results. As shown in Figure A1.3, it is important to insert the 55-gallon drum at an angle with the vented side raised slightly. This allows any gases trapped during installation to vent prior to placing the bag on the outlet port (Lee, 1977). The bags must be sufficiently lightweight to allow the displaced water to open the bag, but must be durable enough to hold up during removal, placement, and transport. Balloons and condoms have been used with success as well as bags. The bag volume must be chosen carefully and checked regularly to ensure that it does not reach capacity. Lee (1977), Lee and Cherry (1978), Boyle (1994), Lewis (1987), and Fellows and Brezonik (1980) give additional information on the use of this type of seepage meter.

It has been found that the barrel and bag type of seepage meters are somewhat prone to errors. Shaw and Prepas (1989) show that the rate of water displacement into the bag is not constant and is higher when the bag is empty and lower when it is close to full. They recommend that the bag be pre-filled with a small volume of water to increase accuracy of measurement. Belanger and Montgomery (1992) also discuss errors associated with bag type seepage meters based on results of tank tests.

Complex automated seepage meters are also available. These have been developed largely for higher rate seepage fluxes or where a finer time resolution is required, such as for measuring tidal fluxes (Sholkovitz *et al.*, 2003). In general, these devices allow seepage to flow through a chamber where the flow rate is measured indirectly. Taniguchi and Fukuo (1993) and Taniguchi and Iwakawa (2001) developed a heat-pulse based instrument where flow rate is estimated by the timed transmission of heat pulses as measured by downstream thermistors in a flow tube (Sholkovitz *et al.*, 2003). An acoustic (ultrasonic) seepage meter has been developed by Paulsen *et al.* (2001), which is based on the timed perturbation of sound in a moving fluid (Sholkovitz *et al.*, 2003). Sholkovitz *et al.* (2003) use the timed dilution of dye, as measured by the change in absorbance of the fluid, to calculate the flow rate.

In typical watershed pond applications, the simple barrel and bag-type seepage meter typically give suitable results for water balance determinations.

#### **A1.4 Evapotranspiration**

Evapotranspiration is comprised of two components, evaporation and transpiration, both of which may influence the soil moisture content. Evaporation is an abiotic process occurring due to a vapour pressure gradient between the soil and the atmosphere. Transpiration is a biotic process that refers to the uptake and subsequent release of moisture into the atmosphere by plants.

A variety of methods are available for measuring evaporation and evapotranspiration rates from the ground surface. The most commonly utilized methods can be classified as direct measurement methods or micrometeorological methods. Atmometers, evaporation pans, and weighing lysimeters are the most widely used methods for direct measurement of evaporation and evapotranspiration. The most commonly used micrometeorological methods are the Bowen ratio energy balance method, the aerodynamic method, the mass transport method, and the Eddy covariance method. These micrometeorological methods of measurement should be considered implicit as evaporative quantities are determined indirectly; that is, they are based either on principles of energy balance or mass transfer.

A review of the literature indicates that the three most popular methods of measuring evaporation and evapotranspiration rates are evaporation pans, weighing lysimeters, and the Bowen ratio energy balance method. Each of these methods is discussed below, along with a brief discussion on the eddy covariance method.

##### *A1.4.1 Evaporation Pan*

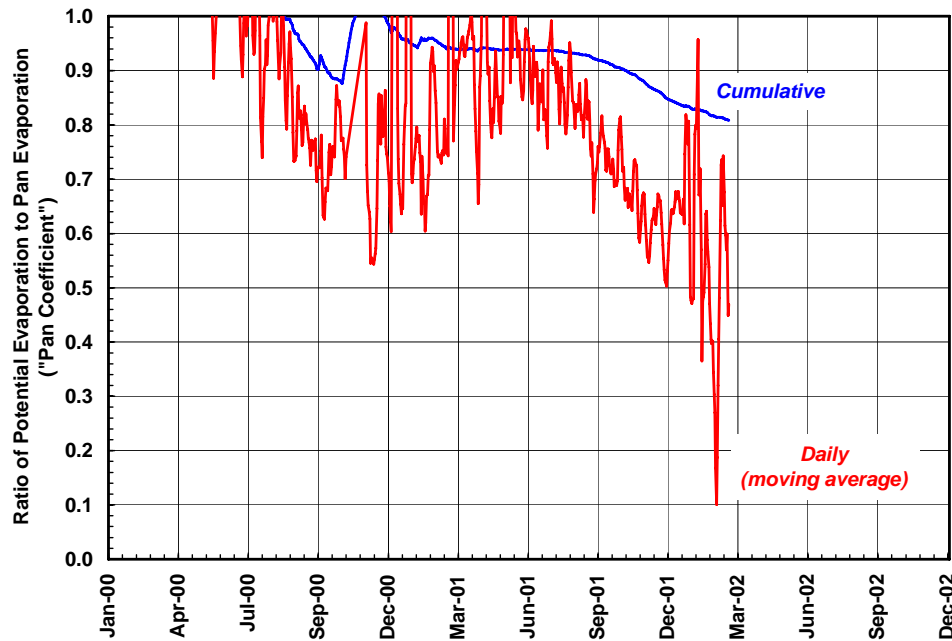
The potential evaporation (PE) is the maximum rate at which water can evaporate from a wet soil surface. It is only a function of climatic conditions. The evaporation rate decreases as the soil surface becomes unsaturated and soil conditions then become the dominant factor controlling

evaporation (Koliasev, 1941). It is important to note that evaporation pans do not provide a measure of actual evaporation (AE) because as the value of suction near the soil surface increases in response to evaporation, the vapour pressure within the soil is reduced. This reduces the vapour pressure gradients near the soil-atmosphere interface, which control the evaporation rate.

Various types of evaporation pans such as sunken pans, floating pans, and surface pans are available. The most common pan is the surface-type pan such as the Class A evaporation pan (Maidment, 1993). The Class A evaporation pan is a circular pan, 1.21 m in diameter, 0.255 m deep, made of 22-gauge galvanized metal, and generally mounted on a wooden frame 0.15 m above ground level (Maidment, 1993). The pan must be level and filled with water to 0.05 m below the rim of the pan. The water level must not drop below 0.075 m below the rim of the pan. A ruler or other graduated rod is used to measure the height of water in the pan on a regular basis. The frequency of measurement required depends on the evaporation rate. In arid climates during the summer months, for example, the pans may need to be measured and re-filled on a daily basis.

A word of caution is necessary regarding the use of an evaporation pan to characterize evaporation. Gray (1973) observed that a Class A evaporation pan overestimated the cumulative PE from a large fresh water reservoir near Weyburn, Saskatchewan by a factor of 1.25 over a six-month period. The difference was attributed to advected energy and the influence of aridity as a result of the soil surrounding the evaporation pan. Figure A1.4 illustrates the ratio of PE (as calculated based on the Penman (1948) method using collected field data) to pan evaporation (as measured at the same site using a Class A evaporation pan) for a semi-arid tropical site. The ratio is shown for both daily and cumulative values over two annual wet/dry cycles. It is evident that the ratio of PE to pan evaporation is most often less than one, decreasing to very low values by the end of this cycle of drying.

When an evaporation pan is used to measure PE, a pan coefficient is required to reduce the measured pan value to a PE value. In general, the person utilizing the data will assume a single pan coefficient for the site based on “experience” or on a selected value from the literature for similar ground cover conditions. However, Figure A1.4 shows that it can be argued the pan coefficient changes on a daily basis, likely due to a number of factors, and definitively shows that the pan coefficient changes on a seasonal basis. Therefore, the Class A evaporation pan does not provide a reliable, site-specific measurement of potential evaporation or actual evaporation.



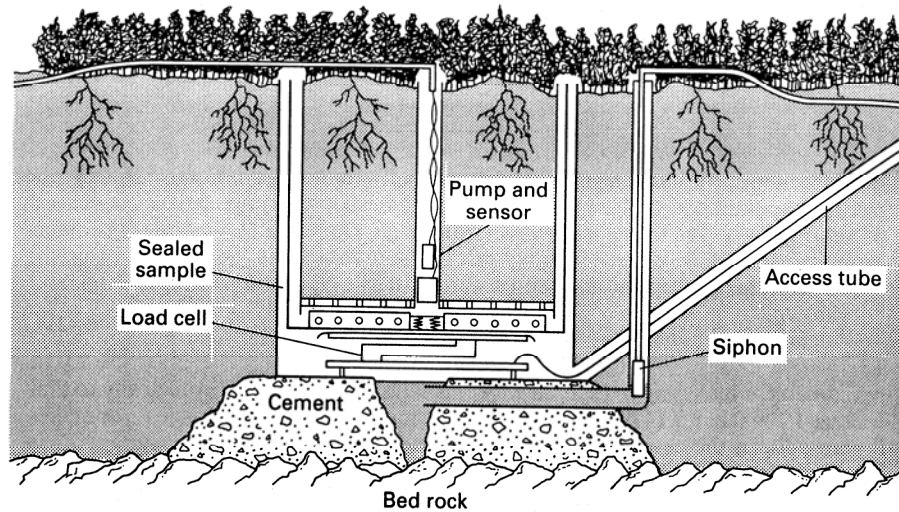
**Figure A1.4** Daily and cumulative pan coefficient for a semi-arid tropical site (from CANMET, 2002).

#### A1.4.2 Weighing Lysimeters

Weighing lysimeters have an extensive and long-established use because they provide a direct measurement of actual evapotranspiration (AET) rates (Maidment, 1993). A weighing lysimeter is a balance that measures the change in mass of a soil volume due to water loss by evapotranspiration. The apparatus is installed in the field such that its surface is flush with the ground surface. The volume of soil within the lysimeter is hydraulically isolated both vertically and horizontally from the surrounding natural soil. This allows complete delineation of the water balance; precipitation is known or measured, surface runoff is zero and deep drainage is either not permitted or measured in a collection sump. Therefore, any net change in mass is due to evapotranspiration.

Figure A1.5 shows an example of a well-designed weighing lysimeter in which vegetation is growing. Lysimeters may vary in size from 0.5 m in diameter and 1.1 m deep to 6.0 m in diameter and several metres deep. A lysimeter should contain an undisturbed sample of soil and vegetation if evapotranspiration from a lysimeter is to be representative of the surrounding area (Maidment, 1993). The spring balance at the base of the lysimeter is usually connected to a datalogger to record changes in mass. Although weighing lysimeters provide relatively accurate estimates of AET from vegetated surfaces, they are difficult and expensive to install properly. A particular feature of concern is that the soil is isolated from the deeper soil surrounding the lysimeter and therefore may not be under the same drainage conditions as the natural soil.





**Figure A1.5** A well-designed weighing lysimeter (from Maidment, 1993).

#### A1.4.3 Bowen Ratio Energy Balance Method

The Bowen ratio energy balance (BREB) method has been used for many years to determine AET rates from various land surfaces. This technique has been reviewed and tested by many researchers in the agricultural industry (e.g. Tanner, 1960; Fritschen, 1966; Fuchs and Tanner, 1967). Woysner and St-Arnaud (1994) successfully used the BREB technique to evaluate evaporation from a bare tailings surface in northern Ontario.

Bowen (1926) introduced the ratio of sensible heat flux ( $Q_H$ ) to latent heat flux ( $Q_E$ ), which has subsequently been termed the Bowen ratio,  $\beta$ . The following relationship may be used to determine  $\beta$ :

$$\beta = \frac{Q_H}{Q_E} = \gamma \frac{\Delta T}{\Delta e} \quad [A1.2]$$

where:

$$\gamma = \text{psychrometric constant, } \frac{Pc_p}{\lambda \varepsilon},$$

$P$  = atmospheric pressure (kPa),

$c_p$  = specific heat of air (kJ/kg°C),

$\lambda$  = latent heat of vapourization (kJ/kg),

$\varepsilon$  = ratio of the molecular weight of water to the molecular weight of dry air, and

$\Delta T$  and  $\Delta e$  = change in air temperature (°C) and vapour pressure (kPa), respectively, over the same height interval above the ground surface.

Typical values of  $\beta$  for various climates are listed in Table A1.1. Substituting Equation A1.2 into the surface energy balance equation, and neglecting the terms of heat storage and advection ( $Q_S$  and  $Q_A$ ), the quantity of  $Q_E$  may be computed as follows (Oke, 1987):

$$Q_E = \frac{Q^* - Q_G}{1 + \beta} \quad [A1.3]$$

where:

$Q^*$  = net radiation ( $W/m^2$ ), and

$Q_G$  = conduction of heat to or from the subsurface soil ( $W/m^2$ ).

Measurements of  $Q^*$ ,  $Q_G$ ,  $P$ , and  $T$  and  $e$  at two heights are required to estimate sensible and latent heat flux at the ground surface. Sensors for the measurement of these parameters are connected to a datalogger for the recording of average data over a specified time interval (typically 20 minutes or less). Atmospheric pressure seldom varies by more than a few percent and therefore,  $P$  may be calculated for the site elevation assuming a standard atmosphere. A schematic of the Bowen ratio monitoring system is shown in Figure A1.6.

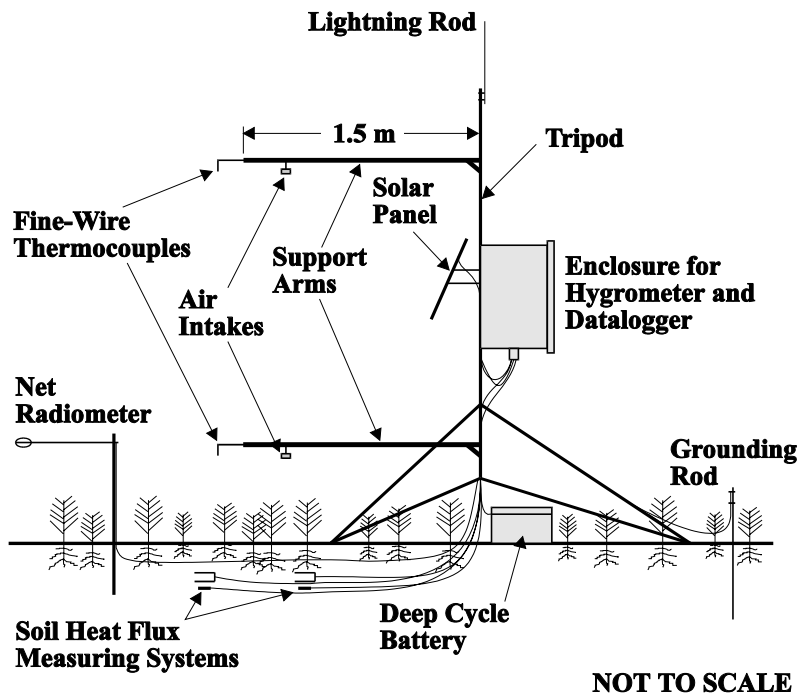
The accuracy of the BREB method depends on the validity of the following three assumptions (Fritschen and Simpson, 1989; Oke, 1987):

- 1) Steady atmospheric conditions during the observation period;
- 2) Constant energy and mass fluxes with height with no vertical convergence or divergence; and
- 3) The transfer coefficients of eddy conductivity for heat and eddy diffusivity for water vapour are numerically equal.

**Table A1.1**

Typical values of the Bowen ratio for various climates (from St-Arnaud and Woynshner, 1992).

Climatic Region	Value of $\beta$
Tropical oceans	0.1
Tropical wet jungles	0.1 - 0.3
Temperate forests and grasslands	0.4 - 0.8
Semi-arid areas	2 - 6
Deserts	10



**Figure A1.6** Schematic of the Bowen ratio monitoring system (from Ayres, 1998).

These assumptions appear to be valid when the instruments for measuring air temperature and vapour pressure are mounted close to the surface and over a large homogenous area (Fritschen and Qian, 1990).

The resolution limits of the gradient sensors lead to two main problems when interpreting the measurements (Maidment, 1993; Ohmura, 1982). The first problem is the possibility of obtaining wrong signs for the energy fluxes (e.g. confusion between evaporation and condensation). Ohmura (1982) presents the following two conditions:

$$\text{If } (Q^* + Q_G) > 0, \text{ then } \Delta T > - \left( \frac{\Delta e}{\gamma} \right), \text{ and}$$

$$\text{If } (Q^* + Q_G) < 0, \text{ then } \Delta T < - \left( \frac{\Delta e}{\gamma} \right) \quad \text{[A1.4]}$$

If Bowen ratio data do not satisfy one of these conditions, then the data are not consistent with the definition of the flux/gradient relationship and should be rejected. Ohmura (1982) encountered this problem with early morning and late afternoon data and during precipitation, when gradients are small.

The second practical problem with the BREB method is the possibility of obtaining an extremely inaccurate magnitude of the energy fluxes, even though the signs are correct. When  $\beta$  approaches -1 in Equation A1.4, the value of  $Q_E$  loses its numerical meaning. Ohmura (1982) provides the following inequality:

$$-\left(\frac{\Delta e}{\gamma}\right) - 2\left[\frac{R_e}{\gamma} + R_T\right] < \Delta T < -\left(\frac{\Delta e}{\gamma}\right) + 2\left[\frac{R_e}{\gamma} + R_T\right] \quad [A1.5]$$

where:

$R_e$  = resolution of the vapour pressure sensor, and

$R_T$  = resolution of the air temperature sensor.

If the Bowen ratio data satisfy the above inequality, then there is a high possibility that  $\beta$  will be very near -1 and therefore, the data should be excluded from evaluation. Ohmura (1982) encountered this problem at similar times as for the first problem (early morning, late afternoon and during precipitation). Fortunately, these practical problems occur during relatively unimportant times, when heat exchange at the ground surface, and therefore evapotranspiration, is low.

In summary, the BREB method is an accepted technique for estimating AET rates from large homogenous surfaces. It is the most reliable micrometeorological method in all-weather conditions (Fritschen and Simpson, 1989). The disadvantages of this technique are that monitoring systems are relatively expensive and the gradient sensors require frequent servicing to obtain representative data.

#### A1.4.4 Eddy Covariance Method

The following summary of the eddy covariance method is taken from Oke (1987).

The eddy covariance (EC) method is used to analyze vertical fluxes in the surface boundary layer and can be used to determine the fluxes of energy required to calculate evapotranspiration. Transport in the boundary layer is governed almost entirely by turbulence. A turbulent entity ( $s$ ) can be divided into two components, a mean value ( $s_{mean}$ ) and a fluctuating value ( $s'$ ) as shown in Equation A1.6:

$$s = s_{mean} + s' \quad [A1.6]$$

The mean vertical flux ( $S$ ) of this entity consists of its density ( $\rho$ ), its vertical velocity ( $w$ ), and the volumetric content of the entity ( $s$ ). Each of the properties can be broken down into a mean and fluctuating part as in Equation A1.6. Simplifications, such as assuming that air density ( $\rho$ ) is virtually constant, result in the following equation to define the mean vertical flux ( $S$ ) of this entity:

$$S = \rho \overline{w's'} \quad [A1.7]$$

The overbar denotes the time average of the instantaneous covariance of  $w$  and  $s$ . For example, using the above method, sensible ( $Q_H$ ) and latent ( $Q_E$ ) heat fluxes, can be written as follows:

$$Q_H = C_a \overline{w'T'} \quad [A1.8]$$

where:

$C_a$  = heat capacity of the air ( $J/m^3K$ ),

$w$  = vertical wind speed (m/s), and

$T$  = temperature (K);

and:

$$Q_E = L_v \overline{w'\rho'_v} \quad [A1.9]$$

where:

$L_v$  = latent heat of vapourization ( $J/kg$ ),

$w$  = vertical wind speed (m/s), and

$\rho_v$  = density of water vapour ( $kg/m^3$ ).

To determine these fluxes, it is necessary to have sensors that can measure rapid changes in vertical wind velocity as well as the entity of interest (e.g. temperature or vapour pressure). Even if the sensors can measure the rapid changes, the datalogger must also be able to read and record the data. This is the primary limitation of the eddy covariance method; the equipment required to quickly and accurately measure and record the data is expensive compared to other methods. For this reason, the eddy covariance method is primarily used in a research setting.

## **A2 SUB-SURFACE HYDROLOGIC MONITORING**

Sub-surface hydrologic monitoring involves measuring and tracking the movement of water through the various soil layers of the watershed. Water that infiltrates into the ground surface may be utilized by vegetation, it may evaporate back into the atmosphere, it may move downslope as lateral drainage or interflow, or it may continue downwards as deep percolation or groundwater recharge. Measurement techniques for measuring soil moisture content, soil suction, and net percolation are discussed in the following section.

### **A2.1 Soil Moisture Content**

Measurements of soil moisture are fundamental to the development of a water balance for a watershed. Soil moisture profiles in the waste and cover layers allow the volume of water stored within the profile to be quantified, and can be interpreted to define the rates and direction of water movement in response to plant root uptake, evaporation, percolation, and interflow.

The five most common methods of measuring the *in situ* moisture content of soils are:

- 1) the gravimetric method;
- 2) the nuclear method;
- 3) time domain reflectometry (TDR);
- 4) frequency domain reflectometry (FDR); and
- 5) the electrical capacitance method.

Each of these methods is discussed below.

#### *A2.1.1 Gravimetric Method*

The gravimetric water content of a soil sample can be easily and accurately determined in the laboratory, as specified in ASTM D2216-92 (ASTM, 1992). A soil sample is dried to a constant mass in an oven at 110°C, until there is no more variation in the mass of the sample. The loss of mass due to drying is considered to be water. The gravimetric water content ( $w$ ) is computed using the mass of water ( $M_w$ ) and the mass of the dry sample ( $M_s$ ) where  $w = M_w/M_s$ . Gravimetric water content can be converted to volumetric water content by knowing the dry density of the soil.

The disadvantage of using the gravimetric method for field monitoring is that it is a destructive method in that a sample of the soil must be taken for every depth and time of measurement. Consequently, this method is time consuming and cannot be automated. Frequent sampling for water content will also alter the homogeneity of the soil profile at a study site. In addition, gravimetric water contents cannot be converted to volumetric water contents without a measurement of the dry bulk density.

### A2.1.2 Nuclear Method

The use of the neutron moisture probe for measuring *in situ* soil water content was established in the agricultural industry (Gardner and Kirkham, 1952). However, in recent years environmental monitoring has increased the use of the neutron method to other fields. Wong (1985) successfully used a neutron moisture probe to measure the fluid content of potash tailings. O'Kane (1996) used this measurement technique to monitor the performance of an engineered soil cover system for sulfidic mine waste in terms of degree of saturation. The neutron moisture probe has gained wide acceptance because the method is non-destructive, relatively fast and can be performed at any time (Silvestri *et al.*, 1991). The disadvantage of the neutron method is that it cannot distinguish chemical species (e.g. leachate from water) (Kramer *et al.*, 1992).

The measurement principles for the neutron probe have been described in detail elsewhere (Silvestri *et al.*, 1991; Kramer *et al.*, 1992) and are reviewed briefly here. Neutron moisture gauges (Figure A2.1) contain a source of fast neutrons and a detector of slow neutrons. When the fast or high-energy neutrons emitted from the source strike a molecule of similar mass (e.g. hydrogen) within the soil, the neutrons lose energy and slow down. This process is referred to as thermalization. The slow neutrons rebound back towards the probe and are absorbed by the nucleus of the gas in the probe. When the slow neutrons enter the nucleus of the gas, a higher energy state results, and emitted photons can then be detected as electrical pulses with an electronic counting device. After processing, this signal is known as the gauge reading. The gauge reading is an indication of the volumetric water content (regardless of whether it is in the form of liquid or ice) of the surrounding medium, providing proper calibration procedures have been performed.

Access tubes must be installed into the soil to use the neutron moisture probe. A hole with the proper diameter must be created in the soil profile prior to installing the access tube. If the diameter is too large, the resulting space between the outside wall of the access tube and the soil will allow moisture to migrate along the void. If the diameter is not large enough, soil may compress and distort along the sides of the access tube. In both cases, the resulting readings from the neutron moisture probe will not be representative of actual soil moisture conditions (O'Kane, 1996).

The material used for the access tube influences the results obtained from the neutron moisture probe (Keller *et al.*, 1990). Steel or PVC access tubes mask the true water content of the surrounding soil as they reduce the counts that would otherwise have been obtained from a borehole with no casing. Aluminium tubing is generally the preferred material for access tube installation because aluminium is virtually transparent to neutrons and does not affect sensitivity (Greacen *et al.*, 1981).



**Figure A2.1** Neutron moisture gauge.

Proper calibration of the neutron moisture probe is crucial to its successful use (Silvestri *et al.*, 1991). Calibration curves traditionally are determined in the laboratory or in the field by measuring the neutron counts from a given probe in a soil at two or more known volumetric water contents, and fitting these with a linear regression model (Kramer *et al.*, 1992). Such a regression takes the form:

$$\theta_w = m (CR) + b \quad [A2.1]$$

where:

- $\theta_w$  = volumetric water content,
- $m$  = slope of the calibration curve,
- $CR$  = count ratio, and
- $b$  = intercept on the vertical axis.

The count ratio is the ratio of the gauge reading to a standard count. The standard count represents the gauge reading while in the wax shield surrounding the source and is a means of ensuring noise is not affecting the count (Silvestri *et al.*, 1991). The standard count should be



performed prior to every measurement session. Taking the standard count on a frequent basis reduces the chance of using a damaged gauge. As an accuracy check, the density and moisture standard counts should be within 1% and 2% respectively of the prior four readings. If the standard is outside these limits, the gauge should be tested more closely (USDA, 2000).

The value of *CR* is largely dependent on volumetric water content; however, it can also be affected by other soil properties, such as the dry bulk density of the soil, and by other chemical components of the soil (Greacen *et al.*, 1981). The inclusion of organic materials in the soil may raise concentration levels of bound hydrogen, carbon, and nitrogen to an abnormally high level and thereby produce a high apparent water content reading. On the other hand, the presence of neutron-absorbing elements (e.g. iron, potassium, manganese, boron, chlorine) decreases the thermal neutron density in the vicinity of the source (Burn, 1964). The gauge reading therefore decreases with increasing concentration of elements of high absorption capacity in the soil. The advantage of field calibration is that all factors affecting neutron probe response, other than moisture content, can be ignored because they are covered in an unbiased fashion in the field calibration (Greacen *et al.*, 1981).

Further calibration and measurement concerns arise due to the radius or sphere of influence (i.e. effective volume of measurement). The radius of influence may vary from 10 cm to 25 cm depending on the concentration of hydrogen in the area (Ruygrok, 1988). In other words, the radius of influence is largest for regions of low water content. Natural soil systems usually have relatively low degrees of saturation near the surface and as a result the sphere of influence may extend past the soil surface. Therefore, near surface measurements during dry soil conditions may result in lower measured water contents than is actually present (O'Kane, 1996).

Other complications with the neutron moisture probe are related to the nuclear source. Operators of the probe must be trained to use the probe properly because there is a risk of exposure to radiation. The probe is considered a hazardous material and requires permitting and placards for transportation, and must be inspected annually to ensure that it meets all safety requirements.

### *A2.1.3 Time Domain Reflectometry*

The early uses of time domain reflectometry (TDR) were in locating breaks in cables and transmission lines. Davis and Chudobiak (1975) moved the application of TDR to soils for the measurement of water content. Over the past 20 years, TDR has been used extensively in the fields of agriculture (Davis and Annan, 1977; Topp and Davis, 1985), geotechnical engineering (Look and Reeves, 1992; Kaya *et al.*, 1994) and environmental monitoring (St-Arnaud and Woyshner, 1992; Benson *et al.*, 1994; Ayres, 1998). This measurement technique has gained wide acceptance because it measures *volumetric* water content in a non-destructive manner, provides an immediate result, and can be automated.

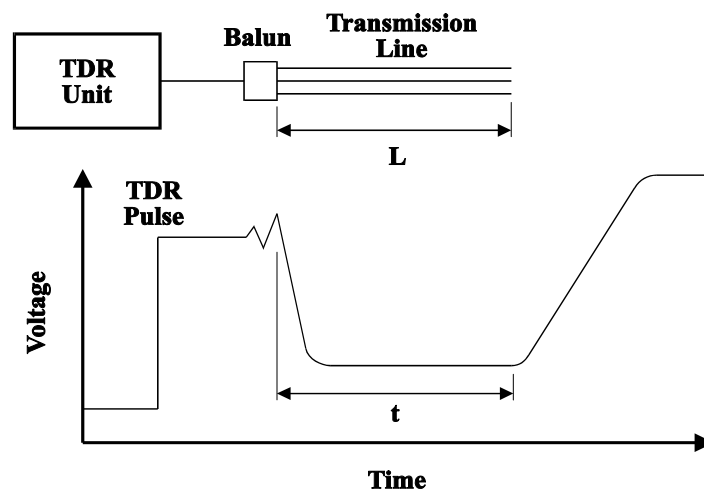
The principles behind measurement of soil moisture content using TDR have been described in detail by Topp *et al.* (1980), Zegelin *et al.* (1992) and others, and are reviewed only briefly here. TDR involves a rapidly rising voltage pulse propagated down a cable, through the soil and reflected back. The measurement of travel time ( $t$ ) through the soil – transmission line allows for the computation of the apparent dielectric constant ( $K_a$ ) of the soil as follows:

$$K_a = \left( \frac{ct}{2L} \right)^2 \quad [A2.2]$$

where:

- $c$  = velocity of light in a vacuum ( $3 \times 10^8$  m/s),
- $L$  = length of the soil - transmission line (m), and
- $t$  = time required for transmission (s).

Figure A2.2 shows the instrument components and idealized output trace of the TDR soil moisture content measurement method.



**Figure A2.2** Instrument components and idealized output trace of the TDR moisture content measurement method (from Ayres, 1998).

The apparent  $K_a$  is strongly dependent on the volumetric water content ( $\theta_w$ ) of the soil because of the large difference in the various components of soil ( $K_{air} = 1$ ;  $K_{soil} \approx 5$ ; and  $K_{water} \approx 80$ ). Topp *et al.* (1980) determined the following empirical relationship between  $\theta_w$  and  $K_a$  provided  $\theta_w \leq 0.6$ :

$$\theta_w = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}K_a - 5.5 \times 10^{-4}K_a^2 + 4.3 \times 10^{-6}K_a^3 \quad [A2.3]$$

Topp *et al.* (1980) concluded that  $K_a$  is only weakly dependent on soil type, bulk density, ambient temperature, and salt content (i.e. pore-water conductivity). Equation A2.3 has been examined

and confirmed by numerous other researchers (Dalton, 1992; Whalley, 1993; Zegelin *et al.*, 1989). As a result, the Topp *et al.* (1980) empirical relationship is known as the “universal” TDR equation for soils. Note that TDR only gives an indication of the volumetric *liquid* water content of soils because the dielectric constant of ice is approximately 3.2 (Spaans and Baker, 1995).

One of the advantages claimed for the TDR technique, based on the empirical fit of Equation A2.3, is that field calibration is not essential. However, Zegelin *et al.* (1992) found that the “universal” TDR equation does not fit well when measuring the water content of organic or fine-textured, heavy clay soils. The electrical nature of these soils is higher than other types of soils, which causes the amount of bound (“ice-like”) water to increase. The dielectric constant for bound water is less than the dielectric constant for free water (Kaya *et al.*, 1994) and therefore, TDR will tend to underestimate  $K_s$  (and therefore  $\theta_w$ ) of soils containing bound water. Zegelin *et al.* (1992) concluded that the Topp *et al.* (1980) equation works best in coarser textured soils such as sands. Equation A2.3 is more readily applicable where changes in water content are desired, rather than determination of absolute values. In short, all TDR measurement systems should be calibrated in the field to obtain quantitative *in situ* moisture content data.

Instrumentation for measuring the apparent dielectric constant of soils generally consists of a multi-wire probe connected to a TDR device via a coaxial cable. The major components of a TDR device are a pulse generator, a timing control, a sampling receiver, and an oscilloscope to display the reflected voltage pulse. A variety of TDR probes are available, such as the standard laboratory coaxial cell, the parallel two-wire probe (Topp *et al.*, 1980), and the coaxial emulating three-wire and four-wire probes (Zegelin *et al.*, 1989). The coaxial emulating multi-wire probes are recommended over the two-wire probes in the field because they give a clearer signal (Zegelin *et al.*, 1989). The probe wires are constructed of varying dimensions; however, the probe wire diameter should be at least ten times the average soil particle diameter to ensure a representative water content measurement (Zegelin *et al.*, 1992). Several probes may be connected to a multiplexer and datalogger system for continuous monitoring of soil moisture content (Baker and Allmaras, 1990).

TDR probes may be installed in a soil profile horizontally, vertically, or any orientation depending on the application (Zegelin *et al.*, 1992). All orientations will give the water content in the soil averaged over the length of the probe. Vertically oriented probes are the easiest to install, but preferential flow of water and heat alongside the probe wires is a concern. Horizontal probes require excavation of a pit with the probes inserted into one or more walls of the pit at required depths. The major advantage of horizontal probes is that they give water content in a horizontal plane, which allows for the accurate determination of water content profiles. The installation of all probes must be performed carefully to minimize the formation of air gaps around the wires because probe sensitivity is highest in the immediate vicinity of the wires (Zegelin *et al.*, 1992).

One of the limitations of the TDR method is the effect of high dissolved solids in the soil water, which leads to higher electrical conductivity of the bulk soil present between the rods of the probe. Ions in solution affect both the waveform quality and the pulse velocity (Nichol *et al.*, 2002). The voltage signal carried on the signal rod may be lost by DC current losses between the voltage carrying rod and the ground rods. The DC loss in high conductivity soils can lead to decreasing signal strength, and difficulty in determining the “true” water content. For commonly used probes, this type of signal loss may prevent measurements in soils with electrical conductivities greater than 5 dS/m. Standard TDR methods are therefore not applicable in materials with high dissolved solids in the soil water phase (e.g. heap leach material which may have 100,000 mg/L in the leach solution). In soils with slightly elevated electrical conductivity, it has been determined that the loss of signal voltage can be reduced by a high resistance coating such as heat shrink. The coating on the rod has a lower dielectric permittivity than most soils and therefore the estimate of apparent permittivity with a coated probe will always be less than what would be estimated using an uncoated probe, muting the affects of the EC.

#### *A2.1.4 Frequency Domain Reflectometry*

The theory behind the measurement of *in situ* moisture content of soils and other fine-textured materials using frequency domain reflectometry (FDR) is similar to that of the TDR method. FDR systems measure the apparent dielectric constant of soils by measuring the change in a radio wave frequency as it passes through the soil (Bilskie, 1997). A factory or “universal” calibration equation supplied with the FDR sensor is used to convert the frequency readings into volumetric water content readings.

FDR measurement systems are similar to that of the TDR measurement system described above. Two-wire probes are generally installed horizontally into the soil profile and subsequently connected to a multiplexer and datalogger system for continuous monitoring of *in situ* moisture content. As with TDR measurement systems, all FDR measurement systems should be calibrated in the field to facilitate the collection of quantitative *in situ* moisture content data, in particular for high clay and organic matter soils (Veldkamp and O'Brian, 2000).

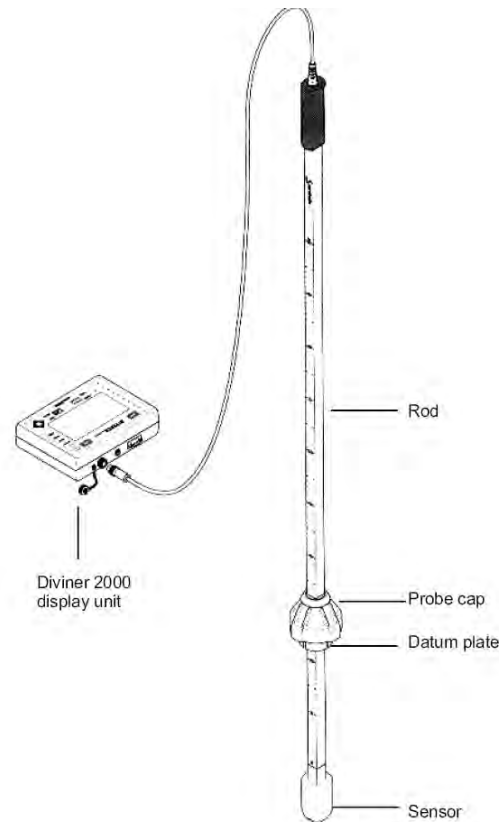
The FDR has the ability to detect bound water in fine soil particles that is still available to plants, which is ideal for sites that are primarily fine-textured. The FDR is less susceptible to soil salinity errors but can be more susceptible to changes in temperature, bulk density, and the presence of air pockets.

### A2.1.5 Electrical Capacitance

Capacitance sensors use the dielectric properties of soil to measure water content. The capacitance sensor is essentially a capacitor that incorporates the soil as the dielectric medium. A high frequency electrical field, created around the sensor, extends into the soil. The magnitude of the frequency is a function of the apparent dielectric constant of the soil, which is dependant on the water content. The more water in the soil, the higher the  $K_a$  value and the lower the frequency measured by the sensor. Additional information on the theory behind the capacitance sensor can be found in Dean *et al.* (1987), Paltineau and Starr (1997), Lane and MacKenzie (2001), and Gaskin and Miller (1996).

A variety of capacitance sensors are available. Some sensors can be inserted directly into the soil, while others require the installation of a PVC access tube. Both manual and automatic data logging capabilities are available. Typically, the sensors that require an access tube are more suitable for watershed-scale monitoring, as they can monitor to greater depths and at various depths within the same location. As with TDR and FDR sensors, capacitance sensors require calibration for the given soil type (Baumhardt *et al.*, 2000; Morgan *et al.*, 1999; and Geesing *et al.* 2004). The readout of this sensor is not linear with water content and is influenced by soil type and soil temperature, therefore; calibration of the instrument is extremely important. Because careful calibration is needed, the long-term stability of the calibration is questionable (Zazueta and Xin, 1994).

Some types of capacitance sensors can be used as a portable moisture sensor, similar to the nuclear moisture probe (Figure A2.3). The benefits of the capacitance method compared to the nuclear probe are that the sensor does not use a radioactive source and measurements can be taken very quickly with good reliability.



**Figure A2.3** Diviner2000<sup>®</sup> Portable Soil Moisture Capacitance Probe (adapted from Sentek, 2000).

## A2.2 Soil Suction

The three most common methods used to measure soil suction in the field are tensiometers, thermal conductivity sensors and electrical resistance (i.e. gypsum blocks). The first two measurement techniques are described in detail by Fredlund and Rahardjo (1993) and are reviewed briefly below. A brief description of gypsum blocks is also provided. All three methods provide a field measurement of matric suction, which along with osmotic suction (reduced chemical energy in the water due to the presence of dissolved salts (Barbour and Fredlund, 1989)) are the two components of total suction.

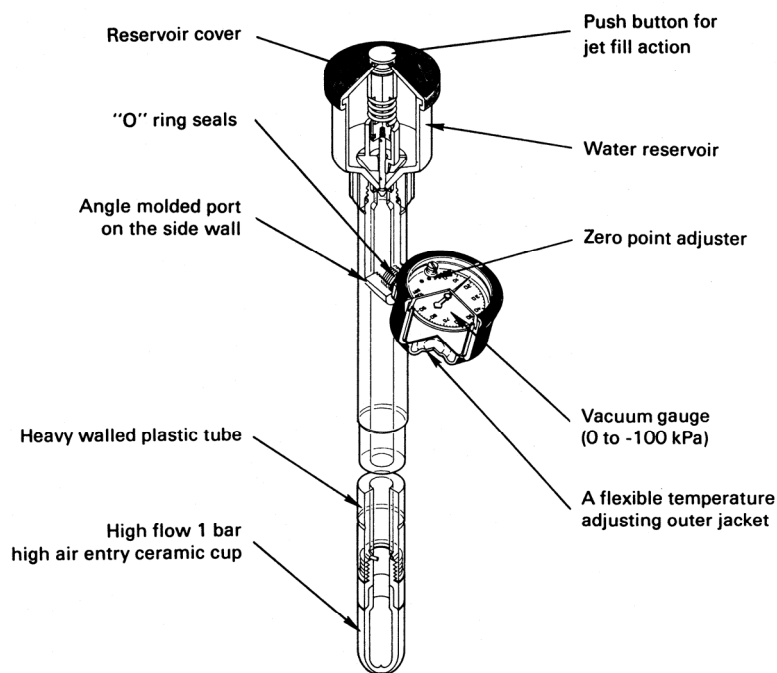
### A2.2.1 Tensiometers

Tensiometers provide a direct measurement of the negative pore-water pressure (or matric suction, assuming the pore-air pressure is atmospheric) in a soil. The tensiometer consists of a porous ceramic, high air-entry cup connected to a pressure measuring device through a small bore capillary tube. The pressure sensor may be a manometer, vacuum gauge, or pressure transducer (Stannard, 1992). The tube and the cup are filled with de-aired water. The cup is

inserted into a pre-drilled hole to provide intimate contact with the soil. After equilibrium has been achieved, the water in the tensiometer has the same negative pressure as the pore-water in the soil. The suction that can be measured at the tip of the tensiometer is limited to a maximum value of 80 or 90 kPa due to the onset of cavitation in the water (Fredlund and Rahardjo, 1993).

If air bubbles are allowed to accumulate within the tensiometer after field installation, the water pressure will slowly increase towards zero (Fredlund and Rahardjo, 1993). Consequently, it is necessary to check the tensiometer on a regular basis, typically every 24 hours. Air bubbles can be removed from the tensiometer with a portable vacuum pump or by flushing the tensiometer. A mechanism for this type of flushing is provided in the 'jet-fill' tensiometer manufactured by Soilmoisture Equipment Corp. This device has a water reservoir and plunger system activated by a push button at the top of the tube for removing air bubbles (Figure A2.4). O'Kane (1996) and Woyshner and St-Arnaud (1994) successfully used jet-fill tensiometers to measure *in situ* negative pore-water pressures in till cover material and mine tailings, respectively.

ASTM D3404-91 (ASTM, 1991) provides guidelines for tensiometer selection, installation and operation. The advantages of using tensiometers include: 1) simple installation and operation; 2) no required laboratory or field calibration; and 3) tensiometers are relatively inexpensive (compared to other methods). However, the tensiometer typically requires human intervention to record data and remove air bubbles from the system.

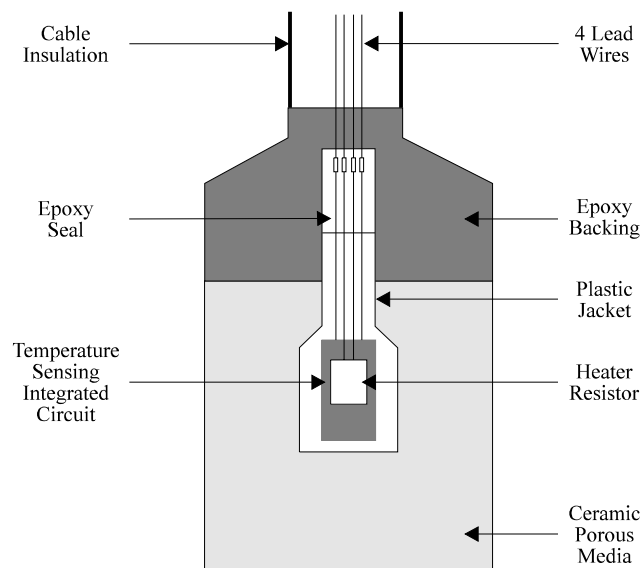


**Figure A2.4** Schematic of a jet-fill tensiometer (from Fredlund and Rahardjo, 1993).

### A2.2.2 Thermal Conductivity Sensors

Thermal conductivity sensors were developed in the agricultural field some years ago (Phene *et al.*, 1971a and 1971b), and were primarily used to assist in irrigation scheduling (Phene *et al.*, 1989). The application of this soil suction measurement technique in geotechnical engineering was recognized nearly two decades ago. Sattler and Fredlund (1989) describe the use of thermal conductivity sensors in the laboratory for measuring matric suction of Shelby tube samples. O’Kane (1996) successfully used this measurement technique to monitor the performance of an engineered soil cover system for sulfidic mine waste.

A thermal conductivity sensor generally consists of a porous ceramic block containing a temperature sensing element and a heater, as shown in Figure A2.5. The porous ceramic block has a wide pore-size distribution that allows water from the surrounding soil to flow in and out of the sensor until equilibrium is reached. Typically, the composition of the ceramic is proprietary, and varies between manufacturers. The soil matric suction is determined by first measuring the temperature of the ceramic block, then heating the ceramic block for a specified period with a small constant current, and measuring the temperature after heating. The initial temperature measurement can also be used as a measure of the *in situ* temperature. Essentially, this procedure measures the rate at which the heat pulse is dissipated into the ceramic block by measuring the difference in temperature before and after heating. The amount of water in the ceramic block affects the heat capacity and heat dissipation within the block such that the rate of heat dissipation increases with water content.



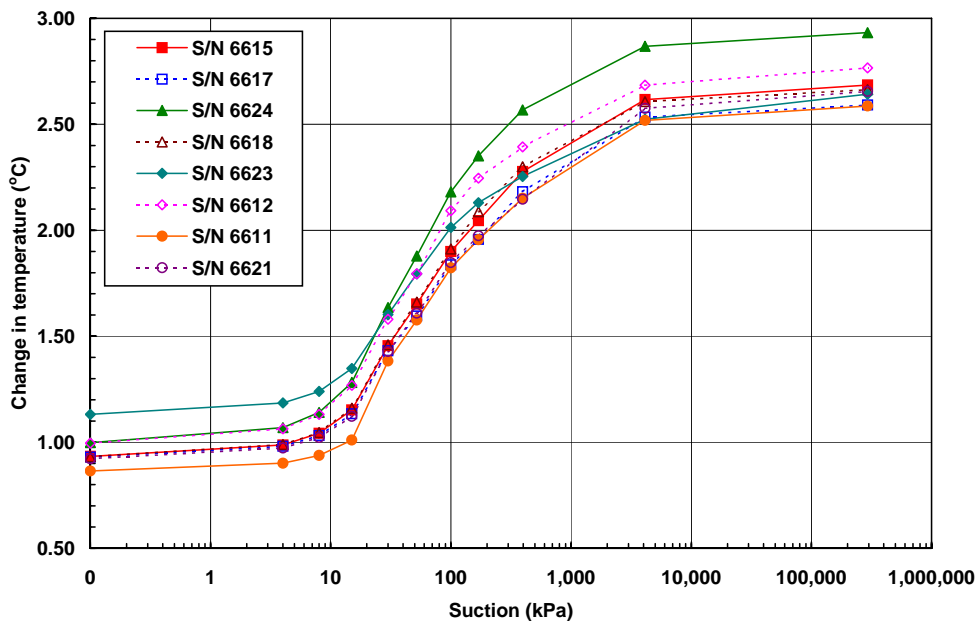
**Figure A2.5** Schematic of a thermal conductivity sensor (from Fredlund and Rahardjo, 1993).



A relationship also exists between the water content in the porous block and matric suction. Hence, the temperature difference in the ceramic block is calibrated in the laboratory against applied levels of matric suction. The temperature difference recorded in the field is stored in the datalogger and a laboratory calibration curve is used to generate matric suction values for each field measured  $\Delta T$ .

In general, a laboratory developed soil-water characteristic curve should be obtained for each thermal conductivity sensor installed in the field because of the uniqueness of each ceramic block. The response of a given sensor is highly dependent on insertion of the temperature sensing unit and heater into the ceramic, which will vary from sensor to sensor. Thermal conductivity sensors do not have to be calibrated in the material into which they will be installed because matric suction is a stress state, as opposed to a material property. The laboratory calibration process also ensures that the heating element and thermocouple inside the sensor ceramic are functioning properly.

Thermal conductivity sensors should be calibrated in the laboratory over a suction range of approximately 0 to 300,000 kPa. This generally involves placing the sensors in a modified pressure plate apparatus to obtain sensor readings for incremental matric suctions up to 400 kPa (see Fredlund and Wong, 1989). Sensor calibration readings between 400 and 293,000 kPa are generally obtained by placing the sensors in sealed jars containing various saturated salt solutions. An example of thermal conductivity sensor laboratory calibration curves is shown in Figure A2.6. This figure demonstrates the importance of calibrating each and every thermal conductivity sensor in the laboratory prior to their inclusion in a field-monitoring program.



**Figure A2.6** Typical laboratory calibration curves for thermal conductivity sensors (S/N refers the sensor serial number).

Thermal conductivity sensors have been found to provide consistent, reliable, matric suction data with time (Feng and Fredlund, 2003; Fredlund and Rahardjo, 1993). These sensors cover a greater range than any other matric potential sensor available. Other advantages include relatively low cost, ease of operation and data analysis, and they have the ability to be automated and remotely controlled (Scanlon *et al.*, 2002).

There have been some disadvantages associated with thermal conductivity sensors. The major limitation associated with these sensors is their inability to measure matric potentials higher than the air entry pressure of the sensor (~ -10 kPa) due to the matrix remaining saturated until it reaches the air entry value. Errors also increase at low suction values (~ -1000 kPa) because the sensors are less sensitive to changes in this range (Scanlon *et al.*, 2002). It has been long recognized that soil matric sensors may exhibit hysteresis, or correspond to different suction values depending if the porous tip is in a wetting or drying state (Phene *et al.*, 1971a; Scanlon *et al.*, 2002; Feng and Fredlund, 2003). The effect of hysteresis is generally ignored because only desorption curves are measured during calibration (Scanlon *et al.*, 2002). A laboratory research program conducted by Feng and Fredlund (2003) suggests an alternative method of calibrating matric suction sensors that takes hysteresis effects into consideration.

Installation of these instruments is extremely important because there must be good contact between the sensor and the surrounding soil, thus making it challenging in very coarse materials. A silica flour slurry can be used to ensure direct contact; however, this method may be challenging in dry soils (Scanlon *et al.*, 2002). In some cases when exposed to positive pore pressures, moisture has been found to enter the sealed portion of the sensor and come into contact with the sensor electronics. In addition, the porous ceramic blocks require careful handling because these sensors are fragile and can easily crack or crumble during calibration and installation (Fredlund and Rahardjo, 1993).

### A2.2.3 *Electrical Resistance*

Electrical resistance methods have been used for many years in the agricultural industry to provide an indirect measurement of the matric suction in soils. The most common electrical resistance sensor is a gypsum block sensor where two electrodes are embedded in a porous block of gypsum plaster. The measured electrical resistance between the two electrodes is a function of the water content in the gypsum block, which can be converted to matric suction through laboratory calibration. Gypsum blocks are relatively inexpensive and can be connected to an automated data acquisition system for continuous monitoring of matric suction.

There are, however, a number of problems commonly encountered when using gypsum blocks, especially in saline (Phene *et al.*, 1971a) or acidic environments. Each block possesses slightly different characteristics and must be individually calibrated. Eventually the gypsum will dissolve into the soil. As well, the presence of dissolved salts in the pore-water affects electrical

conductivity independently of water content. The gypsum, used to mask variations in soil salinity, eventually dissolves, resulting in an unstable matrix for the sensor. Acidic pore-waters also dissolve the gypsum block. Gypsum blocks also exhibit hysteresis that can significantly reduce sensitivity to sudden wetting and drying conditions. Gawande *et al.* (2003) provide a comparison of electrical resistance methods to other methods of water content measurement. As the sensor degrades, the calibration changes with time which may result in inaccurate readings over time.

The life span of a sensor of this type is highly dependent on the soil type. Factors affecting the life of the sensor include soil wetness, erosion, and the soil pH/alkalinity. Freezing can also damage the sensor causing cracking and premature aging of the block. The life of these sensors has been reported to be as little as one year up to five years.

A modified gypsum block sensor (Watermark sensor by Irrrometer Co. Ltd), called a granular matrix sensor, has been used successfully for cover performance monitoring (Aubertin *et al.* 1997; MEND 2.22.2c, Bussière and Aubertin 1999; Bussière *et al.*, 2001). The sensor has a gypsum core embedded inside a granular material and encased in a stainless steel mesh. The granular sensor has some advantages over the block type sensor. The gypsum core dissolves slower than standard gypsum blocks and has a reported life of approximately three to 10 years and freezing will generally not hurt the granular sensors. These sensors have a limited measurement range (20 to 200 kPa) and are therefore most practical for humid climates.

### **A2.3 Net Percolation**

Net percolation is a critical facet to understanding the water balance of a watershed. Often, net percolation is required to evaluate the effectiveness of a soil cover over reactive waste. Despite the importance of this parameter, it is often not given due consideration when planning for an instrumented watershed.

Detailed analyses of the hydraulic gradients within the cover layers and underlying waste material can be used to determine the net percolation through a cover system. Hydraulic head measurements in the cover and waste materials can be obtained by one of the methods described in this manual for measuring *in situ* soil suction (Section A2.2). Suction data can be combined with soil hydraulic conductivity data and the respective soil-water characteristic curve to calculate a value of net percolation.

The preferred method is the installation of a lysimeter, often placed below the reclamation cover layer. The monitoring device described in this section should not be confused with a weighing lysimeter, which was described in Section A1.4.2 for measuring actual evapotranspiration, although the design recommendations in this section would apply to the design of a weighing lysimeter.

### A2.3.1 Design of Field Lysimeters

Measurement of the net percolation from the base of the cover layers into the underlying waste material is likely the most important component of a watershed monitoring program. The units of measurement (i.e. a percentage of precipitation) are simple to understand for all stakeholders, much more so than hydraulic gradients and suction profiles. The apparent ease by which net percolation numbers can be understood simply reinforces the importance of obtaining representative net percolation values. In general, the design and installation of lysimeters to monitor evaporative fluxes as well as net infiltration is well understood and implemented in the soil science discipline; however, the design of lysimeters for watershed monitoring programs in the mining industry have typically not included fundamental aspects of lysimeter design as established in the soil science literature.

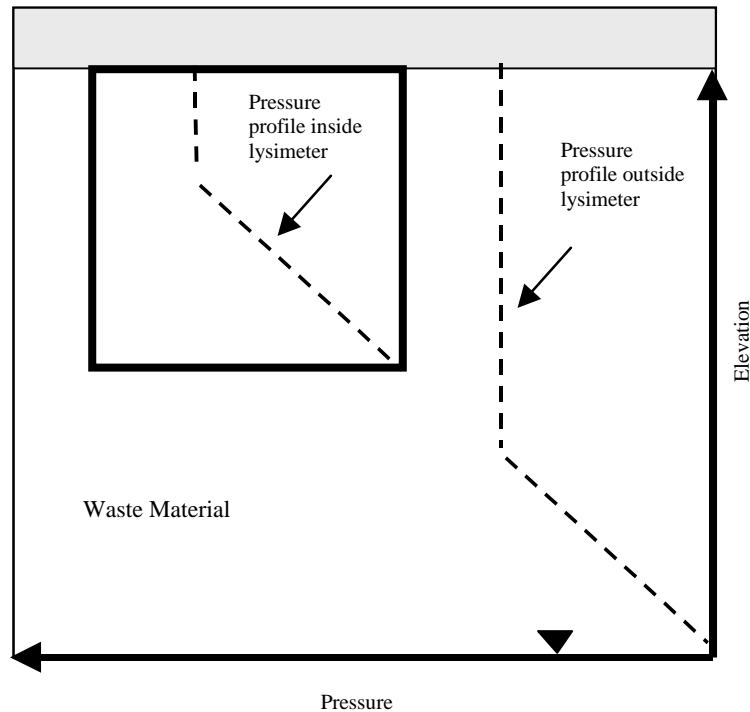
It is strongly recommended that a two-dimensional saturated-unsaturated seepage/flow model be used to aid in the design of each lysimeter installed in a cover system. This is the only method of ensuring that a field lysimeter will give an accurate measurement of the net percolation through the cover system under a range of precipitation events. It is important to note that the design of a lysimeter for one site is not necessarily transferable to another site due to potential differences in climatic conditions, the hydraulic properties of the cover and waste materials, and the slope of the cover system at the location of the lysimeter. The key criterion for designing a field lysimeter is that the measured net percolation rate be the same as that outside the lysimeter. Three requirements for the design of a lysimeter, described below, can be used to verify that the criterion is being met.

The first requirement in the design of a lysimeter is to ensure that the pressure head profile within the lysimeter is the same as that of an *in situ* pressure head profile outside of the lysimeter. This design requirement ensures that bypass flow around the lysimeter is minimized as a result of a difference in the pressure head profiles inside and outside the lysimeter. If the pressure head inside the lysimeter is higher than that outside the lysimeter, at the same elevation, the pore-water will tend to flow around rather than into the lysimeter. Bews *et al.* (1997) and O’Kane and Barbour (2003) showed that bypass flow around a lysimeter is common if the lysimeter is improperly designed. Bews *et al.* (1997) modelled a lysimeter using a SEEP/W model to predict pressure head profiles inside and outside the confines of the lysimeter. The inside and outside profiles had to be nearly identical under the range of probable net percolation rate to meet this criterion.

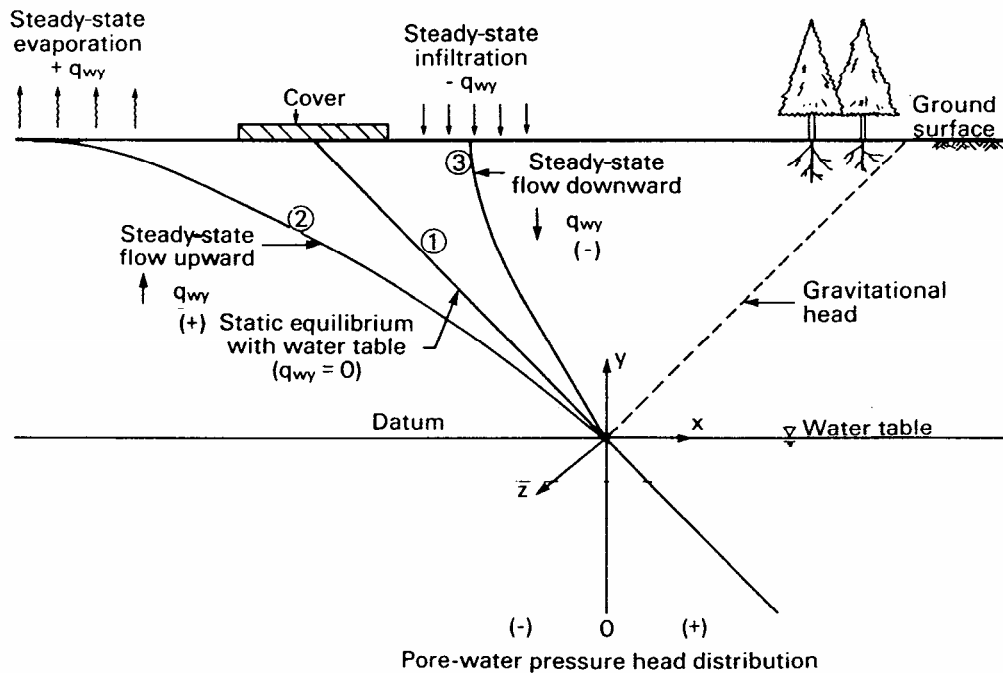
The second requirement for the design of a lysimeter is to ensure that the hydraulic gradient within the lysimeter is the same as the hydraulic gradient present in the waste profile outside the lysimeter. A typical pressure head profile is shown in A2.7 to illustrate the gradient both inside and outside of the lysimeter. The gradient within the waste material below the cover should be approximately equal to 1.0 under conditions of steady-state infiltration. Figure A2.8 demonstrates

the reasoning for the requirement of a gradient profile equal to approximately 1.0 under steady-state conditions. The pressure head profile has a linear distribution with depth (i.e. hydrostatic) if the flux at the surface is zero. When steady state infiltration occurs within a deep unsaturated profile, as in the case of mine waste such as waste rock or tailings, the suction will eventually become constant with elevation. This occurs when the suction developed within the waste is such that the hydraulic conductivity of the waste is equal in value to the net percolation rate. In this condition, the only gradient required for flow is that provided by elevation and the pressure head gradient becomes zero.

The third requirement in the design of a lysimeter is to ensure that the flux at the base of the cover is equal to the flux at the collection point within the lysimeter under a variety of surface flux conditions. This condition should be checked during design simulation under a variety of different surface flux boundary conditions. Sensitivity analysis on the material properties influencing performance of the lysimeter should also be undertaken to ensure that the flux at the base of the cover is equivalent to the flux at the collection point in the lysimeter (O’Kane and Barbour, 2003).



**Figure A2.7** Pressure head profiles for the lysimeter compared to the *in situ* material (adapted from O’Kane and Barbour (2003)).



**Figure A2.8** Static equilibrium and steady-state flow conditions in the zone of negative pore-water pressures (from Fredlund and Rahardjo (1993)).

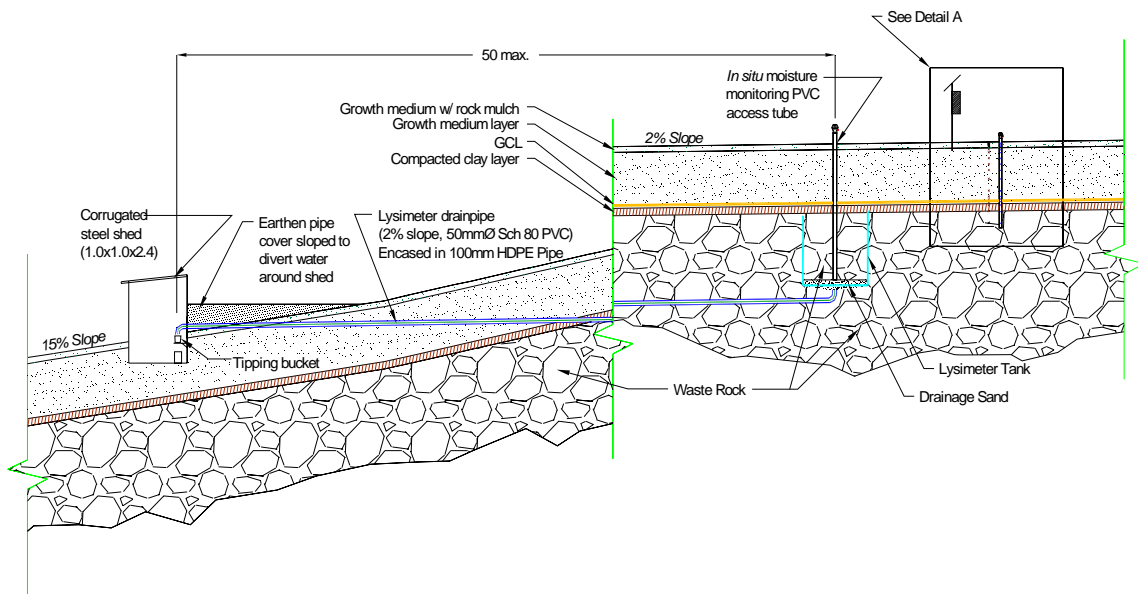
### A2.3.2 Description of Field Lysimeter

A state-of-the-art field lysimeter, shown schematically in Figure A2.9, is typically comprised of the following components:

- Net percolation collection tank;
- *In situ* moisture monitoring system;
- Underdrain system; and
- Net percolation monitoring system.

Plastic vertical storage tanks with a diameter between 2.0 and 2.5 m, which are commonly used in the agricultural industry for storing irrigation water, are ideal for field lysimeters. The tanks are modified on-site by removing the top dome-shaped portion of the tank. A small hole is also cut in the bottom centre of the tank to permit collected water to flow out of the tank and into the underdrain system. Once the tank has been modified, it is then lowered into an excavation and backfilled with the waste material. A thin layer of relatively fine, “clean” sand is placed at the bottom of the tank to act as a drainage medium for any water that may drain from the overlying waste material backfill. An *in situ* moisture monitoring system should be installed within the collection tank to monitor changes in moisture storage in the waste material backfill.

It is often argued that larger scale lysimeters, in terms of the cross-sectional area, should be utilized when monitoring net percolation into run-of-mine waste rock, as a result of the presence of large particles and heterogeneous flow paths. This is a reasonable argument, but one that does not preclude the requirement for the appropriate depth of a lysimeter. It is fundamental to understand that just because a lysimeter has a “large” cross-sectional area (for example 10 m x 10 m), this should not imply that it is acceptable for the lysimeter to be too shallow. A lysimeter that is too shallow will always influence the net percolation being measured, regardless as to whether the cross-section area is larger or not.



**Figure A2.9** A state-of-the-art field lysimeter for measuring net percolation. Note: tank depth and dimensions must be tailored to each specific site.

The underdrain component of the lysimeter collection and monitoring system consists of a pipe that extends from the base of the collection tank to a point just above the net percolation monitoring system. A ‘u-shape’ water trap should be installed at the end of the underdrain pipe to prevent oxygen from entering the underdrain system and subsequently oxidizing the waste material in the collection tank.

The net percolation monitoring system consists of a flow meter to automatically record the time and quantity of water discharged from the lysimeter tank, and a sample bucket to collect net percolation waters for chemical analysis. Tipping bucket rain gauges are ideal for this application because they can be connected to an automated data acquisition system and require minimal maintenance and calibration.

An alternative to an underdrain system is to place a piezometer in the centre of the tank that extends to the bottom. The piezometer is then used to monitor the water collected in the tank,

which is then bailed or pumped out of the tank at regular intervals. This allows for a simpler design than that showed in Figure A2.9 but, because it cannot be automated, it does not give data with the same resolution.



## REFERENCES

- Ackers, P., White, W.R., Perkins, J.A., and Harrison, A.J.M. 1978. Weirs and Flumes for Flow Measurement. John Wiley & Sons, New York, NY.
- ASTM (American Society for Testing and Materials). 1991. Standard guide for measuring matric potential in the vadose zone using tensiometers (D3404-91). *In* 1998 Annual Book of ASTM Standards, Vol. 4.08. ASTM, Philadelphia, Pa.
- ASTM (American Society for Testing and Materials). 1992. Standard test method for laboratory determination of water (moisture) content of soil and rock (D2216-92). *In* 1998 Annual Book of ASTM Standards, Vol. 4.08. ASTM, Philadelphia, Pa.
- Aubertin, M., Bussière, B., Barbera, J.-M., Chapuis, R.P., Monzon, M., and Aachib, M. 1997. Construction and instrumentation of *in situ* test plots to evaluate covers built with clean tailings. *In* Proceedings of the 4<sup>th</sup> International Conference on Acid Rock Drainage, Vancouver, BC, May 31-June 6, pp. 715-730.
- Ayres, B.K. 1998. Field monitoring of soil-atmosphere fluxes through uranium mill tailings and natural surface soils at Cluff Lake, Saskatchewan. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Baker, J.M. and Allmaras, R.R. 1990. System for automating and multiplexing soil moisture measurement by time domain reflectometry. *Soil Science Society of America Journal*, **54**: 1-6.
- Barbour, S.L. and Fredlund, D.G. 1989. Mechanisms of osmotic flow and volume changes in clay soils. *Canadian Geotechnical Journal*, **26**: 551-562
- Baumhardt, R.L., Lascano, R.J. and Evett, S.R. 2000. Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes. *Soil Science Society of America Journal*, **64**: 1940-1946.
- Belanger, T.V. and Montgomery, M.T. 1992. Seepage meter errors. *Limnology and Oceanography*, **37**: 1787-1795.
- Benson, C.H., Bosscher, P.J., Lane, D.T. and Pliska, R.J. 1994. Monitoring system for hydrologic evaluation of landfill covers. *Geotechnical Testing Journal*, **17**: 138-149.
- Bews, B.E., O’Kane, M.A., Wilson, G.W., Williams, D., and Currey, N. 1997. The design of a low flux cover system, including lysimeters, for acid generating waste rock in semi-arid environments. *In* Proceedings of the 4<sup>th</sup> International Conference on Acid Rock Drainage, Vancouver, BC, May 31-June 6, pp. 747-762.
- Bilskie, J. 1997. Using dielectric properties to measure soil water content. *Sensors Magazine*, **14**: 26-32.

- Bos, M.G., Replogle, J.A., and Clemmens, A.J. 1991. Flow Measuring Flumes for Open Channel Systems. American Society of Agricultural Engineers, Republication of book by same title, originally by John Wiley & Sons, New York 1984.
- Bowen, I.S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physics Review*, **27**: 779-787.
- Boyle, D.R. 1994. Design of a seepage meter for measuring groundwater fluxes in the nonlittoral zones of lakes – evaluation in a boreal forest lake. *Limnology and Oceanography*, **39**(3): 670-681.
- Bras, R.L. 1990. *Hydrology: An Introduction to Hydrologic Science*. Addison-Wesley Publishing Company, Inc., Reading, Mass.
- British Columbia Ministry of the Environment Water Management Branch. 1981. Snow survey sampling guide, Report SS13-81, Parliament Buildings, Victoria, B.C. Available from [http://wlapwww.gov.bc.ca/rfc/river\\_forecase/snow\\_surveys\\_manual.pdf](http://wlapwww.gov.bc.ca/rfc/river_forecase/snow_surveys_manual.pdf).
- Burn, K.N. 1964. Calibration of a neutron moisture meter in Leda clay. *Canadian Geotechnical Journal*, **1**: 94 -103.
- Bussière B. and Aubertin, M. 1999. Clean tailings as cover material for preventing acid mine drainage: An *in situ* experiment. *In Proceedings of the Sudbury '99 Conference, Mining and the Environment II, Sudbury, ON, Sept. 13-17, Vol. 1, pp. 19-28.*
- Bussière B., Aubertin M., and Chapuis R.P. 2001. Unsaturated flow in layered cover systems: A comparison between numerical and field results. *In Proceedings of the 54<sup>th</sup> Canadian Geotechnical Conference, Calgary, AB, Sept. 16-19, Vol. 3, pp. 1612-1619.*
- CANMET. 2002. CANMET – CETEM manual on cover system design for reactive mine waste. Prepared by O’Kane Consultants, Report No. 689-01, June.
- Dalton, F.N. 1992. Development of time domain reflectometry for measuring soil water content and bulk soil electrical conductivity. *In Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*. Soil Science Society of America Special Publication No. 30, pp. 143-167.
- Davis, J.L. and Annan, A.P. 1977. Electromagnetic detection of soil moisture: Progress report 1. *Canadian Journal of Remote Sensing*, **3**: 76-86.
- Davis, J.L. and Chudobiak, W.J. 1975. *In situ* meter for measuring relative permittivity of soils. Paper 75-1A, *Geol. Surv. Can.*, pp. 75-79.
- Dean, T.J., Bell, J.P. and Baty, A.J.B. 1987. Soil moisture measurement by an improved capacitance technique, part 1: Sensor design and performance. *Journal of Hydrology*, **93**: 67-78.

- Dodge, R. 2001. Water measurement manual. Revised Reprint, Water Resources Technical Publication, Water Resources Research Laboratory, U.S. Department of the Interior Bureau of Reclamation.
- Farnes, P.E., Peterson, N.R., Goodison, B.E., and Richards, R.P. 1982. Metrication of manual soil sampling equipment by Western Snow Conference Metrication Committee. *In* Proceedings of the 39<sup>th</sup> Eastern Snow Conference (same as Proceedings of the 50<sup>th</sup> Western Snow Conference), Reno, Nevada, pp. 120-132.
- Fellows, C.R. and Brezonik, R.L. 1980. Seepage flow into Florida lakes. *Water Resources Bulletin*, **16**: 635-641.
- Feng, M. and Fredlund, D. 2003. Calibration of thermal conductivity sensors with consideration of hysteresis. *Canadian Geotechnical Journal*. **40**: 1048-1055.
- Fredlund, D.G. and Rahardjo, H. 1993. *Soil Mechanics for Unsaturated Soils*. John Wiley & Sons, Inc., New York, NY.
- Fredlund, D.G. and Wong, D.K.H. 1989. Calibration of thermal conductivity sensors for measuring soil suction. *Geotechnical Testing Journal*, **12**: 188-194.
- Fritschen, L.J. 1966. Evapotranspiration rates of field crops determined by the Bowen ratio method. *Agronomy Journal*, **58**: 339-342.
- Fritschen, L.J. and Qian, P. 1990. Net radiation, sensible and latent heat flux densities on slopes computed by the energy balance method. *Boundary-Layer Meteorology*, **53**: 163-171.
- Fritschen, L.J. and Simpson, J.R. 1989. Surface energy and radiation balance systems: general description and improvements. *Journal of Applied Meteorology*, **28**: 680-689.
- Fuchs, M. and Tanner, C.B. 1967. Evaporation from a drying soil. *Journal of Applied Meteorology*, **6**: 852-857.
- Gardner, W. and Kirkham, D. 1952. Determination of soil moisture by neutron scattering. *Soil Science*, **78**: 391-401.
- Gaskin, G.J., and Miller, J.D. 1996. Measurement of soil water content using a simplified impedance measuring technique. *Journal of Agricultural Engineering Research*, **63**: 153-160.
- Gawande, N.A., Reinhart, D.R., Thomas, P.A, McCreanor, P.T., and Townsend, T.G. 2003. Municipal solid waste *in situ* moisture content measurement using an electrical resistance sensor. *Waste Management*, **23**: 667-674.
- Geesing, D., Bachmaier, M. and Schmidhalter, U. 2004. Field calibration of a capacitance soil water probe in heterogeneous fields. *Australian Journal of Soil Research*, **42**: 289-299.

- Goodison, B.E., Ferguson, H.L., and McKay, G.A. 1981. Measurement and data analysis. *In* Handbook of snow: principles, processes, management and use. *Edited by* D.M. Gray and D.H. Male. Pergamon Press, Toronto, Canada, pp. 191-274.
- Gray, D.M. 1973. Handbook on the Principles of Hydrology. Water Information Center, Port Washington, NY.
- Greacen, E.L., Correll, R.L., Cunningham, R.B., Johns, G.G., and Nicholls, K.D. 1981. Calibration. *In* Soil water assessment by the neutron method. *Edited by* E.L. Greacen. CSIRO, Victoria, Australia, pp. 50-72.
- Hill, R. 1999. How good is your water measurement?. Utah State University Extension, Electronic Publishing, AG/BIE/WM/01. Available from <http://www.extension.usu.edu/files/engrpubs/biewm01.pdf>.
- International Standards Organization (ISO). 1983. Liquid flow measurement in open channels. Handbook 16, International Standards Organization.
- Kaya, A., Lovell, C.W., and Altschaeffl, A.G. 1994. The effective use of time domain reflectometry (TDR) in geotechnical engineering. *In* Time Domain Reflectometry in Environmental, Infrastructure and Mining Applications. United States Bureau of Mines Special Publication No. 19-94, pp. 398-409.
- Keller, B.R., Everett, L.G., and Marks, R.J. 1990. Effects of access tube material and grout on neutron probe measurements in the vadose zone. Groundwater Monitoring Review, Winter 1990, pp. 96-100.
- Koliasev, F.H. 1941. Measures for the control of evaporation of soil moisture. Sbornik Rabot po Agronomi sheskoe Fiziki. **3**: 67-81.
- Kramer, J.H., Cullen, S.J. and Everett, L.G. 1992. Vadose zone monitoring with the neutron moisture probe. Groundwater Monitoring Review, Summer 1992, pp. 177-187.
- Lane, P.N.J. and MacKenzie, D.H. 2001. Field and laboratory calibration and test of TDR and capacitance techniques for indirect measurement of soil water content. Australian Journal of Soil Research, **39**(6): 1371-1386.
- Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnology and Oceanography, **22**(1): 140-147.
- Lee, D.R., and Cherry, J.A. 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. Journal of Geological Education, **27**: 6-10.
- Lewis, J.B. 1987. Measurements of groundwater seepage-flux into a coral reef: Spatial and temporal variation. Limnology and Oceanography, **32**: 1165-1169.
- Look, B.G. and Reeves, I.N. 1992. The application of time domain reflectometry in geotechnical instrumentation. Geotechnical Testing Journal, **15**: 277-283.

- Maidment, D.R. (Ed.) 1993. Handbook of Hydrology. McGraw-Hill Inc., New York, NY.
- McCuen, R.H. 1989. Hydrologic Analysis and Design. Prentice-Hall of Canada Inc, Toronto, ON.
- MEND 2.22.2c. Études sur les barrières sèches construites à partir de résidus miniers, Phase II - Essais en place. Novembre 1999.
- Montes, S. 1998. Hydraulics of Open Channel Flow. ASCE Press, Reston, VA.
- Morgan, K.T., Parsons, L.R., Wheaton, T.A., Pitts, D.J., and Obreza, T.A. 1999. Field calibration of a capacitance water content probe in fine sand soils. Soil Science Society of America Journal, **63**: 987-989.
- Nichol, C., Beckie, R., and Smith, L. 2002. Evaluation of uncoated and coated time domain reflectometry probes for high electrical conductivity systems. Soil Science Society of America Journal, **66**: 1454-1465.
- Ohmura, A. 1982. Objective criteria for rejecting data for Bowen ratio flux calculations. Journal of Applied Meteorology, **21**: 595-598.
- O’Kane, M. 1996. Instrumentation and monitoring of an engineered soil cover system for acid generating mine waste. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- O’Kane, M. and Barbour, S.L. 2003. Field performance of lysimeters used to evaluate cover systems for mine waste. *In* Proceedings of the 6<sup>th</sup> International Conference on Acid Rock Drainage, Cairns, Qld, Australia, July 12-18, pp. 327-339.
- Oke, T.R. 1987. Boundary Layer Climates, Second Edition. Routledge, New York, NY.
- Paltineau, I.C. and Starr, J.L. 1997. Real-time soil water dynamics using multisensor capacitance probes: laboratory calibration. Soil Science Society of America Journal, **61**: 1576-1585.
- Paulsen, R.J., Smith, C.F., O’Rourke, D., and Wong, T.-F. 2001. Development and evaluation of an ultrasonic ground water seepage meter. Ground Water, **39**: 904-911.
- Penman, H.L. 1948. Natural evapotranspiration from open water, bare soil and grass. Proceedings of the Royal Society of London, Series A. **193**: 120-146.
- Phene, C.J., Allee, C.P. and Pierro, J. 1989. Measurement of soil matric potential and real time irrigation scheduling. Agricultural Water Management, **16**(3): 173-185.
- Phene, C.J., Hoffman, G.J. and Rawlins, S.L. 1971a. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: I. Theory and sensor construction. Soil Science Society of America Proceedings, **35**: 27-33.

- Phene, C.J., Rawlins, S.L. and Hoffman, G.J. 1971b. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: II. Experimental results. Soil Science Society of America Proceedings, **35**: 225-229.
- Ruygrok, P. 1988. Evaluation of the gamma and neutron radiation scattering and transmission methods for soil density and moisture determination. Geotechnical Testing Journal, **11**: 3-19.
- Sattler, P. and Fredlund, D.G. 1989. Use of thermal conductivity sensors to measure matric suction in the laboratory. Canadian Geotechnical Journal, **26**: 491-498.
- Scanlon, B.R., Andraski, B.J., and Bilskie, J. 2002. Miscellaneous methods for measuring matric or water potential. In J.H. Dane and G.C. Topp (ed.) Methods of Soil Analysis: Part 4 – Physical Methods. Book Ser. No. 5. SSSA, Madison, WI, pp. 643–670.
- Sentek Environmental Technologies. 2000. Diviner2000 Users Guide: Version 1.2. Sentek Pty Ltd, Stepney, South Australia.
- Shaw, R.D. and Prepas, E.E. 1989. Anomalous, short term influx of water into seepage meter. Limnology and Oceanography, **34**: 1343-1351.
- Sholkovitz, E., Herbold, C. and Charette, M. 2003. An automated dye-dilution based seepage meter for the time-series measurement of submarine groundwater discharge. Limnology and Oceanography: Methods. **1**: 16-28.
- Silvestri, V., Sarkis, G., Bekkouche, N., Soulie, M. and Tabib, C. 1991. Laboratory and field calibration of a neutron depth moisture gauge for use in high water content soils. Geotechnical Testing Journal, **14**: 64-70.
- Smith, C.D. 1995. Hydraulic Structures. University of Saskatchewan Printing Service, Saskatoon, SK.
- Spaans, E.J. and Baker, J.M. 1995. Examining the use of time domain reflectometry for measuring liquid water content in frozen soil. Water Resources Research, **31**: 2917-2925.
- Stannard, D.I. 1992. Tensiometers – Theory, construction, and use. Geotechnical Testing Journal, **15**: 48-58.
- St-Arnaud, L.C. and Woyshner, M.R. 1992. Hydrological Evaluation of the Thickened Tailings Disposal System at Kidd Creek Division, Falconbridge Ltd. Report V2-1-T01, Centre de technologie Noranda, Pointe Claire, Quebec.
- Taniguchi, M. and Fukuo, Y. 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. Ground Water **31**: 675-679.

- Taniguchi, M. and Iwakawa, H. 2001. Measurement of submarine groundwater discharge rates by a continuous heat-type automated seepage meter in Osaka Bay, Japan. *J. Groundwater Hydrol.* **43**: 271-277.
- Tanner, C.B. 1960. Energy balance approach to evapotranspiration from crops. *Soil Science Society of America Proceedings*, **24**: 1-9.
- Topp, G.C. and Davis, J.L. 1985. Measurement of soil water content using time domain reflectometry (TDR): A field evaluation. *Soil Science Society of America Journal*, **49**: 19-24.
- Topp, G.C., Davis, J.L., and Annan, A.P. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, **16**: 574-582.
- USDA (United States Department of Agriculture). 1984. Snow survey sampling guide. Agriculture Handbook 169, Natural Resources Conservation. Available from <http://www.wcc.nrcs.usda.gov/factpub/ah169/ah169.htm>.
- USDA (United States Department of Agriculture). 2000. Nuclear gauge train-the-trainer course. USDA Radiation Safety Staff, Beltsville, Massachusetts. Available from <http://www.cprl.ars.usda.gov/wmru/pdfs/gauge-1.pdf>.
- Veissman, W., and Lewis, G.W. 1996. *Introduction to Hydrology*, Fourth Edition. HarperCollins College Publishers, New York, NY.
- Veldkamp, E. and O'Brian, J. 2000. Calibration of a frequency domain reflectometry sensor for humid tropical soils of volcanic origin. *Soil Science Society of America Journal*, **64**: 1529-1553.
- Whalley, W.R. 1993. Considerations on the use of time domain reflectometry (TDR) for measuring soil water content. *Journal of Soil Science*, **44**: 1-9.
- Wong, D. 1985. A study of brine flow through saturated-unsaturated potash tailings. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
- Woo, M.-K. 1997. A guide for ground-based measurement of the arctic snow cover. Report prepared for the Climate Research Branch of the Meteorological Service of Canada. Available from <http://www.msc.ec.gc.ca/crysys/education/snow/woo.pdf>.
- Woyshner, M.R. and St-Arnaud, L.C. 1994. Hydrogeological evaluation and water balance of a thickened tailings deposit near Timmins, ON, Canada. *In Proceedings of the 3<sup>rd</sup> International Conference on the Abatement of Acidic Drainage*, Pittsburgh, PA, April 24-29, Vol. 2, pp. 198-207.
- Yoder, J. 1999. Plumbing the depths of open-channel flow measurements. Control for the Process Industries. July.

Zazueta, F. and Xin, J. 1994. Soil moisture sensors. Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, University of Florida. Bulletin 292. April.

Zegelin, S.J., White, I. and Jenkins, D.R. 1989. Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry. *Water Resources Research*, **25**: 2367-2376.

Zegelin, S.J., White, I. and Russell, G.F. 1992. A critique of the time domain reflectometry technique for determining field soil water content. *In Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*. Soil Science Society of America Special Publication No. 30, pp. 187-208.