DESIGN, CONSTRUCTION AND PERFORMANCE MONITORING OF COVER SYSTEMS FOR WASTE ROCK AND TAILINGS

VOLUME 4 – FIELD PERFORMANCE MONITORING AND SUSTAINABLE PERFORMANCE OF COVER SYSTEMS

MEND 2.21.4d

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VOLUME 4

FIELD PERFORMANCE MONITORING AND SUSTAINABLE PERFORMANCE OF COVER SYSTEMS

Prepared for MEND

Funded by INCO Ltd.

Edited by:

O'Kane Consultants Inc.

Integrated Geotechnical Engineering Services
Specialists in Unsaturated Zone Hydrology

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SUMMARY

This manual includes a summary volume (Volume 1) and the following four supporting technical documents:

- Volume 2 – Theory and Background;
- Volume 3 – Site Characterization and Numerical Analyses of Cover Performance;
- Volume 4 – Field Performance Monitoring and Sustainable Performance of Cover Systems; and
- Volume 5 – Case Studies.

The information presented in Volume 1 outlined the fundamentals of field performance monitoring, construction issues, and sustainable performance of cover systems. Volume 4 presents additional detail on the topics of field performance monitoring and sustainable performance of cover systems. For clarity, some of the information from Volume 1 is restated in this volume.

This volume is divided into two sections: field performance monitoring and sustainable performance of cover systems. Section 1 includes descriptions of methods for measuring precipitation, evaporation, soil moisture content, soil suction, net percolation, runoff, and erosion. This section ends with a discussion of automated monitoring systems and data management and interpretation.

Section 2 is divided into three topics: a description of the key processes affecting long-term performance, a discussion of surface water management and landform evolution, and a brief discussion on the concept of long-term cover performance.

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1 FIELD PERFORMANCE MONITORING

Field monitoring is an essential and necessary method of evaluating the performance of soil cover systems and provides a direct method of verifying the design of the cover system. Field performance monitoring can be implemented during the design stage with test cover plots (e.g. Aubertin *et al.*, 1997; O'Kane *et al.*, 1998a, 1998b), or following construction of the full-scale cover (e.g. MEND 2.22.4a,b; O'Kane *et al.*, 1998c). Direct measurement of field performance of a cover system is the best method for demonstrating to regulatory agencies and the public that the cover system will perform as designed. The main objectives of field performance monitoring are to:

- Obtain a water balance for the site;
- Obtain an accurate set of field data to calibrate a numerical simulation of cover performance;
- Develop confidence with all stakeholders with respect to cover system performance; and
- Develop an understanding for key characteristics and processes that control performance.

The monitoring programme should be designed to measure the various components that influence the performance of a cover system. These components are shown schematically in Figure 1.1 and are comprised primarily of the elements of the water balance, oxygen flux, and climate. MEND BC.03 provides a detailed overview of field performance monitoring for cover systems. The monitoring system then will include meteorological monitoring, monitoring of moisture storage changes, and monitoring of net percolation, surface runoff, erosion, and vegetation.

In terms of field performance monitoring for a full-scale cover system, a recommended minimum level of monitoring would include meteorological monitoring such as the determination of the potential evaporation and site specific precipitation, cover material moisture storage changes, watershed or catchment area surface runoff, vegetation, and erosion.

Table 1.1 lists typical methods of measurement for the various components of a field performance monitoring system. Methods for measuring precipitation, actual evapotranspiration, *in situ* moisture conditions (moisture content and soil suction), net percolation, and surface runoff / erosion are discussed in the following sections.

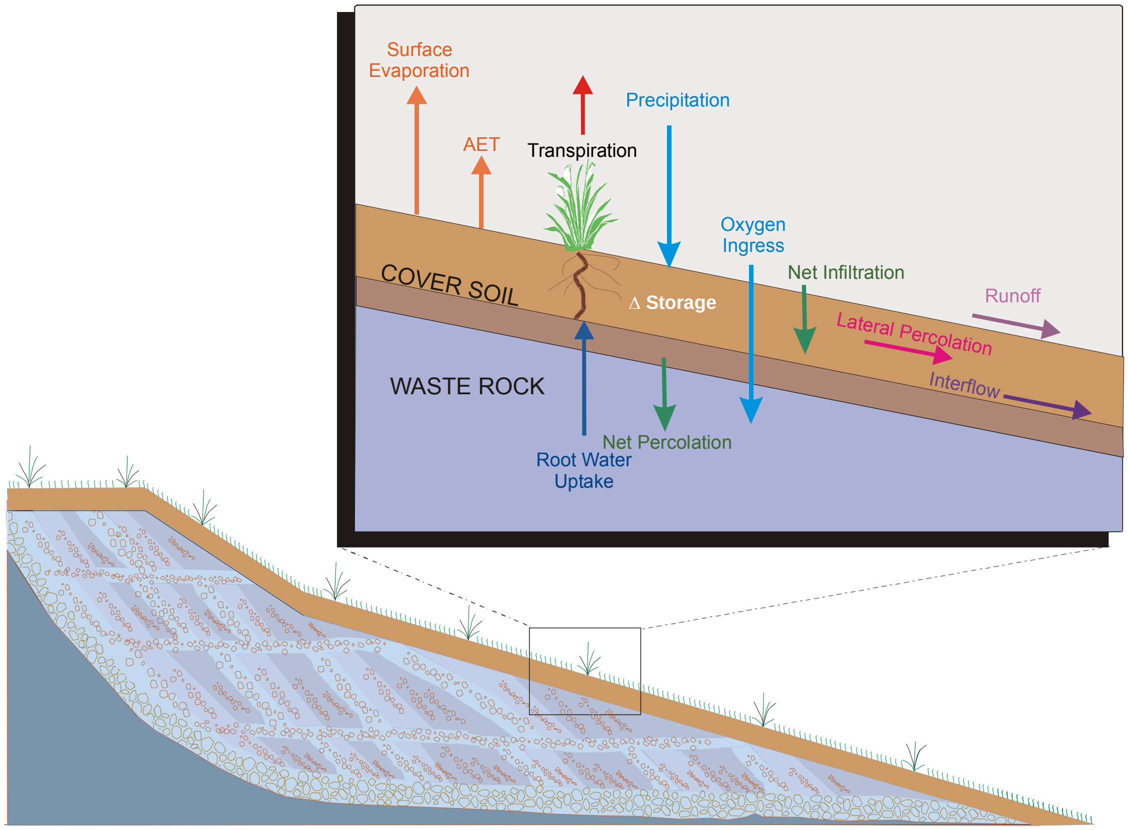

Figure 1.1 Conceptual schematic of the components of a field performance monitoring system.

1.1 Measurement of Precipitation

Measurement of precipitation is the most crucial of the site-specific meteorological measurements. Rainfall should be measured at several locations for large sites to quantify spatial differences in rainfall intensity and volumes. Rain gauges should also be located at all test plot sites. 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.

Other meteorological parameters that should be monitored include: air temperature, relative humidity, wind speed and direction, and net solar radiation. This data is required as input to a soil-atmosphere model and can be used to evaluate the potential evaporation for the site.

Table 1.1
Typical methods of measurement for the components of a field performance monitoring system.

Parameter Measured	Typical Method(s) of Measurement
Precipitation	• Tipping bucket rain gauge (for rainfall) • All-season precipitation gauge (for snowfall) • Snow survey (depth and density of snowpack)
Actual evapotranspiration	• Bowen ratio energy balance (BREB) • Weighing lysimeter • Eddy covariance
Moisture content	• Gravimetric method • Neutron moisture probe • Time domain reflectometry (TDR) • Frequency domain reflectometry (FDR) • Capacitance
Negative pore-water pressure (or soil suction)	• Tensiometer • Thermal conductivity sensor • Gypsum block
Positive pore-water pressure	• Standpipe piezometer • Pneumatic piezometer • Electric piezometer
Pore-water sampling	• Vacuum lysimeter
Net percolation	• Lysimeter • Suction sensor gradients
Temperature	• Thermocouple • Thermistor
Oxygen	• Oxygen analyzer (with sampling ports) • Oxygen consumption test • Oxygen flux meter

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. These three methods are discussed below.

1.1.1 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 requires human intervention to record data and empty the gauge as needed.

All non-recording snow gauges measure snow water equivalent (SWE) directly. SWE is defined as the equivalent depth of water of a snow cover (Gray, 1970). The most common non-recording snow gauge in Canada is the MSC Nipher snow gauge (Goodison *et al.*, 1981). The gauge consists simply 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 in order 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.

1.1.2 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 0.2 mm capacity), which tip back and forth as they are filled in turn by rainfall directed to them by a collecting 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 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; however, the smaller the time interval, the more accurate the determination of precipitation rates. Antifreeze must be added to the catch bucket in cold climates in order 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 and recording gauges.

1.1.3 Snow-Survey Method

The conventional way of determining the SWE of a snowpack is by the snow survey method (Gray, 1970). Snow surveys are typically conducted at regular intervals at designated locations throughout the winter in order to determine the depth and vertically integrated density of the snow cover (Goodison *et al.*, 1981). These measurements are used to compute SWE as follows:

$$SWE = 0.01\ \rho_s\ d_s \qquad [1.1]$$

where,

SWE = snow water equivalent (mm),

ρ_s = density of the snowpack (kg/m^3), and

d_s = depth of the snowpack (cm).

Maidment (1993) reports that an average density of 100 kg/m^3 for new snowfall is often assumed, which gives 1 unit of water for every 10 units of snowfall). The basic snow survey equipment consists of a graduated aluminium tube to measure d_s and to extract a column of snow, and a spring balance (reading directly in water equivalent units) to weigh the tube and its contents (Goodison *et al.*, 1981). Although measurements from this method are regarded as the best approximation of the water equivalent of a snow cover, snow surveying is labour intensive and time consuming.

1.2 Measurement of Evapotranspiration

A variety of methods are available for measuring evaporation and evapotranspiration rates from the ground surface. The most commonly utilized methods can either be classified as a direct measurement method or a micrometeorological method. 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 and the mass transport method. Another micrometeorological method is the Eddy covariance method; this method is not as commonly used because the equipment is costly. 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, except the evaporation pan, which was discussed in a previous section of this manual. A brief discussion is also given on the Eddy covariance method.

1.2.1 Weighing Lysimeters

Weighing lysimeters have an extensive and long-established use because they provide a direct measurement of actual evapotranspiration 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 natural ground. The volume of soil within the lysimeter is hydrologically 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 1.2 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 actual evapotranspiration 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 (see Section 1.5 on collection lysimeter design).

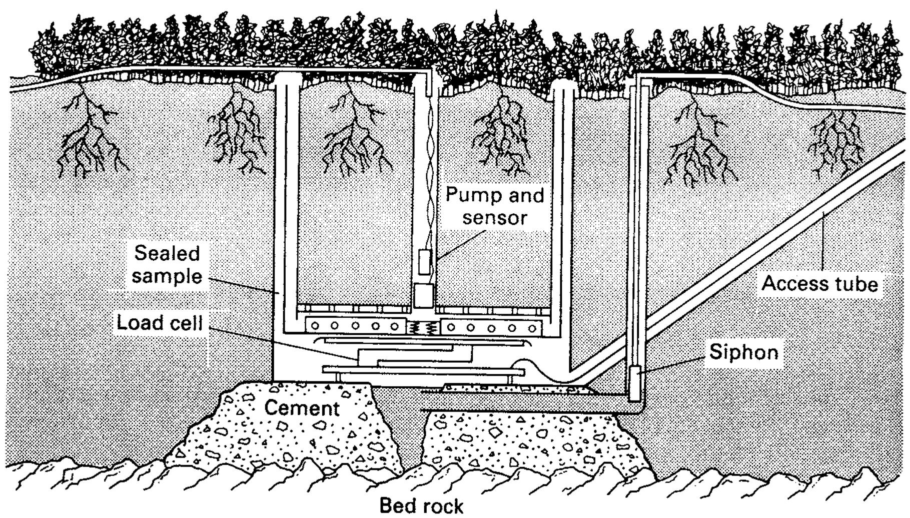

Figure 1.2 A well-designed weighing lysimeter (from Maidment, 1993).

1.2.2 Bowen Ratio Energy Balance Method

The Bowen ratio energy balance (BREB) method has been used for many years to determine actual evapotranspiration 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). Woyshner 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, β. The following relationship may be used to determine β:

$$\beta = \frac{Q_H}{Q_E} = \gamma \frac{\Delta T}{\Delta e} \qquad [1.2]$$

where:

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

P = atmospheric pressure (kPa),

c_p = specific heat of air (kJ/kg°C),

λ = latent heat of vapourization (kJ/kg),

ε = ratio of the molecular weight of water to the molecular weight of dry air, and

ΔT and Δe = change in air temperature (°C) and vapour pressure (kPa), respectively, over the same height interval above the ground surface.

Typical values of β for various climates are listed in Table 1.2. Substituting Equation 1.2 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):

$$Q_E = \frac{Q^* - Q_G}{1 + \beta} \qquad [1.3]$$

where:

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

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

Table 1.2

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

Climatic Region	Value of β
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

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 1.3.

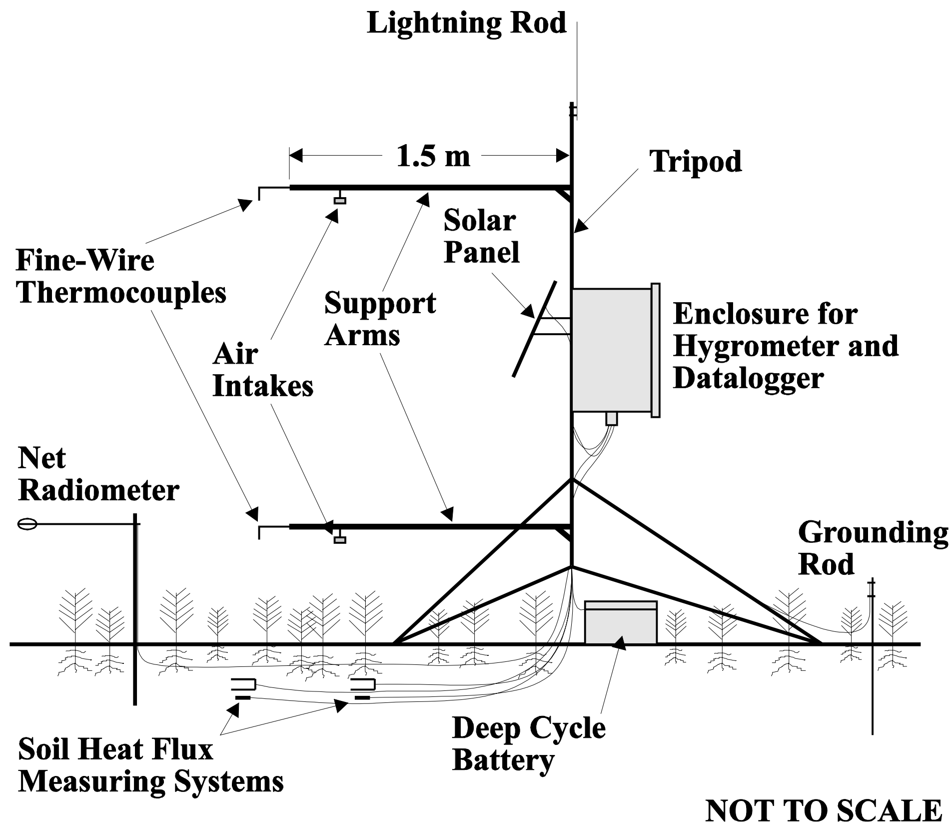

Figure 1.3 Schematic of the Bowen ratio monitoring system (from Ayres, 1998).

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.

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 applying the results of Bowen Ratio 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:

$$\text{If } (Q^* + Q_G) > 0, \text{ then } \Delta T > -\left(\frac{\Delta e}{\gamma}\right) \qquad [1.4]$$

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

If Bowen ratio data do not satisfy one of these conditions, then the data is 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 signs are correct. When β approaches -1 in Equation 1.3, the value of Q_E loses its numerical meaning. Ohmura (1982) provides the following inequality:

$$-\left(\frac{\Delta e}{\gamma}\right) - 2\left[\frac{R_e}{\gamma} + R_T\right] < \Delta T < -\left(\frac{\Delta e}{\gamma}\right) + 2\left[\frac{R_e}{\gamma} + R_T\right] \qquad [1.5]$$

where:

R_e = resolution of the vapour pressure sensor, and

R_T = resolution of the air temperature sensor.

If Bowen ratio data satisfies the above inequality, then there is a high possibility that β 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 actual evapotranspiration 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 in order to obtain representative data.

1.2.3 Eddy Covariance Method

The following information on Eddy covariance is a brief summary of the discussion on Eddy covariance in the book titled Boundary Layer Climates (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 ($\overline{s}$) and a fluctuating value (s') as shown in Equation 1.6:

$$s = \overline{s} + s' \qquad [1.6]$$

The mean vertical flux (S) of this entity consists of its density (ρ), 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 1.6. Simplifications, such as assuming that air density (ρ) is virtually constant, result in the following equation to define the mean vertical flux (S) of this entity:

$$S = \rho\overline{w's'} \qquad [1.7]$$

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

$$Q_H = C_a\overline{w'T'} \qquad [1.8]$$

where:

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

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

T = temperature (K).

$$Q_E = L_v\overline{w'\rho_v'} \qquad [1.9]$$

where:

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

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

ρ_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). 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 currently used primarily in a research setting.

1.3 Measurement of *In Situ* Moisture Content

The four most common methods of measuring the *in situ* moisture content of soils and other fine-textured materials are:

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

Each of these methods is discussed below.

1.3.1 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. The loss of mass due to drying is considered to be water. The water content is computed using the mass of water and the mass of the dry sample.

The disadvantage of using the gravimetric method in the field is that a sampling device must be used to remove soil from the required depths. Therefore, the gravimetric method is time consuming, and cannot be automated. As well, frequent sampling for this test destroys the homogeneity of the soil profile at a study site. Gravimetric water contents cannot be converted to volumetric water contents without a measurement of the dry bulk density.

1.3.2 Nuclear Method

The use of the neutron moisture probe for measuring soil water content *in situ* 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), and it is not practical to automate the neutron moisture probe.

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 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 slow down, a process referred to as thermalization. A fraction of the thermalized neutrons are captured by the detector, giving rise to a signal, which, after processing, is known as the gauge reading. The gauge reading is an indication of the volumetric total water content (i.e. liquid and ice content) of the surrounding medium, providing proper calibration procedures have been performed.

Access tubes must be installed into the soil in order to use the neutron moisture probe for measuring soil water content *in situ*. 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 greatly 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).

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 regressing these to a linear model (Kramer *et al.*, 1992). Such a regression takes the form:

$$\theta_w = m\,(CR) + b \qquad [1.10]$$

where:

θ_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 value of CR is largely dependent on θ_w; 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 in the soil of organic materials 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 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 as well as for general nuclear safety as 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 is still meeting all safety requirements.

1.3.3 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). 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), etc.; however, they are reviewed briefly here. TDR is essentially cable radar in which a very fast rise-time voltage pulse is 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:

$$K_a = \left(\frac{ct}{2L}\right)^2 \qquad [1.11]$$

where:

c = velocity of light in a vacuum (3 x 10^8 m/s);

L = length of the soil - transmission line (m); and

t = time required for transmission (s).

Figure 1.4 shows the instrument components and idealized output trace of the TDR soil moisture content measurement method.

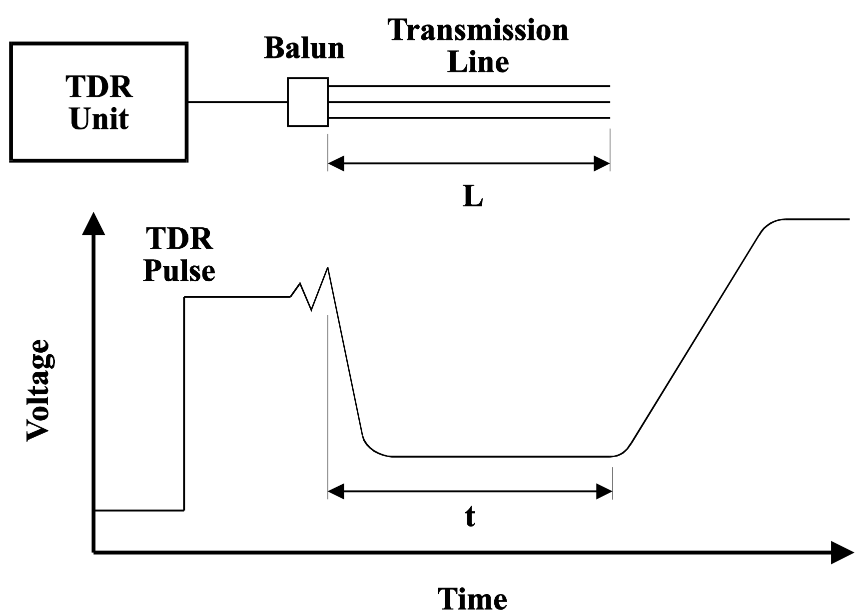

Figure 1.4 Instrument components and idealized output trace of the TDR moisture content measurement method (from Ayres, 1998).

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

$$\theta_w = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \qquad [1.12]$$

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 1.12 has been examined and confirmed by numerous other researchers (Dalton, 1992; Whalley, 1993; Zegelin, 1989; etc.). As a result, the Topp *et al.* (1980) empirical relationship is known as the “universal” TDR equation for soils. 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).

One of the advantages claimed for the TDR technique, based on the empirical fit of Equation 1.12, 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_a (and therefore θ_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 1.12 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 in order 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 probe wires (Zegelin *et al.*, 1992).

One of the limitations of the TDR method is the effect of high dissolved solids in the soil water (Nichol *et al.*, 2002). This leads to higher electrical conductivity of the bulk soil present between the rods of the probe. The voltage signal carried on the signal rod may be lost by DC current loses 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 water content. For commonly used probes, this type of signal loss may prevent measurements in soils with water conductivities of 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 wrapping the rods in shrink wrap reduce the sensitivity of the probe to EC.

1.3.4 Frequency Domain Reflectometry

The theory behind measurement of *in situ* moisture content of soils and other fine-grained 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. 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. All FDR measurement systems should be calibrated in the field, as with TDR measurement systems, to facilitate the collection of quantitative *in situ* moisture content data.

1.3.5 Electrical Capacitance

Automated sensors installed within a PVC access tube can also use electrical capacitance to measure the *in situ* volumetric water content of the material surrounding the access tube. A high frequency electrical field, created around the sensor, extends through the access tube into the soil. The magnitude of the frequency is a function of the apparent dielectric constant of the soil, which is strongly dependent on the volumetric water content of the soil. The more water in the soil, the higher the K_a value and the lower the frequency measured by the sensor. A calibration curve is then used to convert the field measured frequency to a volumetric water content value.

1.4 Measurement of *In Situ* 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 (moisture movement resulting from a concentration gradient), are the two components of total suction.

1.4.1 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 will have 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 90 kPa due to cavitation of water in the tensiometer (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. Alternatively, a jet-fill tensiometer, an improved model of the regular tensiometer, has a water reservoir at the top of the tube for removing air bubbles (Figure 1.5). 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 are: 1) simple installation and operation; 2) no laboratory or field calibration is required; 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.

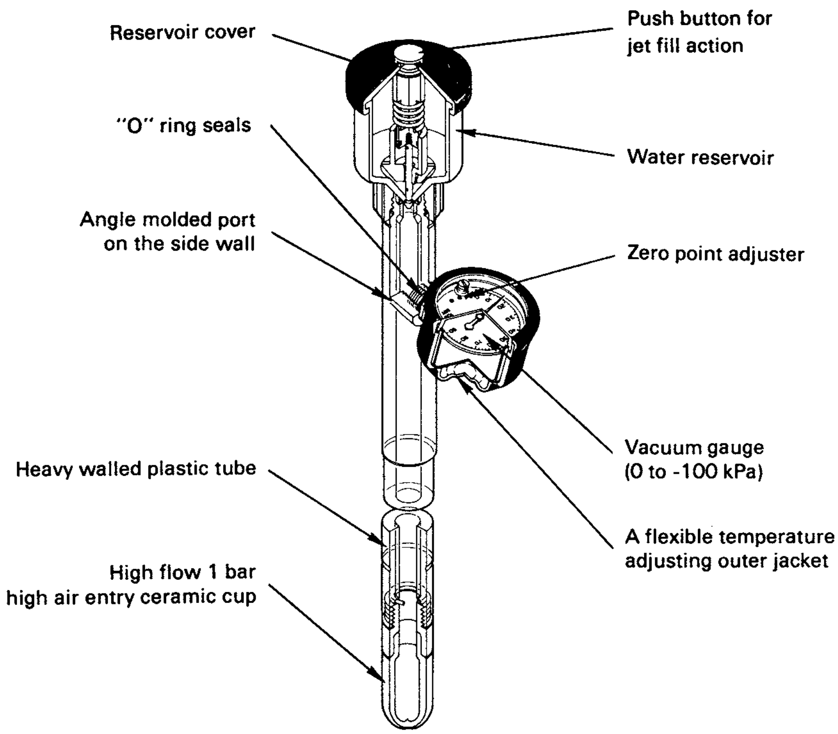

Figure 1.5 Schematic of a jet-fill tensiometer (from Fredlund and Rahardjo, 1993).

1.4.2 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.*, 1987). It is only recently that the value of this soil suction measurement technique was recognized by geotechnical engineers for use in both the laboratory and the field. 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 as shown in Figure 1.6. The porous ceramic block has a wide pore-size distribution that allows for 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. 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 of dissipation of the heat pulse introduced into the ceramic block. The difference in temperature before and after heating the ceramic block is a measure of the water content of the ceramic block. The amount of water in the ceramic block affects the heat capacity and heat dissipation within the block. The heat capacity and thermal conductivity of the ceramic block increases as the water content increases, consequently, the more rapid rate of heat dissipation the higher the water content and vice versa. The change in temperature before and after heating (ΔT) is directly related to the water content of the ceramic block.

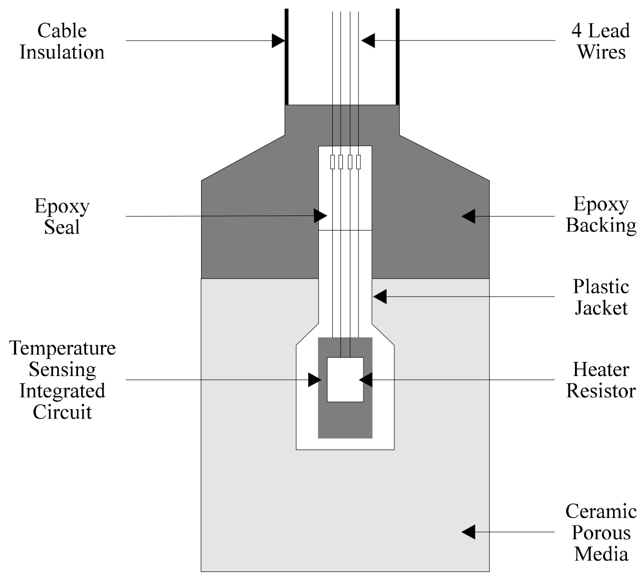

Figure 1.6 Schematic of a thermal conductivity sensor (from Fredlund and Rahardjo, 1993).

A relationship also exists between the water content in the porous block and matric suction (i.e. the ceramic block has its own unique soil water characteristic curve). 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 ΔT.

In general, a laboratory calibration 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 in which they will be installed into because matric suction is a stress state, as opposed to a material property. The laboratory calibration process is also a check 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 some thermal conductivity sensor laboratory calibration curves is shown in Figure 1.7. This figure demonstrates the importance of calibrating each and every thermal conductivity sensor in the laboratory prior to their inclusion in a cover system field performance monitoring programme.

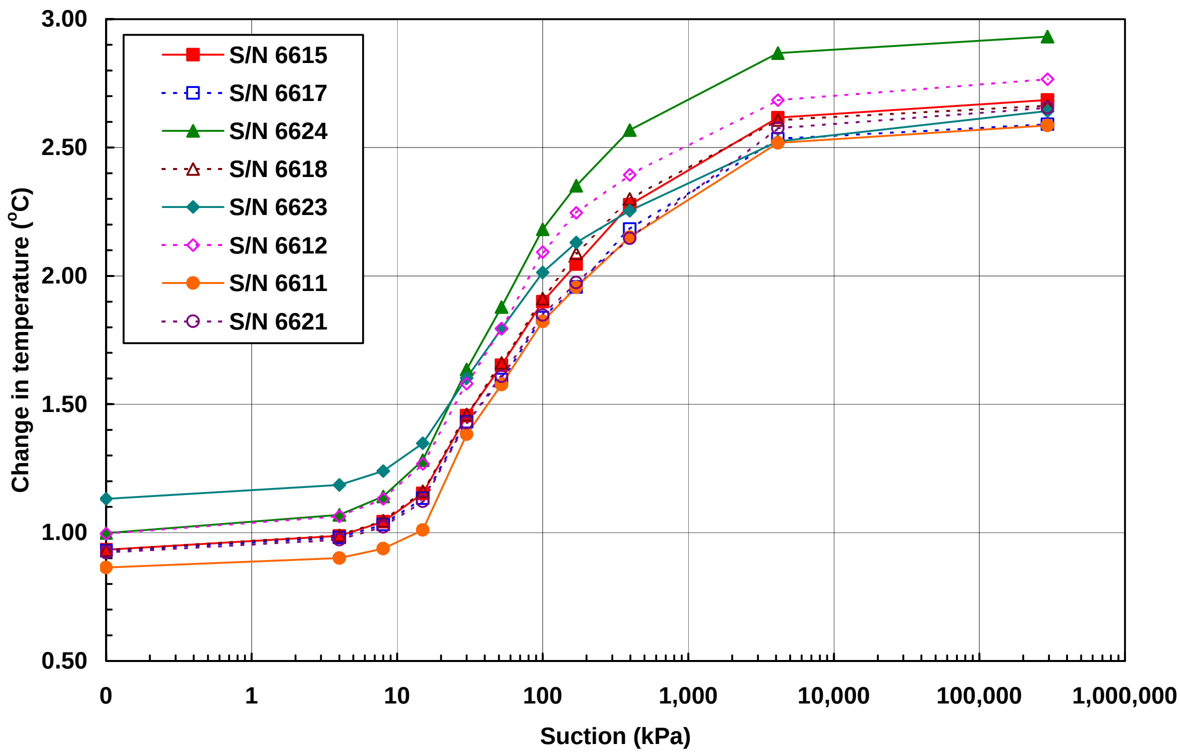

Figure 1.7 Typical laboratory calibration curves from thermal conductivity sensors.

1.4.3 Gypsum Blocks

Gypsum blocks have been used in the agricultural industry for over 40 years to provide an indirect measurement of matric suction in soils. A gypsum block typically consists of two electrodes 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.

However, two problems are usually encountered when using gypsum blocks, especially in saline (Phene *et al.*, 1971a) or acidic environments. The first problem is that the presence of dissolved salts in the pore-water affects electrical conductivity independently of water content. The second problem is that 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.

A modified gypsum block sensor (Watermark sensor by Irrometer Co. Ltd) 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. These sensors dissolve slower than standard gypsum blocks. These sensors have a limited measurement range (20 to 200 kPa) and are therefore most practical for humid climates.

1.5 Measurement of Net Percolation

Two methods are listed in Table 1.1 for measuring net percolation through a cover system.

Detailed analysis of 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 1.4). The suction data can be combined with measurements of hydraulic conductivity and the SWCC to calculate a value of net percolation.

The preferred method discussed below is the installation of a lysimeter either below or within a cover system placed over reactive mine waste. The monitoring device described in this section should not be confused with a weighing lysimeter, which was described in Section 1.2.1 for measuring actual evapotranspiration although the design recommendations in this section would apply to the design of a weighing lysimeter.

1.5.1 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 cover system monitoring programme. 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, which adds to 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 cover system monitoring programmes 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 a field lysimeter will give an accurate measurement of the net percolation through the cover system under a range of precipitation events. Note that the design of a lysimeter for one site is generally not 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 collected net percolation rate is the same as the net percolation outside the lysimeter. Three requirements for the design of a lysimeter can be used to verify that the criterion is being met, which are described below.

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 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 SEEP/W model to predict pressure head profiles inside and outside the confines of the lysimeter. The two profiles had to be nearly identical under the range of probable net percolation rate in order that this criterion was met.

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. The gradient within the waste material below the cover should be approximately equal to 1.0 under conditions of steady-state infiltration. Figure 1.8 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 the mine waste, the suction will eventually become constant with elevation. This occurs when the suction developed within the waste rock 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. To check the validity of the lysimeter design, it is fundamental to apply different surface flux boundary conditions to the model, as well as a sensitivity analysis on the material properties influencing performance of the lysimeter, 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).

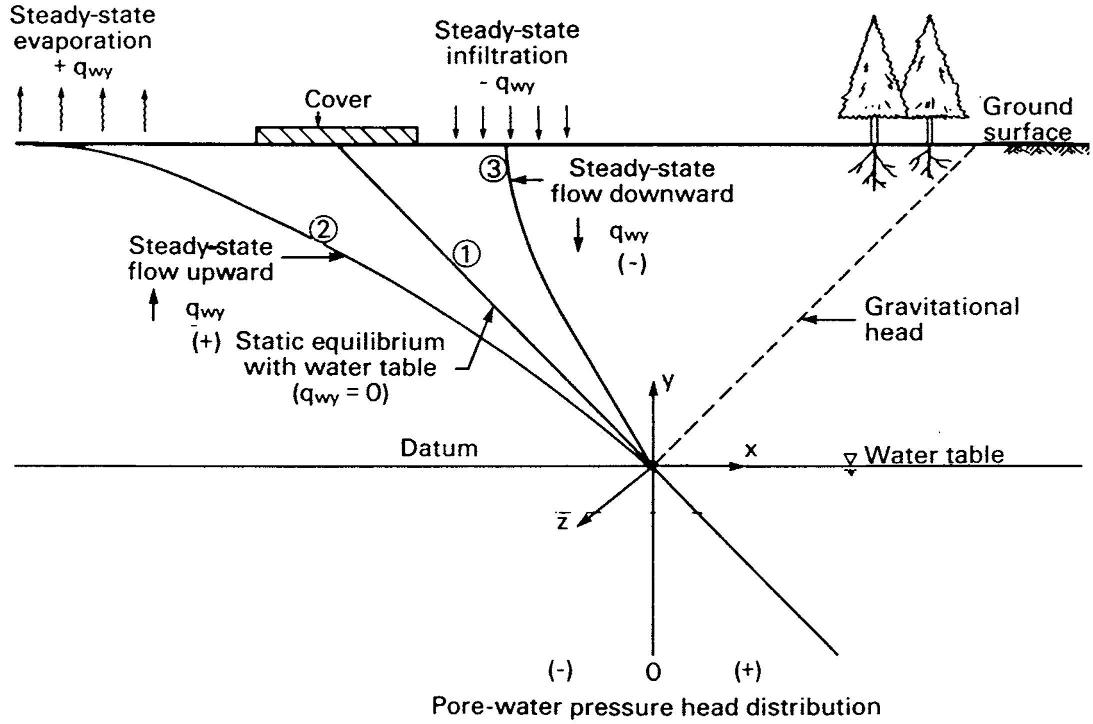

Figure 1.8 Static equilibrium and steady-state flow conditions in the zone of negative pore-water pressures (from Fredlund and Rahardjo, 1993).

1.5.2 Description of Field Lysimeter

A state-of-the-art field lysimeter, shown schematically in Figure 1.9, 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. The tank is then lowered into an excavation and subsequently 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 waters 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.

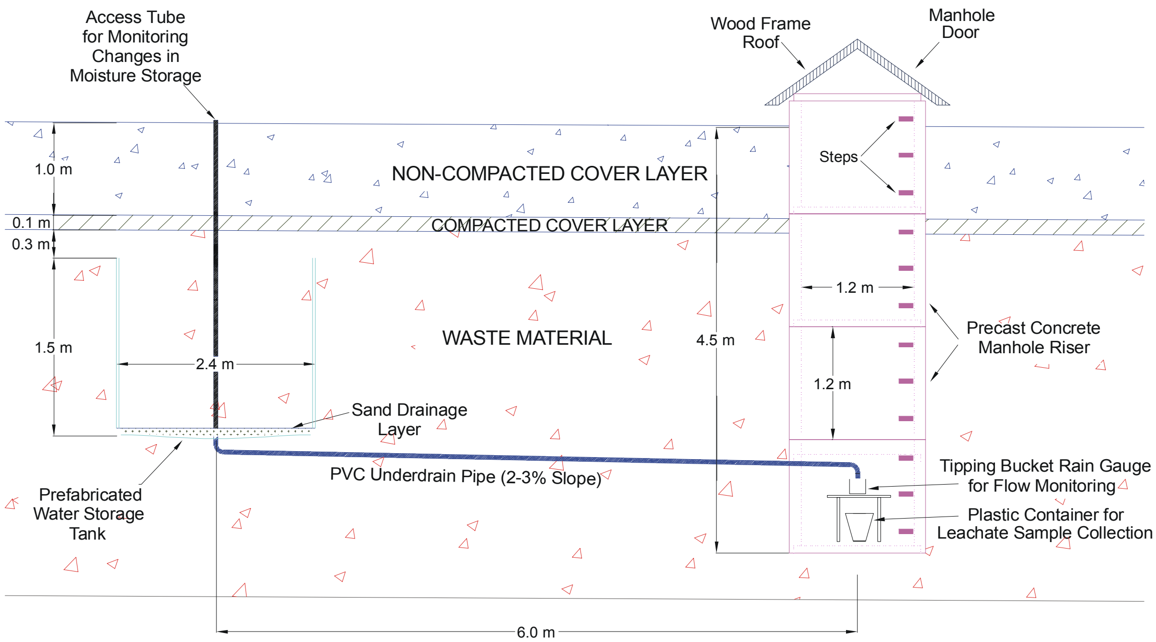

Figure 1.9 A state-of-the-art field lysimeter for measuring net percolation. Note: tank depth and dimensions must be tailored to each specific site.

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 water trap oxygen barrier 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 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.

The installation of a lysimeter as described above establishes an artificial water table within the lysimeter at some depth. Care must be taken to design the lysimeter to prevent the artificial water table from affecting the flow into or out of the lysimeter.

1.5.3 Installation of Field Lysimeters

Field lysimeters should be installed prior to construction of cover trials or a full-scale cover system. 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 a representative area of the cover system (i.e. in a location where the potential inflow of meteoric waters will be representative of the entire cover system). If a lysimeter is being installed on the slope of a waste rock dump, it should generally be located somewhere between the toe and mid-point of the cover system. Installation of a lysimeter near the crest of a sloping cover system may underestimate the net percolation since a smaller volume of water may be transmitted downslope to this location. The desired or optimum location of a lysimeter should be determined following a two-dimensional saturated-unsaturated flow modelling exercise, as discussed in Volume 3.

1.6 Measurement of Surface Runoff / Erosion

Runoff is a very complex process and therefore accurate measurement of local surface runoff from a natural soil system is difficult. The quality of data obtained from surface runoff collection devices is questionable because 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.

O'Kane (1996) attempted to measure local surface runoff from an engineered soil cover system for sulphidic mine waste at Equity Silver Mines Ltd. in British Columbia, Canada. Local surface runoff measurement reservoirs, as illustrated in Figure 1.10, were installed at two locations on the soil cover. The reservoirs were designed to collect runoff from storm events during non-freezing conditions. Mine personnel manually measured and recorded the volume of water stored in the barrels, which was used to compute runoff from the contributing areas. Surface erosion was not assessed as part of this monitoring system. O'Kane (1996) reported that installation and data collection problems led to unreliable measurements from the reservoirs.

Other techniques have been used to assess the quantity of surface erosion. Quine *et al.* (1997) described 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. Measurement of the depth of scour or deposition at the pin allows 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).

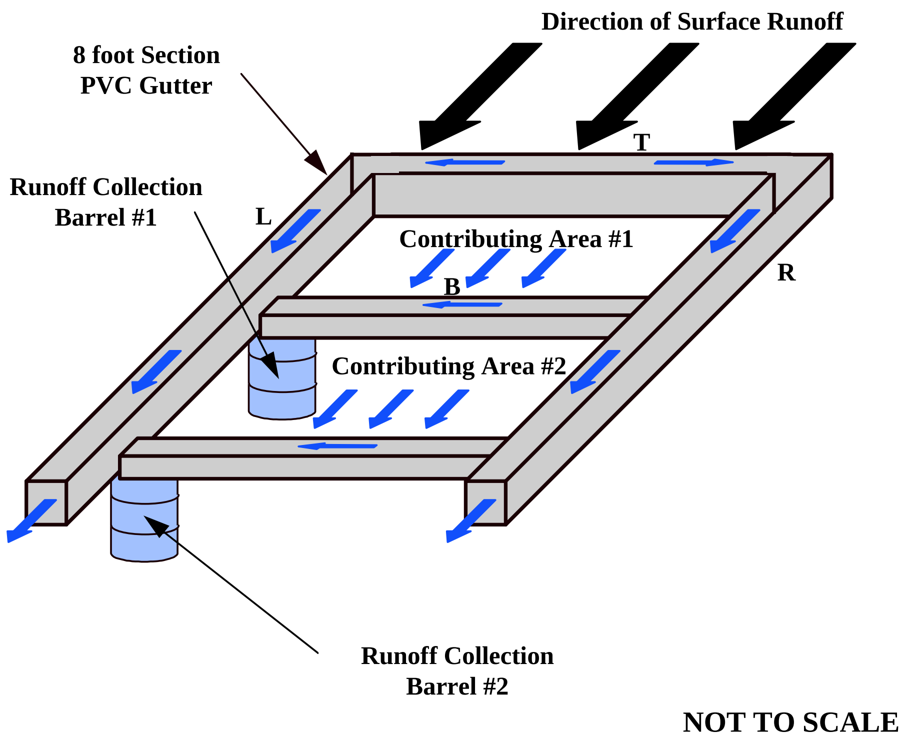

Figure 1.10 Schematic of the local surface runoff reservoirs installed at Equity Silver Mines Ltd. (from O'Kane, 1996).

1.7 General Installation of *In Situ* Monitoring Sensors

The following details should be taken into consideration when installing sensors within a cover 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' soil water characteristic curve for each layer in the cover / waste profile.
- A cover system field performance monitoring programme 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 cover system. For example, orientation of the slope of a waste rock pile will strongly influence evaporation conditions and vegetation conditions (in the northern hemisphere, this implies that a cover system on a north facing slope will possess different performance characteristics than if it was on a south facing slope). Other factors that can influence the location of a monitoring site or a cover system trial area include slope angle, runoff and run-on conditions, slope length, elevation of the monitoring location (if the mine site is in a mountainous terrain), reactivity of the underlying waste, and texture of the underlying waste. 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 in cover system performance. 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.

1.8 Automation of Performance Monitoring Systems

Many of the sensors listed in Table 1.1 can be connected to an automated data acquisition system that typically includes a datalogger, multiplexer, and a solar panel / rechargeable battery power source. The use of automated systems for data collection greatly reduces the need for human intervention and in particular, the demands placed on mine site personnel. Cellular, radio, or telephone communication can simplify data collection requirements at many sites.

1.9 Data Management and Interpretation

The most important task following installation of a field performance monitoring system is the interpretation and dissemination of the field monitoring data in a concise format to interested parties. It is recommended that three levels of data management be conducted to achieve this objective.

1) *Monthly Data Collection:* Field data should be collected from an automated data acquisition system (DAS) on a monthly basis. Routine maintenance would be conducted at this time on each of the monitoring systems. Any manual measurements should be conducted as required or on a monthly basis. The data from each of the monitoring sites should then be evaluated as a whole, as well as for each individual sensor, to ensure that all data acquisition systems and individual sensors are functioning properly and responding to atmospheric forcing as anticipated.

   This monthly effort is utilized to address a common mistake with respect to field performance monitoring systems. That is, if field data is not reduced and quality control checks not performed until an extended period has elapsed, the potential exists that a malfunctioning sensor or data acquisition system will not be discovered. The potential result is that key field data will be lost, even though a significant financial commitment has been made to obtain the field data.

2) *Quarterly Field Performance Monitoring Reports:* It is also recommended that field performance monitoring reports be prepared on a quarterly basis for at least the first two years of monitoring. These reports would typically include:

- A summary of data capture rates and an evaluation of individual sensors;
- Presentation of the field data in a concise format;
- A discussion and summary of performance for each monitoring site, which would focus on the quarterly monitoring period; and
- Recommended maintenance.

If the field monitoring programme is continued beyond two to three years, and an understanding for the system has been developed, then the frequency of the field performance monitoring can be adjusted to reflect the information requirements for long term field performance monitoring. At no point should the monthly quality control checks and maintenance be discontinued if the mine site intends to continue to utilize the data for future analysis and interpretation. Long-term performance monitoring has shown that a commitment to data collection is critical factor in verifying the performance of a cover system.

3) *Annual Field Performance Monitoring Reports:* The annual field performance monitoring report would represent the fourth quarterly report in a given annual monitoring period. This report would be organized as noted above for the quarterly performance monitoring reports; however, the discussion and summary would focus on the entire year of field data. In addition, a more detailed set of field data would be presented.

Ideally, a computer database should be developed to manage the field data obtained from a cover system performance monitoring system. This software would typically be available to all individuals requiring access to the field data. The database would be designed to respond to queries selected by the user, which are a reflection of the individual's needs. For example, the user may query for moisture conditions at a specific location and depth over a range of dates, and then overlay the resulting information with related influential factors such as precipitation. This data could be presented in a tabular or chart format. The user could then export the data or chart to an alternate software package as required.

It is also important to maintain good records of the sensor types, the calibration data, the datalogger programs, and the routine maintenance required for all the instrumentation. A field reference manual that summarizes this information is a useful resource that should be available to all site staff.

2 SUSTAINABLE PERFORMANCE OF COVER SYSTEMS

The behaviour of a cover system will change with time as a result of physical, chemical, and biological processes. These changes may result in changes in the long-term performance, as shown in Figure 2.1. In general, state-of-the-art models are limited to providing quantitative predictions based on some of the physical processes listed in Figure 2.1 that affect long-term performance. Consideration of the effects of long-term changes in biological and chemical processes on performance has been generally dealt with in a qualitative manner, if addressed at all. This leads to difficulty in developing a defensible closure plan using cover systems because of the subjectivity involved with qualitatively evaluating these processes. However, it is essential that the cover system design account for these processes to reduce the uncertainty associated with long-term performance to an acceptable and defensible level.

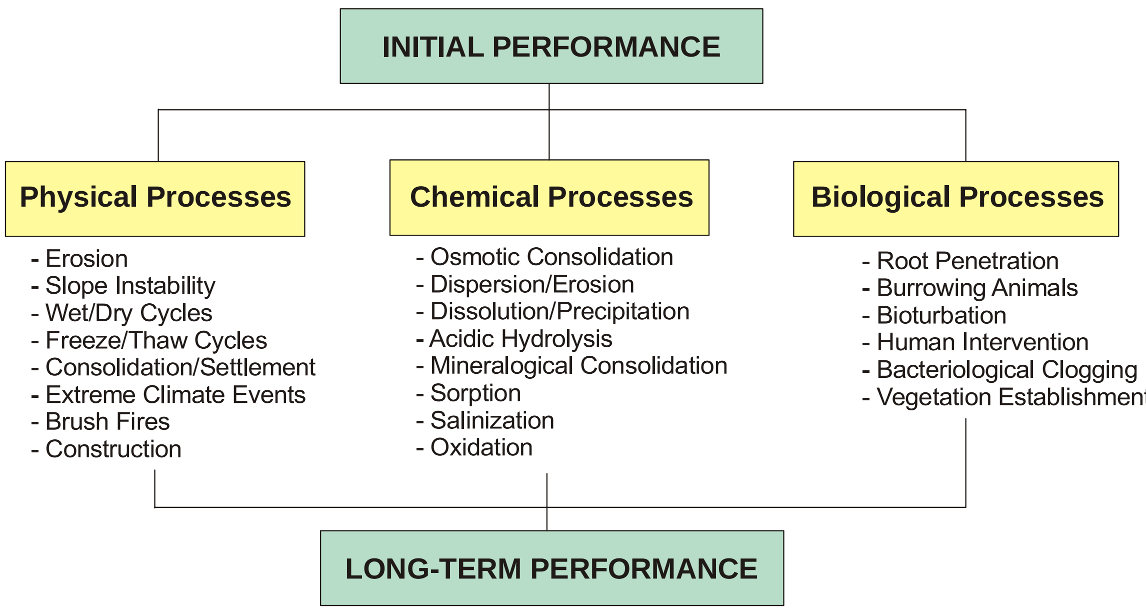

Figure 2.1 Conceptual illustration of processes affecting long-term performance of soil cover systems (INAP, 2002).

2.1 Key Processes Affecting Long Term Cover Performance

An examination of the processes identified in Figure 2.1 shows that their effects can be related to the change in three key properties of cover materials. These three key properties are the saturated hydraulic conductivity, the soil water characteristic curve (SWCC), and the physical integrity of the cover system. These key material properties affect the most common cover system design objectives; namely, controlling net percolation of water and ingress of oxygen to the underlying waste material.

The change in each key property affects the performance of the cover system differently. In general, the change in saturated hydraulic conductivity will most greatly affect covers that incorporate a hydraulic barrier, such as compacted layer covers and capillary break covers. Any increase in the saturated hydraulic conductivity leads to an increase in the percolation rate through the barrier layer. Alternatively, some physical processes (i.e. weathering) can “break down” cover material to a finer textured material, possibly reducing the saturated hydraulic conductivity of the cover material. It is important to note that changes in the hydraulic conductivity of the near surface material will also have an impact on surface runoff.

The integrity of the cover system is a key property because predictions of the long-term performance are based on the physical dimensions of a specific cover design. The term “integrity” in the context of cover performance refers to the physical stability / instability of the cover system with respect to erosion, mass wasting, consolidation, or subsidence. If the natural environment changes the physical limits of the cover design, then the predictions based on the original physical dimensions cannot be considered valid. Examples of these processes might include erosion, which removes material from the cover surface, or subsidence or consolidation of the waste, which then causes changes in the thickness and slope of the cover layers.

The saturated hydraulic conductivity and SWCC are the key hydraulic properties of the cover material. It is appreciated that the relationship between oxygen diffusion and the degree of saturation is also a key material property. However, in the context of this document, this relationship is a considered as being a function of the shape of the SWCC (and hydraulic conductivity function), and as such any change or evolution of the SWCC will also result in a corresponding change in the relationship between oxygen diffusion and the degree of saturation. Tests can be completed to assess the likely changes in the key hydraulic material properties (if any) over time. For example, a sample can be subjected to wet-dry cycles in the laboratory and the change in material saturated hydraulic conductivity can be evaluated. If the physical integrity of the cover system is compromised as a result of interactions of the cover materials with the natural environment then the prediction of the effects of these interactions on the key soil properties is extremely difficult.

The best approach is to identify the physical, chemical, or biological processes that are most likely to affect the integrity of the cover and then estimate the range of possible changes that may occur in the key soil properties. The influence of these changes on performance can be evaluated through the use of a sensitivity analysis.

For example, it is more likely that erosion will adversely affect the performance of a steeply sloping cover system as compared to the influence of burrowing animals. Therefore, even though burrowing animals do exist on the site, their impact on cover performance may be minimal in comparison to the potential detriment to long-term performance that may occur as a result of erosion.

The remainder of this section includes a brief discussion on most of the physical, chemical, and biological processes shown in Figure 2.1. The processes are discussed in terms of the potential impact they may have on the three key properties identified above.

2.1.1 Physical Processes

The physical processes affecting the long-term performance of cover systems are detailed in this section. Each process involves the response of the cover materials to atmospheric forcing. For example, erosion is a possible response of a cover system to energy supplied by a large runoff event likely caused by high rainfall intensity.

2.1.1.1 Erosion

Generally, erosion is considered to reduce the cover thickness through rilling and gullying, but it can increase the cover thickness in flatter, depositional areas. Rills and gullies reduce the length over which oxygen and water must percolate to reach the underlying waste materials. Erosion can also reduce the ability of the top cover layer or growing medium to sustain vegetation by washing away topsoil and fines, leaving only coarser, rockier soil for establishing vegetation.

Cover systems are designed with the assumption that they will remain intact and the basic physical dimensions and structure of the cover layer will not change. Erosion has a potentially significant effect on the long-term performance of a cover system in many climates, but most significantly 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 surface water or runoff flowing over the soil surface. It is generally agreed that the three main erosion processes are interrill, rill, and gully erosion.

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 (Grosh and Jarrett, 1994). Interrill erosion acts evenly over the soil surface, so changes in layer thickness are often not obvious. Smaller soil particles such as silts and clays are most often removed by interrill erosion because the impact of the raindrop hitting the soil surface is adequate to dislodge these smaller particles, but not sufficient to disturb larger sand and gravel sized particles. The removal of fine particles changes the structure of the cover layer at the surface, producing a blocky, open-faced material. This altered material is more likely to allow water to infiltrate across the surface.

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). The runoff flow produces shear forces that act on the soil surface attempting to detach material from the soil matrix. If there is sufficient energy in the rill flow, the soil particles will be entrained or caught up in the flow and transported away. The resistance of the material, defined by its strength and cohesiveness, to these shearing forces will determine the amount of erosion caused by rill flow.

While similar in shape to rills, gullies are much larger erosion features often created by extreme erosion events involving large mass movements of soil. Gullies frequently occur in unconsolidated materials such as desert sands (Archibold *et al.*, 1996) and range in size from shallow, approximately 0.3 metres deep, to deep and wide channels.

Gully erosion processes act on the sidewalls and the headcut of gullies. Piest *et al.* (1975) defined gully erosion as a combination of processes including overland (shear) flow or rill flow, slope stability and mass wasting, and channel cleanout. As documented in interrill and rill erosion, the movement of soil from the gully is a function of the sediment transport capacity of runoff and the rate of soil detachment. Overland flow and mass wasting serve to detach material from the gully channel boundary while transport is achieved from energy supplied by gully flow.

Interrill, rill, and gully erosion are affected by the same set of factors. The factors listed in Table 2.1 are believed to be the most important in terms of the erosion of cover system layers.

Table 2.1
Factors affecting the erosion of cover systems.

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

Each of the factors listed in Table 2.1 must be considered when evaluating the risk of interrill, rill, and gully erosion on the cover system. The factors or combination of factors might have a varying influence on the amount of erosion experienced at a given site. For instance, there might be two areas on the mine site that have similar slope angles and slope lengths, but one slope generally experiences less erosion. Possibly one slope has more vegetation, or does not have seepage flow emanating from its base, reducing the erosion rate.

The following questions should be considered when determining the potential impact of erosion on the long-term performance of the cover system.

- Are there long, unbroken slopes on the cover system?
- What are the angles of these slopes?
- Is the vegetation established on the slope surface? What is the percentage of surface coverage?
- Are there any visible signs of erosion such as rill and gullies on the slope or debris deltas at the base of the slope?
- Do the debris deltas consist of well-graded erosion material or poorly-graded material? What is the size of the poorly-graded material? (Fine materials indicate interrill or rill erosion, while well-graded materials suggest gully erosion.)
- Are there visible signs of seepage at the base of any slopes?
- Are high intensity rain events common at the site? Have they occurred in recent memory and what was their effect on erosion of the cover system? Has an extreme storm event such as the 100 year return period storm occurred in recent memory? What was its effect?
- Are erosion control structures in place on the site? Are they functioning properly?
- Is there any accumulated runoff flow overtopping the crest of the slope?

2.1.1.2 Slope Instability

Erosion and slope stability are often lumped together when long-term performance of a cover system is considered. Slope instability is the mass movement of the entire slope surface destroying the integrity of the cover system or exposing the underlying waste material. Koerner and Daniel (1997) identified the three driving forces leading to slope instability as gravitational, seepage, and seismic forces.

Gravitational forces become an issue when the cover is placed on a slope. A component of the downward gravitational pull will act to push the cover material down the slope. Seepage forces produce high pore-water pressures in the materials at the base of slopes, decreasing the effective stresses within these soils. Both gravitational and seepage forces act to increase the shear stress acting on the cover material. The shear strength of the material counteracts these forces. The shear strength equation for unsaturated soils is presented below (Fredlund and Rahardjo, 1993):

$$\tau = c' + (\sigma_f - u_a)_f \cdot \tan\phi' + (u_a - u_w)_f \cdot \tan\phi^b \quad [2.1]$$

where:

- τ = shear strength;
- c' = effective cohesion
- $(\sigma_f - u_a)_f$ = net normal stress;
- u_{af} = pore-air pressure;
- ϕ' = angle of internal friction;
- $(u_a - u_w)_f$ = martric suction; and
- ϕ^b = angle indicating the rate of increase in shear strength relative to the matric suction.

Seismic forces are created by earthquakes or large-scale movement of the earth's tectonic plates and must be considered in an area with the potential for earthquakes.

Often the driving forces leading to slope instability are evaluated using a commercially available limit equilibrium analysis model.

The following questions should be considered when determining the potential impact of slope instability on the long-term performance of a cover system.

- Is the cover system installed on a slope? If so, what is the slope angle or inclination of the cover material?
- Has slope stability modelling been completed on the waste and cover material layers?
- Are there visible signs of seepage at the base of any slopes?
- Are earthquakes a potential hazard at the mine site? If so, what is the hazard classification for the mine site area? (Low, Moderate, High)

2.1.1.3 Wet-Dry Cycling

Wet-dry cycles will impact the SWCC and saturated hydraulic conductivity of a compacted layer designed to be a hydraulic barrier, and / or an oxygen ingress barrier, and consequently have an impact on cover performance. The importance of a properly designed overlying growth medium layer (i.e. thickness, texture, vegetation development) cannot be overstated in terms of its influence on the long-term performance of an underlying compacted layer.

Wet-dry cycling causes shrinkage and swelling of fine textured materials, which can be of considerable significance from the perspective of cover system integrity. Shrinkage cracks occur locally when the capillary pressures exceed the cohesion or the tensile strength of the soil (Albrecht and Benson, 2001). These cracks, part of the clay macrostructure, can significantly influence the overall performance of a soil cover by altering the hydrogeologic and diffusion characteristics of the cover material.

Shrinkage and swelling involve particle rearrangement. Shrinkage is rapid, and is complete when the decrease in water content is complete. Swelling, however, is a slow process, occurring in the field over months and years. The process of shrinkage and swelling is not completely reversible; the soil will always possess a "memory" of its stress history and will show the effects of previous wet-dry cycles.

Shrinkage and drying cracks are caused by evaporation from the surface in dry climates, lowering of the ground water table, and even desiccation of soil by vegetation during temporary dry spells in otherwise humid climates. The soil tends to increase in volume, or swell, once the climate changes and the soils have access to water again.

The presence of cracks in the cover system can potentially have a significant influence on the hydrologic performance of the cover system. Desiccation of the cover material consolidates the matrix and increases the volume of macropores and cracks, which decreases the saturated hydraulic conductivity within the matrix and increases it within the total soil volume. Cracking of the cover material can then result in higher potential infiltration rates and lower storage capacities. Capillary rise from the water table and evapotranspiration may be hampered by the lower hydraulic conductivity. The overall potential result is that part of the precipitation flows through shrinkage cracks to the subsoil layers, thus bypassing the matrix of the cover system material.

2.1.1.4 Freeze-Thaw Cycling

Freeze-thaw cycling has an impact on the saturated hydraulic conductivity and moisture retention characteristics of soil covers. During freezing periods, water is drawn up from the soil to the freezing front leading to ice lenses within the cover material. The subsequent thaw of the material will decrease the material density as well as increase the water content and void ratio of the material ultimately leading to an increase in the saturated hydraulic conductivity. Wong and Haug (1991) observed that the hydraulic conductivity of clay and till liner materials increased as the number of closed system freeze-thaw cycles increased.

Wong and Haug (1991) discussed the effects of freeze-thaw cycling under two types of freezing conditions, an open system and closed system. An open system possesses a constant source of water that can be drawn to the freezing front. If freezing conditions persist, a large ice lens will be produced reducing the density of the soil material after thaw. A closed system does not have a constant source of water; the ice lens is produced from *in situ* water drawn from the soil materials. This limits the size of the ice lens but causes a redistribution of moisture within the material profile. Upon thaw, the upper part of the material profile will have an increased void ratio and decreased density due to the ice lens, while the lower part of the profile will have a lower moisture content and increased soil density. Wong and Haug (1991) reported cracking within the soil profile below the freezing front. The cracks within the soil profile can lead to increased hydraulic conductivity as described in the wet-dry cycling section.

Casagrande (1931) identified silt as the material most susceptible to freeze-thaw cycling because silt pores are small enough to induce suction gradients during freezing but are large enough to allow an adequate supply of water to the freezing front. It is generally accepted that soils containing more than 10% of clay-sized particles are susceptible to freeze-thaw cycling.

2.1.1.5 Consolidation / Settlement

Consolidation and settlement, as with most physical processes, will affect the integrity of the cover system by reducing the thickness of the cover layers. 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. Consolidation is the physical process of the cover material decreasing in volume from a decrease in the volume of voids within the material. 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 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 2.2 shows a conceptual schematic of the runoff flow on the altered sloping surface.

Holtz and Kovacs (1981) reported that a soil compresses because of:

- deformation of soil grains;
- compression of air and water in the voids; and
- the squeezing out of water and air from the voids.

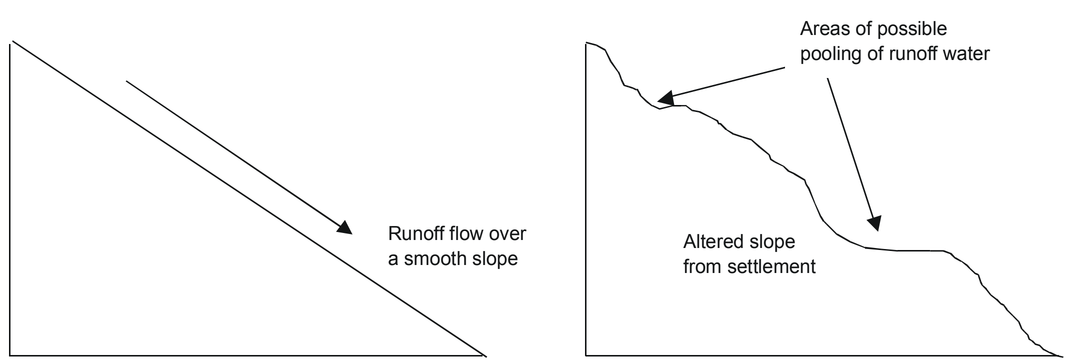

Figure 2.2 A schematic representation of the effects of differential settlement on the surface hydrology of a slope.

Under the low loading condition associated with a cover system, the deformation of soil particles can be considered negligible. An unsaturated soil will have both water and air within the soil matrix, so consolidation will occur as the pore fluids are squeezed out of the soil matrix and the soil particles rearrange into a more compact structure. Due to small variations in the properties of the cover material and the underlying mine waste, some areas will experience settlement while others will not, causing the micro-peaks and valleys conceptually shown in Figure 2.2.

2.1.1.6 Extreme Local Climate Events

Extreme local climate events are likely to have an impact on the integrity of a cover system. Extreme climate events usually refer to storm events causing high rates of precipitation and runoff, leading most often to erosion. However, extreme climate events can also include long periods of drought and desiccation or freezing conditions, which can lead to alterations in the hydraulic conductivity and moisture retention characteristics of the cover materials.

The local climate has a large influence on the design of a cover system. A climate database must be established based on the available weather data associated with the site during the cover design stage. This climate information is often regionally based and not specific to the mine site as many mine sites only possess recent climate information.

Precipitation quantities greater than the historical average, both rainfall and snowfall, can lead to increased percolation through a cover system. Extreme precipitation events have the potential to exceed the storage capabilities of the cover material, saturate the cover system, and produce large net percolation to the underlying waste.

Drought conditions can have an impact on the performance of an oxygen ingress barrier. A cover system designed to limit the transport of oxygen most often depends on the maintenance of a fine textured cover layer in a saturated condition. A period of dry conditions can lead to a reduction in the saturation of this layer, allowing more oxygen to reach the underlying waste. Drought conditions can also lead to desiccation and the cracking of cover layers particularly those with relatively high fines content. Any established vegetative stands will also be threatened by drought conditions, possibly leading to increased percolation when precipitation does occur.

When determining the effect of extreme climate events on the long-term performance of the cover system the following questions should be considered.

- Is local climate data being collected on the site? What parameters are being recorded?
- How long has the information been collected?
- What climate information was the design of the cover system based on?
- What is the nature of precipitation events at the site? Are intense precipitation events common?
- Is the cover designed to limit the ingress of oxygen? Is drying and cracking a concern?
- What is the potential for the cover material to undergo freeze / that cycling, and to what depth?

- Have climate patterns changed in the last 5-10 years, changes that might be attributed to events such as global warming?
- Has a hydrological study of the site been completed and the large return period storm events estimated?
- What is the largest precipitation event measured at the site? How does it compare to the extreme storm events predicted for the site?

2.1.1.7 Brushfires

The potential impact of brushfires on the integrity of a cover system should not be discounted. A brushfire will reduce vegetation, increasing runoff and likely increasing the rate of erosion on the cover system. If evapotranspiration through vegetation is an important component of the cover design, a brushfire can severely decrease the performance of the cover. Re-establishment of the vegetation at mine sites in semi-arid and arid climates following a brushfire can be a difficult and lengthy process.

2.1.2 Chemical Processes

The effect of chemical processes on the long-term performance of a cover system is not as obvious as a physical process such as erosion. Chemical processes have the potential to change the fabric of a cover material. Osmotic consolidation, dispersion, dissolution, acidic hydrolysis, mineralogical consolidation, and sorption are discussed in this section.

2.1.2.1 Osmotic Consolidation

The process of osmotic consolidation can lead to shrinkage of clayey soil materials, causing cracks and fissures to develop in some cover systems. These openings provide a path for fluids to flow, thereby increasing the cover hydraulic conductivity. Barbour (1987) identified two types of osmotic consolidation that may lead to consolidation of clays; namely osmotically induced consolidation and osmotic consolidation. Osmotically induced consolidation results from the release of water due to chemical gradients. Osmotic consolidation results from shrinkage of the clay due to changes in clay particle interactions with changes in pore fluid chemistry.

The desire to use clays in cover systems results from their lower hydraulic conductivity. The problem is that these low permeable clays are also strongly affected by electrolyte solutions (high salts), which can result in osmotic consolidation. When osmotic or osmotically induced consolidation occurs, cracks and fissures develop which increase the hydraulic conductivity of the clay and inhibit the clay layer from preventing seepage into other areas.

Several methods have been formulated to limit the extent of osmotic consolidation including:

- Minimize the clay content;

- Use a high level of effective stress – apply sufficient confinement of the clay so that fractures and cracks are not able to develop (Haug *et al*., 1988); and
- Chemically alter the soil prior to use – reduce the potential for volume change (i.e. pretreat cover material) (Haug *et al*., 1988).

The following questions should be considered when determining the potential impact of osmotic consolidation on the long-term performance of a cover system.

- Does the cover include clayey soils?
- What is the chemistry of the pore fluid in the waste material and cover materials?
- Will a chemical gradient develop thereby inducing osmotic consolidation?
- Will a change in pore fluid chemistry in the clay take place causing osmotic consolidation?
- In the future, could the pore fluid chemistry change?
- What can be done to reduce the effects of osmotic flow and subsequent consolidation?

2.1.2.2 Dispersion/Erosion

Chemical dispersion of clay particles can increase the susceptibility of a clay soil to erosion, consequently this effect should be considered in evaluating the long-term performance of a cover system possessing a clayey soil. Dispersion is the process whereby the long-range repulsive forces between individual clay particles are allowed to increase to a point in which the clay particles are completely disassociated. The contrary behaviour is referred to as “flocculation”. Dispersed clays are prone to increased rates of erosion. Figure 2.3 shows the physical arrangement of dispersed and flocculated clays.

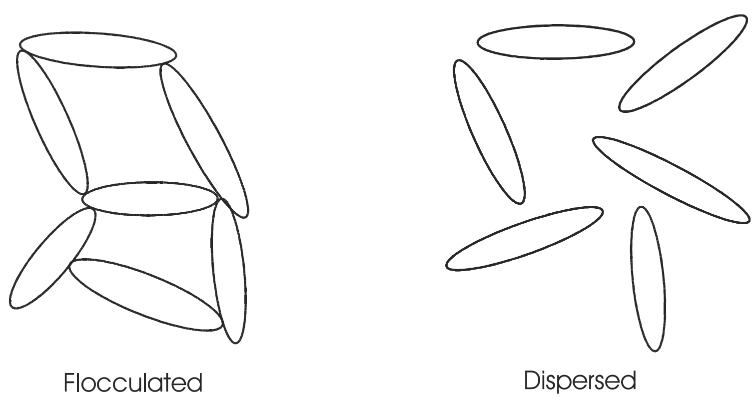

Figure 2.3 Flocculated and dispersed arrangement of clay particles.

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.

In particular, potential for dispersion of clay particles is sensitive to sodium ion adsorption by the clay particles and the ion concentration of the permeating fluid. The sodium adsorption ration (SAR) is used to estimate the susceptibility of a soil to dispersion, and is determined from the following relationship:

$$SAR = \frac{Na^{+}}{\left[\frac{(Ca^{++} + Mg^{++})^{1/2}}{1.41}\right]} \qquad [2.2]$$

The dispersion of clay particles results in the clogging up of the pore spaces and swelling of the clay leading to a decrease in hydraulic conductivity. Increases in ion concentration produce less dispersion and generate a higher hydraulic conductivity.

Work completed by Toride *et al.* (2001) demonstrates that the hydraulic conductivity of a clay-sand mixture strongly depends on the concentration of soil solution and the exchangeable ions it contains. Figure 2.4 shows how an increased SAR results in a lower hydraulic conductivity and hence, a more highly dispersed soil. Figure 2.4 also shows that increased pore fluid concentration results in a higher soil hydraulic conductivity and therefore, more flocculation.

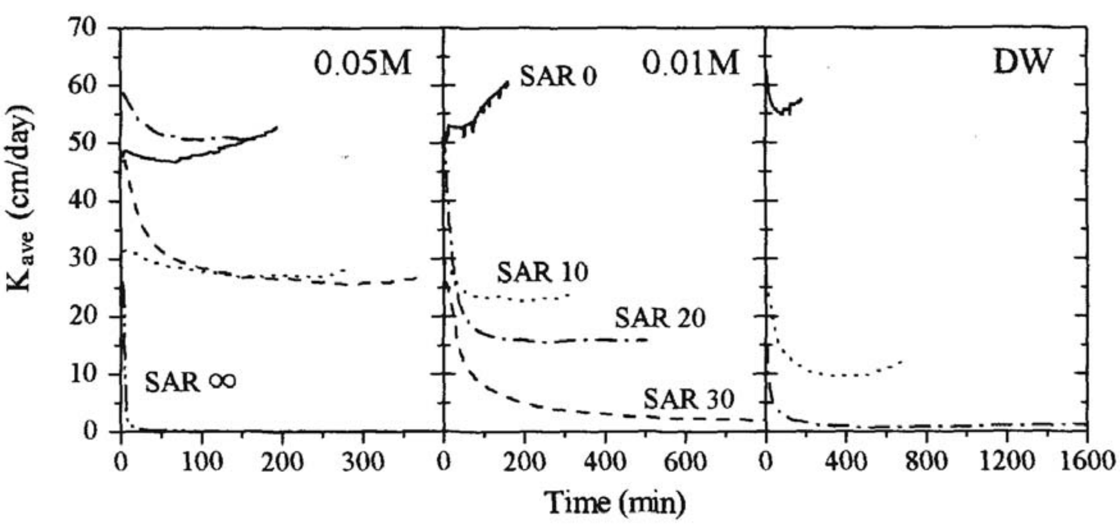

Figure 2.4 Hydraulic conductivity vs. time for varying solution concentration and SAR for a clay-sand mixture (from Toride *et al.*, 2001).

The result of dispersion is an increased susceptibility of the clay to erosion. Dispersed clays have weaker bonds between the clay particles, meaning it takes less energy to break apart bonds between the clay particles. The decreased hydraulic conductivity of dispersive clays leads to increased amounts of runoff during intense rainfall events contributing to increased erosion of the soil layer.

Smectite clays (montmorillonite) are often used in cover systems because of their low hydraulic conductivity and high moisture retention. The significant swelling that occurs in smectitic clays results from weak bonding of the clay plates. The weak bonds allow abundant water and exchangeable cations to enter in between the clay plates and may lead to dispersion. Illitic soils are also quite susceptible to dispersion of clay particles (Morin, 1993).

The following questions should be considered when determining the potential impact of dispersion/erosion on the long-term performance of a cover system.

- Are clayey soils present in the cover system?
- If clayey soils are present, are they dispersed clays?
- Will leachate provide cations into the clay cover layer that may lead to dispersion of clays?

2.1.2.3 Dissolution / Precipitation

The chemical processes of dissolution and precipitation may affect the long-term performance of cover systems. Dissolution removes solid material from the soil while precipitation adds solid material to the soil.

Sparks (1999) suggests there are two steps which precipitation and dissolution reactions must undergo. Firstly, ions must be transported to or from the mineral surface via the aqueous phase. Secondly, reactions must occur on the surface of the mineral grains. These reactions will incorporate or remove the constituent ions from the mineral grains.

Dissolution involves the dissolving of a solid into separate components. Fluid carries the dissolved material away and voids are left in the material's place. In the case of a soil cover system, the chemicals in the fluid entering the cover system may dissolve the cover material. This can result in piping and void spaces within the cover. Carbonic acid is a common acid involved in dissolution reactions:

rain + carbon dioxide (from air) → carbonic acid (reacts with rocks)

$$H_2O + CO_2 \rightarrow H_2CO_3.$$

Carbonic acid dissolves certain rocks and minerals such as limestone and marble. Most rainfall and snowfall is slightly acidic with an average pH slightly less than 7. Highly acidic substances have a pH of 1 while neutral substances have a pH of 7. Wastes containing strong acids have a strong dissolution effect on carbonate phases such as calcite, whereas quartz and amorphous silica are soluble in very strong alkaline solutions.

Precipitation occurs as a result of oversaturation of solute within a solution. Precipitation reactions involve the formation of an insoluble product, or precipitate from solution.

Whether precipitation or dissolution reactions will occur depends upon the solubility of the solute. Using solubility rules and solubility products, predictions can be made as to whether precipitates will form when solutions are mixed or when soluble compounds are added to a solution (Chang, 1998).

Leeder (1999) describes an example of how to determine if an aqueous solution will dissolve certain minerals or precipitate minerals. Laboratory experiments have been performed which provide the maximum concentrations (saturated concentration) of solute that a solution can hold. Concentrations above this value result in oversaturation and subsequent precipitation of solute. Concentrations below this value result in undersaturation and if soluble minerals are present, dissolution can occur.

The following questions should be considered when determining the potential impact of dissolution / precipitation on the long-term performance of a cover system

- What minerals are present in the cover material?
- Are these minerals soluble?
- If they are soluble, is the aqueous solution undersaturated or oversaturated?
- Will dissolution result in void spaces and result in the failure of the cover system?
- Will precipitated minerals compromise the effectiveness of the cover system?

2.1.2.4 Acidic Hydrolysis

Hydrolysis is a reaction that involves a component of water; acidic hydrolysis involves reactions with acids in aqueous solution. In a cover system, minerals in the cover materials may react with acids in the pore fluid 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 picks up a cation from surrounding mineral grains. Minerals in the soil cover that contain ions with a strong attraction to hydrogen ions are susceptible to reacting with an acid. These minerals attract protons and can exchange cations with the acids in solution. The new minerals formed may or may not compromise the integrity of the soil cover.

A common example is the hydrolysis of feldspar. Feldspar is one of the most abundant minerals on the earth's surface. It can react with water to form a secondary mineral such as kaolinite clay. The integrity of the cover may be compromised because clay is more easily weathered than the feldspar, which existed previous to the hydrolysis reaction.

$$\text{feldspar} + \text{hydrogen ions (acid)} + \text{water} \rightarrow \text{clay} + \text{dissolved ions}$$

$$4KAlSi_3O_8 + 4H^+ + 2H_2O \rightarrow Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8SiO_2$$

Strong acids increase the solubility of carbonates, silicates, phosphates and sulphides because of the affinity of these minerals for hydrogen ions, which are more abundant in strong acids (Faure, 1998).

The following questions should be considered when determining the potential impact of acidic hydrolysis on the long-term performance of a cover system.

- What type of fluids will be interacting with the cover materials? What is the solution chemical composition? Is the fluid acidic or will it be in the future?
- What is the chemical composition of the materials within the cover material?
- What are the potential new minerals that could form? How will they affect the integrity of the cover system?

2.1.2.5 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 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, cracks or fissures may develop, thus reducing the effectiveness of the cover system.

2.1.2.6 Sorption

Dissolved minerals within groundwater can be sorbed onto the surfaces of mineral grains in the soil cover. Sorption removes solute from the solution or causes retardation of solute movement. Sorption is assumed to be a reversible reaction. The sorption of minerals changes the chemistry of the cover material and may affect its long-term performance. Sorbed minerals may assist in the development of osmotic consolidation or dispersion / erosion processes.

2.1.3 Biological Processes

The biological processes discussed in this document include the effect of root penetration and burrowing animals.

2.1.3.1 Root Penetration

Root penetration is generally thought to affect the integrity of the cover system and decrease the long-term performance of a cover system. Roots and plant biomass create macropores within the soil structure, allowing water to more easily infiltrate into the cover material and down to the underlying waste material. Koerner and Daniel (1997) summarize the damage that plant roots can have as follows:

- roots may penetrate the barrier layer of a cover system;
- decomposing roots leave channels for movement of water and vapour;
- roots may dry clayey layers, causing shrinking and cracking; and

- roots may enter the waste material and intake salts and undesired metals upward into the cover system and the soil surface.

For these reasons, grass and shrubs are often used to vegetate the surface of a cover system. Shrubs and grass generally possess shallow rooting characteristics that do not reach into the barrier layers of the cover system.

Research on the rooting depths and biomass distribution of tree species has showed that 80% of tree roots and up to 99% of the tree biomass 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.

The following questions should be considered when determining the potential impact of root penetration on the long-term performance of a cover system.

- Is transpiration and control of erosion through vegetation an important design characteristic?
- What are the native vegetation species adjacent to the cover system, and their rooting characteristics

2.1.3.2 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.

2.2 Surface Water Management and Landform Evolution

2.2.1 Surface Water Management

In general, most cover systems consist of two basic landform features. Namely, a large flatter or gently sloping upper surface for the top of the tailings or waste rock pile, and a comparatively steeper sloping surface for the side slopes of the storage facilities, which will promote surface runoff. The following discusses the different approaches to designing a cover system for these landform features.

Cover system design on the sloping surface should focus on management of surface water resulting from rainfall landing on the surface and snowmelt during spring freshet, and limiting erosion, rilling, and gullying associated with the surface small scale runoff, accumulated runoff, and run-on to the area. Provision must be included in the cover system design to address the erosion aspects associated with the surface runoff, in addition to the water balance aspect of the cover system design. The difference between the design for a horizontal surface and a sloping surface is that for the latter condition, infiltration across the surface of the cover material can be significantly reduced as a result of partitioning of rainfall into runoff before infiltration actually occurs.

Ideally, a moisture store-and-release cover system on a relatively flat (or gently sloping surface) should "harvest" all rainfall such that runoff is essentially zero. By controlling all rainfall incident at the surface, surface water does not have to be transmitted off the landform itself.

This approach should always be evaluated to design a moisture store-and-release cover system. It is anticipated however; that separate catchments may need to be created on the upper relatively flat surface to ensure that ponding is not excessive. Figure 2.5 is a schematic of the catchment design on the surface of a large flat area for a moisture store-and-release cover system design. Care must be taken in the design to ensure that sufficient relief is incorporated into the design to resist surface and wind erosion for the time period associated with the environmental risk of managing ARD.

Ponding in the catchment areas shown on Figure 2.5 implies that the infiltration rate at the surface is greater than the rainfall rate, which does not necessarily only occur when the near surface material is saturated. The key issue is to ensure that any ponding that occurs does not lead to an unacceptable net percolation rate to the underlying waste material. Therefore, the surface area of the catchments will need to be determined such that a balance is developed between the cost associated with creating the catchments, and the need to minimize ponding and the potential for increased net percolation.

A two-dimensional (2-D) saturated-unsaturated soil-atmosphere model should be used to determine the appropriate size of the catchments for the large flat surface area of this type of cover system design. A 2-D model, which is physically interfaced with the atmosphere, will be a critical component to designing a sustainable long-term cover system for this type of system.

Managing surface runoff at locations where moisture store-and-release cover systems are typically not constructed requires that positive drainage (i.e. minimal surface ponding) be maintained. Hence, it is fundamental that any engineered structures put in place to control surface runoff are robust, and account for inevitable consolidation, settlement, and erosion of the surrounding and underlying cover material. One of the most common long-term performance problems associated with cover systems is implementation of a poor surface water management system, which will lead to maintenance and repair of surface channels, ditches, berms, etc. that should otherwise have not been required.

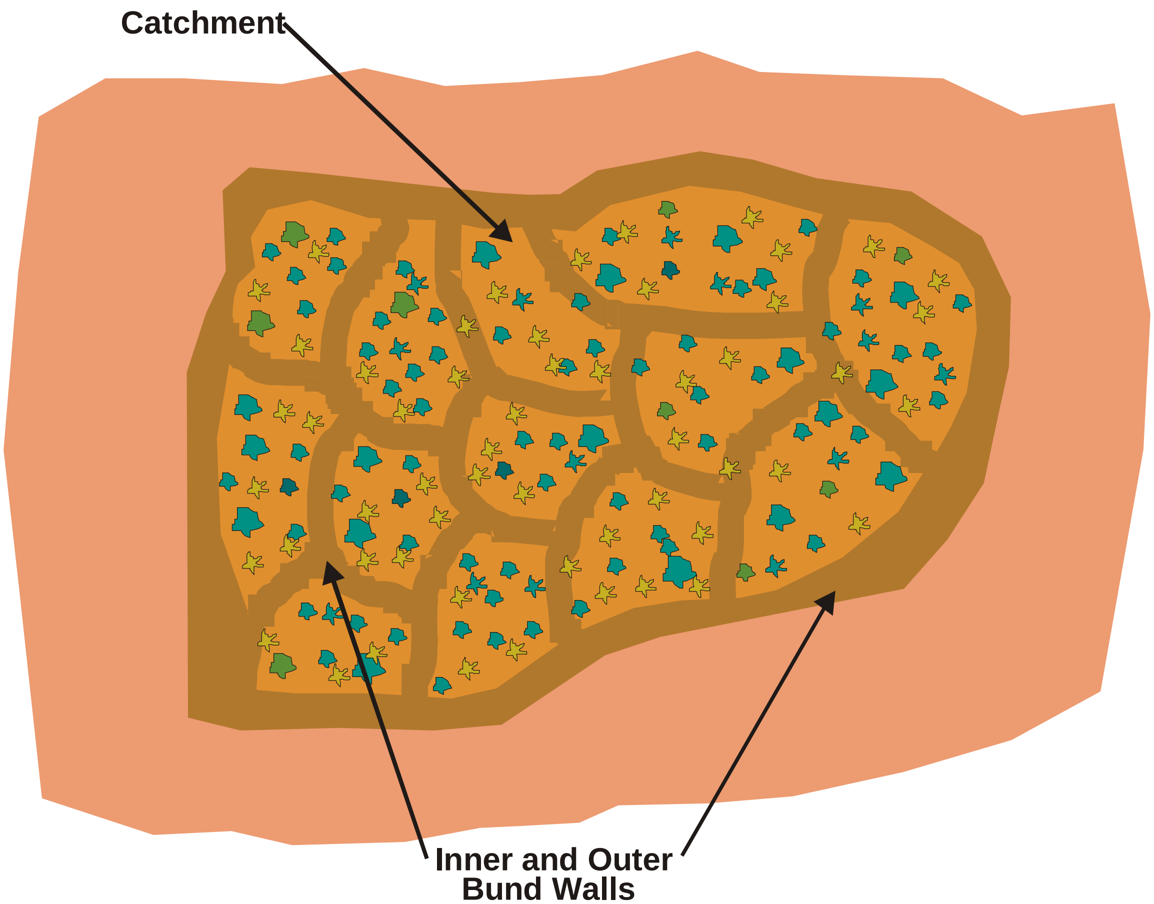

Figure 2.5 Schematic of a moisture store-and-release cover system design for a relatively horizontal and/or gently sloping surface on the top of a waste rock pile or a tailings dam.

2.2.2 Landform Evolution

As discussed in Volume 1, the scope of this manual is limited to cover system design, construction, and performance monitoring. However, a key component of long-term performance is the development of a sustainable landform that addressed issues such as surface water hydrology, watershed management, erosion, and other aspects of landscape engineering. This area of mine closure planning is an emerging technology, which has received greater attention in the past at sites located in Australia, but is now being seen as a critical closure planning issue at many sites in Canada.

In general, the issues typically associated with landform / landscape engineering are not within the scope of this document, although the issues were addressed conceptually in the previous sections. For additional details and information the reader is referred to (Evans, 1997; Hancock *et al.,* 2000; Hancock *et al.*, 2002; Hancock *et al.*, 2003 (in press); Hancock, 2003 (in press); McKenna, 2002; Willgoose, 1994 and 1995; Willgoose and Riley, 1993; Willgoose *et al.*, 1989).

2.3 Defining "Long-Term"

A panel discussion was held at a workshop in 2000 (MEND BC.03) on the design features, monitoring, and resources required to maintain the performance of a cover system in the long term. The two main topics of discussion focused on the design life of cover systems and long-term monitoring and maintenance. Members of the panel discussion stated that a 1,000-year cover system design life is conceivable because man-made structures constructed over 1,000 years ago still exist. The panel did not reach a consensus regarding an appropriate design life for cover systems; however, it was noted that the Canadian Nuclear Safety Commission (CNSC) requires that discharges from a uranium waste storage facility be predicted over a 10,000 year period. Newmont Australia (Australia's largest gold producer) have developed closure standards at several of their Australian operations that specify the containment structure must be designed to maintain physical stability for a 200 to 500 year time frame.

The panel agreed that cover systems should not be viewed as a walk-away solution, but rather as a control measure for minimizing the impacts from ARD. Therefore, a key issue with respect to maintenance was whether personnel would be available to conduct the maintenance, as opposed to ensuring that adequate financial assurance would be in place to cover the maintenance costs.

Clearly there is potential for any cover system to "fail" and allow contaminated seepage to enter the natural environment. Poorly designed cover systems can fail over a 10 to 50 year period, or even up to 100 years after construction. Extending the life of the cover system through proper design is possible by taking into account the factors that affect long-term performance. This effort will provide a significant positive impact on the net present value of any contingency plan required for failure of the cover system. The key is to prevent the cover system from failing in the short term. Rather, the objective should be for the cover system to "fail" over geologic time, augmented by minimal maintenance, such that the natural environment is capable of accepting the incremental "failure".

2.3.1 Long-Term Performance Monitoring

Long-term performance monitoring is critical for evaluating the performance of cover systems. The factors discussed in the previous sections can change the performance of a cover over time. It is important to directly monitor the cover system to evaluate any changes in performance over time. The expected duration of long-term performance monitoring was briefly discussed in the section on data management and interpretation. It is impossible to develop a single rule for how long monitoring should occur that would apply to every cover system. Instead, each system must develop a monitoring strategy integrated within the design of the cover, the regulatory guidelines for the cover, and the needs of the mine operation. In general, it is always better to monitor too much, than too little.

Performance monitoring should also allow "feedback" depending on the needs of all stakeholders, but also in response to the performance being monitored. For example, if the hydraulic conductivity of the cover material is found to be changing with time, a greater frequency of field hydraulic conductivity measurements should be taken to better quantify and understand the changes.

The case studies in Volume 5 will give examples of performance monitoring of cover systems.

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