CHOOSING REPRESENTATIVE CLIMATE YEARS FOR PREDICTING LONG-TERM PERFORMANCE OF MINE WASTE COVER SYSTEMS[1]

M. O'Kane[2] and S.L. Barbour[3]

Abstract. An estimate of seepage from the footprint of a mine waste storage facility is required in order to evaluate potential impacts on the receiving environment. A soil cover system is often used in the design to reduce seepage and minimize meteoric water and/or oxygen from reaching the underlying waste. Typically, predicting cover system performance for use as input to seepage and groundwater models would involve modelling the annual "average", "wettest", and "driest" climate years on record.

This paper uses soil-atmosphere numerical modelling and cover system field performance monitoring from sites in the United States, Canada, and Australia to demonstrate that basing performance of a cover system on the annual average or extreme climate conditions alone can lead to inaccurate assessments of cover system performance. Sites with a variety of different climatic conditions are discussed including the impacts of snowmelt, fall and winter rainfall, and hot dry summers (with associated high intensity rainfall events).

It is found that net percolation rates predicted from the average annual precipitation record for a given site is typically not representative of the long-term average performance. The magnitude and occurrence of various precipitation events throughout the year, coupled with antecedent moisture conditions, plays a major role in actual net percolation rates through a cover system. Therefore, evaluating long-term average cover system performance using the average climate year may in fact result in a predicted net percolation rate that is not representative of the average net percolation. The long-term average performance of a cover system should be determined from a statistical analysis of the net percolation predicted for each year of the climate record. This methodology accounts for the impact of antecedent moisture conditions, as well as the occurrence and intensity of daily rainfall when determining the long-term average net percolation rate.

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[3]Mike O'Kane, President, O'Kane Consultants Inc., Suite 1740 – 246 Stewart Green S.W., Calgary, AB, Canada, T3H 3C8. [3]S. Lee Barbour, Professor, Department of Civil and Geological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK, Canada S7N 5A9.

Introduction

Soil cover systems (also referred to as "dry" covers to contrast them from water or "wet" covers) are one of many closure options for controlling acid rock drainage (ARD) and/or metal leaching from mine waste storage facilities. In "wetter" environments, a cover system will generally be included as a component of a closure plan, along with collection and treatment of seepage. In general, cover systems designed and constructed in drier climates are seen as a "stand-alone" ARD and/or metal leaching control measure. In either case however, a prediction of seepage from the footprint of the waste storage facility is required, whether to assist with designing the collection and treatment system and/or predicting impacts to the receiving environment.

The primary purpose of placing cover systems over reactive waste material following closure of the storage facility is to facilitate recovery of the receiving environment in the short term, and minimize further degradation of the receiving environment in the long term. The primary objectives of a cover system are to minimize the entry of meteoric water and/or atmospheric O_2 into the underlying reactive and/or potentially leachable waste. In order to address the need for predicting seepage from the footprint of a waste storage facility, a prediction of cover system performance is required; because, among other factors, the net percolation and/or O_2 ingress from the base of the cover system will impact on seepage rates and water quality emanating from the footprint.

This paper addresses the need to develop representative upper boundary conditions for predicting cover system performance, and in particular focuses on precipitation conditions, which is generally the key site-specific model input. For the purposes of this paper, the need to determine a representative climate year for predicting cover system performance with respect to net percolation is discussed. However, it should be noted that a similar argument could be made in terms of predicting rates of O_2 ingress.

Background

Cover system performance is often measured in terms of controlling "infiltration", or "net percolation" to the underlying waste. These two terms are often seen as interchangeable; however, this paper uses "net percolation", which is defined as follows, and shown conceptually in Fig. 1. Meteoric water will either be intercepted by vegetation, runoff, or infiltrate into the cover surface. A portion of the water that infiltrates will be stored in the "active zone" and subsequently exfiltrate back to the surface and evaporate, or be removed by transpiration. The infiltration can also move laterally down-slope within and below the active zone (referred to as interflow). A percentage of the infiltrating water will migrate beyond the active zone as a result of gravity overcoming the influence of atmospheric forcing (i.e. evaporation), and result in net percolation to the underlying waste. The net percolation will ultimately impact *in situ* waste moisture conditions and/or seepage from the footprint of the waste storage facility to the underlying bedrock.

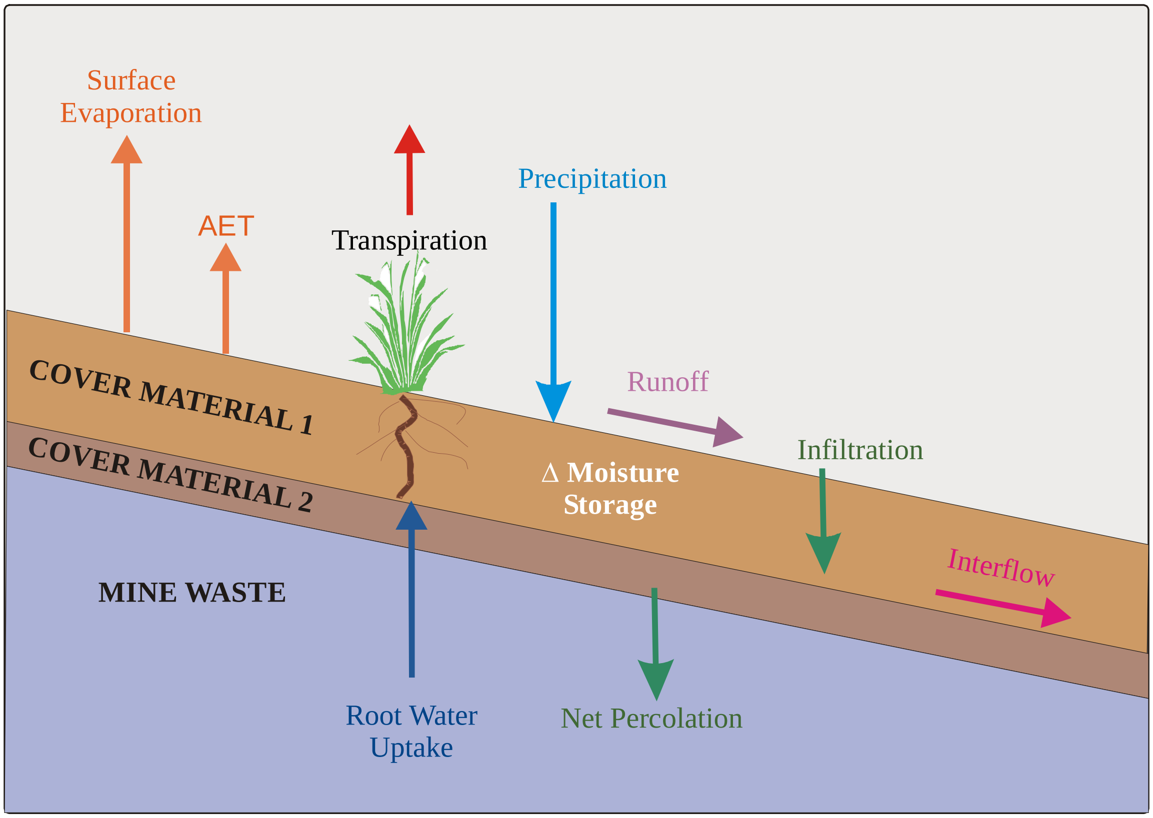

Figure 1. Conceptual illustration of net percolation.

Numerical Modelling

A prediction of cover system performance can be developed using conceptual and/or analytical modelling approaches. However, it is most common to utilize a numerical model. These models operate under the fundamental principles of solving a set of physics subject to boundary conditions and material behaviour (i.e. material properties). The physics govern which processes are occurring in the system, the boundary conditions set limits on the problem, and the material properties change the manner in which physical processes function. In terms of cover system performance, the physics are typically limited to the movement of air (advection and diffusion processes involving oxygen or some other gas of interest (e.g. radon)), as well as the movement of water (including percolation of liquid water (i.e. advection), evaporation (i.e. water vapour), and transpiration). Solute transport, adsorption, and decay (or reaction, e.g. sulfide oxidation) can also be modelled when predicting cover system performance.

Material properties are usually based on some key measurable properties such as porosity, specific gravity, saturated hydraulic conductivity, and moisture retention.

Boundary conditions define the limits of the model and force the physical processes to behave in a certain manner. The key boundary conditions for cover system modelling are:

- upper boundary conditions (e.g. climate and vegetation);
- lower boundary conditions (e.g. location of a phreatic surface, or the negative pore-water pressure to which a material drains); and

- initial conditions (e.g. the initial temperature and moisture content profile for a certain time of year or condition).

Determining Representative Climate Years for Predicting Long-Term Performance

Predicting performance of a cover system has generally utilized an approach where:

- a site-specific climate database is developed over as long a time frame as possible;
- the average, maximum, and minimum precipitation is determined for the database based on annual precipitation; and
- these three years are used as upper boundary conditions during numerical modelling to predict long-term performance.

Examples of this approach were utilized by Swanson (1995), Wilson et al. (1997), O'Kane et al. (1998), O'Kane et al. (2000), Swanson et al. (2003), and Junqueira et al. (2004) to predict performance of cover systems in a variety of climates. However, this approach does not account for the timing, form, magnitude nor occurrence of precipitation events throughout the year, which when coupled with antecedent moisture conditions, plays a major role in the rate of net percolation through a cover system. For example, given a 30-year climate database for a site, with an average precipitation of 500 mm (~ 20 inches) for the 30 years, there is typically at least two if not three or four years where a total precipitation similar to the 30-year average value was recorded. Hence, using the "typical" modelling approach outlined above, one of these years, generally the one closest (numerically) to the average value is used to predict "average" performance of the cover system. However, the particular year chosen, or for that matter any of the years chosen where annual precipitation is similar to the 30-year average, may in fact be similar to the average value because of, among other considerations:

- one or more large precipitation events during the year;
- a number of smaller more consistent precipitation events throughout the year;
- a large snowfall (leading to significant snow melt) with minimal summer rainfall; or
- relatively little minimal snowfall and large summer rainfall events.

In each of these scenarios, the net percolation rate will be different, and is most likely not representative of "average" conditions, because of the influence of antecedent moisture conditions and the occurrence, magnitude, duration, and intensity of precipitation events. Furthermore, a significant percentage of rainfall that is followed by, or occurs during, high potential evaporation (PE) conditions will infiltrate, be "stored" within near surface material, and subsequently be "released" through evapotranspiration, resulting in little to no net percolation. The long-term "average" performance of a cover system should be determined from a statistical analysis of the net percolation predicted for each year of the climate record. The following case studies illustrate this point.

Case Study #1

Case Study #1 is representative of a site that would be classified as "semi-arid" on the basis of annual climate conditions. Average annual PE and precipitation (based on a 20-year climate database) are approximately 890 mm (35 inches) and 385 mm (15 inches), respectively. However, the site experiences cold winters with potential for significant snow pack (and as a result snow melt), as well as hot, dry conditions during summer frequented by thunderstorms. Therefore, while PE exceeds precipitation on an annual basis (on average a 2.3:1 ratio), during winter and spring melt, the ratio is more than likely 1:1 if not less, and during summer the ratio is likely much greater than the average annual ratio. This illustrates the caution that is required when using “annual” criteria for characterizing site climate conditions because depending on the timing and form of precipitation, precipitation may, or may not, result in net percolation.

Soil-atmosphere numerical modeling was conducted for the case study, and predicted annual net percolation, together with the annual PE and precipitation modelled is summarized in Table 1. Note that the annual cycle modelled is from October of the previous year to September of the following year in order to include the precipitation that occurs during the winter, which contributes to snow pack and results in net percolation during spring melt. Hence, each year shown in Table 1 straddles two years (e.g. October 1984 to September 1985).

Table 1. Summary of annual potential evaporation, precipitation, and predicted net percolation for Case Study #1.

	Potential Evaporation		**Precipitation**			**Net Percolation**		
Year	**(mm)**	**(inches)**	**(mm)**	**(inches)**	**Rank**	**(mm)**	**(inches)**	**Rank**
1984-85	*877*	*34.5*	*381*	*15.0*	*10*	*16*	*0.6*	*15*
1985-86	856	33.7	563	22.1	2	101	4.0	2
1986-87	929	36.6	292	11.5	16	3	0.1	17
1987-88	941	37.0	223	8.8	20	0	0.0	18
1988-89	893	35.2	326	12.8	13	20	0.8	12
1989-90	925	36.4	247	9.7	19	0	0.0	18
1990-91	879	34.6	428	16.8	7	50	2.0	7
1991-92	940	37.0	273	10.8	18	7	0.3	16
1992-93	789	31.1	539	21.2	3	119	4.7	1
1993-94	971	38.2	312	12.3	15	19	0.7	14
1994-95	867	34.1	487	19.2	4	73	2.9	5
1995-96	*937*	*36.9*	*402*	*15.8*	*9*	*35*	*1.4*	*8*
1996-97	917	36.1	471	18.5	6	22	0.9	11
1997-98	827	32.6	585	23.0	1	73	2.9	4
1998-99	869	34.2	343	13.5	12	20	0.8	13
1999-00	922	36.3	414	16.3	8	23	0.9	10
2000-01	889	35.0	321	12.6	14	30	1.2	9
2001-02	*863*	*34.0*	*353*	*13.9*	*11*	*60*	*2.4*	*6*
2002-03	931	36.6	283	11.2	17	0	0.0	18
2003-04	837	32.9	474	18.7	5	96	3.8	3
Average	**893**	**35.2**	**386**	**15.2**		**38**	**1.5**	

Three years are highlighted (underlined and *italicized*) in Table 1 (1984-85, 1995-96, and 2001-02) to illustrate the difference in predicted net percolation as compared to that which would be predicted if the "average" year (on a total precipitation basis) were modelled. The average of the annual net percolation rate predicted for each year modelled is approximately 38 mm (1.5 inches). Using the typical modelling approach, the most likely year that would have been modelled to represent the average net percolation would have been 1984-85 because it is the closest, numerically, to the average annual precipitation for the 20-year climate database.

The predicted net percolation for 1984-85 is approximately 16 mm (0.6 inches), which is less than half of the average net percolation predicted for all climate years simulated. A significant percentage of precipitation during this year was recorded during the summer, when evaporation rates were high. Hence, the summer rainfall was stored within the cover system, and then released as evapotranspiration, resulting in little to no net percolation. In contrast, during 2001-02, when 353 mm (13.9 inches) of precipitation was recorded, predicted net percolation was approximately 60 mm (2.4 inches). For this year, a greater amount of snowfall was recorded as compared to 1984-85, which resulted in an increase in the snow water equivalent during spring melt, and higher predicted net percolation. If 2001-02 were chosen as the "average" year that was modelled, net percolation as a percentage of average annual precipitation would be predicted to be approximately 17%, as compared to less than 5% if 1984-85 were chosen as the "average" year. The average net percolation as a percentage of precipitation would be approximately 10%, based on the average net percolation predicted for each year in the 20-year climate database. Predicted net percolation for the 1995-96 year, which had close to the same amount of precipitation as the 20-year average annual, was similar to the average annual net percolation for the 20-year climate database. The issue is however; would this year have been chosen as the "average" year using the typical modelling approach? Most likely not, because recorded precipitation for the 1984-85 year was closer numerically to the average annual precipitation.

Case Study #1 also illustrates that while one can use a single value for net percolation (e.g. 10%), such an approach is misleading because this average value is most likely not representative of conditions for any given year. Net percolation as a percentage of annual precipitation ranged from a net upward moisture flux during dry years, to more than 20% during wetter years. In addition, this case study illustrates that the "wettest" year of the 20-year database does not result in the highest net percolation. The wettest year, from an annual precipitation perspective was 1996-97, when 585 mm (23 inches) was recorded. However, only 73 mm (2.9 inches) of net percolation was predicted for this year, as compared to 1992-93 when predicted net percolation was more than 60% higher (119 mm (4.7 inches)). Lower potential evaporation conditions, a short growing season, and higher snowfall conditions occurred in 1992-93, as compared to 1996-97, which led to an increase in net percolation even though the total precipitation was lower. 1992-93 would be considered to be a "wet" year in comparison to the average annual precipitation, but it would not have been chosen as the "wettest" year on record using the typical modelling approach.

Case Study #2

Case Study #2 is representative of a site that would be classified as "arid", but tropical, on the basis of annual climate conditions. Average annual PE and precipitation (based on a 30-year climate database) are approximately 1959 mm (77 inches) and 506 mm (19.9 inches), respectively. This site does not experience snowfall, and as such all precipitation is in the firm of rainfall. PE significantly exceeds rainfall on an annual basis (almost a 4:1 ratio), although a large percentage of the rainfall occurs during a three to four month period during the summer (the "wet" season), when the PE to rainfall ratio is likely much lower, although would not approach 1:1.

Soil-atmosphere cover system design modelling was conducted for Case Study #2. Predicted net percolation, and modelled annual PE and rainfall for this case study is summarized in Table 2. The climate annual cycle modelled was from November of the previous year to October of the following year in order to start each model at the end of the dry season, just prior to the start of the wet season. The annual model results summarized in Table 2 are "continuous" simulations in that the initial conditions for each year are the final conditions for the previous year. The objective is to illustrate the "memory" inherent with respect to the response of the soil profile to subsequent atmospheric forcing (i.e. infiltration resulting form rainfall and evapotranspiration).

Four years are highlighted (underlined and *italicized*) in Table 2 (1975-76, 1983-84, 1992-93, and 1995-96) to highlight the difference in net percolation predicted based on average and wet climate years, as compared to that predicted for the entire 30-year climate database. The average of the annual net percolation predicted for each year modelled is approximately 77 mm (3.0 inches), as shown at the bottom of Table 2. Using the typical modelling approach, the most likely year that would have been modelled to represent the average net percolation would have been 1995-96 because it is the closest, numerically, to the average annual rainfall for the 30-year climate database.

The predicted net percolation for 1995-96 is near zero, and most likely a net upward moisture flux across the interface of the cover material and underlying waste material. The previous eight to ten years were relatively dry in terms of annual rainfall as compared to the average annual rainfall (with the exception of 1990-91). Rainfall during 1995-96 was most likely satisfying atmospheric demand and available water holding capacity (AWHC = the difference between gravity drained conditions, or field capacity (FC), and the wilting point (WP)) in the soil profile. Therefore, net percolation was essentially zero, which clearly is significantly different than the average of net percolation predicted for each year of the 30-year climate database.

A similar phenomenon was predicted for 1992-93, when annual rainfall was numerically close to the average annual value, but predicted net percolation was only 25% (19 mm, or 0.7 inches) of the average of net percolation predicted for each year of the 30-year climate database. The influence of *in situ* moisture conditions resulting from prior years (i.e. the soil's "memory") is evident.

Annual rainfall recorded during the 1975-76 climate year (the second year modeled) is numerically close to the 30-year average annual rainfall, and predicted net percolation is similar to the average of net percolation predicted for each year (73 mm, or 2.9 inches, as compared to 77 mm and 3.0 inches). However, this is most likely a coincidence as the initial conditions are influenced by the previous year's moisture conditions, as well as the fact that the initial conditions of the 30-year modeling simulation are based on the moisture conditions predicted for a "synthetic" average climate year. The "synthetic average" climate year is obtained by averaging each daily climate input parameter for the entire period of record. For example, rainfall on January 1st of the synthetic average climate year would be the average of all January 1st data for each year of the available climate record. The objective is to "smooth" the modeling process by eliminating high rainfall and other extreme climate conditions such that numerical

Table 2. Summary of annual potential evaporation, precipitation, and predicted net percolation for Case Study #2.

	Potential Evaporation		**Precipitation**			**Net Percolation**		
Year	**(mm)**	**(inches)**	**(mm)**	**(inches)**	**Rank**	**(mm)**	**(inches)**	**Rank**
1974-75	1962	77.2	626.4	24.7	8	98	3.9	8
1975-76	*1920*	*75.6*	*481.7*	*19.0*	*15*	*73*	*2.9*	*11*
1976-77	1770	69.7	800.6	31.5	3	301	11.8	3
1977-78	1724	67.9	745.1	29.3	5	192	7.6	6
1978-79	1820	71.7	268.7	10.6	29	9	0.3	18
1979-80	2054	80.9	404.4	15.9	18	7	0.3	19
1980-81	1905	75.0	455.1	17.9	16	29	1.2	14
1981-82	2045	80.5	519.1	20.4	12	39	1.5	12
1982-83	2087	82.2	404.2	15.9	19	20	0.8	15
1983-84	*1950*	*76.8*	*583.3*	*23.0*	*11*	*77*	*3.0*	*9*
1984-85	2236	88.0	308.1	12.1	25	31	1.2	13
1985-86	2270	89.4	291.7	11.5	27	0	0.0	21
1986-87	1960	77.2	395.1	15.6	21	0	0.0	21
1987-88	2114	83.2	296.4	11.7	26	0	0.0	21
1988-89	2210	87.0	253.4	10.0	30	0	0.0	21
1989-90	2066	81.3	362.7	14.3	22	0	0.0	21
1990-91	1990	78.3	601.1	23.7	10	1	0.0	20
1991-92	2016	79.4	417.6	16.4	17	0	0.0	21
1992-93	*1872*	*73.7*	*515.7*	*20.3*	*13*	*19*	*0.7*	*16*
1993-94	2143	84.4	276.7	10.9	28	0	0.0	21
1994-95	1974	77.7	401.8	15.8	20	0	0.0	21
1995-96	*2000*	*78.7*	*499.1*	*19.6*	*14*	*0*	*0.0*	*21*
1996-97	1794	70.6	903.9	35.6	1	303	11.9	2
1997-98	1730	68.1	685.9	27.0	7	77	3.0	10
1998-99	1807	71.1	602.8	23.7	9	170	6.7	7
1999-00	1701	67.0	740.0	29.1	6	204	8.0	5
2000-01	1709	67.3	895.0	35.2	2	357	14.0	1
2001-02	2015	79.3	352.9	13.9	23	14	0.6	17
2002-03	2052	80.8	309.0	12.2	24	0	0.0	21
2003-04	1882	74.1	794.9	31.3	4	294	11.6	4
Average	**1959**	**77**	**506**	**19.9**		**77**	**3.0**	

instability and water balance modeling problems are greatly minimized. This model is run repeatedly (the final conditions of the previous year used as the initial conditions of the subsequent year) with "synthetic" average climate year data until the initial and final conditions converge. These conditions are then used at the initial conditions for the 30-year continuous simulation.

The 1983-84 climate-year could be argued to be most representative of "average" conditions because the same net percolation was predicted for this year, as for the average of net percolation predicted for each year of the 30-year climate database. Note however, that rainfall during 1983-84 was approximately 77 mm (3.0 inches) greater than the average annual rainfall of 506 mm (19.9 inches). As with Case Study #1, caution is required when characterizing the system based on average conditions. Net percolation as a percentage of annual rainfall ranged from a net upward flux to nearly 40% for the cover system modelled.

Case Study #2 also illustrates the caution that is required when determining the wettest year on record. A common approach to cover system design for waste material situated in an arid or semi-arid climate is the moisture store-and-release cover system. The approach takes advantage of the high evaporative demand for moisture such that infiltration is stored with the cover material, and subsequently evapotranspirates, resulting in low net percolation to the underlying waste and a control on ARD and metal leaching from the waste storage facility. The typical modelling approach would call for modelling the wettest year on record (O'Kane *et al.* (2000) and Junqueira *et al.* (2004)), to determine the highest net percolation anticipated for a certain cover system design. For Case Study #2, this would be the 1996-97 climate year, and net percolation would be approximately 34% of annual rainfall. However, net percolation for 2000-01 is actually higher (40% of annual rainfall), primarily due to the influence of the previous two years, where wetter than average conditions were modelled. Antecedent moisture conditions were not achieved by the end of the dry season during these years, such that moisture storage capacity was not at its maximum prior to the start of the wet season. This resulted in an increase in rainfall during the subsequent wet season to report as net percolation, as compared to if the previous year was similar to an average or drier than average year. Hence, whether or not the wettest climate-year on record results in the greatest net percolation is a function of prior climatic conditions (i.e. the soil's "memory"). Case Study #2 illustrates a key issue, which should be addressed when determining representative climate years for cover system design modelling. It is common that the "worst case scenario" in terms of net percolation results from several wetter than average years occurring in a row, as opposed to the single wettest year on record, particularly if the latter conditions occurs following a dry year.

Case Study #3

Case Study #3 is a summary of measured net percolation at the siliceous tailings cover system field performance monitoring trials at the Teck-Cominco Ltd., Kimberley Operations, located near Kimberley, British Columbia, Canada. Further details of the trials are found in Gardiner *et al.* (1997), O'Kane *et al.* (1999), INAP (2003), and MEND (2004).

Climate at Kimberly Operations is classified as semi-arid due to an annual moisture deficit, however the site typically experiences hot, dry summer conditions and can experience humid fall and winter conditions. The average annual precipitation at the site is 402 mm (15.8 inches), with rainfall accounting for approximately 240 mm (9.5 inches). The average annual potential evaporation for the site is approximately 700 mm (27.6 inches).

A total of seven test plots were constructed on the siliceous tailings storage facility. Figure 2 summarizes net percolation measured at one of the field trials, the moisture store-and-release cover system field trial. This trial consisted of 20 to 60 cm (~ 8 to 24 inches) of relatively uniform and coarse material, overlain by 45 cm (~ 18 inches) of cobbly, non-plastic and well-graded till.

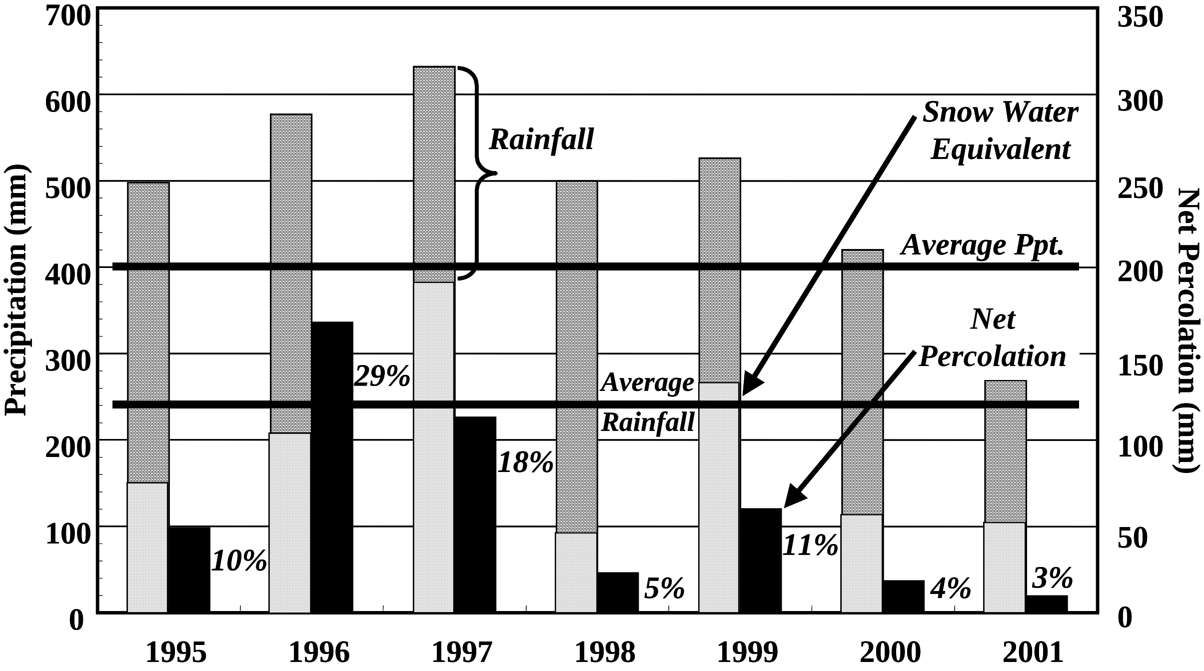

Figure 2. Summary of precipitation (total, snow water equivalent, and rainfall) and measured net percolation for the moisture store-and-release cover system field trial at Teck-Cominco's Kimberley Operations (MEND 2004).

The average net percolation rate for the seven years of monitoring data is approximately 11% (as a percentage of the total precipitation). However, it is clear from the data, that no one year is truly representative of "average" conditions. For example, the relative influence of snowfall (measured as SWE) and rainfall is shown in the net percolation rates measured in 1998 and 1999. These years had roughly equivalent total precipitation as approximately 25 mm (1 inch) more precipitation was recorded in 1999 (526 mm (20.7 inches as compared to 500 mm (19.7 inches)). However, net percolation rates during the two years were quite different (5% for 1998 and 11% for 1999). The difference in performance is due to the precipitation measured as SWE during the years. Only 90 mm (3.5 inches) of precipitation was recorded as SWE in 1998, as compared to 270 mm (10.6 inches) in 1999. The results from 1995 are also similar to 1998 and 1999. Total precipitation was roughly equivalent and SWE was in between the results from 1998 and 1999. Net percolation for 1995 is in between the values measured in the other years. These results are consistent with the modelling results presented in Case Study #1 (in terms of net percolation rates responding to atmospheric forcing). This is due to the similarity in climate regimes; hot dry summers store and release moisture resulting in low net percolation, while winter precipitation generally reports as net percolation.

Total precipitation recorded during the 2000 monitoring year was similar (numerically) to the average annual precipitation; however, net percolation was less than 50% of the seven-year average. SWE for 2000 was less than half of the average annual SWE, which resulted in the lower net percolation rate.

A comparison of the net percolation rates and total precipitation measured in 1996 and 1997 provides further evidence that a great deal of caution is required when assuming that the highest recorded precipitation will result in the greatest net percolation value. Precipitation in 1997 was approximately 640 mm (25.2 inches), as compared to about 580 mm (22.8 inches) in 1996. However, net percolation measured in 1996 was more than 50 mm (~2 inches) higher than that measured in 1997. Even though net percolation was lower in 1997, SWE was higher in 1997 as compared to 1996, which is contrary to the results observed in subsequent years and discussed above. The reason that net percolation rates are higher in 1996 as compared to 1997 is due to that fact that much of the rainfall recorded during 1996 occurred during the late fall and winter, when evaporation rates were low, and the system did not posses the ability to release moisture as evapotranspiration (as occurs during the hot dry summers).

Climate conditions are a key factor controlling performance of the cover system. Higher annual incident precipitation will generally lead to an increase in net percolation rates, which is intuitive, but often not appreciated when predicting long-term performance. However, not so intuitive is the influence on performance due to the time of year in which precipitation occurs and the form of precipitation (i.e. snow or rain). In general, precipitation that contributes to snow pack, or occurs during the winter, will increase net percolation rates, while summer rainfall is buffered by the presence of cover material, and net percolation rates are reduced as a result of the hot dry conditions. Hence, the impact on performance due to higher than average annual precipitation can only be properly understood within the context of whether the higher precipitation was due to rainfall, snowfall, or some combination of rainfall and snowfall.

Case Study #4

Case Study #3 summarizes measured net percolation rates from the BHPBilliton Iron Ore Pty Ltd., Mt. Whaleback cover system field trials. Further details of the trials are found in O'Kane *et al.* (2000), INAP (2003), and MEND (2004). BHPBilliton's Mt. Whaleback Operation is located in the Hamersley Iron Province in the northwest of Australia, approximately 1,200 km north-northeast of Perth, Western Australia. The climate of the region is semi-arid, tropical with an average annual rainfall of approximately 320 mm (12.6 inches). There are two distinct seasons, a hot, wet summer (December to April), and the rest of the year, which is more temperate and generally has lower rainfall. Typically, rainfall occurs in high intensity, short duration events, usually associated with cyclonic activity during the summer. Annual potential evaporation typically exceeds 3,000 mm (118 inches).

Five large-scale cover system field trials, designed using the moisture store-and-release approach, were constructed at Mt. Whaleback. Net percolation rates and rainfall measured at the 200 cm (79 inch) thick field trial, constructed using run-of-mine, inert, well-graded waste (non-vegetated), are presented in Fig. 3.

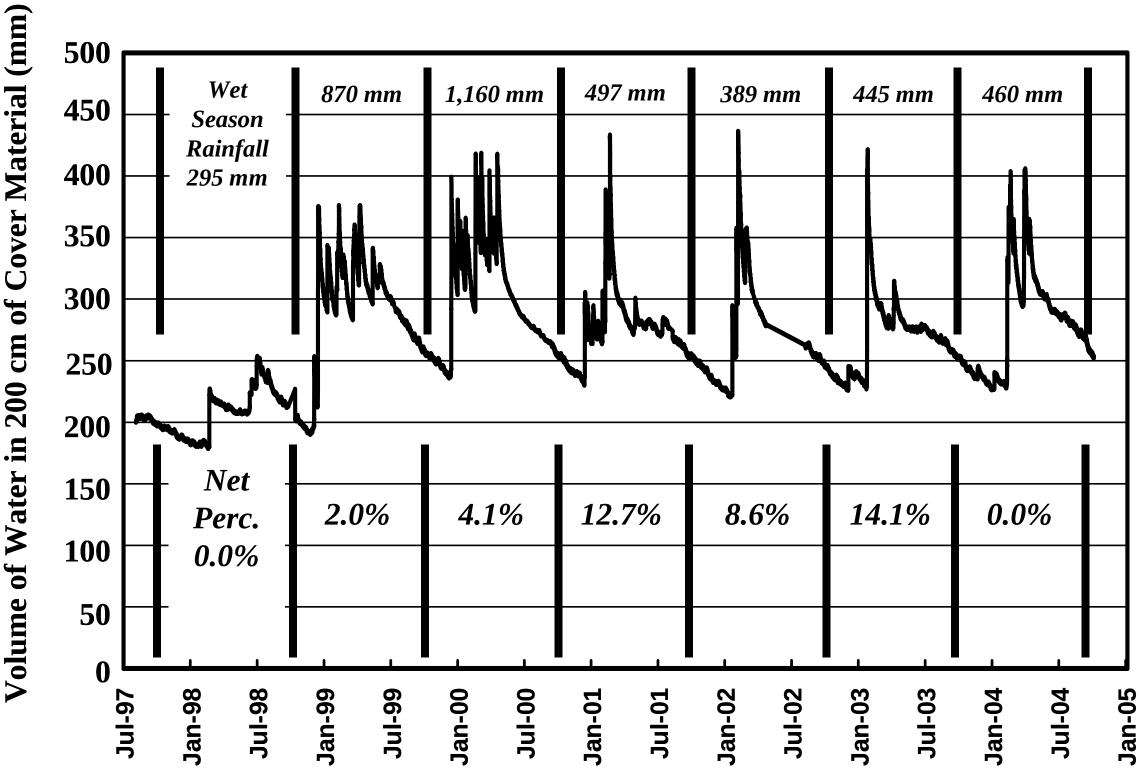

Figure 3. Volume of water in BHPBilliton's Mt. Whaleback Operations 200 cm (79 inch) store-and-release cover system field trial, together with wet season rainfall and net percolation rates (MEND 2004).

O'Kane et al. (2000) states that the highest recorded annual rainfall in the 30-year database was approximately 500 mm (19.7 inches). Predicted net percolation using this "extreme" condition, which is the typical approach when designing moisture store-and-release cover systems, was less than 1% of the 500 mm (19.7 inches) of rainfall (O'Kane et al., 2000). The annual rainfall for the first year of monitoring (October 1997 to September 1998) was 295 mm (11.6 inches). No net percolation was recorded during this monitoring period. Rainfall was significantly higher than 500 mm (19.7 inches) during the next two years when 870 mm (34.3 inches) was recorded in 1998-99 and 1,160 mm (45.7 inches) was recorded in 1999-2000. These two years were followed by another relatively wet year (497 mm (19.6 inches) in 2000-01). Net percolation rates as a percentage of annual rainfall increased from 2.0% to 4.1%, to 12.7% over this three-year period, as shown in Fig. 3.

A number of key points are illustrated in Fig. 3, in terms of developing representative climate years for predicting cover system performance. First, as was shown for the numerical modelling presented for Case Study #2, it is not the wettest year on record (which in the case of the monitoring period shown in Fig. 3 was 1,160 mm (45.7 inches)) that necessarily leads to the highest net percolation value. Net percolation rates were higher during the year following the wettest year because the system did not have sufficient time to return to antecedent moisture conditions at the end of the 1999-00 dry season. Hence, the fact that 2000-01 was also a relatively wet year, coupled with insufficient storage capacity in the cover material as a result of the prior wet conditions, led to the higher net percolation value. If 2000-01 had been a relatively dry year, it is likely that net percolation rates during this year would have been much lower than observed because much of the additional moisture in the system (i.e. the soil's memory) would have been removed by evapotranspiration during the drier year, as opposed to reporting as net percolation due to unsaturated "piston" flow.

The second key point illustrated in Fig. 3 is the time frame over which net percolation occurs, as a result of the influence of conditions experienced during prior years, as well as the time required for moisture transport. The annual net percolation values shown in Fig. 3 are misleading because each year's value is influenced by previous years. It is more appropriate to present net percolation rates, as a percentage of the total rainfall (or precipitation) recorded during the monitoring period, which in the case of the data presented in Fig. 3 would be approximately 6% over the seven years.

Summary

Choosing representative climate years for predicting long-term performance of a cover system is likely one of the most critical components of the cover system design process. The typical approach is to determine the "average", "dry, and "wet" years on the basis of annual precipitation, and then model these three years to develop a sense of the long-term performance of the cover system in terms of "average" and "extreme" conditions. Soil-atmosphere numerical modelling and field performance monitoring were used in this paper to illustrate that this approach is flawed. Assessment of a cover system should be based on modelled or measured performance of the cover system itself (e.g. net percolation, oxygen ingress, available water holding capacity, etc.), as opposed to climate conditions alone.

This paper focused on modelled and measured net percolation rates, but the conclusions reached are also indicative of the approach required when developing an understanding for other performance indicators (e.g. oxygen ingress). Net percolation predicted from the average precipitation record for a given site is typically not representative of the long-term average performance. The magnitude and occurrence of various precipitation events throughout the year, coupled with antecedent moisture conditions, plays a major role in actual net percolation rates through a cover system. The long-term average performance of a cover system should be determined from a statistical analysis of the net percolation predicted for each year of the climate record. This methodology accounts for the impact of antecedent moisture conditions (i.e. the soil's "memory") as well as the occurrence and intensity of daily precipitation events when determining the long-term average net percolation rate.

The data presented in this paper also illustrates that the "wettest" year on record, based on annual precipitation, does not necessarily result in the greatest net percolation rate. In tropical semi-arid climates (Case Study #2 and #4), the most typical scenario leading to an "extreme" net percolation value is one where successive wetter than average years occur, such that *in situ* moisture conditions resulting from previous years, influences moisture storage, and hence net percolation rates. Whether or not this wet year is preceded, and/or followed, by an average, dry, or another wet year will strongly influence net percolation rates. At sites that experience snow fall, and more humid conditions in the spring, followed by hotter and drier summer conditions (Case Study #1 and #3), the extreme net percolation rate will be a function of the volume of late fall, winter, and spring precipitation. Summer rainfall will typically be used to satisfy vegetation requirements, and generally not report as net percolation.

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