Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds – A brief history of the Syncrude Southwest 30 overburden reclamation research program

S. L. Barbour[1], D. Chapman[1], C. Qualizza[2], S. Kessler[3], Boese, C. [4],
R. Shurniak[5], G. Meiers[5], M. O'Kane[5], J. Hendry[6] and S. Wall[6]

A central feature of the reclamation strategy pursued by Syncrude Canada Limited is the establishment of targeted ecosites within recreated landscapes. It is understood that no amount of initial effort can fully create these systems; rather, the reclamation efforts must create appropriate initial conditions from which the final ecosites and landscape can evolve. Consequently, a central requirement of any reclamation effort is the tracking of landscape evolution over time and instrumented watersheds have become the primary tool of choice. The Southwest 30 Overburden hill has provided a unique opportunity to track the evolution of a small watershed for more than 5 years following initial placement of reclamation materials. A central focus of the field effort has been tracking the dynamic fluxes of water and salt within the landscape. These fluxes are central to the final productivity and performance of the landscape. This paper describes how the instrumented watershed and related field activities have been developed and have evolved at this site over the last 5 years. The incremental expansion of the instrumentation from a focus on one–dimensional water balances to multi-dimensional salt and water fluxes is documented, highlighting practical details of instrumentation design, installation and monitoring. In addition the ongoing challenges of maintaining the site instrumentation and the associated data bases, as well as ensuring that the data is interpreted and integrated across the various research disciplines in a manner that still provides input to industry decision making, are also briefly discussed.

1. University of Saskatchewan, Department of Civil & Geological Engineering, Saskatoon, Saskatchewan, S7N 5A9
2. Syncrude Canada Ltd., Fort McMurray, Alberta, T9H 3L1
3. University of Saskatchewan, Department of Soil Science, Saskatoon, Saskatchewan, S7N 5A8
4. NorwestCorporation, Vancouver, British Columbia, V6C 2B3
5. O'Kane Consultants Inc., Calgary, Alberta, T3H 3C8
6. University of Saskatchewan, Department of Geological Sciences, Saskatoon, Saskatchewan, S7N 5E2

INTRODUCTION

The Syncrude Canada Limited (SCL) Mildred Lake mine is situated in the Athabasca Oil Sands Region of north-eastern Alberta and is one of the world's largest operating mines. This region will produce more than 50% of Canada's oil supply within the next 10 years with Syncrude alone supplying 20% of the nation's oil. Large tracts of land are disturbed through these operations. Reclamation of Syncrude's Base Mine alone will involve the reconstruction of 21,000 ha of boreal forest. One of the major concerns limiting development is the time frame to successfully reclaim these disturbances. The ability to demonstrate successful reclamation has, in fact, become a competitive advantage in a region where caps on development due to cumulative environmental impacts are a reality.

Oilsand operators receive operating licenses from the provincial government based on achievable closure and reclamation plans. These plans detail the path the company proposes to follow from pre-disturbance timber harvesting and soil salvage through landform reconstruction and reclamation certification. Certification is only issued by the government when it deems that reclamation on a specific piece of land is complete and successful, at which point the land is returned to the owner, in most cases the crown, and the company is freed of liability.

In order to obtain a reclamation certificate, an operator must demonstrate that the reconstructed "land capability" is equivalent to that which existed prior to disturbance. Land capability is defined as ***"the ability of the land to support a given land use, based on an evaluation of the physical, chemical and biological characteristics of the land including topography, drainage, hydrology, soils and vegetation."*** Equivalent capability is defined as follows: ***"The ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land but that the individual land uses will not necessarily be identical."*** (Alberta Environmental Protection 1994).

A typical boreal forest in the Athabasca region takes between fifty and one hundred years to mature; however as an operator, Syncrude would like to receive a reclamation certificate far in advance of this. As such, the industry has adopted the forest industry time frame of 15 years for certification assessment. At this time trees are considered to have overcome any site limitations and shading competition and are considered "free to grow". However, 15 years is still very early in the life cycle of a boreal forest so the operators face the challenge of demonstrating that the landform is on a successful "trajectory" towards a healthy, sustainable boreal landscape.

Syncrude has targeted much of its sponsored research at defining this critical "trajectory" and the particular mechanisms and processes which are critical in landscape evolution. Syncrude's long term liability is reduced when a credible biography can be written for each reconstructed landform. Syncrude has determined that the there are two critical aspects to any research dedicated to tracking the evolution of these landforms over time; extended scales of study (time and space) and integrated teams scientists and engineers.

In terms of space, the research has tried to focus on studies that encompass at least one complete watershed within the landform. There are several reasons for this: i) it is the primary unit for mine planning, particularly as it relates to routing of surface water ii) it is of sufficient size to address central questions about landscape performance and risk while iii) encompassing a range of target ecosites for a particular parent material, iv) it allows for realistic measurements and estimates of essential fluxes and balances (e.g. water, salt, nutrients), v) it includes sufficient complexity so that the complex interactions between these fluxes are represented while at the same time vi) keeping monitoring and analyses manageable. The research has shown that rapid changes in the hydraulic characteristics of the cover occur within the first 3 to 5 years. Consequently the watershed level research is targeted for a minimum of a 5 year period.

By requiring teams of engineers and scientists to work together, a rigorous assessment of all research results from each program occurs through the lenses of many disciplines, ensuring that synergies are found and that conclusions drawn or recommendations made, are true for all components of the watershed.

Although this has now been established as standard practise for reclamation research at Syncrude, the first instrumented watershed research program was much like the watershed, evolutionary in its development. Syncrude commenced its instrumented watershed research work with the University of Saskatchewan in 1998 on one of our saline sodic overburden areas- the SW30 Dump also known as the Wood Bison Hills(WBH). Following from the example set there, the program was expanded to a tailings sand slope watershed in 2001 and a petroleum coke based landform in 2003. Over the next 10 years instrumented watersheds will be established on major material types including soft tailings, buried sulphur, lean oilsand, and coarse-grained overburden. This paper describes the development of the first instrumented watershed research work by the University of Saskatchewan on saline sodic overburden, highlighting this unique integrated approach to reclamation research and outlining some of the results with a particular focus on the evolution of the landscape that occurs with time.

This program was integral to the development of Syncrude's current plan to construct watersheds on all major types of waste and disturbed soils. These watersheds will be part of an 8 to 10 year program of research focussed on answering the "Big Questions": 1) water and energy balances *(capital and circulation rates)*; 2) salt balances, including inorganics, organics, ions, nutrients, metals *(capital and circulation rates;* 3) plant and ecological responses to 1 and 2, and finally, 4) how to manage these balances optimally. Critical levels of continuing and sufficient monitoring for certification will also be established until the full "biography" of each landform has been written and certification has been obtained.

DESCRIPTION OF RESEARCH PROGRAM

Saline sodic overburden will comprise about one third of the 80 km^2 area comprising Syncrude's final landscape. These soils are Cretaceous marine shales consisting of swelling clays (illite and montmorillonite) that are highly saline (10-20 dS/m) and sodium saturated (SAR >20). The initial question asked of the research group was simply this; "what is the correct soil cover depth to place over saline sodic shales to ensure establishment of a productive boreal ecosystem which will minimize leaching of water through the shale pile resulting in saline seepage and erosion."

An initial 3 year study was developed to address this question through the following objectives:

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

The overall objective of this integrated study was to define the basic mechanisms controlling moisture movement within the reclaimed landscape. Mechanisms were characterized by the installation, verification and continuous monitoring of field instrumentation on the three prototype covers. Once these mechanisms are characterized, their subsequent impact on salt migration and revegetation can be addressed. Numerical models were to be modified and verified to allow SCL a means of undertaking preliminary design of cover alternatives and reclamation strategies for the remainder of the mine site. The monitored study site also provided a valuable field site to track the long-term hydrologic evolution of a reclaimed landscape and provided insight into the hydrologic processes occurring within soil covers on reclaimed overburden, and thus in optimizing cover design.

These study objectives focused on the long-term performance of reclamation cover sites located on the Wood Bison Hills(WBH) (Figure 1). The study area included 3 new alternative prototype layered covers along with an older, previously reclaimed cover located adjacent to a voluntary wetland known as Bill's Lake. The prototype covers drain into a single swale running along their base while the cover surround Bill's lake drains directly into the Bill's Lake wetland. Bison Lake, is a small lake located downstream from Bill's Lake. Any runoff collected from the top of the dump, which was reclaimed in 2001, is collected along a swale and is drained into 2 wetlands situated in series and known as Peat Pond and Golden Pond.

FIELD SITES – INSTRUMENTATION, SAMPLING AND TESTING

The prototype covers were constructed in 1999 with 3 different thicknesses of peat over secondary, sufficient to provide the 'available water holding capacity' required for the development of a sustainable vegetative soil cover in accordance with the soil classification system developed by Leskiw et al. (1999). The Bill's Lake cover, also part of the study, was placed in 1996. Each of the three prototype covers is approximately 1 ha in size (200 m long and 50 m wide) and is placed on a 5 to 1 slope. The prototype covers are placed side by side, west to east and are built as follows: D1, 20 cm of peat overlying 30 cm of secondary; D2, 15cm of peat overlying 20 cm of secondary; D3, 20 cm of peat over 80 cm of secondary. The cover at Bill's Lake consists of nominally 100 cm of mixed peat/secondary. The D3 cover is the control plot, with a cover thickness based on that mandated by Alberta Environment.

Table 1 provides an abbreviated summary of the instrumentation and field measurement programs undertaken at the study site. It is readily apparent from this table that instrumentation of a watershed is begun but never completed. It has involved continual extensions, improvements, repairs, and dedicated monitoring over a period of more than 5 years. This 'evolution' of the instrumentation requires a high level of corporate commitment and the dedication of research personnel, particularly graduate students and research staff. In fact, any success is likely due more to the quality of these people than the quality of the instrumentation. A brief description of the major instrumentation and monitoring activities is provided below. A more detailed description of the field instrumentation is provided in Stolte et al (2000) and Barbour et al (2001).

Soil and Climate Stations

One of the strategic decisions made early on in the study was to initially concentrate the instrumentation at selected locations rather than simply scatter them over a wider area. Consequently, detailed soil instrumentation stations were established in the center of each cover to monitor soil water content using an FDR (frequency domain response) unit, suction using two different types of thermal conductivity sensors, and soil temperature. These first clusters of soil instrumentation were installed through the walls of insulated boxes which would provide permanent access to the soil locations in case replacement was required for faulty sensors. None of these sensors have had to be replaced to date. A 5th instrumentation cluster installed at the top of the hill in a subsequent program was simply installed through the vertical walls of excavated trench and then backfilled soil following installation of the instruments. All instrumentation was calibrated in lab before hand and checked against field data. The instrumentation was wired into a Data Acquisition System (DAS) that records the measurements twice daily at midnight and noon. Neutron probe access tubes were also installed beside each box and at the top and bottom of the slope (Figures 2 and 3).

A meteorological monitoring station and a Bowen Ratio Energy Balance (BREB) apparatus were set up in the center of the cover site, along the border between the D2 and D3 covers. The weather station is located at the center of the prototype covers and records wind speed and direction, air temperature, relative humidity, and precipitation throughout the year. Data is recorded by a DAS on an hourly basis with a daily summary of maximum, minimum and average values. The Bowen ratio station also measures wind speed and direction, net radiation, soil temperature and moisture content, and temperature and vapour pressure at two heights above the ground surface. These measurements are used to calculate actual evapotranspiration. This station records data every 20 minutes during the growing season, from the beginning of May to mid October, and is dismantled for the winter. The location of the Bowen ratio station alternated between Bills Lake and the Prototype cover, spending approximately half of the growing season at each site.

Runoff from both snowmelt and rainfall events was measured by a series of weirs at the toe of the prototype cover. There are four weirs in total; one at the downstream end of each prototype cover and one upstream of the study sites in order to measure water entering upstream. Each weir is equipped with a sonic sensor to measure water levels as they pass through a 60-degree v-notch. The sonic sensors send a signal back to a central DAS every 5 minutes recording the water level from each weir

An interflow measurement system comprised of a geomembrane cutoff, located at the soil cover/overburden interface, and a weeping tile collection system and barrel were installed on each plot in June, 2000. A flow meter attached to the pumping system was used to measure the volume of water captured.

Some of the other measurements and monitoring on the study site are briefly summarized below.

Snow Survey

An annual snow survey has been conducted in late February/early March since 2000 in order to determine the amount of water present as snow just prior to spring melt. The original surveys were concentrated on the three prototype cover systems as well as Bill’s Lake. The survey consisted of a 10 m grid where the depth of snow was taken at every location and a snow core for density analysis was taken at every other location. In 2004 the survey was expanded to cover the entire WBH. Snow density cores were taken every 30 m and a second survey was taken after temporary melting temperatures were experienced in order measure the rate of change of snow depth during these events.

Evaporation Pans

Four Class A evaporation pans were used since 2001 to measure evaporation rates: one located at Bill's Lake, one at Peat Pond, one mid-slope on the prototype covers and one at the top of the hill. Measurements and pan top up was done a minimum once a week.

Infiltration Rings

Infiltration rings consisting of 30 cm (OD) PVC pipe cut in 25 cm lengths were installed in October 2001 to evaluate frozen ground infiltration within the covers. Five rings were installed along each slope and two were installed at Bill's Lake. Infiltration rates were measured during spring melt but while the ground was frozen. The tests were repeated in late August using the same method in order to compare the relative hydraulic conductivity of the frozen and unfrozen ground surface.

Neutron Probe Moisture Measurements

Readings were taken every two weeks using a CPN 503 DR Hydroprobe® moisture gauge to measure moisture profiles at the top, mid and bottom slope positions of each prototype cover and at Bill's Lake. A deep access tube (25m) was installed at the top of the WBH in August 2002 in conjunction with the geochemistry study. The first set of readings was taken in October 2002 and monitoring continued through the summer of 2003.

Diviner 2000

Twenty-eight Diviner 2000 (Sentek) access tubes (1.6 m deep) were installed through the years starting in 2001 at various locations on the WBH. Readings of all tubes were taken weekly and as close to precipitation events as possible in order to establish detailed profiles of water content. The tubes were difficult to install whenever extremely compact or rocky soil was encountered.

Saturated Wedge Pipes(SWP)

A series of nine SWP were installed in June of 2001 upslope of the interflow collection system (three on each prototype cover) in order to define the extent of a free surface along the cover/shale interface near the toe of the slope. An additional nine SWP were installed 10m upslope from the previous SWP in May of 2002. The pipes were constructed of a length of slotted PVC screen attached to section of unslotted PVC capped at the lower end, with the slotted portion extending across the cover/shale interface. The pipes are checked manually, particularly after significant precipitation events or long periods of precipitation. The water level is recorded and when there is sufficient water a sample is collected for chemical analyses. Water was often collected from the lowest row of pipes beginning in the spring and throughout the summer. There was no water in the second row until later in the summer of 2002. As more normal precipitation levels returned in 2003, water ingress to the second row of SWP became more frequent.

Staff gauges

The staff gauges placed in Bill's Lake, Peat Pond, and Golden Pond and in the weir swale at the bottom of the prototype covers were measured frequently. For the 2003 season, staff gauges were replaced with pressure transducers in Bill's Lake and Peat Pond as a part of a separate program with the University of Alberta which is looking at surface water – groundwater dynamics.

Water sampling

Water chemistry samples were collected regularly from Bill's Lake, Bison Lake, Peat Pond, Golden Pond and the swales (when ponded water was present) in addition to the collected water from the interflow system and SWP.

Vegetation

Vegetation on the watershed was monitored for composition, leaf area indices, root growth and stress physiology parameters (transpiration, photosynthesis rates) as part of a program with Dr. Purdy from the University of Alberta.

Geophysics

A geophysical survey (EM31,38 and ERT) in the first year of the program provided a baseline salinity map.

Permanent Photo Record

Photos overlooking each of the three prototype covers, Bill's Lake, and Peat Pond have been taken weekly since 2000. The photos are used to create a photo diary of any changes that take place both year to year and over each season and provide additional data on vegetation cover for use in interpreting soil station monitoring data.

Guelph Permeameter Testing Program

Field measurements of hydraulic conductivity were made with a constant head well permeameter referred to as the Guelph Permeameter. It involves the measurement of the steady-state infiltration rate required to maintain a steady depth of water in an uncased, cylindrical auger hole that terminates above the water table (Reynolds 1993). The values of field saturated hydraulic conductivity (Kfs) that can be measured accurately with the Guelph permeameter range from 1 X 10^{-6} cm/sec to 9 X 10^{-2} cm/s. Beyond these limits there is a reduction in accuracy and precision.

Approximately eight to twelve measurements were made near the location of each neutron probe for a total of approximately thirty measurements over each test cover. Repeated measurements were made within the D1, D2, and D3 covers at a depth of approximately 40 cm, 30 cm, and 60 cm, respectively. A similar set of measurements were made each summer of a three year period.

Soil Chemistry and Shale Geochemistry

An extensive soil-sampling program completed during the summer of 2002 provided a snapshot of the salt distribution approximately 4 years after placement of the reclamation material. The objective of this subprogram was to determine the distribution of major salts in the landscape and to evaluate the extent of salt transfer between the highly saline overburden material and the cover topsoil. Detailed soil profiles were obtained by sampling at 10 locations spaced out along transects taken downslope along each of the different cover prescriptions. Each profile was sampled in 10 cm increments, with a total depth varying between 100 and 200 cm, depending on the depth of the cover-overburden interface, ensuring that at least 30 cm of waste material would be obtained for each profile. Approximately 700 samples were collected. Each of these was sub-sampled for moisture content analysis. Samples were air-dried and ground to pass a 2mm sieve. Major ion concentrations were determined on saturation extracts made from the soil samples.

In addition to the salts present in the pore-fluid of the unoxidized shale, the potential exists for additional salt release due to oxidation of sulphides present within the shale. A separate geochemical investigation focussed on determining the sulphur forms and concentrations present in the overburden and on determining the rate of sulphide mineral oxidation which in turn determines the resultant salt loading. A total of 44 soil gas sampling probes were installed at 4 locations on the north slope of the WBH and at one undisturbed, forested control site. The four instrumented locations on the WBH were chosen to investigate variations due to slope position and cover treatment. Soil O_2, CO_2, N_2 and CH_4 concentrations were measured approximately monthly throughout the field season (May through October) and once during the winter between 2001 and 2003. Gas concentrations were measured using an Agilent M200 portable gas chromatograph. In addition to measuring soil gas concentrations, gas samples were collected approximately monthly for stable isotope analysis of $^{13}C_{CO2}$. The carbon stable isotope analysis will be used to determine the potential source of CO_2 produced in the soil.

In addition to pore-gas chemistry, moisture content and temperature data were required for reaction-rate calculations. Moisture content measurements were collected via three methods; Diviner 2000, neutron probe and gravimetrically. At the top of the 30-Dump, three Diviner access tubes (to 1.6 m) were installed in June 2002 and a 22 m deep neutron access tube was installed in August 2002. Soil samples for gravimetric moisture measurements were collected at the time of both instrument installations. A thermistor string containing thermistors at 0.25, 1.25, 2.25, 3.25, 4.25, 5.25, 9.25, 14.25 and 19.25 m below ground surface was installed in June 2002. For comparison, two Diviner access tubes (to 1.6 m) were installed at the forested control site and soil samples were collected for gravimetric moisture measurements at the time of tube installation. Solid samples collected at the time of deep gas probe installation on the top of the WBH (February 2001) and neutron probe installation (August 2002) were analyzed for sulphur forms and concentrations, carbon forms and concentrations, soluble salts and CEC.

DATA - MONITORING, MAINTENANCE AND MANAGEMENT

Since installation of the stations in 1999, the soil stations, weather station, and weir station at the WBH were all downloaded weekly in the summer and approximately monthly the remainder of the year. The data was checked and analysed for any sensor failure and added to a database. There were no major problems with the stations during this time. The Bowen ratio station, which was only operational during the summer required bi-weekly maintenance of the air temperature and vapour pressure sensors since there were ongoing problems with the thermocouples on the BREB breaking. On a number of occasions of infrequent maintenance, large periods of data were lost when the Bowen station DA system shut down. It was found that the DA system had to be checked regularly to ensure that the data was being recorded correctly and that no data was lost as a result of a system shut down.

Some general comments can be made regarding the performance of the instrumentation clusters. The addition of a snowfall adapter and windshield on the tipping bucket rain gauge in October 2000 allowed the measurement of precipitation during winter and spring. Although the FDR system was calibrated in the laboratory prior to field instrumentation it was not possible to capture all the influences on the FDR in the laboratory. One area that still requires further investigation is the influence that the high salt loading in the shale and lower cover soils may have on the calibration. The FDR responds to the dielectric constant of the soil surrounding the probe and consequently cannot be used when the soil is frozen. The suction sensors rely on heat dissipation rates as a means of interpreting water content in the sensor ceramic, consequently, these sensors do not work below 0^oC as well.

One of the central issues pertaining to the DA system was difficulty with the continual change in personnel on site. This is quite common in a research program given the turnover of graduate students from year to year. This can lead to problems with lack of training in personnel and with continuity of maintenance and data management. All stations at the WBH were downloaded and maintained by University of Saskatchewan personnel until the summer of 2002; however, since that time SCL has asked O'Kane Consultants Inc. to handle all maintenance and monitoring responsibilities for the instrumentation clusters in order to provide continuity in data collection and management.

DATA INTERPRETATION

The overarching goal of the instrumented covers/watershed is to track salt and water fluxes with time. In developing estimates of these fluxes, the interpretation of the data brings into focus the governing mechanisms controlling these fluxes. It is impossible to summarize all of the study results within this paper; however, some of the data set is presented to illustrate some of the interpretations made as to the mechanisms controlling salt and water fluxes within the reclamation covers and watershed.

Water Fluxes and the Water Balance

Detailed monitoring of the volumetric water content within the soil profiles has proven to be invaluable in establishing the essential measurement for any watershed – the volume of water stored within the cover with time. Figure 4 shows a typical data set for the thin (35 cm) and thick (100 cm) layered covers. Detailed profiles over several years help establish patterns which are key to interpretation. For example, it is apparent in this figure that the fluctuations are much more dynamic in the thinner cover. Full saturation of the peat occurs during wet periods and drying of the profile during dry periods extends even to sensors located within the shale overburden. The companion plots of matric suction (not presented) illustrate that the suction levels approach and exceed the wilting point at several points within the cover during the driest years. In addition, the upward movement of moisture from the shale into the cover accelerates the transfer of salt from the shale to the cover via an advective process.

These detailed water contents can also be integrated over the depth of the cover layers to produce a summary graph of water volume held in each cover layer over time. These plots track changes in soil moisture storage(ΔS) over the summer season and from year to year. Detailed tracking of the summer moisture deficit for each cover can then be established based on this detailed monitoring.

The basic water balance for the covers can be written as follows:

$$\Delta S = PPT - R - P - I - AET \qquad \text{Equation 1}$$

where; PPT is precipitation, R is Runoff, P is deep percolation into the underlying shale, I is the down slope movement of water as interflow along the secondary/cover interface and AET is actual evapotranspiration.

A daily water balance was conducted for seasonal and annual conditions. The seasonal balance was performed for the period when AET data was available from the BREB, typically June through October. The annual balance was extended beyond the available data set assuming that

AET is zero from November through April. The water balance for each cover was conducted using daily field evapotranspiration, runoff, and interflow rates as well as the volume of stored water calculated from soil moisture data. To evaluate the performance of the four soil covers, the increase in storage (ΔS) is compared to the measured ΔS at each soil station.

All volumes have been converted into equivalent values of mm/day applied to the entire cover area. Before performing the water balance, the data set was checked thoroughly for erroneous data and inconsistent trends due to instrumentation malfunction. The data set was modified to correct any errors found. More specific comments pertaining to each water balance component are discussed below.

Actual Evapotranspiration (AET): AET data was available from the BREB from mid May to the end of October. The values of AET measured in this way were assumed to be similar for all covers and zero over the winter period when the BREB was removed.

Deep Percolation: Field measurements of saturated hydraulic conductivity were used to estimate a maximum rate of deep percolation through the shale, assuming a downward gradient of unity. A value of 1e-9 m/s was used as tested by Meiers (2002). Deep percolation was assumed to occur at all sites when soil temperatures at the cover base were above 0^{o}C(May through October). In fact, this likely overestimates the actual deep percolation since downward gradients are not present at the shale interface throughout the year.

Interflow: A seasonal interflow rate was calculated by dividing the total volume collected by the number of days flow was observed and distributing that over the cover area. The calculated daily rate was applied to the period when interflow was observed. No interflow collection system was installed at the Bill's Lake site and therefore it was assumed to be zero although indications showed that interflow may be occurring from time to time.

Precipitation: Measured rainfall was assumed to be the same for all covers. Once daily air temperatures remained below zero, typically early November, precipitation was set to zero in the water balance and accumulated as snow until spring melt. Snow melt water equivalents were calculated for the snow pack measurements taken at the end of February. Water equivalents were compared to the recorded precipitation for verification. The snow pack values were found to be similar but considered more site specific to each cover considering snow redistribution due to wind. Additional precipitation recorded between the end of February and spring melt was added to the snow pack water equivalent. The water available in the snow pack was applied as a one time precipitation event. In 2000 the measured snow pack was relatively small, due to a December melt event.

Runoff: Site specific runoff data was calculated from measured weir flows. Some runoff events were not recorded due to errors caused by vegetation under the sensors. Because of large flows during spring runoff and the consecutive weir system it was more accurate to take the cumulative difference between the weirs for the entire runoff period (e.g. 20 to 30 days). This was applied as a one time event on the same day as the winter snowmelt. No useable runoff data was recorded in 2000 due to freezing behind the weirs. Given the relatively small snow pack, the runoff and snowmelt were assumed to be equal and all soil moisture increase was attributed to spring rains.

Increase in Storage(ΔS): Water volumes were calculated from measured water contents. Although water contents were recorded twice daily at the soil stations (noon and midnight) only the midnight readings were used for daily calculations. These readings best represent the soils moisture content responses because regional rainfall typically occurs in the late afternoon or evening. To compensate for inaccuracy of the TDR sensors below 0^{o}C, water content values were assumed to remain constant from freeze up to spring thaw.

ΔS Water Balance: If ΔS was greater than the measured rainfall, it was assumed that the extra moisture was considered to occur as a result of lateral down slope flow within the cover.

The above components were used to calculate a cumulative water balance. Figure 5 illustrates a cumulative water balance for the 35 cm cover in 2000. All data shown is the actual measured values of the six different fluxes. Total precipitation received over the 5 month period was 244 mm with no recorded runoff. The water content measurements indicated a cumulative decrease in moisture storage of 39 mm with no measured interflow. Cumulative deep percolation was only estimated to be 12 mm. The AET exceeded precipitation by July 19 and accumulated to 312 mm by October 23 creating a water deficit for the summer months. Average daily AET rates measured by the Bowen station ranged from 2.6 mm/day in July to 1.2 mm/day in October.

A comparison of the estimated and measured changes in soil storage was quite diagnostic in differentiating the performance of the covers. It was found that the calculated ΔS was nearly identical at the 4 covers because the fluxes dependant on the cover (runoff, interflow, and deep percolation) were minimal in comparison to precipitation and AET. Therefore a single set of values was used to represent the calculated ΔS at all sites. These calculated values were then compared to the ΔS measured at each soil station from June 1 to October 23. Figure 6 illustrates this comparison for the 4 different covers during 2000. The similarities between the measured and calculated ΔS values are exceptional for 2000 with some variation in July and August and again in late September. Soil storage begins to decrease rapidly in June as the growth of vegetation develops AET values of 2.5 mm /day. The large rainfall in June (28 mm) appears to be captured by all the covers. The lower amount of vegetation at the thick (D3) cover explains the slower rate of depletion of soil storage early in the summer; however, by late summer all covers have experienced a similar loss of moisture. One particular feature of note is how the thinner covers (D1 and D2) do not seem to be able to maintain elevated AET rates following rains in late August and mid September. This is likely due to the fact that the vegetation has been overstressed in these covers by late summer as a result of lack of available moisture. Although more moisture becomes available in the late summer rains, the vegetation is not immediately able to make use of this moisture. The two thicker covers seem to have enough storage to sustain vegetation throughout the drier periods of the summer.

Figure 7 illustrates changes in storage for an annual water balance. This figure highlights the significant increases in storage until late June due to snow melt and early spring rains, not seen in the previous figure. This additional moisture provides the greatest benefit in the thicker covers where there is more capacity to hold this moisture for use later in the summer.

One of the most important reasons for extending the time-frame for monitoring over several years is due to the variability of climate. Figure 8 shows the average annual and summer precipitation for the site over the last 20 years. It is important to note that the instrumentation was actually installed in 1999, the second driest year in the last 20 years of record, second only to the antecedent year. In retrospect these anomalous conditions actually helped to distinguish the performance of the various covers since they highlighted the cover performance during years of unusual moisture stress.

The monitoring data illustrated that the values of runoff and interflow are small when distributed over the total area of the covers. As a result changes in storage are approximately equal to the difference in precipitation and actual evapotranspiration.

Detailed monitoring of AET for the covers established an approximate relationship for AET equal to 0.55 of PE. Based on this relationship a simple estimate of historical summer moisture deficit can be calculated for the covers as shown in Figures 9 and 10. The available water holding capacity of the two thinnest covers, as calculated from detailed monitoring and from the industry guidelines (Leskiw 1998), were both approximately 60 to 80 mm. It is apparent that these thin covers will be at risk at regular intervals within climatic cycles. Since the recent monitoring has been coincident with one of these dry periods it is not surprising that there has been evidence of moisture stress within the thinnest covers. This evidence has included direct measurements of transpiration rates (measured in the summer of 2003 by Dr. Purdy at the University of Alberta), the frequency of wilting point suctions and water contents, and the upward movement of water from the shale overburden.

One of the most important observations has been the evolution of field saturated hydraulic conductivity (Kfs) within the cover soils over time. Although the Guelph Permeameter may not be able to define the overall hydraulic conductivity of the cover it has allowed the evolution of Kfs to be tracked with time. Figure 11 illustrates a typical set of frequency distributions for hydraulic conductivity. It illustrates how rapidly the hydraulic conductivity of the covers begins to stabilize following placement. Detailed review of this data by Meiers (2002) concluded that these changes were primarily the result of structural changes produced by freeze/thaw cycling.

Figure 12 illustrates how the value of Kfs for all of the cover soils have changed over the last 4 years. It is interesting to note the relative order of magnitudes of hydraulic conductivity. The peat layer has increased to a hydraulic conductivity in excess of 100 mm/h. In fact this supports the observation that only extremely heavy summer thunderstorms ever produce runoff and even then the runoff volumes are relatively small. In addition, the storage of infiltrating water in the peat layer also allows the percolation rate to the lower secondary to be reduced to lower values. Without this ‘store and release’ mechanism by the peat layer infiltrating waters would likely either runoff or pass through the secondary layer as preferential flow. In either case, the maximum water storage capacity of the cover would not be attained.

One of the confirmations of the evolution of hydraulic conductivity has been the response of the interflow collection system. The cumulative volume of water collected at the base of the three layered covers is illustrated in Figure 13 which shows an order of magnitude increase in the interflow volumes in each of the last 3 years. This is likely due to a combination of the increase in hydraulic conductivity of the secondary and peat layers and to the wetter climatic conditions. Although this increased volume of water moving downslope does not significantly affect the water balance, it is essential, as will be discussed below, in providing a mechanism by which salt diffusing up from the shale can be flushed from the cover.

Modelling of the prototype cover systems was conducted in order to highlight the mechanisms and soil properties which were most important in controlling the dynamics of water fluxes within the cover. The numerical model used was SOILCOVER(CANMET 1996), a coupled heat and moisture movement finite element model which links climatic evapotranspiration demand to soil response through a modified Penman formulation for evaporation and plant transpiration controlled by Leaf Area Index, root depth, and root limiting suctions (Wilson et al 1994).

Three variables were found to be most critical during the calibration exercise; the soil-water characteristic curve(SWCC), hydraulic conductivity function, and vegetation. The SWCC were based on field measurements of volumetric water content and pore-water pressure at various depths within each cover. It was found that multi-modal curve had to be used to capture the effects of soil structure on moisture retention. This was done through superimposing analytic expressions for unimodal SWCC from the literature.

The hydraulic conductivity function is difficult to measure and is generally predicted using a measured hydraulic conductivity for the saturated soil and the SWCC. In this study a set of field estimated hydraulic conductivity values were obtained using the instantaneous profile method. This was supported by measurements of the hydraulic conductivity at 0.5 and 1.0 kPa during the summers of 2000 and 2001 using a Guelph permeameter. This data was used to estimate the hydraulic conductivity function using existing analytic methods. This function was then compared to the hydraulic conductivity data set obtained using the instantaneous profile method.

Green foxtail was the predominant vegetation found on the three prototype covers during the summer of 2000. Typical values of germination conditions, emergence, root depth growth rate and the end of growing season were taken from the literature. The leaf area index was estimated from field measurements. Figure 14 shows the measured and computed change in storage within the D1 cover and comparison to the field monitoring data.

Summary Comments on Water Fluxes

The study demonstrated that the annual water balance is dominated by snowmelt infiltration and runoff in the spring and evapotranspiration over the summer. It appears that all the prototype covers perform well in years of average precipitation, but in years with limiting precipitation, the thinnest layered cover of 35 cm may have limiting moisture storage.

Both the field data and numerical simulations highlight the key role of cover layering on maintaining sufficient volumes of stored water for summer plant use. Numerical models of coupled soil-vegetation-atmosphere moisture fluxes can be used to simulate the performance of these covers in one-dimension if key parameters can be calibrated to field measurements. The detailed monitoring of moisture movement within the cover system along with the modelling of the dynamics of moisture movement in response to climatic forcing has helped to establish the central role played by layering of the covers. The high hydraulic conductivity and storage capacity of the surface peat layer minimizes runoff and maximizes water storage, not only in the peat, but also in the secondary as the peat stores high intensity rainfalls and subsequently re-releases this water slowly into the matrix of the secondary.

The increase in hydraulic conductivity within the cover materials evolves quite rapidly over time, reaching a stable level within 3 to 5 years of placement. This increase in hydraulic conductivity has encouraged the development of a sustained flow of interflow waters downslope, particularly in the thickest cover.

The monitoring program has also demonstrated that a reliable, robust set of instrumentation to track soil moisture can be constructed and maintained over the time frame required by industry.

Salt Fluxes

The geochemical results suggest that the accumulation of salts below the cover/shale interface (1 to 2 m below ground surface) is the result of oxidation occurring within the shallow soil zone. Detailed measurements of pore-gas along cover and shale profile indicate that the greatest O_2 and

CO_2 concentration gradients exist between 0 and 3 m depth. O_2 decreases from atmospheric (20.9 %) to less than 4 % and CO_2 increases from atmospheric (0.04 %) to 4 % within this zone. These results suggest that the primary zone of O_2 consumption and CO_2 production lies between 0 and 3 m depth. The $\delta^{13}C_{CO2}$ data indicates that the soil CO_2 in the shallow zone (0 to 3 m) was derived primarily from an inorganic carbon source (i.e. carbonate dissolution). Electron microprobe analysis indicate the co-existence of pyrite and iron oxide between 0 and 3 m which supports the presence of an oxidizing environment. This is also supported by elevated sulphate concentrations between 1 and 2.5 m into the shale. The CEC analysis of soil samples revealed that below 5 m depth Na was the dominant exchangeable cation, but in samples collected between 1.4 and 4.8 m, the exchangeable Ca was measured to be greater than or equal to Na concentration. The difference in the exchangeable cation distribution between the shallow (0 to 5 m) and deep (3 m to 25 m) profiles points towards salt exchange reactions occurring between 0 and 5 m depth.

The chemistry of soil samples taken from the sampling transects confirms that the salinity at the overburden-cover interface is dominated by sodium and sulphate, consistent with the oxidation of pyrite (Figure 15). Statistical analysis shows that the deeper shale material (>3m below the surface) is significantly less loaded in total dissolved solids than the shale near the cover interface. Although each of the prototype covers, regardless of the prescription, presents noticeably increased levels of total dissolved solids in the two 10-cm layers immediately above the interface, statistical analysis has shown that the mean salt concentrations in the shallow covers(35 and 50 cm) correspond to the upper acceptable limit for salinity expressed as electrical conductivity, while the concentrations for the thicker covers place well within the acceptable salinity range for vegetation.

An ongoing study is looking at the mechanisms for transport of the elevated sulphate concentrations released as a result of shale oxidation however preliminary observations of the increased salinity levels immediately above the interface suggests that diffusion is an important mechanism for 1-dimensional salt redistribution, as illustrated in Figure 16.

The upward diffusion of salts results in the ‘loss’ of the lower portion of the covers as a result of elevated salt and sodicity levels. A diffusive process in the absence of any net ‘flushing’ of the salts as a result of deep percolation or interflow will eventually allow this diffusive halo to expand resulting in salinization of the cover.

This upward diffusion can be countered by deep percolation through the shale or through lateral flushing as a result of interflow. The accelerating rates of interflow were illustrated previously in Figure 13. Figure 17 illustrates how these increased rates of interflow have also been accompanied by elevated rates of salt flushing as the speciation of the interflow salts have changed from Ca-$HC0_3$ waters to water dominated by Na-$S0_4$.

In attempt to illustrate the significance of flushing as a result of interflow a simple model was developed. The model is based on diffusion or diffusion advection across the cover/shale interface in response to an elevated concentration of sulphate in the shale. The model assumed a 1 meter depth of cover over 1 meter of sulphate rich shale. The initial concentration in the shale was varied until a reasonable match to the measured soil chemistry was obtained; however this value was found to be consistent with the results from the geochemical study. The advection rates considered were zero advection (diffusion alone), an upward water flux equal to 1% of the annual precipitation, and downward fluxes of 1% or 2% annual precipitation. The water fluxes were assumed to be steady with time. The soils were considered to have a volumetric water content of 0.25 and a coefficient of diffusion of 2e-10 m^2/s.

The simulation was used to estimate the flux across the cover/shale interface with time. These flux rates were the plotted (Figure 18) alongside the measured flux rates from direct sampling of the cover. These were assumed to have developed by diffusion over a 4 year period. The flux rates collected by the interflow system are also plotted. It was assumed that that the salt loading collected by the interflow was from the entire 1 ha area of the covers.

The model clearly illustrates that sulphate will build up in the cover as a result of diffusion from the shale surface; however, the flux rate into the cover as a result of diffusion will decrease with time. The release rates currently collected by the interflow system are accounting for only about 1% of this salt flux. Successful long-term balance of salt release will require that the release through the interflow system will have to continue to increase or deep percolation into the shale surface (shown by diffusion with 1% infiltration curve) will have to occur.

Summary Comments on Salt Fluxes

The shale immediately below the covers are oxidizing, consuming oxygen and releasing elevated concentrations of various salts. The rate of oxygen consumption and $C0_2$ release are still to be quantified. The geochemistry has demonstrated that the problem of salt release to the cover from the shale is aggravated by the elevated sulphate loadings produced by pyrite oxidation. The field monitoring has demonstrated that multi-dimensional moisture and salt movement is occurring in the covers and although the rates of lateral water movement are not large relative to the water balance they are responsible for the flushing of salts from the cover.

The time to establish some form of stable salt flux from the covers is likely to take more than a decade or more. In the interim the deeper layered covers are expected to perform better for several reasons. First, their greater thickness can accommodate a greater ‘loss’ of effective cover depth due to salinization while still providing for adequate water holding capacity for vegetation. In addition, they are more likely to allow for a water surplus which can be carried along as interflow or deep percolation. Finally, they are more likely to maintain high water contents, and hence, lower oxygen diffusion rates near the shale/cover interface, thereby potentially limiting the rate of sulphide oxidation.

TECHNOLOGY TRANSFER / STUDY INTEGRATION

One of the ‘soft’ research methods that has been very successful is Syncrude’s commitment to host Watershed Research Team meetings. These meetings occur twice each year, a summer meeting on site and a winter meeting in a conference setting. Presentations allow the students present their research results in a supportive and hopefully friendly environment while obtaining invaluable critique and advice from researchers in other disciplines. The summer meeting occurs as a mobile workshop as participants are driven by bus to the various study sites. At each site the principle investigator or student highlights the key aspects of the study. Valuable technology transfer occurs through innumerable conversations on site, in the buses, and at various lunch or supper gatherings and equally important, a sense of ‘team’ is built among the various investigators.

Ongoing technology transfer does not only occur between researchers, it also occurs between the research team and the company or industry. Researchers are frequently invited to present their results to operations departments of the company or at industry wide venues. These presentations not only highlight Syncrude’s contribution to solving reclamation problems, they also help to provide an understanding of the key findings of the research to regulators and other oil-sands companies so that they can work more effectively with Syncrude. Presentations of this type include presentations to industry wide research working groups and various Syncrude departments and their Technical Review Panel.

CONCLUSIONS AND FUTURE STUDIES

The program to date has identified a variety of reliable methods for monitoring the various components of a one dimensional water balance. This water balance indicates that the annual water balance is dominated by snow melt infiltration and runoff in the spring and by evapotranspiration in the summer. Plant growth and ecosystem community development and subsequent changes in water use will have a substantial impact on the over all water balance as the landscape develops.

Field observations were used to calibrate a one dimensional SoilCover model which clearly demonstrated the importance of layering the soil caps. Layered caps were identified as essential to maintain sufficient stored water for plant use through the growing season, with the surface peat layer serving a critical function in storing rain during high precipitation events and then slowly releasing it into the deeper profile, providing for a more even supply of moisture for plant use while promoting the downward flushing of salts from within the soil matrix that may have moved up from the underlying shale. The monitoring of the water balance also revealed that in dry years, the thinner cap (35cm) was unable to store sufficient moisture to prevent the soil from reaching permanent wilting point for a significant portion of the season. The Guelph permeameter study and the interflow collection volumes tracked the rapid evolution of the hydraulic properties of the covers within a period of approximately 3 to 5 years following cover placement.

The geochemistry studies have established that elevated levels of salt loading will be created near the shale surface as a result of oxidation of disseminated framboidal pyrite in the marine shales. Salt distributions in the covers revealed that while salt is moving into the covers, the mechanism is primarily diffusive. The salt flux rates from the mechanism should diminish with time as the concentration gradients decrease. Salt flushing is occurring as a result of interflow along the cover/shale and may also be occurring as a result of deep percolation. Current estimates of salt release through interflow are only approximately 1% of the current diffusive flux rates.

Because of the fundamental nature of this work, the results have application for all operators reclaiming boreal forest. The far-ranging implications of the studies are recognized by the regulators and Syncrude’s stakeholders in the region. As such, the results have been incorporated into industry guidelines/manuals, which serve to regulate reclamation in the boreal forest of Alberta. Two specific examples are:

- Water balance - In situ moisture characteristic curves, hydraulic conductivity and soil chemistry data are being incorporated directly into ‘The Land Capability Classification System for Forest Ecosystems’, which is the government issued manual for soil reclamation in the Oil Sands Region.
- Data and publications from the research programs comprise the background documentation for the Landform design Guidelines for the Oil Sand Region

Syncrude sees this research as essential in helping optimize landscape designs and reclamation activities as well as to significantly improve their ability to consistently obtain reclamation certification.

The fundamental reaction chemistry of overburden materials, as defined from the geochemistry study, is already being used in the design of future sulphur containment systems. The long storage of elemental sulphur is Syncrude's single biggest source of liability.

Syncrude's vision for the watersheds is that in the fist 8 to 10 years detailed instrumentation and monitoring will be undertaken to obtain the answers for the "Big Questions", those being: 1) water and energy balances (*capital and circulation rates*); 2) salt balances, including inorganics, organics, ions, nutrients, metals (*capital and circulation rates);* 3) plant and ecological responses to 1) and 2) and finally, 4) how to manage these balances optimally, that is, identification of optimal reclamation techniques. As critical processes and patterns within each of the watersheds are identified during the research, what constitutes *sufficient* monitoring can also be defined. As the research component winds down, operational monitoring of these critical parameters and patterns winds up, thereby helping to write the "biography" of each landform necessary for certification.

EPILOGUE

This initial three year study has been followed by an expanded multi-disciplinary study jointly funded by SCL and the National Sciences and Engineering Research Council (NSERC). This study encompassed a group eight researchers in the fields of Civil Engineering, Geology, Geography and Soil Science. The global objective of this integrated program is to characterize the unique hydrologic/hydrogeologic system that will develop in reclaimed overburden structures from oilsands mining through a multi-disciplinary research approach to define the salt and water balance within the newly created landscape.

The individual elements of this program include the following:

- ***Quantifying Geochemical Reactions in Mine Waste Piles (Dr. Hendry)*** The objective of this study is to quantify present day geochemical reaction rates including type, depth of occurrence and production rates taking place in the saline-sodic overburden. These production rates are then to be used to estimate the future salt loading to the watershed.
- ***Measurement and Modelling of Evapotranspiration (Dr. Carey)*** This study will define the spatial variability of evapotranspiration over the WBH through the use of three eddy-covariance sites and develop tools for estimating atmospheric fluxes from the landscape which can then be incorporated into a number of the other studies.
- ***Hydrogeology of South Bison Hill (Dr. Barbour)*** The primary objective of this study is to determine the hydrogeologic foundation of WBH by investigating the factors controlling the evolution of the hydrogeologic system. Using this information, an interpretive model of this system will be created.
- ***Impact of Cover Geomorphology on Water and Salt Transport (Dr. Barbour)*** The objective of this study is to investigate mechanisms controlling downslope migration of salt and water in response to climatic and vegetation forcing. focusing particularly on the role of the macro and micro topography within the landscape.

- ***Salt Profiling and Redistribution with Soil Covers (Dr. Mermut)*** This study will continue previous work on mapping the distribution of salts across the cover and across the hill slope.
- ***Watershed Modelling of South Bison Hill (Dr. Elshorbagy and Dr. van der Kamp)*** A central point of integration for this study is to develop an appropriate watershed model to account for the water balance of the South Bison Hill. The model and the resulting water balance will play a major role in evaluating the intra-annual as well as the inter-annual hydrologic performance of the covers.
- ***Impact of Multi-dimensional Preferential Flow and Interflow on Salt Leaching (Dr. Si)*** The objective of this study is to characterize local preferential flow through layered soil covers with the use of tracer testing.
- ***Structure Evaluation by Guelph Permeameter Testing (Dr. Barbour)*** The main objective of this project is to continue to track the evolution of the hydraulic conductivity of the cover materials and shale while developing a more rapid means of estimating hydraulic conductivity through the use of an air permeability testing method.

ACKNOWLEDGEMENTS

The authors would like to acknowledge financial support the National Sciences and Engineering Research Council in co-sponsoring this research. The continuing financial, logistical, and moral support of Syncrude is also gratefully acknowledged. Special thanks must go to the contributions of graduate students and research staff, without which none of this work would have been ever been completed. Any ‘success’ in the development of an ‘instrumented’ watershed is due primarily to them. Thanks Cal, Rob, Sophie, Dale, Denise, Greg, Marty, Curtis, and Sue.

REFERENCES:

Alberta Environmental Protection, 1994. A Guide for Oil Production Sites, Pursuant to the Environmental Protection and Enhancement Act and Regulations. ALberta Environmental Protection, Land Reclamation Division, Edmonton, AB (Code of Practice 1997).

Barbour, S.L., Boese, C., and Stolte., B. (2001). Water balance for reclamation covers on oilsands mining overburden piles. 2001 Canadian Geotechnical Conference, Calgary, Canadian Geotechnical Society, pp. 313-319. (NSERC-Syncrude CRD)

CANMET. 1996. SoilCover User's Manual Version 2.0, MEND 1.25.1.

Leskiw 1998. LCCS reference

Leskiw, L. A., Yarmuch, M. S., and Moskal, T. D., 1999. Reclaimed Soils Related to the Syncrude Capping Study. Prepared for Syncrude Canada Inc. by Can-Ag Enterprises Ltd, July.

Meiers, G.P. 2002. "The Use of Field Measurements of Hydraulic Conductivity to Characterize the Performance of Reclamation Covers with Time. M. Eng. Thesis. Department of Environmental Engineering, University of Saskatchewan, Saskatoon, SK., May.

Reynolds, W.D. 1993. Saturated hydraulic conductivity field measurements, in M. R. Carter, ed. Soil Sampling and Methods of analysis, Canadian Society of Soil Science, 56:599-605.

Stolte, W.J., Barbour, S.L., and Boese, C.D. 2000. Reclamation of Saline-Sodic Waste Dumps Associated with the Oilsands Industry. Canadian Land Reclamation Conference, September, Edmonton, Canadian Land Reclamation Association. (published as a CD) (NSERC-Syncrude CRD)

Wilson, G.W., Fredlund, D.G. and Barbour, S.L. 1994. Coupled Soil-Atmosphere Modelling for Soil Evaporation, Canadian Geotechnical Journal, 31(2), pp. 151-161.

TABLES AND FIGURES:

Table 1 – Summary of Site Instrumentation and Measurements

Measurement	***Method***	***Start Date***
Soil Stations • Water Content • Suction • Temperature	• Frequency Domain Reflectometry (Campbell Scientific), Neutron Probe and Diviner 2000 (Sentek) • Thermal Conductivity Sensor (Campbell Scientific and University of Saskatchewan) plus Tensiometers as field check during summer • Temperature (Campbell Scientific and TCS)	• Stations installed Summer 1999 • Neturon access tubes installed summer 1999. • Diviner 2000 access tube transects August 2001; Upslope of Peat Pond in May 2002 • Deep neutron access tube July 2002 • Soil stations pumped out and repaired July 2003 • Additional top climate and soil station installed in July 2001 following cover placement
In situ Hydraulic Conductivity	• Transects and profiles of Guelph Permeameter • Frozen Ground Infiltration Rings	• Guelph – summer 2001, 2002, 2003 • Frozen ground infiltration rings installed October 2001; measured spring/summer 2002 & 2003
Interflow	• Interflow Collection System • Saturated Wedge Pipes (SWP)	• Inteflow system installed summer 2000; 1st pumped in spring 2001, barrel replacement August 2001; measurements ongoing • SWP – 1st row installed June 2001; 2nd row in May 2002
Runoff	Weirs	• Four weirs installed in cover swale October 1999. • D3 heated shed installed March 2001, replaced October 2003 • D1 and D2 sheds installed October 2001 • Peat Pond inlet weir installed in October 2001, outlet weir October 2002 • Golden Pond weir installed November 2003.
Soil Sampling	• Water content, density, chemistry	• May & August 2001, Summer 2002 programs
Meterology	• Climate station (RH, windspeed, precipitation, net radiation, temperature)and Bowen Ratio Station (Campbell Scientific), Pan Evaporation	• Initially installed mid slope of covers Summer 1999; Bowen Ratio station set up for summers only since 1999; new climate station at top of dump in July 2001
Snow Survey	• Snow depth and soil water equivalent through annual snow survey	• Anuualy done in February since 2000 • Exhaustive survey done March 2004
Surface Ponds	• Leakage – seepage meters, staff gauges, samples for chemistry	• Bill's Lake, Bison Lake begun summer 2000, Peat Pond 2001, Golden Pond 2003
Vegetation	• Sampling for Leaf Area Index, Biomass, root depth, and plant transpiration rates	• One time summer programs
Hydrogeology	• Transects of deep standpipe piezometers	• Two nests installed October 1999 • Six nests installed spring 2000 • Three additional nests installed in October 2003
Shale Geochemistry	• Gas sampling profiles, deep neutron probe, and shallow Diviner 2000	•
Geophysics	• EM31, EM38, ERT	•

Figure 1 Air photo of Wood Bison Hills and study locations

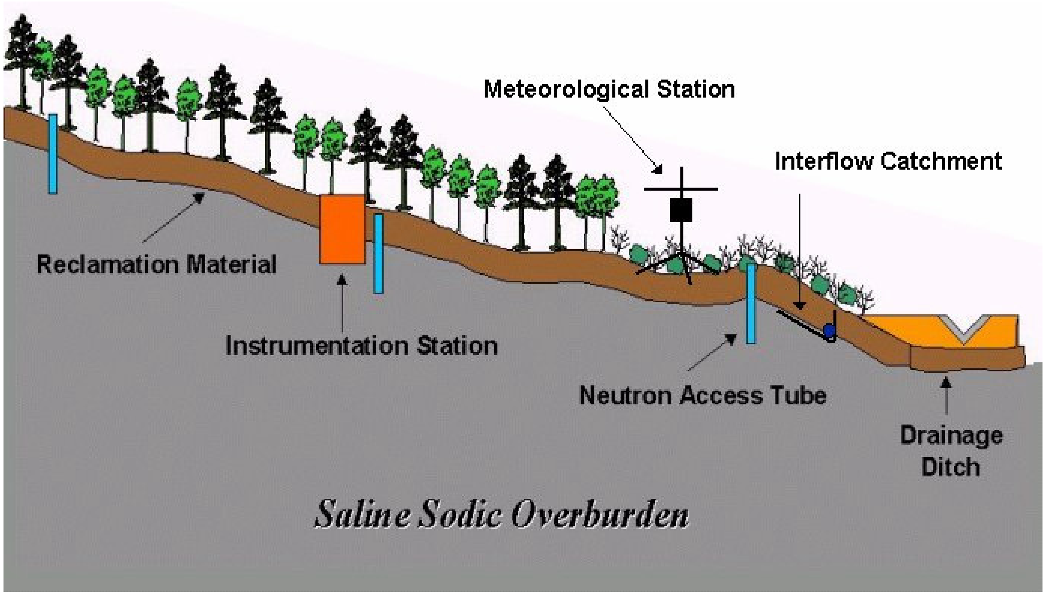


Figure 2 Cross-section of field instrumentation

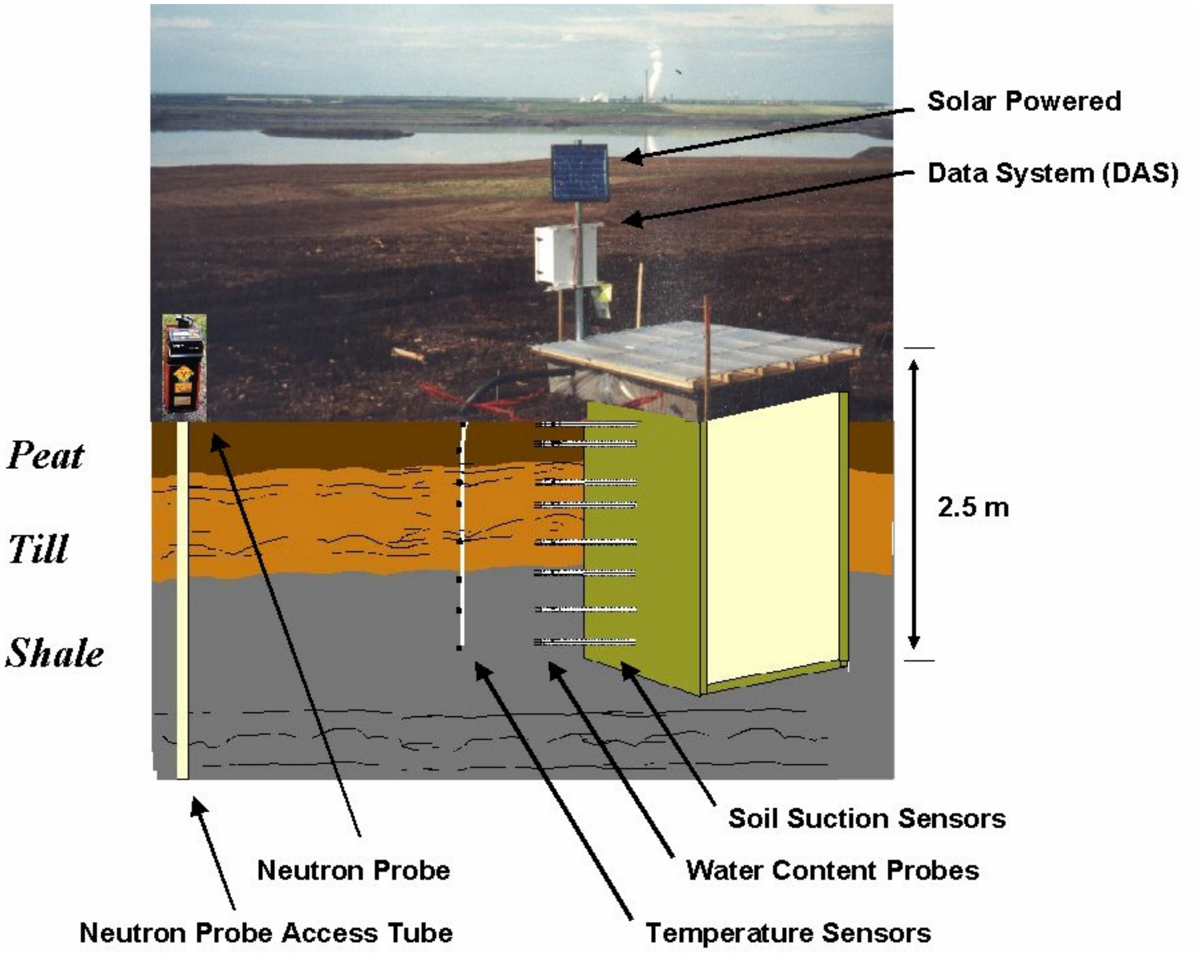
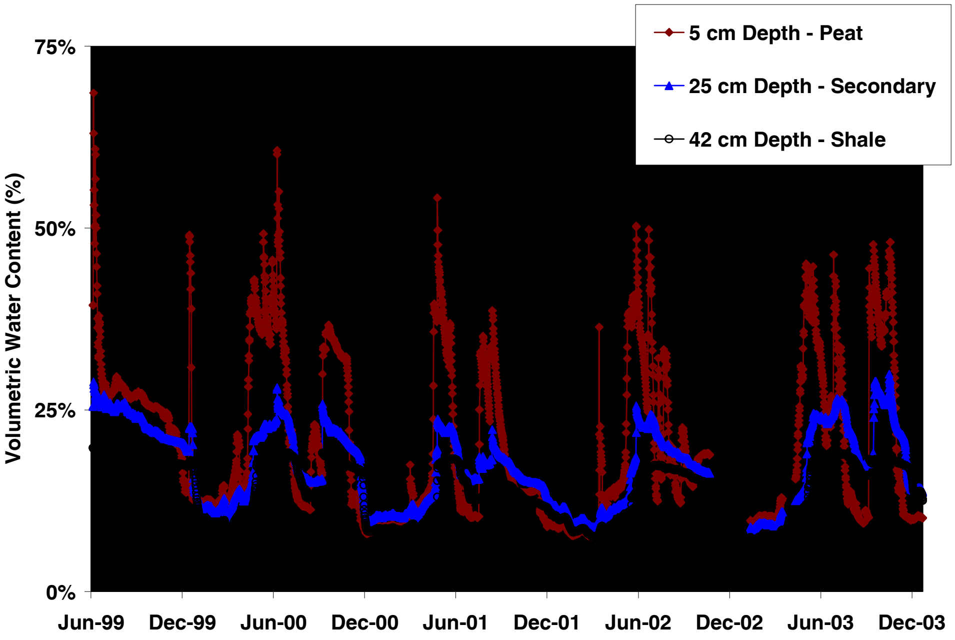
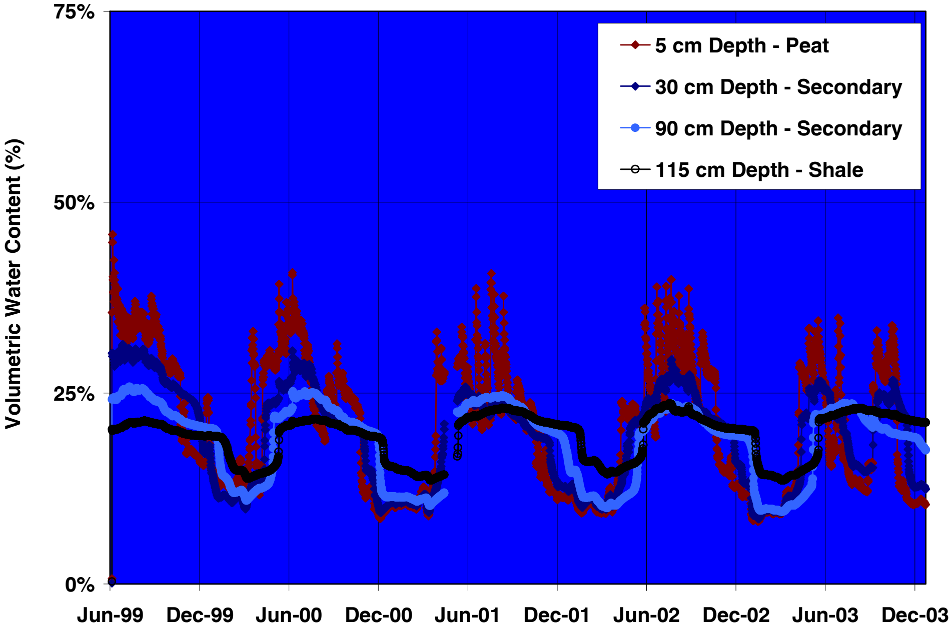


Figure 3 Location of soil sensors



a) 35 cm Layered Cover (D2)



a) 100 cm Layered Cover (D3)

Figure 4 Volumetric water contents with 35 cm and 100 cm layered covers with time (Note sensor readings are not reliable in frozen ground - generally November through April)

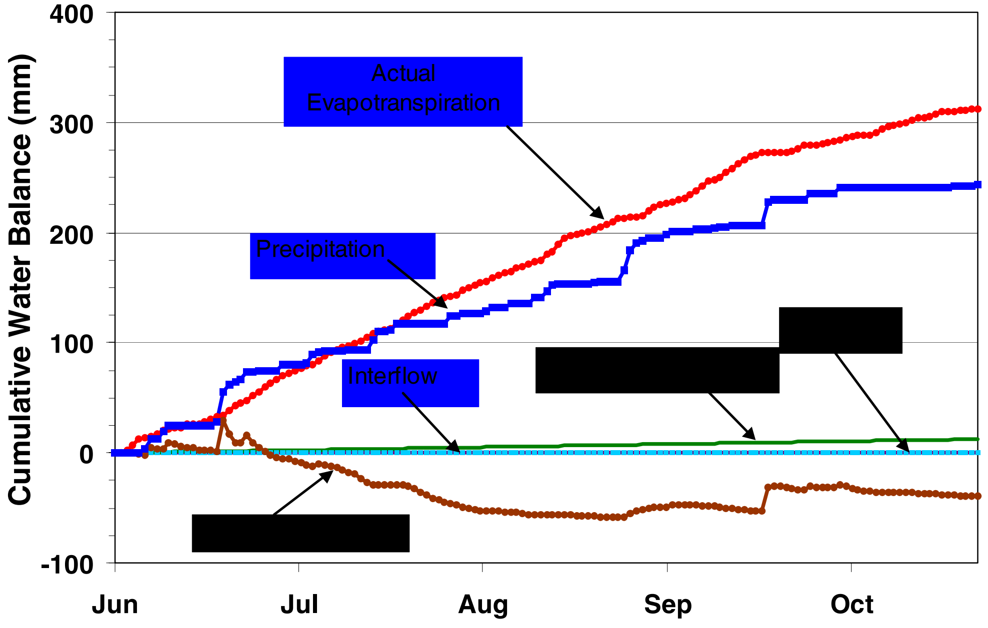


Figure 5 Cumulative water balance for the D2 cover for the summer of 2000

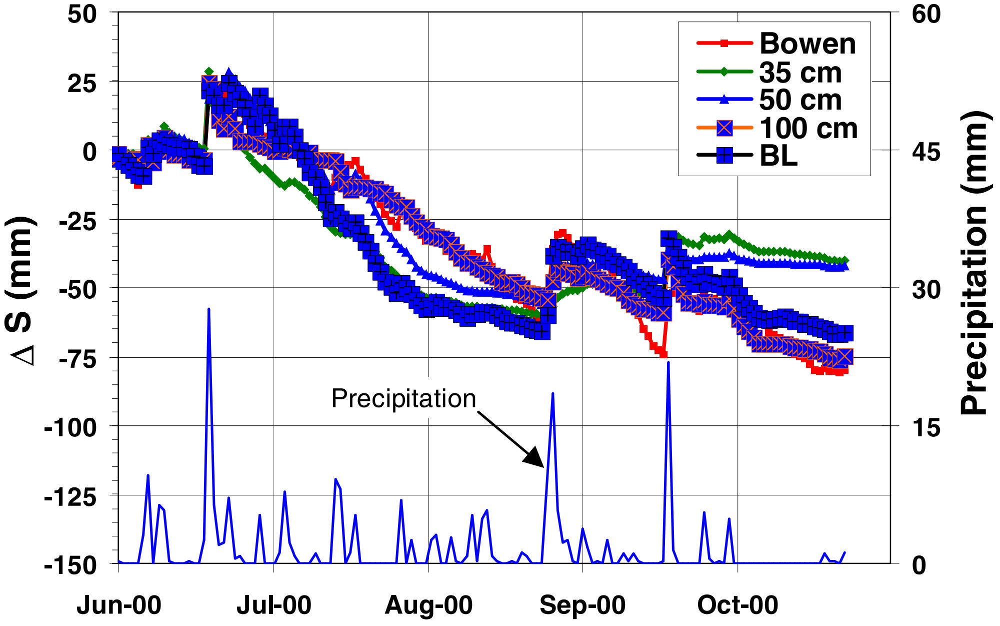


Figure 6   Increase in storage summary for the 2000 summer water balance

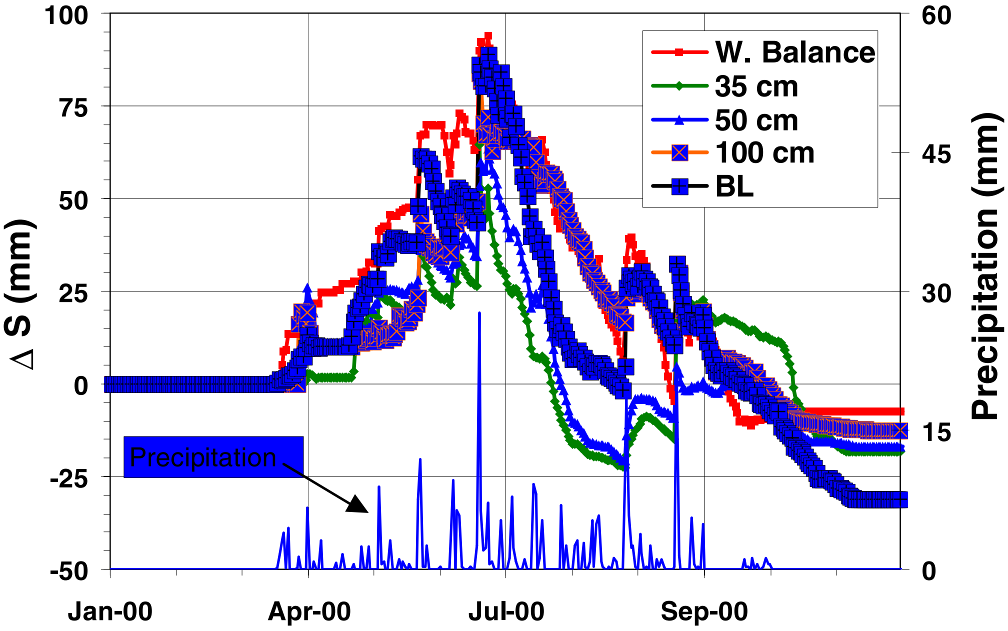


Figure 7 Cumulative water balance for the D2 cover for the year 2000

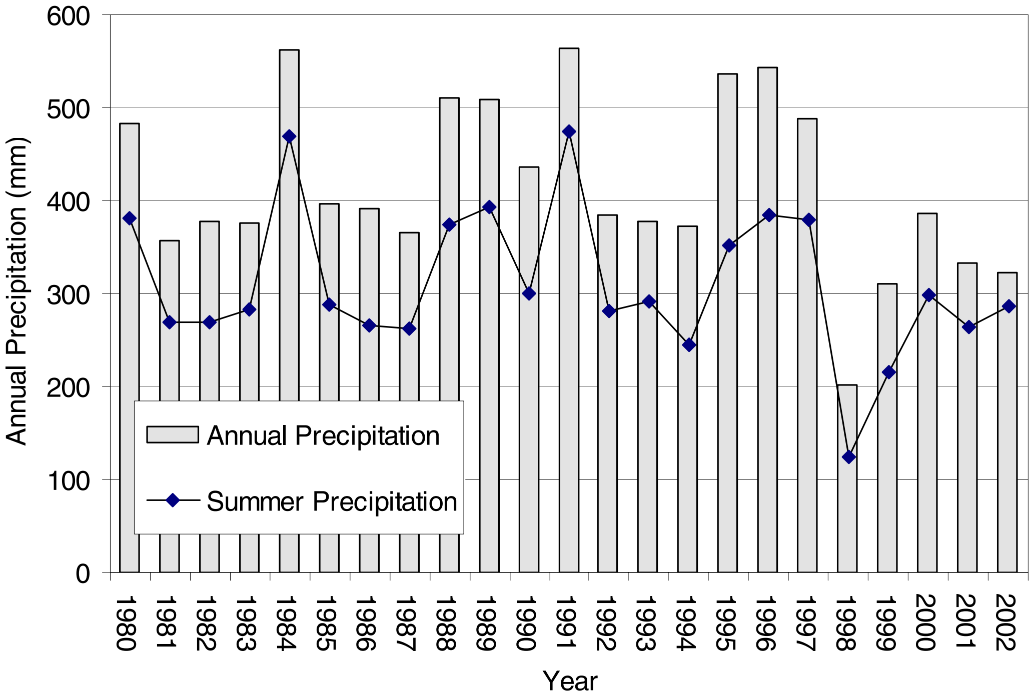


Figure 8 Historical precipitation data for study site

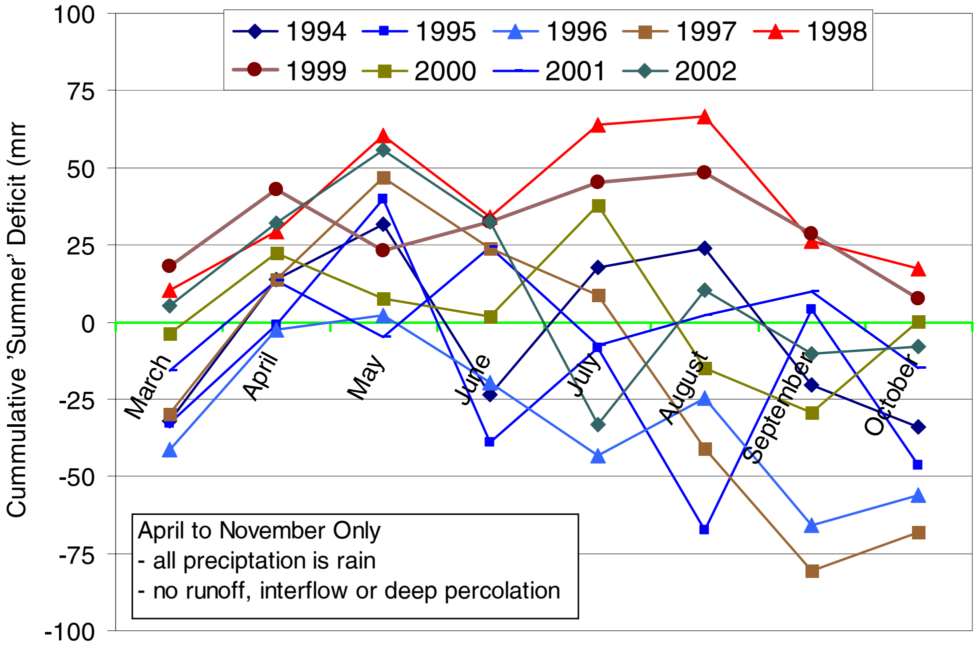


Figure 9 Cumulative moisture deficit based on historical precipitation and potential evaporation

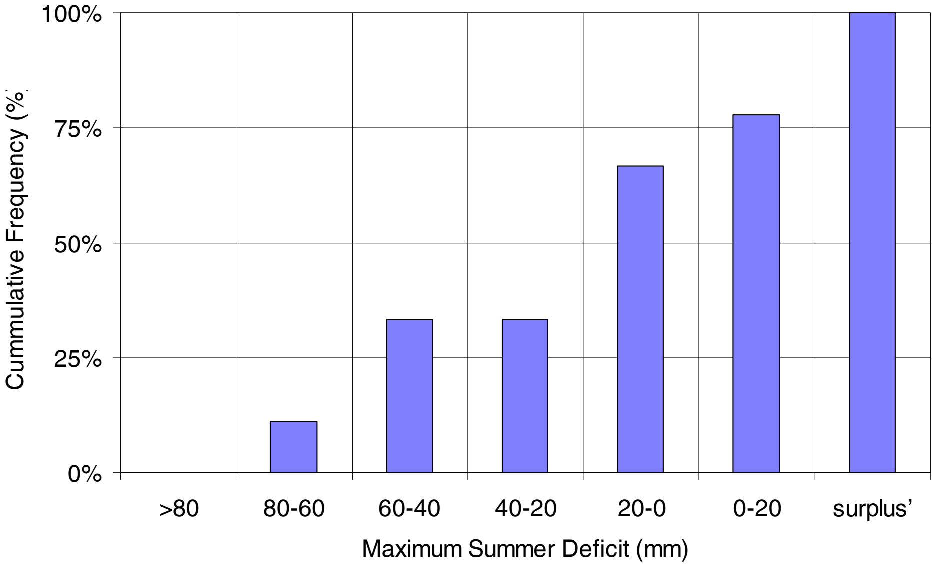


Figure 10 Cumulative frequency for maximum moisture deficit

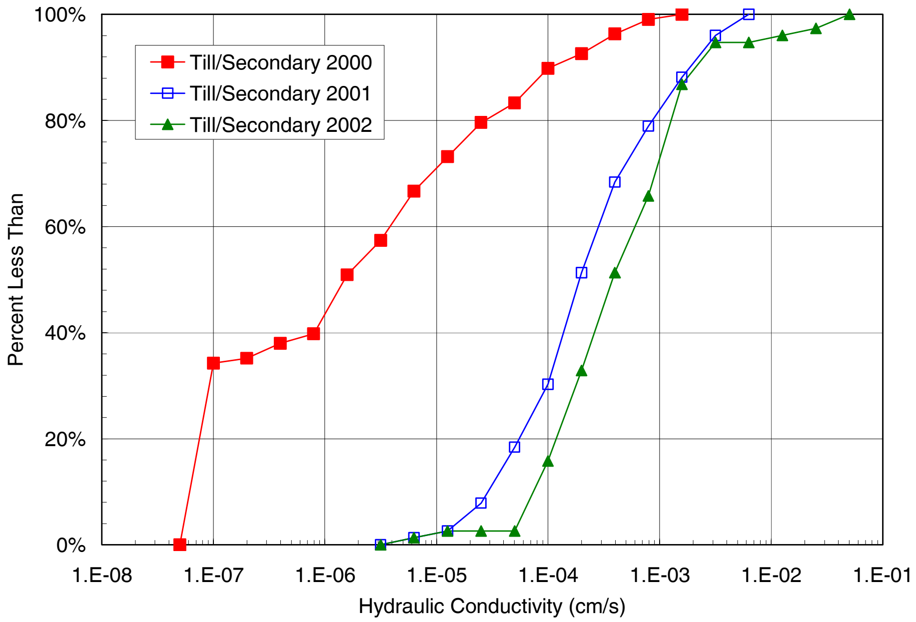


Figure 11 Hydraulic conductivity distribution for Till Secondary measured using Guelph Permeameter (Meiers 2002)

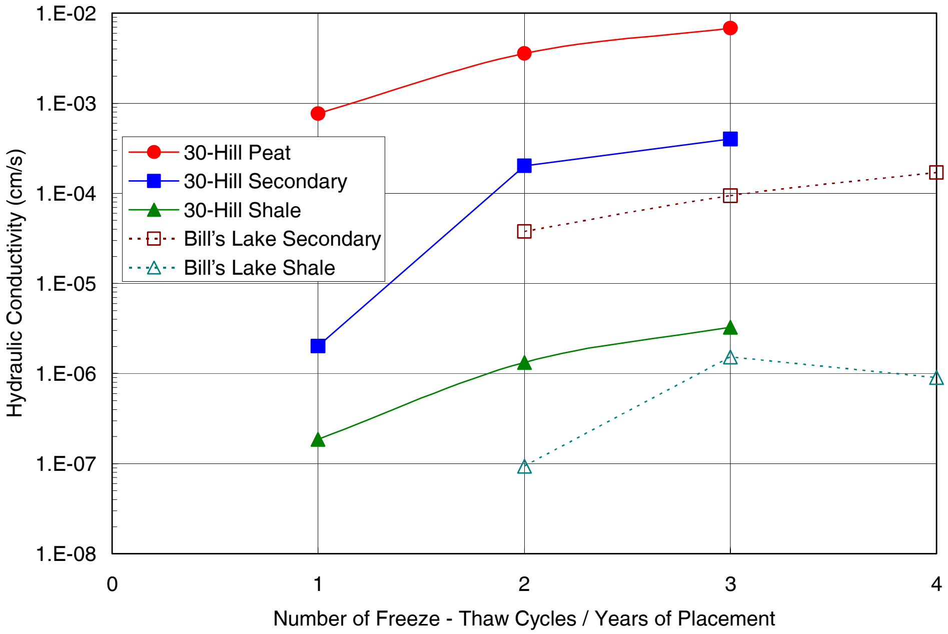


Figure 12 Hydraulic conductivity changes with time in cover soils as measured using Guelph Permeameter (Meiers 2002)

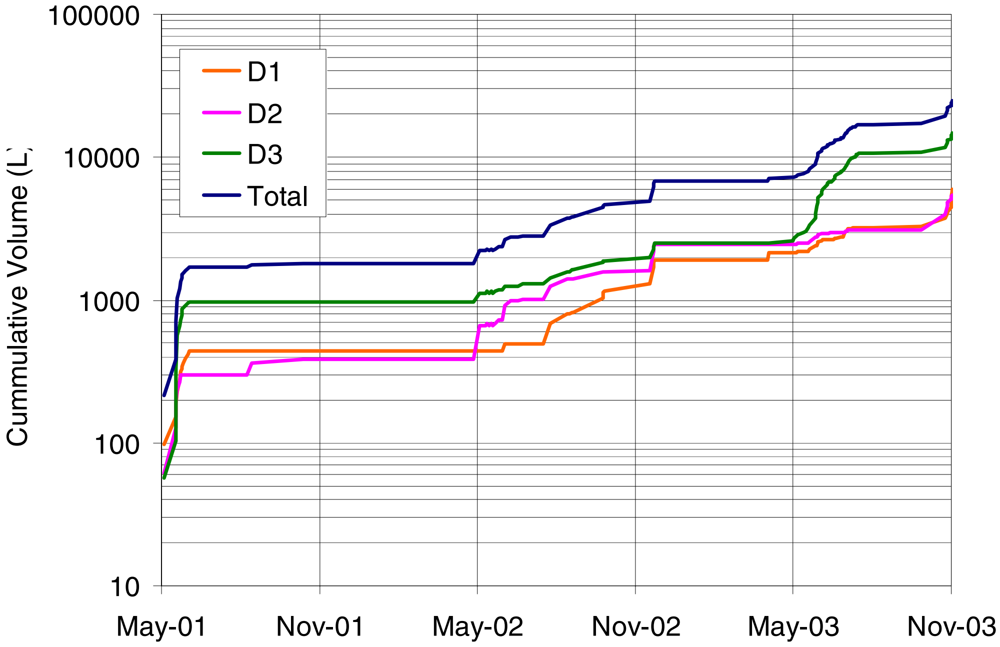


Figure 13 Cumulative volume of water collected in interflow collection system

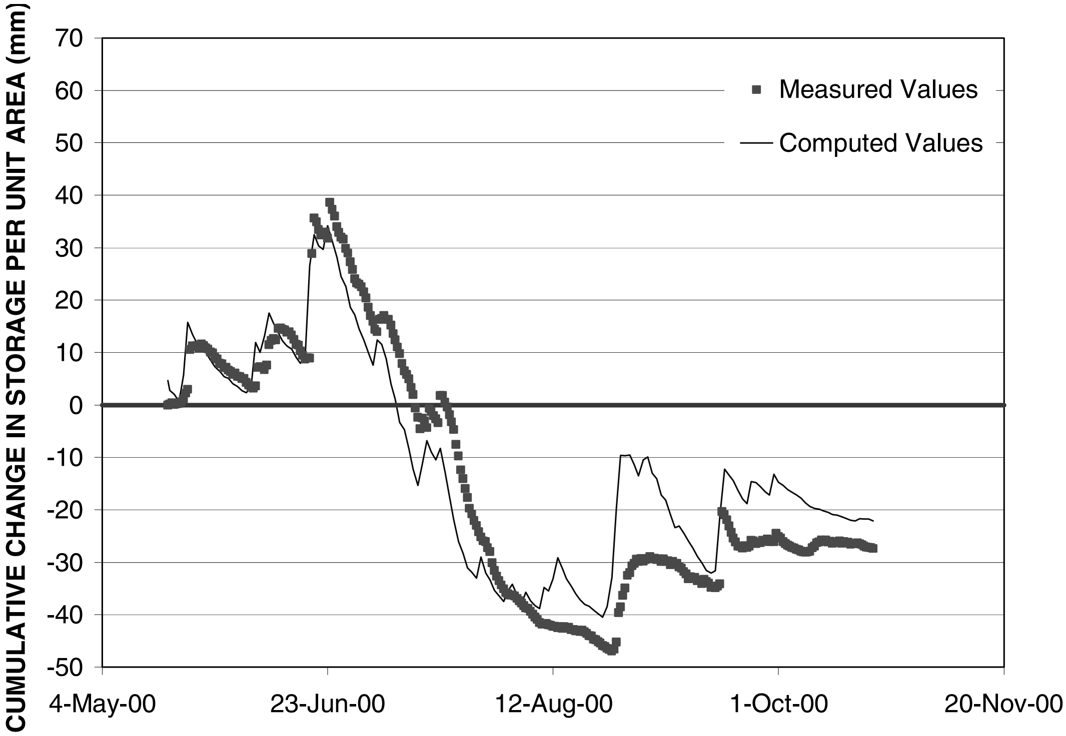
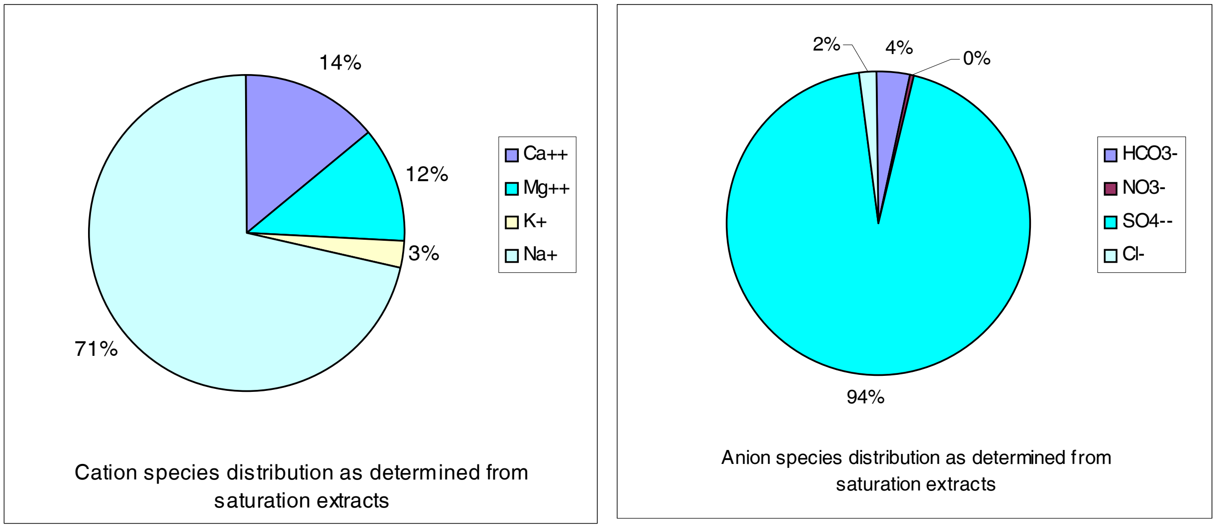


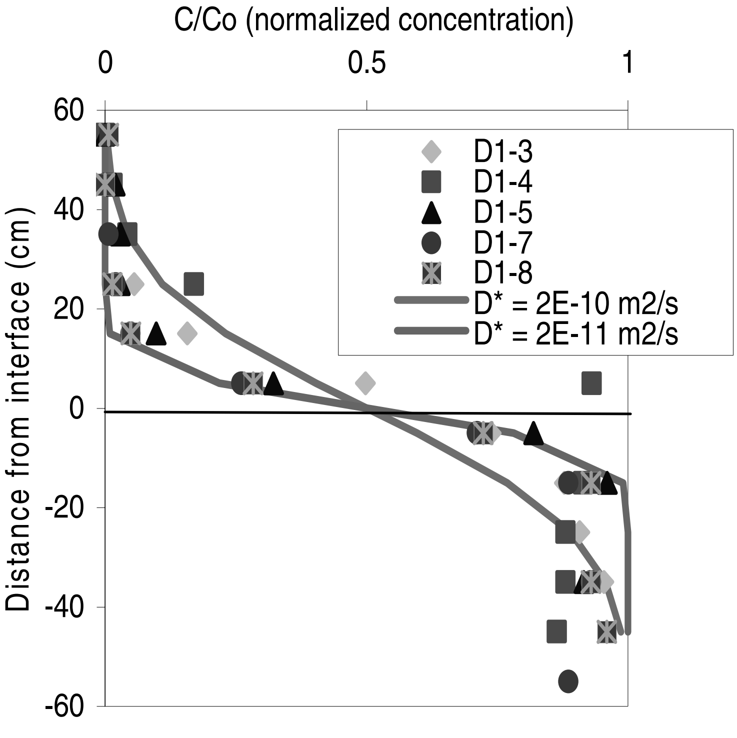
Figure 14 Total cumulative change in storage per unit area for the D1 cover



Cation species distribution as determined from saturation extracts

Anion species distribution as determined from saturation extracts

Figure 15 Distribution of major ions in the subsoil-topsoil system, as determined from saturation extracts



Diffusion profiles for sulfate ion in 50 cm cover

Figure 16 Diffusion profiles and normalized salt concentrations within D1(50 cm) cover profiles

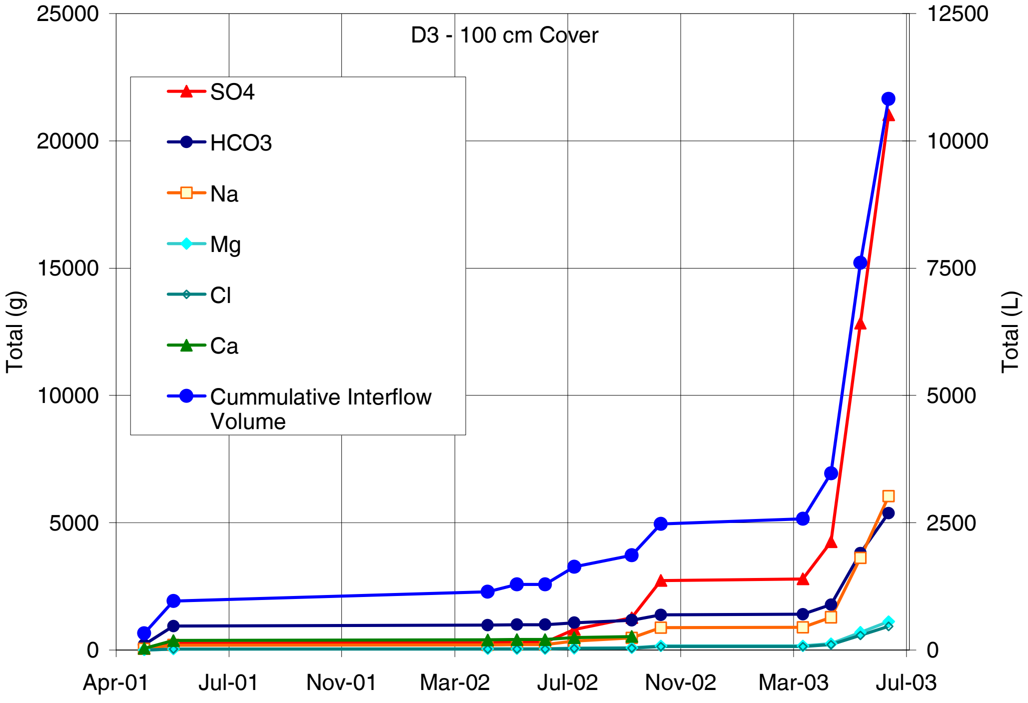


Figure 17 Interflow collection volumes and accompanying salt loading

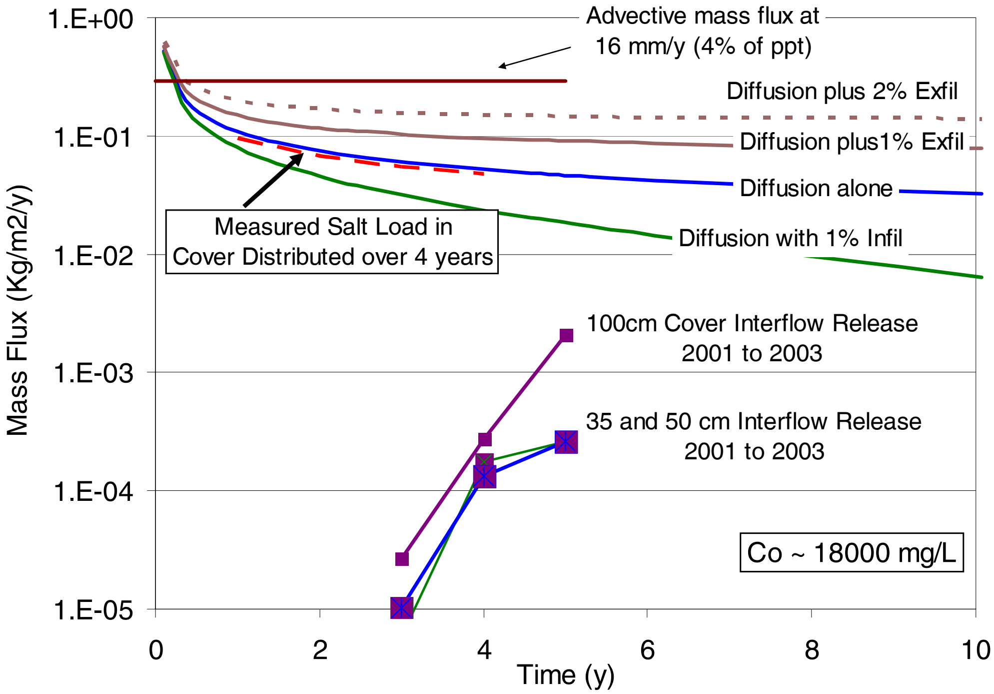


Figure 18 Measured and simulated sulphate fluxes within the cover with time