Probabilistic Approach for Design and Hydrologic Performance Assessment of Reconstructed Watersheds

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Abstract: The oil sands mining industry in Canada has made a commitment to reclaim mining areas to an equivalent capability to that which existed prior to mining. An essential requirement in the design of reclamation covers to meet this objective is that all covers must have a sufficient available water holding capacity (AWHC) in order to supply sufficient moisture for vegetation over the summer moisture deficit typical in the region. AWHC is currently based on static evaluations of wilting point and field capacity under a constant annual evapotranspiration demand. This paper presents an alternative probabilistic approach by which the hydrologic performance of these reclamation soil covers can be assessed. A field-calibrated water balance model is used along with the available historical meteorological record to estimate the maximum soil moisture deficit that a soil cover is able to sustain over the growing season. Frequency curves of the maximum annual moisture deficit are used to assess the probability that a cover is able to provide any particular threshold of moisture demand. The method also allows for a quantification of the predictive uncertainty of the model. The predictive uncertainty is used as a margin of safety to estimate a design value of moisture deficit for various alternative cover designs. This paper recommends procedures for a frequency-based assessment and design of reclamation soil covers in the oil sands industry. This method takes into account climatic variability as well as parameter uncertainty in estimating the soil moisture deficit.

DOI: 10.1061/(ASCE)1090-0241(2007)133:9(1110)

CE Database subject headings: Land reclamation; Water balance; Hydrologic models; Probabilistic models; Canada; Watershed management.

Introduction

The oil sands of northern Alberta, Canada, are mined in large open pits extending to nearly 100 m in depth, with many mines disturbing more than 100 km^2 of the natural environment. Reclamation in these cases requires that entire landforms and drainage systems be reconstructed from mine overburden. These new landforms are then covered with soil layers designed to replicate the performance of the natural A, B, and C soil horizons. The oil sands industry has committed to reconstructing functioning landscapes that reproduce the various functions of natural watersheds, such as habitat function (hosting aquatic ecosystems), production function (e.g., biomass), and carrier function (for dissolved and suspended material). The carrier function plays a central role in land degradation processes such as erosion, sedimentation, and the leaching of salts through moving surface and subsurface water (Falkenmark 1997). The restoration of the above-mentioned functions relies first and foremost on the restoration of functioning hydrologic systems, a central feature of which is sufficient water to sustain revegetation efforts (Qualizza et al. 2004).

The mining of oil sands at Syncrude Canada's Mildred Lake Mine near Fort McMurray, Alberta, involves the stripping and salvage of surficial peat and glacial soils followed by removal of the saline/sodic overburden in order to gain access to the oil-bearing Fort McMurray formation. The overburden is placed in mined out pits or as large surface dumps that are then recontoured before being capped with a soil cover.

The selection of the thickness and texture for the cover layers is based primarily on the production function of the watershed. Currently, alternative soil cover designs are subject to evaluation and classification based on the Land Capability Classification System (LCCS) for Forest Ecosystems in the Oil Sands (Leskiw 2004). The LCCS uses the available water holding capacity (AWHC) to identify the soil moisture regime required for the development of various target ecosites. The AWHC is defined as the volume of water storage within the cover as calculated from the difference between the field capacity and wilting point water contents, integrated over the depth of each cover layer to a maximum depth of 1 m. The LCCS classifies natural soils and vegetation sites into various categories of ecosites (e.g., a, b, d, and e) based on soil moisture and nutrient regimes. The sites under consideration in this paper were targeted for upland forest ("d" ecosites), and consequently have a target AWHC value of 160 mm.

The use of AWHC is similar to the concept of "store and release" or evapotranspiration (ET) covers for landfill or mine waste cover (Albright et al. 2004; Hauser et al. 2001; Khire et al. 1997, 2000). In ET covers sufficient moisture storage has to be available to store all precipitation events so that they can be sub-

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Note. Discussion open until February 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 27, 2006; approved on January 2, 2007. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 133, No. 9, September 1, 2007. ©ASCE, ISSN 1090-0241/2007/9-1110–1118/$25.00.

sequently released through evapotranspiration without allowing deep percolation. In the case of the reclamation covers, the release of minor amounts of water to deep percolation or interflow is not of concern since this will enhance the flushing of salt from the shale/cover interface. Capillary barriers comprised of finer textured soils overlying coarse textured soils are often used in landfill or mine waste covers to enhance this moisture storage and minimize gas fluxes. The reclamation covers discussed in this paper are comprised of layers of a peat–mineral soil mixture, overlying a glacial soil (till or lacustrine) placed directly on the underlying shale overburden. The surface peat/mineral soil layer has a high hydraulic conductivity and large moisture storage capacity that serves to minimize the generation of runoff by allowing individual rainfall events to infiltrate and be stored. This water is then released at a lower rate into the matrix of the underlying glacial soil so that preferential or "bypass" flow through this lower storage layer is minimized (Barbour et al. 2004).

AWHC is a static, deterministic characterization of the moisture regime of the soil cover, which ignores the effects of layering and climatic variability on the hydrologic performance of the cover. The latter influence includes the effects of consecutive or prolonged dry and wet periods within one year as well as over consecutive years. One way to avoid the disadvantages of a static approach such as the use of AWHC would be to assess the hydrologic performance of the covers using a continuous simulation tool that has the ability to test the performance of the soil cover subject to realistic sequences of climatic conditions. The simulation tool should also allow for an assessment of the reconstructed cover as a nonlinear system rather than assuming that layered soils behave like a linear system, that is, simply the sum of individual components (layers).

A methodology for assessing the hydrologic performance of the reconstructed covers, which considers the natural variability of climatic conditions, the effect of soil layering, and the uncertainty of the assessment tool, is needed. The aim of this paper is to develop such a methodology to allow the oil sands industry, regulators, and researchers to assess the risk of failure of proposed reclamation strategies under various climatic scenarios without ignoring the uncertainty of the assessment tool.

Case Study

Syncrude Canada Ltd. has been conducting watershed scale cover experiments at the Mildred Lake mine in order to assess the performance of various reclamation strategies. Alternative prototype soil covers are being monitored to characterize the key mechanisms that control moisture dynamics and to assess their overall hydrologic performance. One of these experimental watersheds involves three 1 ha prototype covers placed on an upland overburden fill area referred to as the South Bison Hills (Fig. 1). The soil covers were constructed in 1999 and have nominal thicknesses of 35, 50, and 100 cm placed on a north facing 5:1 slope. The covers are constructed with two layers: a thin layer of a mixture of peat and mineral soil (15–20 cm thick) obtained by overstripping natural peatlands, placed over different thicknesses of glacial soil (lacustrine or till).

Each cover was instrumented with a soil monitoring station at midslope that provided detailed monitoring of matric suction, volumetric water content, and temperature across the different soil profiles and into the underlying overburden. Additional monitoring included measurements of runoff, interflow along the cover/overburden interface, annual snow surveys, and continuous

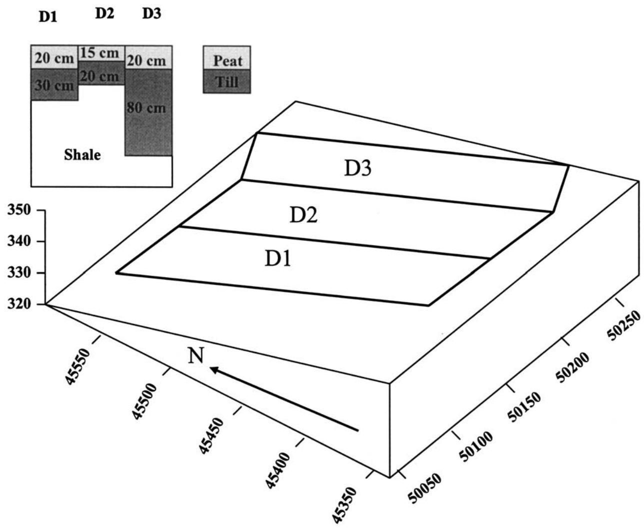

Fig. 1. Prototype cover site

monitoring of site-specific meteorological conditions. The monitoring program has been ongoing over the last 6 years. More details on the site description and collected data can be found in Boese (2004) and Barbour et al. (2004).

In order to assess the ability of the various cover alternatives to maintain sufficient soil moisture during the growing season a system dynamics watershed (SDW) model was developed (Elshorbagy 2006; Elshorbagy et al. 2005; Jutla et al. 2005). The SDW model is a lumped watershed model that simulates the various hydrologic processes occurring in the reconstructed watershed. The model is conceptualized as a control volume that simulates the water balance components among the three soil layers (peat–mineral, till, and shale) including evapotranspiration and runoff on a daily basis (Jutla 2006). The developed SDW model makes optimum use of the extensive monitoring program established for the study site and uses climatic and hydrologic factors to evaluate the hydrologic processes. The dynamics of the watershed under consideration were captured in a causal-loop diagram with multiple feedback loops that govern the entire water-balance system. A combination of physically based formulations (e.g., Green–Ampt for infiltration and soil moisture redistribution, and Penman equation for potential evapotranspiration) and empirical (fitted-parameter) formulations (e.g., actual evapotranspiration based on simulated soil moisture index, and infiltration into frozen soil) was employed in formulating the model. The SDW model was calibrated and validated for each cover under consideration. More details on the model structure and formulations can be found in Elshorbagy et al. (2005) and Jutla (2006).

Methodology

In this present study, the SDW model was used to help define a probability (or risk)-based indicator of the hydrologic performance of reconstructed watersheds. The available historical meteorological record was used as an input to the developed and validated SDW model. The continuously simulated values of the soil water volume as obtained from depth-averaged daily soil moisture content (S), interflow (I), and percolation below the cover depth (P) in each subwatershed (soil cover) were tabulated. The daily moisture deficit (D_i) which could be attributed to evapotranspiration was then calculated as follows:

$$\Delta S = S_t - S_{t+1} \quad (1)$$

$$D_i = \Delta S - (I + P) \quad (2)$$

where t=time index (day); and S, I, and P are in mm. A negative value of ΔS (moisture change) means that there is a soil moisture surplus (i.e., the soil moisture increases); whereas a positive value of ΔS means that the soil cover was able to release moisture from the storage. A positive value of D_i indicates the amount of this water release, which was available for evapotranspiration, since all paths of water loss (interflow and percolation) have been taken into consideration [Eq. (2)]. The daily values of D_i are accumulated over the growing season (mid-May to mid-October). The maximum value of the cumulative D_i in each year is marked as the maximum annual soil moisture deficit (D_m). It should be noted that the rare negative values of D_m indicate a year of water surplus, which is not of concern in this study. The daily time series of D_i may, and most probably will, have an autocorrelation structure whereas the annual maximum series could be treated as independent. This is similar to the case of autocorrelated daily streamflows and independent annual floods (Mays 2005).

The values of D_m can be used as indicators of the hydrologic behavior of the subwatershed since they quantify the ability of the subwatershed to continue to release moisture for vegetation under a variety of climatic conditions. The simulated value of D_m could replace the deterministic value of AWHC if the subwatershed was simulated under an extended climatic record which encompasses the full range of possible variations in climate and climatic cycles. The D_m values reflect the performance of the subwatershed considering the wetness and dryness of the year as well as the distribution of summer rainfall with respect to actual evapotranspiration. The values of the D_m will vary based on the distribution of rainfall within each year as well as the sequence of wet and dry years.

The D_m values are then fitted to a probability distribution, which represents the overall performance of the subwatershed. The distribution could typically range between the two extremes: moisture surplus as represented by negative values of D_m, and moisture deficit as represented by high positive values of D_m. The expected value of the moisture deficit, D_e=mean value of D_m and represents a representative single value for the distribution of D_m. However, the advantage of constructing the distribution of D_m values goes beyond evaluating D_e since it is similar to the frequency curves for storms or peak discharges. It helps identify the probability that the cover will experience any specified value of D_m. It should be noted that higher values of D_e indicate a higher ability to store and release moisture for vegetation and, consequently, greater vegetative productivity.

The deterministic value of AWHC for a soil cover can be evaluated with respect to the D_e and the probability distribution of the D_m values. For example, one can estimate the probability that the AWHC is exceeded, or if it was ever required. The extreme values (e.g., at 99% nonexceedance probabilities) of D_m indicate the maximum ability of the subwatershed to store and release moisture for vegetation. In other words, the extreme values, based on the moisture deficit frequency curves, are the ultimate available water holding capacity (UAWHC). Theoretically, the UAWHC values can be used for the hydrologic design and assessment of the reconstructed watersheds.

Quantifying the Margin of Safety

It is important to remember that the values of moisture deficit (D_i), and thus the annual maximum deficit (D_m), as well as any other values read from the frequency curve, are estimated based on the output of the SDW model adopted in this study. The major source of uncertainty about these estimates stems from the predictive uncertainty of the model. Engineering design requires that a margin of safety (MOS) be used to account for uncertainty (Ormsbee et al. 2004; Dilks and Freedman 2004). Similar to common hydrologic design practise, an appropriate frequency (e.g., 90%) can be preset to determine the design value for each subwatershed. However, a better way of quantifying the MOS in a design procedure would be to quantify the predictive uncertainty of the SDW model. More detailed reviews of types and sources of uncertainty are provided by Bastidas et al. (2003) and Elshorbagy (2005). Regardless of the source of uncertainty (e.g., model parameters, model structure, or input data), the overall predictive uncertainty of the model can be quantified by studying the model residuals (the difference between observed and simulated output).

Similar to the approach of fitting a probability distribution to the D_m values, a probability distribution can be fitted to the residuals of the SDW model. A similar approach was adopted by Borsuk et al. (2002). If the model residuals are found to be heteroscedastic (i.e., the magnitude of the error is dependent on the state variable), the Bayesian approach (Elshorbagy 2005; Freer et al. 1996) could be adopted. In this study, the model residuals are fitted in a probability distribution to identify the prediction interval into which one could expect, for example, that 90% of the residual values might fall. The confidence interval (CI) is used as the uncertainty about the frequency-based assessment of the hydrologic performance of the subwatersheds.

Finally, the predictive uncertainty, as estimated in the previous step and expressed as a percentage, is taken as a measure of the MOS needed for hydrologic assessment and design of the reconstructed watersheds. For the purpose of assessing the performance of the cover, the UAWHC can be considered, but for engineering design purposes, the UAWHC should be reduced based on the estimated MOS. The design value of AWHC (DAWHC) is calculated by dividing the UAWHC by 1 plus the MOS.

Results and Analysis

A time series of 60 years (1945–2004) of daily meteorological data (precipitation and air temperature) were used as input to the SDW model created for each subwatershed (i.e., 35, 50, and 100 cm covers). The model was executed, continuously over the 60 year period, to compute the daily values of moisture change (ΔS) and moisture deficit (D_i) according to Eqs. (1) and (2). Subsequently, the maximum annual moisture deficit values (D_m) were calculated for each year (Fig. 2). Fig. 2 shows that the subwatersheds for the 50 and 100 cm covers follow similar long-term patterns with the thickest cover storing and releasing the most moisture, reflecting higher evapotranspiration rates and, consequently, potential vegetation productivity. The thinnest cover follows the same pattern in some years but tends to behave differently in other years. It seems that the inability of the thinnest cover (35 cm) to store enough moisture towards the end of the growing season affects its performance during the following year. From a hydrological perspective, the thinnest cover behaves in a “flashy” way; it flushes water out quickly during wet periods (increased interflow), and thus fails to store water for use by

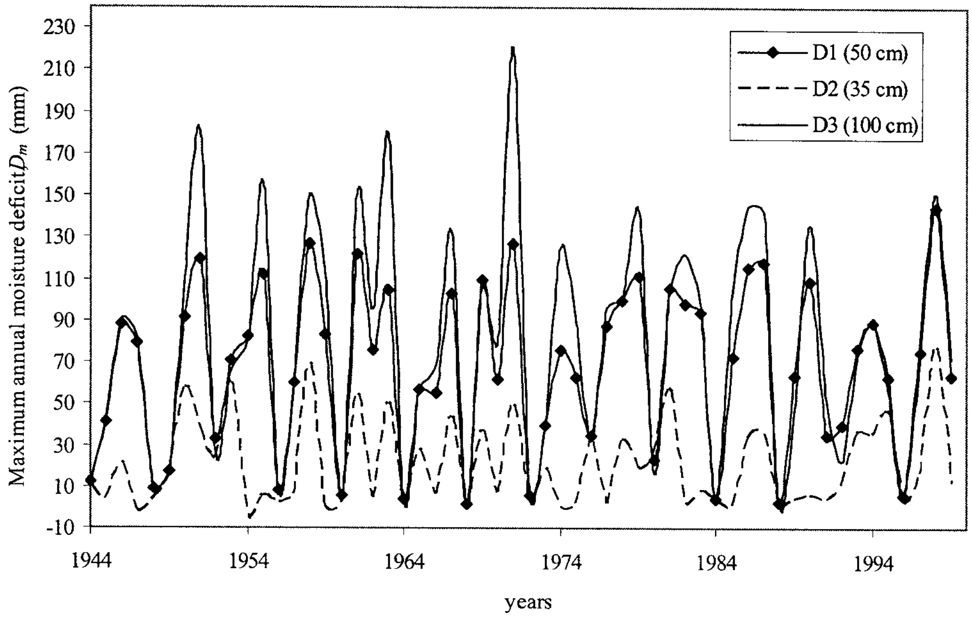

Fig. 2. Maximum annual moisture deficits of the three subwatersheds

vegetation during the drier periods. It does not recover from previous droughts as easily and it will be difficult to sustain vegetation over an extended period of critical conditions.

Statistics of the simulated D_m and actual evapotranspiration (AET) are provided in Table 1. It is evident that both the 50 and 100 cm covers can provide for considerably larger amounts of AET than the 35 cm cover, particularly in years of high AET demand. This is also reflected by their capacity to provide maximum moisture deficits of 67 and 80 mm on average, respectively. Although the difference between 50 and 100 cm covers may be perceived to be marginal with regard to D_e, the 100 cm cover shows an ability to sustain a D_m value as high as 220 mm, whereas the 50 cm cover can only produce a maximum value of 144 mm. The performance of the 35 cm cover was significantly worse than that of the other two with regard to the mean and the extreme values of D_m.

In order to verify the validity of the assumption of independence among the D_m series for the three soil covers, the autocorrelation and periodicity test were conducted using SPSS software. Neither significant autocorrelation nor periodicity was detected, with lag-1 autocorrelation coefficients of 0.18, 0.19, and 0.18 for the D_m series of the 50, 35, and 100 cm covers, respectively. Probability distributions were fit to the simulated D_m values for the three covers. More than 15 different distributions were tested using @RISK software (Palisade Corporation 2004), and the best-fit distributions were selected based on the chi-squared value (Hines et al. 2003) as well as by visual inspection. The best-fit distributions were found to be a beta generalized (α_1, α_2, min, max) for the 35 cm cover and normal distributions (μ,σ) for the 50 and 100 cm covers. In the beta generalized, the values of α_1 and α_2=continuous shape parameters and min and max =continuous boundary parameters (Palisade Corporation 2004). In the normal distribution, μ and σ=continuous location and scale parameters, respectively.

The details of the D_m distributions for the three covers are as follows:

- 35 cm cover; beta generalized (0.808, 2.17, −3.95, 86.83);
- 50 cm cover; normal (67.42, 40.26); and
- 100 cm cover; normal (79.84, 54.98)

The results shown in Fig. 3 help to illustrate the overall hydrologic performance of the various subwatersheds. The extreme values (e.g., 99% nonexceedance probabilities) of the D_m (UAWHCs) indicate that the maximum abilities of the soil cover to store and release moisture for vegetation are 74, 161, and 208 mm for the 35, 50, and 100 cm covers, respectively. These values should be considered with caution since they represent performance that is achieved once in 100 years. Moreover, the values are also affected by the predictive uncertainty of the SDW model used to estimate daily and maximum annual values of soil moisture deficit. It should be noted that the three subwatersheds were modeled under the same climatic scenarios. Therefore, the fact that one of them (e.g., the thickest cover) allowed for a D_m value of up to 208 mm indicates that at least this amount of water was needed for AET even though the other two thinner covers failed to provide more than 74 mm (35 cm cover) and 161 mm (50 cm cover). These differences would be expected to also be reflected in differences in vegetative productivity.

The preset deterministic value of AWHC (160 mm), required for the ecosite desired in the study region, can be evaluated based on the probabilistic performance of the various subwatersheds. It is evident that the required AWHC exceeds the capability of the 35 cm cover. The AWHC of 160 mm is just equivalent to the maximum value of the D_m (161 mm) for the 50 cm cover assessed at 99% nonexceedance probability. For the 100 cm cover,

Table 1. Actual Evapotranspiration and Maximum Moisture Deficit for the Three Subwatersheds

	Actual evapotranspiration (mm)		Annual maximum moisture deficit D_m (mm)	
Subwatershed	Range	Mean value	Range	Mean value
D1 (50 cm cover)	221–453	341	2–144	67
D2 (35 cm cover)	196–263	234	−4–77	20
D3 (100 cm cover)	214–470	352	2–220	80

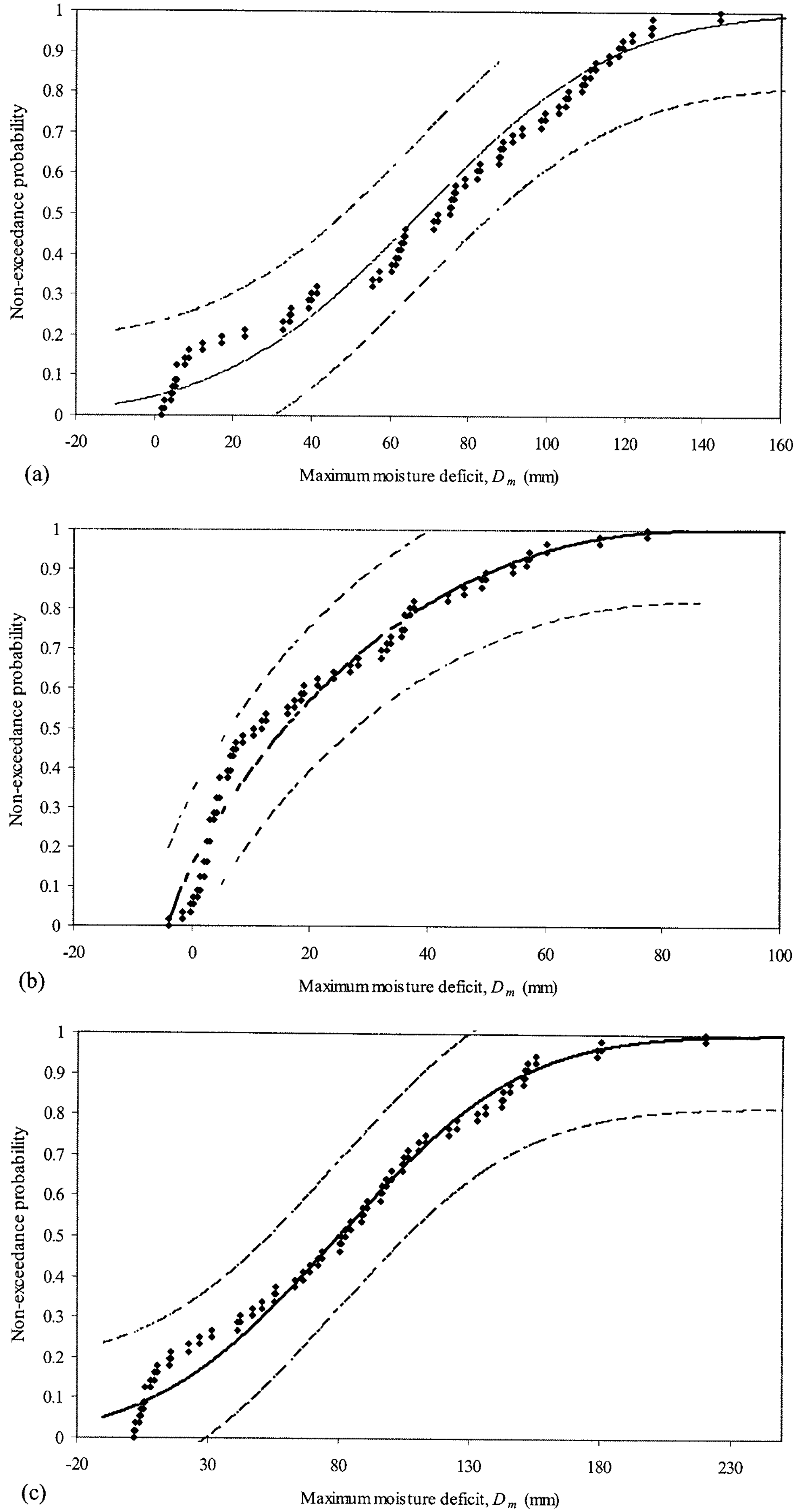

Fig. 3. Frequency curve of the maximum moisture deficit: (a) Subwatershed D1 (50 cm cover); (b) Subwatershed D2 (35 cm cover); and (c) Subwatershed D3 (100 cm cover). The dashed lines are the 90% confidence intervals.

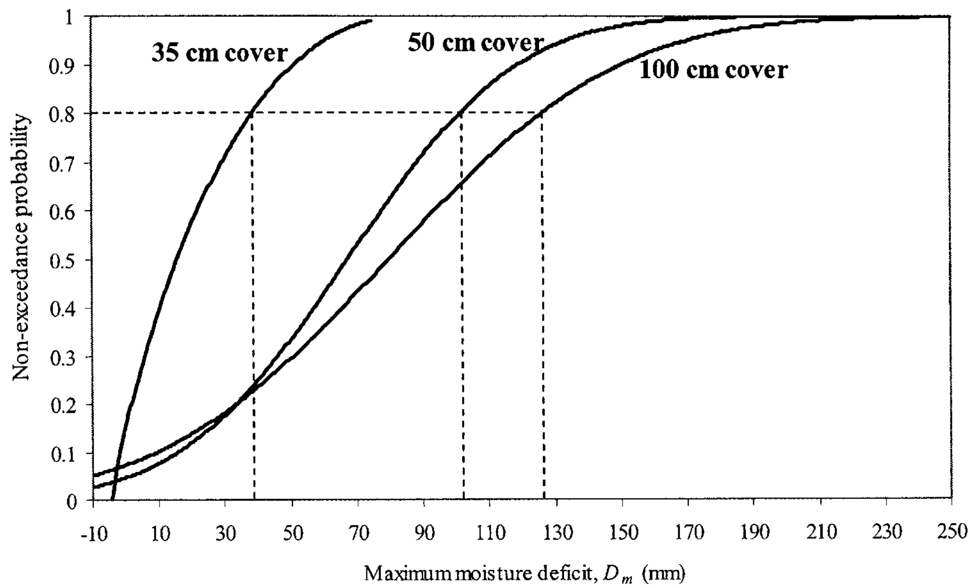

Fig. 4. Stochastic comparison between the hydrologic performances of the three subwatersheds

160 mm occurs at a nonexceedance probability of 93%, which indicates that this cover will only be required to produce this level of moisture holding capacity seven times in 100 years. There is a considerable increase in the cost associated with increasing the thickness of the covers; therefore, from an engineering design perspective, a reasonable frequency or return period should be set for design and assessment purposes.

The probabilistic hydrologic performance of the three subwatersheds can be assessed relative to each other, as shown in Fig. 4 since the expected maximum moisture deficit that could be provided by each cover can be obtained for any specified frequency. For example, if a frequency of 80% is specified, the design values of moisture deficit can be read off the graph as 38, 101, and 126 mm for the 35, 50, and 100 cm covers, respectively.

From this graph one can conclude that the 35 cm cover is clearly inferior to the thicker covers within the moisture-stressed range ($D_m \geq 0$ mm). This means that at any frequency the 35 cm cover provides a lower value of D_m than either of the thicker covers. The 100 cm cover, on the other hand, is only superior to the 50 cm cover on a stochastic basis. Up to a frequency of 20% (D_m value of 34 mm), the 50 cm cover is slightly superior while the 100 cm cover is superior at higher frequencies and higher values of D_m. Apparently, better performance means that the frequency curve is shifted toward the right side of the graph in Fig. 4. It is also interesting to note the steepness of the probability distribution curves for D_m. The steepness of the curve for the 35 cm cover suggests some lack of robustness in being able to provide for a range of possible D_m in response to variable climatic conditions.

The residual values (differences) between simulated and actual soil moisture values were also plotted as probability distributions. These distributions were also fit using @RISK software. It was found that the log–logistic (γ, β, α) distribution provided the best fit, both visually and based on the chi-squared statistic, for all three covers (Fig. 5). The parameters γ, β, and α are the continuous location, scale, and shape parameters. The details of the distributions of the model residuals for the three covers are log–logistic (−1.31, 1.29, 9.65), (−1.36, 1.33, 17.83), and (−2.25, 2.23, 29.55) for the 35, 50, and 100 cm covers, respectively. A prediction interval of 90% is chosen to represent the predictive uncertainty of the model. This results in uncertainty levels of +/−44%, 22%, and 24% for the 35, 50, and 100 cm covers, respectively. These values can be taken as equivalent to the MOS needed for design purposes. Accordingly, the design value of the D_m and the corresponding frequency can be calculated by dividing the maximum value (at 99% frequency) by 1 plus MOS. The design values are 51, 131, and 167 mm for the 35, 50, and 100 cm covers, respectively. The corresponding frequencies are 90, 94, and 94%, respectively.

It should be noted that the MOS values represent the level of confidence in the SDW model results. A higher value of MOS for the 35 cm cover indicates a higher level of uncertainty in the model estimates with regard to the 35 cm cover as compared to the two thicker covers. It is also important to note the percent reduction in frequency (from 99% to the frequency corresponding to an appropriate DAWHC). A bigger reduction is required with the 35 cm cover as compared to the 50 and 100 cm covers because the end (high) portion of the frequency curves is flatter in the cases of the 50 and 100 cm covers as compared to the 35 cm cover. This means that there are fewer values in the positive tail end of the frequency curve of the 35 cm cover, and thus less confidence in the performance of this cover towards the high values of D_m.

Discussion

The proposed probabilistic approach to the hydrologic assessment and design of soil covers for reclamation is currently being considered in the development of guidelines for the oil sands mining industry for the establishment of sustainable reclamation strategies. The probabilistic analysis provides a holistic picture of the hydrologic performance of a proposed soil cover based on climatic variability and considering the uncertainty of the assessment tool. The traditional value of AWHC can be also evaluated using the frequency curves. The probabilistic approach allows the risk associated with a specific soil moisture deficit to be quantified. The proposed methodology to quantify the margin of safety provides the designer with the confidence level expected from the

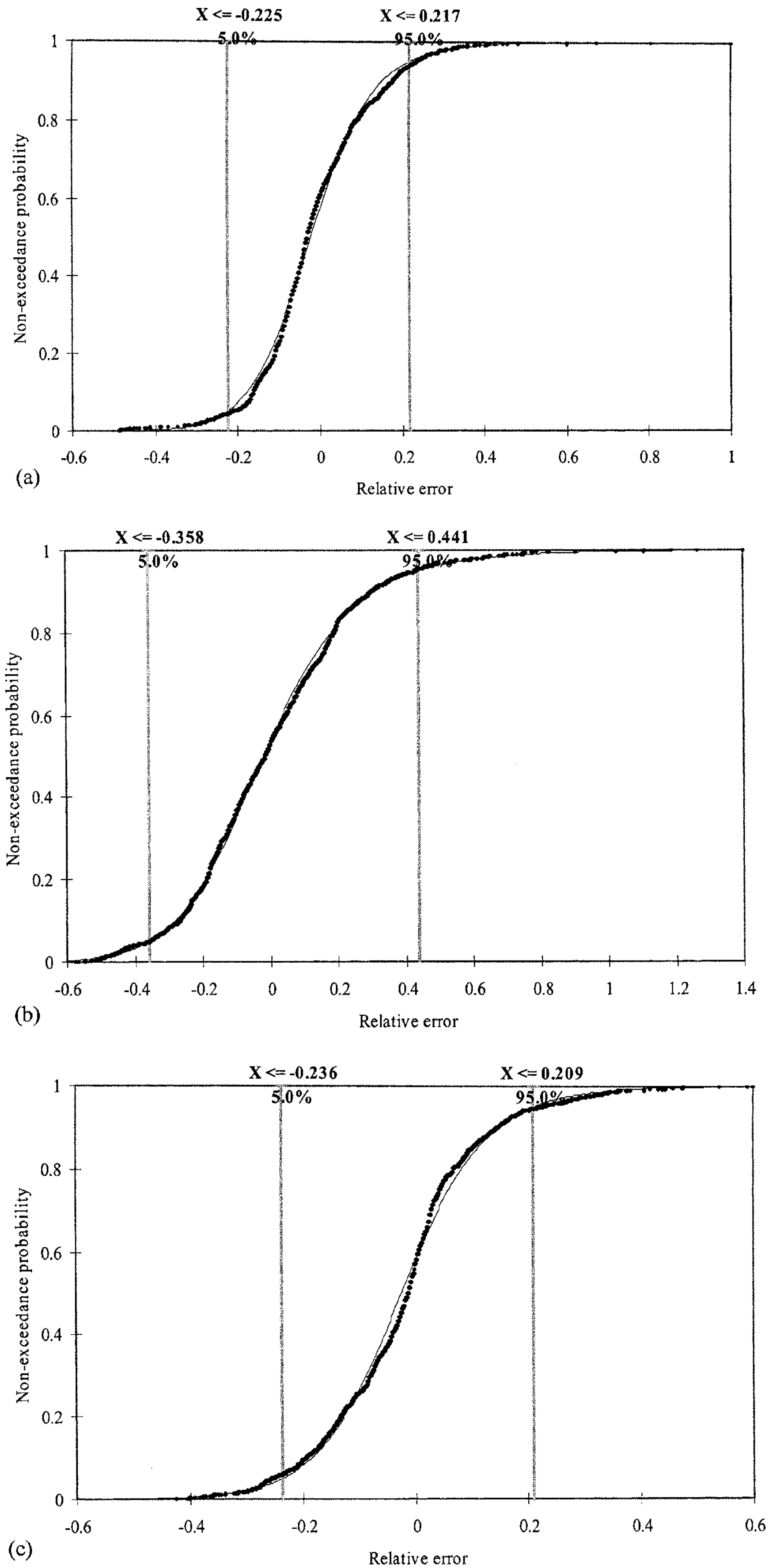

Fig. 5. Frequency curves of the model residuals for the three subwatersheds: (a) D1 (50 cm cover); (b) D2 (35 cm cover); and (c) D3 (100 cm cover)

adopted watershed model. It also allows a framework within which economic decision making can occur in which the risks of cover inadequacy (e.g., cost of replanting) can be compared to initial construction costs (e.g., placing a thicker cover).

For the purpose of hydrologic performance assessment, the analysis and frequency numbers obtained from Figs. 3 and 4 can be used as direct indicators of performance; especially when a comparative assessment is under consideration. There is no need for the MOS. The importance of MOS arises only for design purposes, where numbers need to be reduced to account for the possible uncertainty about the estimation of the soil moisture deficit. For example, if the regulations mandate a soil cover with an AWHC of at least 160 mm, the 50 cm cover should not be selected as it provides 160 mm only as an UAWHC. The 100 cm cover should be the right choice since its DAWHC is 167 mm. Uncertainty could stem from many sources other than the predictive uncertainty, including issues such as the spatial variability and inaccuracy in the measurement devices. Efforts should be made to reasonably quantify all possible sources of uncertainty and include the widest range of uncertainty in the estimation of the MOS.

The probabilistic approach proposed in this paper could play an important role in differentiating among the performance of the various soil covers. Even with a comprehensive instrumentation program in which meteorological variables, soil moisture, soil temperature, and evapotranspiration are monitored for only a few years, it is not easy to assess the relative performances of the three soil covers with regard to long-term productivity (i.e., moisture used in transpiration) or the response of the covers to various climatic conditions. The proposed probabilistic approach does require the use of a simulation using a model that is capable of replicating the hydrologic performance of the soil covers. These simulations may be developed and validated using the data from a limited number of years of monitoring, or they may be based on a model that has been developed a priori and has been validated for similar hydrographic regions.

The most important criterion for assessing the success of the reclaimed site is the ecosystem health. The productivity of the forests (or the response of vegetation) established on reclaimed sites is one of the good indicators of the ecosystem health. Therefore, it is necessary to establish a link between the developed probabilistic assessment of the moisture regime and the vegetation response. Such a relationship is difficult to establish on the young site under consideration. However, another study just started to construct similar frequency curves of moisture deficits for natural forests and old-reclaimed sites in the surrounding regions. The frequency curves of these other sites will be linked to the ecosystem health using yet-to-be-finalized indicators, such as tree rings. Based on the results of the new study, knowledge can be transferred to "forecast" the ecosystem health of the restored forests on the newly reclaimed sites.

The guidelines proposed for the assessment and design of various soil covers can be summarized as follows:

1. Select and validate a hydrologic model to simulate the hydrologic processes on the constructed watershed (the SDW model is proposed for the case study under consideration and could possibly be used in similar situations).
2. Apply the model to a data set of continuous, daily, meteorological data over a sufficient number of years to construct a probability distribution. There is no hard and fast rule about the minimum sample size. Sample sizes as long as 30–60 years have been suggested by the literature.
3. Estimate the daily moisture change and deficit [Eqs. (1) and (2)] and the series of annual maximum moisture deficit (D_m) as explained earlier.
4. Use the D_m values to construct a suitable probability distribution that represents the overall hydrologic performance of the soil cover (Figs. 3 and 4).
5. Identify the ultimate capacity of the soil cover as the D_m value at a nonexceedance probability of 99%. This D_m value represents the UAWHC for the soil cover under consideration.
6. Use the residuals from the hydrologic model to quantify the level of uncertainty about the model results. Use the residual values (based on relative error) to construct a probability distribution of the model error. Use a prespecified value (e.g., 90%) to estimate the prediction interval within which the model error is expected.
7. Use the prediction interval as an estimate of the MOS to be included in the design of the cover's performance. Estimate the DAWHC by dividing the UAWHC by 1 plus the MOS.

The need for frequency-based standards and regulations is an important aspect that regulatory institutions should consider for designing and assessing reclamation strategies. Similar approaches for design have been in practice for a long time in water resources engineering (e.g., the use of storm frequency for designing flood control facilities). Frequency-based regulations and standards have been recommended by the National Research Council (NRC 2001) and are now in practice in applications of total maximum daily loads (TDMLs) for surface water quality management (Borsuk et al. 2002).

Conclusions

The importance of assessing the hydrologic performance of various reclamation strategies for both mine planning and environmental regulation cannot be overemphasized. The current practice relies on a deterministic value of the available water holding capacity estimated on the basis of static soil properties. Such practices are unable to deal with moisture dynamics that occur as the result of soil layering and the influence of climatic variability on the hydrologic performance of the soil cover. The probabilistic approach proposed in this study for the assessment and design of such soil covers provides a sensible and realistic methodology that accounts for both physical variability (such as layering and climatic conditions) and uncertainty in model structure and model parameters. The resultant moisture deficit frequency curves provide a deeper insight into the problem since it allows for the assessment of the overall performance of the soil cover and the risk of encountering prespecified conditions.

Acknowledgments

The writers would like to acknowledge the support of the Natural Science and Engineering Research Council (NSERC) of Canada through the Discovery Grant and the CRD program and also the support of Syncrude Canada Limited. The encouragement of Clara Qualizza, Environmental Scientist, Mildred Lake Mine, Syncrude Canada Limited, is very much appreciated. The excellent work of many graduate students is also acknowledged.

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