System dynamics approach to assess the sustainability of reclamation of disturbed watersheds[1]

Amin Elshorbagy, Antarpreet Jutla, Lee Barbour, and Jim Kells

Abstract: The mining of oil sands in northern Alberta leaves behind large open pits, tailings, and overburden piles in which the surface and subsurface hydrology has been completely disrupted. Extensive reclamation work is required to reconstruct the entire landscape and reestablish the various elements of the hydrologic cycle. Syncrude Canada Ltd. has established a series of small instrumented watersheds in a reclaimed overburden pile at the Mildred Lake mine in northern Alberta, Canada, to test the sustainability of different reclamation strategies. The purpose of these field sites is to assess the performance of different reclamation strategies and track the evolution of the reclaimed landscape with time. The saline–sodic shale overburden has been covered with different (in type and depth) soil layers to provide sufficient moisture storage for vegetation while minimizing runoff and salt transport into the cover from the underlying overburden shale. In this paper, a system dynamics watershed model (SDWM) is developed to simulate one of the reconstructed watersheds and assess its ability to provide common watershed functions. The model is at an early stage, but preliminary results point to the potential of the system dynamics approach in simulating watersheds and testing different scenarios. The tested reclamation strategy seems to be satisfactory within a certain range of hydrologic conditions. Further validation of the SDWM is required, however, before relying on its results for decision support with regard to reclamation strategies.

Key words: sustainability, watershed simulation, system dynamics, reclamation, STELLA.

Résumé : L’exploitation des sables bitumineux au nord de l’Alberta laisse sur place de grandes fosses à ciel ouvert, des résidus et des piles de morts-terrains; l’hydrologie souterraine et de surface a été complètement perturbée. Un travail de remise en état complet est requis pour reconstruire le paysage en entier et rétablir les divers éléments du cycle hydrologique. Syncrude Canada Ltd. a établi une série de petits bassins hydrologiques instrumentés dans un amoncellement de morts-terrains remis en état à la mine Mildred Lake, au nord de l’Alberta, afin d’étudier la durabilité de diverses stratégies de remise en état. Le but de ces sites sur le terrain est d’évaluer le rendement de diverses stratégies de remise en état et de suivre l’évolution temporelle du paysage remis en état. Les morts-terrains de shales salins et sodiques ont été recouverts de différentes (type et profondeur) couches de sol afin de conserver assez d’humidité pour la végétation tout en minimisant l’écoulement et le transport de sels dans la couverture à partir du mort-terrain de shale sous-jacent. Cet article développe un modèle de la dynamique du système du bassin hydrologique afin de simuler l’un des bassins hydrologiques reconstruits et évaluer sa capacité à fournir les fonctions de base d’un bassin hydrologique. Le modèle en est cependant à ses premières étapes, toutefois les résultats préliminaires soulignent le potentiel de l’approche de dynamique de système pour simuler les bassins hydrologiques et vérifier divers scénarios. La stratégie de remise en état qui a été mise à l’épreuve semble être satisfaisante à l’intérieur d’une certaine page de conditions hydrologiques. Cependant, une validation plus poussée du modèle de la dynamique du système du bassin hydrologique est requise avant de pouvoir se fier à ses résultats lors de la prise de décision concernant les stratégies de remise en état.

Mots clés : durabilité, simulation des bassins hydrologiques, dynamique du système, remise en état, STELLA.

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Introduction

The era of considering economic development and environmental protection to be dichotomous has expired. It is widely accepted that development projects that are not proven to be sustainable will face the opposition of professionals, the public, and the financing and government institutions. Sustainability links economic development to environmental protection and management, and to the social well-being of people in a way which guarantees that none of these components will be compromised in the foreseeable future. When economic development, such as oil mining, is based on a resource (i.e., oil) that is an integral part of the natural environment, special care needs to be exercised.

The mining of oil sands in northern Alberta, which is the focus of this paper, leaves behind large pits, tailings facilities, and overburden in which the natural hydrology of surface and groundwater has been completely disrupted. The oil-sands industry is committed to reconstructing functioning landscapes through the design of new reclaimed watersheds to restore the different functions of nature, 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 leaching of nutrients through moving surface and subsurface water, erosion, and sedimentation (Falkenmark 1997). The restoration of the aforementioned functions relies first and foremost on the restoration of functioning hydrologic systems, a central feature of which is sufficient water to sustain revegetation efforts. Such reclamation and restoration efforts are central to making the oil-sands mining industry as sustainable a development as possible.

From the hydrologic engineering perspective, assessing the sustainability of a reclamation strategy implies (*i*) accounting for the different components of the water balance in the reconstructed watershed, (*ii*) identifying the ability of the watershed to allow for vegetation to be established, (*iii*) minimizing undesirable deep percolation of water to underlying layers, and (*iv*) minimizing the detrimental effect of weathering and leaching of saline–sodic water into the surrounding environment. This paper focuses on the first three considerations. To achieve these objectives, two main tasks are to be fulfilled: first, developing a hydrologic model for the reconstructed watershed; and second, identifying the criteria to be used to assess the level at which the aforementioned three considerations is achieved.

Hydrosustainability of watershed reclamation strategy

The mining of oil sands near Fort McMurray, Alberta, involves the stripping of saline–sodic overburden to gain access to the oil-bearing formation. The overburden is placed in large mined-out pits and surface dumps and is recontoured before being capped with a mandated 1 m soil cover. The potential for slope instability, subsidence, and salinization resulting from the character of the saline–sodic material and its interaction with fresh water makes it imperative that the amount of precipitation percolating below the root zone be minimized (Barbour et al. 2001).

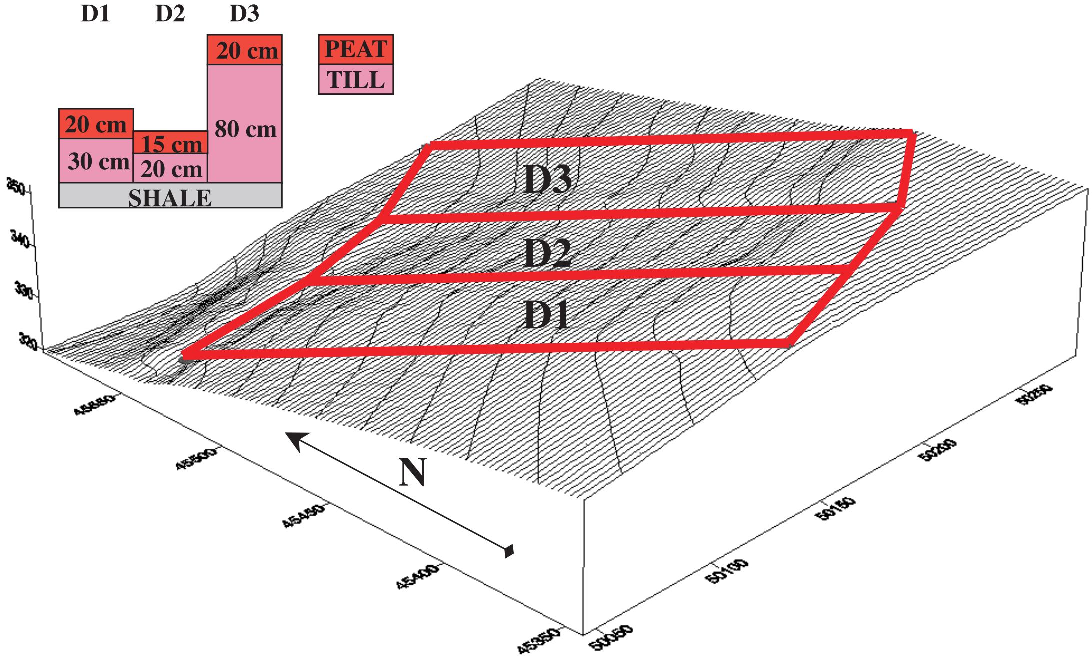
Syncrude Canada Ltd. is conducting large-scale cover experiments at the Mildred Lake mine to assess the performance of different reclamation strategies. Four 1 ha prototype covers were placed on an area referred to as the South Hills Overburden (Fig. 1) to study the basic mechanisms controlling moisture movement within the cover systems. Three covers were constructed in 1999 with thicknesses of 1.00 m, 0.50 m, and 0.35 m and comprising a thin layer of peat (15–20 cm) overlying varying thicknesses of secondary soil. A fourth study site was established in 1996 on a previously reclaimed watershed capped with a 1.0 m cover of peat – secondary mix. A field-instrumentation program was carried out consisting of detailed monitoring of matric suction, volumetric water content, and temperature within the different soil profiles and measurements of runoff, interflow, and site-specific meteorological conditions (Meier and Barbour 2002).

Evaluation of the hydrologic performance of the soil covers to assess their ability to maintain sufficient soil moisture during growing seasons is an important indicator of the efficacy of the cover in restoring the production function of the watershed. Minimizing water percolation to the underlying shale is another indicator of the cover success. In that cast the cover serves to minimize undesirable future subsidence and salinization, which in turn could affect the carrying and production functions of the watershed. The aforementioned two indicators (criteria) are used in this paper to assess the hydrologic sustainability of the cover, and therefore the sustainability of the reclamation strategy. Developing a continuous simulation model will play a central role in quantifying these two indicators and help the mining industry develop a comprehensive understanding of the hydrologic performance of the proposed cover.

Watershed modeling

Although mechanistic models, sometimes called process-based models, are usually data intensive and frequently overparameterized, they have found a wide variety of applications in watershed modeling. The number of available mechanistic models is larger than can be listed in this brief study. However, some of the frequently used models include the following: HEC-HMS for simulation of hydrologic processes that begin with precipitation, then compute infiltration losses, and lastly route the runoff throughout a river basin; the catchment modeling of the NWS River Forecast System (Burnash 1995); and HSPF (Donigian et al. 1995), which covers wide areas of applications including flood control, hydropower studies, storm drainage analysis, point- and nonpoint-source pollution analyses, and others. These models have yet to become common planning or decision-making tools. Towards achieving this goal, Singh (1995) has correctly observed that these models need to be packaged at the level of a user who is not necessarily a hydrologist, and should be integrated with, or at least have the capability of integrating with, social, economic, and management modules. Furthermore, modelers or users of these models should address the issue of the applicability of the models in data-poor conditions, especially when multitudes of field parameters, which are necessary for model cali-

Fig. 1. Prototype cover site (Boese 2004). Scales in metres.



bration, are not measured. Literature suggests that systems analysis has its own place in the field of water resources management, and simulation is an essential tool for developing a quantitative basis for water management decisions (Simonovic 1992). There is a strong need to explore simulation tools that can represent complex systems in a realistic way and in such a manner that watershed managers and operators can be involved in model development to increase their confidence in the modeling results.

Apparently, a modeling approach with specific characteristics is needed. These characteristics are as follows: (*i*) watersheds can be described and simulated in a simple fashion; (*ii*) the model should start simple, relying on the available data (similar to data-driven models), and be expandable to benefit from additional data as they become available; (*iii*) the model should be dynamic to cope with the nature of hydrologic systems; (*iv*) the model should have the ability to simulate both linear and nonlinear processes; (*v*) the model should provide a way to represent the feedback mechanism to handle counterintuitive processes; (*vi*) the model should have the ability to model human intervention and any shocks that might be encountered in the system; and (*vii*) the model should provide the ability to test different policy or management scenarios for better decision making. Although it might appear difficult to have all these characteristics embodied in one modeling approach, the emergence of system dynamics modeling has made it possible. In this paper, an object-oriented simulation environment (STELLA® software), which adopts the system dynamics modeling approach, is utilized. A brief explanation of the principles of system dynamics and the way they are included in STELLA® (High Performance Systems Inc. 2001) is provided in the following section.

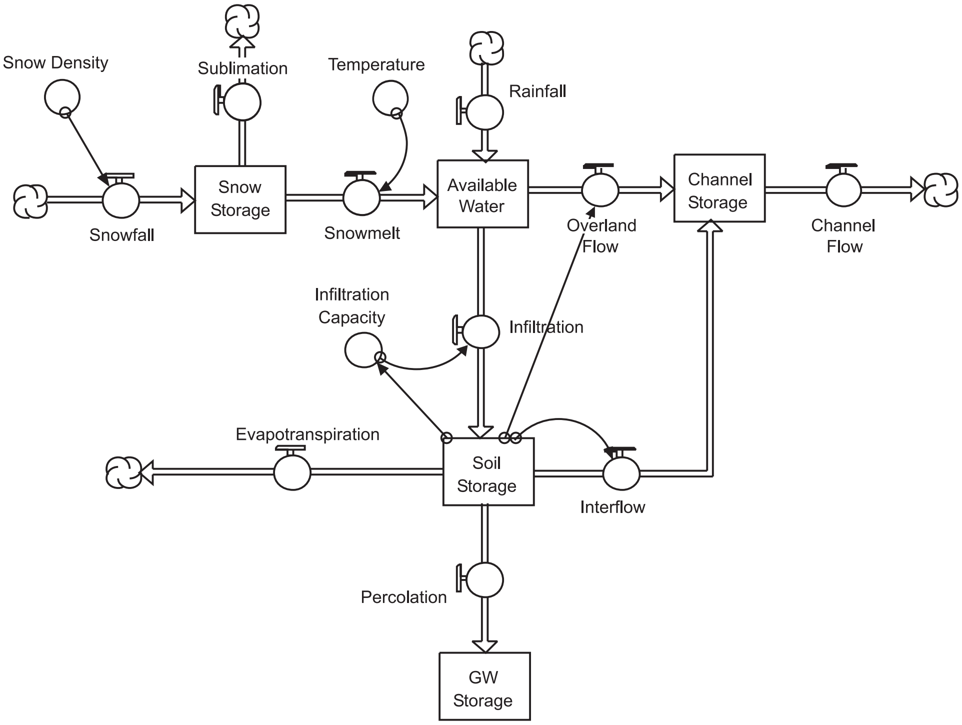
System dynamics approach

The system dynamics (SD) simulation approach relies on understanding complex interrelationships existing between different elements within a system. This is achieved by developing a model that can simulate and quantify the behaviour of the system. Simulation of the system over time is considered essential to understand the dynamics of the system. Understanding of the system and its boundaries, identifying the key variables, representation of the physical processes or variables through mathematical relationships, mapping the structure of the model, and simulating the system for understanding its behaviour are some of the major steps that are carried out in the development of an SD model. It is interesting to note that the central building blocks of the principles of the SD approach are well suited for modeling any physical system.

Like any system that is comprised of certain elements, *stocks* and *flows* are the building blocks of an SD model. A simple illustration of stocks and flows is the accumulation of interest in a bank account (Ford 1999) or inflow of water into a reservoir. Figure 2 shows a simplified model of a watershed. The double line represents the flow of water from a source, represented by a cloud (or a stock), into the reservoir (stock). The cloud can be viewed as a stock that is outside the system boundary. The single lines in Fig. 2 connect objects (i.e., processes or coefficients) together. These are called *connectors*, which show the flow of information inside the model. *Converters* (such as temperature and snow density) can represent any variable as a function of time or any input value or parameter.

The use of the term *feedback* in SD covers any process in which the state of a system influences action, which affects the system, and thereby affects further action. Feedback is one of the most important concepts of SD. A feedback loop is a circle of cause and effect. The cause and effect in feedback loops always runs from a stock to a flow and then back to a stock again. Feedback loops are relationships that generate *goal-seeking* behaviour. Goal seeking is what enables conditions within a system to remain "on course." When deviations do occur, feedback relationships inspire, and then

Fig. 2. Simplified object structure of a watershed. GW, groundwater.



direct, corrective actions that bring conditions back into line. An example of feedback in watershed hydrology is having the soil surface saturated, which should affect the amount of water infiltrating the soil.

Models developed using SD should be calibrated and validated in a way similar to that of any other modeling approach. The governing equations are represented by finite difference expressions used for modeling different elements in a system and are solved using standard numerical schemes. For example, in the case of a stock, a continuity equation for mass balance is developed considering the inflows and outflows, whereas a converter carries a functional relationship between different variables that can be represented in a mathematical or graphical form.

The time interval for simulation is an important aspect that will determine the accuracy of the numerical scheme used for solving the finite difference equations. Understanding the concepts of SD and the way they work is rather difficult unless it is presented within a simulation environment. In this paper, an object-oriented simulation environment, STELLA® software (High Performance Systems Inc. 2001), is used as a sophisticated tool to model the watershed as a dynamic system.

The SD approach differs from traditional hydrologic modeling in three aspects. First, the object-oriented simulation makes the links, including feedback loops, among different components of the system both visual and explicit. This facilitates the process of verifying individual components and subsystems and ensures that all links are reasonable and logical. Second, the SD approach allows for constructing a model that combines process-based and empirical or even qualitative formulations. In the SD approach, it is possible to incorporate a qualitative relationship based on a tentative knowledge of the relationship between two parameters. Simulations can be executed and subsequent modifications of the relationships made until the expected behaviour of the system is achieved. Third, dynamic (time varying) coefficients and system parameters can be easily employed in the SD approach. As Loague and VanderKwaak (2004) noted, one of the biggest, yet ignored, obstacles in effectively exciting a physics-based model is the assumption of time invariance for system parameters. For example, the saturated hydraulic conductivity can be considered changing with time; it does not have to be a single-valued coefficient.

Moreover, an important issue such as equifinality (Beven and Freer 2001) can be easily investigated. The visual structure of components, links, and feedback (Figs. 2, 3) facilitates the task of changing links, and therefore the model structure, in a search for the different sets of model structures that lead to reproducing the observed behaviour of that system. By visually browsing the structure, one could exclude the physically unrealistic structures even if they lead to acceptable results. A similar approach could be taken with different sets of parameters within a single model structure. Such a browsing and elimination process within a visual environment is highly useful in learning about the possible existence of counterintuitive processes in a natural system and understanding the system as a whole. Klemes (1997) noted that a good model should promote understanding of the system.

Although SD concepts have been applied to a wide variety of applications in the fields of social studies, economics, industrial engineering, and urban planning to the point that a scientific journal (*System Dynamics Review*) is dedicated to publish its applications in different fields, the area of watershed hydrology has not benefited enough from this modeling approach. Only a few published articles can be found. A conceptualization of hydrological models using SD has been

Fig. 3. Causal-loop diagram (dynamic hypothesis) of the hydrologic processes in the D3 cover. +, indicates that the two variables at both ends of the arrow change in the same direction; –, indicates that an increase in the first variable leads to a decrease in the second variable, and vice versa.

briefly outlined by Lee (1993), who indicated that the SD modeling approach is a candidate to be an excellent tool for teaching hydrological modeling. A real application of what Lee indicated in 1993 has been materialized by Li and Simonovic (2002), who successfully adopted SD for predicting floods in prairie watersheds (Red River). This paper builds on the success of Li and Simonovic and expands it to more detailed simulations on a smaller scale (i.e., 1 ha watershed).

Model development and formulation

Hydrologic processes

One of the three covers shown as D3 in Fig. 1 is used for the case study presented in this paper to show the utility of the SD, implemented within the object-oriented simulation environment, in modeling the hydrologic performance of the cover D3. A lumped approach to watershed modeling is adopted in this study, given that the total area of D3 is 1 ha. The lumped modeling approach has a long tradition in hydrologic modeling (Beven 2001). The SD watershed model (SDWM) built in this study makes optimum use of the extensive monitoring program established on site and uses climatic factors and hydrologic processes. Simulation of the vertical water balance is conducted using four storages representing (*i*) snow storage, (*ii*) peat storage, (*iii*) till storage, and (*iv*) shale storage. The canopy storage is neglected because the light and short type of vegetation that is dominant on the cover is not intercepting significant amounts of precipitation.

Climatological factors (especially temperature) determine the amount of snowmelt. Along with rainfall, snowmelt constitutes the amount of *water available* for infiltration and overland flow. Soil moisture affects, in the form of a feedback, the amount of infiltrating water. The difference between the amount of water available and infiltrating water will form overland flow, which will go to the channel and can be represented in the model as channel storage.

Evapotranspiration, interflow, and further infiltration to the till layer are losses from the peat storage. Evapotranspiration is dependent on moisture conditions, weather conditions, and the stage of plant growth. Interflow is a function of horizontal hydraulic conductivity, water content, soil temperature, and topographic gradient. Infiltration into the 80 cm till layer is dependent on soil temperature, water content within both 20 cm peat and 80 cm till layers, and the hydraulic properties of the till layer.

Till storage is formed through water entering from the peat layer. Losses from the till storage include evapotranspiration, interflow, and percolation to the shale layer (storage). Factors affecting losses from the till storage are similar to those mentioned in the peat storage. In this study, no interflow or base flow is assumed to be contributing water from the shale to the channel.

Dynamic hypothesis and causal-loop diagram

Watershed modeling is a classical example for an SD approach because a watershed can be perceived as an assembly of nonlinear dynamic processes controlled by a feedback-loop structure. Positive feedback stimulates all factors in a loop to increase or decrease, and the negative feedback loop tends to bring elements of the system to an equilibrium state. When any of the factors is removed from the system, the negative feedback will work to force the system back into equilibrium (Li and Simonovic 2002). The dynamics (dynamic hypothesis) of the watershed under consideration is sketched as a causal-loop diagram shown in Fig. 3. The positive sign (+) at the head of an arrow indicates that the two variables, at both ends of the arrow, change in the same direction. In other words, an increase in the first variable leads to an increase in the next variable. The negative sign (–) means that an increase in the first variable leads to a decrease in the next variable, and vice versa. Positive and negative signs shown inside the loop indicate whether the entire loop is positive or negative. Learning how such interconnected and coupled loops affect the system can help increase the understanding of the dynamics of the watershed.

Model formulation

Mathematical formulations of the major hydrologic processes represented in the model are summarized in the following subsections.

Snow storage

Precipitation falling as snow accumulates as snow storage. Snowmelt rate is calculated by the degree-day factor (Anderson 1976), and the daily snowmelt can be represented mathematically as

$$M = D_\mathrm{f}(T_\mathrm{i} - T_\mathrm{B}) \tag{1}$$

where M is the daily melt (mm/day); T_i is the index air temperature (°C); T_B is the base melt temperature (°C); and D_f is the degree-day melt factor, which can be approximated as follows (Bedient and Huber 2002):

$$D_\mathrm{f} = 0.011\rho_\mathrm{s} \tag{2}$$

where D_f is in millimetres per degree-day above 0 °C, and ρ_s is the snow density (kg/m^3).

Peat storage

Moisture change in the peat storage depends on infiltration from surface, evapotranspiration, interflow, and downward water movement to the till storage.

Before saturation, water infiltrates directly through the peat layer when it is unsaturated (Voinov et al. 2004). If the layer becomes saturated or the rainfall intensity exceeds the saturated hydraulic conductivity (K_s), then infiltration is governed by the Green–Ampt equation. The infiltration process is represented by solving the governing equation of continuity and Darcy's Law in an unsaturated porous media (Richards 1931), which takes the form

$$\frac{\partial\theta}{\partial t} = -\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial\psi(\theta)}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} \tag{3}$$

where θ is the volumetric moisture content, t is the time, z is the distance below the surface (mm), $\psi(\theta)$ is the capillary suction (mm of water), and $K(\theta)$ is the unsaturated hydraulic conductivity (mm/day). The Green–Ampt solution to this equation is adopted in this model. It estimates infiltration capacity (f) based on total infiltration volume (F) and takes the form

$$f = K_\mathrm{s}\left(1 - \frac{M_\mathrm{d}\psi}{F}\right) \tag{4}$$

At the moment of surface saturation, the volume of infiltration F_s is

$$F_\mathrm{s} = M_\mathrm{d}\frac{\psi}{1 - i/K_\mathrm{s}} \tag{5}$$

where f is the infiltration rate (capacity) in mm/day; K_s is the saturated hydraulic conductivity (mm/day); $M_\mathrm{d} = \theta_\mathrm{s} - \theta_\mathrm{i}$ is the initial moisture deficit, in which θ_s is the saturated moisture content and θ_i is the initial moisture content; and i is the precipitation intensity.

According to Li and Simonovic (2002), the period of time during which the temperature remains above and below the active temperature affects infiltration into frozen soils. This phenomenon results in soil defrosting and refreezing. In this paper, Li and Simonovic's concept of the soil defrosting exponentially with accumulation of active temperature is used. The soil refreezes again if temperature drops below 0 °C for a number of days. The active temperature accumulation will be lost and starts again from zero. Accordingly, infiltration f can be multiplied by a coefficient C_tPeat

$$\begin{aligned}
C_\mathrm{tPeat} &= \begin{Bmatrix} (T_\mathrm{I}/T_\mathrm{Imax})^\mathrm{ci} & \text{if } T_\mathrm{I} < T_\mathrm{Imax} \\ 1 & \text{if } T_\mathrm{I} \ge T_\mathrm{Imax} \end{Bmatrix} \\
T_\mathrm{I} &= \begin{Bmatrix} \Sigma(T) & \text{if } T > 0 \text{ and } N < N_n \\ 0 & \text{if } N \ge N_n \end{Bmatrix} \\
N &= \begin{Bmatrix} \Sigma(N_\mathrm{o}) & \text{if } T < 0 \\ 0 & \text{if } T \ge 0 \end{Bmatrix} \\
N_\mathrm{o} &= \begin{Bmatrix} 1 & \text{if } T < 0 \\ 0 & \text{if } T \ge 0 \end{Bmatrix}
\end{aligned} \tag{6}$$

where T_I is the air temperature (°C), T_Imax (°C) is a maximum T_I point at which surface soil is fully defrosted, ci (dimensionless) is an exponent for describing the influence of T_I on soil defrosting, N (days) is the number of continuous days with temperature below active point, N_n is a maximum N after which T_I will be lost and surface soil will refreeze again, and N_o is a logical variable to identify the day in which temperature is higher or lower than the active (positive) temperature.

Evapotranspiration from the peat layer ($\mathrm{ET_P}$) is estimated in the model using empirical formulations (Li and Simonovic 2002) that take into account the available soil moisture

$$\begin{aligned}
\mathrm{ET_P} &= c_\mathrm{P} S_\mathrm{msPeat}^{\lambda} T C_\mathrm{tPeat} \\
S_\mathrm{msPeat} &= \frac{S_\mathrm{P}/S_\mathrm{NP} - S_\mathrm{Prs}}{1 - S_\mathrm{Prs}}
\end{aligned} \tag{7}$$

where c_P is the evapotranspiration coefficient (mm/°C/day); S_msPeat is the effective moisture saturation in peat (dimensionless); λ is the exponential coefficient (>1) that expresses the impact of water saturation on evapotranspiration; S_P and S_NP are the water storage and nominal water storage (mm) in the peat layer, respectively; and S_Prs is the minimum storage that can be attained in the peat layer. S_Prs is taken from the soil water characteristic curve (SWCC) (Boese 2004) to be approximately 0.10. Evaporation from

Table 1. Variables and data used in the developed model.

Hydrologic process	Variables	Data sources
Snowmelt	Air temperature	Field measurement
Evapotranspiration		
Bowen ratio	Radiation, air temperature, vapour pressure	Field measurement
Penman method	Radiation, air temperature, wind speed, relative humidity	Field measurement
Infiltration through each layer	Saturated moisture content, hydraulic conductivity, matric suction, soil temperature	Field measurement; soil water characteristics curve is fed into the model to simulate different scenarios
Overland flow	Peat moisture content, soil temperature	Field measurement and calibrated interflow coefficient
Interflow	Peat and till moisture content, soil temperature	Field measurement and calibrated overland coefficient

Table 2. Calibration parameter values of models I and II.

Parameter	Model I: Penman method and Bowen ratio	Model II: Li and Simonovic 2002
Till infiltration (I_{cT})	0.032	0.035
Shale infiltration (I_{cS})	0.025	0.050
Coefficient of overland flow (C_O)	0.001	0.001
Exponent describing the influence of T_I on soil defrosting (ci)	4.5	4.5
Maximum T_I point at which surface soil is fully defrosted (T_{Imax})	50	50
Interflow (C_I)	0.002	0.0001
Peat evaporation (c_P)	0.26	5
Till evaporation (c_T)	0.15	2.5
Lambda (λ)	—	4.3

the peat layer will occur only if the air temperature (T) is greater than 0 °C and the peat layer temperature is greater than 0 °C. This method, adopted by Li and Simonovic (2002), has been based on the work of Kristensen and Jensen (1975) and is also used in the MIKE SHE model (Refsgaard and Storm 1995).

Another method of estimating evaporation based on the Bowen ratio and the Penman method has been tested. A Bowen ratio station is present on site during the summer season. When data from the Bowen ratio are not available, the Penman method is used to compute the evapotranspiration. Details on both methods can be found in Viessman and Lewis (2003). The empirical formula for evapotranspiration indicated earlier produced better simulation results. Our interpretation is that the empirical formula takes the available soil moisture into account, which indicates less evapotranspiration when moisture is less and suction pressure is higher. Apparently, this method is appropriate in semiarid regions where soil moisture could be a limiting factor for evapotranspiration. Interestingly, this is supported by findings of others that conventional sets of equations may not work well while using the SD approach, although based on the basic theories. A new set of parametric equations works better in SD. This type of approach has been taken by Li and Simonovic (2002), Voinov et al. (2004), and Saysel and Barlas (2001), who used parametric equations to model complex natural systems and obtained encouraging results. Models built within the SD approach work better with empirical formulations that link different components of the system together (e.g., soil moisture and evapotranspiration). Comparison of results using the two different approaches is presented in a later section. Water in excess of infiltration capacity is directed as overland flow (O) in summer. During frozen conditions, part of the available water (AW; from both rainfall and snowmelt) infiltrates into frozen soil (eq. [6]), and the remaining portion contributes to overland flow as follows:

Table 3. Measured parameters of the D3 cover.

Parameter	Value
Porosity of peat	0.5[a]
Porosity of till	0.54[a]
Porosity of shale	0.25[b]
Saturated hydraulic conductivity of peat, K_s (cm/h)	17[b]
Saturated hydraulic conductivity of till, K_s (cm/h)	2.1[b]
Saturated hydraulic conductivity of shale, K_s (cm/h)	0.03[b]

[a]After Boese (2004).
[b]After Shurniak and Barbour (2002).

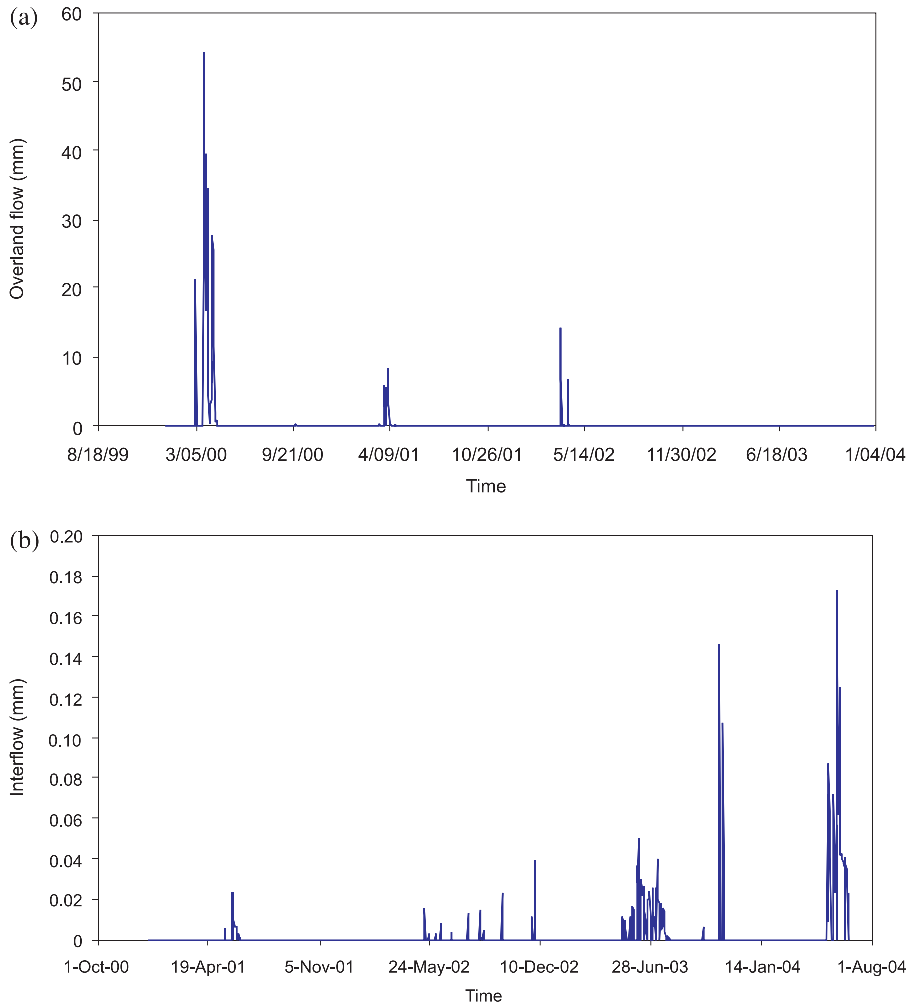
$$[8] \qquad O = (\mathrm{AW} - fC_{\mathrm{tPeat}})C_{\mathrm{O}}$$

where C_O is the coefficient of overland flow, and both O and AW are in millimetres per day.

Till storage

The same factors mentioned previously as affecting the peat storage also affect the underlying till storage. In summer ($T > 0$ °C) water will move down from the peat layer to the till layer following the Green–Ampt equation in the case of a fully saturated soil. When the till layer is unsaturated, the following logic will apply: water moves down from peat to till if (peat layer is fully saturated) and (soil temperature

Fig. 4. Observed runoff on cover D3 from year 2000 to 2003: (*a*) overland flow; (*b*) interflow. Dates are given as month/day/year.



of till >0 °C) and (suction pressure in till layer > suction pressure in peat layer) and (moisture content of the peat θ_{Peat} > moisture content of the till θ_{Till}). If these conditions are true, then infiltration into the till layer is governed by

[9] $$\text{infiltration to till} = (\theta_{Peat}/\theta_{Till})I_{cT}$$

where I_{cT} is the coefficient of till infiltration. Under frozen conditions, the same concept followed in the peat layer (eq. [6]) is replicated for the till layer to estimate C_{tTill}, the till infiltration coefficient. The only difference is that the air temperature in the till layer is replaced by the temperature of the peat layer. Also, evapotranspiration from the till layer (ET_T) is treated in the same way as that in the peat storage

[10] $$ET_T = c_T S^{\lambda}_{msTill} T_{sP} C_{tTill}$$
$$S_{msTill} = \frac{S_T/S_{NT} - S_{Trs}}{1 - S_{Trs}}$$

where c_T is an evapotranspiration coefficient (mm/°C/day); S_{msTill} is the effective moisture saturation in the till (dimensionless); λ is the exponential coefficient (>1) that expresses the impact of water saturation on evapotranspiration; S_T and S_{NT} are the water storage and nominal water storage (mm) in the till layer, respectively; and S_{Trs} is the minimum storage that can be attained in the till layer. S_{Trs} is taken from the SWCC to be approximately 0.11. Interflow (I) is estimated as follows:

[11] $$I = (TS - \theta_{sTill} D_{Till})C_I$$

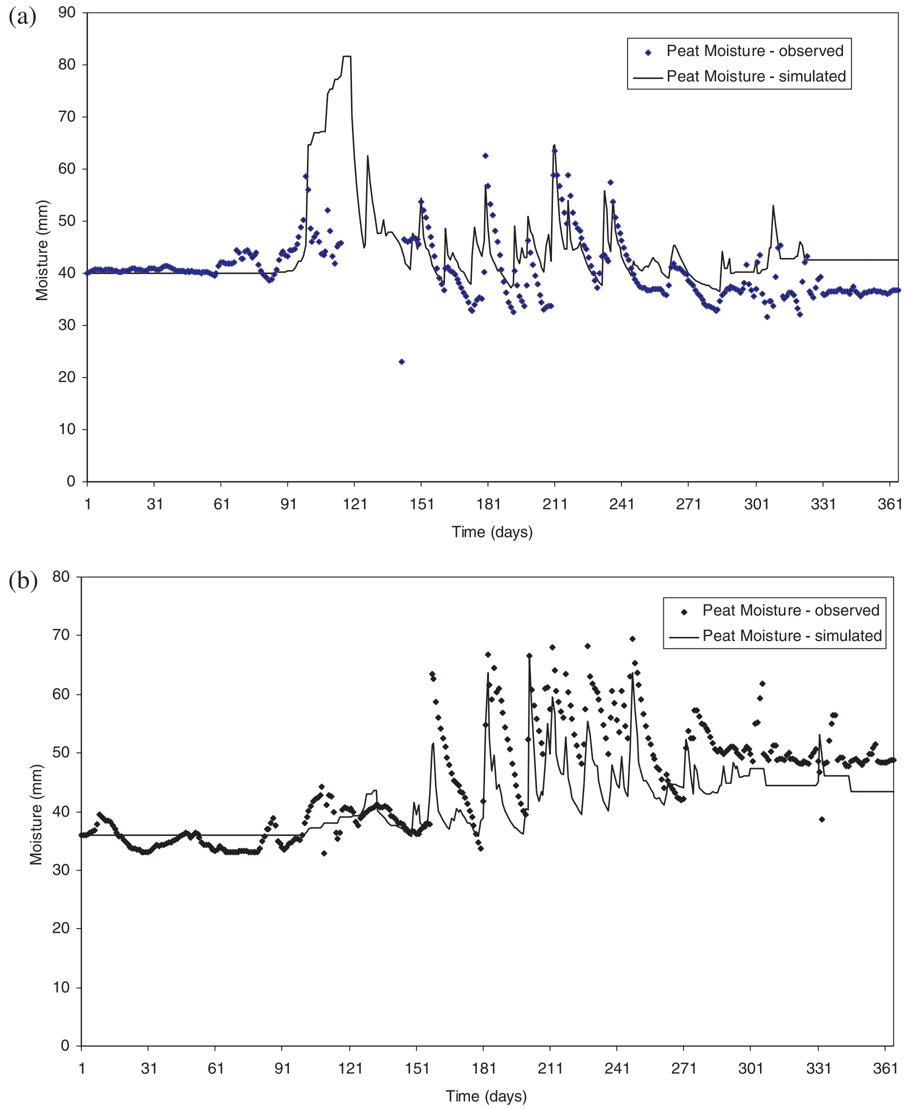
where TS is the till storage (mm), θ_{sTill} is the porosity of the till layer, D_{Till} is the depth of the till layer (mm), and C_I is the interflow coefficient. Interflow will occur only if the temperature of the till layer is greater than 0 °C.

Shale storage

Moisture change in the shale storage depends on percolation from the till layer and interflow. Water will percolate from the till layer to the shale layer following the Green–Ampt equation in the case of fully saturated soil. When the shale layer is unsaturated, then the following logic applies: water percolates to the shale layer from the till layer when (the till layer is fully saturated) and (the soil temperature of the till and shale is greater than 0 °C) and (the suction pressure in the shale layer is greater than the suction pressure in the till layer). If these conditions are true, then percolation into the shale layer is governed by

[12] $$\text{percolation to shale} = (\theta_{Till}/\theta_{Shale})I_{cS}$$

Fig. 5. Observed and simulated moisture of peat layer: (*a*) calibration year; (*b*) validation year.



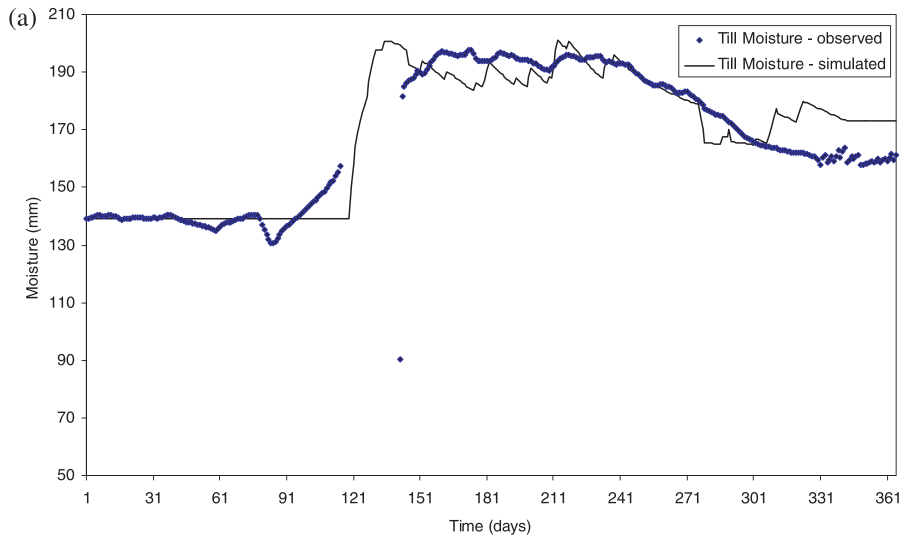
where I_{cS} is a coefficient of shale percolation, and θ_{Shale} is the volumetric water content in the shale layer. A list of the data and variables used in the developed SDWM is presented in Table 1.

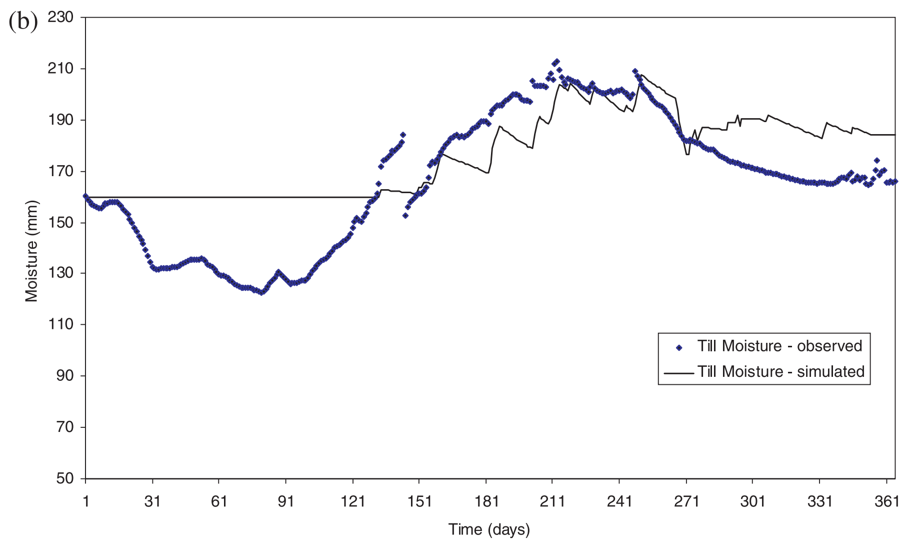
Model calibration and validation

The description of the model structure and formulation shows that the developed model (SDWM) is a combination of process-based and empirical formulations, minimizing the number of parameters that need to be calibrated. The model has a set of calibration parameters (Table 2), however, that were discussed earlier. These parameters need to be estimated (calibrated) during the model calibration process. It is observed through field measurements from 2000 to 2003 that both interflow and overland flow have small values compared with soil moisture and evapotranspiration. The coefficients attached to those two processes reflect this fact (Table 2). The values of the measured parameters are provided in Table 3, and available data on overland flow and interflow are shown in Fig. 4 (note the interflow values in Fig. 4*b*). The only significant value of overland flow was in March 2000 due to a sudden and severe snowmelt event. The values of total precipitation in the years 2000–2003 are 330, 367, 337, and 236 mm, respectively. The available water is distributed mainly between soil moisture (peat, till, and shale) storage and evapotranspiration. A calibration coefficient is associated with the evapotranspiration to account for the uneven distribution of vegetation and spatial variability of meteorological conditions. The two developed models (model I using the Penman method and Bowen ratio for estimation of evaporation and model II using formulations developed by Li and Simonovic 2002) are validated in this paper by testing the overall performance of the model in simulating the soil moisture storages of different layers (peat, till, and shale) and the overland flow. Year 2001 is used for calibrating the models, and year 2002 for validation purposes.

The model is executed to simulate the daily hydrologic processes of the D3 cover. The simulated and observed daily soil moisture and runoff values, based on model II, are shown in Figs. 5–8. Discontinuities of the observed values in the figures are due to missing data. It should be noted that

Fig. 6. Observed and simulated moisture of till layer: (*a*) calibration year; (*b*) validation year.

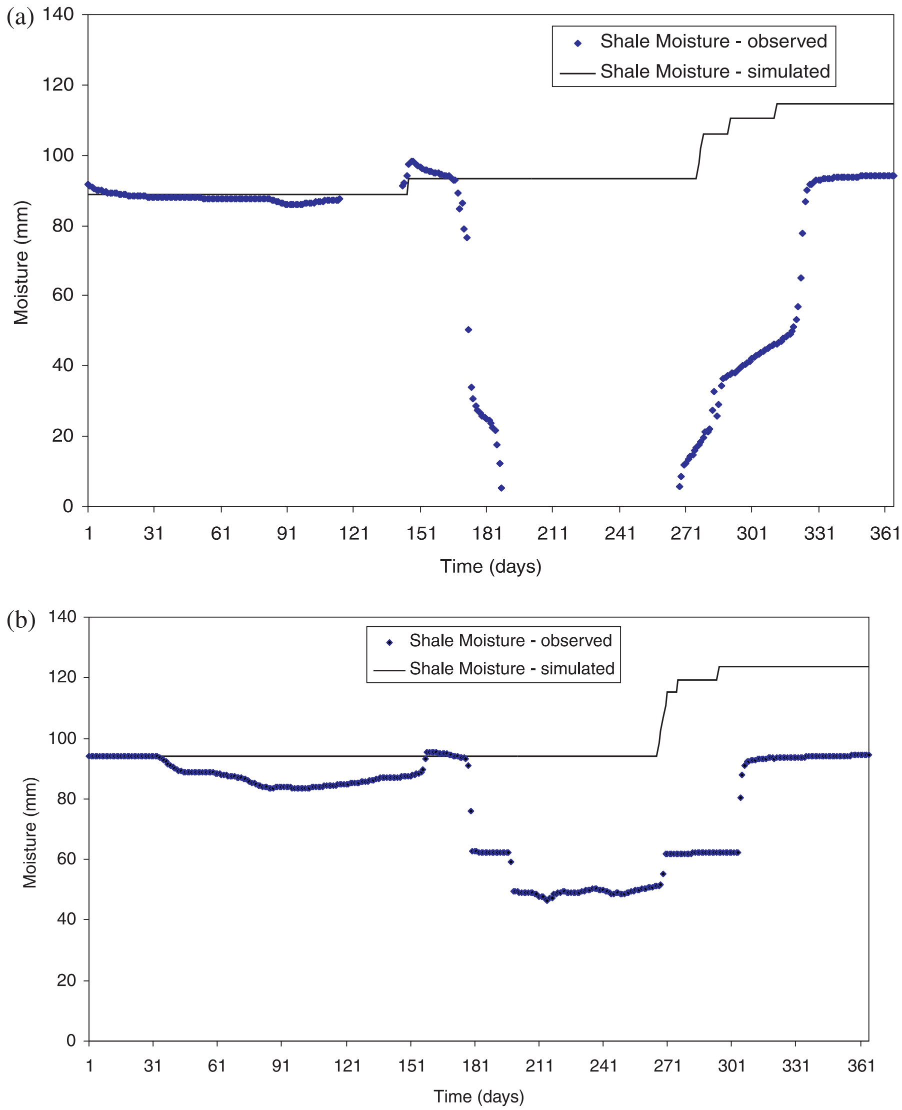




comparison with observed data in the winter season should be done with extreme caution. The time domain reflectometry (TDR) sensors used to monitor the soil moisture content (Boese 2004) fail to provide reliable readings under frozen conditions. Therefore, the simulations start in January assuming the last moisture reading when soil temperature was positive, not using the moisture reading of 1 January. This may help explain the discrepancy between observed and simulated soil moisture during the winter season (Figs. 5–7). Only the top 50 cm of the shale layer is considered for calculating the shale moisture content. Unfortunately, field personnel have indicated that considerably less reliability can be associated with moisture reading in the shale layers. The sensors work efficiently when there is a change in moisture content. Under saturated conditions, water may be continuously percolating downward to the shale while the sensors do not measure any change in moisture content. It is our belief, supported by simulation results, that water starts to percolate into the shale layer at the start of the winter season when the topsoil is frozen and the bottom part of the till layer is saturated. This may need further verification, however. Severe drops in the observed shale moisture (Fig. 7) are impossible to interpret from a physical perspective, knowing that such drops indicate the shale layer has been drained to a level much below that of the wilting point. Failure of moisture sensors is the only reasonable interpretation, and this is supported by the observations of field personnel.

Although the model performance in simulating runoff is less accurate than its performance with regard to soil moisture, it is satisfactory given the fact that runoff is a sudden event due to snowmelt and does not constitute a significant portion of the water balance. In the calibration year, the model produced an early runoff event due to significant increases in air temperature, which is apparently translated into snowmelt. Such an amount of snowmelt has not been recorded as runoff at the weirs. Runoff trapped in small depressions before reaching the swale and absence of accurate snow surveys (actual snow depth at the time of melt) could be among possible reasons for such a discrepancy. It is worth noting that the challenge and the distinctive feature of the case under consideration is that simulating soil moisture

Fig. 7. Observed and simulated moisture of shale layer: (*a*) calibration year; (*b*) validation year.



of different layers is the main vehicle used to validate the model performance. This differs from the traditional watershed simulation in which runoff is used to judge the validity of the watershed model.

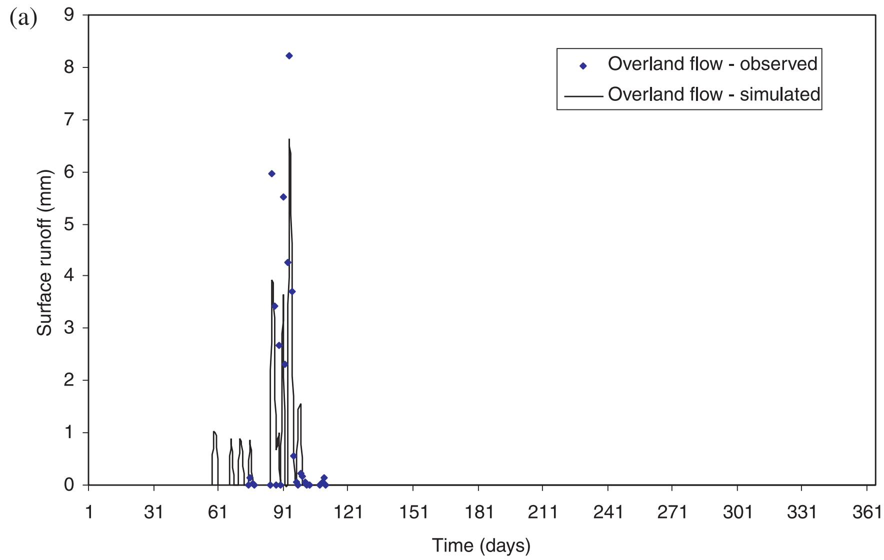
The results of model I are not shown for brevity reasons, but Table 4 provides a comparison of results based on root mean squared error (RMSE) and mean relative error (MRE). Accordingly, model II, which provides better results, is selected for further analysis to test the hydrologic performance of the D3 cover under two different wet and dry scenarios.

Scenario generation, results, and analysis

The sustainability of the D3 cover can be addressed further by testing the performance of the cover under extreme weather conditions. The total annual precipitation in 2001 (the year used for calibrating the developed SDWM) was approximately 366 mm of water. The historical precipitation record over the last 30 years in the area indicates that total annual precipitation was as low as 200 mm in 1998 and as high as 650 mm in 1973. The developed model (SDWM) is tested further using two extreme scenarios. In scenario 1, the total annual precipitation is assumed to be double that of year 2001 (i.e., 720 mm), and in scenario 2, the annual precipitation is considered to be half that of year 2001 (i.e., 183 mm). The soil moisture of different soil layers and the runoff are shown in Fig. 9 for scenario 1 (wet year). Similar graphs for scenario 2 (dry year) are shown in Fig. 10. During simulation, the matric suction values are calculated based on updated soil moisture values. The SWCCs of the different soil layers (Boese 2004) are used by the model to estimate matric suction at each time step.

Under wet conditions, no significant changes occur with regard to the amount of water that percolates to the shale layer, with the exception of a slight increase in the amount that percolates early in the winter season when the upper soil layer starts to freeze while the temperature of the lower soil layers remain above 0 °C. What really happens at the zone of interface between till and shale needs further exploration, however. The till layer continues to hold a larger amount of water (average of 20 mm higher than the year 2001 moisture level), although remaining below saturation

Fig. 8. Observed and simulated overland flow: (*a*) calibration year; (*b*) validation year.



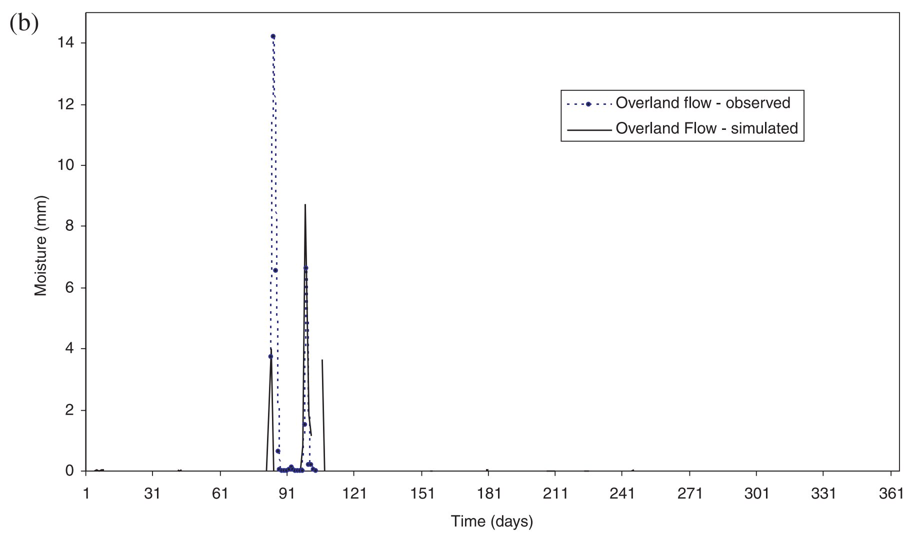


Table 4. Simulation accuracy of models I and II during calibration and validation.

		Model I		Model II	
Layer	Year	MRE (%)	RMSE (mm)	MRE (%)	RMSE (mm)
Peat	2001	12	5	12	6
	2002	16	10	8	5
Till	2001	8	19	3	10
	2002	15	32	9	21
Overall	2001	10	12	8	8
	2002	16	21	9	13

conditions. The peat layer holds an average additional 12 mm of water throughout the growing season. In this scenario, the availability of water in both the peat and till layers allows for higher amounts of evapotranspiration. In the case of scenario 2 (dry conditions), both the peat and till layers maintain moisture levels above the wilting point (approx. 20 and 90 mm for the peat and till layers, respectively) throughout the growing season. The peat layer plays an important role in dry years by holding the available moisture during snowmelt and redistributing it over time. Evapotranspiration decreases, logically, during the dry year because of higher soil suction pressure; however, moisture levels (in both peat and till layers) remain above the wilting point. This increases the possibility of vegetation survival during dry years.

Discussion

The developed system dynamics watershed model (SDWM), constructed within the STELLA object-oriented simulation environment, demonstrates potential capabilities for assessing the hydrologic performance of the watershed under consideration. The carrying function (ability to hold water and minimize deep percolation to the shale layer) and production function (making water temporally available for vegetation to grow), which are two major indicators of sustainability, are tested using the developed SDWM. Al-

Fig. 9. Soil moisture of different layers for scenario 1 (wet conditions).

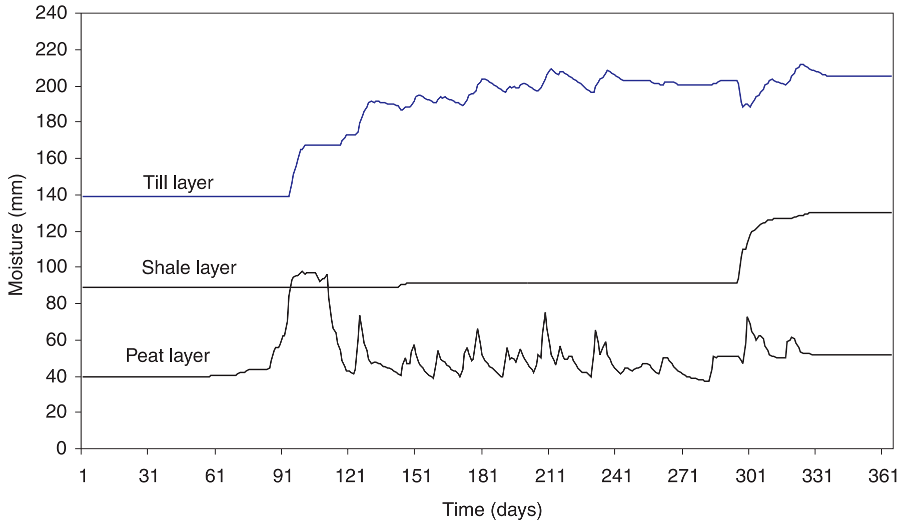
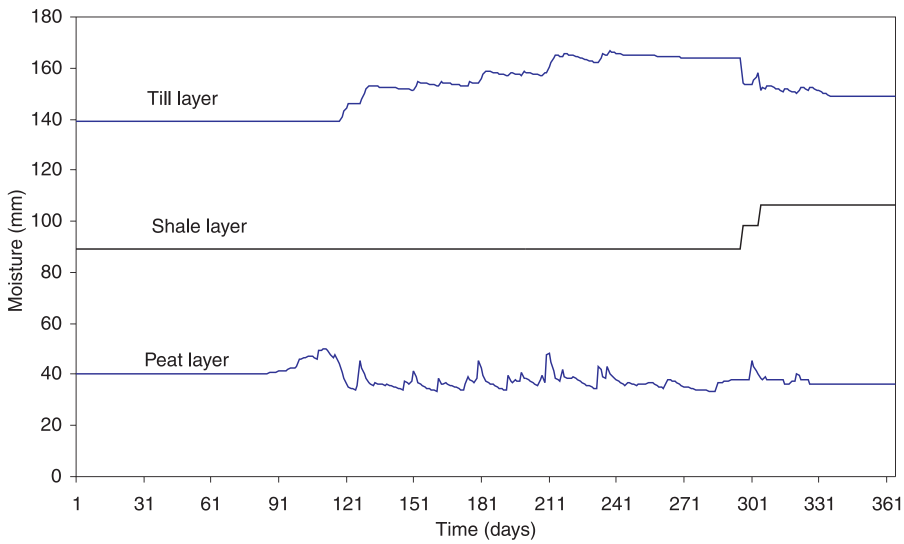


Fig. 10. Soil moisture of different layers for scenario 2 (dry conditions).



though salts and other water-quality parameters are beyond the scope of this paper, water- and soil-quality components can be added to the developed SDWM to address the performance of the reconstructed watershed in this regard. Adding other components of contaminant transports or socioeconomic indicators is easy in an object-oriented simulation environment such as STELLA.

Testing the hydrologic equilibrium and stability of the watershed and the proposed soil cover strategy is a good measure of the sustainability of the watershed. The earlier analysis indicates that the watershed is in a state of neutral equilibrium within a range of precipitation from one half to two times the normal annual precipitation. Further testing of neutral equilibrium, which means that available water is redistributed among different components of the water balance (e.g., peat storage, till storage, evapotranspiration) under different scenarios without having large amounts of water percolating to the shale, could be conducted using the developed SDWM. When a "wetter" scenario (precipitation is more than 2.5 times that of year 2001) is tested, percolation to shale started to increase, indicating a case that can be called "unstable equilibrium." This can be considered a case of failure for the proposed cover. If the frequency of precipitation in the area is known, then chances of "failure" of the cover can be identified. For example, if such a wet year has a probability of occurrence of once in 100 years, then the proposed cover can be considered risky on average 1% of the time.

It is worth mentioning that this approach assumes that the cover is not encountering geotechnical changes over time (e.g., subsidence). To address the possibility of encountering geotechnical changes, the modeling exercise can be repeated over a number of years. The redistribution of percentages of water over different components of the water balance can be observed to learn about physical evolution of the cover over time. This next step can be achieved utilizing the ongoing monitoring program on site. The SDWM is a lumped dynamic watershed model; coupling such a model with a geographical information system (GIS) can make it a distributed model that could be of greater use to hydrologists. Coupling system dynamics and GIS is a research and technical challenge that hydrologists and computer scientists need to work on.

An important note regarding observed data (soil moisture, runoff, and meteorological factors) should be taken into consideration when comparing simulated versus observed values. Although the SDWM is a lumped model indicating, for example, depth-averaged soil moisture over the entire area of 1 ha, the measurements are taken at a single location and varying depths. The spatial variability, not captured by point measurements, of hydrologic processes (Bromley et al. 2004) is expected and unavoidable. A depth-averaged value of measured soil moisture is taken as a representative of the watershed. Considering observed values to be a strict reference that should be closely simulated is unrealistic. A careful consideration of the nature of observations could lead to better models (Menenti et al. 2004).

More importantly, the developed SDWM is still at an early stage. Extending its applicability and validity over the other covers (D1 and D2) and possibly in undisturbed watersheds is necessary before concluding that the model is ready for testing possible future scenarios. This paper demonstrates the potential of this modeling approach as an easy-to-construct and easy-to-use watershed simulation environment. It is advisable to test the model thoroughly before using its results for decision support regarding the reclamation strategies of oil-sand industries.

Conclusions

Watershed modeling plays a central role in assessing the hydrologic performance of reconstructed watersheds. A system dynamics watershed model (SDWM) is developed and used in this paper to assess one of the cover strategies implemented by one of the major oil companies in northern Alberta. The developed model suggests that the proposed cover could be successful in restoring two of the major watershed functions that can label the cover strategy as a sustainable solution to the problem of watershed disturbance. The SDWM developed in this paper is a lumped hydrologic model. Coupling such a model with a GIS can make it a distributed watershed model with a more extensive application in watershed hydrology. Extensive validation and analysis of results' uncertainty of the developed model are necessary before relying on the model for future decision support in the area of reconstructed watersheds.

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