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A generic system dynamics model for simulating and evaluating the hydrological performance of reconstructed watersheds

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Abstract

The mining of oil sands in northern Alberta, Canada, involves the stripping and salvage of surface soil layers to gain access to the oil mines. The oil sands industry has committed to reconstructing these disturbed watersheds to replicate the performance of the natural soil horizons and to reproduce the various functions of natural watersheds. The selection of the texture and thickness of the reconstructed soil cover layers is based primarily on the concept that all covers must have sufficient moisture for vegetation over the growing season. Assessment of the hydrological performance of the reconstructed soil covers is crucial to select the best cover alternative. A generic system dynamics watershed (GSDW) model is developed, based on the existing site-specific SDW model, and applied to five reconstructed watersheds located in the Athabasca mining basin, Alberta, Canada; and one natural watershed (boreal forest) located in Saskatchewan, Canada; to simulate the various hydrological processes; in particular, soil moisture patterns and actual evapotranspiration, in reconstructed and natural watersheds. The model is capable of capturing the dynamics of the water balance components in both reconstructed and natural watersheds. The developed GSDW model provides a vital tool, which enables the investigation of the utility of different soil cover alternative designs and evaluation of their performance. Moreover, the model can be used to conduct short- and long- term predictions under different climate scenarios.

1 Introduction

Hydrological models have been adopted, modified, and applied to solve a wide spectrum of hydrological problems. The difficulty of modeling watershed hydrology lies primarily in that the response of the watershed system is strongly controlled by its spatial and temporal heterogeneity, and this heterogeneity cannot be precisely known or described. In general, the focus of watershed modeling studies has been on the rainfall-runoff modeling process (Beven, 2001). Over the past few decades, countless

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number of watershed models has been developed around the world for a variety of different applications. However, the main challenge remains in applying the limited and imperfect knowledge of the corresponding hydrological processes and, in the mean time, providing an acceptable prediction of the real world (Schaacke, 2002). For example, hydrological processes, such as soil moisture redistribution and evapotranspiration (ET), are intricately linked; therefore, the understanding of their mutual interaction could lead to a more accurate simulation of the processes responsible for land-atmosphere interaction (Mahmood and Hubbard, 2003).

Infiltration, soil moisture redistribution, and ET are the main hydrological processes affecting the behavior of natural and restored (reconstructed) watersheds. Hence, the proper simulation of these processes is vital to the accurate representation of the hydrology of both watersheds (Elshorbagy et al., 2007). Despite the importance of the ET process and the soil moisture redistribution in defining the water balance of the arid and semi-arid regions, relative to the rainfall-runoff relation, there is limited literature available on the simulation of both as targeted outputs. This key role, of both processes, is pronounced in the evolving hydrological behavior of the reconstructed watersheds resulting from mining industry.

The rapid growth of the oil sands industry results in a huge disturbance to the natural ecosystem where soil and overburden materials are removed to provide access to mining materials. The mining process is followed by a re-establishing process, through which the disturbed landscape is planned to replicate the performance of natural watersheds, this process is also known as land reclamation process (Haigh, 2000; Barbour et al., 2004). The adverse impact of disturbing the natural ecosystem can be intensified by the expected climate change and its projected consequences. Consequently, it is crucial to simulate and predict, as accurate as possible, the hydrological behaviour of the reconstructed watersheds (soil covers). Watershed models provide a vital tool that can assist in achieving this goal by simulating the hydrological behaviour of a variety of possible soil cover designs. The aim of this paper is to develop a generic system dynamics watershed model (GSDW), which provides a reliable, simple, and comprehensive tool that facilitates the assessment of the sustainability of various reconstructed watersheds. The validity of the proposed model is assessed thorough its capability in reproducing the hydrological behaviour of the reconstructed and natural watersheds. The proposed model can be used as a decision making tool that could contribute to the understanding of the nonlinear and complex hydrological processes of the reconstructed watersheds. The paper starts with a brief overview of the previous efforts in modelling reconstructed watersheds. The following three sections are devoted to the description of the system dynamics hypothesis, model conceptualization, and model formulation. The fourth section presents the results of the model application and simulation together with the discussion of these results. The main remarks and conclusions are provided in the last part of this paper.

2 Modeling of Reconstructed Watersheds

The literature of reconstructed watersheds, in general, emphasized the geotechnical perspective. Julta (2006) noted that most of the publications targeted modeling an individual component of the hydrological cycle. For example, the HELP (Hydrological Evaluation of Landfill Performance) model, which was developed by Schroeder et al. (1994), is one of those models. It is a water budget model through and out of landfills (Yalcin and Demirer, 2002). Berger et al. (1996) simulated the water balance of a landfill cover system using the HELP model, where they achieved good lateral drainage simulation, yet failed to model the linear leakage of comprehensive soil liners. Although this performance was attributed to the reason that HELP model was still in the evolution stage, it works better only for simple landfill covers. It has a poor performance in estimating the long-term hydrologic processes, and it considers grass as the sole vegetation type (Berger, 2000).

Shurniak (2003) used SoilCover model to predict moisture movement in a variety of reconstructed soil cover systems. The root zone water quality model (RZWQM) was also used to simulate the volumetric soil water content of the reconstructed slopes of the South West Sand Storage (SWSS) in northern Alberta (Mapfumo et al., 2006). This model is extensively used in many agricultural studies, however, it tends to overestimate the saturated hydraulic conductivity and accordingly underestimates the surface soil moisture contents, especially in wet conditions. Seep/W (GeoSlope, 1991), is another 2-dimensional finite element software, which was applied by Yanful and Aube (1993) to model the moisture retention of a soil cover consisting of clay placed between an upper fine sand layer and lower coarse sand layer. The simulated moisture contents and hydraulic heads at various depths were compared with the results of the measurements of column laboratory tests.

Elshorbagy et al. (2005) developed a site-specific system dynamics watershed (SDW) model to simulate the daily hydrological processes in an inclined reconstructed subwatershed in northern Alberta, Canada. This model was extended by Elshorbagy et al. (2007) to simulate other inclined watersheds, However, the model remained a site-specific model. Elshorbagy and Barbour (2007) presented a probabilistic approach, using the SDW model, to assess the long-term hydrologic performance of three inclined reconstructed watersheds. The validated SDW model was used along with the available meteorological historical data to generate continuous simulated records of the daily depth-averaged soil moisture content. These records were used to estimate the maximum annual moisture deficits as indicators of the hydrologic performance of the considered watershed. The probabilistic approach is used to quantify the predictive uncertainty of the SDW model. However, the efficiency of this approach depends on the reduction of the predictive uncertainty of the used model, which can be mitigated through a relatively generic model that can simulate various reconstructed and natural watersheds under potential and uncertain changes of the prevailing climatic conditions.

3 GSDW Model Development and Formulation

The proposed GSDW model is a lumped conceptual model capable of simulating various components of watershed hydrology. This model is an upgrade/generalization of the existing site-specific SDW model, which was developed by Elshorbagy et al. (2005, 2007). The model uses sets of meteorological, vegetation, and hydrological data to evaluate different hydrological processes on a daily basis. The developed model is entitled "generic" in the sense that it is aimed to be implemented on a wide spectrum of watersheds, soil cover alternatives, and topographic conditions in semi-arid regions, in a user-friendly environment, for the purpose of assessing the performance of reconstructed watersheds. The system dynamics simulation environment (STELLA), (HPS, 2001), is used as the simulation environment for modeling the watershed as a dynamic system.

The system dynamics (SD) approach is based on the understanding of the complex relationships existing among the different elements within the considered system. In general, the SD approach could be defined as; "a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behaviour" (Forrester, 1980a, 1980b). Ford (1999) defined the SD approach as a method of analyzing problems in which time is an important factor. The main issue in using the SD modelling approach is to understand the system and its boundaries, moreover, to identify its key building blocks, and the proper representation of the physical processes through relatively accurate mathematical relationships. SD models have the potential of implementing a combination of empirical formulations and physically based concepts (Elshorbagy et al., 2007). Even more, the SD approach allows for building on a tentative knowledge of the relation between two parameters to incorporate a qualitative relationship between those parameters. The proposed GSDW model will have the ability to simulate relevant hydrological processes, e.g., canopy interception, evapotranspiration, surface runoff, lateral interflow, infiltration, and soil moisture redistribution in unsaturated/saturated layers, based on the surface energy and water balances. Particular attention is given to the parameterization, where it is kept as simple as possible and, in the mean time, reliant on widely available relevant data. A schematic diagram of the major processes modelled by the proposed GSDW model is shown in Fig. 1.

Figure 1 shows the simple daily water balance of the GSDW model, which consists of three storage components, namely: (1) the canopy storage, (2) surface storage, and (3) soil storage. The canopy storage includes interception of precipitation and losses through direct evaporation. Interception losses depend mainly on the precipitation intensity, duration, and frequency. Moreover, these losses are also affected by the vegetation type and its maturity stage, which is represented by the Leaf Area Index (LAI). Meteorological conditions, such as air temperature, influence the snow melt rate of the snow pack, which in turn affect both the above surface and surface storage components.

Both the snow melt and rainfall contribute to the virtual stock named the surface water storage. The surface water storage is typically the available water for infiltration and overland flow. The rate of infiltration to the first (top) soil layer is affected by soil moisture, soil temperature, and the available water in the surface water storage. The difference between the surface water storage and the infiltrated water is the overland flow. The GSDW model takes into account the effect of layer inclination (slope), and soil and air temperature on the generation of overland flow.

The soil storage component includes the storage of different soil layers comprising the soil cover and the underneath layers. The GSDW model is accounts for different soil cover alternatives by permitting the user to incorporate up to six different soil layers. Losses from any layer storage include evapotranspiration, interflow, and downward moisture movement to the subsequent layer. The ET component of the GSDW model aggregates both evaporation and transpiration, which is controlled by the soil moisture content and other climatic conditions. The generation of interflow in any specific layer, is dependent on its hydraulic conductivity, soil temperature, soil moisture, and gradient. Based on the previous analysis, soil moisture, climatic factors and the layer gradient and air/soil temperature are the main factors controlling the two dimensional (vertical and horizontal) water movements. The SDW model (Elshorbagy et al., 2005, 2007) did not include a canopy interception losses module. Building on the existing SDW model a canopy storage module was developed and included in the developed GSDW model. Also, interflow is allowed from all layers. The main advantage of the GSDW model is its capability to handle a wide spectrum of sites (natural/reconstructed sites), various numbers of layer stratifications, thicknesses, and gradients (slopes).

3.1 Causal-Loop Diagram

The system dynamics hypothesis of the developed GSDW model is represented in a causal-loop diagram as shown in Fig. 2. The feedback loops illustrate the mutual interaction between the different factors affecting the watershed hydrological processes. The negative and positive signs denote the type of relationship between corresponding variables. Figure 2 is partitioned into several parts; (a) available water (snowfall and rainfall); (b) canopy interception; (c–f) soil layers and the surface and subsurface (vertical/horizontal) water movement dynamics.

Loop [1], in part a, shows that the canopy storage increases by the increase of the intercepted water, which leads to a reduction of the interception capacity and a consequent decrease in the interception rate. Loop [2], in the mean while, shows the adverse direct effect of direct evaporation on the canopy storage. An increase in canopy storage will lead to an increase in direct evaporation due to the increase in the surface area, which in turn leads to a decrease in canopy storage. Loop [3], in part c, demonstrates the moisture dynamics of the first layer storage. Water infiltrates into the first layer leading to a corresponding increase in the layer storage. Increasing the amount of layer storage reduces the infiltration capacity of the considered layer. As the soil moisture dynamics of all soil layers are regulated by soil temperature; frozen soil conditions limit the infiltration rate, interflow, and the available water for evapotranspiration. Loop [4], on the other hand, describes the evapotranspiration process in the first layer. An increase in the layer moisture leads to a corresponding increase in its evapotranspiration, which in turn leads to a decrease in its moisture storage content. Loop [5] represents the generation of the interflow from the first layer. It shows that an increase in the layer moisture content leads to an increase in the generated interflow, which in turn leads to a decrease in the layer storage. Following the same logic, every layer will pursue the same sequence of dynamics.

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3.2 Model Formulation

The following is presentation and explanation of the modifications and improvements suggested to the SDW model. For furtherer details on the SDW model components, reference is made to Elshorbagy et al. (2005; 2007).

3.2.1 Canopy storage

Dingman (2002) states that interception losses range from 10–40% of the gross precipitation in different vegetation patterns. Therefore, the consideration of the interception losses, as one of the hydrological water balance components of the simulated watershed, improves the AET predictability of the developed model. Two different approaches are used to incorporate the canopy interception component, based upon the data availability; (i) a simplified version of Valente et al. (1997) conceptual model, and (ii) the van Dijk and Bruijnzeel (2001) analytical model. Valente et al. (1997) developed a conceptual model, where the canopy interception component divides the gross rainfall into three downward water fluxes; (1) free throughfall, (2) canopy drip, and (3) stem-flow. This is in addition to a vertical direct evaporation component. The canopy structure is characterised by four parameters, namely; (i) canopy storage capacity, (ii) trunk storage capacity, (iii) canopy cover fraction, and (iv) trunk diversion coefficient. The GSDW model includes the corresponding parameters representing the aforementioned physical characteristics, such as the canopy storage capacity (S_c), trunk storage capacity (S_t), trunk evaporation as a fraction of the total evaporation (ε), and the canopy drip as a fraction of the drainage (1-ρ). These parameters are based on detailed information of the vegetation structure. The leaf area index (LAI) is used as an indicator of the canopy interception, which can be deduced based on the ratio of the canopy shaded areas to the bare areas. The evaporation rate from the canopy (E_c) is computed as the sum of both the trunk and the canopy evaporation. The Penman equation is used to compute the rate of evaporation (E_p) of the intercepted water. Equations 1, 2, and 3 are the mathematical representation of the evaporation rates from different

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canopy components:

$$E_{cc} = \begin{cases} (1-\varepsilon)\, E_p \left[C_c(t)/S_c\right] \mathrm{for} C_\mathrm{c}(t) < \mathrm{S_c} \\ (1-\varepsilon)\, E_p \mathrm{for} C_\mathrm{c}(t) \geq \mathrm{S_c} \end{cases} \tag{1}$$

$$E_{ct} = \begin{cases} \varepsilon E_p \left[C_t(t)/S_t\right] \mathrm{for} C_\mathrm{t}(t) < \mathrm{S_t} \\ \varepsilon E_p \mathrm{for} C_\mathrm{t}(t) \geq \mathrm{S_t} \end{cases} \tag{2}$$

$$E_c = (E_{cc} + E_{ct})\, F \tag{3}$$

where E_{cc} is the leaves evaporation, $C_c(t)$ is the actual amount of water stored on the canopy leaves in mm, E_{ct} is the trunk evaporation, $C_t(t)$ is the actual amount of water stored on the trunk in mm, and F is the fraction of area covered by the forest canopy. The main practical drawback of the Valente et al. (1997) model lies in its extensive data requirements.

The van Dijk and Bruijnzeel (2001) model; based on a modification of Gash et al. (1995) interception model, elegantly retains some of the simplicity of the empirical approaches. It is based mainly upon the LAI, and the canopy storage (S_c). The model assumptions are; (i) the relative evaporation rate $\bar{E}/\bar{R}$ can be expressed as a function of LAI, and (ii) the canopy storage capacity (S_c) is linearly related to LAI. Dijk and Bruijnzeel (2001) approach is represented in the GSDW model with the following formulas:

$$S_c = S_L LAI \tag{4}$$

$$c = 1 - e^{-k.LAI} \tag{5}$$

$$E_c = c.E_p \tag{6}$$

where S_L denotes the specific leaf storage (the depth of water retained by the leaf per unit LAI). TheS_L-values as suggested by Pitman (1989) experimentally ranges between

(0.4–5.88); c is the canopy cover fraction, k is the extinction coefficient and it depends on the leaf inclination angle and distribution; the k-values ranges between 0.2 and 0.8; and E_p is the Penman potential evapotranspiration. The GSDW model provides the user with the flexibility to use either approaches, in addition to a third selection, where the canopy interception is not accounted for due to lack of required information on the canopy coverage, especially in the newly reconstructed watersheds.

3.2.2 Surface water storage

The change in the surface water storage (SW) can be expressed mathematically by:

$$\frac{d(SW)}{dt} = P - f_{L1} - O_F \tag{7}$$

where P (mm/day) represents the precipitation, in either the form of snow or rainfall, f_{L1} is the infiltration rate to the top soil layer (mm/day), and O_F represents the overland flow in mm/day.

3.2.3 Soil storage

The developed GSDW model is designed to facilitate the consideration of multilayer soil cover, as opposed to pre-set number of covers in the SDW model. This expands the applicability of the model to simulate a wide variety of alternative, in addition to, enhancing its soil moisture predictably. Therefore, the vertical movement of the soil moisture between any two subsequent layers is described by considering layer (i) as a control volume and schematizing the water balance. As an example, the change of the moisture storage in the ith layer depends on downward movement of water from the upper i-1th layer, evapotranspiration, interflow from the ith layer, and the downward water movement to the underlying i+1th layer. Therefore, the change of moisture storage in the ith layer can be expressed as follows:

$$\frac{dS_i}{dt} = f_i - f_{i+1} - ET_i - I_i \tag{8}$$

where S_i is ith layer storage in mm, f_{i+1} is the downward water movement rate to the underlying layer in mm/day, I_i is the interflow rate for of the ith layer in mm/day, and ET_i is the evapotranspiration rate from ith layer in mm/day.

Voinov et al. (2004) suggested that infiltration rate of the top soil layer is equal to rainfall intensity before soil saturation is reached. In fact, some studies suggested that the rate of infiltrated water from a typical cover system is correlated to the degree of saturation of the soil, soil moisture retention characteristic, and climatic factors (e.g. rainfall) (Milczarek et al., 2000; Milczarek et al., 2003). On the other hand, Green–Ampt equation governs the vertical movement of water during the saturation stage under the condition of soil temperature being greater than zero (unfrozen soil). The infiltration capacity (rate) based on total infiltration volume is expressed by the Green–Ampt equation in the case of a fully defrosted saturated soil (Dingman, 2002):

$$f_i = K_{si}\left(1 - \frac{(\theta_{si} - \theta_{ii})\psi_i}{F_i}\right) \tag{9}$$

where K_{si} is the saturated hydraulic conductivity of the ith layer in mm/day, θ_{si} is the saturated moisture content of the ith layer (%),θ_{ii} is the initial moisture content of the ith layer (%),ψ_i is the suction pressure head at the wetting front in the ith layer in mm, and F_i is the cumulative volume of infiltration in the ith layer in mm.

The literature advocates that some methods are used for quantifying infiltration into frozen soils; however, one of the drawbacks of such methods is the intensive data requirement during frozen conditions (Elshorbagy et al., 2007). Other studies denote that the frozen soil layer do not impede infiltration (Iwata et al., 2008). An empirical approach for snowmelt infiltration was suggested by Li and Simonovic (2002) and has been validated by Julta (2006). This approach is based mainly upon the idea that infiltration rates in frozen soils are influenced by temperature and temperature accumulation. The infiltrated water will gain its dynamics based upon the temperature index, where soil will refreeze if the temperature drops below zero for a number of days. The active temperature accumulation will be lost and will start again from zero (Li and Simonovic, 2002). Consequently, the infiltration into frozen soil is computed by multiplying infiltration rate of the ith layer, f_i, by an empirical coefficient, C_{ti}.Reference is made to Elshorbagy et al. (2007) for further details.

The movement of water between any subsequent layers is limited if the upper layer moisture content is less than the wilting point (residual moisture content). Moisture movement will start when the upper layer moisture is greater than the residual moisture content, and it starts contributing to the lower layer moisture until it reaches saturation. Once the lower layer reaches saturation, the maximum rate at which water can be absorbed by the lower layer will correspond to the minimum value of the saturated hydraulic conductivity of this layer and the subsequent layer. Otherwise, the following logic will apply: if (soil temperature of (i) greater than 0°C) then (if ($\Psi_{i-1} > \Psi_n$) then (no movement of water) else (if ($\theta_{i-1} >$ *wilting point of* ($i-1$) *layer*) then (if (($i-1$) *layer is saturated*) then (Min (drainable water from layer ($i-1$), follow Eq. 9)) else (follow Eq. 10)) else (no movement of water)) else (infiltration in frozen soil) where, Eq. 10 is an empirical equation, which can be written as follows (Elshorbagy et al., 2007):

$$f_i = \frac{\theta_{i-1}}{\theta_i} \frac{S_{i-1}}{\Delta t} I_{ci} \tag{10}$$

where I_{ci} is the coefficient of the ith layer infiltration, which is determined during calibration of the model, and Δt is the solution time interval. Equation 10 suggests that the moisture redistribution between any subsequent layers is strongly dependent on the moisture contents of both layers. In addition to this, no downward moisture movement is allowed if the suction of the upper layer is greater than that of the lower layer.

3.2.4 Evapotranspiration module

In the developed model, the potential evapotranspiration is computed using the penman equation derived in Mays (2005), while an empirical formula is used for the actual evapotranspiration calculation, based on the simulated soil moisture index, and the air temperature. To calculate the actual evapotranspiration from any soil layer; an empiri-

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cal formulation used by (Julta, 2006; and Elshorbagy et al., 2007) takes into consideration the available moisture, air and soil temperatures.

Sankarasubramanian (2002) mentioned that the classical actual evapotranspiration relationships perform poorly for basins with low soil moisture storage capacity. However, the previous empirical formulas proved to give better simulation results than the conventional potential Penman equation for PET (Elshorbagy et al., 2007). These parametric empirical equations provide better estimates of the actual evapotranspiration due to their dependence on the soil moisture content of the considered layer. The GSDW model adjoins both the estimated E_c from the canopy storage and from different soil layers (net AET) to model the total actual evapotranspiration (AET).

3.2.5 Interflow component

The interflow component is restricted to the incidence of sloping layers. The model formulations account for the angle of inclination, which affects the interflow rate. Interflow (I_i, mm/day) from the ith layer is estimated as follows:

$$I_i = \left(\frac{S_i}{\Delta t} - \frac{\theta_{si} D_i}{\Delta t}\right) \cdot C_i \cdot C_{\text{Slope}} \tag{11}$$

where C_{Slope} is the slope coefficient and it depends on the slope value. D_i is the depth of the ith layer in mm, and C_i is the interflow coefficient, it has to be mentioned that C_i is a calibration parameter. Interflow generation is mainly restricted to two conditions; (a) the temperature of both layers, (i) and ($i-1$), are above zero, and (b) the ith layer is fully saturated. However, if the temperature of layer ($i-1$) is less than 0°C and the soil temperature of the ith layer meets the previous conditions, then interflow is computed by multiplying the interflow coefficient by the rate of available water in the ith layer and the slope coefficient.

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3.2.6 Overland flow component

Overland flow is estimated by considering the excess rainfall, which is directed as an overland flow (O_F) in the summer as soon as the top soil layer becomes fully saturated, and it is computed as follows:

$$O_F = \left(\frac{SW}{\Delta t} - f_{L1}\right) \cdot C_{\text{Slope}} \tag{12}$$

where f_{L1} layer (1) infiltration rate, O_F is the overland flow in mm/day. The overland flow generation is also dependant upon the air/soil temperature and the gradient of the soil cover.

4 Case Studies

4.1 Reconstructed watersheds

The reconstructed watersheds study area is located in north of Fort McMurray (57°39′N and 111°13′W), northern Alberta, Canada. The oil sands industry has developed a system for stabilizing the surface of the reconstructed soil covers that enables re-vegetation. A few reconstructed watersheds formed of various soil covers (various soil types, layering, and depths) are selected for this study: (i) three inclined prototype soil covers (D1, D2, and D3-Covers). The three covers were constructed with a thickness of 0.5 m, 0.35 m, and 1.0 m compromised of 0.2 m, 0.15 m, and 0.2 m of peat/mineral mix overlying 0.3 m, 0.2 m, and 0.8 m thickness of glacial till, respectively, overlying saline sodic shale. The purpose of these experimental covers is to evaluate the performance of different alternatives in terms of moisture holding capacity and sustaining the vegetation. The three covers has a slope of 5H:1V with an area of 1 ha each. These covers were constructed in 1999 and seeded with barley nurse crop, and tree seedlings of spurce and aspen (Boese, 2003). The D-covers were used by Elshorbagy et al. (2007) to develop the site-specific SDW model; (ii) Hill top: a horizontal reconstructed cover system located on the South Bison Hill (SBH), attached to the D-covers, was constructed in 2001 of 0.2 m of peat/mineral mix overlying 0.8 m of till. The area of the site is approximately 2 km^2, rising 60 m above the surrounding landscape and has a large relatively flat top several hundred meters in diameter. The major plant species on the top of the SBH are foxtail barley (*Hordeum Jubatum*), and minor species include fireweed (*Epilobium angustifolium*) (Parasuraman et al., 2007); (iii) South West Sand Storage (SWSS), which was constructed of 0.2–0.4 m of Till/secondary cover material over 1.0 m of tailings sands. It is currently the largest operational tailings dam in the world, with approximately 40 m high with a 20H:1V side slope ratio. The vegetation varies with groundcover including horsetail (*Equisetum arvense*), fireweed (*Epilobium angustifolia*), and white and yellow clover (*Melilotus alba, Melilotus officinalis*). Tree species include Siberian larch (*Larix siberica*), hybrid poplar (*Populus sp. hybrid*), trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and willow (*Salix sp.*) (Parasuraman et al., 2007).

An intensive monitoring program for measuring both hydrological and meteorological measurements is carried out in these experimental fields to monitor the evolution of the reconstructed watersheds. The hydrological variables include the matric soil suction, volumetric moisture content (measured on bi-daily using TDR sensors at different depths), and soil temperature of different soil layers, measured on hourly basis, for the corresponding soil moisture measurement depths. Additional monitored variables include runoff and interflow. Measurements of the latent heat fluxes are made with the eddy covariance technique (EC) and reported in 30-min interval. A weather station is used to provide hourly meteorological measurements of air temperature (AT), precipitation (P), net radiation (NR) and other meteorological variables. A Bowen Ratio station is also used to estimate the potential evaporation. It measures AT and water vapour gradients on hourly basis. More details on the field instrumentation and monitoring program can be found in Boese (2003); and Julta (2006).

4.2 Natural Watersheds

The GSDW model is used to simulate the hydrological performance of a natural watershed to validate its capability in capturing the dynamics of the different water balance components in natural watersheds. Verifying the ability if the GSDW model to simulate both reconstructed and natural watersheds confirms the utility of the proposed model to conduct short- and long-term predictions under different climatic conditions. Therefore, the area of the former Boreal Atmosphere Exchange Study (BOREAS), covering a large portion of Saskatchewan and Manitoba with an area of 1000 km by 1000 km, is used as a study area that represents a mature natural watershed. This region includes young and old aspen and old black spruce forests. The old aspen site (OA), considered in this study, is located near the south end of Prince Albert National Park, Saskatchewan (53.629° N, 106.198° W). The field instrumentation of the OA site has been providing continuous measurements since 1997 as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program (http://berms.ccrp.ec.gc.ca). The soil is well drained loam to clay loam. The top 0.1 m layer is an organic layer (leaf litter, plus fermentation layer); 0.07–0.3 m of till mixed with sand and clay. Overlying a layer of 0.45 m derived from gravely and clay enriched till. The forest canopy is dominated by trembling aspen with an average height of 21 m (Balland et al., 2006). AT and P data are collected at 30-min intervals and are available from BOREAS/BERMS data base (http://berms.ccrp.ec.gc.ca/data/data_doc/BERMS_main.doc).

Thermocouple sensors are set to measure the soil temperature every 30-min at 0.02, 0.05, 0.10, 0.20, 0.50 and 1.00 m below the moss layer. CS615 soil moisture sensors (TDR) are used to measure the volumetric moisture content of the soil at 0.08, 0.23, 0.45, and 1.05 m below the ground surface. NR is measured using Middleton CNR-1 net radiometer above the canopy. Measurements of the latent heat fluxes are made with the eddy covariance technique (EC) and reported with 30-min interval. LAI is measured near the flux tower using a plant canopy analyzer (PCA) (model LAI-2000). Additional information regarding the saturated hydraulic conductivity and the soil water

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retention function could be obtained from Cuenca et al. (1997). The GSDW model was calibrated on the year 2000 data and validated with year 1999 data. Reconstructed and natural watersheds evaluated in this study are well instrumented to permit tracking of hydrological changes.

5 Results and Analysis

5.1 Calibration and validation of the GSDW model

The goodness-of-fit between the measured and simulated datasets are generally quantified using multiple performance indicators, covering different aspects of comparison. This paper uses the root mean square error (RMSE), the mean absolute relative error (MARE), and the correlation coefficient (R) as the main performance indicators, in addition to the visual comparison. Both RMSE and MARE are overall error measures, where the first is a real valued metric while the latter is a relative value metric. The RMSE is biased towards high values, which tend to produce high error values, while the MARE is less sensitive to high values, as it does not square the error magnitude (Dawson et al., 2007). Due to these limitations, R is used as a complementary error measure that quantifies the overall agreement between the observed and predicted values. The RMSE, MARE and R statistics are calculated using the following equations:

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2\right]^{0.5} \tag{13}$$

$$\mathrm{MARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{O_i - S_i}{O_i}\right| \tag{14}$$

$$R = \frac{\sum_{i=1}^{n} (O_i - \bar{O}_i)(S_i - \bar{S}_i)}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O}_i)^2 \sum_{i=1}^{n} (S_i - \bar{S}_i)^2}} \quad (15)$$

where n represents the number of instances presented to the model; O_i and S_i represent observed and simulated counterparts; and $\bar{O}_i$ and $\bar{S}_i$ represent the mean of the corresponding variable. As mentioned before, most of the watershed modelling efforts was focused on modeling the rainfall-runoff process, which plays a key role in understanding the hydrological condition of the concerned watersheds and predicting their behaviour over time. These predictions are used in flood warning systems, navigation, water quality management and many water resource applications. However, the land reclamation of disturbed watersheds concentrates on replicating the performance of natural watersheds in terms of supporting the vegetation growth. Consequently, it is crucial to simulate and predict, as accurate as possible, the overall hydrological behaviour; not only runoff generation but also other hydrological processes that directly impact the ecological function of the watershed. As a result, the calibration of the GSDW model was performed based on two main hydrological processes, directly connected with the ecological function of the reconstructed watersheds; namely; soil moisture, and the actual evapotranspiration. The calibration was performed by setting individual parameter values and executing a series of simulations. This process was repeated (trial and error) until no further improvement in the values of the error measures, and the visual match between simulated and observed AET, could be attained by changing the parameter values. It has to be noted that the GSDW model is also capable of predicting the runoff generated by the reconstructed watersheds, as will be shown later in this section.

The reason for using various sites in this study was to test the model performance over a variety of different reclamation strategies compared to at least one natural site. For example, the model is applied to an inclined soil layers site, as in the case of the

D-covers and the SWSS sites on a set of different soil layers with a variety of thicknesses and for both reconstructed and natural watersheds. Table 1 lists the calibration parameters used for calibrating the model on the different study areas together with their corresponding values. As expected in arid and semi-arid regions, the ET process and soil moisture content play the dominant role in the hydrological performance of the watersheds. Therefore, the calibration of the GSDW model indicates the model sensitivity to the lambda coefficients ($\lambda\, n$), which is a main factor in the AET equations, and the Infiltration coefficients (Icn), which directly affects the moisture distribution in each layer.

5.2 Simulation results of the GSDW model

Table 2 lists the model performance indicators with regard to its ability to simulate the soil moisture content of the study sites. The values of RMSE, MARE, and R were satisfactory in most cases. The results presented in Table 2 show that the model performance with regard to the D-covers is quite comparable to the findings of Elshorbagy et al. (2007) using a site-specific model built for the D-covers. For the SBH, SWSS and OA sites, the model provided satisfactory results, the RMSE values ranges between 2.5–4.8 mm, which indicates that the average error is not more than ±5 mm away from the mean soil moisture value.

The D2 cover soil moisture dynamics has a flashy response compared to the other two D-covers. Moreover, the RMSE of the GSDW model is lower than the values obtained from the site-specific SDW model; which indicates a considerable improvement. This could be attributed to the modifications incorporated into the GSDW to account for the contribution of the developing canopy as well as the stabilizing of the D-covers in general. The R statistic indicates that the GSDW model captures the general trend of the soil moisture in particular for the surface peat layer where R ranges from 0.30 to 0.77 in the validation phase. The subsurface till layer of the D2-cover shows a relatively low correlation of 0.10, whereas the D3-cover and the SWSS site show negative correlation coefficients, which can be attributed to the high spatial variability of the soil moisture measurements in the reconstructed watershed, as well as the effect of the depth- averaging.

The simulated soil moisture dynamics of the surface and subsurface soil layers are shown in Figs. 4, 5, and 6 for the SWSS, SBH, and the natural old aspen watersheds, respectively. For the three figures, in the winter period, there was no significant dynamics for the moisture content because soil during this period was and is usually frozen and the model behaved accordingly. As cited by Boese (2003), the sensors used for the measurement of soil moisture at the study sites were not operating reliably during the frozen conditions; also, the ET values should be neglected during the winter season. Therefore, the evaluation of the soil moisture behaviour in the winter season is not significant and may mislead the analysis of the model results. Therefore, only the values of the growing season are considered.

As the air temperature reaches active threshold value, snow starts melting and infiltrates into the soil layers. A sudden increase of moisture content ensues once the surface layer is defrosted, and it corresponds to the amount of snow that is accumulated when the active temperature was below zero. After the snowmelt period, soil moisture in the surface layer fluctuates due to the variation of rainfall intensity and evapotranspiration. This period lasts until the temperature falls down below the active air temperature and the soil starts refreezing again in the fall. Figures 4, 5, and 6 show consistency of soil moisture profiles with rainfall events. The surface layer storage component is responsive to rainfall events, whereas the responses of the subsurface layers are not as fast. In general, the results indicate that the simulated soil moisture patterns are quite similar to the observed patterns. In Fig. 4, there are few recorded increases in the observed soil moisture, in the SWSS site, though the soil was frozen, this could be attributed to either an error in the measurement or contribution of the preferential flow to the soil pores. Figures 5, and 6 show an increase in the simulated soil moisture storage in the 2nd layer during the summer period, in both the SBH (year 2006) and OA (year 1999). This sudden increase is correlated with a rainfall event of 41 mm and 60 mm, respectively.

In case of sudden rainfall events, the increase in the soil moisture storage is due to the restriction on the lateral subsurface flow movement in flat landscapes. Figure 7 presents the cumulative AET over the growing season period for the validation years measured using the EC against the simulated AET values. The graph presents an overall agreement of the observed and the simulated AET for the three sites, in both magnitude and trend. The reasonable match between measured and simulated AET values provide another indication of the ability of the GSDW model to capture the dynamics of the hydrological processes in the reconstructed and the natural sites. The model slightly overestimated the cumulative AET fluxes in both the reconstructed SWSS and the natural OA sites, where the measured AET values using the EC method were 319 mm and 338 mm, respectively. The corresponding simulated AET values were 326 mm and 365 mm, respectively. For the SBH site, the GSDW model underestimated the cumulative AET values, with a measured cumulative AET of 276 mm and a simulated corresponding AET flux of 261 mm. The error between the measured and simulated cumulative AET flux values for the SWSS, SBH, and the OA sites were 2%, 5%, and 8%, respectively.

Figure 8 demonstrates the precipitation time series of 2006 jointly with the corresponding observed and simulated overland flow for the SBH site. As shown in the figure, the measurements do not show any considerable overland flow, except a small event due to snowmelt. In the summer, although there was a significant precipitation event around day 190, no overland flow was recorded but the GSDW model captured the events and produced considerable overland flow in the considered time period.

6 Discussion

During the preliminary stages of the watershed development, soil moisture plays the key role in the vegetation growth especially in the root zone layers (Kilmartin, 2000). Therefore, there is a need for a tool that facilitates the simulation of the response of various soil cover designs to evaluate their performance. The GSDW model simulates the soil moisture in different sites reasonably well. The model was able to simulate the soil moisture response with a reasonable accuracy of less than 5 mm, on average, away from the observed values. It has to be noted that many previous efforts of simulating similar sites resulted in agreement between the observed records and the simulated values in trend only, not in magnitude. For example, Balland et al. (2006) modeled the snow pack, soil temperature, and soil moisture in the OA site, where there was an agreement between the measured and simulated snow pack and soil temperature. However, Balland et al. (2006) mentioned that for the simulated soil moisture, the agreement was in trend not in magnitude. They attributed this difference in the model performance to local conditions and actual sensor surroundings, in addition to different uncertainties associated with the modeling procedure itself.

Generally three sources of uncertainties in the modeling process can be distinguished; errors in input variables, model assumptions and parameterization, and algorithms of process description. Gee and Hillel (1988) pointed out that precision in precipitation is seldom less than ±5%. The EC method, which is used as a direct measurement of the AET, have an accuracy range from ±15 to ±20% for hourly evapotranspiration measurements and up to ±8 to ±10% for longer periods (Eichinger at al., 2003; Strangeways, 2003). However, the GSDW model managed to simulate the cumulative AET to a very reasonable accuracy, less than ±8% of the annual measured AET value, with minor overestimation and underestimation periods. These differences can be attributed to the canopy effect and other sources of uncertainties in the model formulation itself. Also, the propagation of errors in the water balance may result in uncertainty in the simulation of any hydrological process.

The spatial and temporal variability of soil physical parameters within the same site adds an extra level of uncertainty to the measured data. The required characteristic of the soil physical properties for the GSDW model, such as the saturated hydraulic conductivity and the pore size distribution, are subject to high degree of spatial and temporal variability (particularly in reconstructed soil covers). As tabulated by Elshorbagy et al. (2007) the saturated hydraulic conductivity, as an example, increased by 400% from 2000 to 2001. Therefore, a safe monitoring period for the reconstructed watersheds is essential; it is suggested by Rick (1995) to be a seven years period. This monitoring period will allow tracking of different changes and evolution encountered in reconstructed watersheds.

The GSDW model does not account for macrospores; nevertheless, flow in macrospores play an important role for soil water fluxes. Therefore, further improvement to the GSDW model could be achieved by incorporating macrospores flow, which will enhance soil moisture simulation, and consequently other hydrological processes. As expected in arid and semi-arid regions, the GSDW model shows that the AET process and soil moisture content play the dominant role in the hydrological performance of the watersheds. The sensitivity of the model to the ET-related calibration parameters confirms this fact and validates its structure to reasonably simulate different hydrological processes in the reconstructed watersheds.

7 Conclusions

The present study presented a generic system dynamics watershed model (GSDW), which provides a simple, reliable, and comprehensive tool that facilitates the hydrological simulation tasks, and thus the assessment of the sustainability of various reconstructed watersheds. It is a lumped conceptual model capable of simulating various components of watershed hydrology. The model uses sets of meteorological, vegetation, and hydrological data to evaluate different hydrological processes on a daily basis. The validity of the proposed model was assessed by evaluating the predicted soil moisture, actual evapotranspiration, and runoff. The GSDW model simulates the different hydrological processes, e.g. soil moisture redistribution, actual evapotranspiration, and runoff, in different sites reasonably well (trend and magnitude). The simulation results show that the model performance with regard to the D-covers is quite comparable to the findings of Elshorbagy et al. (2007), with considerable improvements in soil moisture simulation. For the three case studies, the model provided good results, based on the three selected performance measures. Spatial and temporal variability of the soil moisture measurements and the depth-averaging procedure sometimes affect the values of the performance measures, and consequently the overall assessment of the GSDW model. However, both the simulated soil moisture and runoff show consistent behaviour with the different rainfall events, which verify the validity of the GSDW model results. As expected, the GSDW model results indicate the sensitivity of the top layer to rainfall events and other meteorological conditions, compared to the trimmed effect on the response of the subsurface soil layers. Generally, the GSDW model is capable of capturing the dynamics of the various water balance components in both reconstructed and natural watersheds. The developed GSDW model provides a vital tool, which enables the investigation of the utility of different soil cover alternative designs and evaluation of their performance. The model facilitates further probabilistic analysis and scenario analysis, which provides the mining industry with a comprehensive decision support tool.

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Table 1. Calibration parameter values for the developed GSDW model.

Parameter	D1	D2	D3	SBH	SWSS	OA
Infiltration coefficient (I_{c1}) *(dimensionless)*	0.0044	0.008	0.08	0.003	0.02	0.003
Infiltration coefficient (I_{c2}) *(dimensionless)*	0.003	0.004	0.002	0.002	0.002	0.002
c_i^a *(dimensionless)*	6	6	6	4	6	4
C_1^b (mm/day°C)	0.22	0.45	0.35	0.15	0.35	0.1
C_2 (mm/day°C)	0.16	1.7	0.03	0.1	2.1	1.9
C_3 (mm/day°C)	0.02	0.1	0.02	0.09	0.02	0.09
Interflow coefficient (C_I) *(dimensionless)*	0.3	0.3	0.3	–	0.3	–
Lambda[c] (λ_1) *(dimensionless)*	5.15	3.15	3.15	2.7	3.95	1.6
Lambda (λ_2) *(dimensionless)*	1.1	0.3	1.3	1.9	0.9	2.9
Lambda (λ_3) *(dimensionless)*	0.2	0.2	0.3	0.3	0.2	0.3
Melt factor *(dimensionless)*	0.7	0.6	0.7	0.5	0.7	0.6

[a] c_i is an exponent describing the influence of TI on soil defrosting;
[b] c_1 evapotranspiration constant (mm/day°C) from the (1st layer; and
[c] λ_i is an exponential coefficient, used to calculate the AET, modified from the SDW to be temperature dependant.

Table 2. Performance Statistics of the GSDW Model.

Site	Layer	Year	MARE (%)	RMSE (mm)	R
D1[a]	Peat	2005	7	2.9	0.83
		2006	13	3.5	0.30
	Till	2005	2	1.5	0.32
		2006	7	2.7	0.62
D2[a]	Peat	2005	18	3.8	0.44
		2006	14	3.4	0.42
	Till	2005	26	4.1	0.33
		2006	29	4.4	0.10
D3[a]	Peat	2005	11	3.3	0.77
		2006	8	3.1	0.57
	Till	2005	2	2.4	0.4
		2006	6	4.3	–0.22
SBH[a]	Peat	2005	9	3.0	0.71
		2006	6	2.5	0.59
	Till	2005	3	2.9	0.49
		2006	5	4.0	0.35
SWSS[b]	Till	2005	6	3.1	0.35
		2006	6	3.1	0.67
	Tailing sand	2005	10	4.8	–0.1
		2006	8	4.1	0.44
Old Aspen[c]	A-Horizon	1999	9	2.8	0.69
		2000	7	2.8	0.87
	B-Horizon	1999	10	4.4	0.87
		2000	5	3.1	0.16

[a] Calibration year 2005; validation year 2006;
[b] Calibration year 2006; validation year 2005; and
[c] Calibration year 2000; validation year 1999.

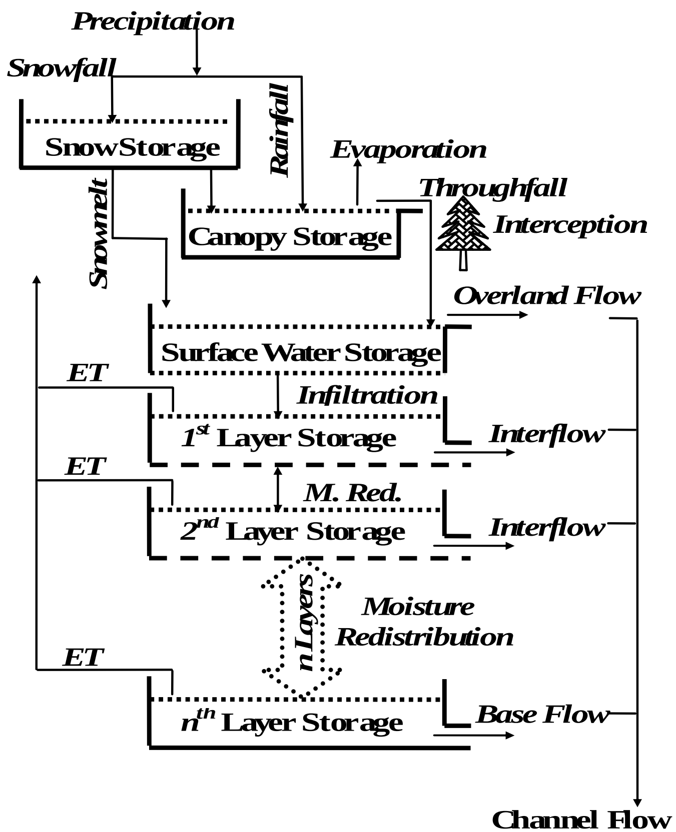

Fig. 1. A schematic diagram of the GSDW model structure.

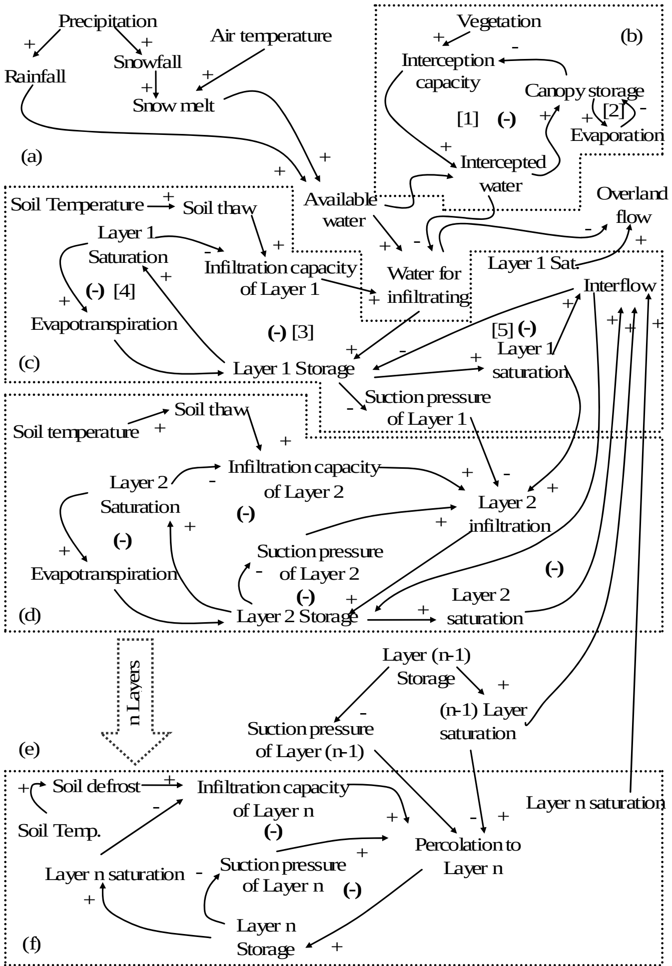

Fig. 2. Causal-loop diagram of the developed GSDW model.

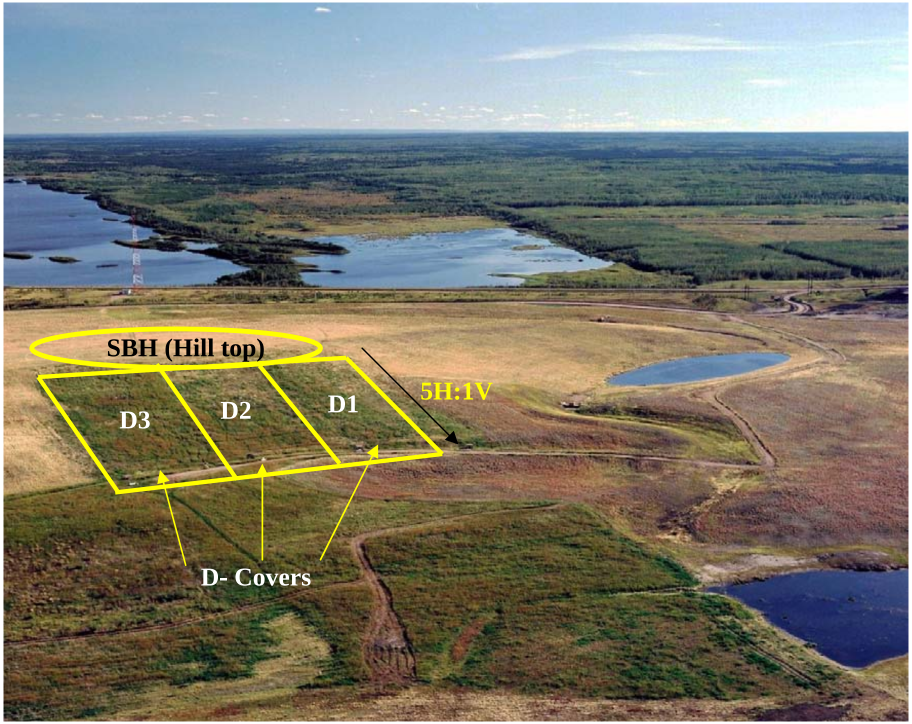

Fig. 3. South Bison Hill (SBH) hill top and the D-Covers (after Julta, 2006).

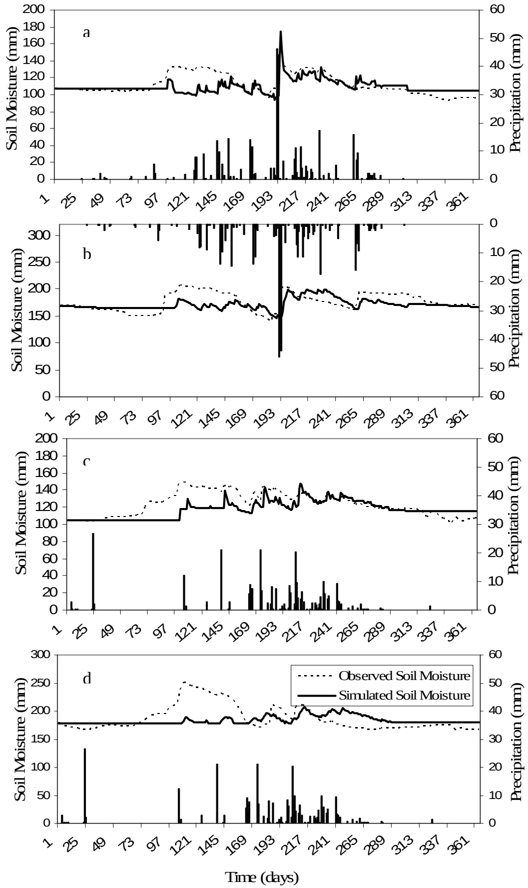

Fig. 4. Simulated and observed moisture in the SWSS watershed; **(a)** Till layer calibration (2006); **(b)** Tailings sand layer calibration (2006); **(c)** Till layer validation (2005); **(d)** Tailings sand layer validation (2005).

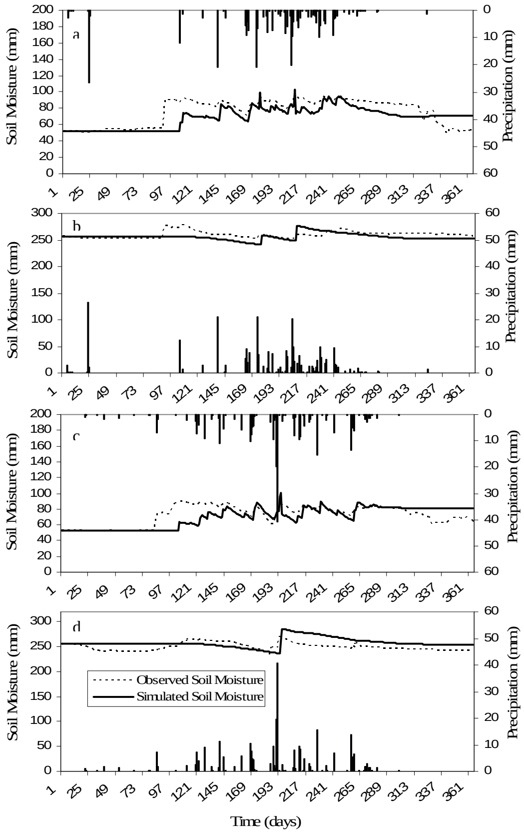

Fig. 5. Simulated and observed moisture in the SBH watershed; **(a)** Peat layer calibration (2005); **(b)** Till layer calibration (2005); **(c)** Peat layer validation (2006); **(d)** Till layer validation (2006).

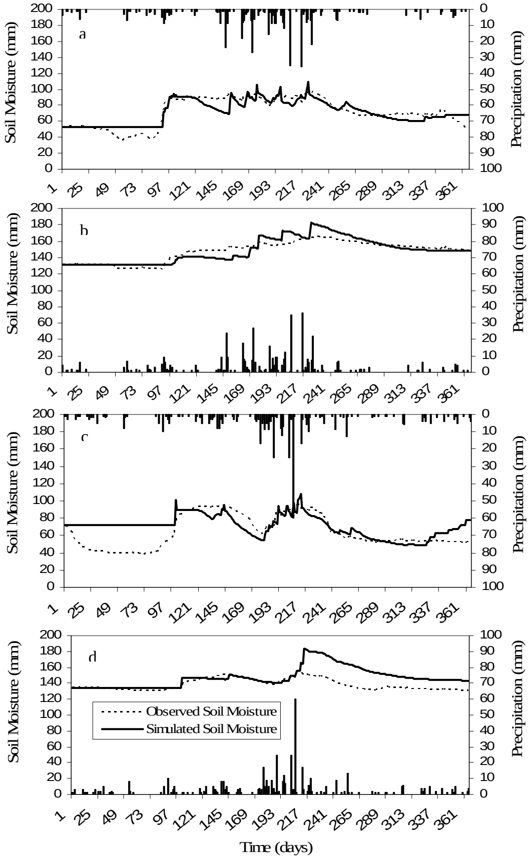

Fig. 6. Simulated and observed moisture in the Old Aspen watershed; **(a)** A-Horizon calibration (2000); **(b)** B-Horizon calibration (2000); **(c)** A-Horizon validation (1999); **(d)** B-Horizon validation (1999).

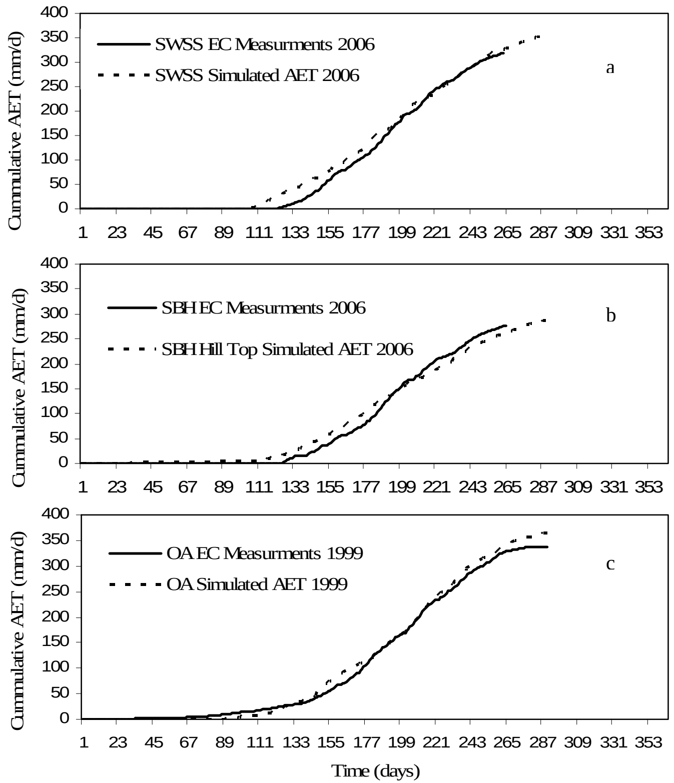

Fig. 7. Simulated and observed actual cumulative evapotranspiration for the SWSS, SBH, and OA sites, respectively.

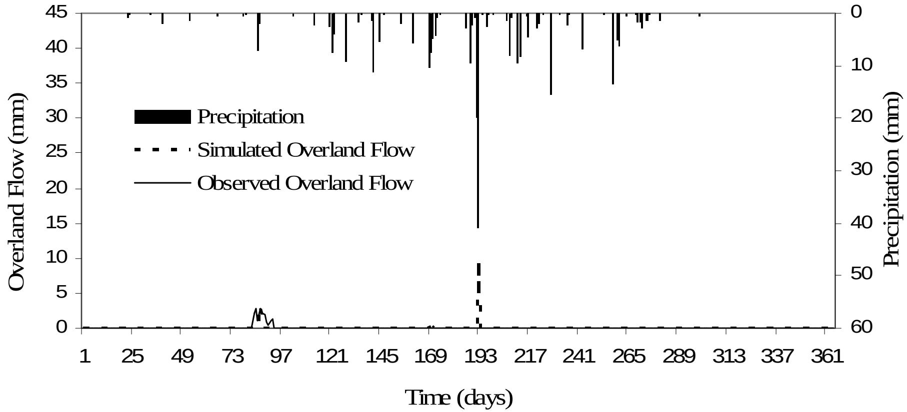

Fig. 8. Simulated and Observed Runoff (overland flow) and precipitation of the SBH Site in 2006.