# Reclamation for aspen revegetation in the Athabasca oil sands: Understanding soil water dynamics through unsaturated flow modelling

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[1]University of Alberta, Earth and Atmospheric Sciences. Edmonton, Alberta, Canada T6G 2E3; [2]University of Alberta, Department of Biological Sciences, Edmonton, Alberta, Canada T6G 2E9; [3]Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, Ontario, Canada N2L 3C5; and [4]CSIRO Land and Water, Glen Osmond, South Australia, Australia SA 5064. Received 19 November 2010, accepted 14 July 2011.



Carrera-Hernández, J. J., Mendoza, C. A., Devito, K. J., Petrone, R. M. and Smerdon, B. D. 2012. **Reclamation for aspen revegetation in the Athabasca oil sands: Understanding soil water dynamics through unsaturated flow modelling**. Can. J. Soil Sci. **92**: 103–116. Reclamation of mined areas in the Athabasca oil sands region is required by law, with the ultimate goal of revegetating to species characteristic of predisturbance native plant communities. To develop adequate reclamation strategies, an analysis of soil water dynamics is of utmost importance, as is understanding the impact of the thickness of the reclamation cover. In this work, soil water dynamics and fluxes at the water table were simulated for three reclamation scenarios and compared with the fluxes obtained for natural conditions assuming that aspen is the target reclamation species. According to the simulations, a reclamation thickness between 0.5 and 1.0 m can be used to provide water for revegetation. The numerical simulations show that the reclaimed landscapes have fluxes at the water table that exhibit less fluctuation than natural conditions. To limit the interaction between the water table and atmospheric fluxes, and to limit upward flux, the water table should be deeper than 2.0 m on reclaimed landscapes that use aspen for revegetation, particularly when reclamation takes place during a dry climatological cycle.

**Key words:** Unsaturated flow, reclamation, revegetation, numerical modelling

Carrera-Hernández, J. J., Mendoza, C. A., Devito, K. J., Petrone, R. M. et Smerdon, B. D. 2012. **Restauration des sols par plantation de trembles dans la région des sables bitumineux de l'Athabasca : comprendre la dynamique sol-eau par modélisation de l'écoulement à non-saturation**. Can. J. Soil Sci. **92**: 103–116. La loi exige que les sols exploités dans la région des sables bitumineux de l'Athabasca soient restaurés, le but ultime étant de rétablir la végétation indigène, telle qu'elle existait avant la perturbation. Pour échafauder les stratégies adéquates, il est capital d'analyser la dynamique du sol et de l'eau, mais aussi de comprendre quel impact a l'épaisseur de la couche à restaurer. Dans le cadre de cette étude, les auteurs ont simulé la dynamique de l'eau et les écoulements au niveau de la nappe phréatique selon trois programmes de restauration, puis en ont comparé les résultats aux écoulements observés dans des conditions naturelles, en présumant que le tremble était la principale espèce à rétablir. Selon les simulations, une couche de 0,5 à 1,0 m de sol fournira l'eau nécessaire à la végétalisation. Les simulations numériques indiquent que les écoulements fluctuent moins dans les paysages restaurés que dans les conditions naturelles au niveau de la nappe phréatique. Pour restreindre les interactions entre les flux de la nappe phréatique et ceux de l'atmosphère, et limiter les flux ascensionnels, la nappe phréatique devrait se trouver à plus de 2,0 m de profondeur dans les reliefs restaurés par la plantation de trembles, surtout lorsque la restauration survient durant la partie sèche du cycle climatologique.

**Mots clés:** Écoulement à non-saturation, restauration, végétalisation, modélisation numérique

The Athabasca oil sands is a large scale development that will require reconstruction of ecosystems at the scale of whole landscapes (Johnson and Miyanishi 2008). This is the result of mining operations, which leave behind large pits, tailings facilities and overburden in which the natural hydrology of both surface and ground water has been completely disrupted (Elshorbagy et al. 2005). In 1967, the Great Canadian Oil Sands initiated the world's first large-scale oil sands operation in the Athabasca oil sands (Alberta Energy 2011a). Since then, production of synthetic crude oil from oil sands has increased from less than 5% of Alberta's total oil production to 38% in 2005, when Alberta accounted for approximately 62% of total Canadian oil production (Alberta Sustainable Resource Development 2005). The oil sands are located in the Cold Lake, Peace River and Athabasca regions of northern Alberta and cover approximately 140 200 km$^2$ (Alberta Energy 2011b) (Fig. 1). Oil sands near Fort

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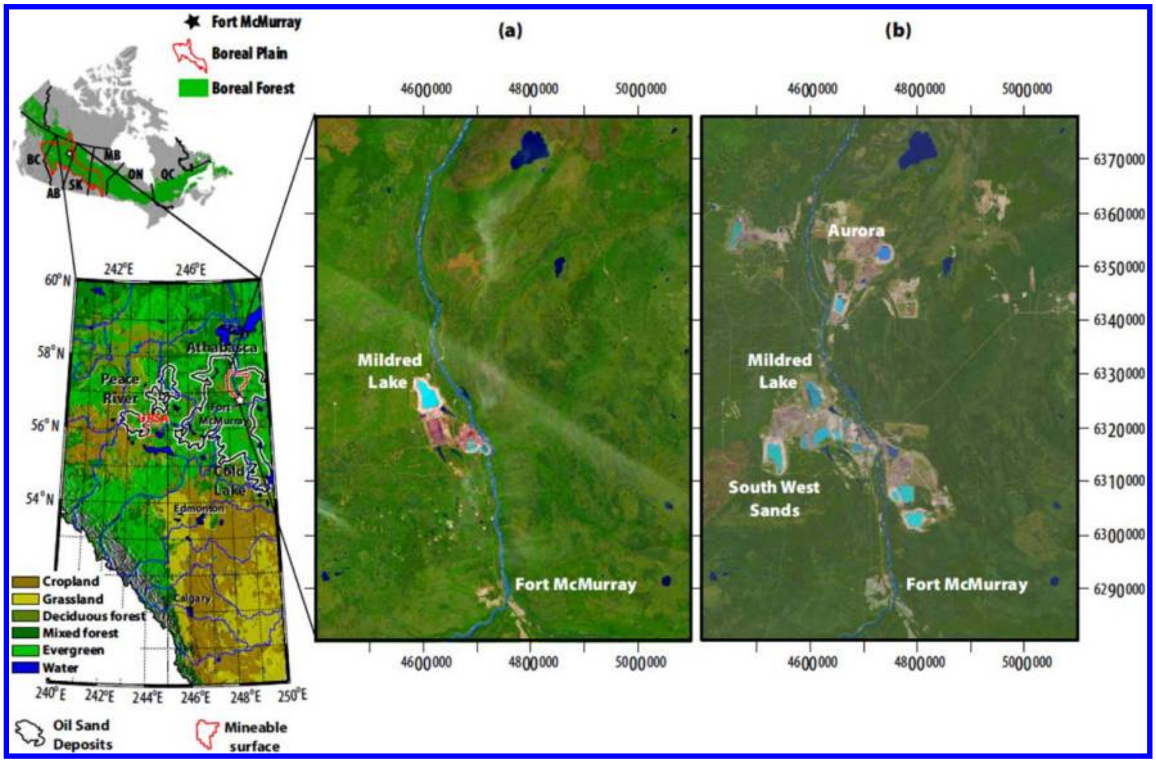


**Fig. 1.** Location of the oil sands regions and the boreal plains within the Canadian boreal forest, with disturbance in the Athabasca region illustrated through the use of a LANDSAT-5 colour composite for (a) August 1985 and (b) September 2010 with coordinates given in meters, UTM-12. The Alberta inset shows the Utikuma Region Study Area (URSA) where evapotranspiration data for aspen were measured.

McMurray account for 66% of the Athabasca oil sands area (93 000 $km^2$), with a total surface mining area of 4800 $km^2$, out of which 663 $km^2$ have already been disturbed (Alberta Environment 2011).

Although oil production from oil sands can be undertaken with different methods, open mining is currently the most common method of oil extraction and has the largest impact on ecosystems (Johnson and Miyanishi 2008). In areas where the oil sands deposit is found at less than 45 m below the surface, surface mining is used to access the oil-impregnated sands (Fung and Macyk 2002). After mining takes place, reclamation of the affected area is required, with the goal of achieving a land capability equivalent to that which existed prior to disturbance (Alberta Environment 2006). Thus, reclaimed areas in the oil sands region are required to have species characteristic of native plant communities (Alberta Environment 2009). The disturbance of the boreal forest caused by the growth of oil sands mining from 1985 to 2010 can be observed in Fig. 1. Because different reclamation strategies have been applied, the present study uses numerical modelling to explore the relationship between soil water and the water table on hypothetical reclamation scenarios to recommend an adequate soil prescription to sustain vegetation.

Before mining, surface soils and near-surface geological materials (to a depth of 3 m) are salvaged and stored for future use in reconstructing landforms during site reclamation. As described by Johnson and Miyanishi (2008), the mine tailings produced during bitumen extraction are a mixture of water, clay, sand and residual bitumen. The mature fine tailings left after sand removal are a stable clay and water suspension that would take centuries to settle; to speed the process, gypsum is added to bind the clay and produce consolidated tailings. Thus, the end substrates for reclamation are overburden, tailings sand and consolidated tailings sand. Soil and peat from the original stripped sites and from neighbouring undisturbed areas are mixed and used to cover these substrates prior to revegetation, with tailings sands representing a substantial proportion of the reclaimed soil profile on reclaimed landforms (Fung and Macyk 2002). Under natural conditions in this region, organic soils are dominated by black spruce [*Picea mariana* (Mill.) Britton, Stern & Poggenb.] and tamarack [*Larix laricina* (Du Roi) K. Koch], while mineral soils are dominated by a coniferous-deciduous forest mix. Trembling aspen (*Populus tremuloides* Michx.), Balsam poplar (*Populus balsamifera* L.) and white spruce [*Picea glauca* (Moench) Voss] are typically found on the uplands (Fung and Macyk 2000).

Selecting the texture, thickness and final landscape is vital for any reclamation scenario (Keshta et al. 2010) and, currently, reclamation methods vary across mine sites based upon parent material and construction strategies (Rowland et al. 2009). Over the past 30 yr, the main prescriptions that have been used included a peat-mineral mix or subsoil or both over tailings sands, overburden, Clearwater shale or lean oil sands (Rowland et al. 2009).

As an example, reclamation practices at Bills Lake included placement of 20 cm of peat and 80 cm of glacial till over marine shale in 1992, a standard practice at Syncrude Canada Limited for most reclaimed landscapes (Purdy et al. 2005). Different studies have analyzed the reclamation treatments implemented on top of tailings sands (McMillan et al. 2007; Kelln et al. 2008, 2009). Recently, Mackenzie and Naeth (2010) recommended the use of upland surface soils in reclamation, because addition of the litter-fibric-humic layer aids in creating diverse ecosystems on reclaimed upland landscapes by providing a source of propagules for revegetating upland boreal forest communities and improving nutrient availability for plants. This recommendation, which has led to revised regulatory requirements (A. Naeth, personal communication, University of Alberta, Edmonton, AB) contrasts with previously used strategies, where establishment of woody plant species on reclaimed landscapes relied on out planting desired species and expecting the remainder of species to establish naturally (Alberta Environment 2009).

To develop adequate reclamation strategies, an analysis of soil water dynamics is of utmost importance, because a soil cover prevents erosion of the reconstructed landscape while at the same time supplying sufficient water for sustainable vegetation growth and development (Meier and Barbour 2002). The need to understand soil water dynamics on reclaimed substrates has motivated different studies where numerical modelling has been used (Elshorbagy et al. 2005; Mapfumo et al. 2006; Elshorbagy and Barbour 2007; Keshta et al. 2009, 2010). Elshorbagy and Barbour (2007) and Keshta et al. (2010) used long-term climatological data to develop probability curves of soil water deficits for three experimental covers of different thicknesses (0.35, 0.50 and 1.0 m). Keshta et al. (2010) concluded that under the stress of high water requirements, the 1.0-m cover might be able to release the required water, while the other two covers (0.35 and 0.50 m) may fail to release the water required by vegetation.

The studies that have analyzed reclamation strategies in the oil sands region have not analyzed the temporal evolution of long-term soil water dynamics, or the effect of different soil cover depths on water fluxes to and from the water table. To overcome this gap, the present study uses numerical modelling to explore the relationship between soil water and the water table on hypothetical reclamation scenarios, using water table depths commonly found on the Boreal Plains landscape through daily simulations from 1919 to 2006. The advantage of using long-term simulations is that they provide insight into the behaviour of water flow during both wet and dry cycles. The interaction of the water table with reclaimed areas needs special attention because final reclamation of the affected areas in the oil sands region will require the development of peatlands and wetlands, which, in most cases, are ground water fed.

## MATERIALS AND METHODS

To understand soil water dynamics and water table fluxes on reclamation scenarios, a series of virtual experiments using numerical models was developed. These virtual experiments considered aspen as the main revegetation species along with four different water table depths and three different thicknesses of reclamation material. Trembling aspen was selected as the target vegetation because it is present on moderately fine-textured, well- to moderately well drained soils on level to gentle slopes (Corns et al. 2005) and because it is the most important deciduous tree in the Canadian Boreal Plains, both ecologically and commercially (Hogg et al. 2002).

Daily climatological data from Fort McMurray (1919–2006) were used as input into the model, along with measured reference and actual evapotranspiration rates (ETo and ET, respectively) on aspen stands. Runoff was not considered in the numerical experiments because on much of the boreal plains, both the sub-humid climate and the deep glacial sediments result in large available soil water storage capacity, with runoff occurrence having a return period of 25 yr or more (Redding and Devito 2008). The setup of the virtual experiments is illustrated in Fig. 2, which shows that net atmospheric fluxes are applied on top of the column, while the water table was fixed at the bottom. The variable discretization used is also shown, being finer at both the top and the bottom of the column.

### Numerical Simulations

Numerical simulations were undertaken to study the effect of different thicknesses of reclamation material used (0.0, 0.5 and 1.0 m) on fluxes at the water table and soil water dynamics. The simulations were undertaken using the numerical code HydroGeoSphere (Therrien et al. 2010), which uses the control volume, finite element approach to simulate variably saturated flow. HydroGeoSphere solves either linear equations (for full saturated flow or solute transport) or non-linear equations (for variably saturated subsurface flow and surface flow). To solve non-linear equations, HydroGeoSphere uses the Newton-Raphson linearization method and a preconditioned iterative solver for the matrix equation. HydroGeoSphere includes options for adaptive time-stepping and for unsaturated flow, using upstream weighting of the relative permeability

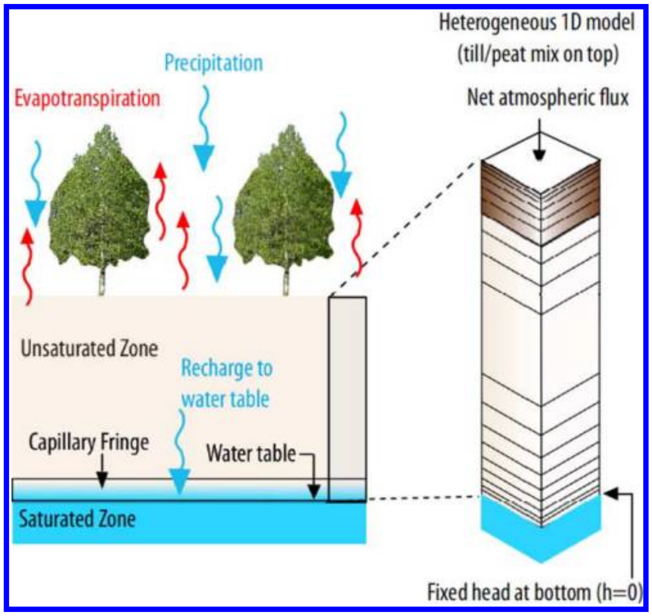


**Fig. 2.** Virtual experiment set up showing the boundary conditions and variable discretization used.

to ensure monotonicity of the solution (Forsyth 1991), which yields saturations that always remains in the physical range, (between 0.0 and 1.0) as demonstrated by Forsyth and Kropinski (1997). On the adaptive time stepping procedure, the time step is defined according to the rate of change of a solution unknown (e.g., hydraulic head or saturation) (Forsyth and Sammon 1986; Forsyth and Kropinski 1997).

For the virtual experiments developed in this work, the adaptive time step option of HydroGeoSphere was used. The output was processed through a series of awk scripts to get daily and/or monthly data, because for some days HydroGeoSphere required 50 or even more subdaily time steps to converge. The data were then plotted with the R statistical language (R Development Core Team 2010) to visually compare both saturation profiles and fluxes at the water table. Three thicknesses of reclamation material were used (0.0, 0.5 and 1.0 m) as to date, no standard prescription for reclamation exists (Rowland et al. 2009). The three thicknesses considered were applied on top of tailings sand with water table depths fixed at 2, 4, 6 and 12 m of both homogeneous and heterogeneous columns. These depths were used because they are representative of the Boreal Plains (Smerdon et al. 2008).

In addition to the one-dimensional simulation of soil water dynamics on reclaimed scenarios, numerical simulations were also undertaken on sand, loamy sand, sandy loam and loam with the same water table depths to compare soil water dynamics and fluxes at the water table between undisturbed and reclaimed scenarios. The hydraulic properties of the materials used (Table 1), along with the van Genuchten (1980) relationships for sand, loamy sand, sandy loam and loam, were taken from Carsel and Parrish (1988) and used in HydroGeoSphere to generate their corresponding tabular relationships of saturation versus relative hydraulic conductivity (Ks) (Table 1), and saturation versus head (matric potential in the unsaturated zone) (Fig. 3). The reclamation material used in the simulations was a till/peat mix that had been used in reclamation prototypes in the oil sands region, with its characteristic curves (Fig. 3) taken from those published in Shurniak and Barbour (2002). The relationships for tailings sand were taken from Syncrude (2007). As illustrated in Fig. 3a, the values of the matric head saturation curve for tailings sand are between loam and sandy loam, while its relative Ks saturation curve shows relative Ks values larger than sand (Fig. 3b).

## Net Atmospheric Fluxes

The undertaken simulations used net atmospheric fluxes as input at the top of the columns. These fluxes were determined by subtracting daily actual evapotranspiration from precipitation, which includes snow water equivalent. In the following sections, a brief description of the method used is given; the details can be found in Carrera-Hernández et al. (2011). Long-term climatological data from Fort McMurray do not include daily reference evapotranspiration. Thus, daily reference evapotranspiration (mm/day) had to be derived from daily climatological data available from the Fort McMurray climate station. Although the Penman-Monteith method is generally recommended (Allen 2000), data at this location were not available for its application; thus the Hamon (1963) method was selected in this work. The Hamon method relates the reference evapotranspiration (ETo) with air temperature:

$$\mathrm{ETo} = 29.8 \times \mathrm{D} \times \mathrm{e}_a^*/(\mathrm{Ta} + 273.2) \quad (1)$$

where $e_a^*$ is the saturation vapour pressure (kPa) at the mean daily temperature $T_a$ (ªC) and $D$ is day length (hours). Evapotranspiration data (both ETo and ET) were collected using the eddy covariance technique (Baldocchi et al. 1988) at two locations within the Utikuma Region Study Area.

Turbulent flux data, radiation and energy flux information were collected at the tower locations during the same periods. Flux and energy data were collected from the aspen dominated uplands in the study catchment on

**Table 1. Hydraulic properties of materials used in the numerical experiments; saturated conductivity is for the vertical direction ($K_z$)**

| Material | Saturated Ks (m $d^{-1}$) | Porosity |
|---|---|---|
| Sand | 0.7123 | 0.43 |
| Sandy loam | 0.1060 | 0.41 |
| Loam | 0.0240 | 0.43 |
| Tailings sand | 0.0860 | 0.35 |
| Till and peat mix | 0.0318 | 0.45 |

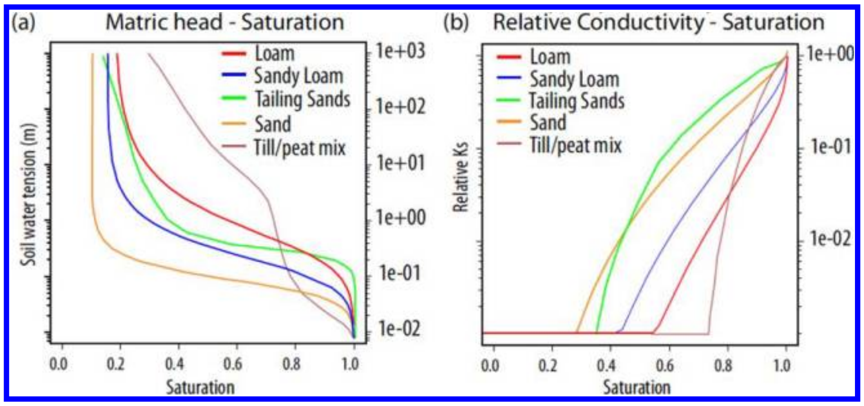


**Fig. 3.** Saturation curves for tailing sands, sand, loamy sand, sandy loam and loam; (a) saturation matric head and (b) saturation relative *Ks*. Curves are based on tabular values determined from the van-Genuchten parameters of Carsel and Parrish (1988) for natural materials. For tailings sand, these curves were developed from the values provided in Syncrude (2007), while those for the peat and till mix were taken from Shurniak and Barbour (2002).



both north-facing and south-facing slopes. From these field measurements, a ratio between reference and actual evapotranspiration (α) was determined for mature aspen. The α values thus determined were then applied to the long-term reference evapotranspiration values obtained through Eq. 1 to develop the 1919–2006 daily actual evapotranspiration values used in the simulations. The α ratio varies within the year (Fig. 4), with lower values in May and peaking in July; this ratio was assumed constant for all years. Although it would be expected for the α ratio to exhibit some inter-annual variability over the considered period, the uncertainty introduced by its uniformity is also expected to be minimal, because it is well documented that the relationship between ETo and ET is mainly controlled by radiation (i.e., climate) (Stagnitti et al. 1989). However, it should be kept in mind that to fully capture the dynamics of evapotranspiration, the effect of soil water deficit on actual evapotranspiration needs to be considered.

## Snow Pack Dynamics

Adequate modelling of snowpack accumulation and melt need particular consideration, as the snowpack's size and properties affect the timing of thaw in the soil and the amount of liquid present in the spring (Bartlett et al. 2006). Snowmelt was determined through the degree-day method, where daily snowmelt (m) is related to mean daily air temperature ($T_a$) and a melt factor (M) whenever $T_a$ exceeds a threshold temperature ($T_{thr} = 0$ °C):

$$m = M(T_a - T_{thr}) \tag{2}$$

where $M$ (mm °C$^{-1}$ d$^{-1}$) varies with time. The melt factor ($M$) varies with time and is related to changes in snow density following the relationship derived by Kuusisto (1980) for forested areas.

The complete methods to capture snow pack dynamics (Carrera-Hernández et al. 2011) were calibrated and validated with climatological data from Fort McMurray (Fig. 5), as snowpack depth data were available from 1956 to 1998. The snow pack dynamics obtained with this method (Fig. 5) show that the simulation of daily snowpack dynamics is adequate and that the largest daily precipitation events are caused by rainfall. These large precipitation events occur simultaneously when the largest evapotranspiration rates are expected in June through July (Devito et al.

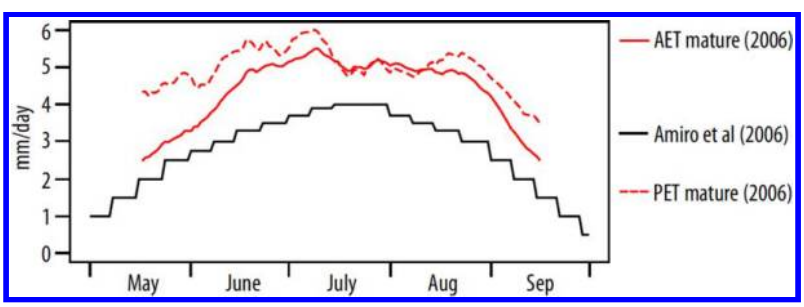


**Fig. 4.** Moving average (30 d) of both reference evapotranspiration (ETo) and actual evapotranspiration (ET) measured on top of mature aspen stands; ET values of Amiro et al. (2006) obtained at the BOREAS old aspen site in Saskatchewan are shown for comparison.

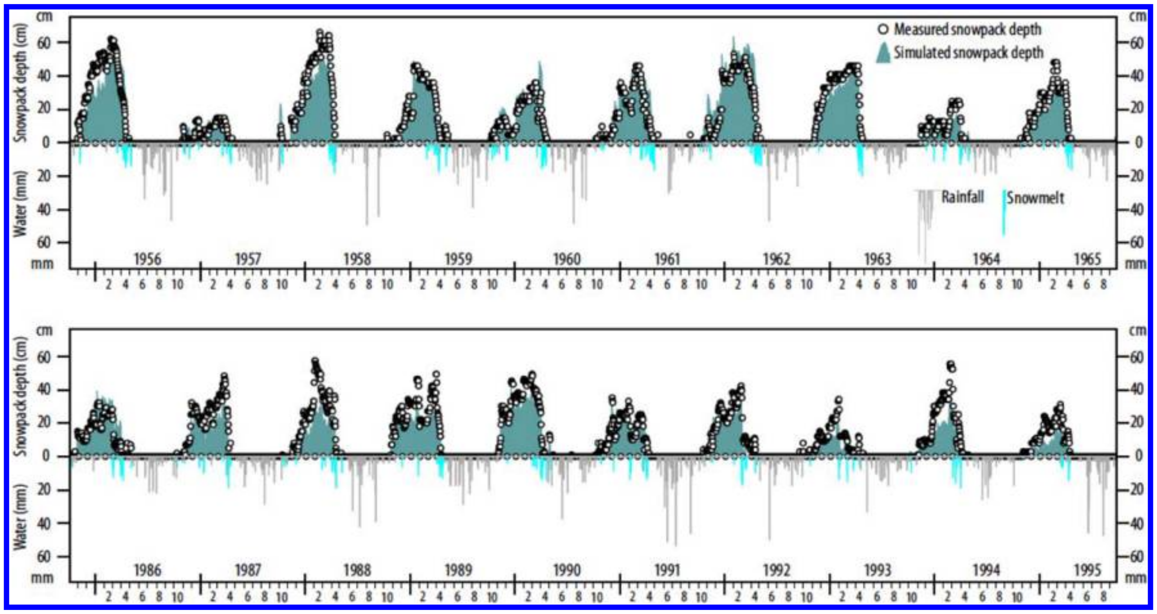


**Fig. 5.** Daily precipitation and snow pack dynamics (i.e., depth and snow water equivalent) at Fort McMurray.

2005). With this approach, snowmelt can also occur during winter, when the atmospheric conditions are warm enough (Fig. 5). The daily values generated were aggregated on a yearly basis to represent the percentage of snow water equivalent to yearly precipitation, as illustrated in Fig. 6a, which shows the normals (1971–2000) for precipitation, potential evapotranspiration and the 5-yr moving average of these two variables. The moving average is used to illustrate the climate variability in Alberta, as both dry and wet cycles occur. This cyclic nature needs to be considered because soil water dynamics depend on atmospheric fluxes. According to Mwale et al. (2009) these cycles can have periods of 4, 8, 11 and 25 yr. From the daily actual evapotranspiration and precipitation values, daily net atmospheric fluxes to the model were determined (Fig. 6b shows these data aggregated on a monthly basis) and used as input to the model.

## Vertical Discretization and Lower Boundary Conditions

A sensitivity analysis to boundary conditions and vertical discretization was undertaken because there is no guideline on how to discretize the vertical domain or which lower boundary condition should be used for one-dimensional unsaturated flow modelling. The sensitivity analysis to vertical discretization was undertaken with three different discretization schemes: constant, variable at the top of the column and variable at both the top and bottom of the columns.

For constant discretization cases, spacings of 5, 1 and 0.5 cm were used (C1, C2 and C3, respectively). For the first variable top discretization case, the spacing at the top of the profile (V1) was 0.1 cm, which was incremented by a factor of 1.04 to reach a maximum spacing of 2.5 cm. The second variable discretization case at the top (V2) had an initial spacing of 0.2 cm, incremented by a factor of 1.2 to reach a maximum spacing of 20 cm. The first case of variable discretization at both the top and bottom of the column (V3) used an initial distance of 0.1 cm and a factor of 1.1 for a maximum distance of 10 cm, while the second case (V4) used the same initial distance and factor, but a maximum value of 5 cm. The last variable discretization used (V5) used an initial spacing of 0.1 cm, but a factor of 1.05 and a maximum distance of 1 cm. The sensitivity analysis to vertical discretization made use of a fixed water table at the bottom of the modelling domain. Through this analysis the use of a variable vertical discretization was found to drastically reduce the time required to complete the simulation. Based on these results, it appears that when both simulation times and flux differences are considered, V3 is an adequate selection as the computation time is adequate, and the fluxes are similar to those obtained with finer discretizations.

With the use of the selected vertical discretization (V3), three lower boundary conditions were analyzed: fixed water table, free drainage (unit gradient) and seepage boundary (e.g., head dependent) for the four materials used. In the first type of boundary condition, the water table was fixed at a certain elevation, above which unsaturated flow occurs. In the case of a seepage face, seepage occurs when the hydraulic head rises above the elevation of the seepage nodes. In HydroGeoSphere, seepage occurs whenever the pressure in the medium is greater than atmospheric pressure. The unit gradient lower boundary condition assumes that free drainage exists in the vertical direction. Through this analysis,

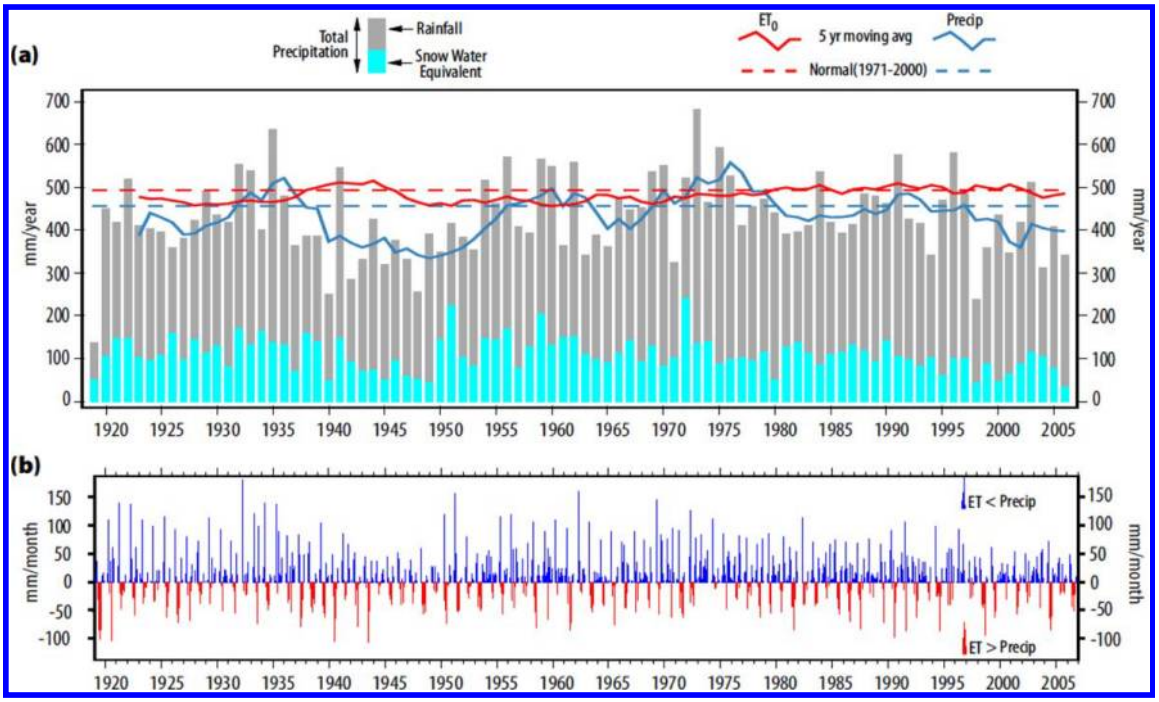


**Fig. 6.** Atmospheric fluxes at Fort McMurray on an annual basis, along with snow water equivalent (a) and net monthly fluxes aggregated from daily net fluxes (b). The annual fluxes show normals (1971–2000) for reference evapotranspiration and precipitation, with their 5-yr moving average.

simulation times increased dramatically for coarser materials (i.e., sandy loam) and the model could not converge for coarse materials (i.e., sand).

These slow simulation times, difficult convergence and in some cases failed convergence can be explained by the fact that the first years of simulation were very dry years (Fig. 6) and that the unit gradient boundary condition does not allow flux from the water table into the soil when water is extracted from the top, a condition that does occur when a fixed water table is used. These results are in agreement with Wang et al. (2009) who compared the use of a fixed water table and unit gradient lower boundary condition, concluding that selecting a fixed water table is more appropriate on regions where upward flux is important.

Based on the results of the sensitivity analysis, the spatial discretization of the one-dimensional simulations was selected to vary at both the top and bottom, starting

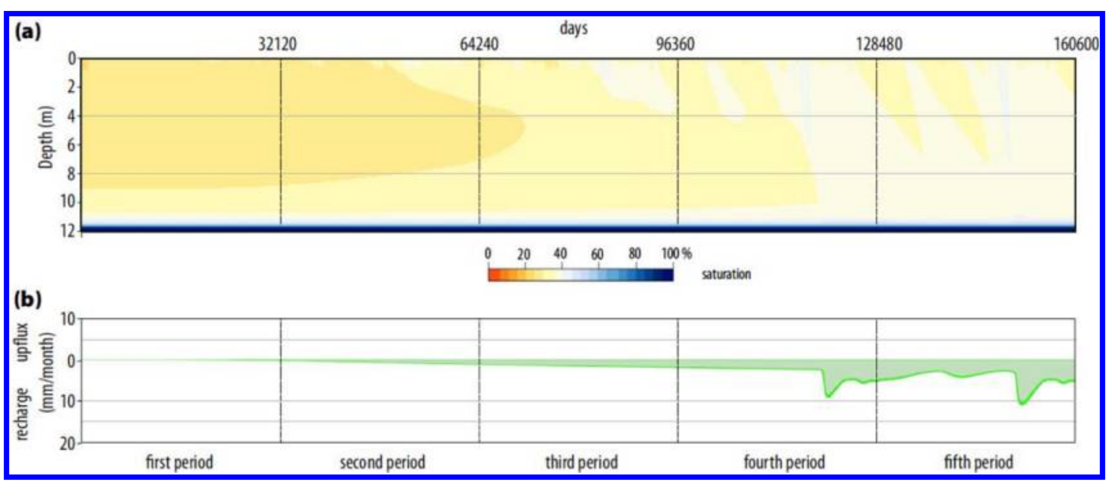


**Fig. 7.** Complete simulation for the 12-m tailings sand profile showing: (a) daily soil water and (b) monthly fluxes at the water table aggregated from daily values. Each period covers the 88 yr or 32 120 d with data from Fort McMurray. Fluxes at the water table stabilize toward the last third of the fourth period, thus requiring more than 308 yr of spin up time.

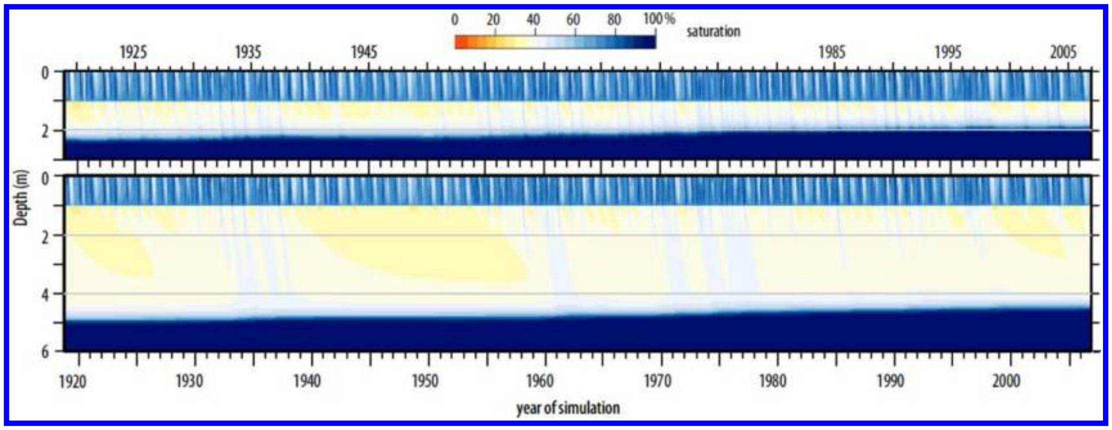


**Fig. 8.** Water table fluctuation for different initial water table depths; water table rises slowly, even for the shallowest case shown.

with 0.1 cm, and increased by a factor of 1.1 to reach a maximum spacing of 10 cm, while the water table was fixed at the bottom of each column. These options were selected because this variable discretization provides efficient solution times and accuracy, and a more physically based representation of the water table in sub-humid regions.

The steady-state model assumed a dry soil profile, and its solution was used as a starting point in the transient simulation. This assumption required a long spin up time, particularly for the 12 m homogeneous tailings sand case (Fig. 7). For this case, four periods with 88 yr of daily data (1919–2006) (Fig. 6) were required to use all the climatological cycles in this work. The simulation stabilizes toward the last third of the fourth spin up period (Fig. 7). A continuous dry front is visible on the soil profile even during the first half of the fourth spin up period (Fig. 7a), until a recharge peak of approximately 9 mm $mo^{-1}$ occurs (Fig. 7b). The timing of this peak is also reproduced on the fifth period, although it reaches a larger value (11 mm $mo^{-1}$). The fluxes at the beginning and end of the fifth

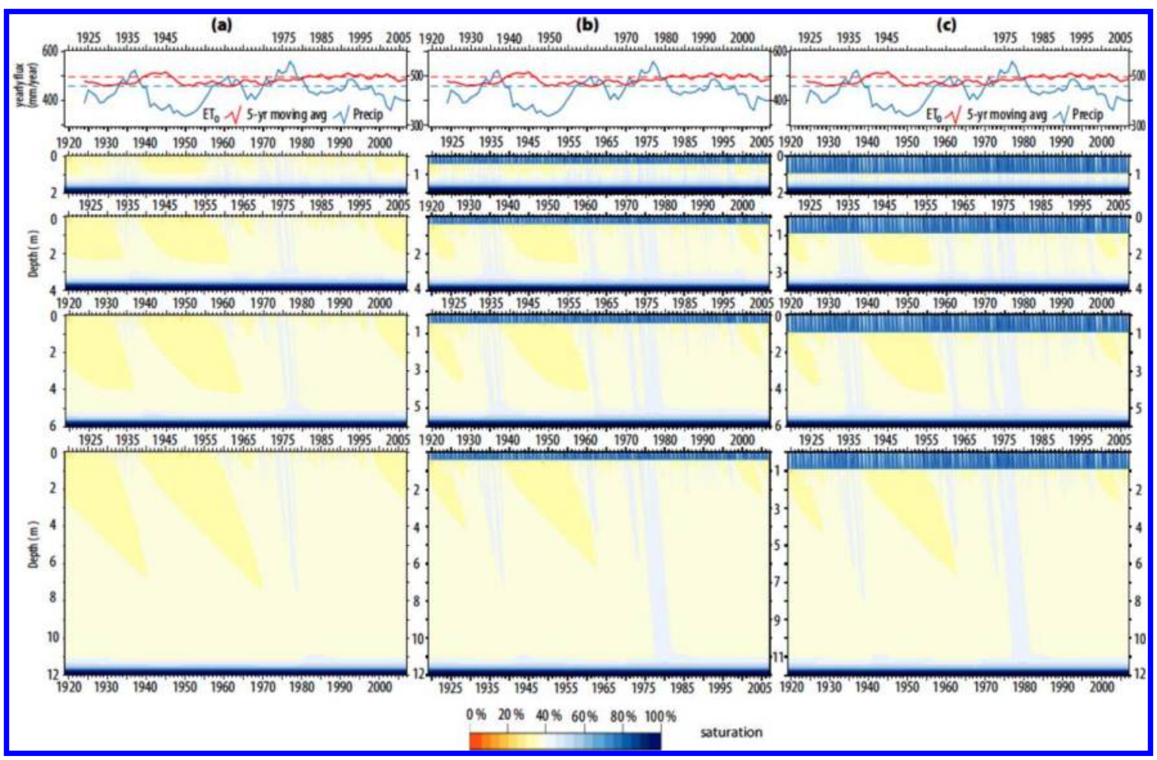


**Fig. 9.** Daily soil water dynamics for different depths of capping material used on top of tailings sand: (a) 0 m, (b) 0.5 m and (c) 1.0 m considering different water table depths commonly found on the boreal plains (2, 4, 6 and 12 m). The top plot shows the variability of the climatological conditions for the simulated period (1919–2006).

period showed that the transient simulation has reached a numerically table condition at this period. For the other water table depths used, the solution became stable faster (i.e., three periods only). The analysis undertaken in this work made use of four spin up times for all cases.

One assumption of the one-dimensional models developed in this work was the use of a fixed water table at a given depth. This assumption was verified by running the simulations and then obtaining the mean daily flux at the water table for the entire simulation length (without the spin up periods) for each material and depth used. These fluxes were then used as a lower boundary condition in a one-dimensional model to analyze how much the water table would fluctuate. The results of these analyses are shown in Fig. 8 for the case of a 1-m thickness of reclamation material. The water table rises slowly, even for a shallow water table. For the simulated 88 yr, the water table rises approximately half a metre. Based on these results, the assumption of a fixed water table to determine both soil water dynamics and fluxes at the water table seems adequate. The water table is expected to show less variation in the field, because a shallower water table would increase the gradient at the bottom of the one-dimensional model, thus increasing outflow.

## RESULTS AND DISCUSSION

The developed virtual experiments allow analysis of soil water dynamics and fluxes at the water table for hypothetical reclamation strategies during wet and dry cycles, instead of for a couple of years as has been done previously. The daily soil water dynamics for the four water table depths (2.0, 4.0, 6.0 and 12.0 m) and the three thicknesses of reclamation material used (0.0, 0.5 and 1.0 m) are shown in Figure 9 for 1919–2006 along with the five year moving average of precipitation and reference evapotranspiration and their respective normals (1971–2000). For comparison, the soil water dynamics obtained with the same atmospheric fluxes on natural conditions (sand, sandy loam and loam) are shown.

For the three reclamation scenarios (e.g., depths) used, soil water presents a similar behaviour to that of the relationship between the moving average of reference evapotranspiration and precipitation (Fig. 9, top), which clearly shows the presence of both dry and wet cycles. Through the use of long-term data, these cycles

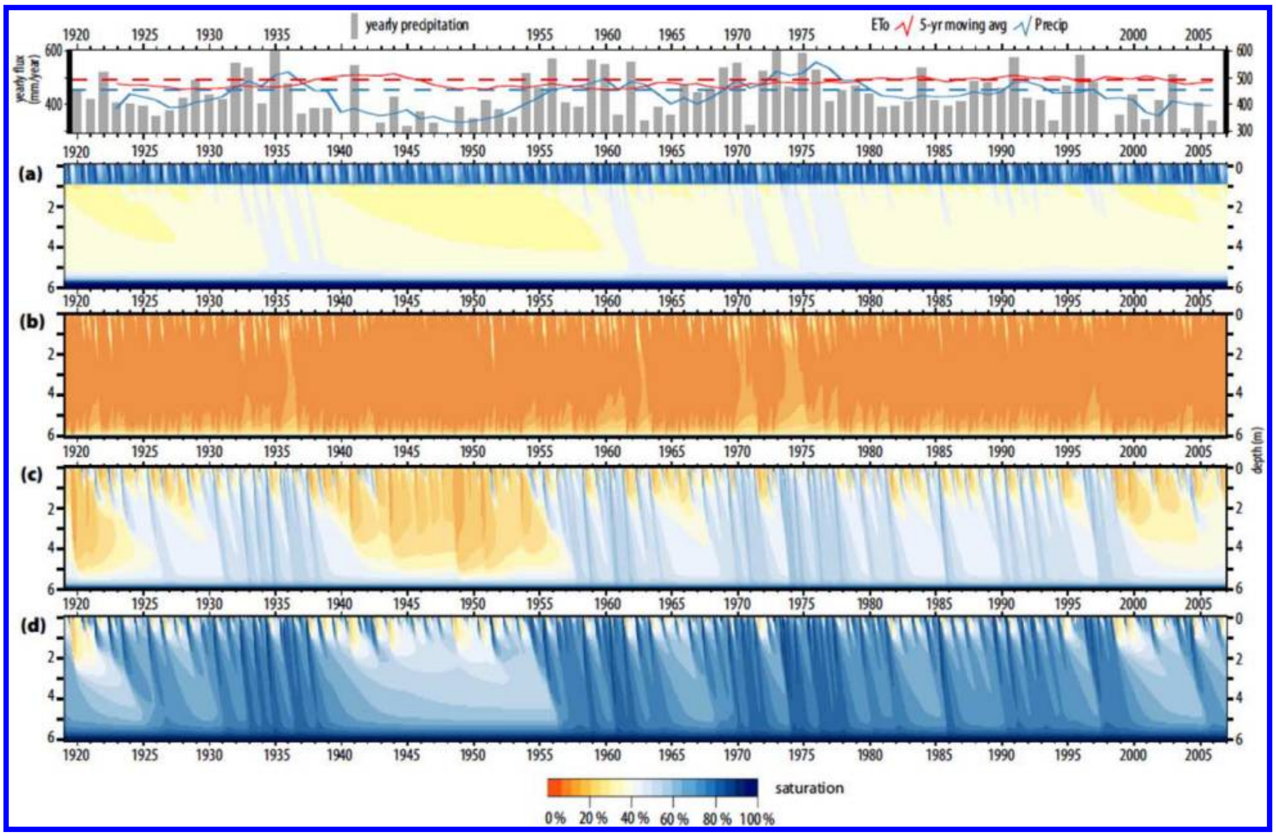


**Fig. 10.** Daily soil water dynamics for a water table fixed at a depth of 6 m for different materials (a) reclamation scenario with 1 m of till and peat mix on top, (b) sand, (c) sandy loam and (d) loam. The top plot shows the variability of the climate conditions for the simulated period (1919–2006) along with their respective normals (1971–2000).

are considered in the model, and it can be seen that on the simulated period (1919–2006), there have been three wet and four dry cycles, with dry cycles being longer. According to climate records (Fig. 6), wet cycles have had durations of 4, 5 and 10 yr, while dry ones have had 9, 22, 6 and 27 yr (Fig. 9, top). The last dry cycle, which started in 1979, has continued to date (2010). This Figure shows that the 1936–1958 cycle has been the driest of all, while 1969–1979 the wettest. The soil water profiles also reflect the cyclic pattern of climate, showing one large drying front starting in 1919 and another one in the 1930s, with a small one appearing around 1965. The effect on soil water of the wet periods are easier to observe on the soil profiles, particularly the one caused by the wet period of the mid 1970s, as the profile clearly increases its water content.

The profiles for reclaimed columns (Fig. 9) illustrate the impact of using a reclamation material on top of tailings sand, as it holds water, distributes it in time and makes it available to vegetation. The impact of a fine-textured layer on top of coarse materials was also noticed by Booth and Loheide (2010), who through numerical simulations observed that the removal of a 0.5-m silt loam layer decreased the reservoir of soil water available to plant roots. This situation is evident by comparing soil water content of the reclamation material (Fig. 9), showing that soil texture plays a major role in the modulation of the impact that inter annual rainfall fluctuations have on the fitness and existence of vegetation (Fernandez-Illescas et al. 2001).

The amount of water present for vegetation when a depth of 1.0 m is used on top of tailings sand is clearly seen for all simulated column depths (Fig. 9c). However, the soil water difference caused by the selected thickness of reclamation material is easier to visualize on the deepest column used (12 m), as when it is not present (Fig. 9a), the profile shows larger drying fronts. However, when 0.5 m of capping material is used, the profile starts to gain water by 1932 and in the case of the shallow water tables (2, 4, 6 m) a significant increase of water at the bottom is observed. For the 12-m case a small increase in water can be seen, around 1943 (Fig. 9c). It is interesting that there is not an important difference for this depth (12 m) when a thickness of 0.5 or 1.0 m of reclamation material is used on top of the profile.

For a shallow water table (2 m), water increases considerably when a capping layer is added, particularly for 1 metre, and more interaction between the water table and atmospheric fluxes is observed (Fig. 11). This water increase is easier to see on the 4 m case: when no material is used, there is only one sharp increase of water, starting around 1973, which occurs during the wettest cycle. When 0.5 m of reclamation material is used, this event and those of the early 1930s and that of 1970 are clearly connected to the water table, a situation that is more pronounced in the case of the thickest layer

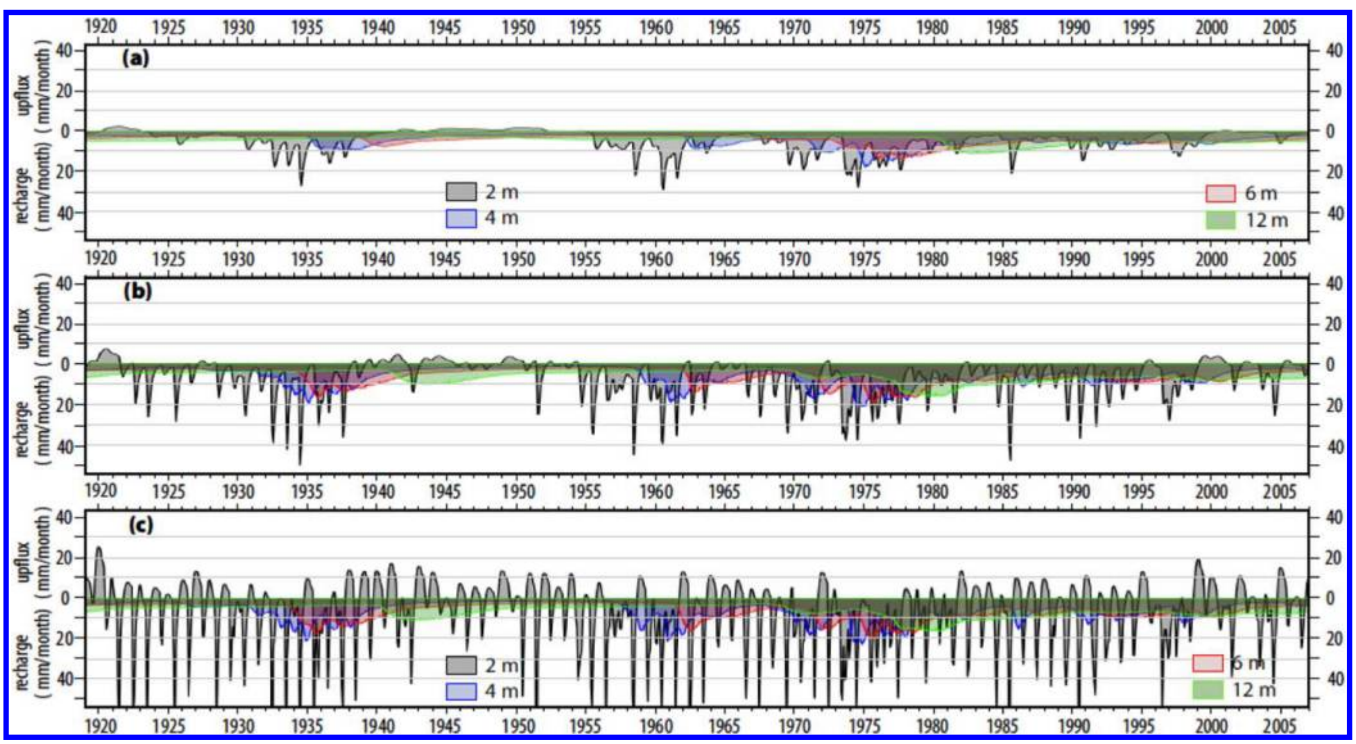


**Fig. 11.** Monthly fluxes at the water table for different depths (2, 4, 6 and 12 m) for three different depths of capping material on top of tailing sands (a) 0 m, (b) 0.5 m and (c) 1.0 m. These monthly fluxes were aggregated from daily data to improve their visualization.

considered. The soil water profiles for the reclaimed scenarios may seem counterintuitive because it would be expected for the soil cover to hold water. This situation does not occur because the reclamation cover is near saturation most of the time, thus creating ponding conditions on the reclamation cover. Because of this, water moves faster on the soil for the two hypothetical reclamation thicknesses, as evidenced by the observed wetting fronts.

The appearance of drying fronts on the reclaimed profiles can also be seen on the undisturbed profiles (Fig. 10), where colours vary according to the different retention capacity of each material used in the simulations. The saturation profiles for a 6-m-deep water table are shown for sand, sandy loam and loam along with the reclamation scenario that used a 1-m-thick till/peat mix on top of tailings sand. The profile for sand (Fig. 10b) shows that ground water moves upward into the soil; a situation that does not seem to occur on the other profiles (years 1945–1960).

To quantify these fluxes Figs. 11 and 12 show the monthly fluxes at the water table (aggregated from daily data) for both reclamation and undisturbed scenarios, respectively. The fluxes at the water table for the reclaimed simulations are affected in different ways as a function of the thickness of the reclamation cover (Fig. 11). For the case of a 12-m column, the fluxes toward the water table (i.e., recharge) are clearly affected, because when no reclamation material is used, there is a recharge increase from less than 5 to 10 mm mo$^{-1}$ towards the end of 1981 (Fig. 11a). When 0.5 m of reclamation material is used, a similar increase is observed earlier, around 1942 (Fig. 11b), a situation that also occurs when 1.0 m is used (Fig. 11c). For the two thicknesses of reclamation material considered, recharge behaves in a similar way for the 12-, 6- and 4-m-deep water table. When compared with the homogeneous tailings sand scenario with depths of 4 and 6 m, the timing and amount of recharge are also modified. However, this increase is not

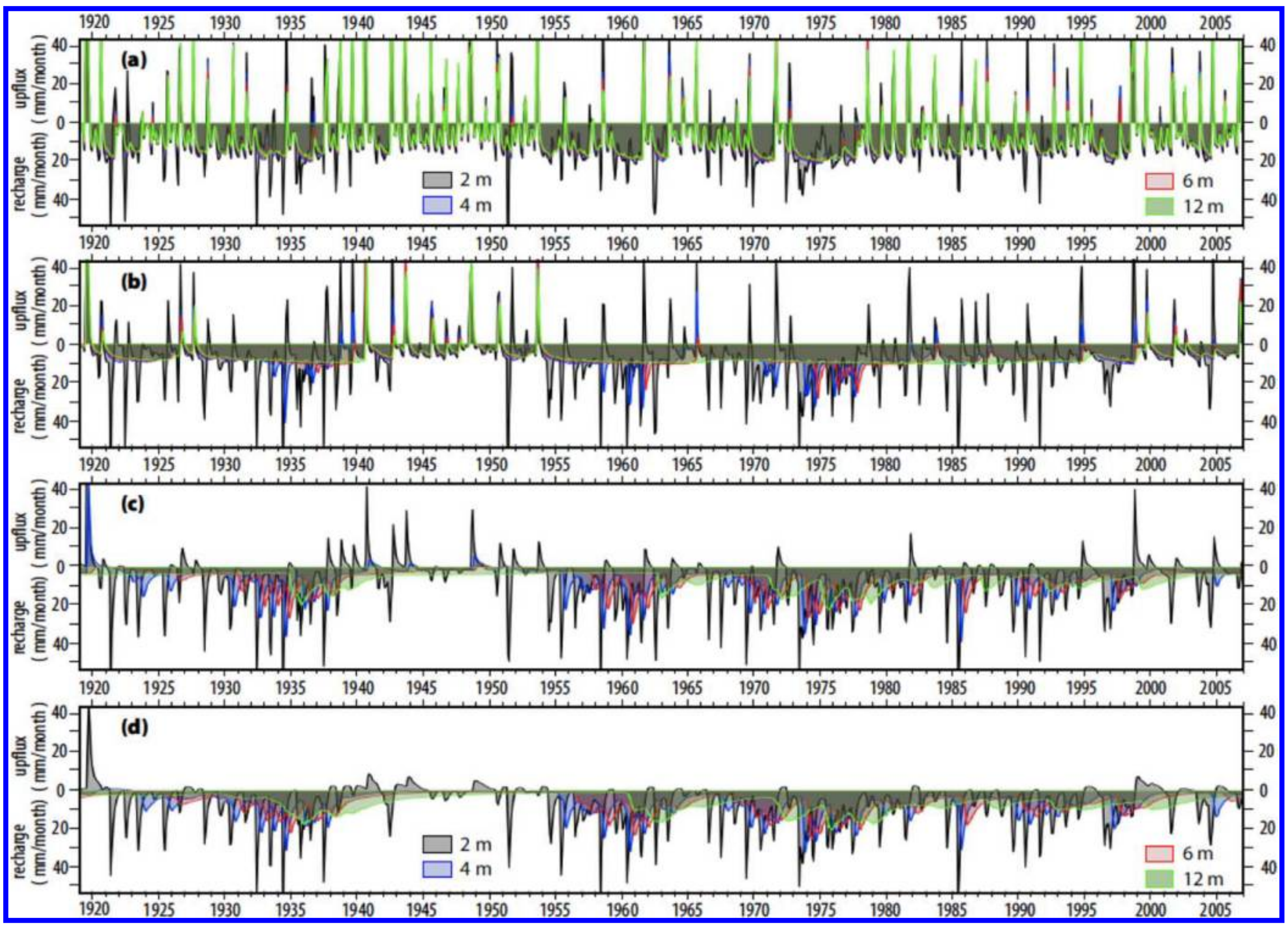


**Fig. 12.** Monthly fluxes at the water table for different depths (2, 4, 6 and 12 m) for four different soil textures found on the Boreal Plain: (a) sand, (b) loamy sand, (c) sandy loam, (d) loam. These monthly fluxes were aggregated from daily data to improve their visualization.

of concern, because water is being released from the surface. What is of concern is water that moves from the water table towards the vegetation (in this case, aspen). This upward flux only occurs on the shallowest water table considered (2 m). For the homogeneous tailings sand case, upward flux is barely observed in 1922, reaching about 2 mm $mo^{-1}$. For the two capping depths considered, upward flux is only present on the driest cycles, reaching a maximum value of around 7.5 mm $mo^{-1}$ in the early 20s for the 0.5-m case. However, for the 1.0-m-thick scenario, upward flux is around 20 mm $mo^{-1}$ in 1920 and around 10 mm $mo^{-1}$ for several dry years. This upward flux might be of concern due to ground water quality (i.e., salinity).

On undisturbed scenarios, the fluxes at the water table (Fig. 12) exhibit more oscillations than those obtained for the reclaimed scenarios, with larger upward fluxes for all materials used, except for loam (Fig. 12d). Loam values are similar to those observed on the reclaimed scenarios for the shallowest water table (2.0 m) and thickest reclamation cover (1.0 m). The fluxes simulated on the hypothetic undisturbed conditions exhibit a large interaction with the water table, in particular for sand and loamy sand for even the deepest columns used (12 m). If the reclaimed scenarios had this strong interaction, upward flux from the water table may reach the root system of the vegetation used for reclamation. This is of concern if reclamation takes place during a dry cycle. Thus, the design of a reclaimed landscape should aim at having a water table deeper than 2 m. According to the undertaken simulations this depth should be around 4 m to avoid this situation.

The selected thickness of reclamation material to be used is not only a function of soil water available to plants, but also a matter of vegetation tolerance to salinity. Currently, freshwater peatlands dominate the landscape prior to mining, but the post-mining reclamation landscape will have wetlands that span a salinity gradient (Trites and Bayley 2009). Lilles et al. (2010) found that high soil water and nutrient availabilities facilitated survival of forest vegetation despite the high levels of salinity. Purdy et al. (2005) suggested that forest vegetation can establish over saline soils as long as the salts are below the rooting zone, which typically occurs within fine sediments. Further work should include a transport model and crop parameters related to salinity stress to address this issue. From the developed simulations, it can be concluded that in the long-term, either a 0.5- or 1.0-m-thick reclamation cover can sustain vegetation. The final thickness selection can be determined based on the root system of the target vegetation.

## CONCLUSIONS

Placing reclamation material on top of tailings sand helps to sustain vegetation, because it holds water, distributes it in time and makes it available to vegetation. The use of reclamation cover with a thickness between 0.5 and 1.0 m may be enough to sustain vegetation on reclaimed oil sands prescriptions; however, the selection of adequate thickness should also consider the requirements of the root system of the target vegetation for reclamation. Upward flux from the water table into the soil profile is only observed on the 2-m-deep column for the three reclamation scenarios and is only present on the driest cycles. This situation is of concern if the vegetation on the reclaimed area is not tolerant to salinity. In contrast, the fluxes at the water table observed on natural conditions reflect a larger interaction between the water table and atmospheric fluxes, a situation that may not favour vegetation growth. The simulated fluxes and soil water dynamics were obtained using evapotranspiration rates that corresponded to aspen and vegetation with lower water requirements may decrease upward fluxes from the water table. To limit the interaction between the water table and atmospheric fluxes, the water table should be deeper than 2.0 m on reclaimed landscapes that have a similar water requirement to aspen.

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