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Landscape restoration after oil sands mining: conceptual design and hydrological modelling for fen reconstruction

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Extraction of oil sands in the relatively dry Western Boreal Plains near Fort McMurray, Alberta, destroys the natural surface cover including fen peatlands that cover upto 65% of the landscape. Industry and environmental monitoring agencies have questioned the ability to reclaim fen peatlands in the post-mine landscape. This study proposes a conceptual model to replace fen systems with fen peat materials supported by groundwater inflow from a constructed watershed. A numerical model is used to determine the optimum system geometry, including the ratio of upland to fen area, thickness and slope of sand materials, and thickness of peat and of the liner that would result in flows that sustain peat wetness to a critical threshold soil water pressure of −100 cm of water at a peat depth of 10 cm. We also test the sensitivity of the system to variations in the value and spatial configuration of the hydraulic conductivity (K) of locally available materials. The optimal conditions were achieved using an upland area at least twice that of the fen, underlain by a sloping (3%) layer of fine-grained material with hydraulic conductivity (K) of 10^{-10} m/s, that maintains lateral groundwater flow in a sand layer with K of 10^{-4} to 10^{-5} m/s. Using daily climate inputs that included 1998, the driest summer on record, the model suggests that adequate wetness can be sustained in the fen for the growing season, and that the extent of water table recession was similar to undisturbed systems during that period.

Keywords: restoration; reclamation; peatland; hydrology; hydrogeology

Introduction

The restoration of natural landscape features following open pit mining operations has been a topic of considerable research and practical investigation for several decades [1]. With the goal of returning a massively disturbed ground surface to a stable terrestrial system that is sustainable from both an ecologic and hydrologic standpoint, various field scale reconstruction projects have been undertaken. These have been primarily focussed at sites of industrial mineral extraction and heavy metal mining [2]. Over the last three decades, the largest open pit mining activities worldwide have been associated with the extraction of oil sand ore [3]. One of the

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major centres of oil sands mining has been in the Athabasca Oil Sands deposits north of Fort McMurray in Alberta, Canada (Figure 1). As part of the extraction process, overburden materials along with the terrestrial vegetation and surficial hydrologic features that overlie the oil sand across hundreds of square kilometers of the land surface have been stripped off and stockpiled or used as construction materials. In fact, oil extraction activities there are expected to cover an area of $\sim$1400 km^2 by 2023 [4]. The scale of the open pit mining operation is unprecedented and significant pressure is now on the oil sands mining companies to develop plans for landscape restoration that will be appropriate for the climatic conditions of northern Alberta [5].

In the relatively dry climate of the Western Boreal Plain, and especially in the oil sands development areas near Fort McMurray, peatlands, primarily fens [6], comprise $\geq$65% of the landscape [7]. Regulatory requirements specify reclamation to a landscape of 'equivalent capability' [5]. The regulation provides several options for post-mined landscapes. One example is the development of end-pit lakes that would result in the construction of landscape features that are not currently native to the Western Boreal Plain. Another alternative is to re-establish peatland terrain in the reclaimed areas. This has not previously been attempted because conventional wisdom dictates that peatlands take thousands of years to develop [8]. However, if peat materials acquired by surface stripping are emplaced in a hydrogeological setting that sustains the requisite wetness condition [9], coupled with peatland restoration techniques to establish a plant community [10], creation of a fen peatland system may be possible. Although damaged fens have been restored [11,12], there are no published reports of fen creation. The fundamental problem is to design a groundwater system that can support the inflows required to sustain the hydrological and ecological processes and functions of a fen peatland. This study considers the possibility of engineering the landscape to provide the requisite hydrological conditions for fen peatlands, based on a combined conceptual and mathematical model of the associated groundwater flow processes.

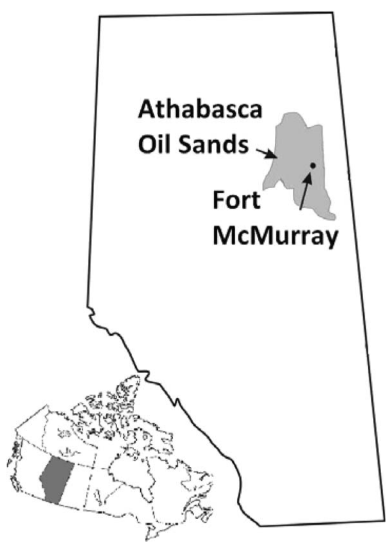

Figure 1. Map of Alberta, Canada, showing the location of the Athabasca oil sands deposits.

Fen peatlands are mineratrophic systems that are partly sustained by surface and/or groundwater input, in addition to direct precipitation [13]. Some fens are sustained through a significant input of groundwater [14]. This is likely the case for fen systems in the relatively dry climate of the Western Boreal Plain. Indeed, some fens in this setting have been shown to receive strong groundwater discharge [15]. Other fen features are bordered by uplands with highly transient and deep water tables [16] that appear to provide little groundwater input yet the fen system remains viable year round [17]. There remains, therefore, a poor understanding of the linkages between fens and groundwater source areas in the Western Boreal Plain, particularly in the upland setting.

The ability of certain upland-wetland configurations to support discharge to fens is clearly feasible, based on their current existence in the natural landscape. The main premise of the current study is to examine a suite of hydrologic conditions that could sustain these fen-upland systems through the development and numerical testing of a realistic conceptual model. The goal is to provide a potential approach to re-establish the fen-upland systems within the post-mined landscape in the oil sands region. The general approach is to test (by modelling) a hypothetical fen-upland system, whose geometry and hydraulic properties, combined with local climate inputs, can sustain an adequate level of wetness to support a prescribed set of fen functions. Coarse sand tailings from processed oil sand would form the primary aquifer, overlying a clay-based liner that directs recharged water laterally to a peat unit derived from fen peat (i.e. currently being stripped to expose the oil-bearing sands).

The specific objectives of this study are first to determine the optimum system geometry, including the ratio of upland to fen area; thickness and slope of sand materials; and thickness of peat and of the lower permeability liner that would permit annual hydrologic sustainability of the constructed wetland. Secondly, we will use numerical simulation to examine the sensitivity of the system to variations in the value and spatial configuration of the hydraulic conductivity (K) of locally available materials. The results are intended to support the establishment of a pilot-scale facility to access the feasibility of re-establishing fen-upland systems within the oil sand mining areas.

Study area and methods

In the Fort McMurray area, surficial overburden deposits consist mainly of glacial till, which varies in composition from silt to clay-rich and ranges in thickness from non-existent to tens of metres. Immediately underlying the glacial sediments are the Cretaceous Clearwater and McMurray Formations. The Clearwater is composed of loose shale and siltstone, and the McMurray is an oil-bearing sand formation. These in turn overlie thick Devonian deposits of limestone and shale [18]. The lower geologic units in the region consist of Methy Formation reefal dolomite and Precambrian basement rocks [18].

As a result of the mining of the oil sand ore in the region, significant quantities of the till overburden have been stripped and stockpiled. In addition, the oil extraction process produces tailings materials ranging from fine to medium grained sands, along with a finer secondary tailings fraction. The till and sand materials, as well as the non-processed oil sand, are easily accessible for use in the construction of an upland-fen system. Their hydraulic properties are described later.

The geometry of the system is guided by our conceptualisation of a fen system originating in a valley-bottom setting with lateral inputs of groundwater that are an important component to the water budget [13]. For the purposes of modelling, the actual dimensions are not as important as the relative proportions of the layers and zones, thus the actual size is somewhat arbitrary. In practice, however, there is likely a minimum size for which stable fen conditions could be created, because edge effects would become large as the system size decreased. Consequently, a fen with ~2 m of peat, covering an area of about 1 ha, was thought to be an appropriate size. Tailings sand (the 'aquifer') up to about 5 m thick covered by a 0.2 m soil layer form the upland (contributing area for the fen, which we initially define with an area twice that of the fen). To prevent deep seepage water loss, a low-permeability liner created from lean oil sand or till materials with thickness must underlie these materials. Our initial estimate of the liner thickness is 1 m. To make the simulation conservative, the model domain includes a permeable sand tailings base area onto which the system would be placed (Figure 2a).

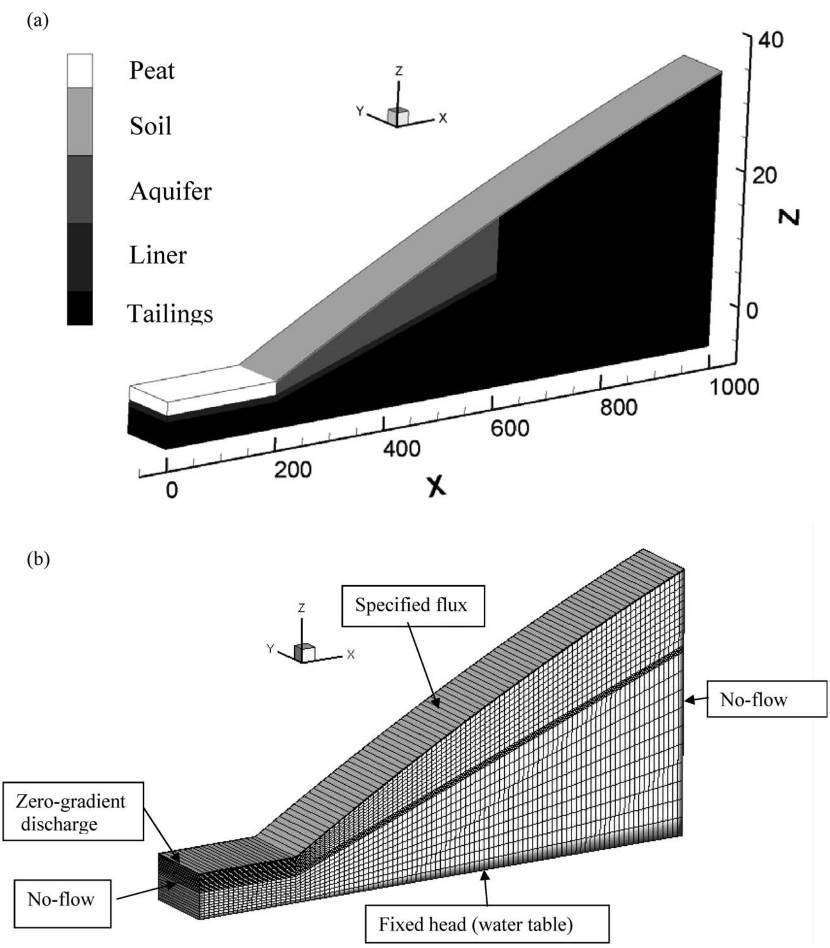

Figure 2. (a) Materials distribution and (b) finite-element grid and flow boundary conditions.

The conceptual model defined above was used as a base for the simulation experiments. In considering the highly transient nature of the problem on an annual cycle and the partially saturated conditions that exist throughout the year through portions of the flow system, an advanced numerical modelling platform was required to evaluate the feasibility of the proposed conceptual model and to investigate the sensitivity of the main controlling features of the system. The details of the model are provided below.

Model description and setup

HydroGeoSphere [19,20] was used to model the proposed fen system in a quasi 3-D approach where a cross-sectional domain oriented through the central axis of the constructed fen was selected for the analysis (Figure 2a). The model is a fully integrated, variably-saturated flow and transport code that has three-dimensional capabilities and can accommodate the generation of surface water flow. A finite element numerical scheme was used for the domain discretisation. The peat material that comprises the fen requires a certain minimum level of saturation to support peatland plant communities and to reduce peat oxidation. Previous work in bog peatlands [15] suggests the pressure in the upper peat-soil layer should not drop below -100 cm for more than about 2 days at a time. No such thresholds have been established in fens. However, the vascular plants more common in fen systems may not have such stringent requirements. To remain conservative, we use this criterion to evaluate the suitability of the proposed design. In the model the fen peat (and constructed upland aquifer) rests directly on the liner that slopes toward the fen. The relatively low hydraulic conductivity of this unit is intended to limit water from percolating downward to the regional water table and instead direct it laterally into the fen. The aquifer sand affects the storage of infiltrated water and controls the rate at which it seeps to the fen. It is overlain by a 20 cm soil layer composed of a mixture of peat and till [21], and provides a layer which controls infiltration and maintains a higher level of saturation than aquifer sand, which would be more suitable for plants. The tailings sand upon which the system rests initially has the same hydraulic properties as the aquifer sand. Its high permeability ensures that under the long-term average rate of infiltration it remains unsaturated, and that infiltrating water passes readily to the regional water table, unless diverted laterally by the liner. This, along with the low specified pressure head conditions represents the most difficult conditions likely to be chosen for fen creation.

The soil hydraulic properties were based on water retention and hydraulic conductivity relations for local materials including peat and soil cover materials [21], and for sand and clay-till overburden [22] for oil sands sites. On the basis of these relationships and determining K_{unsat} as a function of relative permeability, functional hydraulic relationships were defined for each material as shown in Figure 3. As part of the sensitivity analysis in this study, aquifer and liner material properties were varied (Table 1). Van Genuchten parameters [23] for peat and soil were not reported by Shurniak and Barbour [21], so a look-up table was constructed for use by the model to define the water retention relationship in the model, based on their published characteristic curves.

The two parameters that control the movement of water in the surface domain are the Manning coefficient (a measure of the frictional resistance to flow) and the rill storage height (the depth of depressions in the upper surface). No sensitivity analyses

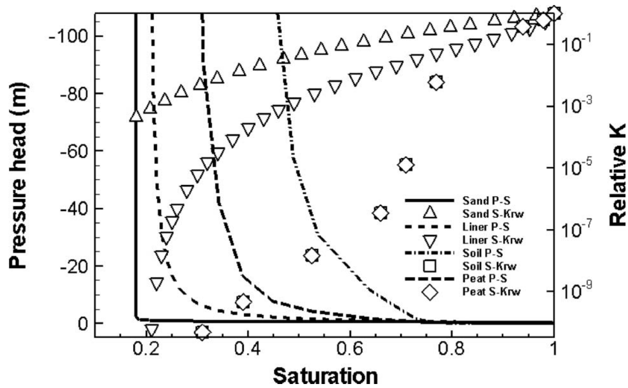

Figure 3. Moisture retention curves, where P-S denotes the pressure *vs.* saturation relationship and S-Krw denotes the saturation *vs.* relative K relationship.

Table 1. Description of material properties for sensitivity analyses.

	Saturated K (m/s)	Porosity	Van Genuchten α (m^{-1})	Van Genuchten n
Tailings	1×10^{-5}	0.35	1.9	6
Liner I	1×10^{-9}	0.55	1.9	1.8
Liner II	1×10^{-10}	0.55	1.9	1.8
Liner III	1×10^{-8}	0.55	1.9	1.8
Aquifer I	1×10^{-5}	0.35	1.9	6
Aquifer II	1×10^{-4}	0.35	1.9	6
Peat	1×10^{-5}	0.7	–	–
Soil	1×10^{-5}	0.4	–	–

were performed for these parameters. Instead, a Manning coefficient equal to 0.0003 $d/m^{1/3}$ was assigned, which is typical of a grassy surface. A rill storage height of 0.01 m was chosen, which is small enough not to impede flow, but large enough to enhance model stability.

Boundary conditions

In HydroGeoSphere, water can move freely between the surface and subsurface domains (Figure 2b), depending on the size and direction of the head gradient between them. The entire top surface of the model domain, coinciding with the surface water domain, is a boundary of assigned flux to represent meteorologic conditions. To establish initial flow conditions (hydraulic head and saturation) throughout the simulation domain, a uniform P-ET flux value estimated from the difference between annual average precipitation (P) and evapotranspiration (ET) was run to steady state to develop this initial condition for subsequent runs.

Daily precipitation and temperature data from 1940 to 2004 were used to determine rainfall (P) and potential evapotranspiration (PE). Daily precipitation was considered to be rain if temperature was above 0°C, and the daily water input was equal to the rain plus snowmelt (if any). If the daily average temperature was less than or equal to 0°C, precipitation (if any) was stored (i.e. snow accumulation).

Snowmelt (M) was determined on the basis of air temperature (T_a) using a melt factor (M_f) approach, where

$$M = M_f \times (T_a - M_{BASE}) \quad (1)$$

where, $Mf = 0.12$ mm $^\circ C^{-1}$ hr^{-1} [24], adjusted to a daily value, and M_{BASE} was 0°C.

PE was determined from the Thornthwaite temperature index approach outlined in [25], where

$$PE = 29.8 \cdot D \cdot \frac{e_a^*(T_a)}{T_a + 273.2} \quad (2)$$

where, PE is in mm/d, D is hours of daylight, and $e_a^*(T_a)$ is the saturation vapour pressure (kPa at the given air temperature (°C)). For the steady state condition, ET was determined from PE based on the locally derived ratio of ET/PE = 0.61 [26]. Evapotranspiration was assumed to be nil unless air temperature was above zero. Sublimation losses from the snowpack may be important [27], but were not accounted for. On the basis of this approach the average annual net flux (P-ET) was 179 mm. Thus, for the steady-state simulations the daily net flux of 4.904×10^{-4} m/d was initially applied until a steady-state condition was achieved, and then set to zero to simulate drought.

For the transient simulations, the evapotranspiration formulation of Panday and Huyakorn [28] was used to define evaporation and transpiration as a function of soil water content based on PE as defined above. We defined two ET zones, which represent the different characteristics of the fen and upland soil zones in the model domain. In each case, the water loss by evapotranspiration is distributed through the top 20 cm, corresponding to the thickness of the soil layer, with a quadratic function that focuses loss of water by evapotranspiration to the near-surface nodes, and is modified by a multiplier that accounts for the water storage condition of the soil.

In both evaporation and transpiration, a limiting level of saturation is specified, below which no ET losses can occur. In this study, the wilting point was chosen for this lower limit for both evaporation and transpiration (Table 2). At saturations below the wilting point the evaporation and transpiration functions are multiplied by zero. The saturation limit for the wilting point was interpolated from the pressure-saturation relationship by assuming a pressure head value of −143 m (interpreted from Figures 6 – 13 in Dingman, 2002 [25]).

There is also an upper limit of saturation above which the full PE is applied. In this study, the field capacity was chosen for the upper limit of the transpiration function. The saturation limit for the field capacity was interpolated from the pressure-saturation relationship by assuming a pressure head value of −3.4 m

Table 2. Limiting saturation values for constraining evaporation and transpiration.

	Fen	Upland soil
Evaporation minimum	0.3	0.43
Evaporation maximum	0.69	0.75
Wilting point	0.3	0.43
Field capacity	0.57	0.72

(interpreted from Figures 6 – 13 in Dingman, 2002 [25]). The upper saturation limit for the evaporation function was interpolated from the pressure-saturation relationship by assuming a pressure head value of -1 m. The multiplier rises to 1.0 at the upper saturation limit.

Other boundary conditions include a zero-gradient discharge boundary along the upper edge of the model at $x = 0$ (Figure 2b). This condition uses the surface water depth and the Manning equation to calculate a discharge flux by assuming that the slope of the water surface equals the slope of the ground surface at the boundary, and allows water to flow freely from the surface water domain should water depths in the peat exceed the elevation of this outlet point. Conceptually, this is similar to outflow over a weir, whose surface elevation is identical to the peat surface elevation, and allows surface water to drain from the system without having to specify a flow rate or water depth. The rest of the left hand boundary is a no flow boundary (i.e. water is only able to leave at the very top node as surface water outflow), based on the assumption that it is located at the centre of the fen, and thus by symmetry is a groundwater divide.The right boundary of the model is assumed to be located at the groundwater divide in the upland region, and is likewise represented in the model as a boundary of zero flux.

For the subsurface domain, a constant hydraulic head of -5 m is assigned to the bottom boundary, which ensures that the water table does not drop below the bottom of the domain considering the geometry of the specified system and the position of the datum at the lowest point on the ground surface. This lower boundary condition is intended to represent the presence of a regional water table and offers a pathway for water to bypass the fen system and discharge from the model domain if it moves below the liner.

Sensitivity analysis procedure

A base-case model geometry is defined with domain length 1000 m, peat length 200 m, peat thickness 2 m, liner thickness 1 m, liner slope 3% (outside the fen). The upland to fen surface area ratio is defined by specifying the length of the liner – when the liner does not extend to the right boundary, the domain to the right of the liner is effectively removed from the area that recharges the fen. The model domain was set up this way to simplify the procedure for altering the upland to fen ratio. The upland to fen surface area ratio for the base-case is 2:1 (i.e. liner length outside fen 400 m, length of fen deposit 200 m). The aquifer sand thickness varies from 2 m near the peat to about 8 m at the upland end of the liner and about 11.4 m at the right end of the domain (Figure 2b).

In the sensitivity analysis, key features of the proposed design are modified one at a time, and in each case, new equilibrium conditions and responses to drought are simulated then compared with the base case. Four sets of simulations are done with steady-state inputs (equivalent to 179 mm/y), each set with a different combination of liner and aquifer sand hydraulic conductivity. In each of these sets the influence of the geometry of the systems is tested by systematically changing the liner thickness, length and slope, and aquifer thickness. The steady-state simulations are used to find an optimal geometry and hydraulic conductivity, and then a transient simulation is done with these optimal properties to gauge the transient response of the fen. The sequence and characteristics of the material and system geometry in each set of simulations are summarised in Tables 3 and 4.

Steady-state saturation and extended drought

For the initial run (Steady-state case 1), the permeability of the liner is fixed at 1×10^{-9} m/s (Liner I) and aquifer at 1×10^{-5} m/s (Aquifer I); the upland to fen surface area ratio is 2:1; liner thickness is 1 m and the liner slope is 3% (Table 4). Applying a steady-state surface flux of 179 mm/y (4.9×10^{-4} m/d) results in the steady-state saturation condition shown in Figure 4. The degree of saturation in the upland region of the sand is uniform, with a value of about 0.19. This level of saturation results in a relative *K* (Krw) that, when multiplied by the saturated *K*, gives an effective *K* that is sufficient to move the recharge water through the

Table 3. Summary of material properties used for each simulation case.

Steady state case 1	Liner I 10^{-9} m/s	Aquifer I 10^{-5} m/s
Steady state case 2	Liner II 10^{-10} m/s	Aquifer I 10^{-5} m/s
Steady state case 3	Liner II 10^{-8} m/s	Aquifer I 10^{-5} m/s
Steady state case 4	Liner II 10^{-10} m/s	Aquifer II 10^{-4} m/s
Transient case 1	Liner II 10^{-10} m/s	Aquifer II 10^{-4} m/s
Transient case 2	Liner I 10^{-9} m/s	Aquifer II 10^{-4} m/s

Table 4. Summary of sensitivity analysis performed for various domain characteristics for each simulation case presented in Table 4.

	Ratio	Liner thickness (m)	Slope (%)	Aquifer thickness (m)
Base	2:1	1	3	2–8
Thicker liner	2:1	2	3	2–8
Longer liner	3:1	1	3	2–11
Shorter liner	1:1	1	3	2–5
Higher slope	2:1	1	6	2–8
Thicker aquifer	2:1	2	3	2–13

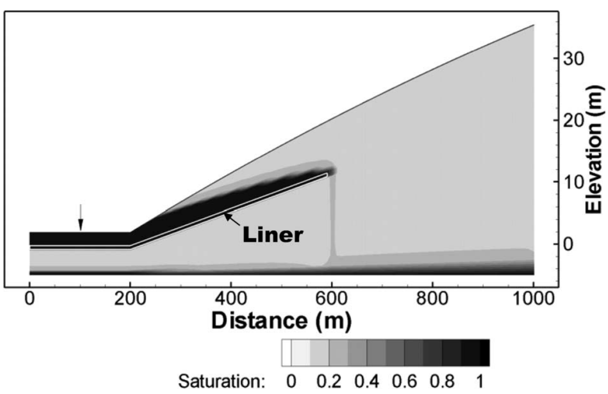

Figure 4. Initial water saturation for Liner I, Aquifer I properties with extent of liner indicated by white line. The arrow represents the position in the fen (10 cm below the surface), for which pressure is reported in the following simulations.

unsaturated sand under a unit hydraulic gradient. The level of saturation in the peat and liner materials are near 1.0, indicating that K of the liner is low enough to cause sufficient water to be diverted to the peat to maintain the water table at or above ground surface under conditions of long-term average infiltration.

The long-term drought condition is simulated by setting the surface boundary flux to zero. The impact of this on the pressure head in the fen is shown for a point (arrow in Figure 4) located at $x = 100$ m and at a depth of 0.1 m below fen surface. For the base case scenario, pressure is maintained above the critical value for a period of 88 days regardless of the variations in the liner geometry and aquifer thickness (Figure 5). The only design change that has a noticeable effect on the pressure response in the fen is when the thickness of the clay liner is doubled. In this case, the time it takes for pressure to drop below the critical value (-1 m of water) increased from 88 to 93 days. Changes in the upland design features have little effect on the pressure response in the fen.

If evaporation and transpiration (ET) are reduced to zero for Steady-state case 1, soil-water pressure remains above the critical value for over 6 years (not shown in Figure 5). Therefore, we can conclude that the pressure drop in the fen in this scenario is almost exclusively because of the effect of water losses to ET. The low hydraulic conductivity of the liner combined with the unsaturated conditions below the liner effectively maintains the water within the shallow subsurface environment without significant leakage losses.

For the next set of simulations (Steady-state case 2), K of the liner is lowered by one order of magnitude to 1×10^{-10} m/s (shown as Liner II in Table 3) to determine if this would restrict seepage losses and thereby divert more water to the fen. The outcome is that the pressure in the fen is maintained above the threshold for about 105 days (Figure 6), an increase of 17 days relative to using the Liner I. None of the upland design changes have any significant impact on the pressure response.

As a final component of the liner sensitivity assessment (Steady-state case 3), the liner K is raised by one order of magnitude from the base case to 1×10^{-8} m/s. The long-term drought caused the pressure in the fen to drop below the critical value

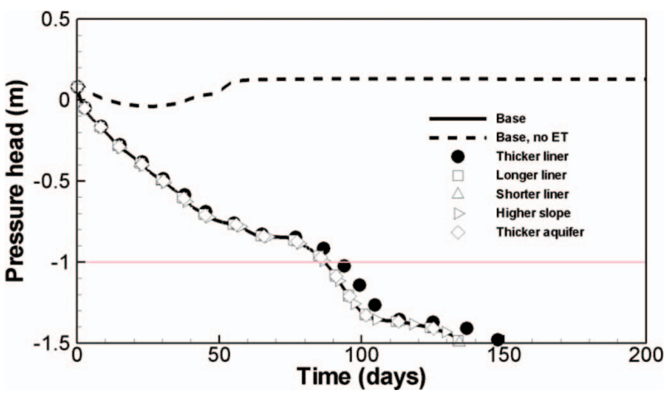

Figure 5. Steady-state case 1. Pressure response in fen because of changes in design features and using Liner I, Aquifer I properties. The horizontal grey line in this and subsequent pressure *vs.* time graphs represents the threshold pressure defined by Price [15].

within 5 days (not shown), indicating that this liner is far too permeable to maintain water flow to the fen.

Steady-state case 4 examines the effect of increasing aquifer sand K to 1×10^{-4} m/s. Under long-term drought conditions, 112 days are required for the pressure in the fen to drop below the critical value (Figure 7), an increase of 24 days relative to the Aquifer I/Liner I case response. In this scenario the higher K of the aquifer sand allows water to flow downslope more rapidly to the fen. Under this scenario the longer liner (upland to fen surface area ratio of 3:1) also has a significant impact on the pressure response, increasing the time to reach critical pressure to 176 days, an increase relative to the base case of 64 days. The shorter liner (upland to fen surface area ratio of 1:1) reduces the time to reach critical pressure to 106 days, a decrease relative to the base case of 6 days.

These results indicate that the aquifer sand permeability is an important design feature, and if it is too low, it may prevent water from reaching the fen quickly enough to prevent a critical pressure drop there from ET losses during a drought.

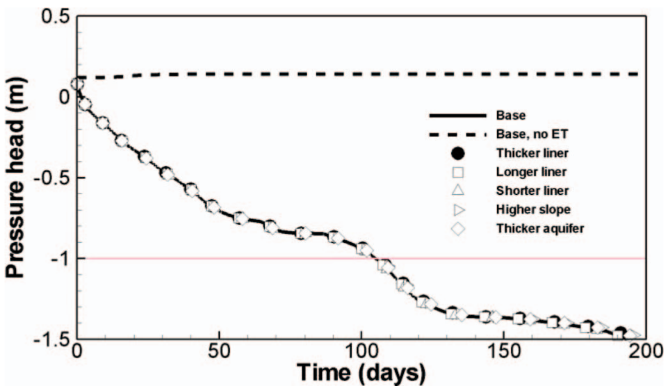

Figure 6. Steady-state case 2. Pressure response in fen because of changes in design features and using Liner II, Aquifer I properties.

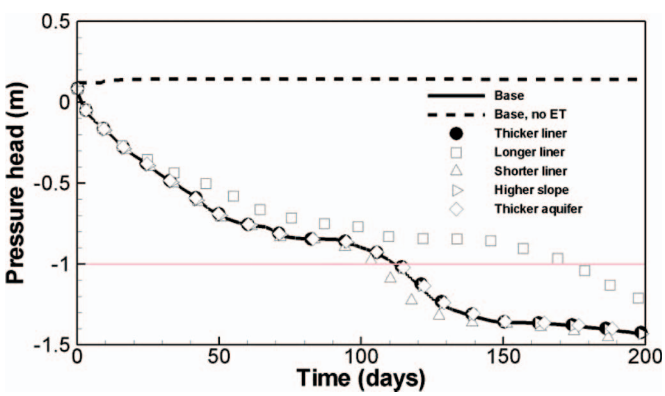

Figure 7. Steady-state case 4. Pressure response in fen due to changes in design features and using Liner II, Aquifer II properties.

Modelling transient climate input

We have chosen to model a period (October 1997–2001) during which the most severe drought on record occurred (1998). The model was run with daily climate inputs. The steady state saturations, which were used as the initial condition for the sensitivity analysis, were also used in the transient climate scenarios. Therefore, the modelled fen is initially well-saturated, with ponded water on its surface. We chose the month of October 1997 as the starting point for the simulation, because it is at the end of a relatively wet period, when it is likely that real fens would also be well saturated. The simulation period from October 1997 until March 1998 (onset of drought) therefore allows the model some time to adjust the initial moisture distribution so that it reflects the transient climate inputs more realistically.

Transient case 1 is based on the optimal materials as discerned above, corresponding to Liner II ($K = 10^{-10}$ m/s) and Aquifer II ($K = 10^{-4}$ m/s). From October 1997 to April 1998 the simulations show the fen has been sufficiently rewet to include ponded water to a depth of about 0.1 m (Figure 8). In a field setting, this would become frozen, and sublimation losses would be negligible. Snowmelt in April drains quickly, and the effects of a water deficit then become marked during the very dry summer of 1998. The steep decline on the water pressure is punctuated by a major rainfall in July, but continues to decline until the end of October, when the trend reverses and the pressure begins to rise, continuing to do so until the water level recovers entirely to its spring maxima coinciding with snowmelt. The rise in pressure over the winter period reflects groundwater input from the upland since precipitation (snow) is stored at the surface. A similar pattern occurs in 1999 and 2000, although the degree of drying is much less, corresponding to smaller water deficits in those years.

Changes in geometry do not substantially alter the pattern of water pressure, except that the longer liner (upland to fen surface area ratio of 3:1) causes earlier rewetting; and a shorter liner (upland to fen surface area ratio of 1:1) results in

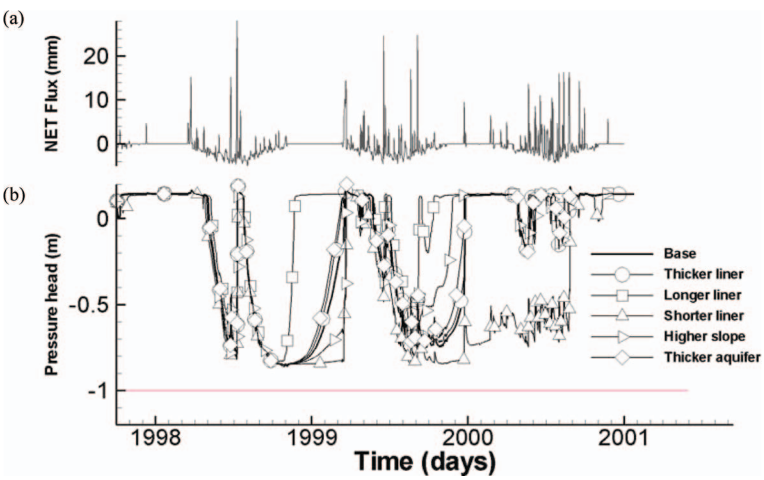

Figure 8. Transient case 1. (a) NET Flux (mm) and (b) Transient pressure response to daily climate inputs (rain, snowmelt, evaporation and transpiration) and using Liner II, Aquifer II properties.

incomplete recharge. The water pressure in the fen is therefore sensitive enough to liner length to suggest that an upland to fen surface area ratio of 1:1 is inadequate, even with the favourable material properties. Altering the slope of the upland and liner has a relatively minor effect. The simulated water pressure in 1998 drops almost to the threshold value by September, and remains there over the winter when the plants are dormant. The low pressure at this time therefore has little consequence because the plants' water requirements are negligible.

Transient case 2 tested less optimal materials (higher permeability Liner I (10^{-9} m/s)). The drop in pressure over the course of the year (not shown) is substantially more and the pattern of pressure is more erratic. In this case, the pressure falls throughout the winter of 1998, because the higher hydraulic conductivity of the liner does not retain water so effectively, and soil-water pressure in the peat never really recovers for the duration of the simulation. The threshold conditions using Liner I, therefore cannot be sustained in drought years, and represent the absolute upper limit of liner K that could be used.

Discussion and conclusion

The results indicate that there are limitations to the construction of a fen system on a post-mined landscape related to the availability of suitable materials. The assessment was made on the basis of achieving a threshold level of wetness in fen peat when an upland source area provides adequate seepage. Simulation modelling using local climate inputs showed that the most important feature of such a system include a liner of sufficiently low hydraulic conductivity (ideally 1×10^{-10} m/s) and a sandy aquifer with sufficiently high hydraulic conductivity (10^{-4}–10^{-5} m/s). The main geometric feature of design is that the upland to fen surface area ratio be greater than or equal to 2:1. On the basis of transient simulation using daily estimates of P and ET during the most severe drought on record, the above design maintained the specified level of wetness for the growing season. The adequacy of this threshold can be judged against local data for that same period. At undisturbed fen sites of the Utikima Lake region the water table in fens dropped to 1.6 m below the surface during 1998 [17]. This compares to a water table of $\sim$1.3 m in the current simulations. Evidently, these natural sites can tolerate periods of drought more extreme than we have set for a threshold (-1 m). It is noteworthy, however, that in both this simulation and in the field study [17] the minimum water table corresponded to a dormant period for plants (November), and that much of the previous growing season experienced water pressures above the threshold specified here.

The purpose of this study was to determine the optimal material properties and system geometry that would sustain a certain level of wetness in fen peat that is thought sufficient to reduce its oxidation rate, and provide a growth medium for fen plants. As there are no such created fen systems to study, this hypothetical system was constructed and the water flow and stores were modelled as a way of narrowing down the design options rather than building by trial and error. There remains a great deal of uncertainty. Foremost is the absence of any data against which the simulations can be directly compared. The climate inputs have a range of certainty from moderate (P) to less certain (ET). The role of interception is not considered. The hydraulic characteristics range from reasonable estimates of saturated hydraulic conductivity, to uncertainties associated with the water retention and unsaturated

Table 5. Time for pressure 0.1 m below fen surface to drop below −100 cm during extreme drought conditions ($P = 0$ mm/y), from a condition of steady-state saturation produced by the average surface flux (P-ET) of 179 mm/y.

	Upland to fen ratio 1:1	Upland to fen ratio 2:1	Upland to fen ratio 3:1
Liner I (10^{-9} m/s); Aquifer I (10^{-5} m/s)	88*	88*	88*
Liner II (10^{-10} m/s); Aquifer I (10^{-5} m/s)	105	105	105
Liner II (10^{-10} m/s); Aquifer II (10^{-4} m/s)	106	112	176
Liner III (10^{-8} m/s); Aquifer I (10^{-5} m/s)	5	5	5

*When liner thickness is doubled, the critical time was 93 days.

hydraulic conductivity functions. In particular, the water retention function of disturbed peat material is poorly defined. Nevertheless, the design features suggested by these simulations provide a reasonable starting point if a pilot system is to be constructed.

The sensitivity analysis suggests that a low permeability liner is the key to sustaining the requisite wetness conditions in the fen. Liner III ($K = 10^{-8}$ m/s) is clearly inadequate for directing water laterally (Table 5). Liner I ($K = 10^{-9}$ m/s) can do so, but the flow towards the fen is sufficiently slow (with Aquifer I sand) that leakage through the liner is still significant enough that adding flow from an extended upland (upland to fen surface area ratio of 3:1) makes no difference, since the opportunity for vertical seepage losses are too great. If Liner I is all that is available then its thickness should be increased. When liner material K is lowest (Liner II $K = 10^{-10}$ m/s) and aquifer sand high (Aquifer II $K = 10^{-4}$ m/s) the effect of an extended upland (Upland to Fen ratio of 3:1) becomes substantial (Table 5), and the overall time to threshold condition increases by nearly 60% compared to the base case geometry (upland to fen surface area ratio of 2:1). The above set of analyses implies that a fen system with Liner II and Aquifer II properties offers the most hope of sustaining threshold conditions during periods of drought.

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