Flow Modeling of a Syncrude North East In-Pit Hummock for the Sandhill Fen in Fort McMurray, Alberta

By

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Abstract:

The groundwater flow of a reclamation site in Alberta's Oil Sands was modeled using the MODFLOW 3D code. The site was simulated to determine the flow characteristics of a reclamation hummock. Such hummocks are required to maintain a mounded water table to sustain plant life placed on top as a part of reclamation. Sensitivity analysis was conducted initially by varying the water table depth. The hydraulic conductivity of the material, and recharge were then varied, in addition to adding a low conductivity cover layer, in order to monitor the water table response. Modeling found that a lower than predicted hydraulic conductivity value would be required to maintain a desired mounded water table at 1.5m depth. Additionally the hummock was found to be sensitive to flooding and drought conditions. Design topography such as swales and ridges were found to function as desired, by acting as areas of discharge and recharge respectively.

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1.0 Introduction:

The Alberta Oil Sands represents a vast resource of 173 billion barrels of proven oil. This resource has caused surface disturbance over an area of 500 square kilometers to date (Alberta's Oil Sands, 2009). In order to extract bitumen overburden material is stripped off and stock piled. Bitumen rich sand is then excavated creating 100m deep pits which are then backfilled with a mix of fine tailings and tailings sand. Mineral soils associated with the oil sands have a saline-sodic geochemistry, making them challenging to reclaim due to generated groundwater chemistries, which are unfavorable to plant life. As a part of land use agreements energy companies who disturb the area are required to reclaim land to its original state. This represents a vast challenge for engineers charged with the task of designing stable, natural landscapes. Syncrude's North East in Pit site (NEP) is set for reclamation to commence this year; at the time of writing, material is being placed for the initial landforms which will later be covered with a mineral-peat cover system and re-vegetated. A 51.5 hectare area is currently in the final stages of design by BGC Engineering Inc. to meet the reclamation needs dictated by Syncrude's land use agreement. Energy companies such as Syncrude are required to create a mix of boreal forest and peatland such as fens to restore the original animal habitats. This area has been named the Sandhill Watershed and will consist of a fen running the length of the site with a series of hummocks along its perimeter providing it with groundwater inputs. These hummocks must maintain a mounded water table condition at a depth of approximately 1.5m in order to provide water for reclamation plant cover without drowning root systems. This thesis will examine the groundwater behavior of one of these hummocks under several different flow and recharge conditions to determine a set of likely groundwater conditions for the designed geometry. The conditions will be investigated using the 3D finite volume software MODFLOW from the United States Geological Survey.

2.0 Background:

2.1 Study Site:

Syncrude's NEP site is located along Alberta Highway 63 in the district of Fort McKay, approximately 40km outside of Fort McMurray. The Sandhill Fen site is located at the North Eastern end of the NEP as shown below in figure 1.

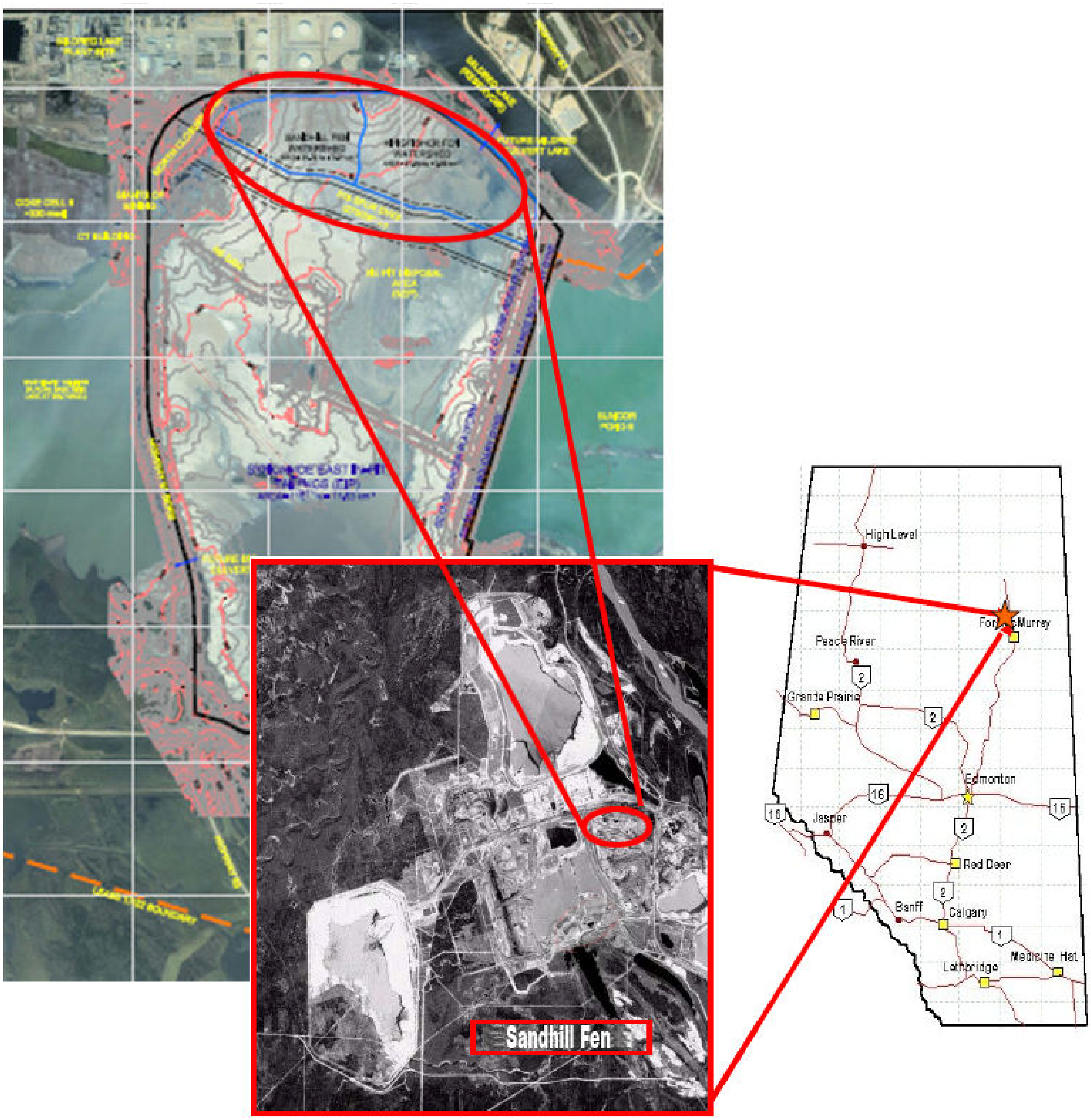

Figure 1: Site location.

The NEP was originally an open pit. It has since been diked and filled with hydraulically placed fine tailings. The mixtures of fine tailings with lenses of sand exist to approximately 50 meters depth. The exact stratigraphy is unknown and is currently being defined using CPT drilling however, the sediments exhibit a high water content and low hydraulic conductivity values. These fines are expected to consolidate over time and, with the added pressure of reclamation cover, release saline, sodic process water into the reclamation environment. On top of the tailings, tailings sand has been hydraulically beached to a thickness of approximately ten meters depth forming a large gentle swale trending west to east across the Sandhill Fen site. The area was originally covered in boreal forests and peatlands such as fens. Fens are a type of peatland similar to bogs where a layer of peat one to two meters thick maintains a water table within plus or minus 20cm of the surface throughout the year. While they tend to receive mineral rich water from an aquifer source, the majority of input water is provided by precipitation. The Sandhill Fen site is isolated by a large in-pit dike to the South, the constructed Sandhill Berm to the East and the pit walls to the North and West. The entire water shed has been isolated so that it may be carefully instrumented to define the water conditions of the site for future reclamation projects. The hummock being modeled is located at the South-West end of the fen at the headwaters as illustrated below in figure 2. In addition to the groundwater fen to be constructed in the main swale a perched fen will be placed behind the design hummock and isolated using a clay liner as in figure 2.

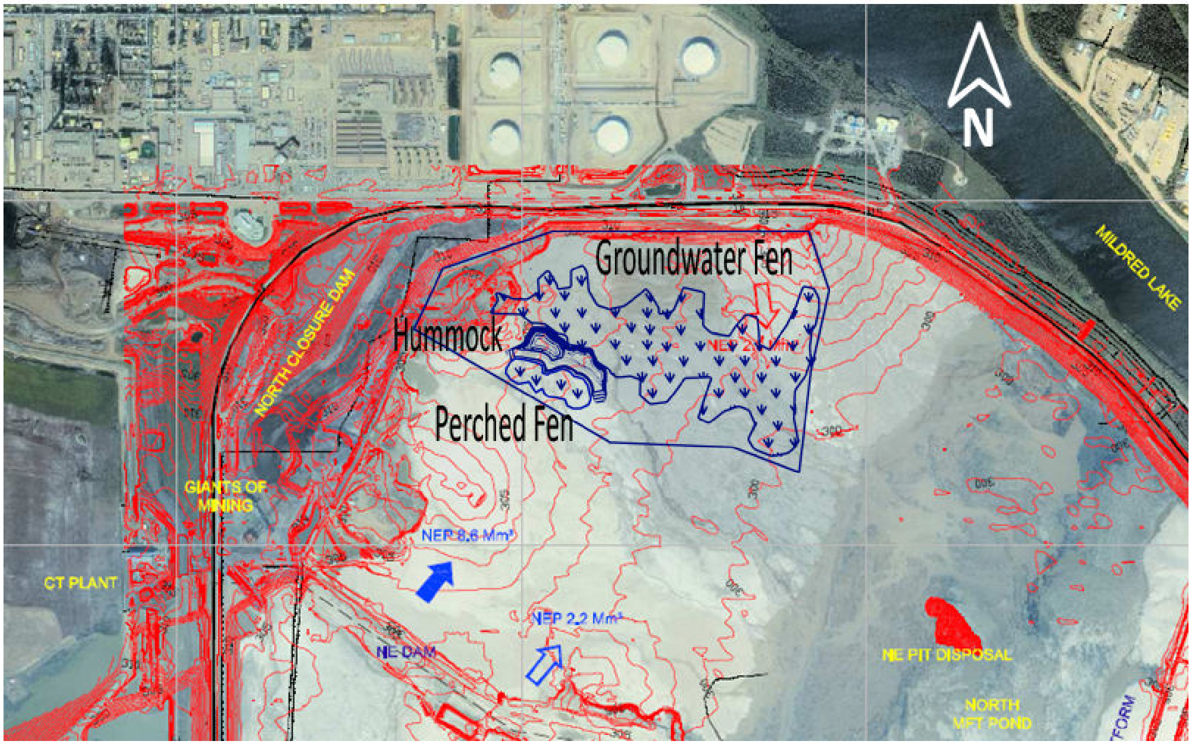

Figure 2: Hummock and Fen Location.

2.2 Climate:

The climate of the Fort McMurray region is continental humid (Kottec et al. 2006). Temperatures range from 18.0 °C in July to -20.7 °C in January with 20% of annual precipitation being accounted for by snow (Kelln, Barbour, Qualizza, 2008). Annual mean precipitation for the area is 442mm (1945-1995) and actual evapotranspiration values range in the area of 300mm (Kelln, Barbour, Qualizza, 2008). As a result of the expected water chemistry from the tailings, it is important to understand the groundwater conditions of the hummocks, to determine if they can provide the groundwater the fen requires and perhaps act as a filter for the tailings water.

2.3 Hummock Geometry and Design:

The design hummock is to be a showcase featuring some of the most complex geometry of any hummock on the site. It includes two peaks of 8m and 5m above grade with a saddle 4m above grade in between. The perimeter is highly irregular creating a series of ridges and swales designed to create microclimates. To create the most realistic topography possible, the ridges have been designed to have a convex topography created by varying the slopes from 1:2 Horizontal to Vertical at the toe to 1:5 at the crest. Similarly the swales have a concave topography using slopes of 1:5 at the toe and 1:2 at the crest. The toes of the hummock at the South ends have been flattened to 1:7 to allow for trucks to deliver reclamation material. A flattened bench was created along the Southern crest of the hummock to allow for truck traffic. The hummock will be constructed from tailings sand and covered with a veneer of overburden material and peat to allow for plant growth. The tailings sand for construction will be placed using a cyclostacking method to the rough topography and then graded to the final format. Although the hummock has been carefully designed, during grading operators will be given an outline of the desired topography, but a lack of precision is considered positive, in order to increase natural variability.

2.4 Previous Work:

No work has been conducted directly on tailings sand reclamation slopes. However, several papers have been published on the distribution of moisture and salts within reclamation cover systems. The main difference between these systems and the one in this paper are that the majority of covers are designed to be evapotranspiration covers which prevent infiltration, where in this case a mounded condition is desirable. These studies provide insight into the behavior of covers which were not addressed in this thesis. Additionally they provide insight into the transport of salts. Finally they provide a guideline for a field program which could be instituted on this sight.

2.4.1 Water Balance for Reclamation Covers on Oil Sands Mining Overburden Piles:

This paper reviewed the performance of varied thicknesses of peat placed over top of secondary till material as evapotranspiration covers. The overburden shales of the Clearwater formation tend to be saline sodic, making it desirable to isolate them from infiltration. The site used is called the Wood Bison site; it is located at the South end of the NEP. The site was instrumented to measure soil water content, soil suction, and soil temperature as well as air temperature, relative humidity, precipitation and wind speed. V-notch weirs were installed to measure surface runoff. This level of instrumentation allowed the authors to determine site specific evapotranspiration data and infiltration. This study found that cover materials remain frozen until the spring melt in May. The overburden shales had hydraulic conductivity values K on the order of 10^{-6} to 10^{-5} cm/s, which is on a similar scale to the tailings sand modeled. From modeling the authors determined that water would not percolate into the shales if their K value was $1x10^{-8}$ cm/s or less. Given the K values used for tailings sand in this thesis, it would appear that percolation will be possible through the cover system. The authors assumed no surface runoff for the purposes of modeling as the amount was negligible in the water balance and the peat material had such a high K value as to be able to retain the majority of precipitation. This study found that the designed cover systems could store between 100mm and 300mm of water depending on cover thickness. Evapotranspiration peaks in the summer but then drops off to less than 1mm/day when killing frosts start. The authors concluded that cover storage is controlled by precipitation and evapotranspiration and that surface runoff is a relatively small component.

2.4.2 Controls on the Spatial Distribution of Soil Moisture and Solute Transport in a Sloping Reclamation Cover:

This paper also investigated the performance of several different thicknesses of reclamation cover over a saline sodic overburden dump. The moisture dynamics of the site were found to vary greatly with the seasons. The overburden piles for this site had elevated levels of Ca^+ and Na^+ like the tailings sand in this thesis. The author’s review of previous work found that K values for the overburden shale can be increased by two orders of magnitude, as a result of macroporosity created by freeze thaw cycles over three to four years. This may be important for the Sandhill fen if the water table is found to be highly sensitive to changing K. This study also found a perched water table at the cover and shale interface. Data from a series of 55 boreholes placed in a 5m by 5m pattern was used for modeling input. The site was modeled using CTRAN/W and SEEP/W in a quasi 1D state and, was run in steady state to represent the average site conditions. Sites in the oil sands have approximately 185 days a year when the cover is unfrozen and flow can occur. Piezometer investigation showed that moisture distribution in the top 30cm of cover does not reflect the slope topography. The moisture at the base of the cover shale interface was found to weakly reflect the slope topography. This suggests that the hummock's water table should loosely reflect surface topography. The spring melt accounts for 20% of annual precipitation on sites like this. Surface runoff only occurs during spring snowmelt. As this thesis does not specifically cover spring runoff conditions ignoring surface runoff appears to be acceptable. The study showed that the toe of the slope is wetter through the summer and fall with perched conditions developing in the upper slope due to preferential flow during snow melt. The lower slopes were wetter during the spring due to surface runoff accumulation and similarly the upper slopes were dryer due to the lack of accumulation. The upper portions were found to be drained by subsurface flow. Lower slope water levels dropped in mid June due to the cessation of interflow.

Interflow and deep percolation are the dominant transport mechanisms in the lower region. In the mid and upper slope regions salt transport is limited by reduced antecedent moisture conditions coupled with the slightest amount of interflow or deep percolation. Evapotranspiration accelerates salt migration in lower zones. The mid and upper zones don't have significant migration as long as they stay moist. Deep percolation will attenuate transport in flat areas during spring and early summer. The paper concluded that the cover systems currently in use are adequate to prevent the migration of salts.

2.4.3 Hydrogeology of South Bison Hill:

The South Bison Hill is located at the base of the NEP. It is an overburden structure constructed of saline, sodic, pyritic shales of the Clearwater Formation. The hill is constructed of four segments. The first one is constructed of tills placed in lifts. The use of lifts generated a hydraulic conductivity ratio of 10:1 horizontal to vertical. The second segment consists of a pit filled by end dumping. The third segment was placed over the in-filled pit and constructed of higher quality overburden in 5m lifts. The smaller lifts created a more densely packed material with a K anisotropy ratio of 100:1 horizontal to vertical. Hydraulic conductivity values were obtained from rising head tests conducted in 25 piezometers across the site, resulting in K values ranging from $1x10^{-7}$cm/s to $1x10^{-4}$cm/s. These values also fit within the range of K values for the tailings sand. Modeling was conducted in SEEP/W using 15% of the total yearly precipitation as infiltration. 400mm/year of precipitation translated to 6mm of flux into the shale through the cover. This infiltration value is significantly lower than the value use in this thesis however; the cover system of the South Bison Hill is designed to prevent infiltration. Modeling showed a permanent water table 30m below the surface and, perched water tables within the top 20m of the overburden as a result of lower k values from compacting the lifts. Compaction appears to be a useful method for controlling K values during construction and could potentially provide mounding conditions in NEP hummocks.

3.0 Materials and Methods:

3.1 Site Groundwater Conditions:

The Sandhill Watershed is designed to be an instrumented water shed and as such is carefully isolated on all sides. To the southern perimeter is a large Spur Dyke which creates a groundwater divide. The eastern perimeter is being isolated with the Sandhill Berm constructed of tailings sand, rockfill, and a clay core. The northern and western perimeters are similarly isolated using small dykes. The bottom of the tailings sand cover is bounded by fine tailings, which are regarded to be a no-flow boundary as well for purposes of modeling. Initial piezometer investigations have suggested a water table at approximately 2m depth recharging on the perimeters of the swale and gently discharging into the centre, although flow is very gentle and the gradients low.

3.2 Soil Properties:

Properties of the Tailings sand were obtained from McKenna, and are summarized in table 1. The sand is uniform consisting almost entirely of quartz. Grains are subangular to subrounded and deposits tend to be homogeneous, with an anisotropic hydraulic conductivity (McKenna, 2002). Hydraulic conductivities of $2x10^{-4}$ to $8x10^{-4}$cm/s are defined by McKenna. A midrange value of $5x10^{-4}$cm/s was used as a base case value. A factor of 10 was used for the anisotropy of horizontal to vertical conductivities as suggested by McKenna.

Property	Typical Range of Values
% Sand Average	81 (CoV =20%)
% Silt Average	10 (CoV =100%)
% Clay Average	4.4 (CoV =180%)
D_{10} (micron)	70 – 100
D_{50} (micron)	150 – 200
D_{90} (micron)	225 – 350
Coefficient of curvature, Cc	1.0 - 1.5
Coefficient of uniformity, Cu	1.7 - 2.6
Moisture content (mw/ms) %	10 – 30
Saturated moisture content (mw/ms) %	20 - 30
Void ratio	0.6 - 0.9
Dry density, kg/m^3	1500 - 1700
Wet density, kg/m^3	1700 - 1900
Permeability, cm/s	2×10^{-4} to 8×10^{-4}

Table 1: Geotechnical properties of Syncrude tailings Sand. Taken from McKenna 2002.

These results were obtained from a series of laboratory and field tests including: piezocone dissipation testing, reconstituted sample tests, frozen core tests, coffee can percolation tests, infiltration tests, standpipe slug tests, field pump tests, and field gradient analysis. A value of 0.20 was used for the specific yield, as recommended by Roger Beckie (personal communication, 15, January, 2009) for unconfined conditions. A value of 0.26 was used for the specific storage coefficient from Johnson 1967.

3.3 Model Geometry:

Modeling was conducted using Waterloo Hydrogeologic Inc Software's Modlow 3D. The hummock topography was input into Gemcom's Surpac and converted into an Excel file. From this Golden Software Surfer 8 was used to create a 100 by 100 grid file and convert it to a tab delimitated text document for input into Modflow. The modeling domain extended from an elevation of 322m to 280m and divided into eleven layers of approximately equal thickness. A 100 by 100 grid identical to that used by Surfer was applied to the model area. The model grid is shown below in figures 3 and 4 with an overlay of the hummock topography.

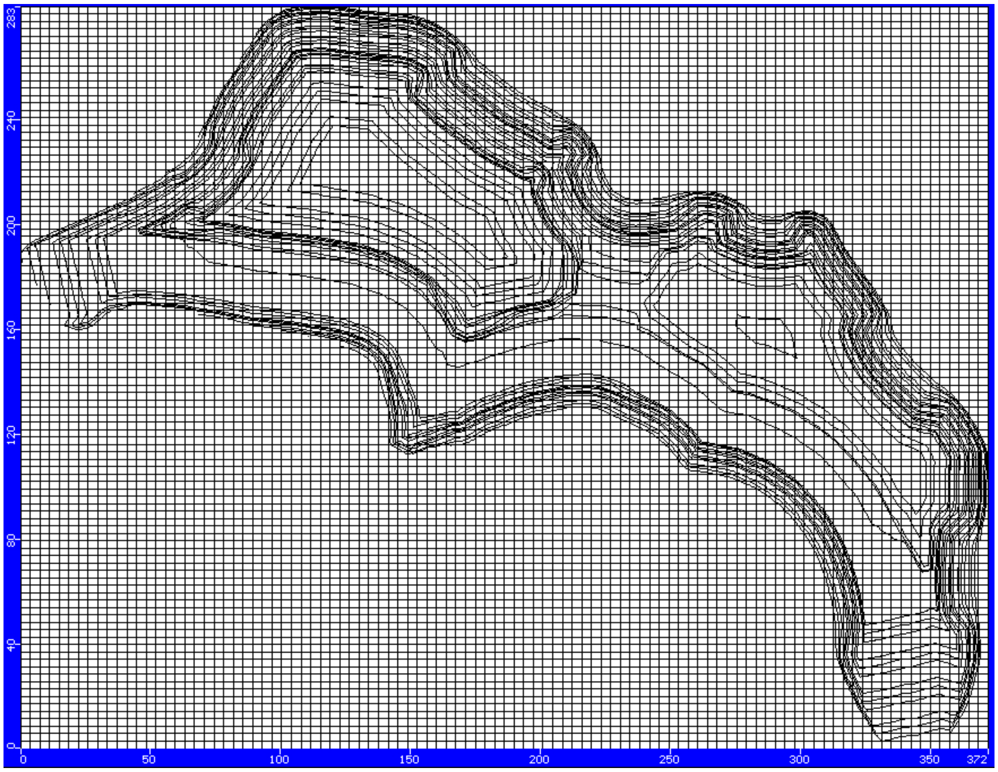

Figure 3: Numerical model grid, plan view.

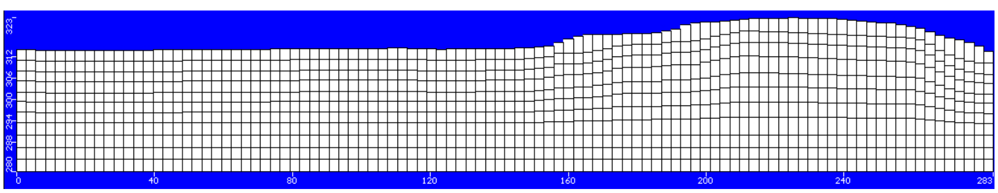

Figure 4: Numerical model grid, section view through column 34.

The perched fen and groundwater fen were not modeled, as their behavior is not expected to impact the performance of the hummock. Although the perched fen runs onto the back of the design hummock, it will be an isolated water system due to its clay liner. Similarly the groundwater fen exists in the hummock's discharge region, making it impossible for it to contribute water to the hummock. In addition the groundwater fen will be isolated by a clay liner. The entire model area was defined as tailings sand. Given the unknown properties of the fine tailings and the fact that flow through them is not expected it was reasonable to model the behavior of the sand alone. The reclamation cover was ignored for similar reasons. As the ground water table was not designed to be located within it and its only effect would be on evapotranspiration, which was directly factored in to the recharge rate, it was not modeled. The resulting boundary value problem for this model is shown below in figure 5.

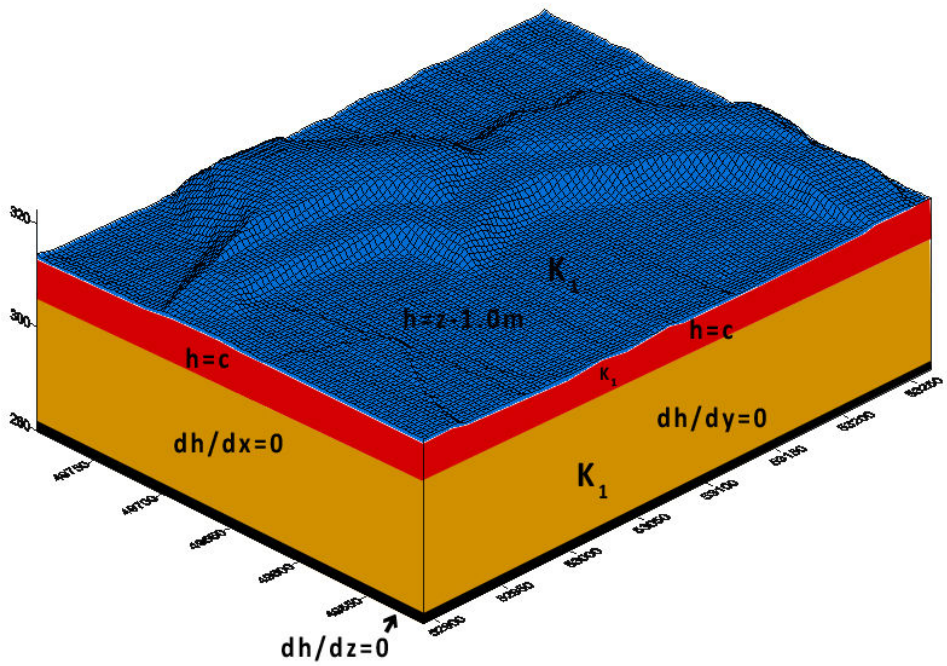

Figure 5: Boundary value problem.

3.4 Numerical Modeling:

Numerical modeling was conducted using MODFLOW 3D which uses finite volume analysis to solve problems. The problem is discretized into a series of cells to which MODFLOW applies and solves the partial differential equation describing the three-dimensional movement of groundwater of constant density through porous material, shown below in equation 1 (Andersen, 1993).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t}$$

Equation 1: 3D groundwater movement of constant density through a porous material.

Where:

K_{xx}, K_{yy}, and K_{zz} are the values of hydraulic conductivity along the x, y, and z coordinates;

h is the potentiometric head;

W is a volumetric flux per unit volume and represents sources and/or sinks of water ;

Ss is the specific storage of the porous material; and

t is time (Andersen, 1993).

The software uses this equation and user inputted boundary conditions to determine the groundwater flow within the model. Users may define layers as confined, unconfined, or confined/unconfined. Modflow allows for the simulation of drains, recharge, evapotranspiration and rivers as well as drains. The software accepts user specified constant head, and constant flux as boundary conditions (Andersen, 1993).

4.0 Modeling:

4.1 Modeling Cases:

For the purposes of modeling the problem was separated into five separate cases, to represent different flow conditions, as well as to calibrate the model.

4.1.1 Case 1:

Case 1 was run first in order to perform some basic sensitivity analysis, and to calibrate the model. It involved setting a constant water table set to similar topography as the hummock. This water table was then set at several different depths, in order to predict recharge values required, depending on adjusted values of K. For case 1 a simplified water table was created by generating a 10 by 10 grid file from the original hummock topography. This file was then used to generate a 100 by 100 grid file smoothing out all the minor features of the topography. This file was then modified in excel to a set distance below surface of: 0.5, 1.0, 1.5, or 2.0 meters below surface. These values represent an average depth as the smoothed topography did not perfectly match the hummock topography. Each case was run through with K values ranging from $5x10^{-4}$cm/s in the x and y direction to $1x10^{-5}$cm/s in the x and y direction, stepping by half orders of magnitude. The vertical specific recharge, and groundwater recharge affected by constant head were obtained by correcting zonebudget volumetric fluxes to zone areas. The groundwater recharge affected by constant head was interpreted as the equivalent recharge required to establish the specified water table elevation for the areas. Scenarios which suggested the problem specified recharge would be sufficient to maintain the desired water table were then used as base cases for Case 2.

4.1.2 Case 2:

Given the suggested K value of $1x10^{-5}$cm/s in the x and y direction from Case 1, Case 2 proceeded to use a less well defined water table to determine exact groundwater topography. The constant head values assigned to the hummock area were deleted, in order to simulate placement of the hummock on the existing topography. Using the design recharge and the K value from Case 1, simulations were run with the same water table depths as Case 1, to determine the resulting groundwater table geometry.

4.1.3 Case 3:

Given the determined K value from cases 1 and 2, it was desirable to determine if different hummock geometry would provide the desired mounding condition. To this end it was assumed that the tailings sand had a K of $5x10^{-4}$cm/s in the x and y direction and that a cover layer the thickness of layer 1 (3.7m thick) was placed and compacted on top. The geometry of this cover system is illustrated below in figures 6 and 7 where blue cells are the cover material.

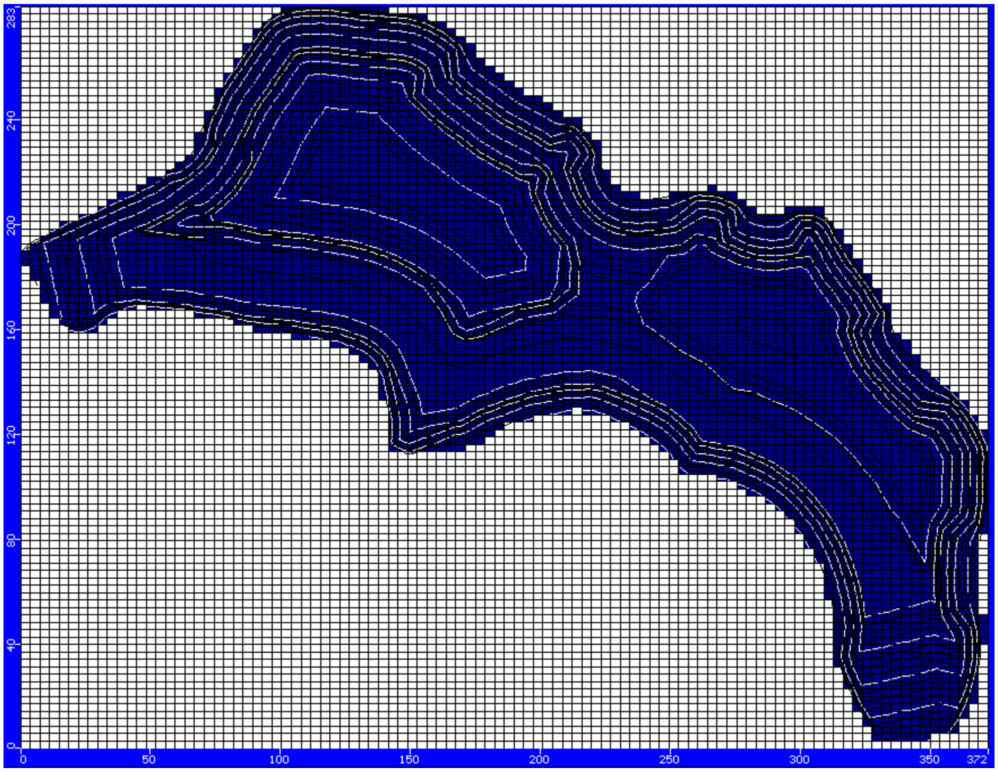

Figure 6: Cover system geometry, plan view.

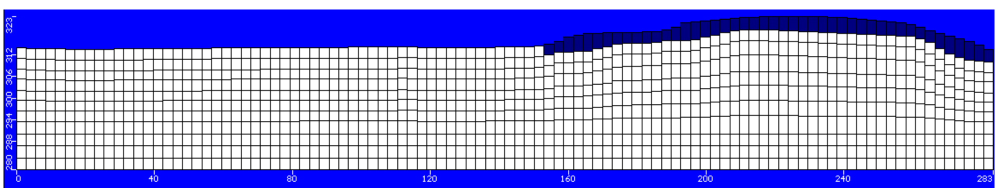

Figure 7: Cover system dimensions, section view through column 34.

Modeling was run altering both the K value for the cover, as well as the sand, in order to avoid a perched water table condition, as hummock flow is desirable for this problem.

4.1.4 Case 4:

Case 4 was run to simulate an extended drought (limited recharge) during the summer, when evapotranspiration is still high.

4.1.5 Case 5:

Case 5 was run in order to simulate an extreme rainfall event during the summer months, as is sometimes experienced.

4.2 Boundary conditions:

The edges of the model had constant head values equal to the top layer assigned to a depth of 10m, in order to simulate a flow through condition existing within the sand layer. These boundary conditions are illustrated below in figures 8 and 9 where maroon cells have an assigned constant head value.

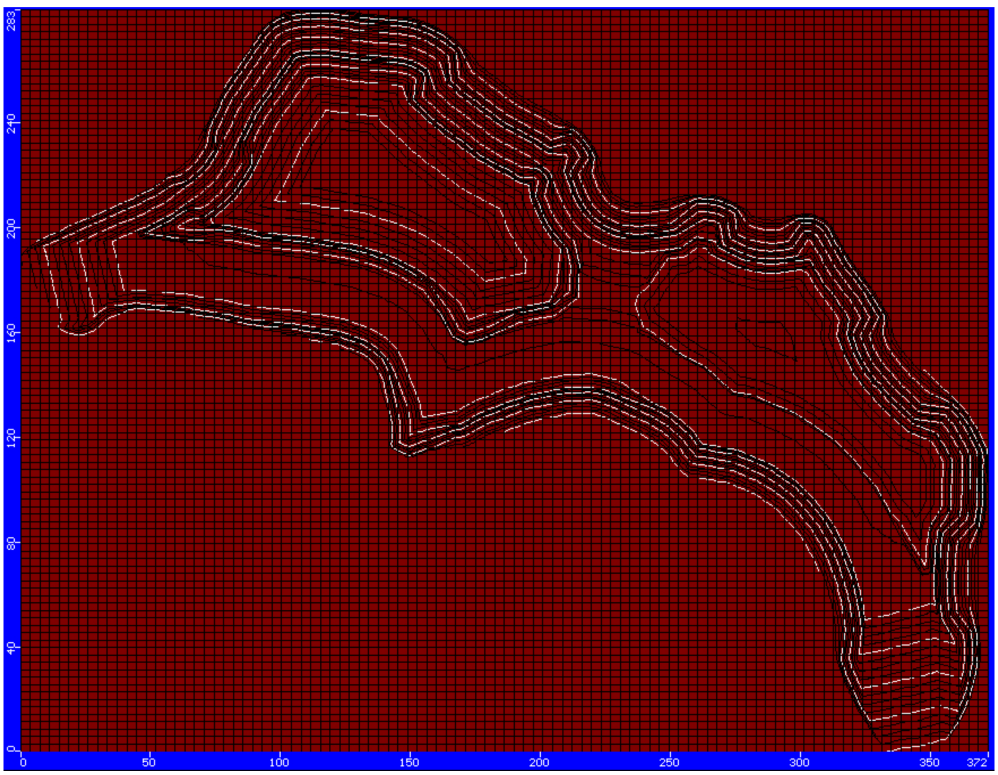

Figure 8: Constant heads assigned for case 1, plan view of layer 1.

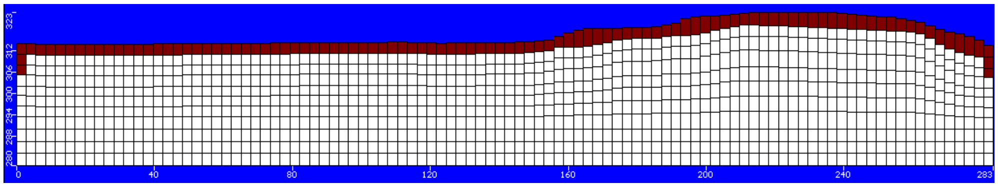

Figure 9: Constant heads assigned for case 1, section view through column 34.

This also allowed for a gentle south-west to north-east flow following the gentle topography of the swale. The remaining layers were set to no-flow boundaries at depth. Constant head values for the edges were copied from the top layer to create hydrostatic conditions. This set of boundary conditions was applied to all cases, as it represents the overall hydrology of the site and does not apply to the hummock's behavior. For Cases 2 through 5, when the hummock was undefined, the constant heads for the hummock were simply deleted from the assigned models. This is illustrated below in figures 10 and 11.

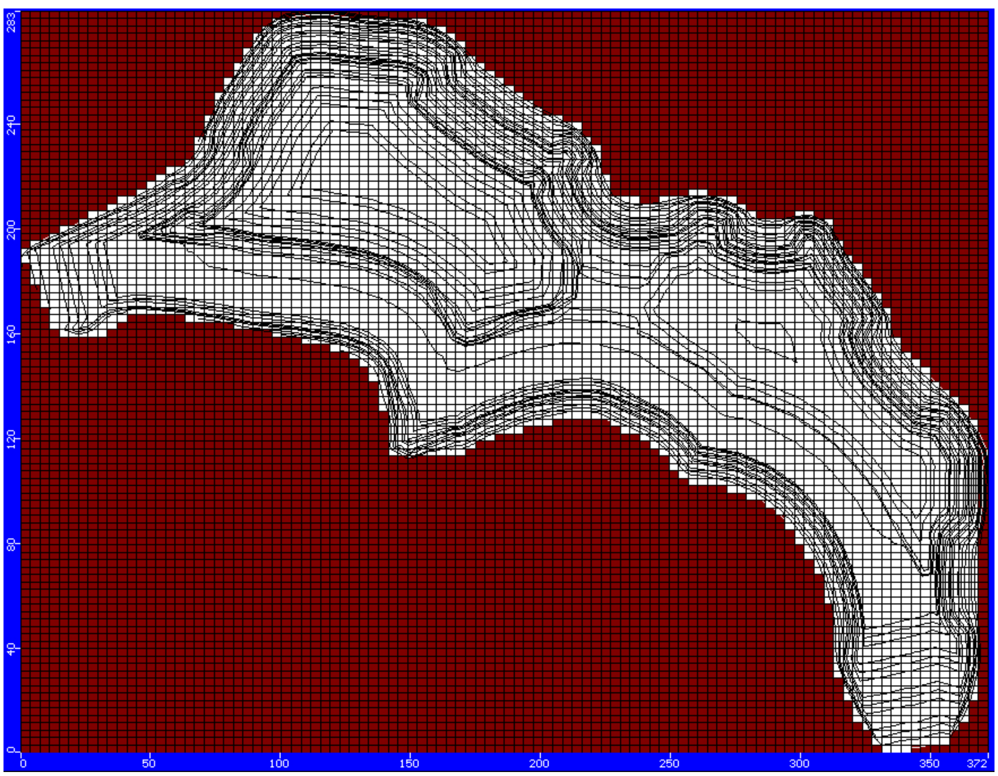

Figure 10: Constant heads assigned for cases 2-5, plan view of layer 1.

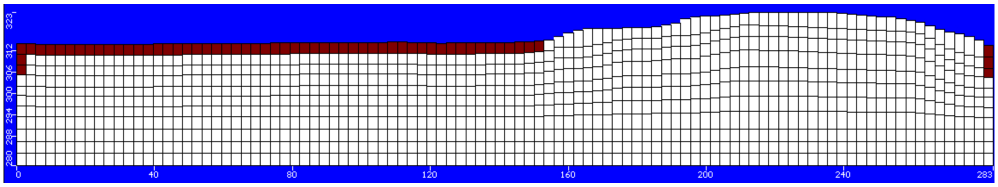

Figure 11: Constant heads assigned for cases 2-5, section view through column 34.

Models in Cases 1 and 2 were run with water tables set at depths of 0.5, 1.0, 1.5, and 2.0m depth to allow for a variety of likely water table configurations. Cases 3 through 5 were run with a 1.5m water table depth, as it was determined to be most likely from Cases 1 and 2. Cases 1, 2 and 3 had starting heads for all layers defined at 322m so as to ensure the model began in saturated conditions. Cases 4 and 5 used the determined water table from Case 2 with a water table at depth 1.5m assigned for the low-lying areas as the starting heads, in order to simulate expected average site conditions. For Cases 2 and 3 a recharge of 140mm/year was defined. This was based on the annual precipitation of 442mm/year and an evapotranspiration of 300mm/year (Kelln, Barbour, Qualizza, 2008). For Case 4 a recharge of 440mm/year with an evapotranspiration of 520mm/year was used to yield a moisture deficit of 80mm which is common for this region (Kelln, Barbour, Qualizza, 2008). Additionally cases were run with no recharge and limited recharge. For the limited recharge scenario evapotranspiration was set to the annual average of 300mm/year and recharge was varied in order to conduct sensitivity analysis. Case 5 utilized the average yearly evapotranspiration of 300mm. Additionally Environment Canada's maximum rainfall of 94.5mm/month was applied which resulted in a yearly recharge of 1134.0mm/year. Sensitivity analysis was also conducted with slightly larger than average recharge values to determine the amount of recharge required to "snap" the water table to surface.

4.3 Model Inputs:

In order to determine the residence time of water within the hummock, several particles were created in MODFLOW and placed along the perimeters of each peak, and tracked forward in time using

MODPATH software. These particles also assisted in visualizing the flow path of water through the hummock. To determine the recharge for different topographical areas of the site the zonebudget tool was used. Nine zones in total were defined in order to encompass the different topographical characteristics of the hummock. The locations of the zones are summarized in table 2 below.

Zone Number	Location	Expected Relative Water Table Height
Zone 1	Low lying areas not included in hummock	Set
Zone 2	General Hummock	-
Zone 3	8m section swale	High
Zone 4	8m section ridge	Low
Zone 5	5m section Southern swale	High
Zone 6	8m section peak	Very Low
Zone 7	5m section ridge	Low
Zone 8	5m section swale	High
Zone 9	Saddle	Low

Table 2: List of zone budget zone locations and expected relative water table heights.

The WHS solver was used for all modeling. The solver parameters can be found below is table 3.

Parameter	Value
Maximum number of outer iterations	500
Maximum number of inner iterations	25
Head Change criterion for convergence	0.01
Residual criterion for convergence	0.001
Damping factor for outer iteration	1
Relative residual criterion	0
Factorization level	0

Table 3: Input parameters for WHS solver.

Recharge was set to only be applied to the highest active cell in a column and rewetting was disabled. This model was run in steady state to represent the average conditions within the hummock. Rewetting was not required as the hummock was initially fully saturated with a starting head of 322m for Cases 1, 2, and 3 which then generated the initial water tables for cases 4 and 5. All layers were set to type 3 in Modflow which is “confined/unconfined, variable S, T.” This is the most variable condition and yielded satisfactory results.

5.0 Results:

5.1 Case 1:

Modeling with a fully defined water table found it impossible to maintain the set water table with the design recharge for the K values taken from McKenna. As a result K values were successively lowered by half orders of magnitude, until realistic recharge requirements were met. Table 4 below shows the required recharge to maintain a 1.5m depth water table given a Kxy of $5x10^{-4}$cm/s.

Water table depth = 1.5m			$K_{xy} = 5x10^{-4}$ cm/s	$K_z = 5x10^{-5}$ cm/s	
	Zone Areas (m^2)	Total Input Volume (m^3/day)	Recharge Volume (m^3/day)	Input(mm/yr)	Recharge(mm/yr)
Zone 1	64896.34	362.41	22.822	2038.32	128.36
Zone 2	27198.84	224.26	219.63	3009.50	2947.37
Zone 3	2532.92	22.457	20.342	3236.11	2931.33
Zone 4	2068.55	10.331	8.9826	1822.93	1585.00
Zone 5	1928.48	5.8787	3.1116	1112.65	588.93
Zone 6	2897.99	58.495	58.495	7367.41	7367.41
Zone 7	1201.35	7.1893	6.8722	2184.29	2087.95
Zone 8	1917.95	21.232	21.226	4040.61	4039.46
Zone 9	895.74	2.7053	0.92559	1102.37	377.16

Table 4: Zone Balance results for water table depth =1.5m and $k_{xy} = 5x10^{-4}$cm/s

As table 1 shows, with the initially dictated K value,and design recharge of 140mm/year, maintaining the simplified water table at the desired depth is not possible. Figure 12 below shows a graph of the above values compared to the design recharge.

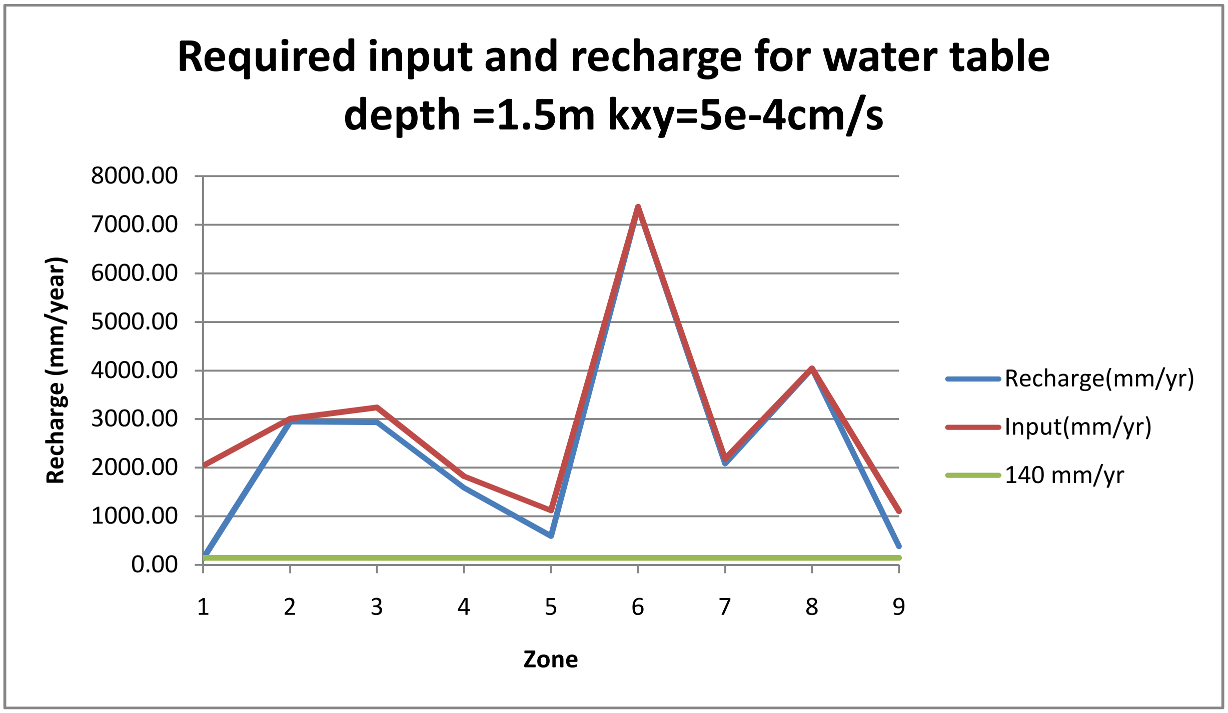

Figure 12: volumes for hummock with 1.5m depth constant water table kxy $5x10^{-4}$cm/s.

As shown the difference between input volume and recharge volume is greater for certain areas than others. Zones 3, 5 and, 9 have significantly higher input volumes than their recharge volumes. This suggests that the swales are receiving inflow for other areas in the hummock, and are acting as discharge points. Zone 1 showed a much higher input volume than recharge volume, as all other zones are flowing into it. The saddle and peak of the 8m hummock, zones 8 and 6 respectively took the greatest amount of recharge. This fits with the expected relative water table heights listed in table 2 above and as the pathlines in figure 13 below. Figure 12 additionally shows that zone 6 recieves no input from other zones and, the saddle recieves only limited input from the peak of the 8m section which, has already been shown to be a dry zone. The maximum particle velocity was 0.0012cm/s, allowing particles to exit the hummock from the peak of the 8m section in as little as one year.

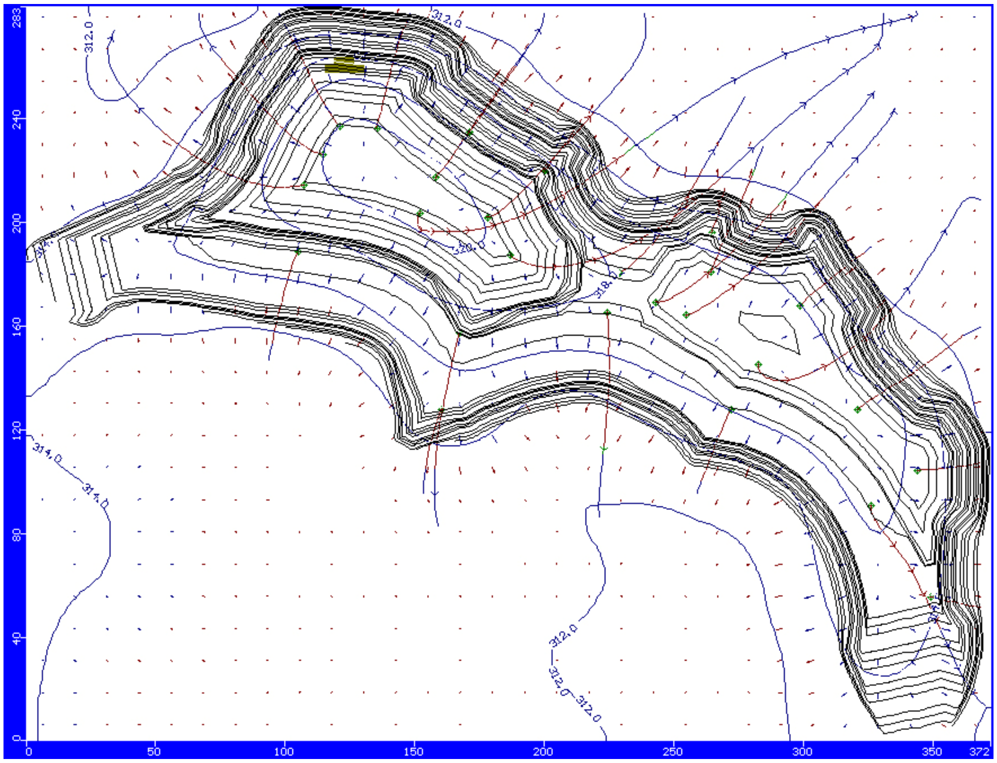

Figure 13: Flow velocity vectors and pathlines for defined water table 1.5m deep, K_{xy} = 5x10^{-4} cm/s.

Reduction of the Kxy to 1x10^{-5}cm/s yielded similar flow vectors but at a reduced maximum velocity of 2.3x10^{-5}cm/s. Particles exited the hummock on the order of 14 years. Table 5 below summarizes the volume inputs for the lowered k value.

	Water table depth = 1.5m		K_{xy} = 1x10^{-5} cm/s	K_z = 1x10^{-6} cm/s	
	Zone Areas (m^2)	Total Input Volume (m^3/day)	Recharge Volume (m^3/day)	Input(mm/yr)	Recharge(mm/yr)
Zone 1	64896.34	7.0989	0.42174	39.93	2.37
Zone 2	27198.84	4.4068	4.3044	59.14	57.76
Zone 3	2532.92	0.44399	0.39925	63.98	57.53
Zone 4	2068.55	0.23235	0.18107	41.00	31.95
Zone 5	1928.48	0.11736	0.057894	22.21	10.96
Zone 6	2897.99	1.1635	1.1635	146.54	146.54
Zone 7	1201.35	0.14079	0.13368	42.78	40.62
Zone 8	1917.95	0.41624	0.41605	79.21	79.18
Zone 9	895.74	0.054875	0.017461	22.36	7.12

Table 5: Zone Balance results for water table depth =1.5m and k_{xy} = 1x10^{-5} cm/s

Under closer examination the simplification of the water table had erased much of the fine topography, resulting in a water table like that found in figure 14, which compares the water tabel to hummock topography.

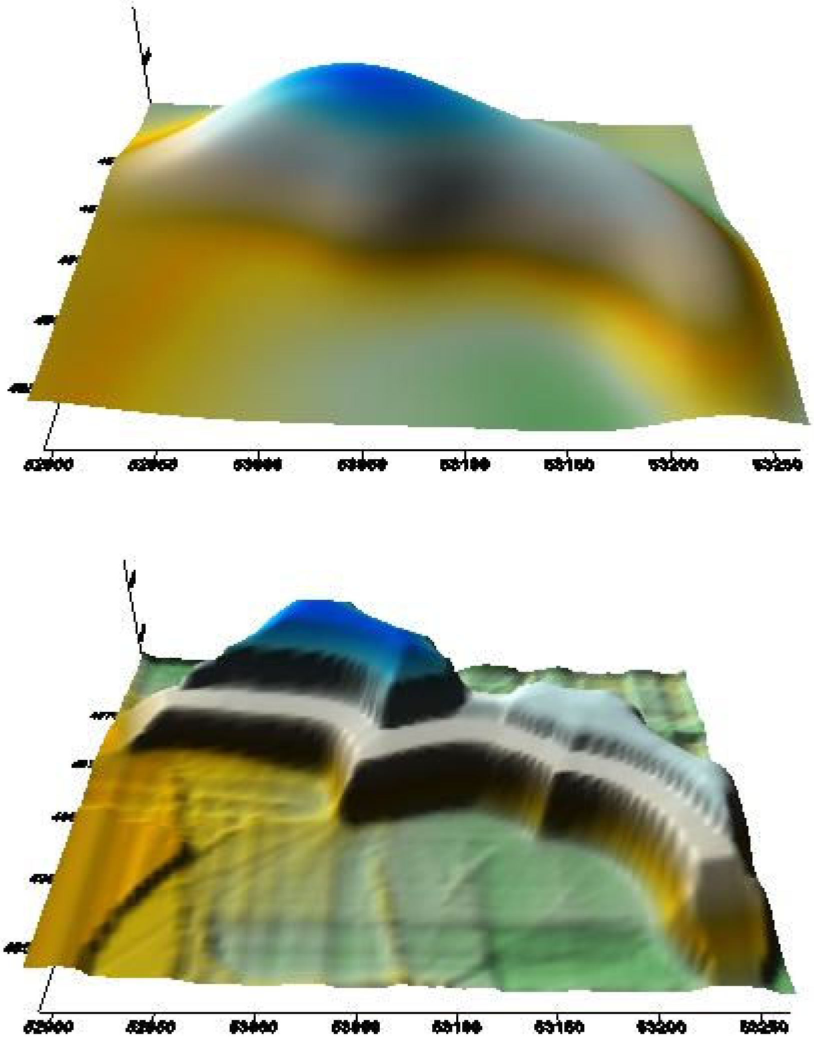

Figure 14: Defined water table compared to Hummock Topography (8x Vertical Exaggeration).

Given that zone one required so little recharge to remain wetted and 1.5m was the desired depth to maintain the water table 1.5m was chosen as the depth to model with the hummock undefined.

5.2 Case 2:

Sensitivity analysis from case 1 suggested that a k_{xy} value of $1x10^{-5}$cm/s would produce the desired water table. To confirm this analysis was run with 140mm/year recharge with water tables from 0.5 to 1.5m depth using k values of $1x10^{-4}$cm/s. As predicted a flat water table resulted from these inputs. The 1.5m depth model was then used decreasing the k values by half orders of magnitude. Mounding conditions occurred when kxy values reached $1x10^{-5}$cm/s. Sensitivity analysis was run using the 1.5m depth water table starting a k=$2.75x10^{-5}$cm/s (a quarter order of magnitude below $5x10^{-4}$cm/s) reducing to $2.0x10^{-5}$cm/s, 1.5 $x10^{-5}$cm/s and finaly 1.25 $x10^{-5}$cm/s. Dry cells were found in all cases until a k value of 1 $x10^{-5}$cm/s was used. The presence of dry cells suggests unacceptable water table geometry, as cells have a thickness of approximately 3.7m, lowering the water table well beyond the acceptable level. Figure 15 below shows the dry cell overlay (dry cells shown as yellow) for the following cases, and figure 16 below shows sections through column 34 located through the peak of the 8m hummock section.

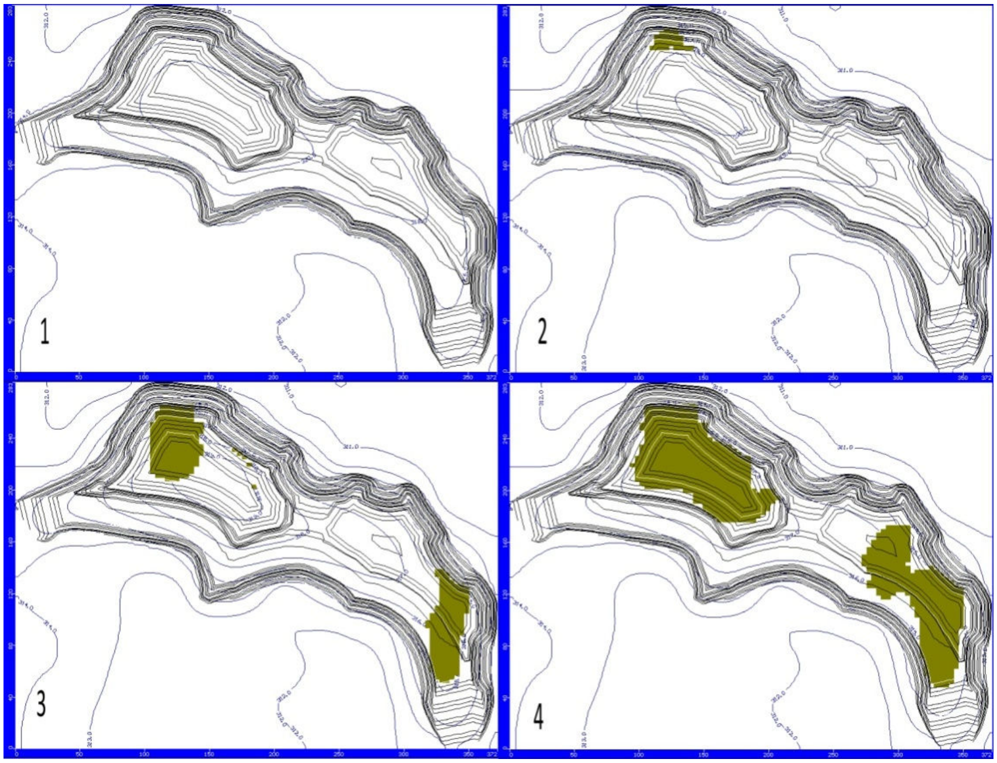

Figure 15: Dry cell overlay for case 2, 1.5m water table depth. K=1.0 x10^{-5}cm/s(1), 1.25 x10^{-5}cm/s(2), 1.5x10^{-5}cm/s(3), 2.0 x10^{-5}cm/s(4).

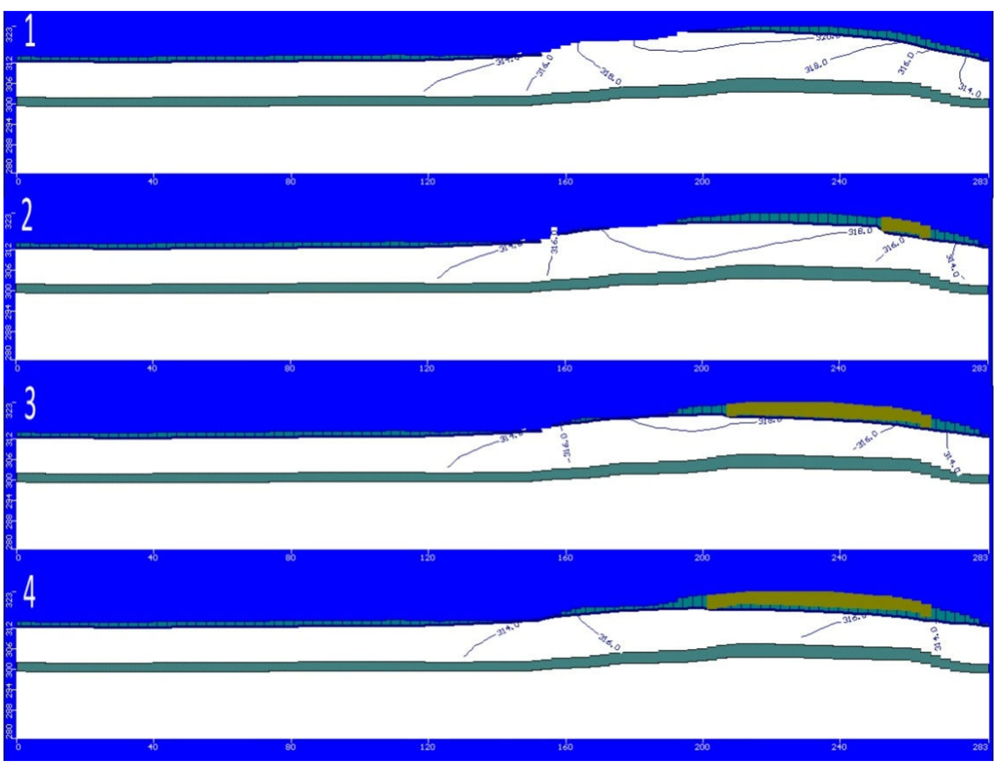

Figure 16: Section lines through column 34 for case 2, water table depth 1.5m K=1.0 x10^{-5}cm/s(1), K=1.25x10^{-5}cm/s(2), 1.5 x10^{-5}cm/s(3), 2.0v^{-5}cm/s(4).

The geometry of the water table in case 2 was similar to the defined condition. However, the table snapped to the surface along the Southern truck track. This has implications for salt transport as well as plant reclamation. In addition the curvature mirrored topography even less closely. The Northern edge of the 8m section had a notably lower water table than the rest of the area, dropping to 2.2m depth in places. The Northern edge of the 5m section had a minimum water table depth of 1.0m and reached surface in several areas both on the North and South faces. The water table divide appears to run along the southern edge of the peak's plateaus. Water flows into the saddle from the 8m peak but, not from the 5m peak. Water leaving both peaks does preferentially travel into the swales on the North and exit in the fen area. Particles released on the peak of the 5m section are beginning to discharge into the fen area after approximately 11 years and particles from the 8m peak release after approximately 18 years. The maximum particle velocity is 4.1 x10^{-5}cm/s, slightly higher than in Case1 although, still on the same order of magnitude. Figure 17 below illustrates discharges into zone 1 from the perimeter zones of the hummock in terms of mm/year.

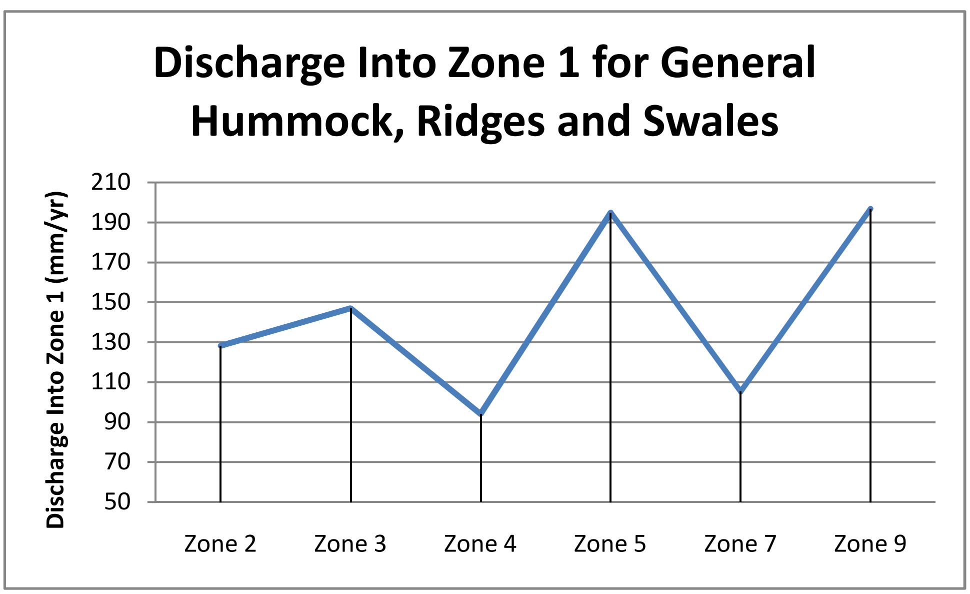

Figure 17: Discharges into zone one from hummock ridges, swales and zone 2 (general hummock)

This illustrates that the swales (zones 3,5,9) are indeed discharging more water than the ridges of average hummock area, confirming them as wet zones, as predicted.

5.3 Case 3:

To test possible cover systems k was initially set to 5 $x10^{-4}$cm/s for the general area and layer one of the hummock was set to K=1.0 $x10^{-5}$cm/s to represent compacted cover. As results were unsatisfactory for this scenario, a variety of lower K's for the sand and the cover were used in an attempt to maintain a mounded water table. The combinations and their outcomes are summarized below in table 6.

Scenario	Ksand (cm/s)	Kcover (cm/s)	Resulting water table
1	$5x10^{-4}$	$1x10^{-5}$	Flat
2	$5x10^{-4}$	$5x10^{-6}$	Flat
3	$5x10^{-4}$	$1x10^{-6}$	Perched for entire hummock
4	$2x10^{-4}$	$1x10^{-6}$	Perched for entire hummock
5	$8x10^{-5}$	$1x10^{-6}$	Perched, almost mounded in 5m section
6	$5x10^{-5}$	$1x10^{-6}$	Perched under peak of 8m section

Table 6: Cover and soil k configurations and resulting water table.

Figure 18 below shows the behaviour of the hummock for scenarios 1 and 3. In scenario 1 the tailings sand is acting as a drain for the cover, resulting in a flat water table. In scenario 3 the cover system has a low enough k value to maintain its own water table. This scenario has resulted in the water table snapping to the surface which, is inappropriate for reclamation, as it would drown plant root systems. K values on the order of 10^{-6} cm/s are at the threshold of being considered aquitards (Bear 1972). Values this low are typically associated with silts and clays, not as sand like that being used in this design (Bear 1972). Plots 2 and 4 in figure 18 show identical dry cell configurations. This suggests that Ksand=$5x10^{-4}$ is not capable of maintaining a mounding condition, regardless of cover system.

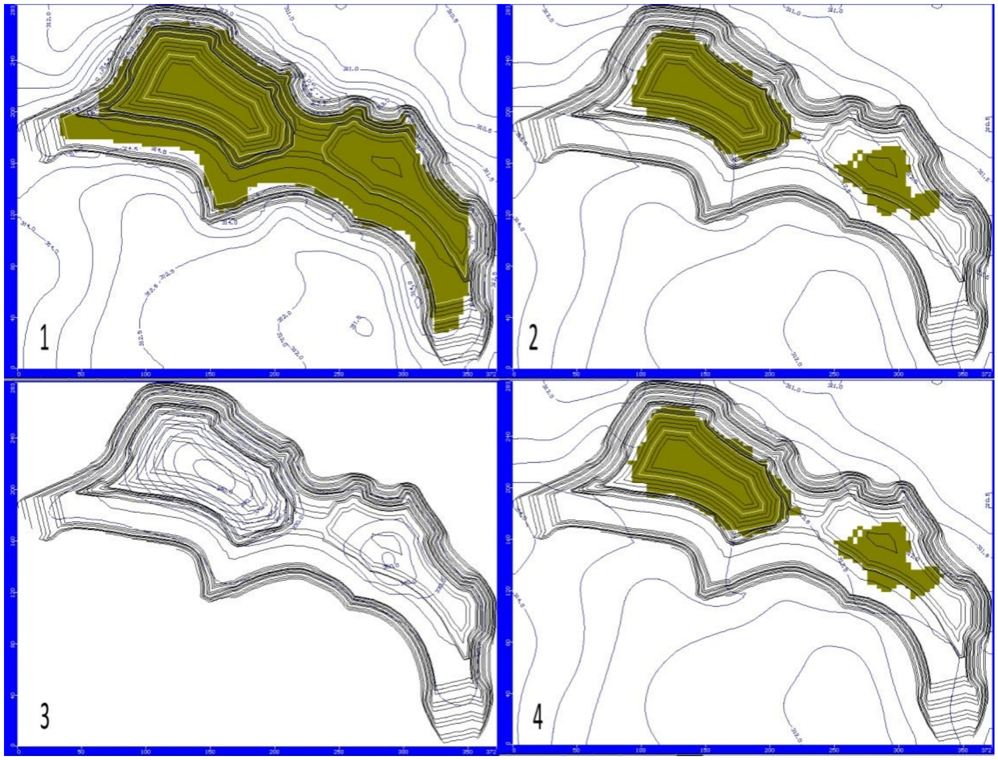

Figure 18: Dry cell overlay for case 3, 1.5m water table depth. Ksand=5.0x10^{-4}cm/s, Kcover=1x10^{-5}cm/s, Layer 1(1), Ksand=5.0x10^{-4}cm/s, Kcover=1x10^{-5}cm/s, Layer 2 (2), Ksand=5.0x10^{-4}cm/s, Kcover=1x10^{-6}cm/s, Layer 1 (3), Ksand=5.0x10^{-4}cm/s, Kcover=1x10^{-6}cm/s, Layer 2 (4).

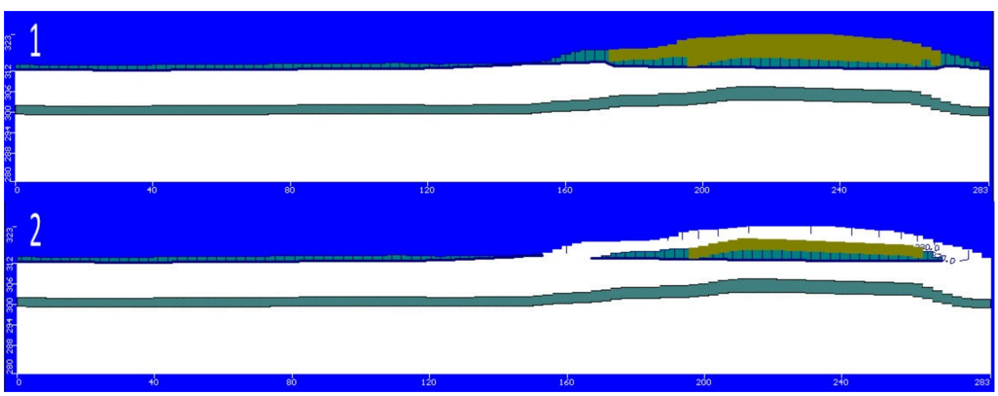

Figure 19: Section lines through column 34 for case 3, water table depth 1.5m Ksand=5.0x10^{-4}cm/s, Kcover=1x10^{-5}cm/s (1), Ksand=5.0x10^{-4}cm/s, Kcover=1x10^{-6}cm/s (2)

Figure 18 also illustrates the high head values found in the 1x10^{-6}cm/s cover layer which, are up to 70m above the ground surface. This suggests that there is either a large volume of surface runoff, or the material has such a low conductivity that it is capable of maintaining large artesian pore water pressures, in an unconfined condition. Neither of these options are particularly desireable for the purposes of this design.

5.4 Case 4:

Analysis run on the hummock suggested that it is very sensitive to drought conditions. Given a moisture deficit of 80mm, which is common during the summer months (Kelln, Barbour, Qualizza, 2008) the water table was found to drop back to a flat condition. This can be expected as the K value of $1x10^{-5}$cm/s was found to be the threshold where mounding would occur given the design recharge. The model can then be expected to be sensitive to decreased recharge when using this K value. Several different scenarios for this moisture deficit were considered whereby the standard annual recharge was compared to summer evapotranspiration, as well as a scenario with no recharge and 80mm evapotranspiration. Both scenarios yielded the same moisture deficit, and the same water table. This would be cause for concern, were it not for the fact that the majority of precipitation for the area occurs during the summer months (Canadian Climate Normals). Analylsis conducted with limited recharge values suggested that the saddle region and swales to the south will be the first to dry, given an insuffiecient recharge of 140mm/year (Figure 20).

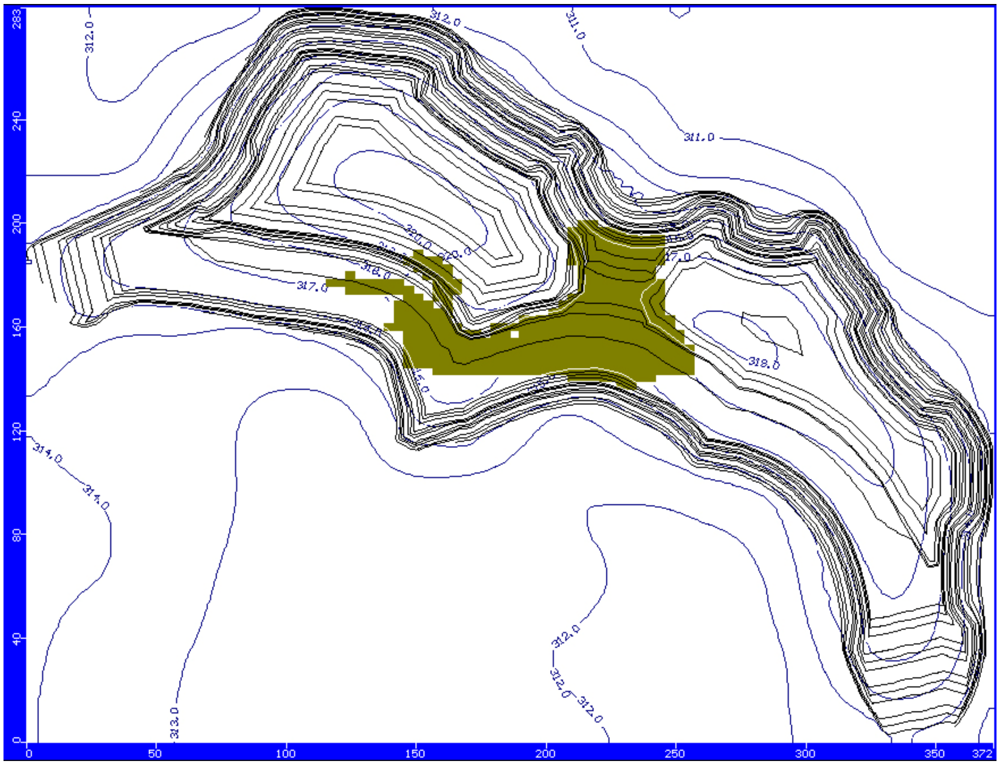

Figure 20: Drying Pattern for decreased recharge (140mm/year) with Evapotranspiration set to 300mm/year.

In addition, in cases where zero recharge was used drying occured most easily in the saddle and northern peak of the 8m section, suggesting that limited recharge can maintain a generally wet condition with select dry spots.

5.5 Case 5:

As with drought analysis, flood sensitivity analysis suggested that the hummock is vulnerable to flooding conditions. Conditions with recharge as much as 50mm/year higher resulted in the water table snapping to surface. Higher recharges resulted in increased heads within the layers, which in this case were interpreted to be surface discharge and runoff. However these conditions will only represent a problem for the first few seasons, after which the hummock will be fully vegitated, resulting in increased interception of precipitiation and evapotranspiration. As an added check against the conditions modeled, evapotranspiration which can be up to 7mm/day in the summer, (Kelln, Barbour, Qualizza,

2008) translates to an annual value of 2555mm/year, while the average monthly precipitaiton is on the order of 75mm/month or 900mm/year. This suggests that evapotransipration will deal with all but the most severe of weather conditions. Moisture deficits are common in the summer on the order of 70-80mm, (Barbour et all 2001, Elshorbagy et al, 2005) further suggesting that flooding conditions are unlikely.

6.0 Discussion:

6.1 Conclusions:

From the modeling conducted, it would appear the the hydraulic conductivity specified by McKenna of $5x10^{-4}$cm/s is insufficient for maintenance of a mounded water table of sufficient height, in a hummock of this topograhy. It should be noted that this value was derived from extensive field testing but, was obtained for use of the sand as a construction material in berms where, in conjunction with a core, a higher conductivity may be desireable in order to maintain a low phreatic surface. In situ testing used to obtain this value would not have taken into account the effects of constuction methods such as compacted lifts on the value of K. The K value obtained for mounding conditions was $1x10^{-5}$cm/s. This value is still within the range of appropriate conductivities for sand (Bear, 1972), and may represent a higher fines content or placement in small lifts as in (Chapman, Barbour, O'Kane, 2006). With this in mind it may be appropriate to construct the hummock from tailings sand mixed with fines, instead of a clean cyclostacked sand as was originally planned. Additionally Chapman, Barbour, O'Kane, has suggested that construction in lifts can significantly lower the K value of a material. The hummock could be constructed entirely in two 5m lifts, which may be feasable. As this condition may not be desirable for construction purposes a cover system was also investigated. However, analysis concluded that a mounded water table would be very difficult if not impossible to maintain with a low K cover system.

For a cover with $K=1x10^{-6}$cm/s which is an appropriate value to find in a fat clay (Bear, 1972) a perched water table condition still existed within the hummock. In addition this resulted in a fully saturated cover which is not desireable for growth of reclamation plants. The simplified water table conditions in Case 1 appear to have been an accurate model for predicting the resulting water tables in Case 2. Due to a lack of available information the boundary conditions for the site were constructed from this author's memory of the site and may not be a completely accurate representation. However, the entire model exists as a simplification of actual site conditions and for an initial investigation the boundary conditions specified are accurate enough. Results from drought and flood analysis suggest that the hummock is very sensitive to both conditions. However, due to a lack of site specific data, input climate data may not be completely accurate. In addition, given the available data, it would appear that periods of extreme evaporation are accompanied by periods of increased precipitation and vice versa, suggesting that the site's weather may be self buffering.

The most likely water table conditions were taken to be those found in Case 2 with a water table depth of 1.5m. For this case particle velocities allowed water to exit the hummock from the peak in approximately 14 years. Although no concentration data was used in this model, it would seem to the author that the flow rates are slow enough that resulting groundwater infiltrating the fen may be diluted by rainwater to an acceptable concentration of salts.

Cases existed where head equipotentials suggested values up to 40m above the ground surface. There are two possible explanations for this behavior. Firstly, the K value of the material could be so low that it is possible to maintain these massive artesian pressures. This case is unlikely, given the unconfined site conditions. Secondly, the more likely explanation is that the material is saturated and surface runoff is occurring. Modflow does not model surface flow and as a result high head values are reported.

For this model the truck bench in the back was found to be a wet area, with the water table at surface however, Case 2 did not directly model evapotranspiration due to uncertainty with vegitation and extinction depth. Therefore it is unlikely that this condition will actually exist. However, were this the case it would be important to monitor this area to avoid gullying during periods of high precipitation, as this landform must maintain its functioning for the next thousand years.

6.2 Recommendations for future work.

Modeling conducted at this stage was in steady state and represented average site conditions throughout the entire year. Future work should involve several transient state models in order to represent the four seasons as well as transitions between them such as spring runoff. In addition modeling was conducted with limited data. Further modeling should be conducted with piezometer data from site in order to accurately establish boundary conditions. Given that construction is currently underway field tests could be conducted on the bare hummock to determine actual hydraulic conductivity values in situ. Site specific climate data should be combined with expected reclamation cover leaf area and root depth etc. to determine hummock specific evapotranspiration values to provide more accurate models. Given that the climate of the region allows for temperatures to drop to -20°C in the winter modeling run for the entire year should include thermal behavior of the soils and insulation of reclamation cover as the hummock may freeze up at depth during these frigid months. Particle velocities were considered for this model; the next step is to translate those into plumes of saline-sodic water in order to determine the likely discharge chemistry into the groundwater fen.

In order to confirm groundwater chemistry predictions in the field environment, piezometers and observation wells should be installed in conjunction with construction on both the surface of the hummock and in the fen discharge area.

7.0 References:

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8.0 Appendix:

Attached to this document is a burned DVD which contains all the modeling and analysis conducted.

A breakdown of the file tree is listed below.

Root:

- Case 1; Defined Water Table
  - 0.5m depth
    - Modflow files
  - 1.0m depth
    - Modflow files
  - 1.5m depth
    - Modflow files
  - 2.0m depth
    - Modflow files
  - 2.5m depth
    - Modflow files
- Case 2; Hummock Undefined
  - 0.5m depth
    - Modflow files
  - 1.0m depth
    - Modflow files
  - 1.5m depth
    - Modflow files
  - 2.0m depth
    - Modflow files
  - 2.5m depth
    - Modflow files
- Case 2; Mounding Sensitivity 1.5m
  - 1.25e-5
    - Modflow files
  - 1.50e-5
    - Modflow files

2.00e-5

Modflow files

2.75e-5

Modflow files

Case 3; Cover System

Sand 5e-4, Cover 1e-5

Modflow files

Sand 5e-4, Cover 1e-6

Modflow files

Sand 5e-4, Cover 5e-6

Modflow files

Case 4; Drought

Modflow files

Case 5; Heavy Rain

Modflow files

Analysis and Tables

Recharge calculations for zones.xlsx

Folders for Cases 1 through 3 contain sub-folders with Modflow files relating to that specific sub case. All folders which are listed as containing “Modflow files” contain all the necessary files to view and run that particular model. In addition, these folders contain the .txt and .grd files required to generate the surface topography and where applicable, the defined water table.

The Analysis and Tables folder contains the Excel file used to translate the zonebudget outputs into recharge values.