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# ANALYSIS OF SOIL SUCTION CHANGES IN EXPANSIVE REGINA CLAY

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## ABSTRACT

The prediction of seasonal soil suction changes is critical to the analysis of volume change in unsaturated, expansive soils. A one-dimensional moisture flow model was developed to study the boundary flux and suction conditions in a soil profile at a test site in Regina, Saskatchewan. The test site was part of an extensive study related to ground movements and associated distresses caused to underground water mains. A parametric study was performed to evaluate the effects of net radiation, wind speed, precipitation, soil properties and initial suction conditions on the actual evaporation, net infiltration, water content, soil suction and depth of suction change in the soil profile for a period from 1 November 2005 to 31 October 2006.

## RÉSUMÉ

La prédiction de changements saisonniers de succion de sol est critique à l'analyse de changement de volume dans aux sols non saturés et expansifs. Un modèle de flux d'humidité dans une dimension a été développé pour étudier le flux de frontière et les conditions de succion dans un profil de sol à un site de test dans Regina, Saskatchewan. Le site de test faisait partie d'une étude vaste apparentée aux mouvements de sol et les détresses associées a causé aux tuyaux souterrains. Une étude paramétrique a été exécutée pour étudier les effets de rayonnement net, la vitesse de vent, la précipitation, les propriétés de sol et les conditions de succion initiales sur la quantité de véritable évaporation, l'infiltration nette, et la variation de succion de sol et la profondeur de changement de succion dans le profil de sol pour une période du 1 novembre, 2005 au 31 octobre, 2006.

## 1 INTRODUCTION

The City of Regina was developed on a post-glacial lake deposit called Regina Clay. The deposit is highly plastic, unsaturated, expansive clay that exhibits large volume changes as the soil water content changes. As a result of the volume changes, light infrastructures buried in the expansive soils are often subjected to severe distress during their service. Recently, the breakage rate of asbestos cement water mains in their water distribution system has increased in older areas of the City (Hu and Hubble, 2007). A study is currently being conducted by the NRC Center for Sustainable Infrastructure Research in Regina to investigate the causes of failures of the water mains. Climate induced soil volume change was determined to be one of the critical factors behind the failures.

To better understand the behaviour of the water mains during their service, a section of water main was instrumented and installed in an older area of Regina. A series of sensors were also buried in the backfill and in the native soil around the trench to monitor the working environment of the water main (Hu and Lotfian, 2006). Due to the critical role played by matric suctions on the soil volume change in expansive clay soils, the soil suction conditions around the test site were analyzed to study their responses to external environments.

In this paper, a one-dimensional moisture flow model was developed to study the suction and water content change of the soils around the test site. The boundary flux conditions were estimated considering the detailed climatic condition collected at a weather station in the city and vegetation around the test site. Soil properties and initial suction conditions for the modeling were obtained from laboratory tests. A range of net infiltration at ground surface, suction and water content changes of the clay soils were analyzed for the climatic conditions over a period of one year from 1 November 2005 to 31 October 2006.

## 2 SITE OVERVIEW

The study site is located in the Emerald Park subdivision, a well developed residential area in south central Regina. The park area and front yards of the houses are grass covered. Various mature deciduous and coniferous trees with up to 560 mm trunk diameters and 12 m heights (Figure 1) have grown in the park as well as in front of the houses. Water mains of 0.15 m diameter were installed at approximately 2.8 m depth under the pavement. Houses and big trees may have significant impact on the radiation, wind speed and air temperature at the test location.



Stratigraphy and water content conditions at the site were determined from two boreholes drilled to 15 m depths in October 2005. Borehole 1 was located immediately north of the water main on the pavement. Borehole 2 is located in the park approximately 8 m from the south shoulder of the Emerald Park Road. Soil laboratory tests include index tests, soil-water characteristic curves, saturated hydraulic conductivity tests, constant volume consolidation tests and measurement of soil suction using the filter paper method.

vapour transfer rather than capillary transfer. Whatman No. 42 filter paper was used together with a calibration curve suggested by Leong *et al.* (2002). Measured suctions were about 3000 kPa for the upper 4 m of clay, about 700 kPa for the lower 5.5 m of clay and about 2000 kPa for the underlying till. Dry density ranged from 1400 to 1680 kg/m<sup>3</sup>. Three saturated hydraulic conductivity tests on clay samples retrieved at depths of 2.7, 3.7 and 4.6 m indicate a saturated hydraulic conductivity of  $2.0 \times 10^{-9}$ ,  $2.8 \times 10^{-9}$  and  $2.0 \times 10^{-9}$  m/s, respectively. Constant volume oedometer tests on samples from 3 and 4.5 m depths showed an initial void ratio of 0.93 and 0.97, swelling index of 0.125 and 0.116, and a corrected swelling pressure of 550 and 500 kPa, respectively.

Figure 3 shows the relationship between water content and suction obtained from both the pressure plate test and filter paper methods. Two boundary soil-water characteristic curves (SWCC), (i.e., the drying and wetting curves), can cover the range of data points as shown in Figure 3. The middle curve was fitted with the Fredlund and Xing (1994) equation.

The hydraulic conductivity functions were estimated from the SWCC and saturated hydraulic conductivity, using the Leong and Rahardjo (1997) equation. Three hydraulic

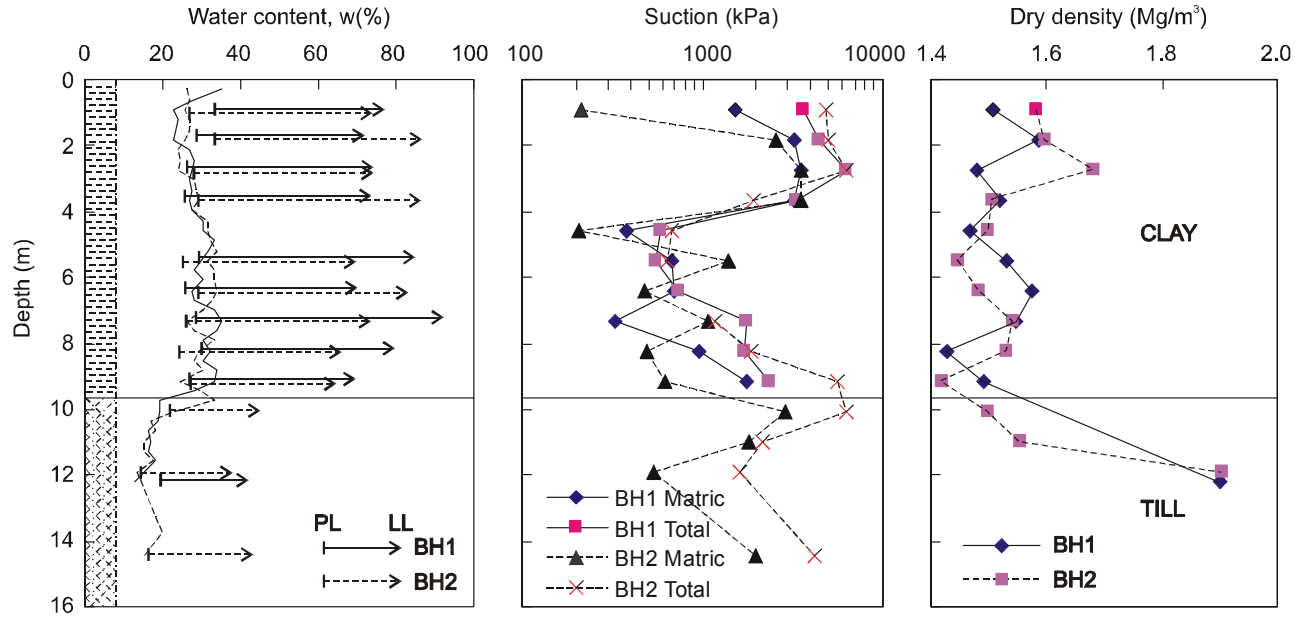


Figure 2. Soil profile and index properties

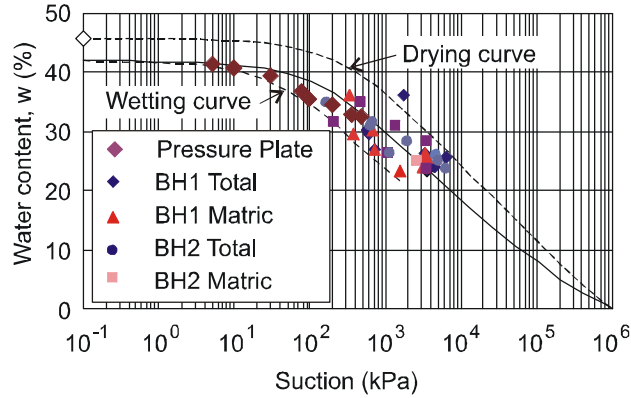


Figure 3. Soil-water characteristic curves

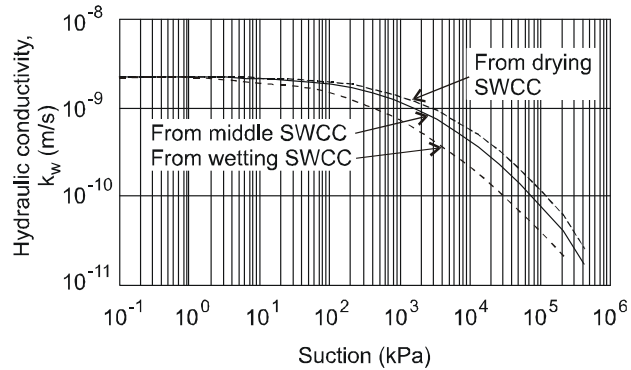


Figure 4. hydraulic conductivity functions

conductivity functions corresponding to the three SWCC shown in Figure 3 are presented in Figure 4. The middle curve was used for the analysis in this study.

#### 4 GOVERNING PDE FOR MOISTURE (LIQUID/VAPOUR) FLOW

Wilson (1990) presented the governing partial differential equations of heat and mass transfer and their solutions. The governing partial differential equation for a one-dimensional, vertical liquid and vapour flow can be written as follows (Wilson, 1990):

$$\frac{\partial}{\partial y} \left[ (k_y + k^v) \left( \frac{\partial h}{\partial y} - 1 \right) + k_y \right] + S = m_w^2 \gamma_w \frac{\partial h}{\partial t} \quad [1]$$

where  $h$  is total head,  $k_y$  is the hydraulic conductivity in the vertical direction,  $k^v$  is the vapour conductivity in the vertical direction (m/s),  $S$  is the root uptake sink term,  $\gamma_w$  is the unit weight of water (kN/m³), and  $m_w^2$  is the slope of the SWCC (kPa⁻¹).

The vapour conductivity can be expressed as:

$$k^v = \frac{\bar{u}_a + p_v}{\bar{u}_a} \frac{g W_v p_v}{R(T + 273.15)} \frac{D^{v*}}{\rho_w} \quad [2]$$

where  $\bar{u}_a$  is total pressure in the bulk air phase (kPa),  $u_a + u_{atm}$ ;  $u_a$  is pore-air pressure (kPa);  $u_{atm}$  is atmospheric pressure, 101.325 kPa;  $R$  is universal gas constant, 8.314 J/(mol.K);  $W_v$  is molecular weight of water vapour

(kg/kmol);  $T$  is temperature ( $^{\circ}\text{C}$ );  $p_v$  is partial pressure of water vapour (kPa); and  $D^v$  is the diffusion coefficient of vapour through the soil.

The diffusion coefficient of water vapour through a soil can be estimated as follows:

$$D^{v*} = \alpha \beta D^v \frac{W_v}{RT} \quad [3]$$

Where  $\alpha$  is tortuosity factor of the soil,  $\alpha = \beta^{2/3}$  (Lai et al. 1976);  $\beta$  is cross sectional area of soil available for vapour flow per total area,  $\beta = (1-S)n$ ;  $S$  is degree of saturation;  $n$  is porosity;  $D^v$  is molecular diffusivity of water vapour in air. Kimball *et al.* (1976) presented the following equation for  $D^v$ :

$$D^v = 0.229 \times 10^{-4} [1 + (T + 273.15)/273.15]^{1.75} \text{ (m}^2/\text{s)}$$

## 5 EVAPORATION AND EVAPOTRANSPIRATION

Evapotranspiration consists of the combined processes of evaporation and transpiration. The analyses in this study has been performed using Penman equation (Penman, 1948) for potential evaporation and an equation suggested by Wilson *et al.* (1997) for actual evaporation.

The potential evaporation at the soil-atmosphere boundary can be calculated as follows (Penman, 1948):

$$PE = \frac{\Gamma Q_N + E_a \eta}{\Gamma + \eta} \quad [4]$$

where  $PE$  is potential evaporation per unit time (m/day);  $\Gamma$  is the slope of the saturation vapour pressure curve with respect to temperature (mmHg/ $^{\circ}\text{F}$ );  $Q_N$  is heat budget (m/day),  $\eta$  is psychrometric constant (0.27 mmHg/ $^{\circ}\text{F}$ ); and

$$\Gamma = a_1 + 2a_2 T_a + 3a_3 T_a^2 + 4a_4 T_a^3 + 5a_5 T_a^4 + 6a_6 T_a^5 \quad [5]$$

where  $T_a$  is the atmospheric air temperature,  $a_1 = 0.6283580754$ ,  $a_2 = 0.0411427320$ ,  $a_3 = 0.0017217473$ ,  $a_4 = 0.0000174108$ ,  $a_5 = 0.0000003985$ , and  $a_6 = 0.0000000022$ .

The  $E_a$  parameter (m/day) can be calculated as follows (Gitirana, 2005)

$$E_a = f(u) p_{vsat}^{air} (1 - RH_a)$$

where  $p_{vsat}^{air}$  is saturation vapour pressure of the air above the surface (mmHg);  $f(u) = 0.35[1 + 0.146(3.6W_w)]$ ;  $W_w$  is wind speed (m/day); and  $RH_a$  is the relative humidity of air.

The heat budget can be calculated as follows (Gray 1973):

$$Q_N = \frac{R_e}{L} \quad [6]$$

where  $R_e$  is net radiation; and  $L$  is latent heat of evaporation,  $L = 591 - 0.51T_a$ .

Actual evaporation (AE) at the ground surface can be calculated as follows (Wilson, 1997):

$$AE = PE \left( \frac{p_v - p_v^{air}}{p_{vsat} - p_v^{air}} \right) \quad [7]$$

Vegetation plays a significant and dynamic role in the evapotranspiration process (Saxton 1982). The potential transpiration is a function of the leaf area index (LAI), which is the ratio of the surface area of the leaves and the surface area of the soil covered. The LAI is used to reduce the amount of net radiation intercepting the soil surface which in turn reduces the computed potential evaporation (Unsaturated Soils Group, 1996). The potential transpiration is calculated as follows (Ritchie, 1972):

$$PT = 0 \text{ if } LAI < 0.1$$

$$PT = PE(-0.21 + 0.70LAI^{0.5}) \text{ if } 0.1 \leq LAI < 2.7$$

$$PT = PE \text{ if } 2.7 \leq LAI$$

where  $PT$  is potential transpiration rate (m/day).

The predefined LAI curves for excellent, good, and poor vegetation condition are suggested in SoilCover (Unsaturated Soils Group 1996). Growth season for vegetation was assumed for the period from April to October for this study.

It was assumed that mass flux due to transpiration can be distributed in a triangular shape in the soil (Tratch 1995). The potential root uptake (PRU) at a given point in the soil is calculated as follows:

$$PRU = \frac{2PT}{R_T} \left( 1 - \frac{R_n}{R_T} \right) \quad [8]$$

where  $R_T$  is total thickness of the root zone (m); and  $R_n$  is depth of a given point (m).

The actual transpiration sink is calculated from the potential transpiration by a reducing term that is based on the moisture availability:

$$S = PRU \times PLF$$

where  $S$  is actual transpiration sink term in Eq. (1) ( $\text{m}^3/\text{day}$ ); and  $PLF$  is a plant limiting factor.

The  $PLF$  is a reduction term that describes a decrease in transpiration with an increase in matric suction. A limiting point of 500 kPa and a wilting point of 2500 kPa were

assumed for this study. The PLF is unity for suction less than 500 kPa. Between 500 kPa and 2500 kPa the plant limiting factor is reduced linearly as a function of the log of matric suction. The actual transpiration reaches zero at suction equal to 2500 kPa.

## 6 COMPUTER PROGRAM

Several commercial software packages are available to model the moisture flow in soils, including SoilCover (Unsaturated Soils Group, 1996), HYDRUS-2D (Simunek *et al.*, 1999), Vadose/W (Geo-Slope International Ltd., 2005), SVFlux (SoilVision Systems Ltd., 2007) and FlexPDE (PDE Solutions Inc., 2004). SVFlux and FlexPDE were used for the analyses in this study.

## 7 CLIMATIC DATA

The study period for this modelling task is from 1 November 2005 to 31 October 2006. Climate data obtained at the weather station located at the Regina International Airport, approximately 5 km from the site was used. Climatic data obtained for this period include daily precipitation, air temperature, wind speed, and relative humidity. Solar radiation was not collected at this weather station. The data from 1 November 1999 to 31 October 2000 for Swift Current, SK, the closest and most recent solar radiation data available, were used.

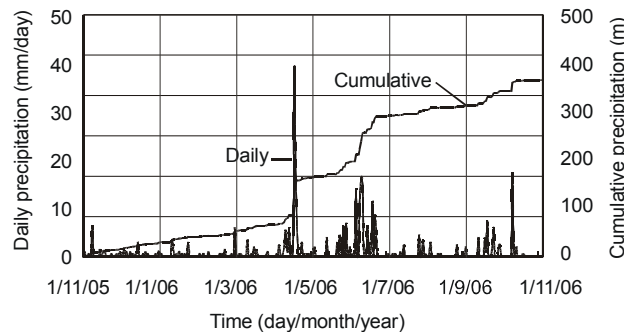


Figure 5. Daily and cumulative precipitation

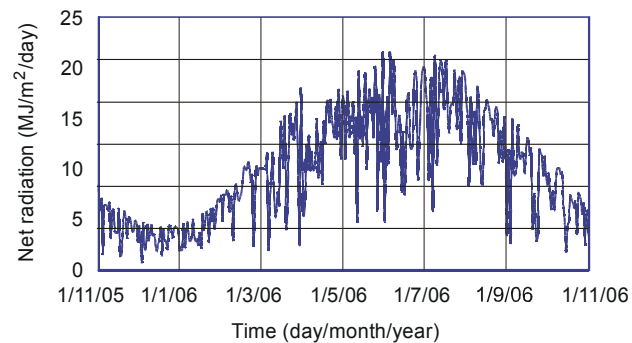


Figure 6. Daily net radiation

The recorded daily precipitation is presented in Figure 5. Annual precipitation of 366 mm for the study period was recorded. A maximum daily precipitation of 39 mm was measured on 17 April 2006. The park area is approximately 7860 m<sup>2</sup>. The park is watered twice a week for 60 to 75 minutes each time with 11.4 m<sup>3</sup>/hour for 16 weeks from 23 June to 12 October. The park watering was distributed to two days a week and considered as an additional precipitation amount.

The net infiltration (or moisture flux) at the ground surface was determined from the amount of precipitation, park watering and estimated actual evaporation. Actual evaporation was estimated based on the potential evaporation and a limiting function (Wilson *et al.*, 1997).

Daily net radiation was estimated from solar radiation, using an albedo value of 0.1 for the period from 1 November to 31 March and 0.3 for the period from 1 April to 31 October. The estimated daily net radiation is presented in Figure 6.

Figure 7 shows the recorded daily air temperature. The temperature was essentially below zero for the months from November to March, with an average temperature of about -10 °C. Average temperature for the months from April to October was about 10°C. Recorded daily average air temperature varied from -28 °C in March 2006 to 26 °C in July 2006. Recorded daily wind speed and relative humidity are presented in Figures 8 and 9, respectively.

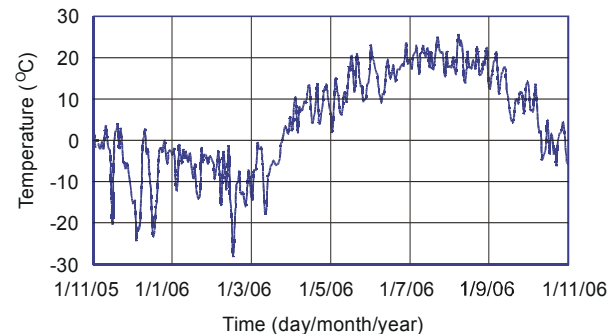


Figure 7. Daily air temperature

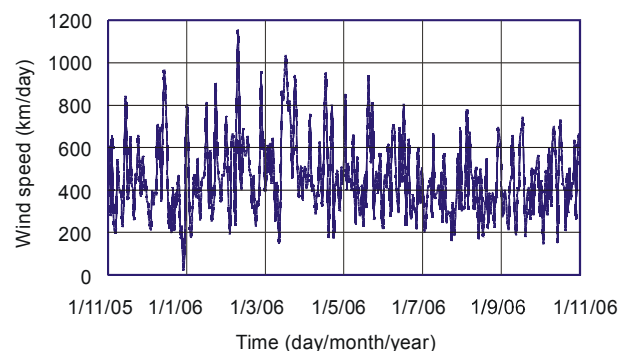


Figure 8. Daily wind speed



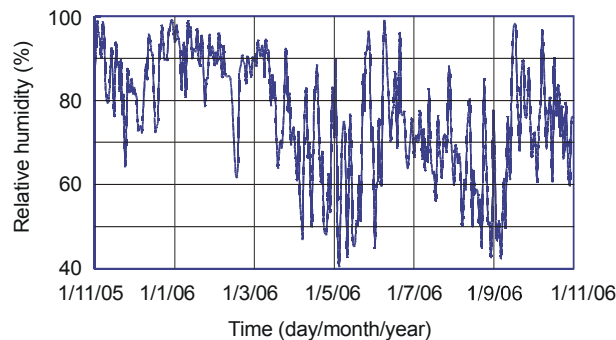


Figure 9. Daily relative humidity

Because the site is located in a residential/park area with mature trees (Figure 1), the daily wind speed and net radiation recorded at the weather station may not directly reflect the site conditions. A factor of 0.5 was applied to these data for the analysis in this study to represent the wind speed and net radiation. Air temperature in the park may be somewhat lower than the recorded temperature on a hot day; however, this was not considered in this study.

Vegetation conditions at the site were described using the leaf area index (LAI) function. A root zone from ground surface to 0.15 m depth was assumed to represent the grass portion of the vegetation in the park. Water uptake by mature trees was not included in the current model.

## 8 NUMERICAL MODELLING RESULTS AND DISCUSSION

A one-dimensional moisture flow model was used. The soil profile at a location in the park relatively far away from mature trees was chosen for the model to exclude the water uptake by the mature trees. The model considered 9.5 m of clay overlying 5.5 m of till. It was assumed that the upper 4 m of clay was fissured; a higher value of saturated hydraulic conductivity was used for the fissured portion of clay.

Climatic conditions were applied on the top boundary, no flux conditions were applied at the lower boundary. It was assumed that no infiltration took place during the winter time from November to March, when temperatures were below zero. Precipitation for this period was accumulated mathematically and applied on 1 April 2006.

Soil properties used for the analysis are shown in Figure 3 for the SWCC and Figure 4 for the hydraulic conductivity function. Initial suction conditions were estimated from the suction profile shown in Figure 2. A constant suction of 1600 kPa was used for the upper 4 m of clay, 600 kPa for the lower 5.5 m of clay and 2000 kPa for the till.

A parametric study was performed to determine the significance of each of the input parameters to the predicted results. Parameters considered included the

climatic data, vegetation conditions, soil properties, initial soil conditions, thickness of the fissured clay layer and the amount of park watering. The climatic data included daily precipitation, net radiation and wind speed. Soil property data included the SWCC and hydraulic conductivity functions for the fissured clay, intact clay and the till. A reasonable range of the values for each parameter was selected and shown in Table 1. During the sensitivity analyses, the parameter under consideration was varied while all other parameters were kept unchanged and equal to the "base case" value.

Figure 10 shows the predicted results of the cumulative boundary fluxes for the "base case" analysis. Positive flux indicates moisture enters into the soil while negative flux indicates moisture leaves the soil. For a total precipitation of 424 mm, including 366 mm of precipitation and 58 mm of park watering, the predicted total net cumulative flux is -139 mm. The total cumulative potential evaporation, actual evaporation and potential transpiration are -594 mm, -566 mm, and 400 mm, respectively.

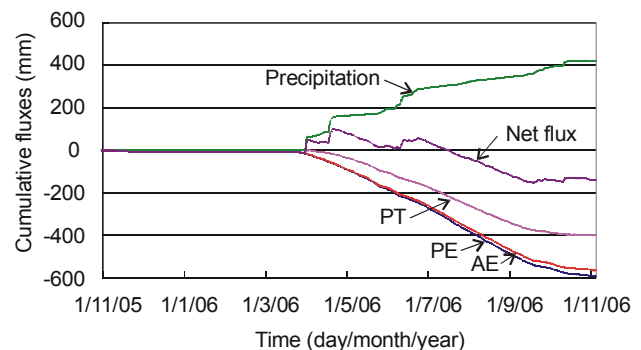


Figure 10. Calculated cumulative boundary fluxes. PE, potential evaporation; AE, actual evaporation; PT, potential transpiration.

Figures 11 and 12 present the suction and water content change versus time at various depths, respectively. Figure 13 shows suction profiles at various times for the "base case" analysis. Soil suction reached equilibrium condition in December 2005 and remained relatively unchanged until April 2006. Variation in suction was more pronounced near ground surface. A zone of suction change was predicted to a depth of 13 m in the till layer; however, only minor suction change was predicted in the till. Under the applied climatic condition, predicted suction in the clay varied from 600 to 2150 kPa. September appeared to be the month with highest soil suction in the soil. Figure 14 shows volumetric water content profiles at various times. Predicted volumetric water content in clay varies from 40 to 46 percent.

Table 1 and Figure 15 present the results of the parametric study. These results suggest that soil properties, including the SWCC and hydraulic conductivity, have only minor effects on the predicted results. Initial suction condition also appears to have



Table 1. Results of the parametric study

| Parameter                                  | Base case value | Value range         | Cumulative infiltration range (mm) | Variation (%) |
|--|-----------------|---------------------|------------------------------------|---------------|
| Wind speed scale factor                    | 0.5             | 0.3 to 1.0          | -89 to 265                         | -36 to 91     |
| Net radiation scale factor                 | 0.5             | 0.3 to 1.0          | -9 to -452                         | -94 to 225    |
| Precipitation scale factor                 | 1               | 0.75 to 1.5         | -230 to 43                         | 65 to -131    |
| Leaf area index                            | Good            | No to excellent     | -143 to -138                       | 3 to -1       |
| Park watering factor                       | 1               | 0 to 5              | -195 to 84                         | 40 to -160    |
| Thickness of fissured layer                | 4               | 0 to 5              | -135 to -139                       | -4 to 0       |
| Permeability of fissured clay (m/s)        | 2.27E-08        | 1.14E-8 to 2.27E-7  | -136 to -142                       | -2 to 2       |
| Permeability of clay (m/s)                 | 2.27E-09        | 2.27E-9 to 2.27E-8  | -138 to -137                       | < 1           |
| Permeability of till (m/s)                 | 1.00E-10        | 1.00E-11 to 1.00E-9 | -137 to -136                       | <2            |
| SWCC for clay                              | Middle curve    | Drying to wetting   | -138 to -140                       | <1            |
| Initial suction of upper 4 m of clay (kPa) | 1600            | 1000 to 2000        | -141 to -135                       | 1 to -3       |
| Initial suction of lower 5 m of clay (kPa) | 600             | 400 to 800          | -139 to -138                       | 0 to -1       |
| Initial suction of till (kPa)              | 2000            | 1000 to 2500        | -141 to -138                       | 1 to -1       |

insignificant effect on the predicted infiltration rate. The parameters that have the most significant effect on the predicted cumulative infiltration are the net radiation, precipitation and park watering.

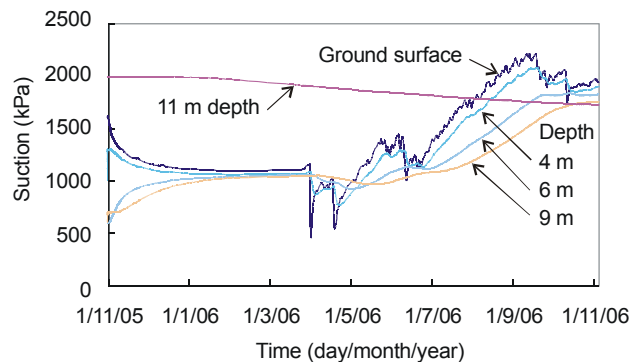


Figure 11. Suction change versus time at various depths

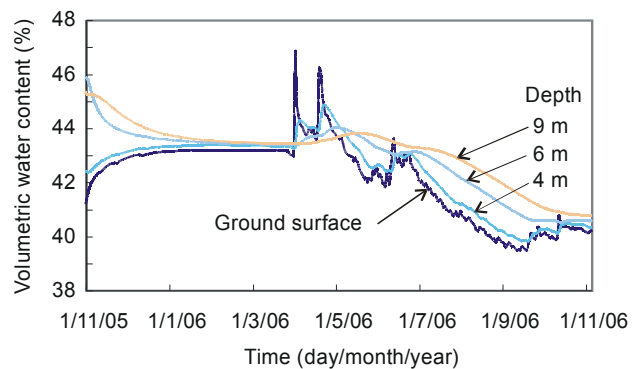


Figure 12. Volumetric water content change versus time at various depths

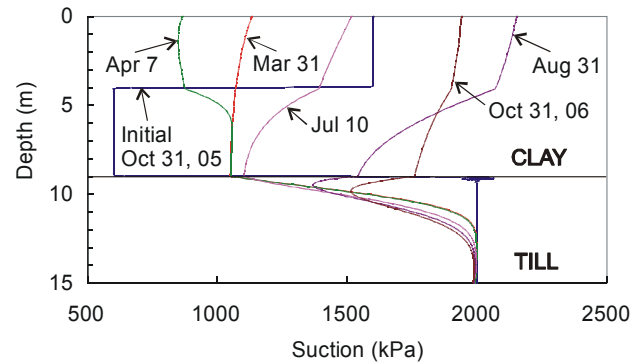


Figure 13. Suction profiles at various times

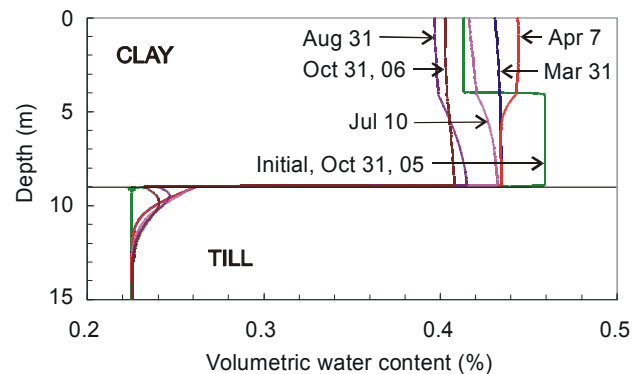


Figure 14. Volumetric water content profiles at various times

## 9 SUMMARY

The computed infiltration at ground surface and soil suction in the expansive soils in the Regina area was

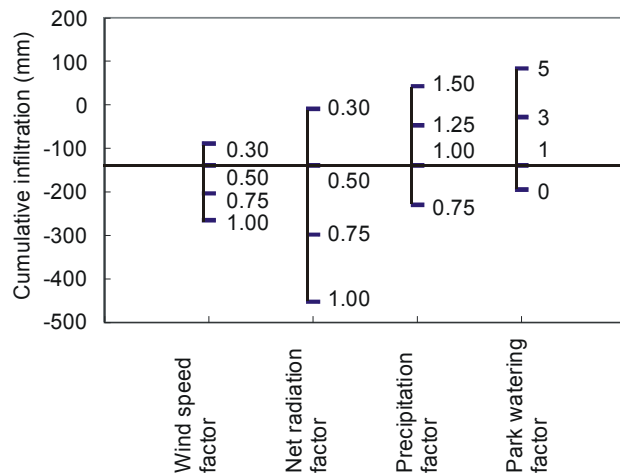


Figure 15. Effect of variable parameters on calculated cumulative infiltration for period from 1 November 2005 to 31 October 2006

found to depend strongly on weather variables such as solar radiation, precipitation and wind speed. The amount of park watering was also found to be of significant importance to the estimated infiltration. Soil properties such as the SWCC and hydraulic conductivity functions appear to have only minor influence on the modelling results under the specific site condition considered. With an annual precipitation of about 400 mm, the annual net infiltration varied from -452 to 84 mm for the site under study. Suction changes can take place throughout the clay soil profile and into till to a maximum depth of approximately 13 m. The month of September was found to have the highest soil suctions in the soil near the ground surface and the greatest range of soil suction values throughout the profile.

## 10 ACKNOWLEDGMENT

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