# Climate Change Effects on Expansive Soil Movements

## Les effets du changement climatique sur les mouvements d'un sol gonflant

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ABSTRACT: Climate change effects on expansive soil movements are quantified using the Thornthwaite Moisture Index (TMI). The TMI is calculated from the moisture deficiency and surplus, both related to rainfall, and the potential evapotranspiration which is derived from temperature. The predicted temperature increase and rainfall reduction in 2030 and 2070 are used to derive the TMI of an area. In this way, values of TMI at present, in 2030 and 2070 are derived for Adelaide, Melbourne, Perth and Sydney. Established relationships between TMI and the depth and magnitude of soil suction changes for sites with and without the presence of trees, and the relationships between soil movement and soil suction changes, are used to predict the increase in soil movement for a site. A specific example is given for Melbourne for a site without trees and with a group of trees. It is shown that a significant increase in predicted soil movement is expected with climate change. Therefore a continuing revision of footing design standards would be required in order to cater for the effects of climate change.

RÉSUMÉ : Les effets du changement climatique sur les mouvements des sols gonflants sont quantifiés utilisant l'Indice d'Humidité de Thornthwaite (IHT). On calcule l'IHT utilisant le manque ainsi que le surplus de l'humidité, tous les deux liés au niveau des précipitations, ainsi que l'évapotranspiration potentielle, dérivée de la température. L'augmentation prévue de la température et du niveau des précipitations en 2030 et 2070 servent à obtenir l'IHT d'une région. De cette manière, les valeurs de l'IHT actuelles sont obtenues pour Adelaïde, Melbourne, Perth et Sydney. Les liens établis entre l'IHT et la profondeur ainsi que l'ampleur des changements de la pression d'eau négative des pores du sol pour des sites avec et sans la présence des arbres, et les liens entre le mouvement du sol et les changements de la pression négative des pores du sol, sont employés afin de prévoir l'augmentation du mouvement du sol pour un site. Un exemple spécifique est fourni pour Melbourne pour un site sans arbres mais aussi avec un groupe d'arbres. On démontre qu'une augmentation importante du mouvement du sol est attendue avec le changement climatique. Donc, une révision continue des normes de projet de fondations serait requise afin de préparer les effets du changement climatique.

KEYWORDS: climate change, expansive soil, Thornthwaite Moisture Index, tree effects

## 1 INTRODUCTION

There is considerable scientific evidence that emissions from economic activity are causing changes to the earth's climate (Stern 2007). For example, in south-eastern and south-western Australia, current predictions indicate that generally, the 2030 and 2070 temperatures are expected to increase by about 1°C and 3°C respectively, and the 2030 and 2070 winter and spring rainfall is predicted to decrease significantly (CSIRO 2007).

Should these predictions prove accurate, these temperature increases and rainfall reductions are expected to cause increased changes in soil moisture content from those at present. As well, soil moisture changes due to trees become more adverse during periods of hotter and drier weather, when the tree demands more soil water than is available from rainfall. As expansive soils have the potential for undergoing significant movement with soil moisture changes, thus impacting on the stability of structures, the effect of climate change on soil moisture changes needs to be predicted so that provisions can be made to effectively respond to the challenges of climate change when dealing with expansive soils.

Notwithstanding that the current predictions could prove to be inaccurate, present day geotechnical engineers are faced with the challenge of dealing with climate change in order to cater for the possibility that the event that the current predictions suggest, may actually eventuate.

## 2 CLIMATE CHANGE PREDICTIONS

CSIRO (2007) has made predictions of climate change for Australia, and a summary of the predictions for changes in temperature and rainfall from present day averages for Adelaide, Melbourne, Sydney and Perth in 2030 and 2070 is shown in Table 1 for the emission scenarios as defined in CSIRO (2007).

Table 1: Climate Change Predictions from CSIRO (2007)

| | | Adelaide | | Melbourne | | Sydney | | Perth | |
|---|---|---|---|---|---|---|---|---|---|
| | Season | 2030 | 2070 | 2030 | 2070 | 2030 | 2070 | 2030 | 2070 |
| Temp °C | Summer | +0.9 | +3.0 | +1.0 | +3.1 | +1.0 | +3.1 | +0.9 | +2.9 |
| | Autumn | +0.9 | +2.8 | +0.8 | +2.7 | +0.9 | +3.0 | +0.8 | +2.7 |
| | Winter | +0.8 | +2.4 | +0.7 | +2.2 | +0.8 | +2.6 | +0.7 | +2.3 |
| | Spring | +0.9 | +3.0 | +0.9 | +2.9 | +1.0 | +3.3 | +0.9 | +2.9 |
| Rainfall % | Summer | -2 | -5 | -1 | -4 | +1 | +2 | -4 | -12 |
| | Autumn | -1 | -4 | -2 | -5 | -2 | -6 | -4 | -12 |
| | Winter | -6 | -19 | -4 | -12 | -5 | -16 | -7 | -22 |
| | Spring | -8 | -23 | -7 | -21 | -6 | -17 | -9 | -27 |

Notes on Table 1: 2030 predictions are A1B emission scenario 50 percentile; 2070 predictions are A1F1 emission scenario 50 percentile

The predictions given in CSIRO (2007) are relative to 1990, however in this paper they are considered to be relative to long term average temperatures and rainfall at the present time. It can be seen from Table 1 that generally, the 2030 and 2070 temperatures are expected to increase by about 1°C and 3°C respectively. Table 1 also indicates that the 2030 and 2070 winter and spring rainfall is predicted to decrease significantly.

The magnitudes of the predicted changes in temperature and rainfall for 2030 and 2070 are expected to cause a decrease in soil moisture content from that experienced at present, thus leading to higher soil shrinkage on expansive soil sites.

In order to quantify the effect of climate change predictions on the magnitude of soil moisture changes, it is necessary to first establish the relationship between climate and seasonal rainfall and temperature. This is undertaken in this paper using the Thornthwaite Moisture Index.

## 3 THORNTHWAITE MOISTURE INDEX

Thornthwaite (1948) proposed an empirical method for estimating potential evapotranspiration as a climatic factor. Thornthwaite's method enables potential evapotranspiration (*PE*) to be estimated using only monthly average temperature data (*t*) for a particular location, and a simply derived adjustment factor, which is applied to correct for latitude and month length by Equation (1)

$$PE = 16\left[\frac{10t}{I}\right]^{a} \text{ x Latitude correction factor} \qquad (1)$$

where

$$a = 0.000000675I^3 - 0.0000771I^2 + 0.017921I + 0.49239$$

In Equation (1), the heat index (*I*) is given by Equation (2)

$$I = \sum_{i=1}^{12} i\ , \quad \text{where } i = \left(t/5\right)^{1.514} \qquad (2)$$

By enabling estimation of monthly potential evapotranspiration and balancing this with monthly rainfall, Thornthwaite (1948) made it possible to estimate seasonal moisture deficiencies and surpluses.

A moisture deficit is defined as the amount by which the net monthly potential evapotranspiration exceeds monthly rainfall during a period of zero soil moisture storage. Similarly, a moisture surplus is the amount by which the net monthly rainfall exceeds potential evapotranspiration when soil moisture storage is at capacity (defined as being 100 mm water); this surplus is assumed to drain as runoff. Soil moisture recharge occurs during months when the net moisture balance is positive and soil water storage is below capacity at the beginning of the month, while soil moisture depletion occurs when the net moisture balance is negative, but the soil water storage at the beginning of the month is non-zero. During the spring, soil moisture is rapidly utilized by vegetation, particularly annual grasses, which quickly mature, then die off once the soil moisture has been depleted.

The Thornthwaite Moisture Index (TMI) is calculated from the derived moisture deficiency and surplus by Equation (3).

$$TMI = \frac{100(\Sigma Surplus) - 60(\Sigma Deficit)}{\Sigma PE} \qquad (3)$$

Determination of the TMI based on present day monthly temperature and rainfall averages for Perth is outlined in Table A1 of Appendix A. It is shown that for Perth at the present time, the TMI = +16.

The TMI is used to categorize the climate of a particular location. A higher positive value of TMI corresponds to a wetter climate, while a greater negative number is associated with a more arid climate. Therefore climate change predictions of higher temperatures and lower rainfall will result in a smaller TMI than at present for a particular locality.

## 4 PREDICTED CHANGES IN TMI

The author (Mitchell 2011,2012) used the seasonal temperature rise and general rainfall decline predictions (Table 1) for Adelaide, Melbourne, Sydney and Perth for 2030 and 2070 and applied them to the current climate averages to yield new average TMI estimates for each city in 2030 and 2070. An example for Perth for 2070 is given in Table A2 of Appendix A, and the results for all four cities are shown in Table 2.

Table 2: TMI Predictions for 2030 and 2070

| | TMI | | |
|---|---|---|---|
| City | Present | 2030 | 2070 |
| Adelaide | -19 | -26 | -34 |
| Melbourne | -8 | -14 | -24 |
| Perth | 16 | 6 | -14 |
| Sydney | 43 | 27 | 3 |

It is seen from Table 2, the predicted TMI for each city examined decreases with time, indicating increasing aridity.

From a geotechnical perspective, predictions of a lower TMI and hence an increase in the severity of desiccation of the soil profile could potentially lead to an increase in the magnitude of expansive soil movements for regions of Adelaide, Melbourne, Sydney and Perth characterised by highly expansive soils. This is quantified in the next section.

## 5 RELATIONSHIPS BETWEEN EXPANSIVE SOIL MOVEMENTS AND TMI

By the Australian standard AS2870-2011, the characteristic surface movement ($y_s$) of a site is determined from the design soil suction changes and the soil instability index ($I_{pt}$) over the depth of design soil suction change ($h = H_s$) by Equation (4) and Figure 1 (the surface soil suction change is $\Delta u_s$ = 1.2 pF by AS2870 - 2011).

$$y_s = \sum_{h=0}^{H_s} I_{pt}\Delta u \Delta h \qquad (4)$$

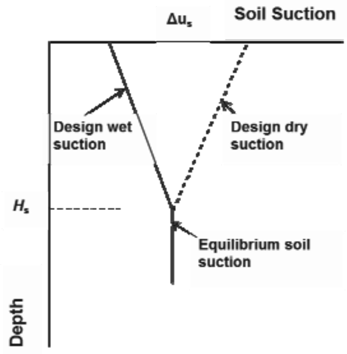

Figure 1. Design soil suction extremes for a "normal" site by AS2870-2011

Equation (4) and Figure 1 are for "normal" sites such as sites that are not affected by trees. When considering tree effects, one recommended method of AS2870-2011, considers an additional soil suction as shown in Figure 2. This leads to an additional soil movement due to trees ($y_{t\,\max}$) by Equation (5).

$$y_s + y_{t\max} = \sum_{h=0}^{H_t} I_{pt}\Delta u \Delta h \qquad (5)$$

The value of $y_{t\ \max}$ is corrected for the distance of the tree from the footing of a building to give the actual tree effect $y_t$.

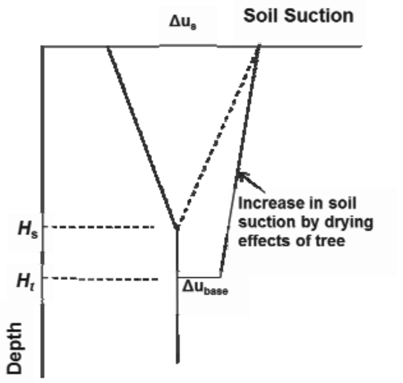

Figure 2. Design soil suction extremes for a site with a group of trees by AS2870-2011

By AS2870-2011, the parameters $H_s$, $H_t$, and $\Delta u_{base}$ increase with a decreasing Thornthwaite Moisture Index for the site as shown in Figure 3 for $H_s$, and $H_t$ ($H_t$ is shown for a tree group) and in Figure 4 for $\Delta u_{base}$ (shown for a tree group). As the magnitude and depth of soil suction changes increase with decreasing TMI associated with a drying climate, by Equations (4) and (5), expansive soil movements will increase.

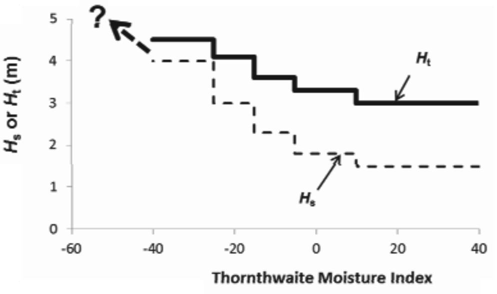

Figure 3. Relationships between $H_s$ and $H_t$ and TMI by AS2870-2011

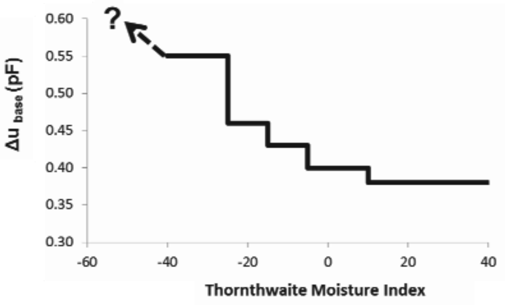

Figure 4. Relationship between $\Delta u_{base}$ and TMI by AS2870-2011

For the predicted future decrease in TMI of a location shown in Table 2, the increased depths of soil suction changes $H_s$ and $H_t$ and the increased soil suction change $\Delta u_{base}$ can be determined from Figures 3 and 4 respectively, and the predicted increase in soil movement can then be calculated from the soil suction changes by Equations (4) and (5).

## 6 EXAMPLE

The author (Mitchell 2011, 2012) has illustrated the implications of a predicted decrease in TMI by determining the soil movement at present, in 2030 and in 2070, for a site in Melbourne for a group of trees where $y_{tmax}$ from Equation (5) is equal to $y_t$, for a soil profile assumed for simplicity to be uniform clay of $I_{pt}$ = 2.5%.

By Table 2, the TMI at present, and as predicted in 2030 and 2070, are respectively -8, -14, and -24. By Figure 3, the values of $H_s$ corresponding to these TMI values are respectively 2.3 m, 3.0 m and 4.0 m, and the $H_t$ values are respectively 3.6 m, 4.1 m and 4.5 m, and by Figure 4, $\Delta u_{base}$ = 0.43, 0.46 and 0.55 respectively.

Table 3 summarises the results of the predicted soil movement by Equations (4) and (5) for the Melbourne site.

Table 3: Predicted Soil Movement for a site in Melbourne

| | $y_s$ (no trees) | $y_s$+$y_t$ (with trees) |
|---|---|---|
| Present | 35 mm | 65 mm |
| 2030 | 45 mm | 75 mm |
| 2070 | 60 mm | 95 mm |

It can be seen from Table 1 that a significant increase in predicted soil movement is expected with climate change. Therefore a continuing revision of footing design standards would be required in order to cater for the effects of climate change.

## 7 CONCLUSIONS

This paper has shown how climate change effects on expansive soil movements can be quantified using the Thornthwaite Moisture Index (TMI). This is because the TMI is calculated from the moisture deficiency and surplus, both related to rainfall, and the potential evapotranspiration which is derived from temperature, so that predicted temperature increases and rainfall reductions in 2030 and 2070 can used to derive the future TMI of an area. Values of TMI at present, in 2030 and 2070 were derived for Adelaide, Melbourne, Perth and Sydney. Established relationships between TMI and the depth and magnitude of soil suction changes for sites with and without the presence of trees, and the relationships between soil movement and soil suction changes, are used to predict the increase in soil movement for a site. A specific example is given for Melbourne for a site without trees and with a group of trees. It is shown that a significant increase in predicted soil movement is expected with climate change. This implies that a continuing revision of expansive soil movement predictions and footing design standards would be required in order to cater for the effects of climate change.

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## APPENDIX A

### TABLE A1: DETERMINATION OF THE TMI FOR PERTH, AT PRESENT

| Perth, Australia | | | | Present Day | | | | | Latitude 31.95º S | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Total** |
| **Rainfall** | 9 | 13 | 19 | 46 | 123 | 182 | 173 | 135 | 80 | 55 | 22 | 14 | **871** |
| **Ave. temp (*t*)** | 24.3 | 24.7 | 22.8 | 19.9 | 16.7 | 14.0 | 13.3 | 13.4 | 14.9 | 17.0 | 20.3 | 22.7 | |
| **Heat index (*i*)** | 10.95 | 11.23 | 9.95 | 8.09 | 6.21 | 4.75 | 4.40 | 4.45 | 5.22 | 6.38 | 8.34 | 9.88 | **89.86** |
| **Latitude Corr. factor** | 1.21 | 1.03 | 1.06 | 0.95 | 0.91 | 0.84 | 0.89 | 0.95 | 1.00 | 1.12 | 1.15 | 1.23 | |
| **Potential evap. (*PE*)** | 137.4 | 120.8 | 106.2 | 72.8 | 49.4 | 32.2 | 30.8 | 33.4 | 43.3 | 62.9 | 91.6 | 122.1 | **903** |
| **Water balance** | -128.4 | -107.8 | -87.2 | -26.8 | 73.6 | 149.8 | 142.2 | 101.6 | 36.7 | -7.9 | -69.6 | -108.1 | |
| **Storage** | 0 | 0 | 0 | 0 | 73.6 | 100 | 100 | 100 | 100 | 92.1 | 22.4 | 0 | |
| **Deficit** | 128.4 | 107.8 | 87.2 | 26.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 85.7 | **435.9** |
| **Surplus** | 0 | 0 | 0 | 0 | 0 | 123.4 | 142.2 | 101.6 | 36.7 | 0 | 0 | 0 | **403.9** |
| a = 1.970 | | | | | | | | | | | | | |
| **TMI = 16** | | | | | | | | | | | | | |

Notes on Table A1: Water balance = Rainfall – PE; Storage = previous month's storage + water balance for month (= 0 if result is negative, and =100 if result ≥ 100 mm); Deficit = |water balance| – storage$_{\text{previous month}}$ (if storage for month = 0); and Surplus = water balance + storage$_{\text{previous month}}$ – 100 (if storage for month = 100).

### TABLE A2: DETERMINATION OF THE TMI FOR PERTH, PREDICTED FOR 2070

| Perth, Australia | | | | 2070 | | | | | Latitude 31.95º S | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Total** |
| **Rainfall** | 7.9 | 11.4 | 16.7 | 40.5 | 108.2 | 142.0 | 134.9 | 105.3 | 58.4 | 40.2 | 16.1 | 12.3 | **694** |
| **Ave. temp (*t*)** | 27.2 | 27.6 | 25.5 | 22.6 | 19.4 | 16.3 | 15.6 | 15.7 | 17.8 | 19.9 | 23.2 | 25.6 | |
| **Heat index (*i*)** | 12.99 | 13.28 | 11.78 | 9.82 | 7.79 | 5.98 | 5.60 | 5.65 | 6.84 | 8.10 | 10.21 | 11.85 | **109.9** |
| **Latitude Corr. factor** | 1.21 | 1.03 | 1.06 | 0.95 | 0.91 | 0.84 | 0.89 | 0.95 | 1.00 | 1.12 | 1.15 | 1.23 | |
| **Potential evap. (*PE*)** | 174.6 | 154.0 | 130.8 | 87.4 | 57.8 | 35.0 | 33.3 | 36.1 | 51.6 | 75.7 | 112.8 | 153.2 | **1102** |
| **Water balance** | -166.7 | -142.5 | -114.0 | -47.0 | 50.4 | 107.0 | 101.6 | 69.2 | 6.8 | -35.5 | -96.7 | -140.9 | |
| **Storage** | 0 | 0 | 0 | 0 | 50.4 | 100 | 100 | 100 | 100 | 64.5 | -32.3 | 0 | |
| **Deficit** | 166.7 | 142.5 | 114.0 | 47.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 173.1 | **643.3** |
| **Surplus** | 0 | 0 | 0 | 0 | 0 | 57.4 | 101.6 | 69.2 | 6.8 | 0 | 0 | 0 | **235.0** |
| a = 2.427 | | | | | | | | | | | | | |
| **TMI = -14** | | | | | | | | | | | | | |

Notes on Table A2: From Table 1 for Perth in 2070, predicted monthly rainfall decrease below present day averages is 12% for summer (i.e. December to February), 12% for autumn (i.e. March to May), 22% for winter (i.e. June to August) and 27% for spring (i.e. September to November). Also from Table 1, the predicted average monthly temperature increase over present day averages is 2.9°C for summer, 2.7°C for autumn, 2.3°C for winter, and 2.9°C for spring.