An extension of the Thornthwaite Moisture Index for geotechnical engineering purposes

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ABSTRACT

The Thornthwaite Moisture Index (TMI) was first published in 1948 as a means of classifying climate for agricultural purposes in the United States of America. Since then the TMI has been adapted by civil engineers and incorporated into design standards such as, AS2870 Residential Slabs and Footings. The response of structures and utilities placed near the ground surface such as foundations of light structures, buried pipes and road pavements, is determined by the soil properties and climatic interaction, or change in moisture content of soil in the reactive zone. The importance of the climate on civil buried structures is becoming increasingly important as evidence of climate change further emerges. This paper highlights the deficiencies of using the TMI as a quantitative measure of climate in civil design. It presents an extension of the TMI climate classification to take into account seasonality and the effect this may have on pavements, structures and utilities founded within the reactive zone.

1 INTRODUCTION

It is well established that climate has a significant influence on buried structures close to the ground surface. For example, the performance of road pavements, railway lines, buried pipes, foundations for light structures and landfill clayey liners are all affected by climate. While computer modelling capability of this interaction has improved in recent times, a good climate classification indicator is still needed to correlate to the essential performance indicators of these structures for their engineering evaluation and design. Commonly, the TMI is used for this purpose. The TMI was developed as a general climate classification index for agriculture that takes into account the climatic factors and its influence on the general landscape, for example overall water balance taking into account the influence of soil water storage and plants. Currently we have computer models such as Vadose/W and SVFlux to account for the influence of soil water storage and plants in detail. Therefore, there is no need to incorporate them in the classification of the climate, which primarily involves solar radiation, precipitation (rain and snow) and ambient humidity and temperature and wind. The incorporation of soil water storage, which is very subjective and simplistic in the TMI calculation, and plants makes the TMI too general for its use as a quantifiable measure in engineering correlations. Additionally, many engineering buried or surficial structures do not have interaction with plants as a matter of common situation; it is the exception rather than the rule.

This paper highlights deficiencies of the TMI, as it is currently used, for engineering purposes, and proposes an alternative index, dubbed the Climate Classification Index (CCI), for engineering design purposes. The current focus is on road pavements, where the influence of climate is well known qualitatively but not taken into account quantitatively.

2 ROAD PAVEMENTS

A road pavement system comprises three structural layers – the subgrade at the bottom, the subbase above the subgrade and the base layer at the top. Road pavements are generally classified into two categories – rigid and flexible. Rigid pavements in Australia comprise a concrete base over a rigid or flexible subbase. Flexible pavements include any combination of semi-bound or unbound subbase and base materials overlain by either an asphalt or sprayed seal wearing surface. This paper focuses only on unbound granular pavement with thin bituminous seals and the effect of their performance due to climatic interaction.

2.1 Unbound Granular Pavements

Unbound granular pavements with thin bituminous seals are normally the favoured form of construction along less heavily trafficked routes, such as rural roads, due to their cost effectiveness. In 2003, approximately 85 percent of the sealed Australian road network comprised rural arterial and local roads (Austroads 2005). Moisture infiltration has long been recognised as one of the major causes of premature distress in pavement structures, while in-service moisture variations in foundations and embankments comprising reactive (expansive) clays cause distortion and cracking in pavements (Austroads 1997). Some mechanisms for moisture movement, either liquid or gaseous, into and out of pavements are shown diagrammatically in Figure 1, highlighting the significant interaction that can prevail in a road pavement with a thin bitumen seal.

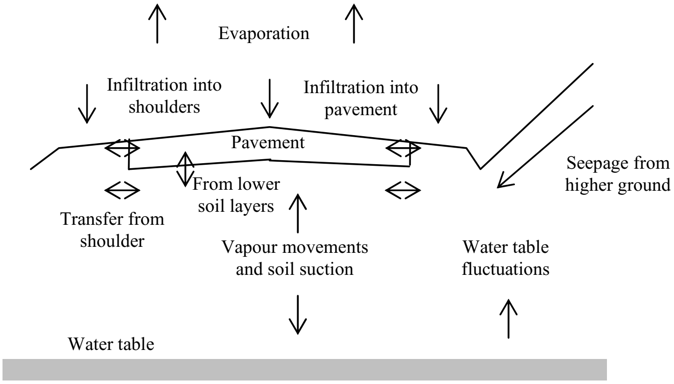

Figure 1: Moisture movements in road pavements (Austroads 2004)

Excess pavement moisture typically leads to excess pore pressure development upon loading. Pore pressure is a measure of load distribution between the pavement structure and the water held in the voids of this structure. It is a useful tool in predicting early life failures (Wijeyakulasuriya 2005). Accurate estimation of in-service moisture content variation can allow the pavement designer to modify the design (grading to suit the moisture content) and guide repeated load triaxial testing for confirmation. Therefore, it will be very beneficial if a rational simplified approach can be developed to predict in-service moisture levels, taking into account climate interaction with the pavement system. This is the aim behind developing the CCI.

3 THORNTHWAITE MOISTURE INDEX

The TMI was published in 1948 as a means of classifying a climate at a location of interest. The TMI quantifies the aridity or humidity of a soil-climate system by summing the effects of annual precipitation, evapotranspiration, soil water storage, moisture deficit and runoff (Thornthwaite 1948). It is defined in terms of two simpler indices – the aridity index (I_a) and humidity index (I_h), given by Equations 1a and 1b:

$$I_a = 100\left(\frac{D}{PET}\right) \text{ and } I_h = 100\left(\frac{R}{PET}\right) \qquad \text{(1a and 1b)}$$

where PET is the potential evapotranspiration of the site, D is the moisture deficit and represents the quantity of water which cannot be evapotranspired since it is not available, R is the moisture surplus, or runoff, and represents the quantity of water which could not infiltrate wet ground (Fityus 2003). The combination of the two indices gives (Thornthwaite and Mather, 1955):

$$TMI = I_h - I_a \qquad (2)$$

It should be noted that in the original Thonthwaite equation, a factor of 0.6 was included for the aridity index because it was considered that water can enter a soil profile more easily than it can be extracted. The revised definition as given by Equation (2) is adopted here. Mather (1974) showed that when it is assumed that there is no net change in soil water storage the TMI becomes:

$$TMI = 100\left(\frac{P}{PET} - 1\right) \qquad (3)$$

where P is the annual precipitation. The calculation of PET is performed by using Thornthwaite's semi-empirical formula. A typical climate classification based on the TMI is given in Table 1. Fityus (2003) analysed various approaches for computing the TMI, which he referred to as the year-by-year analysis (average TMI of yearly values computed from monthly data), the average-year analysis (single year TMI calculation based on average monthly data), and simplified-average-year analysis (using Equation 3 ignoring water storage). On the basis of an analysis of a large number of sites in the Hunter Valley Region, he concluded that the average-year analysis is heavily dependant on the assumed initial water storage. In contrast, the year-by-year analysis provided consistent values that were less dependant on the assumed initial storage. Interestingly, however, the simplified from of the average-year analysis resulted in values very similar to the year-by-year analysis. Therefore, the use of these two approaches was suggested.

TMI analyses were performed using the above three approaches for 10 sites in Queensland and 15 sites in Victoria with at least one pair of sites from Victoria and Queensland corresponding to the site classifications listed in Table 1. The number of years of data analysed varied between 20 and 26 depending on the available data sourced from the Bureau of Meteorology. In agreement with Fityus (2003), it was found that the year-by-year and simplified analyses gave very similar TMI values and the average-year analysis TMI values varied significantly depending on the assumed initial storage conditions. A sensitivity analysis was performed on the Mt Isa data in which the initial and maximum storage values were varied independently. The year-by-year and simplified analyses resulted in unchanged TMI values whereas the average-year TMI values varied significantly.

Table 1: Climate classification based on the TMI (Fityus 2003)

Classification	TMI	Classification	TMI
Wet coastal/alpine	>40	Dry temperate	-25 to 5
Wet temperate	10 to 40	Semi-arid	-40 to 25
Temperate	-5 to 10	Arid	<-40

3.1 Limitations of the Thornthwaite Moisture Index

Two limitations were identified with the current use of the TMI. Firstly, there is ambiguity in calculating the TMI and it can be dependant on the initial storage assumed. Since rainfall can vary considerably from year to year, so too can the TMI. The use of the values of TMI based on limited periods of weather records should be avoided. At present it appears that a twenty year minimum data record is required (Fox 2002). As suggested by Fityus (2003), if a simplified form of the TMI (Equation 3) is used, the influence of storage may be avoided.

Secondly, the TMI gives a single value applicable to a typical year for a certain location. However, it is very clear that the TMI when calculated for each month, fluctuates significantly. Therefore, the effect of seasonal climate variability is not accounted for in single value TMI designation. It is increasingly evident that seasonal changes are very important for the performance of engineering structures. For instance, two sites with similar TMI values but with significantly different seasonal variations can produce substantially different effects on engineering structures. To illustrate this point, consider these two geographically dissimilar locations – Mt Isa in Queensland and Mildura in Victoria. The average TMI from 1976 to 2006 using the simplified TMI calculation is -67 at Mt Isa. The average rainfall over that period was approximately 460mm per year. At Mildura, the average TMI for the same period is -64 and the average rainfall was approximately 280mm. Despite having similar TMI values, the average yearly rainfall distributions are significantly different between the two sites, as shown in Figure 2. At Mt Isa, there is distinctly a wet period from October to March (6 months) with a dry period from April to September (6 months). At Mildura, the average yearly rainfall distribution is relatively consistent with slightly less rainfall between October and March (6 month dry period) and slightly more between April and September (6 month wet period). It is interesting to note that the average yearly pan evaporation at Mt Isa is always higher than the rainfall but at Mildura the average yearly rainfall is higher than the average yearly pan evaporation between June and August. With the higher rainfall and the more extreme difference between the wet and dry periods at Mt Isa compared to Mildura, the potential exists for a higher degree of wetting/drying associated with seasonality at Mt Isa despite having very similar TMI values. In the light of these limitations, we propose a new climate indexing method that is considered to be more suitable for quantification of climate for engineering performance evaluation.

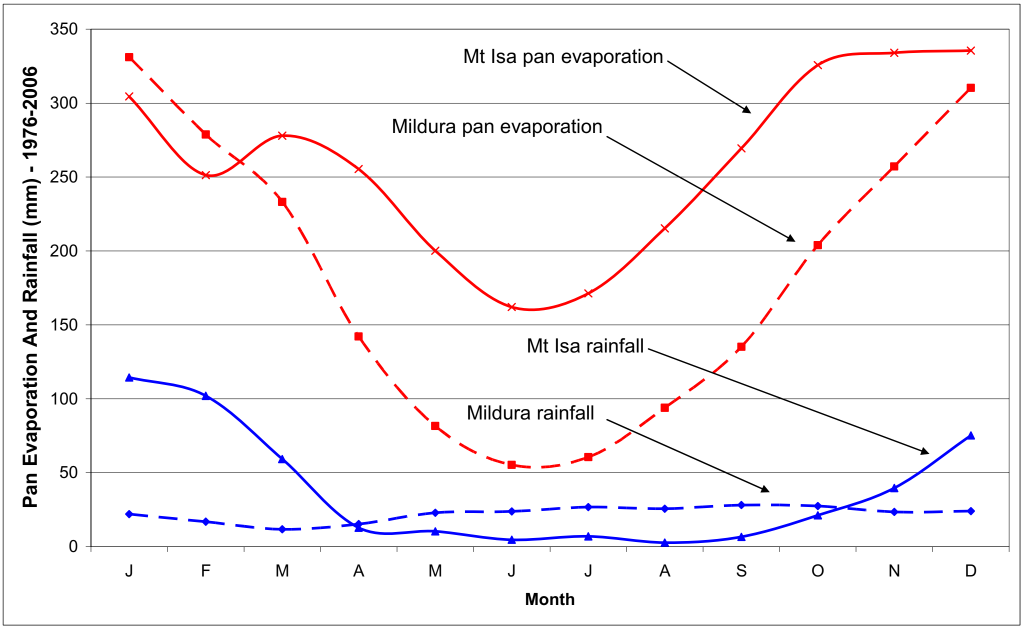

Figure 2: Average yearly rainfall and pan evaporation distributions at Mt Isa and Mildura

4 NEW CLIMATE CLASSIFICATION INDEX

Climatic effects on a soil profile or on an engineering structure are a function of heat from the sun, the wind, ambient humidity, temperature and precipitation. The effects of solar radiation, ambient humidity, temperature and wind may be represented by a single variable, i.e., potential evaporation, PE (Mather, 1974). The potential evaporation can be measured by pan evaporation, which is accurate enough for engineering calculation purposes. Alternatively, it could be estimated from the Penman equation:

$$\left(E=\frac{\Delta}{\Delta+\gamma}E_r+\frac{\gamma}{\Delta+\gamma}E_a\,;E_r=\frac{R_n}{l_v\,\rho_w}\,;E_a=K(u)(e_s-e)\right) \qquad \text{(4a, 4b and 4c)}$$

where E is the potential evaporation, Δ is the slope of the saturation pressure versus temperature curve at the mean temperature of the air, γ is a psychrometric constant, E_r is the net radiation, E_a is the turbulent mass transfer, R_n is the net radiation, l_v is the latent heat of vaporisation, ρ_w is the density of water, K(u) is a mass transfer coefficient, e_s is the saturated vapour pressure at air temperature, and e is the actual vapour pressure (Reed). Precipitation P can be considered as the other independent variable representing climate (Mather 1974). On the basis of this rationale, the Climate Classification Index (CCI) is proposed as:

$$CCI_j=\frac{\sum P_i}{\sum PE_i} \qquad (5)$$

where P_i and PE_i are the daily rainfall and potential evaporation, respectively, for the analysed period j (e.g., consecutively for a year). It was found that one can compute the CCI for a different period k (e.g., 10 years either consecutive or disparate) by taking the weighted average for the corresponding PE values as follows:

$$CCI_k=\frac{\sum\left(CCI_j\times PE_j\right)}{\sum PE_j} \qquad (6)$$

where CCI_k is the CCI for the period k, such as long term average CCI applicable to a site. In fact, this computational algorithm is valid for the simplified TMI calculation given in Equation 3. Alternatively, the CCI for period k can be calculated by using daily values of precipitation and potential evaporation data for the entire period k, and this calculation should result in the same value obtained from Equation 6.

The above approach can be used to compute a long term average CCI applicable to a site, herein known as the average CCI or CCI_{av}. In order to take into account the seasonal variation during a year, another level of division in CCI is suggested. It is recommended that the year is divided into wet and dry seasons, and CCI_{wet} and CCI_{dry} are calculated for these seasons. Based on these calculations, CCI_s is calculated to capture the seasonal variation of CCI within years, as given below:

$$CCI_s = CCI_{wet} - CCI_{dry} \qquad (7)$$

The climate classification for the site can be designated by two indices CCI_{av} and CCI_s. If necessary the CCI seasonal subdivision could be for three or four seasons if the rainfall and potential evaporation distributions warrant it but more variables would be required to capture variation within the seasons. Therefore, it is considered that the division of wet and dry seasons is appropriate at this stage. It may not be necessary to have the same number of months for the wet and dry periods or to have them as consecutive months for this designation. Further research is necessary to examine these divisions in more detail.

4.1 Climate Classification Indices at Mt Isa and Mildura

Both average and seasonal CCIs were computed for Mt Isa and Mildura. CCI_{av} for Mt Isa was 0.15 and 0.12 for Mildura. A visual inspection of Figure 2 was used to determine the wet and dry periods. As explained in Section 3.1, the wet and dry periods for Mt Isa were chosen to be from October to March and April to September, respectively. The wet and dry periods for Mildura were chosen to be April to September and October to March, respectively. Figure 3 shows the wet and dry period CCIs at Mt Isa and Mildura from 1976 to 2006. The variation from year to year is due to the variation in rainfall and pan evaporation. Also shown are the average values for wet and dry periods. It is clear in Figure 3 that, on average, the wet indices at both Mt Isa and Mildura are 0.23 and 0.25, respectively. At Mt Isa CCI_{dry} is 0.03 and the corresponding value at Mildura is 0.08. Therefore, the seasonal indices (CCI_s) at Mt Isa and Mildura are 0.20 and 0.17, respectively.

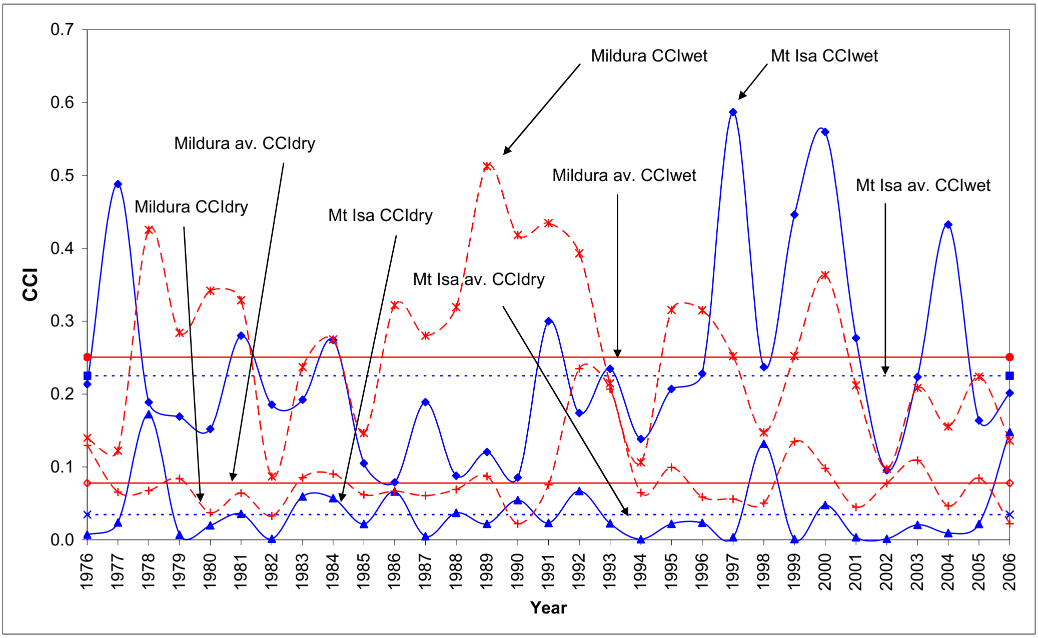

Figure 3: Wet and dry Climate Classification Indices for Mt Isa and Mildura

Potential distress to a pavement due to seasonal effects is caused by the combination of the geometry, climatic drivers (i.e. the amount of rainfall and potential evaporation) and the materials present. For the case of the same construction geometry and pavement and in situ materials, the potential for distress due to seasonal variation is higher in Mt Isa (CCI_s 0.20) than at Mildura (CCI_s 0.17).

5 POSSIBLE ADAPTATION OF THE CLIMATE CLASSIFICATION INDEX

The relationship between water content (e.g. degree of saturation or volumetric water content) and suction is commonly used to model the climatic influence on a soil profile. The relationship between the water retention curve and CCI_{av}, corresponding to the average suction (commonly referred to as the equilibrium suction), and CCI_s, corresponding to seasonal fluctuation in suction, is considered to be a future direction of research that could allow the pavement mix designer to use the expected maximum in-service moisture content to use with RLT testing. However, further work is needed to examine these ideas in detail.

6 SUMMARY

Unbound granular pavements with thin bituminous surfacings comprise approximately 85 percent of the sealed Australian road network, predominantly outside of highly populated cities. It is well understood that changes in moisture affects the performance of pavement material. A means of incorporating climatic effects into pavement design has not yet been resolved.

The TMI was devised to classify climates for agricultural purposes. It has been adopted by some to use as a guide for engineering design. For instance, AS2870 Residential Slabs and Footings makes use of the TMI for footing design. However, this qualitative index is not accurate enough to be used as an engineering quantitative indicator due to its inherent variability, incorporation of soil and plant influence in its calculation and lack of ability to capture seasonal effects. An index which accounts for seasonal effects and has a lower bound of zero would be more appropriate as a quantitative measure. The potential effect of seasonal climate and in situ moisture variations were discussed. An extension of the TMI, the CCI, addresses seasonal effects and provides an upper and lower bound on expected average climate conditions, based on a number of years of meteorological data, for a particular site. Future research will include a means of relating seasonal CCI values with water retention curves of pavement and subgrade materials. It is envisaged that this will lead to a climate classification system which provides the designer with a guide to the in-service pavement moisture range. This has the potential for significant savings in capital and operating costs.

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