ON THE USE OF THE THORNTHWAITE MOISTURE INDEX TO INFER DEPTHS OF SEASONAL MOISTURE CHANGE.

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ABSTRACT

The use of the climatic parameter, the Thornthwaite Moisture Index (TMI) as a predictor of the depth of seasonal moisture change (H_s) is now widely accepted. Many workers have published studies which include TMI-based maps of H_s for specific regions of Australia. The use of the TMI for this purpose involves many compromises and assumptions which can significantly affect the maps that are produced. These include differences in the methods used to estimate potential evapotranspiration, differences in the quality and quantity of data used as a basis for the map, judgment exercised in making interpolations of the point data and the limited basis for the correlation between TMI and H_s. This paper explores the significance of these factors in regard to their likely effects on H_s prediction maps, and it recommends that published studies include sufficient information so that the background and reliability of maps can be assessed and appreciated. This information includes data on the length of the climatic records used, details of the potential evapotranspiration model used and a map showing the position of the data points upon which interpolated maps are based. It concludes that where such information is not provided, inconsistencies between outcomes/maps produced by different authors may be difficult to resolve.

1 INTRODUCTION

The design of footings to resist the effects of reactive soils is now a well established feature of the Australian building practice (Walsh and Cameron, 1997). Generally, before a footing can be designed in any particular situation, some indication of the potential for reactive soils to cause adverse effects to the completed structure must be obtained. This can be expressed as a site classification, quantified in terms of a characteristic surface movement for the site (AS2870, 1996).

The characteristic surface movement is a predicted quantity, calculated on a basis of soil profile information, soil behaviour and climatic effects. In a simple consideration, the potential for ground movement can be estimated in terms of a small number of important factors. These are:

- The thickness of clay layers in the soil profile
- The position (proximity to the surface) of clay layers in the soil profile
- The reactivity of clay layers in the soil profile
- The effects of burial depth
- The depth to which seasonal effects will cause wetting and drying of the reactive clay layers (H_s)
- The magnitude (severity) of the wetting and drying of each reactive layer
- Whether or not there is lateral confinement (the extent to which cracks may exist in the soil).

Many of these factors relate to the current state (spatial characteristics) of the soil profile, and can be quantified from a detailed borehole log. Soil reactivity can be assessed by physical testing. The last three factors, however, have temporal aspects which mean that they can not be readily quantified from soil profile observations made at any particular instant in time. The range and depth of seasonally induced moisture change and the maximum depth of cracking can only be directly quantified in a reliable way by long term site monitoring of soil profile behaviour as the site experiences many cycles of seasonally induced wetting and drying. Such data is very rare and, where it does exist, it is very locally specific. In practice, the design phase of an engineering project is invariably short and there is insufficient time to allow a statistically significant set of observational data to be collected. Further, as the collection of data on the depth and distribution of soil moisture change is a relatively time consuming and laborious task, there is little incentive to gather it over wide areas, on a pre-emptive basis. Consequently, such data seldom exists where and when it is needed.

In order to employ sound engineering principles in the design of foundations in reactive soils, it is necessary to produce rationally-based estimates of these climatically-controlled parameters.

In the absence of good observational data, other means of estimation must be employed. As the climate is the main driving force for changes in soil moisture (in environments that are otherwise unaffected by specific human activity), then it follows that some measure of the climatic tendency toward aridity or humidity might reasonably be employed as an estimator of important climatically-driven design parameters. Over the past 20 years or so, the use of a climatic index, the Thornthwaite Moisture Index, or TMI, has become generally accepted as a reasonable basis upon which depths of seasonal moisture change (H_s) can be inferred. A number of studies, applying this approach to produce depth of seasonal drying maps for various parts of Australia, have been published in the Australian geotechnical literature. This purpose of this paper is to provide some discussion on the limitations of this approach and on the need to ensure that the approaches adopted are providing consistent advice.

2 HISTORY OF THE USE OF THE TMI IN FOUNDATION DESIGN

As early as 1961, Russam and Coleman attempted to employ the TMI as an indicator of long-term equilibrium suction values beneath covers such as pavements and foundation slabs. Their approach was based on the assumption that, in the absence of shallow water tables, the equilibrium suction beneath a ground cover would be dominated by the severity of the climate, through its effect on areas extraneous to the cover. This work was extended by Aitchison and Richards (1965) in an attempt to employ the TMI to the estimation of potential soil suctions beneath covered areas in different regions across Australia.

Wray (1978) employed the TMI as a predictor of the moisture changes that occur beneath the edges of ground covers. He assumed that climatic influences dominated in the process of wetting and drying beneath the edges of foundation slabs and so he was able to establish a correlation between the TMI and the distance to which moisture changes penetrated beneath the edges of a slab (or ‘edge distance’).

McKeen and Johnson (1990) used the TMI in the estimation of diffusion rates for moisture in unsaturated soils, which were in turn used in the estimation of the active zone depth. This elaborate, yet rational, procedure was developed on the consideration that the active zone depth is a function of the relative speed with which water can move in and out of the soil profile, and that this should be strongly influenced by both climate and soil dependent phenomena. The diffusion coefficient was estimated from an empirical equation, derived from measured data, in terms of the TMI, the inverse moisture characteristic of the soil and the suction compresion index. Once obtained, this diffusion coefficient was employed in a simple, steady state, unsaturated soil model to estimate the depth to which climatically-driven suction changes might penetrate.

Smith (1993) adopted a similar, but simplified, approach to the estimation of the active depth that assumed that the effects of climate dominated in the establishment of soil moisture distributions in the active zone and that the influence of specific soils could be disregarded without significant error. He proposed a direct empirical correlation between the TMI and the depth of climatically induced soil moisture change. He used the earlier TMI values that were determined by Aitchison and Richards (1965), to contour the inferred depth of soil suction change across Victoria. This application has now found its way into the Australian Standard for Residential Slabs and Footings (AS2870, 1996) and is used routinely with success.

More recently, Perera *et al*. (2004) presented a new model to predict suctions beneath pavements using the TMI in conjunction with the Plasticity Index and a grading curve parameter.

Despite the interest shown by a few expansive soils researchers and its usefulness as a parameter estimation tool to guide design, widespread use of the TMI by the geotechnical profession has been slow to occur. This was, in part, apparently due to a perception within the geotechnical profession that the TMI is a difficult quantity to calculate. When the original work of Thornthwaite (1948) and the calculation method are considered, the basis of this perception is evident. Evaluation of the TMI was made easier by a revision of its definition (discussed subsequently) and the publication of instructions and tables to facilitate its calculation (Thornthwaite and Mather 1955; 1957).

In 1998, Fityus, Walsh and Kleeman extended the work of Smith (1993) to cover the Hunter Valley region in Australia. This work involved the calculation of new TMI values for 38 sites across the region. During this work, the revised definition of the TMI was discovered (Thornthwaite and Mather 1955), that, after thorough testing and evaluation, was found to give reliable TMI values with greatly reduced computational effort. Since then, a number of subsequent studies have further extended the application of the TMI to cover other parts of Australia. These include Walsh, Fityus and Kleeman, (1998), Barnett and Kingsland, (1999), Fox, (2000, 2002), McManus *et al*. (2004) and Chan and Mostyn (2008). Further extensions are expected.

3 DEFINITION OF THE THORNTHWAITE MOISTURE INDEX

The Thornthwaite Moisture Index is described as an aridity index and effectively it is a ratio between the available rainfall and the potential for evapotranspirative loss at a particular location. Thornthwaite (1948), defined the Thornthwaite Moisture Index in terms of two simpler indices: I_a, which represents the potential for aridity, and I_h, which represents the potential for humidity. The aridity index is given by

$$I_a = 100\left(\frac{D}{PE}\right) \quad \textbf{(1)}$$

and the humidity index by

$$I_h = 100\left(\frac{R}{PE}\right) \quad \textbf{(2)}$$

where, *PE* is the net potential for evapotranspiration at the site, *D* is referred to as the moisture deficit and represents that quantity of water which cannot be evapotranspired from a 'dry' site because it is not available; *R* is the moisture surplus, or runoff, and represents that amount of rainfall which cannot infiltrate a 'wet' site. In the above context, a 'dry' site is one in which all potentially extractable soil water is exhausted and evapotranspiration cannot occur, whilst a 'wet' site is one which is effectively at field capacity and into which water can no longer infiltrate. It is useful to refer to the extractable ground moisture at a particular time as stored water and the conditions prevailing at 'dry' and 'wet' sites as minimum water storage and maximum water storage, respectively.

In the original work of Thornthwaite (1948), the aridity and humidity indices were combined to give the Thornthwaite Moisture Index as

$$TMI = I_h - 0.6 I_a \quad \textbf{(3)}$$

The factor of 0.6 is based on the idea that water can enter a soil profile more easily than it can be extracted. It assumes that rainfall will continue to augment a depleted storage, regardless of the level of storage, until a saturated condition is reached, whereas actual evapotranspiration will fall below potential evapotranspiration as storage diminishes and the vegetation struggles to satisfy its full requirements. In essence, the factor of 0.6 assumes that a surplus of 60mm in one season will balance a potential deficiency of 100mm in another. Equation **(3)** was employed by Aitchison and Richards (1965) to calculate the Thornthwaite Moisture Index values used by Smith (1993) to estimate soil movements.

The TMI of equations **(3)** and **(4)** is defined as a yearly index which is calculated, using a water balance approach, from monthly values of precipitation and potential evapotranspiration. A guide to the calculation of TMI values is given in McKeen and Johnson (1990). In summary, the calculation of TMI values (from equation (3)) proceeds as follows.

1) Monthly rainfall totals are extracted from climatic records.

2) Monthly potential evapotranspiration estimates are made using an appropriate method (this is discussed in more detail below).

3) Initial and maximum water storage (antecedent ground moisture) values are estimated for soil profiles in the region.

4) Surpluses (*R*) and Deficits (*D*) are calculated on a month by month basis using a simple water balance approach. The water balance proceeds according to simple rules, so that in any month,

- any rainfall on to ground which is at less than maximum storage will add to storage until maximum storage is reached and then yield a surplus runoff.
- any potential for evapotranspiration from ground which has some storage greater than the minimum storage will deplete storage until it is exhausted and then go unsatisfied- a deficit.
- rainfall following a period of deficit does not reduce the deficit it goes immediately into storage,
- potential evapotranspiration after a period of surplus cannot be satisfied from the surplus it is satisfied immediately from the storage.

5) The monthly evapotranspiration, surpluses and deficits are then totalled and substituted into equations **(1)** and **(2)** to allow the TMI to be calculated.

The TMI is an annual index, calculated from historical monthly data, and it is possible to calculate a unique TMI value for any given year at a particular site. Obviously, the TMI will vary from year to year, as some years are wetter or drier than others. Fityus *et al*. (1998) presented data for sites in the Hunter Valley where the annual TMI varied between -20 and +100 within records of 30 to 40 years. There is, thus, no single unique TMI value for a particular site. This was also noted by

McKeen and Johnson (1992). The usual approach to deal with this is to calculate annual TMI values for a statistically significant number of years, and then to average these values to produce characteristic values for a particular site.

A significant potential issue arises from the process of calculating TMI values using a water balance, due to the need to employ initial, minimum and maximum profile storage values at each site. This data seldom if ever exists for a site and values must be assumed. For long term analyses employing long data records, the predicted TMI values become relatively insensitive to the assumed storage values, but for records of shorter duration the predicted TMI values may be affected significantly.

4 ALTERNATIVE DEFINITION OF THE THORNTHWAITE MOISTURE INDEX

The Thornthwaite Index formula was revised by Thornthwaite and Mather in 1955 (Mather,1974), leading to the omission of the 0.6 factor, to give

$$TMI = I_h - I_a \qquad \textbf{(4)}$$

Using this simplified formula, and assuming that in the longterm there is no net change in soil storage, it can be shown (Mather 1974) that the Thornthwaite Moisture Index becomes

$$TMI = 100\left(\frac{P}{PE} - 1\right) \qquad \textbf{(5)}$$

where P is the annual precipitation for a site. It was shown in Fityus *et al*. (1998), that the correlation of the TMI from equation **(3)** to the depth of soil moisture change, can also be made with the TMI calculated using equation **(4),** although the nature of the correlation is changed. Fityus *et al.* (1998) also demonstrated that use of equation **(5)** leads to a major simplification, in that TMI values can be calculated without having to carry out a water balance calculation.

Using equation **(5),** a TMI value for any length of record can be obtained directly from annual precipitation and potential evapotranspiration values. If average annual precipitation and potential evapotranspiration values are used, then this allows a useful simplification in that it avoids the need to calculate surpluses and deficits and, hence to perform water balance calculations. More significantly, however, it avoids the inconsistencies introduced through assumptions of initial and limiting storage values. Chan and Mostyn (2008) claimed that approaches which seek to calculate TMI values based on long term monthly climatic averages do not produce the same results as approaches which seek to average the results of a month-by-month water balance conducted over the long term. This is, however, not strictly correct. As recognised by Fityus *et al*. (1998), this is only the case when equation **(3)** is used to calculate the TMI. However, if the revised definition of the TMI given by equation **(4)** is employed, the use of long term averages does produce consistent TMI values. This was demonstrated by Fityus *et al*. (1998).

Despite the simplifications afforded by equations **(4)** and **(5),** most other authors of TMI-based H_s maps have chosen to either adopt the original values of Aitchison and Richards (1965) or to calculate new values of TMI based on the original TMI definition in equation **(3)**. Hence the issues arising from assumptions of initial and limiting storage values remain.

5 ISSUES WITH USING THE TMI TO ESTIMATE H_S

From the foregoing discussion, and in the general absence of directly applicable measured data, the TMI would seem to offer a rationally-based, readily-applied means of estimating H_s values across Australia. It is now a widely accepted part of Australian site classification practice and its value is being continually recognized by the series of studies producing TMI-based H_s distribution maps for different regions throughout Australia.

However, all TMI-based interpretations require a number of assumptions and compromises which have the potential to affect the accuracy of TMI maps and the compatibility between the different interpretations. This does not imply that any of the published interpretations are incorrect or inadequate; it simply recognizes that not all interpretations have the same basis. The differences and their implications are discussed in this section.

Major differences in predicted TMIs may arise from differences in the calculation method used to estimate the potential evapotranspiration. The definition of the TMI does not specify how these estimates should be obtained. This is because potential evapotranspiration is a difficult to estimate quantity with a complex theoretical basis. Potential evapotranspiration is the total amount of evaporation and transpiration which would occur from a ground surface, if the storage in the ground was unlimited. Evapotranspiration is truly a function of many variables including air temperature, leaf temperature, ground temperature, humidity, wind speed, solar radiation, soil type and vegetation type. This is mostly of interest to agronomists seeking to optimise the irrigation of particular crop species and in these cases efforts are made to measure most of the above parameters.

There are many approaches to the estimation of potential evapotranspiration. The original work of Aitchison and Richards (1965) used expressions by Prescott (1949) and Tucker (1954), which are understood to be forms of the Penman potential evapotranspiration equation, which takes most of these variables into account (B.G. Richards personal. communication, 1998). Unfortunately, complete sets of measured data are only available in exceptional cases. For example, the data of Aitchison and Richards (1965). contain only 8 (or so) values across the wider Hunter region and these are not sufficiently well distributed to enable a reliable extrapolation across the entire Hunter Valley.

The studies of Fityus *et al*. (1998) and Chan and Mostyn (2008) employed a simpler and more approximate method of estimating the potential evapotranspiration. This is the Thornthwaite evapotranspiration equation (Chow, 1964). Calculation of the PE using the Thornthwaite formula is relatively straightforward, and is described in Chow (1964) and McKeen and Johnson (1990). The Thornthwaite equation uses only the mean monthly temperature and geographic latitude as input parameters, assuming a nominal vegetative cover. While the simpler approach of the Thornthwaite evapotranspiration equation may be less rigorous and is likely to lead to lower quality estimates of PE, the required data is much more readily available and so a greater number of points are possible. The mean monthly temperatures can be estimated as the average of the mean monthly maximum and minimum temperatures. This data is readily available for many locations across Australia.

Clearly, the Thornthwaite evapotransiration equation cannot hope to provide as good an estimate as more rigorous models such as the Penman equation. It is very likely that, given the number of factors that can potentially affect evapotranspiration, different estimation methods will result in different predicted values. This in turn, may significantly affect the predicted value of the TMI. Hence, in evaluating the reliability or consistency of any particular map of TMI (or H_s inferred from it), it is important to know which potential evaporation model was used in its development. If there are inconsistencies between maps derived by different authors in different areas, differences in the potential evapotranspiration models adopted would be one likely cause.

Differences in calculation methods are not the only source of inconsistency in maps of TMI or H_s. The maps themselves are interpolations of point data, and the nature and reliability of the interpolation is affected by the number of points available, their spatial distribution and the method of interpolation/contouring applied. There is a potential trade-off between the accuracy that is lost by adopting a simpler potential evapotranspiration equation and the accuracy that is gained by having a greater number of TMI values upon which to base the interpolation. As noted above, the comprehensive work of Aitchison and Richards (1965) only contained around 8 TMI values for the Hunter Valley. After assembling as much reliable data as could be found, Fityus *et al*. (1998) were able to produce 38 simpler estimates of the average TMI across the Hunter.

There is no good argument to suggest that fewer values based on a more rigorous analysis lead to a more reliable interpretation than a larger number of more approximate values. Nor is there any reason to suggest the contrary. At present, the state of research is insufficient to resolve this issue. Regardless of this it is generally necessary, and justified, to make the interpolation of whatever point data is available to include an amount of local knowledge and logical presumption. Fityus *et al.* (1998) presented contoured maps of both rainfall and potential evapotranspiration for the Hunter Valley and it is clear for each of these that there are strong correlations to the topography and elevation, although they are correlated in different ways. It is logical that rainfall, temperature, humidity etc should all affect the depth of drying at any particular location, and that these should vary with proximity to the coast and due to orographic effects. Hence, interpolations guided by position, elevation and topography are reasonably improved, and to some extent compensated in regard to the deficiencies arising from insufficient data. However, the subjectivity associated with such an interpretation could produce a result that is more speculation than fact.

With these ideas in mind, it is prudent to consider the context in which the many disparate studies and maps might be compiled and adopted in practice. It is considered that, at least, any published study should provide minimum information comprising:

- The number of TMI values upon which a map is based
- Data recording the length of the climatic records upon which each of the TMI values is based
- A version of the map showing the position of the individual data points
- A detailed description of the potential evapotranspiration model employed.

Only when this information is available, can potential users of such studies reasonably evaluate the quality of the information presented.

6 OTHER CONSIDERATIONS

Recent attention has been focused upon the significance of climate change for the application of the TMI as a predictor of foundation drying (McManus *et al*. 2004). There is mounting evidence that the climate is changing and well established statistical evidence for some areas that the early part of the 20th century was wetter than the latter part. Whilst such changes should be evaluated, such an evaluation raises issues that must be addressed. The first of these relates to the increased difficulty that arises from subdividing climatic history into short periods of presumed consistent behaviour. The foregoing discussion has already alluded to the difficulties in sourcing sufficiently long climatic/data records at a statistically significant number of locations. If the already sparse and limited data is further broken down into different time intervals, even fewer data points become available as a basis for interpolation. Certainly, this reduces the confidence in any spatial prediction, and makes the significance of climatic variations even harder to evaluate. If changes in the TMI are to be used to evaluate the effects of climate changes, then comparisons should be limited to actual TMI values calculated for the same locations, not interpolations. Further, it is essential that the same evapotranspiration model and TMI definition be adopted for the calculation of all TMI values compared at the same location. It is likely that the difference in TMI values arising from climate change will be smaller than the differences arising from the use of different PE prediction models. Hence comparisons with the now historical values of Aitchison and Richards (1965) will only be valid if TMI values based on more recent data are calculated using exactly the same approach. Precise details of the origin of data must be included in any published study on the effects of climate change, along with sufficient data to allow the statistical significance of the outcomes to be appreciated.

In regard to the absolute accuracy of depth of drying predictions, good predictions require not only reliable distributions of the TMI, but also a reliable correlation of the TMI to the depth of drying. This aspect of the approach is another significant source of uncertainty. This is because the original correlation between TMI and H_s proposed by Smith (1993) was based on only three points of data. Fityus *et al.* (1998) introduced three additional values, which were generally in agreement with the correlation trend suggested by the data of Smith (1993). However, the basis for the adopted correlation remains limited, and this should be appreciated by all users of TMI-based H_s relationships. More research to better define this correlation is needed.

Fityus *et al.* (1998) pointed out a shortcoming of the originally defined correlation of TMI to H_s, which suggested that H_s should change in a discontinuous stepwise manner at nominated threshold values of TMI, as indicated in Table 1.

Table 1: Original correlation between TMI and H_s. (Smith 1993).

TMI	Classification	Depth of Moisture Change H_s
>40	Wet Coastal/Alpine	1.5m
10 to 40	Wet Temperate	1.8m
-5 to 10	Temperate	2.3m
-25 to -5	Dry Temperate	3.0m
-40 to -25	Semi-arid	4.0m
<-40	Arid	>4.0m

Clearly it makes no sense that H_s should be discontinuous either side of a line on a map. To remedy this, Fityus *et al.* (1998) proposed that particular values of H_s should be tied to particular values of TMI, so that H_s is continuous across contours of TMI on a map, and so that values of H_s can be estimated by interpolation between H_s contours of known value. This relationship is given in Table 2. More recently, Chan and Mostyn (2008) recognized the same shortcoming, but instead, suggested that polynomial function be fitted through the original discontinuous TMI-H_s correlation.

Table 2. Revised correlation between TMI and H_s. (Fityus *et al.* 1998)

TMI	Classification	Depth of Moisture Change H_s
>40	Wet Coastal/Alpine	1.5m
10 to 40	Wet Temperate	1.5 - 1.8m
-5 to 10	Temperate	1.8 - 2.3m
-25 to -5	Dry Temperate	2.3 - 3.0m
-40 to -25	Semi-arid	3.0 - 4.0m
<-40	Arid	>4.0m

7 CONCLUSIONS

Whilst the proliferation of TMI based maps for different parts of Australia has the potential to provide much needed information upon which to base site classifications, it is likely that such maps will contain a number of assumptions which could lead to inconsistencies in the maps produced by different authors, for adjacent areas. In order for the reliability and comparability of different maps to be assessed and appreciated by users, it is necessary that the nature of the data and analyses be clearly documented with the publication of the maps. The discussion presented in this paper should be helpful to anyone seeking to combine or reconcile the maps from different authors for applicability over wider areas.

From the discussion provided, it is clear that there is still much research to be done to improve the applicability and reliability of the approach. This includes work to compare the different definitions of the TMI and methods for estimating the potential evapotranspiration, studies to confirm or improve the correlation between TMI and H_s, and research to determine whether climate change has had, or is having, a significant effect on H_s.

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