THE INFLUENCE OF CLIMATE AS EXPRESSED BY THE THORNTHWAITE INDEX ON THE DESIGN DEPTH OF MOISTURE CHANGE OF CLAY SOILS IN THE HUNTER VALLEY

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ABSTRACT: The paper presents details of the method used to determine the Thornthwaite Index which is a measure of aridity. This index is then used to provide improved estimates of the depth of design moisture change needed for estimating reactive clay movement in the Hunter Valley. Importantly, the method described is consistent with the methodology and philosophy of AS 2870.

INTRODUCTION

This paper is concerned with the determination of the design depth of suction change which characterises the depth \( H_s \) to which moisture changes can be expected in a reactive clay site. This parameter is needed for the design of residential slabs and footings in accordance with AS 2870, where at present only limited guidance is given on the values to be used for Newcastle and the Hunter Valley.

In the past, an aridity climate parameter, the Thornthwaite Moisture Index (TMI), has been used to classify regions in Victoria. The extension of the use of the Index to provide improved estimates of \( H_s \) for the Hunter Valley seems appropriate. It was found that the actual calculation method of the TMI has been poorly defined and a considerable amount of investigation was needed to get reliable results compatible with those used previously. Nonetheless this was achieved and improved guidance as to \( H_s \) values in the form of a contour map are provided for the Hunter Valley.

It should be noted at this point, that the actual depth to which moisture changes occur at a particular site, is affected by a large number of factors. These are not limited to climatic effects, but also include surface and subsurface ground conditions and specific site modifications made during site development. This is discussed further in the next section. It should also be noted that the effects of climate are complex, and that any efforts to quantify them are likely to be, to some extent, inadequate. This paper adopts an extremely simple approach to account for climatic effects which enables simple data from a wide spatial distribution of sites across the Valley to be employed, but at the likely expense of a reduction in accuracy. More rigorous account can be taken of climatic effects, but due to a lack of comprehensive data, this is only possible for small number of sites in the Valley, thus requiring gross and unjustifiable extrapolations. Thus, the results of this paper are considered to be the best estimates possible, subject to limited available data. It is believed that the sacrifices made in adopting a simple model to account for climatic effects are significantly outweighed by the gains which result from a greatly improved spatial coverage of the Valley.

THE EFFECT OF CLIMATE ON RESIDENTIAL FOOTING DESIGN

In order to fully understand the purpose of this paper, it is useful to set it in the context of the design of residential slabs and footings which is now routinely carried out using AS 2870 Residential Slabs and Footings — Construction. Underlying that Standard is the acceptance that the critical design criterion for most Australian conditions is the swelling and shrinkage movements of reactive clays.

Reactive clays swell on wetting and shrink on drying by significant amounts. These clays react
or respond to moisture loss or gain with movement, which depends primarily on:
- Depth of reactive clay close to the surface of the site;
- Influence of non-reactive upper layer of soil;
- Nature of the clay;
- Design range and depth of moisture change which is in turn dependent on climate.

In this report we are mainly concerned with the influence of climate on the depth of moisture change. It should be appreciated that this depth only defines the zone over which moisture changes may occur. Whether these changes actually eventuate or cease movement depends upon the existence of reactive clay within that depth. For many shallow soil profiles typical of the Hunter Valley the actual depth of clay soil may be far less than the value of $H_s$. As always, a proper site investigation is needed.

The identification of a reactive clay site and its accurate classification is not a simple exercise. There is no single test that will confidently assess a particular site. Even laboratory testing to determine the reactivity of the clay itself is not easy, although swell-shrink tests offer some guidance. The Standard offers three methods of assessing a site in order of preference as:
- Visual assessment;
- Profile identification;
- Movement estimates.

In Newcastle and the Hunter Valley, because of the lack of long term established data, the movement estimate method is commonly used. The design is directly based on an estimate termed $y_s$ of the surface movement of the site as the clay in the profile changes from the design dry to wet moisture conditions. This requires an identification of these design moisture conditions.

In order to relate these changes more directly to environment or climate, the moisture conditions are expressed in terms of suction. In their natural state, reactive clays are often partially saturated, i.e. when the void spaces are partly filled with water and partly with air. The water is actually in a state of very high tensile stress when the soil is dry. Soil suction is a measure of that tensile stress and is given the unit, $pF$. The drier the soil the more tightly the water is held and the higher the suction. On the other hand low suctions are associated with wetter soils. Happily, total suctions for practical purposes can be measured indirectly by use of psychrometers that measure the humidities that are in equilibrium with soil moisture. The number in the field usually ranges from 2 to 3 (wet) to 4 to 5 $pF$ (dry). For example, the suction in a soil, field saturated but drained, is about 2 $pF$, while wilting point is approximately 4.2 $pF$ (depending on the type of vegetation) (Walsh et al., 1997).

In practice the design suction change is usually greatest at the surface and decreases with depth. For simplicity a triangular suction profile or distribution has been adopted in AS 2870, characterised by a change in surface suction $\Delta u$, and a depth of design suction change $H_s$. The important variables are the values of suction change and the depth over which they occur, and this depth is a climate related phenomenon. From observations, depths could be expected to range from 1 metre for temperate climates to 4 m for arid climates.

In order to determine the value of $y_s$, several essential parameters are needed:
- The movement per unit change in suction or Instability Index $I_{ps}$ from tests;
- The surface change of suction in the area $\Delta u$;
- The depth of design suction change $H_s$; and
- The actual soil profile, i.e. the clay that is within that depth (most important).

The determination of $y_s$ involves the summation, for each layer, of the product of the change in suction, the depth of the layer and the instability index. In effect, this means it is the area of the suction change profile, over the affected clay layers that is important (refer to Walsh et al. (1997) for a more detailed discussion).

The value of $I_{ps}$ is determined from testing and is a number averaging around 4% for the Newcastle area.

The surface change of suction $\Delta u$ is generally found to be 1.2 $pF$ but for Newcastle a value based on limited data has been adopted of 1.5 $pF$. Although there may be a considerable case for changing the value of $\Delta u$ to the more accepted levels of 1.2 $pF$, that is outside the scope of this paper.

The only limited advice as to the design depth of suction change $H_s$ is given in AS 2870 where values in Table 2.4 give 1.5 m for Newcastle/
Gosford and 2.0 m for the Hunter Valley. No identification is made of the geographic limits of these values. It is interesting to note that the same table gives values of 3 m for drier areas such as Albury, and that parts of the Upper Hunter Valley may be considered to have a similar climate.

Thus designers are faced with considerable uncertainty as to the values of \( H_s \) to use, and the areas to which they apply. It is the purpose of this paper to provide more specific design guidance on this matter.

**METHODS FOR THE DETERMINATION OF \( H_s \)**

The depth of design suction change \( H_s \) can be only be directly determined by a large number of observations under a considerable range of conditions which must include design dry and wet conditions. The statistical definition of \( y_s \) gives some indication of the difficulty of the task, in that in AS 2870, \( y_s \) is defined as the value which has a less than 5% chance of being exceeded in the life of the structure, which may be taken as 50 years.

Moreover, the value of the soil parameter \( I_{ps} \) is recommended to be taken as the mean value for a particular horizon. This means the conservatism must be built in to the suction profile. In part, this is achieved by the use of the conservative triangular distribution, compared with the real behaviour where the reduction is often more rapid than linear with depth. Nonetheless, the value of \( H_s \) must represent a reasonably cautious value.

Statistically this could dictate observation on hundreds of sites over decades.

An alternative approach is to use accumulated experience in specific areas along with extrapolation or interpolation using a meaningful climate parameter.

In some cities particularly Adelaide, Melbourne and Albury, considerable experience has resulted from years of research, observation and field experiments. The values of \( H_s \) for these areas can be extrapolated if a suitable parameter is used. The critical issue is the aridity of the area and one parameter that deals specifically with this concept is the Thornthwaite Index. Moreover the use of this index has already been endorsed by AS 2870 in figure D2 which sets out the values of \( H_s \) for all of Victoria using previously published Thornthwaite Index values. Implicit in this table is a direct relationship between Thornthwaite Index and \( H_s \) ranging from 1.5m for wet values >40 to 4.0 m for dry values of -40 to -25.

Thus the index has the appeal of relevance to aridity and to legitimacy in AS 2870 terms. Unfortunately, it was found that the TMI is not easily defined or determined. In order to provide design information, these difficulties were resolved as outlined in this paper. Thus improved and authoritative recommendations for \( H_s \) for the Hunter Valley are provided, which are consistent with the methods and philosophy of AS 2870.

**THE THORNTHWAITE MOISTURE INDEX**

As outlined in the previous section, there is a correlation between the aridity of a region as expressed by the Thornthwaite Index and the depth to which soil drying occurs. Thornthwaite (1948), defined a moisture index (the Thornthwaite Moisture Index, or TMI) as a relative measure of climatic potential for a particular region. It was defined 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

\[
I_a = 100 \left( \frac{H_s}{H_s} \right) \tag{1}
\]

and the humidity index by

\[
I_h = 100 \left( \frac{H_s}{H_s} \right) \tag{2}
\]

In these equations, \( P_E \) 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 run off, 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 saturated, 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

\[ TMI = I_h - 0.6I_o \]  

(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 60 mm in one season will balance a potential deficiency of 100 mm in another. Equation (3) was employed by Aitchison and Richards (1964) to calculate the Thornthwaite Moisture Index values used by Smith (1993) to estimate soil movements. 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

\[ TMI = I_h - I_o \]  

(4)

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

\[ TMI = 100\left(\frac{P}{E_T} - 1\right) \]  

(5)

where \( P \) is the annual precipitation for a site. This is a useful simplification in that it avoids the need to calculate surpluses and deficits. It will be shown in the following sections, 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).

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 McKee and Johnson (1990). In summary, the calculation of TMI values (from equations (3) and (4)) 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 onto ground which is at less than maximum storage, will add to storage until maximum storage is reached, and then yield run off: a surplus;
   • any potential for evapotranspiration from ground which has some 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.

In this study, an average TMI is used as an indicator for each particular site. This is discussed in a later section. There are two possible methods of calculating average TMI values. The first is to employ long term monthly average values of precipitation and potential evapotranspiration, and carry out the water balance over one year. This yields an average TMI value. The second is to employ full historical monthly precipitation and potential evapotranspiration values, and conduct a continuous water balance analysis over the full historical record. This yields a set of yearly TMI values which can then be averaged. In this study, most TMI values have been calculated using the first of these approaches. The relative merits of each approach are also discussed in a following section.

There are many approaches to the estimation of potential evapotranspiration. Potential evapo-
transpiration is the total amount of evaporation and transpiration which would occur from a ground surface, if the storage in the ground was unlimited. It is truly a function of many variables including air temperature, leaf temperature, ground temperature, humidity, wind speed, solar radiation, soil type and vegetation type. In most cases it is of interest to agronomists seeking to optimise the irrigation of particular crop species, and efforts are made to measure most of the above parameters. The original work of Aitchison and Richards (1965) used expressions by Prescott and Tucker, which are understood to be forms of the Penman potential evapotranspiration equation, which takes most of these variables into account (B. G. Richards, pers. comm.). Unfortunately, complete sets of this type of climatic data are only available in exceptional cases. Consequently, the data of Aitchison and Richards contain only 8 (or so) values across the wider Hunter region, and it was considered that these are not sufficiently well distributed to enable a reliable extrapolation across the entire Hunter Valley.

In an effort to obtain a better representation of potential evapotranspiration trends across the Hunter Valley, an alternative calculation method was employed. The method chosen is the Thornthwaite evapotranspiration equation (Chow, 1964). The Thornthwaite equation uses only the mean monthly temperature and geographic latitude as input parameters, assuming a nominal vegetative cover. This simpler approach may be less rigorous, but the required data is much more readily available. This enabled 38 estimates of monthly evapotranspiration to be made across the Hunter. While the simpler approach of the Thornthwaite evapotranspiration equation is likely to lead to lower quality estimates of PE, it is important to remember that it is the relative variation in PE across the Hunter Valley which is of primary interest, and not the precise values. The final TMI results can be calibrated by comparison with field observation to account for any discrepancies.

Calculation of the PE using the Thornthwaite formula is relatively straightforward, and is described in Chow (1964) and McKeen et al. (1990). The mean monthly temperatures, \( t_i \) (in °C), can be estimated as the average of the mean monthly maximum and minimum temperatures. This data is readily available for many centres across Australia. The mean monthly temperatures are then used to calculate monthly heat index values, \( h_i \), by

\[
h_i = (0.2 t_i)^{1.54}
\]

and a yearly index \( H_p \), by

\[
H_p = \sum_{i=1}^{12} h_i
\]

where \( i \) designates a particular month, and \( y \) a particular year. The monthly (30 day) PE values (\( PE_i \)) are then given by

\[
PE_i = 1.6 \left( \frac{10a}{H_p} \right)^2
\]

where \( a \) is given by

\[
a = 6.75 \times 10^{-7} H_2^3 - 7.71 \times 10^{-5} H_2^2 + 0.1792 H_2 + 0.49239
\]

These monthly PE values are then adjusted for latitude (accounting for the average daily length of daylight in each month) as well as the number of days in the month (see McKeen & Johnson, 1990).

CLIMATE IN THE HUNTER VALLEY

As explained in the previous section, the Thornthwaite Moisture Index is based on historical rainfall data, and estimates of potential evapotranspiration. In order to better understand the role of each of these components in the results of this study, their respective variations have been contoured across the Hunter Valley.

The climatic data used in this study was assembled from a variety of sources, including the Bureau of Meteorology (BOM 1972, 1977), Bridgeman (1984; and pers. comm.), and the Hunter Valley Research Foundation (McMahon, 1964). Data comprising monthly rainfall totals and monthly average maximum and minimum temperatures were obtained for 38 sites across the region (listed next page).

The length of data records varied from 6 to 91 years, with most records exceeding 20 years. Although there were many sites with some
recorded data, those listed above were the only sites where both temperature and rainfall records could be obtained.

The average annual rainfall is plotted in Figure 1. Comparison of this data with other plots of Hunter Valley rainfall (McMahon, 1964; Bridgman, 1984) indicates that the data set used exhibits most of the major trends in rainfall distribution across the Valley. The differences that exist result mainly because the data from which the contours of Figure 1 were drawn, consist only of the annual rainfall totals at each of the above sites. Other plots are based upon all available rainfall records, which include many more sites. All plotted at different variances, the distribution is plotted from 798 mm/annum of varying lengths in contouring.

The estimation is plotted at different variances, that the variation considerably falls, with the than about 10 potential for each the Valley, at moderates with the theoretical quantity of potential for the Hunter Valley, it is not error associated with this.
The differences in rainfall ends in the data from one more sites. Also, each of the rainfall plots were plotted at different times and so employ data sets of varying length, and use different methods of contouring.

The estimated annual potential evapotranspiration is plotted in Figure 2. The values range from 798 mm/year to 897 mm/year, with a coefficient of variation of 0.041. Figure 2 suggests that the variations in PE across the Valley are considerably less than the variations in rainfall, with the range of the variation being less than about 100 mm. The trends suggest that the potential for evaporation is greatest in the base of the Valley, adjacent to the Hunter River, and moderates with increasing elevation.

As the potential evapotranspiration is a theoretical quantity, and as a comprehensive set of potential evapotranspiration estimates for the Hunter Valley has not been found in the literature, it is not possible to accurately assess the error associated with using the simplified Thornthwaite PE approach. Some guidance is available through comparison of the results with data from seven pan evaporation recording sites across the Valley. These range from 1026 mm/year to 1727 mm/year, with a coefficient of variation of 0.162. While these results suggest that pan evaporations are more spatially variable, it has to be remembered that pan evaporations and potential evapotranspiration are fundamentally different quantities, and that there is no necessity that they should exhibit the same degree of spatial variation.

Perhaps a better indication is given by the estimates of McMahon (1964) who quoted eight potential evapotranspiration values across the Valley, based on pan evaporation data. The values range from 702 mm/year to 860 mm/year, with a coefficient of variation of 0.065. These estimates suggest that the values used in this study may be slightly high, but that the degree of spatial variation they exhibit is reasonable.

Figure 2. Potential evapotranspiration in the Hunter Valley (Thornthwaite method).
Before considering the regional trends in the TMI across the Valley, and the implications for the depth of moisture change, consideration must first be given both to the method and the equation used to calculate the TMI.

As the TMI is an annual index, calculated from historical monthly data, it is possible to calculate a unique TMI value for any given year. Obviously, it will vary from year to year, as some years are wetter or drier than others. If unique values are calculated for many years, then the average climatic conditions can be estimated from the average of all of the yearly values. For the purposes of this study, this approach will be referred to as the year-by-year analysis. The disadvantage of calculating the index with a year-by-year analysis is that it requires that a statistically significant number of both temperature and rainfall records to exist for the same years. This does not always occur.

An alternative to the year-by-year analysis is to assemble monthly average temperatures and monthly average rainfall using all existing data, and calculate the TMI for a single, average year. Here, this is referred to as the average year analysis. The disadvantage of the average year analysis is that the results of a water balance analysis performed over only one year of data, are sensitive to the values of initial and maximum water storage that are used (So and Smax, respectively). For this study, historical soil storage data at all of the sites considered did not exist, and so values were estimated.

Another alternative is to use the simplified form of the average year analysis, which avoids the use of the water balance altogether. This can be done if the TMI is calculated using equation (5) (Mather, 1954), and will be referred to here as the simplified analysis. However, equation (5), which is analogous to equation (4), differs from the approach of previous workers, who employed equation (3), the original expression of Thornthwaite (1946).

To facilitate a comparison between the various analysis approaches, long data sets were extracted for five sites, with corresponding temperature and rainfall values. The data was analysed using the year-by-year analysis and the average analysis (using both equation (3) and (4)), and also by the simplified analysis (using equation (5)). The results are presented in Tables 1 and 2. Table 1 compares the three methods using an assumed maximum storage of 150 mm, and different assumptions for the initial

<table>
<thead>
<tr>
<th>Equation (3) 60% Aridity Index</th>
<th>Nobby's</th>
<th>Scone</th>
<th>Williamtown</th>
<th>Jerry's Plains</th>
<th>Maryville</th>
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</thead>
<tbody>
<tr>
<td>$S_0 = 0$, Average year analysis</td>
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<td>-12.6</td>
<td>20.2</td>
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<td>$S_0 = 120$ mm, Average year analysis</td>
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<td>-4.7</td>
<td>33.4</td>
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<td>$S_0 = 150$ mm, Average year analysis</td>
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<td>36.9</td>
<td>-6.2</td>
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<tr>
<td>Year by Year Analysis</td>
<td>40.3</td>
<td>-5.5</td>
<td>40.7</td>
<td>-11.0</td>
<td>38.1</td>
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<th>Equation (4) 100% Aridity Index</th>
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<td>$S_0 = 0$, Average year analysis</td>
<td>17.7</td>
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<td>-27.4</td>
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<td>$S_0 = 80$ mm, Average year analysis</td>
<td>27.0</td>
<td>-16.4</td>
<td>28.7</td>
<td>-18.3</td>
<td>24.8</td>
</tr>
<tr>
<td>$S_0 = 120$ mm, Average year analysis</td>
<td>31.7</td>
<td>-11.8</td>
<td>33.4</td>
<td>-13.8</td>
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<tr>
<td>$S_0 = 150$ mm, Average year analysis</td>
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<tr>
<td>Year by Year Analysis</td>
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<td>-20.5</td>
<td>31.7</td>
<td>-27.0</td>
<td>29.0</td>
</tr>
</tbody>
</table>

| Simplified Analysis | 32.3     | -20.9 | 31.4        | -27.4          | 28.8      |

**THORNTHWAITE MOISTURE INDEX CALCULATIONS**

Water storage, assuming different values.

The results from an average year are referred to as results up to 17 TMI assumptions. It represents an average of results obtained using the TMI approach, avoiding several methods using a single assumption.

The results are year-by-year analysis, assuming different values.

Comparison approach using results (see Table 5) does not have a consistent set of results from a single approach or a simplified annual rainfall analysis.

Comparison values in Tables 1 and 2, reveal that Thornthwaite conditions. T1 values are significant, and the different TMI are changeable.
Table 2. Effect of assumed maximum water storage on TMI, using the year-by-year analysis.

<table>
<thead>
<tr>
<th></th>
<th>Nobby’s</th>
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<th>Jerry’s Plains</th>
<th>Maryville</th>
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<td>$S_{max} = 100\text{mm, Year-by-year}$</td>
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<td>-5.1</td>
<td>41.2</td>
<td>-10.5</td>
<td>38.6</td>
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<td>$S_{max} = 150\text{mm, Year-by-year}$</td>
<td>40.3</td>
<td>-5.5</td>
<td>40.7</td>
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<td>38.1</td>
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<tr>
<td>$S_{max} = 200\text{mm, Year-by-year}$</td>
<td>39.9</td>
<td>-5.9</td>
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<td>Equation (4) 100% Aridity Index</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{max} = 100\text{mm, Year-by-year}$</td>
<td>32.5</td>
<td>-20.5</td>
<td>31.7</td>
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<tr>
<td>$S_{max} = 150\text{mm, Year-by-year}$</td>
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<td>-20.5</td>
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<tr>
<td>Simplified Analysis</td>
<td>32.3</td>
<td>-20.9</td>
<td>31.4</td>
<td>-27.4</td>
<td>29.8</td>
</tr>
</tbody>
</table>

water storage, So. Table 2 assesses the effect of assuming different maximum water storage values.

The results of Table 1 indicate that the average year analysis approach is very sensitive to the assumed initial storage, with variations of up to 17 TMI units possible using different assumptions. It is considered that these variations represent an unacceptable degree of uncertainty in results obtained using the average year analysis approach, and that this approach should be avoided.

The results of Table 2 show that the results of year-by-year analyses are not significantly affected by assumptions of maximum storage, and so, the approach could be adopted to give consistent estimates of the TMI.

Comparisons between the simplified analysis approach using equation (5) and the year by year results (see Tables 1 and 2) suggest that equation (5) does circumvent the uncertainties associated with a single year analysis, and confirms that consistent results can be obtained using either a year-by-year analysis of a long data record, or a simplified analysis based on average annual rainfall and potential evapotranspiration values.

Comparison of the two sets of year-by-year values in Table 1, calculated using equations (3) and (4), reveals differences of between 7 and 15 TMI units, with equation (4) predicting more arid conditions. This difference is again considered significant, and it clearly indicates that the two different TMI equations cannot be used interchangeably. Whilst equation (3) has been used by previous workers (Aitchison et al., 1965 and McKeen et al., 1991) there is no reason to suggest that it gives a better climatic index than equation (4); indeed, that equation (4) results from a review of equation (3) would suggest that equation (4) is the better form of the index. For the purposes of this study, the revised TMI expression of equations (4) and (5) is to be adopted as the required climatic indicator. In adopting a different form of the TMI, it is necessary to review the correlation between the TMI and the depth of moisture change. This is done in the next section.

The principal advantage in adopting the revised form of the TMI is that it allows the simplified average year analysis to be adopted, thus removing the limitation that only sites with corresponding temperature and rainfall records can be analysed.

DEPTH OF MOISTURE CHANGE IN THE HUNTER VALLEY

Previous workers (Smith, 1993) correlated the TMI with the depth of moisture change on the basis of field observation data from 3 different regions in Australia. These were:

<table>
<thead>
<tr>
<th>Location</th>
<th>TMI(%)</th>
<th>Depth of Moisture Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brisbane</td>
<td>34</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Melbourne</td>
<td>-1</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Adelaide</td>
<td>-26</td>
<td>4 m</td>
</tr>
</tbody>
</table>

From this information, they proposed the following classifications:
To accurately correlate TMI to the depth of moisture change in the Hunter Valley, some field observation data are necessary. Such data are scarce, and mostly anecdotal. AS2870 lists a moisture change depth of 1.5 m for the Newcastle region, although in the authors’ experience, this value seems low, and is likely to be realistic only in the wettest areas of the region, such as Port Stephens. In the authors’ experience, a value of around 1.7 m is considered appropriate for much of the Newcastle region.

Data for the upper Hunter Valley is rarer yet. From recent discussions with a senior soil scientist with the Scone office of the Soil Conservation Service (Ken Reynolds, personal comm.), it is believed that the greatest depths of drying observed in the upper Hunter region are around 3 m. Using these observations as a basis, the following information can be used to define a correlation between TMI and depth of drying. Note that the TMI values listed are those calculated in this study using the simplified analysis (equation (5)).

<table>
<thead>
<tr>
<th>Location</th>
<th>TMI(%)</th>
<th>Depth of Moisture Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nelson Bay</td>
<td>53.7</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Maryville</td>
<td>24.4</td>
<td>1.7 m</td>
</tr>
<tr>
<td>Scone</td>
<td>-25.4 to -24.3</td>
<td>3 m</td>
</tr>
</tbody>
</table>

This information indicates that the previously employed correlation between TMI and depth of moisture change may be generally appropriate for the TMI values determined across the Hunter region. However, the correlation of Smith (1993) does have a shortcoming in the way in which it is defined, in that a map of TMI contours will imply that the depth of moisture change should increase abruptly across a contour line. For example, a site with a TMI of 24 has a depth of moisture change of 3 m, while an adjacent site with a TMI of 26 has a depth of moisture change of 4 m. It is proposed that this shortcoming be overcome in the present work by defining a specific depth of moisture change to correspond to a particular TMI, and allowing values in between to be interpolated. The proposed correlation is thus:

<table>
<thead>
<tr>
<th>Location</th>
<th>TMI(%)</th>
<th>Depth of Moisture Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Coastal/Alpine</td>
<td>&gt;40</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Wet Temperate</td>
<td>10 to 40</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Temperate</td>
<td>-5 to 10</td>
<td>2.3 m</td>
</tr>
<tr>
<td>Dry Temperate</td>
<td>-25 to -5</td>
<td>3.0 m</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>-40 to -25</td>
<td>4.0 m</td>
</tr>
<tr>
<td>Arid</td>
<td>&lt; -40</td>
<td>&gt; 4.0 m</td>
</tr>
</tbody>
</table>

It seems inadvisable to attempt to extrapolate for TMI values greater than 40 or less than -25. Of the 38 sites considered, only five TMI values fell below -25, with only one below -30 (Note that for this site the data set was small).

The TMI values for the 38 sites across the Hunter are contoured in Figure 3. It is apparent from a comparison of Figures 1 and 3, that the distributions of rainfall and TMI across the Valley have similar characteristics. This suggests that the influence of rainfall is much more significant than the influence of potential evapotranspiration in the calculation of TMI values in the Hunter Valley, and results from the comparatively small spatial variations in the predicted potential evapotranspiration.

As in Figure 1, Figure 3 is likely to be affected by the sparsity of data points, and the limitations of linear interpolation. These result in important trends being omitted in areas of sparse data. To reduce these effects, the contours of Figure 3 have been reinterpreted to produce Figure 4, using topographic information as well as the authors’ experience and knowledge of the Hunter Region. Figure 4 thus represents the recommended estimates of depths of moisture variation for the Hunter Valley. This information should be interpreted and used in light of the information presented in the introduction and the following sections of this paper.

IMPLICATIONS FOR DESIGN

The above data have some significant implications for design of footing systems in the Hunter Valley and somewhat fewer implications in the Newcastle area. The assessment of the impact depends upon the interpretation of the information on cracking depth.

Currently, t value between climate with t with more sev are given. For specific value while no spec Hunter Valley the depth of c been observed now be expect comm.) sugg figure. This cc Adelaide wher 0.75 Hz. It wo the depth of c Newcastle zov used for the an tour. For Newcastle somewhat, fro
Currently, the cracking depth is taken to be a value between 0.33 $H_S$ and $H_S$ depending on climate with the greater depths being associated with more severe climates. Some specific values are given. For example, Newcastle is assigned a specific value of 0.5 $H_S$ based on limited data while no specific value is associated with the Hunter Valley. Anecdotal evidence exists that the depth of cracking in the Hunter Valley has been observed as 2 m in an area where $H_S$ would now be expected to be 3 m (Ken Reynolds pers. comm.) suggesting 0.66 $H_S$ as a reasonable figure. This correlates well with Melbourne and Adelaide where the depth of cracking is taken as 0.75 $H_S$. It would not seem unreasonable to take the depth of cracking as 0.66 $H_S$ except for the Newcastle zone itself where 0.5 $H_S$ should be used for the area bounded by the 1.8 metre contour.

For Newcastle the value of $H_S$ will now vary somewhat, from the coast where a value of 1.5 is specified, to 1.8 m at Thornton and West Wallsend. Of course where $H_S$ is 1.5 or nearly so, there will be no change.

However at the latter locations which are in the “Newcastle” area, which would previously have been associated with a $H_S$ value of 1.5 m, the increase would have some effect. The implication for $y_S$ values is not directly obvious, but if the site consisted of clay to at least 1.8 m, then in this area, the value of $y_S$ would be increased by 20%, causing quite a few Class M sites to be reclassified into more expensive Class H sites. If the clay depth is not at least 1.8 m then the effect would be less; for example for a depth of 1.0 m the increase in suction changes is nearly offset by the greater cracking depth.

For the zone now classified as 1.8 m to 2.3 m, e.g. Maitland, and regarded reasonably as being in the Hunter Valley for which $H_S$ was 2.0 m, the new assessment would result in little change. Indeed there could be a minor reduction in $y_S$. 

**Figure 3.** Thornthwaite Moisture Index in the Hunter Valley.
estimates resulting from the use of 0.66 $H_d$ for the cracking depth.

For the dry, temperate parts of the Hunter Valley the changes will be quite significant. Previously it would have been possible to use a value of $H_d$ of 2.0 in this area, whereas now the value is 2.3 to 3.0 m. Thus the value of $y_s$ determined would be increased substantially. However part of this is offset by the effect of cracking depth. For the increase from 2.0 m to 2.3 m, $y_s$ would only increase by 4% instead of 15%. For the increase from 2.0 m to 3.0 m, in an extreme case of a very deep clay, $y_s$ would increase by 35% rather than 50%. For shallower clays the increase would be more moderate.

In the upper Hunter not only do the $y_s$ values increase by up to 35% but the standard foundation designs increase from M to M-D or H to H-D, because $H_d$ is 3.0m or more. These so called deep seated movements can be associated with larger edge distances and potentially more severe design loadings for the same movement and as a consequence the designs are heavier. For example, for articulated masonry veneer, the fabric is increased from F82 to F92, while the beam depth is increased by 100 mm for the same Class H site classification. This could add a further $1000 to the cost of construction.

Is it justified? This is a difficult question that only can be resolved as experience accumulates. However, it does seem that if the clays are deep, the climate in large areas of the Hunter Valley is severe enough to produce large damaging movements. Many sites will only have shallow clay depths and the increase in $H_d$ will be offset by the increase in cracking depth, resulting in little or no change. Once again the need to check the actual depth and location of clay in the profile is emphasised.

**RESEARCH IMPLICATIONS**

The variation of TMI from year to year is, as expected, not insignificant. In theory, the
Figure 5. Variations in TMI at particular sites when considered on a year-by-year basis.
Table 3. Variations in Yearly Thornthwaite Index.

<table>
<thead>
<tr>
<th></th>
<th>Nobby’s</th>
<th>Scone</th>
<th>Williamtown</th>
<th>Jerry’s Plains</th>
<th>Maryville</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of Record</td>
<td>1958</td>
<td>1965</td>
<td>1957</td>
<td>1957</td>
<td>1969</td>
</tr>
<tr>
<td>No of Years</td>
<td>36</td>
<td>22</td>
<td>43</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>Average TMI</td>
<td>+32.5</td>
<td>-2.4</td>
<td>+31.7</td>
<td>-21.0</td>
<td>+29.0</td>
</tr>
<tr>
<td>Std Dev</td>
<td>+37.8</td>
<td>+21.0</td>
<td>+33.3</td>
<td>+18.0</td>
<td>+28.4</td>
</tr>
<tr>
<td>Max</td>
<td>+102.0</td>
<td>+20.4</td>
<td>+110.8</td>
<td>+10.61</td>
<td>+96.3</td>
</tr>
<tr>
<td>Min</td>
<td>+33.1</td>
<td>-62.9</td>
<td>-40.5</td>
<td>-65.4</td>
<td>-25.9</td>
</tr>
</tbody>
</table>

60% Aridity Index

| S<sub>max</sub> = 10, Average year | 40.8 | -5.1 | 41.2 | -10.5 | 38.6 |
| S<sub>max</sub> = 15, Average year | 40.3 | -5.5 | 40.7 | -11.0 | 38.1 |
| S<sub>max</sub> = 20, Average year | 39.9 | -5.9 | 40.3 | -11.4 | 37.6 |

100% Aridity Index

| S<sub>max</sub> = 10, Average year | 32.5 | -20.5 | 31.7 | -27.0 | 29.0 |
| S<sub>max</sub> = 15, Average year | 32.5 | -20.5 | 31.7 | -27.0 | 29.0 |
| S<sub>max</sub> = 20, Average year | 32.5 | -20.5 | 31.7 | -27.0 | 29.0 |

Simplified method, average year | 32.3 | -20.9 | 31.4 | -27.4 | 29.8 |

However, it has to be conceded that the correlation used in this report is between the average TMI value and the characteristic suction design profile, and that this method of correlation is based on reliable calibrations in other regions. Thus technically, it is not necessary to account for the actual temporal variability in the TMI values at any site, and indeed, it would be misleading to do so. This is not to say that an improved calibration, more closely based on characteristic values for both the established areas and new areas such as the Hunter, would not be a good approach if the data were available.

Ongoing work at Newcastle University will allow depths of cracking, depths of drying, actual suction change and actual surface movements to be better understood. This will allow the predicted depths here to be checked directly in specific locations greatly enhancing the accuracy of prediction methods. Such data will also facilitate comparison between predicted and calculated surface movements so that the full set of recommended AS 2870 parameters can be checked for consistency.

CONCLUSION

The possibility of using the Thornthwaite Index as a measure of aridity or climate, and in turn, using this as a indicator of the design depth of suction change, as was done in Victoria, has been investigated. In practice it was found the index has several definitions and interpretations. However, since the application of this index is based on an empirical correlation, it is mainly important that the approach is consistent in a particular case, and this has been achieved. A principal outcome of this study has thus been a greater understanding of the intricacies of the Thornthwaite Index and the paper sets out an algorithm by which the index can be generated from readily available climate data. It is hoped that this work can be used as a template for similar studies in other areas.

A second important result, and the fulfilment of the principal aim of this study, has been the development of a contour plan defining the design depth of suction for the Hunter Valley for use in site classification in accordance with AS 2870. This plan represents a significant improvement on the previously existing information.
The opportunity was also taken in the study to investigate some of the alternative methods of calculating the index taking into account year by year variability. With further research this latter method may lead to new knowledge about the implication of climate variability of the appropriate design parameters.

**REFERENCES**


SALMON C. 1996. Climatic effects on clay in Australia. Final-year project, University of Newcastle (unpubl.).

