

Climatic Factors for AS2870 for the Sydney Region

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Summary AS2870-1996 “Residential Slabs and Footings – Construction” correlates depths of design suction change (H_s) to regional climatic zones as delineated by the Thornthwaite Moisture Index (TMI). TMI is a measure of aridity, quantifying the cyclical wetting and drying of soils. TMI is a function of rainfall, potential evapotranspiration and soil water-holding capacity, and provides an indication of moisture balance.

In this paper TMI is calculated for various Bureau of Meteorology sites across Sydney, based on meteorological records. The results are plotted and contoured to give a map of TMI isopleths for the metropolitan region. This paper complements previous work in other States, and will provide improved estimates of H_s needed for the calculation of characteristic surface movement (y_s) in metropolitan Sydney, for classification of residential sites under AS2870-1996.

NOTATIONS

a	Factor for calculating adjusted potential evapotranspiration
d_i	Deficit for month i
e_i	Evapotranspiration for month i
e_i'	Adjusted potential evapotranspiration for month i
h	Depth from ground surface
h_i	Heat index for month i
Δm_i	Moisture balance for month i
n	Number of years of record
p_i	Precipitation for month i
r_i	Runoff for month i
t_i	Temperature for month i
$t_{max\ i}$	Mean monthly maximum temperature for month i
$t_{min\ i}$	Mean monthly minimum temperature for month i
Δu	Suction change
y_s	Characteristic surface movement
D_i	Day length correction factor for month i
D_y	Deficit for year y
E_y	Evapotranspiration for year y
H_s	Depth of design suction change
H_y	Heat index for year y
I_{ps}	Shrinkage index
I_{pt}	Instability index
N_i	Number of days in month i
R_y	Runoff for year y
S_i	Storage for month i
S_{i-1}	Storage for month $(i-1)$
S_{max}	Maximum soil storage
TMI	Thornthwaite Moisture Index

1. INTRODUCTION

Residential foundation design is primarily governed by soil movement, with the majority of structural damage caused by excessive soil movement. This paper presents the use of TMI as a tool to better predict soil

movement behaviour for the design of residential slabs and footings.

AS2870-1996 “Residential Slabs and Footings – Construction”, defines the *characteristic surface movement*, y_s , as “the movement of the surface of a reactive site caused by moisture changes from characteristic dry to characteristic wet condition in the absence of a building and without consideration of load effects”. There are many variables used for the estimation of y_s , one of which is the *depth of design suction change*, H_s , the depth at which the soil moisture condition is constant with climate variations. H_s can be estimated by considering climatic factors, one of which is TMI . This paper presents the estimation of H_s , from TMI values for the Sydney region.

2. TRADITIONAL METHODS OF DETERMINING H_s

2.1 Development of AS2870

The Australian Standard AS2870 “Residential Slabs and Footings” came into existence to standardise various state regulations or practices on the design of residential footings. The Standard offers guidance, and sometimes definitive rules, for the design of house foundations in different soil materials, particularly in reactive clays. It is the authors’ opinion that this Standard represents close to world’s best practice in the design of footings for small structures on reactive soils.

In New South Wales, there had been many structural failures in buildings constructed on reactive soils, particularly in the late 1970s during a state-wide drought (NSW Builders Licensing Board, 10). As a result, the Builders Licensing Board commissioned the study of swelling soils in Sydney (Coffey and Partners Pty Ltd, 4), and subsequently published “Classification of NSW Soils for Housing” (BLB, 10) as a guide for engineers, designers and builders.

At a similar time, the Standards Association of Australia Committee published the draft Australian Standard for Residential Slab and Footings (DR85108, 15) for public comment. This draft Standard defined several key risk management objectives as follows:

- Design foundations allowing for a 5% chance of exceedence in the life of the building. It identifies the life of a building as 50 years.
- Calculate characteristic surface movements expected for 95% of all houses, thus allowing 1 in 20 houses to perform less satisfactorily.

AS2870 was first published in 1986, with revisions in 1988, 1990 and 1996.

2.2 Characteristic Surface Movement

The characteristic surface movement at any given site, in accordance with AS2870-1996, is given by:

$$y_s = \frac{1}{100} \int_0^{H_s} I_{pt} \Delta u \cdot dh \quad (1)$$

The following sections contain some reflection on the development of the variables governing y_s .

Suction Change Δu

AS2870 defines soil suction as “a measure of the internal stress caused by moisture in unsaturated clays. It is useful in the analysis of reactive clays because it is more strongly a function of the climate and vegetation than it is of soil type.”

Soil suction changes as a result of climatic variations. At a depth below the surface this seasonal suction change reduces to an equilibrium level (see Figure 1). The depth at which this equilibrium sensibly occurs is termed the *depth of design suction change*, H_s .

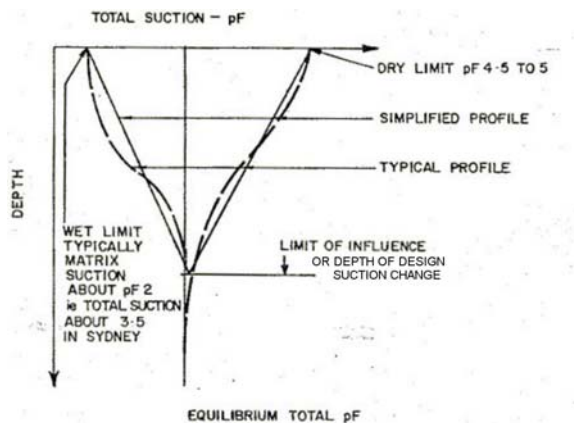


Figure 1. Soil Suction Profile with Depth (Coffey, 4)

Since its inception, the Standard has given a maximum surface suction change value for Sydney of 1.5 pF. There is little published support for this value but it is important to understand that the Standard is a “package”

where H_s , Δu and α combine together to provide an estimate of y_s .

Instability Index I_{pt}

The instability index, I_{pt} , is the change in height of clay per unit suction change, taking into account the applied stress, lateral restraint and suction range during the test. It is given by:

$$I_{pt} = \alpha \cdot I_{ps} \quad (2)$$

where

$$\alpha = \begin{cases} 1.0 & \text{cracked zone (unrestrained), or} \\ 2.0 - h/5 & \text{uncracked zone (restrained)} \end{cases}$$

Depth of Cracked Zone

The cracked zone relates to the zone in which predominantly vertical shrinkage cracks exist seasonally. Within this zone, swelling is unrestrained, that is, it occurs both horizontally and vertically. The depth of cracked zone for a particular location is dependent on its seasonal climatic conditions. Little research relating to this variable has taken place to date, and the Standard gives values ranging from $0.25H_s$ to $1.0H_s$.

Shrinkage Index I_{ps}

The shrinkage index I_{ps} is defined as “the percentage change in height of clay per unit suction change without any load or lateral restraint” (Walsh and Cameron, 23). The laboratory test methods used to determine the index include the shrink-swell test, loaded shrinkage test, and the core shrinkage test.

Where more than one test is performed on the same soil horizon, the Standard prescribes the use of average values of test data in the calculation of I_{pt} .

2.3 Depth of Design Suction Change H_s

H_s , as defined in the preceding section, is dependent on climatic variation. H_s is prescribed in the Standard for major cities. Different values for H_s have been suggested for Sydney in the Standard revisions, ranging from 1 m to 3 m. H_s is very difficult to quantify in the field, and empirical methods for its determination include the use of *TMI*.

AS2870-1996 uses *TMI* to calculate H_s in Victoria, based on the work by Aitchison and Richards (1). The Standard also states that *TMI* may be used to estimate H_s for other locations.

3. THE DEVELOPMENT OF THE THORNTHWAITE MOISTURE INDEX

TMI was originally developed as an agricultural index to aid farmers in their prediction of crop needs. It was adopted in the engineering field for the estimation of subgrade moisture, in terms of soil suction. Its relationship with soil suction distribution gives *TMI* relevance in the calculation for characteristic surface movement (y_s) in reactive clays.

3.1 TMI as an Agricultural Index

Dr. C.W. Thornthwaite, an American climatologist, developed a method of assigning soil moisture balance by way of assessing the climatic conditions. The relationship between water surplus (r) and water deficiency (d) and how it relates to water need (e) in soil constitutes an index of humidity or aridity. Dr Thornthwaite (22) proposed the following relationship:

$$TMI = \frac{100r - 60d}{e} \quad (3)$$

3.2 TMI as an Engineering Parameter

Work in the 1960s by engineers investigating pavement subgrade moisture conditions has led to the use of *TMI* in engineering, and in particular, in the soil physics field. Research by Russam and Coleman (13), and Aitchison and Richards (1) in Australia demonstrate a relationship between *TMI* and the soil suction in pavement subgrade. Richards, Peter and Emerson (12) drafted a map of *TMI* for Australia, as reproduced in Figure 2.



Figure 2 – TMI for Australia (Richards et.al., 12)

More recently, civil engineers have used the relationship between *TMI* and soil suction profile to assess the behaviour of footings founded on expansive soils (Mitchell, 9 and McKeen et.al., 8).

3.3 TMI for Calculating Soil Movement

Australian engineers such as Smith (14), Fityus et.al. (5), Barnett and Kingsland (2), and Fox (6,7) have broadened the work by Aitchison and Richards in the 1960s to use a climatic index, *TMI*, to assess H_s .

AS2870-1996 “Residential Slabs and Footings – Construction” correlates H_s to regional climatic zones as delineated by *TMI*, as reproduced in Figure 3 for Melbourne. However, to date, the relationship between H_s and *TMI* for the Sydney region has not been assessed in detail.

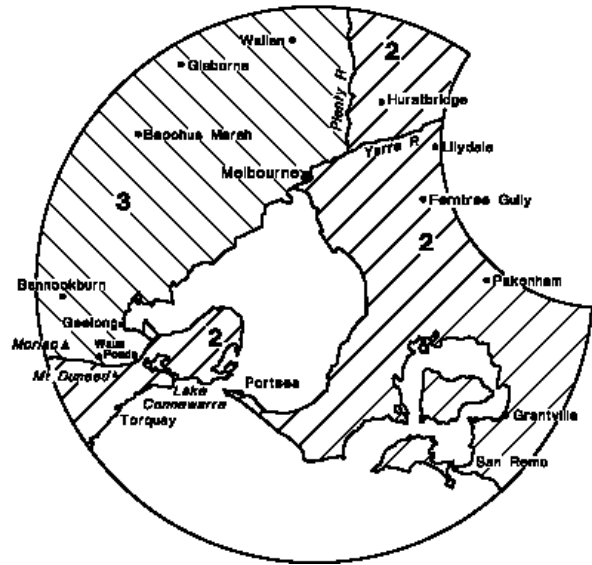


Figure 3 - Melbourne Climatic Zones as delineated by *TMI* (AS2870-1996)

4. METHODOLOGY FOR CALCULATING TMI

TMI is an annual water balance based on rainfall and estimated evapotranspiration, calculated on a monthly basis. High positive values indicate a wetter climate, and high negative values occur in arid regions.

The following, reproduced from Thornthwaite (22), are major components in the computation of *TMI*:

1. Determination of the adjusted potential evapotranspiration.
2. Computation of a moisture balance to determine allocations of water to storage, deficit, or runoff.
3. Computation of annual summations that are used to determine the index value.
4. Determination of statistical parameters, ie, mean, standard deviation, and range of annual *TMI*.

4.1 Determination of the Adjusted Potential Evapotranspiration e'_i

To determine the adjusted potential evapotranspiration e'_i , the following inputs are required:

- Mean monthly temperature (t_i), calculated as the average of $t_{max\ i}$ and $t_{min\ i}$ in monthly values for the period of record.
- Day length correction factor (D_i), given in Table 1, for twelve months.
- Number of days for each month (N_i).

1. Heat Index (h_i)

$$h_i = (0.2 \cdot t_i)^{1.514} \quad (4)$$

2. Annual Heat Index (H_y)

$$H_y = \sum_{i=1}^{12} h_i \quad (5)$$

3. Unadjusted Potential Evapotranspiration (cm/mth)

$$e_i = 1.6 \cdot \left(\frac{10 \cdot t_i}{H_y} \right)^a \quad (6)$$

$$\text{where } a = 6.75 \times 10^{-7} \cdot H_y^3 - 7.71 \times 10^{-5} \cdot H_y^2 + 0.017921 \cdot H_y + 0.49239 \quad (7)$$

4. Adjusted Potential Evapotranspiration (cm/mth)

$$e'_i = e_i \cdot \frac{D_i N_i}{30} \quad (8)$$

4.2 Determination of the Moisture Balance

The inputs for determining the moisture balance include:

- Monthly Precipitation (p_i), in cm, for the period of record.
- Adjusted Potential Evapotranspiration (e'_i), calculated as above, for the period of record.

The decision tree in Figure 4 illustrates the method to determine the storage (S_i), deficit (d_i) and runoff (r_i) for each month.

4.3 Calculation of TMI

The annual TMI_y for year y is calculated as follows:

$$TMI_y = \frac{100 \cdot R_y - 60 \cdot D_y}{E_y} \quad (9)$$

where for year y ,

$$R_y = \sum_{i=1}^{12} r_i \quad (10)$$

$$D_y = \sum_{i=1}^{12} d_i \quad (11)$$

$$E_y = \sum_{i=1}^{12} e'_i \quad (12)$$

TMI for a particular location is:

$$TMI = \frac{1}{n} \sum_{y=1}^{y=n} TMI_y \quad (13)$$

where n is the years of record. The equation calculates TMI in cm.

The statistical parameters, such as mean, standard deviation, and range of annual TMI , are important indicators of the climatic conditions of a particular location. Where less than 20 years of record is available for a particular location, these parameters will assist in determining the relevance of TMI data.

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
20	1.14	1.00	1.05	0.97	0.96	0.91	0.95	0.99	1.00	1.08	1.09	1.15
25	1.17	1.01	1.05	0.96	0.94	0.88	0.93	0.98	1.00	1.10	1.11	1.18
30	1.20	1.03	1.06	0.95	0.92	0.85	0.90	0.96	1.00	1.12	1.14	1.21
35	1.23	1.04	1.06	0.94	0.89	0.82	0.87	0.94	1.00	1.15	1.17	1.25
40	1.27	1.06	1.07	0.93	0.86	0.78	0.84	0.92	1.00	1.15	1.20	1.29

Table 1. Day Length Correction Factor, Southern Hemisphere (McKeen et.al., 8)

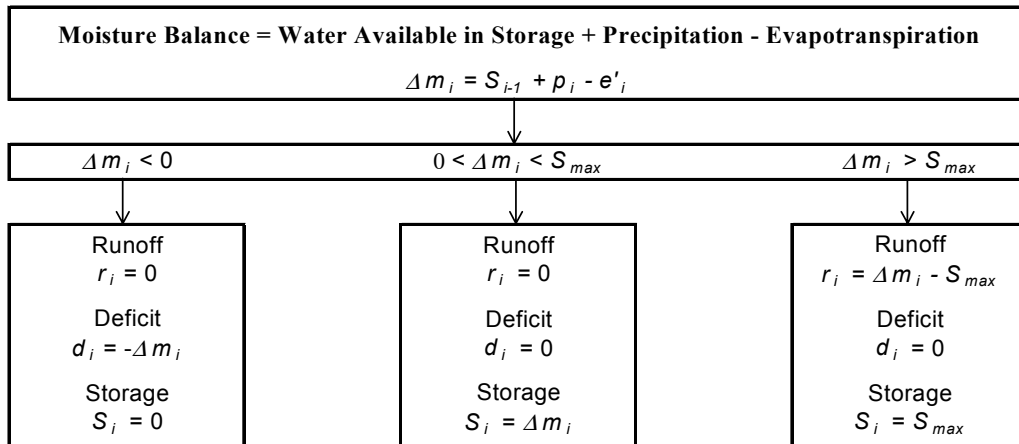


Figure 4. Decision Tree for Moisture Balance Computation

This methodology makes the following assumptions:

1. January is selected as the start month.
2. The soil storage capacity is the holding capacity of the soil, which is dependent on soil type. For the purpose of *TMI* calculation the value of 100mm is used. This value appears to be adopted in all such calculations in Australia.
3. The initial soil storage is taken to be zero (0 cm) if the location of interest is dry in January, 10 cm if it is wet, and 5 cm if it is temperate. The choice of initial storage value has little effect for long record.
4. *TMI* for a location is defined to be the average of the annual *TMI* calculated for that location (Richards, 11). For locations with meteorological records of less than 20 years, *TMI* may not give a true reflection of the location's climate.

4.4 Other Proposed Methods

Alternative methods have been proposed in recent years for *TMI* calculation, which generally use long-term monthly average climatic values instead of monthly values for the period of record, that is, *TMI* of an average year, not the average *TMI*. It is important that actual data is used, as *TMI* is essentially an index of extreme climatic conditions, aligned with the risk-based principles of the Standard. These alternative methods inevitably produce misleading *TMI* values. This will be discussed further in an extended paper.

5. TMI MAP OF SYDNEY

A *TMI* map, presented in Figure 5, has been plotted from *TMI* results from 40 stations in the Sydney region where both temperature and rainfall data are available for at least 5 years. *TMI* values from 23 other locations, where only rainfall data are available, are also used. At these locations temperature data from similarly placed locations are used in the computation. Where the record length is between 5 years and 20 years, the statistical spread is considered for contouring purposes. For reasons of space the results are not tabulated here, but will be reproduced in a separate paper.

The map indicates that the coastal fringes in the Sydney Basin are of a wet coastal climate, becoming more arid with distance from the coast. The Blue Mountain ranges, however, has a cooler alpine climate.

The relationship between climatic zones and the value of H_s is reproduced in Table 2.

Climatic Zone & Description	<i>TMI</i> range	H_s
1 Alpine / Wet coastal	> +40	1.5m
2 Wet temperate	+10 to +40	1.8m
3 Temperate	-5 to +10	2.3m
4 Dry temperate	-25 to -5	3.0m
5 Semi-arid	< -25	4.0m

Table 2. Climatic Zones (AS2870-1996)

From Figure 5, it is demonstrated that the climate of Sydney varies from the wet coastal to the drier temperate, with H_s varying from 1.5m to 2.3m.

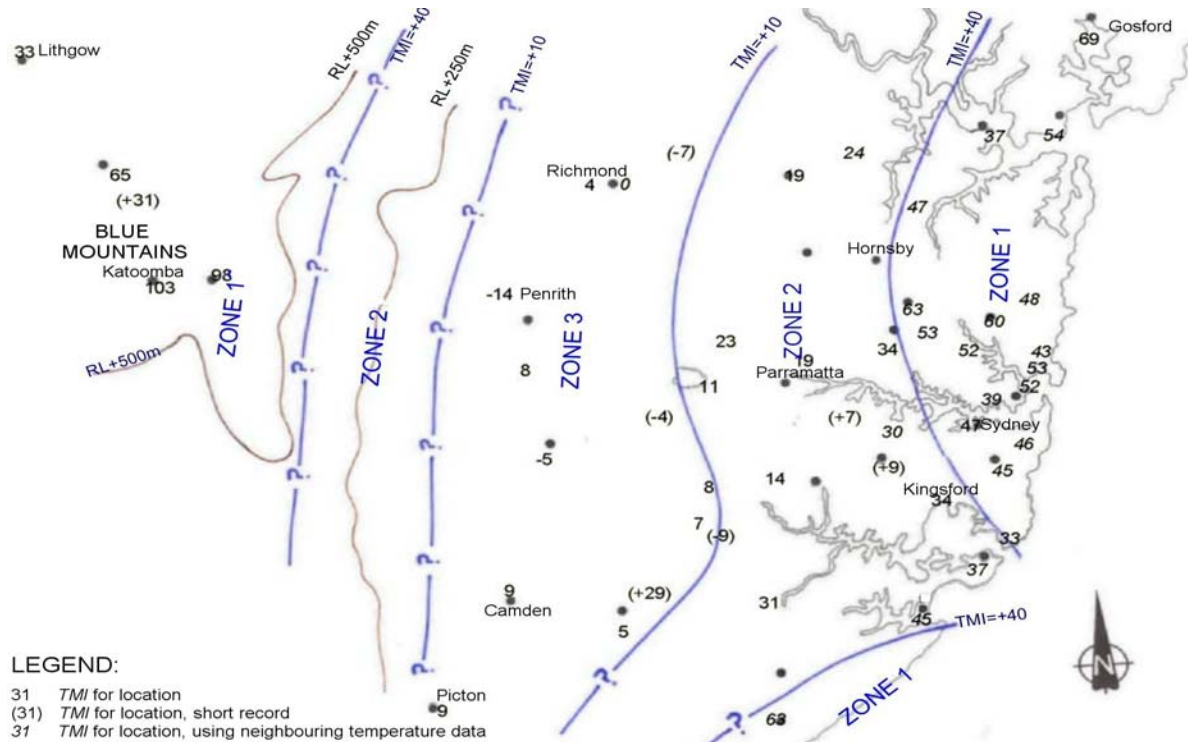


Figure 5. *TMI* Map of Sydney

5.1 Coffey and Partners Study, 1985

It is the authors' experience that the current Standard works wells in Sydney when correctly applied in investigation, design and construction. It is therefore important not to adopt a new H_s value without consideration to the rest of the "package".

Coffey (4) performed a detailed study of reactive soils in Plumpton Park, Quakers Hill and Minchinbury, which includes calibration of reactivity with measured soil movement. The calibration was based on a H_s of 1.5m, which is a widely accepted value for Sydney, and a higher Δu value of 1.5 pF was given as a result of the calibration. This calibration was adopted in AS2870.

According to Figure 5, these three sites have a H_s value of 1.8m. As the Standard is a "package" where H_s , Δu and α combine together to estimate y_s , a different, lower value of Δu may be considered for Sydney as the result of a re-calibration. This will avoid yielding higher y_s for the area and producing conservative footing designs.

6. CONCLUSION

The use of *TMI* as a tool for estimating climate-derived H_s values is investigated in this paper. *TMI* values calculated for 63 locations in Sydney are provided, and a contour map produced for use in site classification in Sydney, in accordance with AS2870-1996.

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