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Beyond Agriculture:
Exploring the application of the
Thornthwaite Moisture Index
to infrastructure and possibilities
for climate change adaptation

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Abstract

In 1948 the Thornthwaite Moisture Index was introduced as a new global climate classification system. Since its advent, the use of the index has moved beyond climate classification for agricultural systems. This paper reviews the application of the Thornthwaite Moisture Index in the design and maintenance of infrastructure. Furthermore, this paper investigates the possible application of the Thornthwaite Moisture Index in climate change adaptation for infrastructure. An adapted road degradation model for Australia is presented illustrating the effects on pavement degradation under changing climate conditions using the Thornthwaite Moisture Index.

1. Introduction

In 1948, C.W. Thornthwaite introduced a new climate classification system to the scientific community - the Thornthwaite Moisture Index (TMI) (Thornthwaite, 1948). Prior to the introduction of this index, the climate had been defined in terms of general descriptive observations and had no empirical data as a base. Thornthwaite however introduced a moisture index to describe climate types which could be calculated using actual data from the region under investigation. The Thornthwaite Moisture Index describes the aridity or humidity of the soil and climate of a region, and is calculated from the collective effects of precipitation, evapotranspiration, soil water storage, moisture deficit and run off (Austroads, 2010).

The TMI was revolutionary for its time, with applications far beyond the realm of climate classification (Keim, 2010). It was quickly accepted by the scientific community and has been employed across a diverse range of scientific research areas in a vast number of applications. Initially, the TMI was used to map the climate zones of the USA and the world (Thornthwaite, 1931, 1933). This was further extended in applications in the agricultural field as an indicator of suitable climates for various crops types. Following this concept the TMI has been used to map the extent and characteristics of ecological communities. The index has also seen application in terms of describing the hydrological functioning and water balance of catchments due to its numerical base. The TMI also laid the fundamental foundation for another popular climate index, Palmer's drought index which is still widely used today as a meteorological descriptor of drought conditions (Keim, 2010, Palmer, 1965). The TMI is still used in contemporary studies in a variety of applications. However, this paper focuses on the application of the TMI in the design and maintenance of infrastructure.

The Intergovernmental Panel on Climate Change (IPCC) has stated that some degree of climate change is now unavoidable regardless of future reductions in emissions (IPCC 2007). As a result, it is necessary to consider how to adapt our current systems to the changing climate. How to adapt infrastructure to climate change is an ongoing challenge for the engineering community. The Australian Federal Government has identified infrastructure as one of the national priorities for adaptation action (Commonwealth of Australia, 2010). Recognition of the risks associated with climate change is required for better planning of new infrastructure and moderating potential damage to existing infrastructure (Taylor and Philp, 2010). The long design life of infrastructure means that the infrastructure designed today will need to be able to resist climatic pressures in 20 or

100 years from now (Meyer, 2008, TRB, 2008, Commonwealth of Australia, 2010). However, adaptation of infrastructure is likely to only occur as structures reach the end of their design life, as such maintenance and operations impacts on existing infrastructure also need to be considered.

Climate change is a global problem with global impacts. However, climate change impacts will vary spatially and according to characteristics of transport infrastructure installed in each locality. As such a single design safety factor to take climate change into account may not be suitable for application by infrastructure designers and managers. However, an index that takes into account the climate of the locality could be combined into infrastructure design and maintenance calculations to allow the changing climate to be included. It is proposed that the Thornthwaite Moisture Index has the ability to fulfil this role. This paper investigates where the Thornthwaite Moisture Index is currently used with respect to infrastructure and how this could be applied to adapting infrastructure to climate change. A mathematical model of road pavement degradation, suitable for scenario planning purposes and including climate impacts represented by the TMI, is described in the paper. A small application of the model is also provided, which reveals some interesting effects for climate change scenarios.

Section 6 of the paper provides a consolidated list of the nomenclature used in the model, and should be used as the basic reference for the factors and variables employed in the equations of the mathematical model.

2. The Thornthwaite Moisture Index

As stated previously, the Thornthwaite Moisture Index (TMI) can be generally described as reflecting the aridity or humidity of the soil and climate, calculated from the collective effects of precipitation, evapotranspiration, soil water storage, moisture deficit and run off (Austroads, 2010)

Thornthwaite hypothesised that climate could not be described by a single meteorological observation, such as precipitation. He came to this conclusion after observing conflicting examples of ecological communities with the same annual precipitation, which in northern Europe resulted in fertile forests but only supported sparse desert vegetation in Africa (Keim, 2010, Thornthwaite, 1948). This led him to consider the notion of effective precipitation and further the notion of potential evapotranspiration. After significant research he discovered that the actual evaporation and transpiration is not what must be compared with precipitation in order to obtain a moisture index, but, rather, the potential evapotranspiration (Thornthwaite, 1948).

Thornthwaite identified potential evapotranspiration as a climatic element of great importance. However, it represented a theoretical construct that would be possible under ideal soil moisture and vegetation conditions, and he found it very difficult to determine. He then went on to describe indices for humidity (Ih) and aridity (Ia) to define water surplus or deficit in terms of the water need or potential evapotranspiration.

Thornthwaite theorised since water surplus and water deficiency occur at different seasons in most places, both must enter into a moisture index. The final moisture index determined by Thornthwaite is described below in equations 1 and 2.

The Thornthwaite Moisture Index M is:

$$M = Ih - 0.6Ia \tag{1}$$

Or

$$M = \frac{100\alpha - 60\beta}{\gamma} \quad (2)$$

where I_h and I_a are indices of humidity and aridity respectively, α is water surplus, β is water deficiency, and γ is water need or potential evapotranspiration.

Thornthwaite used the index to describe various climate types according to the moisture index limits. Thornthwaite's climate classifications are listed in Table 1.

Table 1. Thornthwaite's climate type classifications (Thornthwaite, 1948)

Thornthwaite Climatic Type		Thornthwaite Moisture Index
A	Perhumid	>100
B4	Humid	80 to 100
B3	Humid	60 to 80
B2	Humid	40 to 60
B1	Humid	20 to 40
C2	Moist subhumid	0 to 20
C1	Dry subhumid	-20 to 0
D	Semi arid	-40 to -20
E	Arid	-60 to -40

An example of the application of the TMI to define climate regions is shown in Figure 1. A joint study conducted in 2004 mapped the TMI for Australia based on climate conditions in 2000 as shown in Figure 1 (Austroads, 2004). This figure illustrates the diversity of the Australian climate, with each of Thornthwaite's climate classes represented.

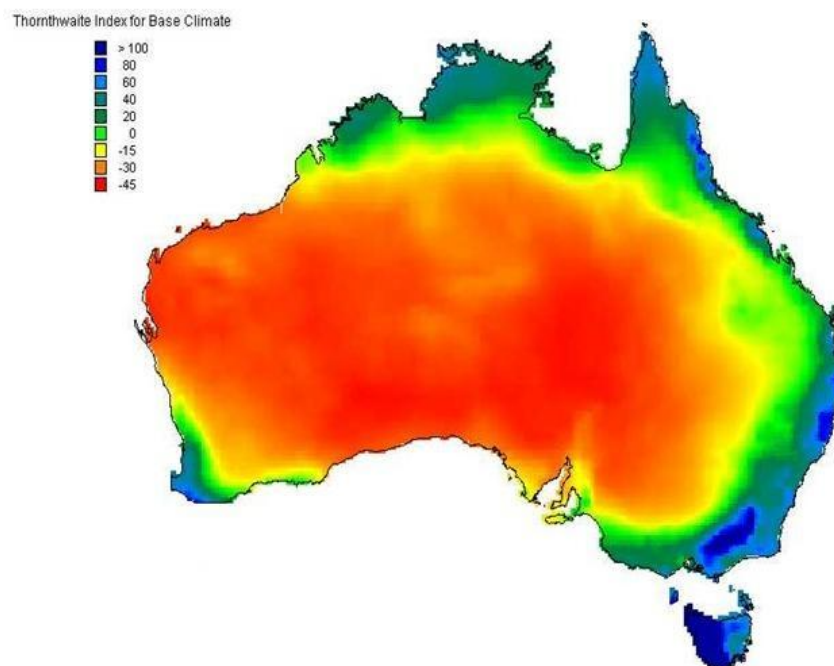


Figure 1 Thornthwaite Moisture Index for Australia in 2000 (Austroads, 2004)

A further simplification of the index was given by Gentilli (1972), which relates the Thornthwaite index to 'effective annual rainfall' (P_e).

$$M(t) \approx 1.25P_e(t) - 60 \quad (3)$$

$$P_e(t) = \sum_{m=1}^{12} P_{em}(t) \quad (4)$$

$$P_{em}(t) = 1.65 \frac{P_{Tm}(t)}{(T_m(t) + 12.2)^{1.1111}} \quad (5)$$

where $P_{Tm}(t)$ is monthly total rainfall, $P_{em}(t)$ is the effective monthly rainfall, and $T_m(t)$ is mean monthly temperature, in the months m of year t .

This approximation for the TMI is of practical use because it relates the index directly to specific, observable (or predictable) climate variables.

3. Application of the TMI to Infrastructure Design & Maintenance

Climate can influence infrastructure in many ways. It is an important consideration in the design process to determine the suitability of the infrastructure to the environment in which is placed, and impacts the ongoing condition and design life of the infrastructure. For example road pavements are directly affected by soil moisture conditions which can weaken them, and make them more susceptible to damage by heavy vehicles, shortening their effective life (Austroads, 2004).

As the Thornthwaite Moisture Index is representative of climatic conditions based on actual data it is possible that it has application to the design and maintenance of infrastructure. The following paragraphs discuss examples where the TMI has been applied in this context with respect to the design or maintenance of infrastructure.

3.1 Pavement and Foundation Design

Generally, site characterisation is an important part of any footing, pavement or foundation design as reactive soils can cause adverse effects on the completed structure. The characteristics of subgrade soils underneath pavements such as the extent of soil shrinkage and swelling are critical factors in the serviceability of road pavements. Potential ground movements are estimated in terms of a number of factors, including climatic influence. Climate is the driving natural influence in soil moisture changes and as such design procedures generally include climatically driven design parameters. The use of TMI has become generally accepted as a reasonable basis upon which depths of seasonal moisture change can be inferred and is widely accepted in foundation and pavement design (Fityus and Buzzi, 2008).

In 2008 Fityus and Buzzi undertook a review of literature where TMI was used to infer seasonal moisture change for pavement and foundation design. They found as early as 1961 (Russam and Coleman, 1961) TMI was used as an indicator of the long term equilibrium suction values between covers such as pavements and foundation slabs. Aitchison and Richards (1965) extended this work to

investigate the use of TMI in the estimation of potential soil suctions beneath surface covers. The review also discussed the works of Wray (1978) who used TMI to estimate the distance moisture penetrated under the edges of slabs, McKeen and Johnson (1990) who used TMI to estimate diffusion rates for moisture in unsaturated soils and therefore estimate the active zone depth, and Perera et al. (2004) where the TMI was used as a part of a model to predict suctions beneath pavements. Further from their findings this review has found additional applications in this field.

Carpenter et al. (1974) conducted a study on the environmental influences important in studying non load associated pavement cracking in west Texas, USA. The project was part of a comprehensive program to verify the environmental cracking mechanisms and recommend maintenance and construction measures to alleviate the problem. Several mechanisms independent of traffic loads were found to generate pavement cracking including reflection cracking, thermal cracking, selective adsorption of asphalt by porous aggregates, and moisture changes. The TMI was found to be related to the equilibrium suction level which develops in the subgrade along the centre line of a pavement (Carpenter et al., 1974), further supporting Aitchison and Richards (1965) who found the state of moisture beneath a pavement to be very influential on pavement behaviour.

Jayatilaka and Lytton (1997) incorporate the TMI in their methodology for predicting the ability to predict the roughness in a given wheel path in pavements with or without vertical moisture barriers. The study developed alternative design procedures for determining the soil deformation likely to occur and for predicting the impact of the soil deformations on pavement performance by including provisions for environmental input parameters such as the TMI. This study has been applied with success to road pavement design and pavement in the USA. This work was further refined and developed into the windows based GUI model WINPRESS (Lytton et al., 2005).

Main Roads Queensland also use the TMI to determine specific design requirements with respect to the road network (MRQ, 2009). The TMI value for the site in which the road pavement is constructed is used to determine the height of the pavement from the natural ground level. The minimum embankment height in regions with $TMI \geq 0$ and rainfall > 500 mm/year must be above the influence of any water, but not less than 200 mm from the natural ground to the underside of the lowest pavement layer. Conversely, in regions with the $TMI < 0$, the minimum embankment height should be 100 mm, unless some unusual condition such as a perched water table or irrigation, for example, is likely to exist.

One of the main factors that influence the design and type of foundation systems is the potential heave value of the ground on which they are placed. The potential heave at a particular site can be predicted by several methods including the Post Tensioning Institute method which incorporates the TMI (Bryant and Haque, 2011). The Post Tensioning Institute commenced research efforts in 1976 to develop guidelines for the design of slab-on-grade foundation systems on expansive soils (Bryant and Haque, 2011). This method was added to the US Uniform Building Code Standards and Standard Building Code for the design of ribbed foundation in expansive soils in 1988 and sees continued use in the industry (Bryant and Haque, 2011).

3.3 Pavement Degradation and Maintenance

Pavement degradation modelling is used to inform maintenance schedules for transport infrastructure. These models in part use climatically driven parameters to model the impact on pavements in different environments. The following paragraphs provide examples of pavement degradation models that have used the Thornthwaite Moisture Index in their estimations.

3.3.1 Pavement Life Cycle Cost Model

ARRB Transport Research group have developed a network pavement life cycle costing (PLCC) model to estimate pavement related maintenance and rehabilitation costs for road networks in Australia (Linard et al., 1996). Life cycle costs are estimated by the model on the basis of predicted pavement performance. Several separate components are modelled to generate the final life cycle cost. The TMI is an important parameter representing the climatic condition of the roads analysed in these component models, and impacts the total life cycle cost of the pavements.

Pavement performance is estimated using a simplified approach employing a model calibrated for Australia which predicts pavement deterioration in terms of the change in road roughness for a set of defined road categories (Martin and Roberts, 1998). PLCC also takes into account the improvement of roads following rehabilitation. The improvement in both roughness and strength of the road following rehabilitation is predicted using another component model (Martin, 1994, Martin and Ramsay, 1996) based on Australian pavement performance data (Austroads, 2004).

Road user costs generated by travel time and vehicle operating costs are considered alongside the road agency costs related to maintenance and rehabilitation of the road network. These costs are used in a present value discounted cash flow analysis, with the total of both road user and agency costs equalling the total life cycle cost. The PLCC model estimates the minimum possible (or optimum) total life cycle cost for the unconstrained annual agency budgets based on achieving the minimum present value sum of road agency and road user costs, over a 60 year analysis period using a real discount rate of 7% (Austroads, 2004). A genetic algorithm is used to optimise the vast number of options for maintenance and rehabilitation using the constraints of maximum allowable network roughness and road agency budget limits.

3.3.2 Highway Development and Management (HDM-4) Model

The Highway Development and Management software (HDM-4) was the result of an international effort to develop improved road investment appraisal methods. HDM-4 can be used to undertake detailed pavement performance analyses, works scheduling and other tasks including modelling environmental performance with respect to greenhouse gas emissions (ISOHDM, 2002). Compared to the PLCC model previously discussed, HDM-4 requires a more detailed set of independent pavement performance parameters including amongst others roughness, rutting, cracking, potholing, revelling and strength (Austroads, 2004). However, HDM-4 also relies on the use of TMI as the main climatic component represented in the model. Because of the intensive data requirements HDM-4 presents a more detailed level of analysis compared to other models and tends to be used on a smaller scale than, for example, the more simplified PLCC model. HDM-4 is able to provide detailed pavement performance projections over time with the ability to predict changes in the pavement over time with respect to parameters such as the average roughness, structural cracking and the number of potholes.

HDM-4 estimates total life cycle costs that include both road user costs and agency costs. HDM-4 uses an estimation of the routine maintenance costs required to keep the pavement in sound operational condition as the base case. Routine maintenance options are known as treatments and are applied in the model in response to predicted road deterioration. The treatment selected is based on the minimising the present value of the total life cycle cost of the road subject to any restraints of the project.

3.3.3 Austroads Structural Deterioration Model

Austrroads (2010) undertook a project to develop a pavement performance prediction model to reflect the performance of Australian flexible pavements. Prior to this study most pavement performance models in use were developed from data gained in Brazil, the Caribbean and Kenya from 1971 to 1984 (Austrroads, 2010).

The project developed a network level structural deterioration model to estimate the strength of pavement or subgrade responsible for roughness and rutting to predict changes in the pavement with increasing age. Strength deterioration analysis was undertaken in terms of the overall strength of the pavement using the modified structural number (SNC). SNC historically has been used to represent the strength of the pavement and subgrade system in predicting pavement performance at a network level (Austrroads, 2010).

The project found that the current strength of pavements in Australia could be described in terms of the TMI, the age of the pavement and its design life. Relationships were described for both asphalt and unbound granular pavements as listed in equations 6 and 7 respectively.

$$S(t) = 0.991S_0 \left[2 - \exp(0.00132M(t)) + 0.256 \left(\frac{t}{N} \right) \right] \quad (6)$$

$$S(t) = 0.9035S_0 \left[2 - \exp(0.0023M(t)) + 0.1849 \left(\frac{t}{N} \right) \right] \quad (7)$$

where $S(t)$ is the modified structural number at t years, and N is the design life.

The structural deterioration models show that the impact of TMI was greater on the deterioration of unbound granular pavements than it was for asphalt pavements. These models were noted to have limitations however, and are only reliable for pavement sites where a decreasing trend of TMI occurs caused by reducing annual rainfall over time.

3.3.4 ARRB Marginal Cost Model

Under a recent project commissioned by the National Transport Commission and Austrroads, the Australian Road Research Board (ARRB) Group developed an engineering/economic model representative across the Australian sealed road network to estimate the marginal cost of heavy vehicle road wear for different road types (ARRB, 2011).

The model considers both long and short term costs, with the results presented in terms of indexed marginal cost rather than absolute cost values. This indexation allows the marginal costs for different road types to be compared relative to each other (ARRB, 2011). Short term marginal costs were based on the assumption that maintenance would not increase the road strength beyond its original design. Long term costs were related to road strengthening activities, for example road upgrades to accommodate heavier loads.

The marginal cost estimates generated are based on the way a road would deteriorate under a number of input parameters considering the road type, location (urban or rural) and condition, traffic conditions and climatic conditions. The marginal cost analysis was simplified by aggregating road types into four major road classifications: freeways, urban arterial roads, rural arterial roads and local roads. Pavement types considered included cement-stabilised, asphaltic concrete and granular.

The climatic conditions were accounted for in the model using the TMI under the first five different climate types defined by Australian Standard AS2870 (Standards Australia, 2011) as shown in Table 2, adapted from ARRB (2011). Table 2 in this paper has been extended from the table in ARRB (2011) to include all parts of Australia, including the arid regions. The climate types defined in this table provide a more reasonable description of Australia’s climatic zones than do those originally proposed by Thornthwaite (see Table 1).

Table 2. Australian climatic types adapted from the Australian Standard AS2870 climate classes (Standards Australia, 2011)

Climatic Types for Australia		Thornthwaite Moisture Index Value Ranges
i	Alpine/coastal	>40
ii	Wet temperate	10 to 40
iii	Temperate	10 to -5
iv	Dry temperate	-5 to -25
v	Semi arid	-25 to -40
vi	Arid	< -40

3.3.5 Victorian Grants Commission Road Funding Model

The TMI has also been used directly in determining the priority for funding of maintenance and rehabilitation works of roads in the state of Victoria, Australia. The Victorian Grants Commission uses a climate cost modifier based on the TMI to rank the level of need of the council road preservation works relative to others. The climate cost modifier recognises that certain climatic conditions have an adverse impact on road durability and increase the costs of asset preservation in affected areas (Victorian Grants Commission, 2006). The TMI was converted into a cost index where 20 TMI equals 1.0 on the cost index scale which was assumed to be the “average” climate for Victoria. The cost index scale used for Victoria ranges from 0.775 to 1.30. The cost index scale was further broken down by nine road types due to the variance in climate impacts of road type. For example the condition of natural surface roads is strongly related to climate factors and as such the cost modifier factors range from 0.75 (favourable) to 1.15 (adverse). However the cost modifier factors range from 0.90 (favourable) to 1.10 (adverse) for kerbed roads as they are less impacted by climate factors compared to natural surface roads.

4. The Thornthwaite Moisture Index and Climate Change

The effects of climate change and the need for adaptation of infrastructure to changing climatic conditions provide the opportunity for new applications of the Thornthwaite Moisture Index. Where the TMI is included as a parameter in infrastructure design and assessment it may be possible to analyse and adapt to the changing environment. The following paragraphs describe examples where this has been applied.

4.1 Analysing the costs of climate change

The impacts of climate change on infrastructure will impact infrastructure in both the long and short term, both directly through the physical effects of the changing climate and indirectly as populations shift. Generally infrastructure is a long term investment designed with a relatively long serviceable life to maximise the benefits of the investment. Roads are generally constructed to have design lives

of 20 to 40 years. Understanding what the effects of climate change would have on infrastructure over this time period would allow managers and operators to budget and better prepare suitable management plans for infrastructure

In 2004, Austroads conducted a study on the likely impacts of climate change on transport infrastructure. One of the aims of the project was to identify the likely effects of climate change on existing road infrastructure and potential adaptation measures in road construction and maintenance.

A regional climate model was used to generate future climate scenarios out to the year 2100, outputting a variety of climatic variables relevant to road pavement deterioration, including TMI, for a 0.5 degree geographical grid across the Australian continent (Houghton and Styles, 2002). Climate modelling scenarios to year 2100 indicated the areas with the highest TMI change and hence the greatest potential change in road infrastructure maintenance costs are south-west Western Australia, north-east Victoria, southern NSW, south-west Tasmania and the far north (Houghton and Styles, 2002).

The data output from the climate modelling was then entered into the PLCC and HDM-4 models, discussed previously, to review and compared predicted maintenance costs under the climate change scenario for year 2100. The pavement deterioration estimations in these models were dependent on both the TMI and traffic loads and allowed both the direct physical and indirect effects of climate change on pavements to be analysed.

Overall the results of the cost analyses showed the environmental effects of climate change on agency and road user costs are minor compared to the dominating impact of population changes (Austroads, 2004). A decrease of between 0 and 3% in the required pavement maintenance and rehabilitation budget was predicted based solely on change in climate factors. This reflects the slowing of pavement degradation rates under the predicted warmer and drier Australian climate. More specifically, the PLCC model estimated a 3% or \$10.8 million decrease in the optimised agency cost for maintenance and rehabilitation of roads due to climate change. The results from HDM-4 were comparable to PLCC despite the more rigorous input data required, once again reflecting a 3% decrease in climate change associate costs for the maintenance and rehabilitation of road infrastructure (Houghton and Styles, 2002).

Several limiting factors exist with respect to the results of this study. These include the fact that significant regional variations in climate change effects were unaccounted for, and there was also no analysis of cost impacts under extreme weather events which will impact pavements under the climate change scenarios. The pavement performance analysis also assumed constant pavement design strengths, implying that if traffic loads change in response to climate change, then existing pavements will reach the end of their useful lives earlier requiring rehabilitation, also increasing costs to road agencies. In all likelihood where traffic loads are increased pavements would be rehabilitated to cope with the increased load.

Overall the study allowed foresight into how general climate changes will impact the overall national highway network in Australia, and allow managers and operators to prepare for the changes ahead.

4.2 Use of TMI to adapt infrastructure to climate change

Austroads (2010) provided a mathematical model of road pavement degradation that includes climate variables and the potential impact of climate change, expressed in terms of the Thornthwaite Moisture Index. This model is now extended for use in climate change studies for road

pavements, as described below. Overall pavement degradation is expressed in terms of the International Roughness Index (IRI), $R(t)$ (m/km) at time t , where $R(t)$ is given by

$$R(t) = R_0 + \Delta R(t) \quad (8)$$

in which R_0 is the initial roughness index of the pavement and $\Delta R(t)$ is the change in roughness over time t . The road will be considered to have reached the end of its service life when

$$R(t) \geq R_{max}$$

Thus determination of t_{max} , where

$$R(t_{max}) = R_{max} \quad (9)$$

will indicate the time of failure of the pavement.

The overall roughness of a sealed pavement is made up of considerations of rutting and surface cracking, which are affected by traffic load and climate, and this can be assessed in terms of changes in IRI. The following scenario planning model has been developed from that given in Austroads (2010).

$$\Delta R(t) = 196.74Z(t) + 0.016c(t) + 0.25r(t) + 0.972E(t) \quad (10)$$

in which $Z(t)$ represents the cumulative traffic load on the pavement, $c(t)$ is the percentage of cumulative cracking (% total lane area, 0-100%) by year t , $r(t)$ is the cumulative rutting deterioration for a sealed granular pavement by year t , and $E(t)$ is an environmental/climatic term, given by the following equation.

$$E(t) = \lambda(t)R_0t \quad (11)$$

In equation 11

$$\lambda(t) = 0.0197 + 0.00000155M(t) \quad (12)$$

where $M(t)$ is the value of the TMI in year t .

The impacts of traffic load on pavement condition are represented by the term $Z(t)$ in equation (10). This term exists in two alternative forms, $Z_1(t)$ and $Z_2(t)$, depending on the seal type for the road pavement. It is given by

$$Z_j(t) = v_j(t)Q(t)\exp[\lambda(t)t] \quad (13)$$

in which

$$v_j(t) = \frac{1}{[1 + (S_0 - 0.0000758c(t)b_j\phi)]^5} \quad (14)$$

where $j = 1$ for single seal, $b_1 = 0.6$; $j = 2$ for double seals, $b_2 = 0.9$, and ϕ is the nominal maximum size of seal aggregate (mm) and the initial Modified Structural Number (MSN) (S_0) for the pavement can be estimated from the observed MSN at time t ,

$$S_0 = \frac{1.1068S(t)}{2 - \exp\left[0.0023M(t) + 0.185\left(\frac{t}{N}\right)\right]} \quad (15)$$

$$S(t) = 3.2D_0^{-0.63} \quad (16)$$

which is an estimate of the MSN for the pavement at time t , based on the result (D_0 , mm) of a Falling Weight Deflectometer test (see NCHRP, 2006) – assuming that such test results can be obtained. It is also possible (and perhaps inevitable in scenario planning) to use a default value for S_0 , and Austroads (2010) suggests a default value of $S_0 = 4.5$.

$Q(t)$ is the cumulative traffic load on the pavement, expressed as the number of Equivalent Standard Axles¹ (ESA) imposed on the pavement, and measured in mega-ESA. A convenient method for calculating $Q(t)$ given in Austroads (2008).

Cumulative rutting deformation $r(t)$ up to time t for the road pavement is given by

$$r(t) = (t - 1)^{0.617}y(t) \quad (17)$$

where

$$y(t) = 0.594Q(t) - 0.000102\bar{u}(t) + \frac{0.022(100 + M(t))}{S_0} \quad (18)$$

and $\bar{u}(t)$ is the annualised pavement maintenance expenditure (\$/lane-km/year) by year t . Typical values for maintenance costs are given in Austroads (2010).

Cumulative cracking deterioration ($c(t)$) (as a percentage of pavement surface area) is given by

$$c(t) = 100 \left[1 - \frac{2}{1 + \exp\{w_j(t)\}} \right] \quad (19)$$

where

$$w_j(t) = \left(\frac{a_j t_c(t)}{8 - 0.04M(t)} \right)^{3.5} \quad (20)$$

in which $j = 1$ is for a sealed granular pavement for which $a_1 = 0.234$, and $j = 2$ is for an asphalt pavement with $a_2 = 0.682$.

Cracking age t_c , the elapsed time from the commencement of cracking, is given by

¹ A standard axle is a dual-wheeled (4-tyre) axle transmitting a load of 80 kiloNewton (KN) on to the road pavement surface. Traffic load is thus measured as an equivalent number of standard axles passing over a road section. See Austroads (2008) for full details.

$$t_c(t) = t - \tau_c \quad \text{if } t > \tau_c, \text{ otherwise } t_c(t) = 0 \quad (21)$$

in which seal life τ_c , before the onset of cracking, is given by Oliver's equation (see Oliver, 2006):

$$\tau_c = \left[\frac{0.158T_{min} - 0.107F + 0.84}{0.0249(T_{min} + T_{max}) - 0.216d + 0.000381\phi^2} \right]^2 \quad (22)$$

Note that the temperature variables T_{min} and T_{max} in equation 22 are average annual values up to a particular point in time, and so can be varied in response to changes in climate. The factor d in the equation is the result (in days) of the ARRB Durability Test, and usually has a value in the range 8-10. The factor F is a risk factor, ranging in value from 1 (low risk) to 10 (high risk). Typical values are in the range 6-8, with the factor being higher for higher traffic loads.

In an environment where traffic loads, climatic factors (and maintenance regimes) may vary over time, then the pavement degradation model needs to be written in terms of incremental (year by year) effects. Austroads (2010) provides an initial version of such a model, although this is only concerned with changes in annual traffic load. A more general incremental model is needed, so that the effects of variation in other factors, such as road maintenance expenditures and climate change can be included. On the basis of the Austroads incremental model, we can write the following expression for the IRI ($R(t)$) at time t years after initial construction or rehabilitation of the pavement:

$$R(t) \approx R_0 + \sum_{i=1}^t \delta R(i) \quad (23)$$

The requirement is then to define $R(t)$ in terms of the incremental changes in the variables in equation 10, and so produce an equivalent model based on the incremental changes over each year. The starting point is to consider the incremental change in IRI ($\delta R(t)$) between year $t-1$ and year t . This is

$$\delta R(t) = \Delta R(t) - \Delta R(t-1) \quad (24)$$

and, following the form of equation 10, $\delta R(t)$ can then be written as

$$\delta R(t) = 196.74\delta Z(t) + 0.016\delta c(t) + 0.25\delta r(t) + 0.972\delta E(t) \quad (25)$$

where

$$\delta Z(t) = Q(t)v(t) \exp[\lambda(t)t] - Q(t-1)v(t-1) \exp[\lambda(t-1)(t-1)] \quad (26)$$

$$\delta c(t) = 200 \left\{ \frac{\exp[w(t)] - \exp[w(t-1)]}{(1 + \exp[w(t)])(1 + \exp[w(t-1)])} \right\} \quad (27)$$

$$\delta r(t) = (t-1)^{0.617}y(t) - (t-2)^{0.574}y(t-1) \quad (28)$$

$$\delta E(t) = R_0(\lambda(t)t - \lambda(t-1)(t-1)) \quad (29)$$

Solution of equation 9 using equations 23-29 provides a model of pavement life dependent on changes in traffic, maintenance and environmental variables over time. Note that the form of equation 28 is compatible with the equivalent expression in Austroads (2010).

4.3 Application of the model

Two applications of the model are provided. The first indicates the likely difference in road pavement degradation for a given pavement, traffic load and maintenance program, but where the pavement is located in different climate zones. The second application shows the modelled degradation for a road pavement at a location undergoing climate change over a 50 year period.

Figure 2 shows the model results for a given road pavement under a set traffic load but located in different climate zones (from those defined in Table 2): class iii temperate, class iv dry temperate, class v semi arid, and class vi arid. These classes would represent climatic conditions found along a north-south axis located in the Mid North region of the state of South Australia, which is the focus for our field research. Basically the model suggests that the drier the climate, the longer lasting the pavement (all other factors, including the influence of extreme weather events, being the same). This is intuitively correct. There are however some interesting behaviours in the model, for climate classes iv and v for which the two curves twist around each other. The model is nonlinear and so such behaviour, possibly dependent on the specific values of the input factors in the model, is plausible. The South Australian Department of Planning, Transport and Infrastructure (DPTI) generally accepts a maximum value of the IRI (R_{max}) of 5.3 m/km as a value indicating a pavement in poor condition and in need of rejuvenation or rehabilitation. In Figure 2 this value of the IRI is exceeded in years 35 onward, first for the class iii situation, then class iv, class v and finally class vi. Note that this modelling exercise is for purposes of illustration of the potential impacts of climate only. For instance, it assumes a very simple, regular maintenance regime with no major rehabilitation of the pavement over its life.

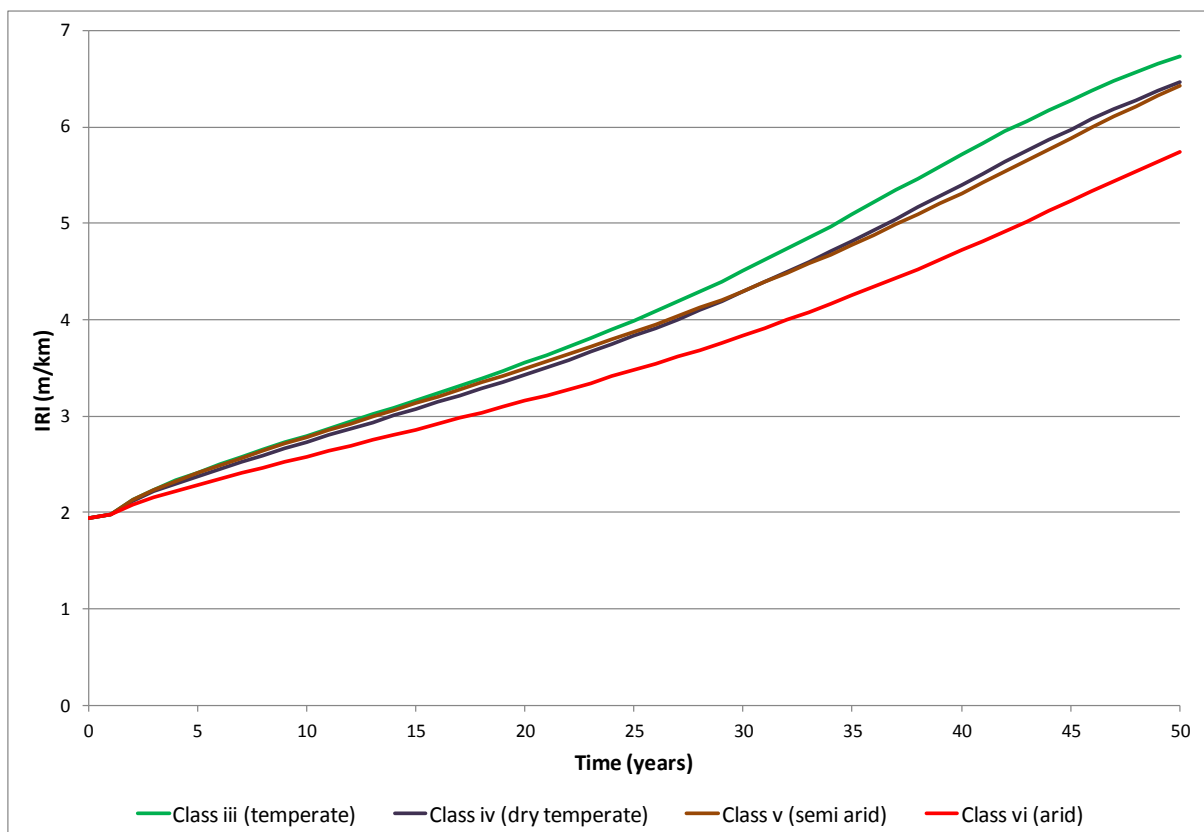


Figure 2 Modelled effects of climate conditions on pavement degradation – same pavement design, traffic load and maintenance schedule in different climate zones

Figure 3 provides an example of the use of the model for a changing climate. It compares the forecast degradation over 50 years of a road pavement under different climate scenarios, with all other variables (traffic load and maintenance schedules) remaining the same. Three scenarios are presented in this plot, using the Australian climate classes in Table 2:

- Scenario 1, in which the climate is classified as ‘dry temperate’ (Australian TMI class iv) over the 50 year period
- Scenario 2, in which the climate changes (linearly) from ‘dry temperate’ to ‘semi arid’ (Australian TMI class v) over the 50 years, and
- Scenario 3, in which the climate is ‘semi arid’ (Australian TMI class v) throughout the 50 year period.

The effects of climate and climate change are quite apparent in this graph. The move to a drier, warmer climate (Scenario 2) extends the effective life of the pavement (as measured by the IRI) when compared to Scenario 1. Scenario 3 shows the longest modelled effective life. In terms of the DPTI criterion for R_{max} , the effective pavement life is 26 years in Scenario 1, 28 years in Scenario 2, and 31 years in Scenario 3.

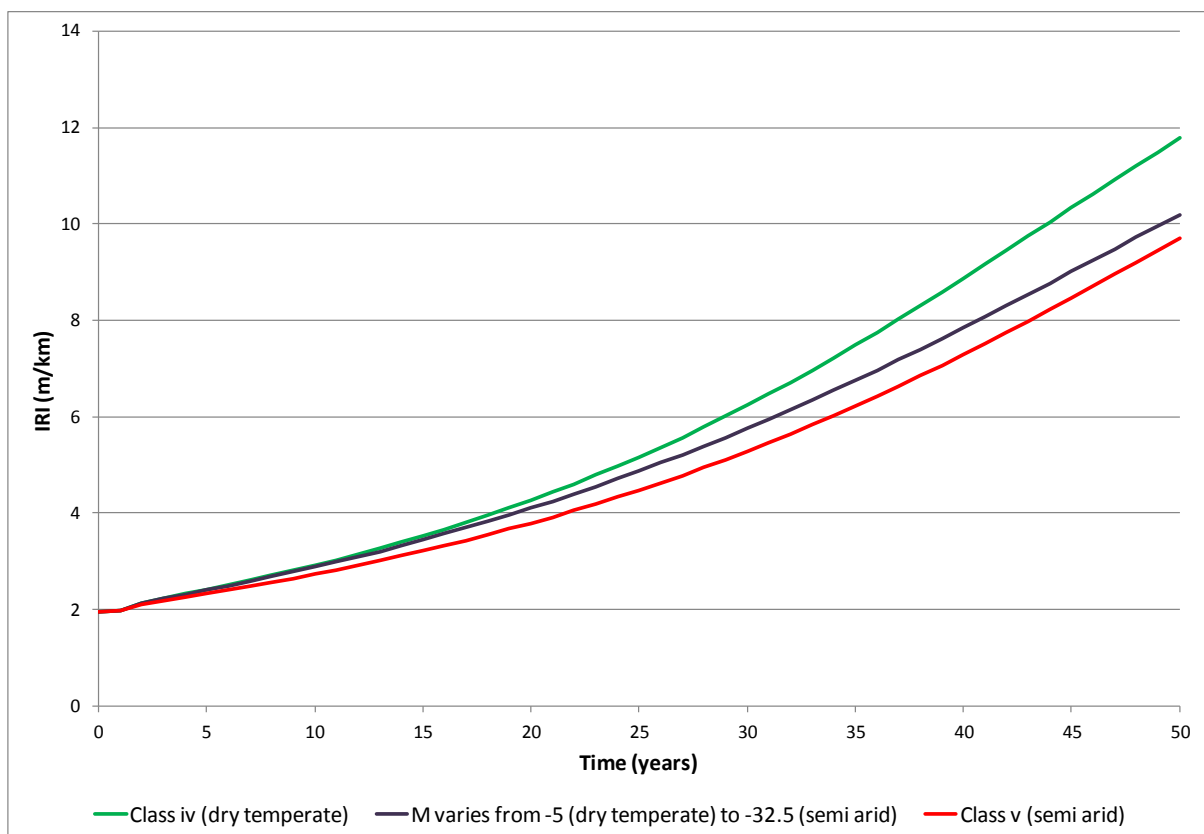


Figure 3 Modelled effects of climate change on pavement degradation with a changing climate scenario

However, there is more to the state of a road pavement than the evolving state of its IRI. In terms of climatic conditions, severe events such as thunderstorms and resultant flash flooding can have major

(and, for the road in question, even 'catastrophic' impacts). Such events would affect those sites where channelled surface water would cross the road surface, e.g. at fords or floodways along the road. In arid and semi-arid areas where creeks and watercourses are often dry for most of the time, overall road design and construction economics may hinder the construction of major facilities such as bridges or major culverts. In these cases, well exemplified by the roads in the Mid North region of South Australia, road crossing points at water courses may be left as fords, or have some form of minor culvert structure installed. These structures may fail under an extreme rainfall event and consequent flash flooding, leading to washouts of the road requiring substantial repair and leading to significant disruptions in the regional road network (Taylor, 2008). Given that thunderstorms and flash flooding tend to be more pronounced under the drier (semi-arid and arid) climate classes, climatic shifts towards these conditions may well cause significant problems for road network managers, in addition to the general state of the road pavements.

5. Summary

This paper demonstrates the widespread application of the Thornthwaite Moisture Index in the area of infrastructure, beyond its initial application in agricultural production. A review of literature and best practice revealed several key areas where the TMI has been applied with respect to infrastructure.

In the practice of pavement and foundation design the TMI has been widely accepted as an indicator of climate induced soil behaviour, simplifying the design process and removing the need for extensive field testing. TMI has also been found to be widely used in the area of pavement degradation and maintenance planning. The index was found to be used as a climate indicator in degradation estimates. These estimates were further used by several models to imply costs and other impacts such as greenhouse gas emissions. TMI has also been shown to be used to represent climate impacts in order to rank road maintenance priorities for government funding. TMI has been further applied in Australia to analyse the impacts and costs of climate change on transport infrastructure.

The use of the TMI was not found to be geographically limited and has been applied across many continents with success. The widespread nature of the application and geographical suitability of the TMI makes it a suitable candidate for consideration in climate change adaptation. The variation in climate change impacts with locality can make finding a representative climate factor difficult. However the TMI has been successfully applied across varying localities and can be calculated for specific regions under investigation, using generally available rainfall and temperature data. This regional flexibility simplifies the development of climate change adaptation procedures by providing the option for a standardised approach, for example across Australia, rather than piecemeal adaptation of infrastructure on a case by case basis. This was further demonstrated by the method given for modelling road degradation in Australia.

Some simple applications of the pavement degradation model were presented, which indicate the potential impacts of climate change on road pavement condition and the effective lives of pavements under different climate scenarios. The model incorporates pavement structure, traffic load and maintenance regimes as well as climatic and environmental factors, and should be useful for scenario planning studies aimed at forecasting the potential impacts of climate change on road network management and the need for adaptation by road authorities to climate change.

6. Nomenclature

a_j	Coefficient in cumulative cracking deterioration equation: $j = 1$, granular sealed pavement, $a_1 = 0.234$; $j = 2$, asphalt pavement, $a_2 = 0.682$
b_j	Coefficient for estimating field layer thickness (FLT) of bitumen binder: $j = 1$, single seal, $b_1 = 0.6$; $j = 2$, double seal, $b_2 = 0.9$
$c(t)$	Cumulative cracking (% total lane area, 0-100%) by year t
$\delta c(t)$	Incremental cracking (% total lane area, 0-100%) in year t
d	days
D_0	Maximum falling weight deflectometer (FWD) deflection from pavement test (mm)
$E(t)$	Environmental/climate term in cumulative roughness deterioration equation, up to year t
$\delta E(t)$	Incremental environmental/climate term in roughness deterioration equation, for year t
F	Risk factor in ARRB seal life equation ($1 = v$ low, $10 = v$ high)
Ih	Index of humidity
Ia	Index of aridity
$M(t)$	Thornthwaite Moisture Index for climate pavement conditions in year t
N	Pavement design life (years)
$P_e(t)$	Effective annual rainfall (mm) in year t
$P_{Tm}(t)$	Total monthly rainfall (mm) in month m of year t
$P_{em}(t)$	Effective monthly rainfall (mm) in month m of year t
$Q(t)$	Cumulative traffic load per lane in Mega-ESA (millions of Equivalent Standard Axles), to the end of year t
r_{max}	Mean maximum vertical deformation from original surface profile (mm)
$r(t)$	Cumulative rutting deterioration for sealed granular pavements by year t
$\delta r(t)$	Incremental rutting deterioration for sealed granular pavements in year t
R	International Roughness Index (IRI), in m/km
R_0	International Roughness Index at $t = 0$
R_{max}	Maximum value of IRI for a road considered to be in serviceable condition
$\delta R(t)$	Incremental deterioration in IRI for a sealed granular pavement, in year t
$\Delta R(t)$	Cumulative deterioration in IRI for a sealed granular pavement, after t years
$S(t)$	Modified Structural Number for pavement/subgrade strength at year t
S_0	Modified Structural Number for pavement/subgrade strength at year $t = 0$ [Default value 4.5]
t	Time since construction or last rehabilitation (years)
t_c	Cracking age (elapsed time from commencement of cracking, in years): $t_c = t - \tau_c$ if $t > \tau_c$ otherwise $t_c = 0$
$T_m(t)$	Mean monthly temperature ($^{\circ}\text{C}$) in month m of year t
T_{min}	Average annual minimum temperature
T_{max}	Average annual maximum temperature
$\bar{u}(t)$	Annualised pavement maintenance expenditure (\$/lane-km/year) by year t
$v_j(t)$	$v_j(t) = \frac{1}{[1 + (S_0 - 0.0000758c(t)b_j\phi)]^5}$
$w_j(t)$	$w_j(t) = \left(\frac{a_j t_c(t)}{8 - 0.04M(t)} \right)^{3.5}$
$y(t)$	$y(t) = 0.594Q(t) - 0.000102\bar{u}(t) + \frac{0.022(100 + M(t))}{S_0}$
$Z(t)$	Traffic load term in cumulative roughness deterioration equation
$\delta Z(t)$	Change in traffic load term in incremental roughness deterioration equation, in year t
α	Water surplus
β	Water deficiency
γ	Water need
$\lambda(t)$	Environmental coefficient, which varies in response to changes in the Thornthwaite Moisture Index $M(t)$

τ_c	Seal life (years)
\emptyset	Nominal maximum size of seal aggregate (mm)

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