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

Michelle Philp and Michael Taylor October 2012

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

Or

$$/ \quad L \frac{s\,r\,r\grave{U}\,F\,x\,r\acute{U}}{\hat{U}} \qquad (2)$$

where Ih and Ia are indices of humidity and aridity respectively, Ù is water surplus, Ú is water deficiency, and Û is water need or potential evapotranspiration.

Thornthwaite used the index to describe various climate types according to the moisture index limits. Thor v š Z Á] š [• classifications are listed in Table 1.

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A further simplification of the index was given by Gentilli (1972) which relates the Thornthwaite
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/ :P, N s ä t w 2$_{Ø}$:P, F x r (3)

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2$_{Ø}$:P, L Í 2$_{Ø\,à}$:P,
à @ 5 (4)

2$_{Ø\,à}$:P, L s ä x w $\frac{2_{í\,à} :P,}{:6_{à} :P, E s t ä t ; ^{5\,ä\,5\,5\,5\,5}}$ (5)

where $P_{Tm}(t)$

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 WINPRES (Lytton et al., 2005)

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 ‰Œ}À] u}Œ Œ •}v o •Œ]‰š]}v }(µ•šŒ o][• o]u š] Ì} 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 R

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 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

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

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

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

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).

$$\Delta R(t) = 196.74\,Z(t) + 0.216\,c(t) + 0.25\,r(t) + 0.972\,E(t) \qquad (10)$$

in which Z(t) represents the cumulative traffic load on the pavement, c(t) is the percentage of cumulative cracking (% total lane area, 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.

$$E(t) = m(t)\,R_0\,t \qquad (11)$$

In equation 11

$$m(t) = 0.2197 + 0.2000015\,M(t) \qquad (12)$$

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).

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in which seal life ç U (} Œ š Z } v • š } (Œ l] v P U] • (see Oliver, 2006) ç :o] À Œ [• ‹ µ

ì Ö L d [r ä s w 6 à Ü á F r ä s r y (E r ä z v] / [r ä t v { : 6 à Ü á E 6 k v ; F r ä s x @ E r ä r r u z î s 6] h 6 (22)

Note that the temperature variables T_{min} and T_{max} in equation 22 are average annual values up to a

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, cl77(g)ms iiv)3(ery)-91()9(e,)-4

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

- ^ v Œ] } í U] v Á Z] Z š Z o] dry temperate [Australian TMI class) over the 50 year period
- ^ v Œ] } î U] v Á Z] Z š Z o] u š Z dry temperate o] v š Z Œ o Ç • (Œ } u Z (Australian TMI class) over the 50 years, and
- ^ v Œ] } ï U] v Á Z] Z š Z o Australian TMI class) throughout the 50 year period.

2̧	Seal life (years)
Î	Nominal maximum size of seal aggregate (mm)

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