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# TMI for urban resilience:
# Measuring and mapping long-term climate change effects on soil moisture

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## Abstract:

The effect of climate change on the shallow expansive foundation conditions of residential dwellings is costing several hundred billion dollars worldwide. The design and costs of constructing or repairing residential footings is greatly influenced by the degree of ground movement, which is driven by the magnitude of change in soil moisture. The impacts of climate change on urban infrastructure are expected to include accelerated degradation of materials and foundations of buildings and facilities, increased ground movement, changes in ground water affecting the chemical structure of foundations, and fatigue of structures from extreme storm events. Previous research found that residential houses that were built less than five years ago have suffered major cracks and other damage caused by slab movement after record rainfall.

The Thornthwaite Moisture Index (TMI) categorises climate on the basis of rainfall, temperature, potential evapotranspiration and the water holding capacity of the soil. Originally TMI was mainly used to map soil moisture conditions for agriculture but soon became a method to predict pavement and foundation changes. Few researchers have developed TMI maps for Australia, but generally, their accuracy is low or unknown, and their use is limited.

The aims of this paper are: (1) To produce accurate maps of TMI for the state of Victoria for 100 years (1913 to 2012) in 20 year periods using long-term historical climatic data and advanced spatial statistics methods in GIS; and (2) Analyse the spatial and temporal changes of TMI in Victoria.

Preliminary results suggest that a better understanding of climate change through long-term TMI mapping can assist urban planning and guide construction regulations towards the development of cities which are more resilient.

**Keywords:**

Urban resilience, Thornthwaite Moisture Index, Housing, Climate change, GIS

## 1. INTRODUCTION

Light construction, such as low rise residential buildings, on expansive soil is a well-known engineering challenge (Popescu, 1979). Expansive soils are characterised by their typical behaviour of swelling in wet conditions and shrinking when it is dry (Nelson and Miller, 1992). The downward movement of the ground is called subsidence, and the upward movement is called heave. The resulting ground movement from soil moisture change can cause serious damages in the foundations of built structures.

This type of soil can be found all over the world (list of references for all continents in Osman, 2007). Approximately 30% of Australia and 50% of the surface area in Victoria (The Atlas of Australian Soils, Northcote, 1960-1968) are covered by moderate to highly expansive soils. In Victoria, footing and slab defects had the highest average defect cost; and all housing defects cost nearly AU$1 billion per annum (Mills et al, 2009). Holland (1981) in his book on the design, performance and repair of housing foundations, investigated a large number of samples and concluded that about 50% of the housing failures in Victoria occurred in moderately to highly expansive soil.

Therefore, before a footing can be designed, some understanding of the potential adverse effects from reactive soils to the completed construction structure must be obtained. Fityus and Buzzi (2008) listed some ways of developing this understanding. On-site tests, such as the analysis of soil profile, can provide important information. Laboratory testing of soil reactivity can also provide local and immediate information about potential impacts. However, they highlight that soil behaviour has a temporal aspect, such as the ones related to seasonality, and some required information is not available immediately or in the short term. Generic climatic averages of temperature and rainfall for large areas where a site is located are normally used to fill this gap of information.

Climate change, however, limits the use of simple climate averages at a certain point in time. New climate patterns are forming, particularly in the last decade. A large number of dwellings built in the past, designed for climate conditions of that time, are now susceptible to new climatic patterns. In France, for example, subsidence-related losses caused by drought on reactive soils have increased by more than 50% within two decades, costing affected regions an average of EUR 340 million per year (Mills, 2003). Losses from two droughts in the 1990s resulted in losses of US$2.5 billion in the UK (Ruquet, 2002).

New light construction to be built in the present should also consider how new climate patterns would affect built structures into the future. Climate change will further magnify the risks of structural damage, as soil movements become more frequent and severe. Including climate change in the process of foundation design for light construction would lead to more resilient urban environments. A resilient environment should experience reduction of its vulnerability or enhancement of its adaptive capacity (Leichenko, 2011). Achieving this theoretical concept of resilience needs specific tools able to measure vulnerability, to devise actions for adaptability, and to measure the results of such actions (Bosher et al, 2007).

The Australian Standard 2870 (AS 2870) provides guidelines and performance requirements for the design of footing and slabs systems, with an emphasis to the issue in sites with reactive soils and significant ground movement (SA, 1996). Section 2 of AS 2870 addresses the site classification and investigation requirements. It presents a map of climatic zones for the state of Victoria, based on Thorthwaite Moisture Index (TMI) classification, and relates these zones to different soil profiles. This map is suggested by the Standard to be used, together with other local analysis, as a guide to the design of light construction foundations. The AS 2870 TMI map currently available, however, was produced using climate data from the 1970s, and does not reflect the current climate conditions in the region.

Few researchers have developed TMI for Australia. Examples cover parts of a state (The Hunter Valley in NSW by Fityus et al, 1998), few states (Queensland by Fox, 2002; Victoria by Lopes and Osman, 2008) or the whole country (AustRoads, 2004). Those maps have different time frames and spatial scales. The methods applied to produce those maps also differ significantly, from simple empirical isopleth design, to more complex computer spatial interpolations.

Only the work developed by Lopes and Osman (2010) presented an attempt to use TMI mapping to infer the impacts of climate change in soil moisture patterns in Australia with focus on the impacts of soil moisture change on housing. They produced three maps for Victoria for three periods between 1948 and 2007. Their findings suggested the trend of drying soil conditions in Victoria. This present paper represents a progress on this previous work, by adding a more robust and analytical method to produce the TMI maps (geostatistical interpolation), and a more extensive historical climate data now available.

Some important work on TMI and climate change has been developed in Australia, but mainly with focus on road infrastructure. AustRoads (2004) analysed the impacts of a climate change scenario on the conditions of the existing road infrastructure and future demand for more infrastructure related to demographic changes and urbanisation. Thornthwaite moisture index was mapped for 2000 and 2100, considering a steady fourfold increase in carbon emissions. Using coarse spatial scale, a cell resolution of 50 km x 50 km, in the TMI grid map, they suggested that changes in TMI were not very pronounced in most of Australia. Moreover, they found that Australia is generally getting hotter and drier, and this can be a good impact for the transport infrastructure management, since roads in areas with higher value for TMI (wetter regions) are expected to deteriorate faster than those with a lower value for the same traffic loading.

McCabe and Wolock (1992) developed a study to examine the effects of long-term changes in climate (temperature and precipitation) on the Thornthwaite moisture index. Using Delaware River Basin (Maryland-Pennsylvania/USA) in the period from 1950 to 1983, they estimated how doubled-$CO^2$ conditions could be detected in terms of changes in the moisture index. Results indicated that temperature and precipitation under the increased CO2 emissions would cause TMI to decrease, implying significantly drier conditions in the study area than currently exist. The decrease in the moisture index is attributable to the predicted increases in temperature and the absence of an offsetting increase in the precipitation.

Residential construction is a substantial part of the building industry in Australia. According to the latest Census of Population and Housing in 2011, there are 8.6 Billion dwellings in Australia, being 11% unoccupied. And based on a Housing Industry Association report (HIA, 2012) there is an average of 155,000 new dwellings being built each year in Australia with a total investment of AUD 425 Billion. An additional AUD 323 Billion a year is also invested in renovation of existing dwellings in Australia. Victoria alone accounts for almost 30% of the national investment in new and renovated housing. Producing new and renovated buildings that are durable in the long term is essential for the Australian economy, environment and social welfare.

TMI maps and TMI change maps can be very helpful in producing more resilient urban areas. The majority of losses in catastrophes are due to weather-related events worldwide, such as windstorm, hurricane, tropical cyclone, hailstorm, flood, drought, wildfire, extreme temperature episodes, and sea level rise and tidal surges (Mills, 2003). Over the past 50 years the number of weather related natural disasters has been steadily rising. Another important and often overlooked class of losses are related to small scale and long term weather-related processes, such as the residential damages caused by soil moisture change (Osman and Lopes, 2008; Mills, 2003).

Understanding the impacts of climate change on the soil moisture, and its relationship with building foundations, together with continued climate monitoring, can result in a dynamic mapping of the soil characteristics and better indicators for construction in the present that will be resilient now and in the future. Although there is uncertainty associated to climate change impacts, particularly for individual extreme events, the extensive available data may allow some levels of predictability for some medium and long term weather-related processes. This can be the case of the dynamics of TMI change, which needs further investigation.

The aims of this paper are twofold. First, it is focused on producing accurate maps for Thornthwaite Moisture Index with good spatial and temporal scale. Using the state of Victoria as a case study, we mapped TMI for 100 years (1913 to 2012) in 20 year periods using long-term historical climatic data and advanced spatial statistics methods in GIS. A spatial resolution of 1km$^2$ is used in the grid output. Second, we analysed the spatial and temporal changes of TMI in Victoria over the last century, investigating and identifying the magnitude and location of the change across the study area.

Section 2 of this paper presents the research design, describing the methods applied for historical TMI mapping, which involves the calculation of TMI and the use of geostatistics for TMI mapping. Section 3 presents the case study. The methodology is tested in Victoria, and results are provided in relation to the understanding of climate data and TMI, to the quality of TMI estimation using geostatistics, and to the evaluation of TMI change over time. Section 4 discusses these results and their implications to the housing industry. Finally, Section 5 concludes the study, indicating the main findings and required further developments and research.

## 2. RESEARCH DESIGN

The methodology applied in this research combined two techniques: climate classification using Thornthwaite Moisture Index (TMI), and TMI mapping through spatial interpolation in a Geographic Information System (GIS).

The combination of the methods described below allows us to (1) get a better understanding of the patterns of climate data across space and over time, (2) produce accurate maps of soil moisture (TMI), and (3) evaluate the change of soil moisture over the long term.

### 2.1 Climate classification using TMI

The Thornthwaite Moisture Index (TMI) was introduced as a new classification system for climate by geographer C W Thorthwaite in 1948 (Thornthwaite, 1948). TMI was a revolutionary proposal for its time, because it introduced a theory and a calculation method in a field previously dominated by description of observations (Keim, 2010).

After identifying that same rates of annual precipitation and temperature profiles could result in a diversity of ecological communities in different regions of the globe, Thornthwaite developed the notions of effective precipitation and potential evapotranspiration (PET) as part of a water balance model for climate classification (Philp and Taylor, 2012). TMI is an indicator of the supply of water in an area relative to the demand for water under prevailing climatic conditions (Equation 1).

$$TMI = \frac{100\alpha - 60\beta}{PET} \tag{1}$$

Where,

$\alpha$ = Water surplus

$\beta$ = Water deficiency

$PET$ = Potential evapotranspiration (water need)

And,

$\alpha = P - PET$

$\beta = PET - AE$

P = Precipitation

AE = Actual evapotranspiration

Weather is the present conditions of the elements which compose the climate, such as temperature, humidity, atmospheric pressure, wind and precipitation, and their variations over short periods. A region's climate is generally assessed over a long period of time, in order to include cyclic processes and natural variations. For the TMI calculation a range of 20 years is recommended (McManus et al.2003).

Table 1 presents the climatic zones according to TMI classification, adapted by the Australian Standard AS 2870 (SA, 1996). Positive TMI values indicate that precipitation exceeds PET in an average year, indicating wet conditions, while negative TMI values indicate that PET exceeds precipitation in an average year, indicating a dry condition (Keim, 2010).

Table 1. TMI Climatic Zones

| Climatic Zone for Australia | | Thornthwaite Moisture Index |
|---|---|---|
| 1 | Alpine/Coastal | >40 |
| 2 | Wet temperate | 10 to 40 |
| 3 | Temperate | -5 to 10 |
| 4 | Dry temperate | -25 to -5 |
| 5 | Semi-arid | -40 to -25 |
| 6 | Arid | < -40 |

TMI has been employed across a diverse range of research areas, such as suitability for agriculture (Devasenapathy et al, 2008), road infrastructure management (Austroads, 2004; Arampamoorthy and Patrick, 2010; Philp and Taylor, 2012), and light urban construction (Lopes and Osman, 2010).

In this research, TMI has been calculated for weather stations over a period of 100 years, based on historical climate data. Details of the calculation procedures applied are described in Lopes and Osman (2010). Each weather station was identified by a code, location (latitude, longitude, and altitude), TMI value for each year over a 100 year period, and the average TMI value for 20 year intervals over this period.

### 2.2 TMI mapping using spatial interpolation in GIS

Spatial interpolation is a method to estimate the values for a variable at unobserved locations in geographic space based on the values at observed locations within the same area. Having scattered data as input, it generates a continuous surface as output (Lam, 1983).

The rationale behind spatial interpolation is the first law of geography, which states “everything is related to everything else, but near things are more related than distant things” (Tobler, 1970). This means that it is possible to estimate the value for a variable at any location based on existing observations in the surroundings of this location. Therefore, spatial interpolation is an analytical form of filling gaps in data availability.

Different mathematical techniques can be used for this estimation, from simple deterministic models such as IDW (Inverse Distance Weighted), to robust geostatistical models such as Kriging (Mitas and Mitasova, 1999). The best performing interpolator varies according to the characteristic variability of the input data, density of observations, effect of geographic factors such as elevation, spatial scale, etc (Mardikis et al, 2005). The surface produced by interpolation is always a model. Different interpolation models applied to the same input data result in different outputs.

Kriging is used extensively in the geosciences, including applications for climate data (Hofstra et al, 2008), because it involves in-depth analysis of the input data attributes, variability and spatial dependency. From the understanding of existing spatial patterns of the data, parameters required for the estimation model can be identified. Co-Kriging is an extension of the ordinary Kriging method, which allows the model to include not only the variable under estimation, but also co-variables which can improve the estimation. Kriging and co-Kriging also produce indicators of the quality/accuracy of the resulting estimation.

In this research we have used spatial interpolation to generate continuous maps of TMI climatic zones for the whole study area, based on existing climatic data for a number of weather stations within the same area. ArcMap 10.1 has been used as the GIS platform for the interpolation.

The weather stations with TMI values have been located on a map by their latitude, longitude and altitude. The patterns of TMI values in the study area have been analysed using geostatistics in terms of their absolute and relative spatial distribution and dependency. After a clear understanding of the existing patterns, a TMI map for each time interval has been produced using spatial interpolation methods. A number of spatial interpolation methods have been tested. The most accurate method was Co-Kriging with latitude, longitude and altitude as co-variables. Details of the interpolation models are out of the scope of this publication. A paper focused specifically on the TMI interpolation process used in this research is under progress.

## 3. TESTING THE METHODOLOGY IN VICTORIA, AUSTRALIA

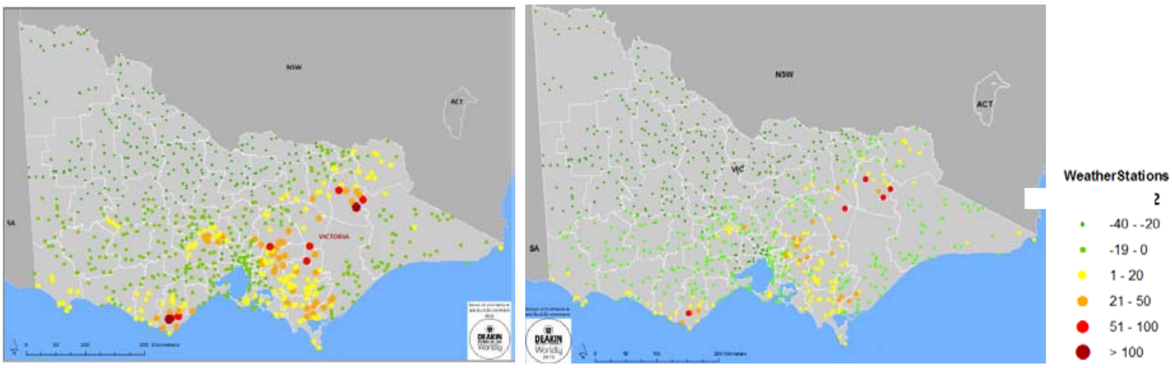
The State of Victoria, in Australia, has been used as case study. This research investigated the soil moisture change in Victoria over a period of 100 years (1913 to 2012), divided into 20 year intervals:

- T1 – 1913 to 1932
- T2 – 1933 to 1952
- T3 – 1953 to 1972
- T4 – 1973 to 1992
- T5 – 1993 to 2012

### 3.1 Understanding climatic data and TMI

This research used the Climate Data Silo, produced by the Queensland Centre for Climate Applications/Department of Natural Resources (Jeffrey et al, 2001), which contains a complete and comprehensive historical database of climate data for Australia.

A typical pattern of TMI distribution was found in Victoria, when analysing the distribution of TMI values across 737 weather stations in the state. The majority of the state surface has negative values of TMI, which means the precipitation is lower than the evapotranspiration, causing a general deficit in the soil moisture (dry conditions). Few areas have positive TMI values (precipitation above evapotranspiration, wet conditions). They are clustered in the alpine region (high altitude areas), and some highly vegetated coastal portions of the state. This general pattern, with slight local differences, was found for all five time intervals over the 100 years period. Figure 1 presents this typical pattern for Victoria, for the first and last time periods (T1 and T5, respectively).



(a) T1 – 1913 to 1932 (b) T5 – 1993 to 2012

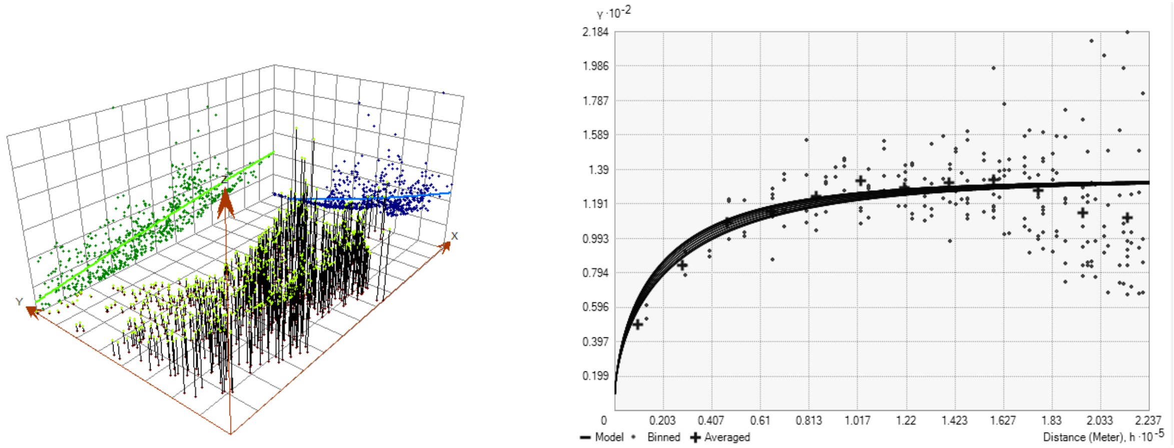
Figure 1: Spatial distribution of TMI for weather stations in Victoria

### 3.2 Estimating TMI based on geo-statistics

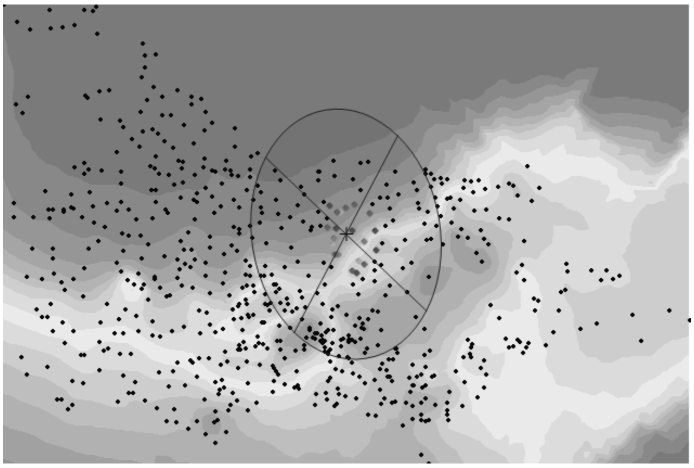
Different interpolation methods were tested (IDW with different weights, Spline, Ordinary Kriging with different parameters, and Co-Kriging with different parameters). The method that produced the most accurate results of TMI mapping for all five time intervals in Victoria was Co-Kriging with latitude, longitude and altitude as co-variables. This is consistent with findings from Carvalho et al (2010), who applied similar method for estimating TMI in a region in Brazil.

The method for Victoria required spatial trend removal for TMI values, normalisation of the altitude attributes, and anisotropy, for all the five periods. The generic models produced for each one of the five time intervals were similar, but parameters were specific to the input data for each period, and slightly different. This occurred because the model adapts to the climatic changes experienced over time.

Figure 2 presents the geostatistics analysis used to identify the parameters for spatial interpolation. Spatial trend analysis (Figure 2.a) identify the trend function of the input data in a three dimensional space. For Victoria, TMI grows from north to south and from west to east, both in a non-linear way. The semivariogram (Figure 2.b) describes the spatial dependency of the input data, and the existence of anisotropy. In Victoria, TMI variance increases with the distance between weather stations, indicating spatial dependency. The range of lines in the graph shows that there are some variations in the best fit function when different directions are considered. This implies anisotropy. Neighbourhood influence analysis (Figure 2.c) presents the distance that should be taken into consideration when estimating TMI values by interpolation. It is defined by the spatial dependency level in the semivariogram. Moreover, the shape of the neighbourhood is influenced by the existing anisotropy. In Victoria, the spatial dependency among TMI values is stronger in north/south direction than east/west. If there was no directional influence, the neighbourhood would be a perfect circle.



(a)Spatial trends (b) Semivariogram/Spatial
dependency



(c) Neighbourhood influence/anysotropy

Figure 2: Spatial Interpolation parameters for TMI map in Victoria, T1 (1913 to 19320

Figure 3 presents the resulting interpolated TMI map for the interval T1 (1913 to 1932). Using the TMI values for the existing weather stations and the parameters from the geostatistical analysis presented in Figure 2, the spatial interpolation model produced a grid surface with TMI values in each cell of the area covering the state of Victoria. Each cell has a spatial resolution of 1km$^2$ (1km x 1km). This procedure has been repeated for the five time periods, with their specific model parameters and input data.

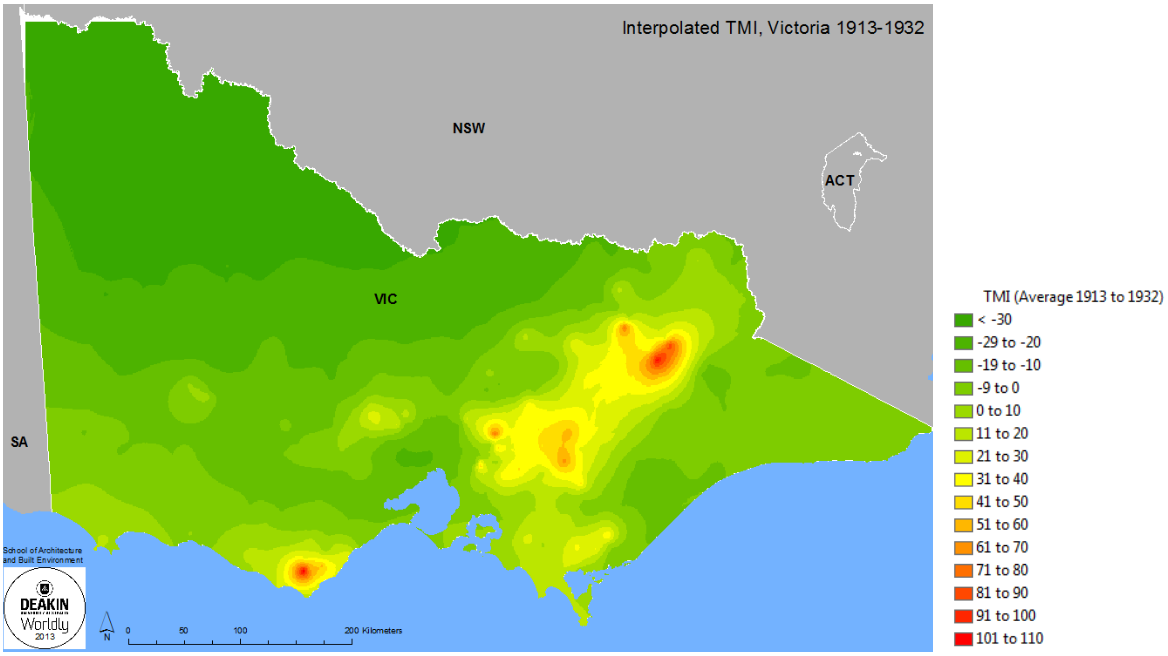


Figure 3: Spatial interpolated TMI map of Victoria for T1 (1913 to 1932)

This research used 90% of the weather stations to produce the TMI map, and the remaining 10% for validation of the process. Comparing observed and interpolated TMI values for the validation stations resulted in a high level of accuracy, with correlation coefficients (R) above 0.9 for all five intervals.

### 3.3 Evaluating TMI change

When analysed individually, the TMI maps for the five time intervals seem to have similar spatial patterns along the whole 100 years period, with a dry north and a wet coastal and alpine regions. However, slight variations on the climate zone boundaries have accumulated over the time periods. Comparing the TMI climate zones for the first (T1) and the last (T5) time intervals, it was identified that almost 30% of the surface of the State of Victoria had its TMI climatic zone changed. The change was always towards a drier condition (Figure 4).

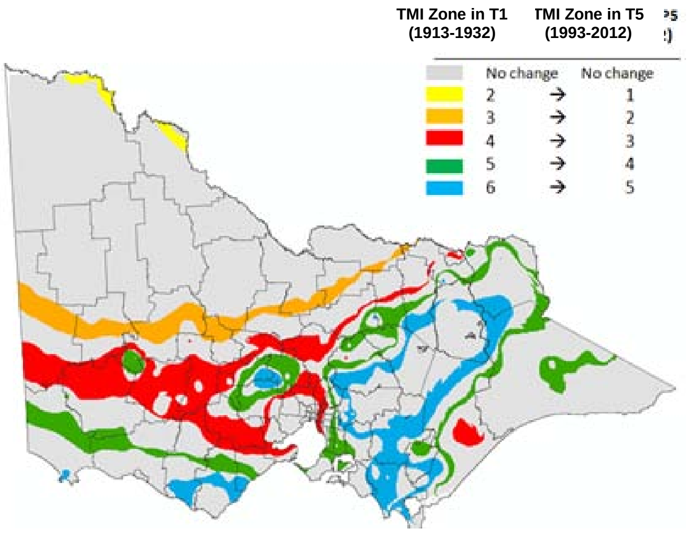


Figure 4: TMI Climate Zones Change in Victoria over the last 100 years

The analysis of the magnitude of TMI change between each pair of time intervals demonstrated that the pace of change has accelerated over time, and most of the change experience in the last 100 years, has actually occurred in the last 20 years interval. Figure 5 presents the change in area (km$^2$) for each TMI climate zone (1, 1A, 2, 3, 4 and 5) for each pair of time intervals. The area covered in Victoria by TMI climate zones 1, 1A and 2 had generally decreased, and most of this change has occurred in the last time interval (T4 to T5). At the same time, the area covered in Victoria by TMI climate zones 4 and 5 had generally increased, and most of this change has also occurred in the last time interval (T4 to T5).

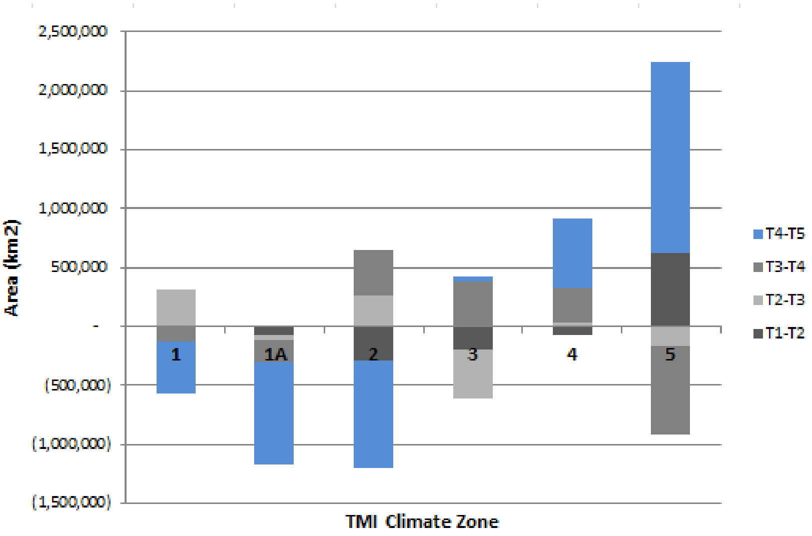


Figure 5. % of area change for each TMI climatic zone for the time intervals along the last 100 years

## 4 DISCUSSION OF RESULTS

This research, using Victoria as a case study, achieved its expected outcomes. The results have been summarised and divided into three topics, and impacts to the housing sector are discussed.

### 4.1 Development of a better understanding of the climate and soil moisture data

The geostatistical method selected for producing the TMI maps requires a thorough analysis of the input data before the modelling phase. This procedure is intrinsic to the geostatistical interpolation methods, and was essential in gaining a visual and mathematical understanding of the climate input data for the selected case study. For each individual period of time, the analysis involved a clear understanding of how climate data is distributed in space, how and where it varies, and which factors affect this variation. The knowledge produced from the geostatistical analysis was used for defining the interpolation parameters. GIS provided the platform for developing the quantitative geostatistical analysis with excellent visualisation capabilities in graphs, diagrams and maps. The main output of this research are the interpolated maps representing the magnitude and location of soil moisture measurement, based on TMI climate classification.

The geographical pattern of TMI in Victoria was characterised as mainly dry. The area of the state where rainfall is lower than evapotranspiration (TMI < 0), resulting in low soil moisture, varies from 72 to 84% over the last century. These dry soils are spread all over the state, with exception of the west coast, the alpine region, and part of the east coast of Victoria.

This pattern has been consistent over the whole century, with slight changes on the boundaries of climate zones between time periods.

Rural land uses, such as agriculture, recreation and conservation, have historically paid more attention to the impacts of climate for their development. In urban areas, the capacity of technology to produce structures and comfort with artificial systems, limited the considerations of climate. Particularly in the last two decades, the accelerated symptoms of climate change demonstrated the impacts of the modern urbanisation. These symptoms, such as increased temperatures and weather-related disasters, are a result, in significant part, from the intensive production of greenhouse emissions typical of our cities. Housing research has increasingly been involved with climate change issues. This present paper highlights one aspect within this context: the impact of climate change on soil moisture, and its further effect on causing residential foundation damages. The next two sections discuss how the understanding of climate change process through TMI can be used for climate change adaptation strategies.

## 4.2 Production of accurate TMI maps

We could not find any detailed documentation on the TMI maps produced for Australia reported in the literature. The source and characteristics of the input data, the methods applied and its parameters, and the level of accuracy of the final product are unknown.

In this research, we focused on the process of producing TMI maps in order to achieve high accuracy in the final product. Two factors have affected this achievement. First, we used extensive climate data available from the work of Jefrey et al (2001). This data is extensive in time, covering climate data in Australia from 1889, and it is also extensive in space, since it covers the whole country, having a large number of weather stations in each state. Second, we used a geostatistical method of interpolation, Co-Kriging, which is a very robust and scientific mathematical model to estimate the value of variables based on existing samples within a region. This type of model is also able to produce indicators of the level of accuracy achieved in the final product. This is essential if practical applications of the maps in planning and management are expected.

The main impact of this research for the housing sector is in the provision of important guidelines for construction of residential foundations that relies on up-to-date climatic data, and accurate methods. As mentioned before, the Australian Standard 2870 for residential footing and slabs currently display a TMI map for Victoria which is out of date and potentially inaccurate. This research provides a TMI map for the period 1993-2012, which characterises with significant accuracy the current TMI climate classification in Victoria.

Since the methodology developed in the production of these TMI maps are documented in details in a project report (Leao and Osman-Schlegel, 2013), the method can be replicated for future mapping in the same area, allowing further comparability. The documentation can also be used to extend the methodology to new areas, or to test and introduce improvements.

The industrial sector involved with the development of new technologies for residential foundation on expansive soil can also benefit from the use of TMI maps. They can assess how their technologies and systems are performing in practice in areas which suffered soil moisture change.

## 4.3 Assessment of TMI change over the century

This research produced five TMI maps for the state of Victoria, continuously covering the last century, using the same interpolation method, and with known indicators of accuracy. These settings allowed us to compare the maps and develop an understanding of how the changing climate patterns through the last century had influenced the soil moisture. This is the most important outcome of this research.

TMI mapping, as reported in many different applications in the literature worldwide, has been used to classify climate zones according to its moisture index for a specific point in time. This is a limited use that does not explore to full extent the capacity of TMI as an important climate index. With accelerated climate change, the understanding of the process of change became more important than the understanding of the current state. For climate classification using TMI it means that not only the mapping of current TMI is necessary, but the understanding of how current patterns are formed from the past, and how much has changed and where.

Victoria is getting drier. Almost 30% of the surface of Victoria has changed its TMI climate zone. The dry regions (TMI 4 and 5) are extending towards the south, reducing the wet areas on the coast and the on the alps (TMI zones 1, 1A and 2).

The understanding of this trend is very important in order to assess potential impacts of TMI change on existing residential stock. Drier conditions can intensify subsidence-related damages in dwellings. The housing stock built in Victoria in the last three decades has used the AS 2870 TMI map as a guideline which is out of date. Part of this stock is located in areas in which soil moisture has changed as a response to new climate patterns. The location and quantification of the existing stock at risk of damage from soil moisture change can be introduced in strategies for retrofitting. Current literature on research and practice for urban retrofitting is focused on technologies and systems to produce housing which uses less energy, uses required energy more efficiently, and produce less greenhouse emissions as a way to mitigate the effects of climate change. Those retrofit initiatives can be less effective in achieving their goals if a dwelling is susceptible to structural damages caused by subsidence or heave processes, such as cracks and leaks in walls, floor and duct elements.

The understanding of the progressive trend of soil moisture change, with the consideration of some scenarios for climate change in the future produced by available research, can also be used to foresee potential future TMI states. In this case, as an adaptation strategy, new building stock produced in the present can last longer by considering potential future conditions on the regions under development.

## 5 CONCLUSIONS

The results and recommendations presented and discussed above, such as the understanding of climate conditions and processes through historical TMI mapping, the inclusion of TMI in retrofitting strategies for the existing built stock, and the use of forecast TMI in adaptation strategies for the new housing stock, can potentially have a significant impact on producing more resilient urban environments. Built environments which have learned from the past, know the present, and consider trends for the future.

We anticipate some of the next steps of the research.

First, some methodological improvements in the methodology will be assed. This includes testing how different time segmentation of the 100 year period influences the soil moisture change; evaluating the inclusion of other co-variables, such as geology and vegetation; and assessing how anthropogenic factors affects TMI, such as irrigation, revegetation or clearance of areas, and impervious surfaces.

Second, after the focus on the production of the accurate historical TMI maps, the scope of the study will be directed to the issue of housing damage. We will assess the relationship between TMI change and subsidence or heave related residential damage in the last 20 years, by comparing areas at risk and records of subsidence or heave related residential damage. Zones for future urban growth in areas at risk will also be identified.

Third, the mapping will be extended geographically. After the case study in Victoria, historical TMI mapping will be extended to the whole of Australia, covering all the states and territories.

Fourth, the mapping will be extended temporally. After assessing historical mapping from the past to the present, the method will be tested into the future, using scenarios of climate change produced by CSIRO research.

We presented in this paper the first stage of our research in urban resilience. The ultimate goal of the broad research is to develop a dynamic model, based on continuous monitoring of TMI, to assist in retrofitting and adaptation strategies for existing and new housing stock. Residential construction is a substantial part of the building industry in Australia. Producing new and renovated buildings that are durable in the long term is essential for the Australian economy, environment and social welfare.

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