Methodology for Development of Drought Severity-Duration-Frequency (SDF) Curves

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

Drought monitoring and early warning are essential elements impacting drought sensitive sectors such as primary production, industrial and consumptive water users. A quantitative estimate of the probability of occurrence and the anticipated severity of drought is crucial for the development of mitigating strategies. The overall aim of this study is to develop a methodology to assess drought frequency and severity and to advance the understanding of monitoring and predicting droughts in the future. Seventy (70) meteorological stations across Victoria, Australia were selected for analysis. To achieve the above objective, the analysis was initially carried out to select the most applicable meteorological drought index for Victoria. This is important because to date, no drought indices are applied across Australia by any Commonwealth agency quantifying drought impacts. An evaluation of existing meteorological drought indices namely, the Standardised Precipitation Index (SPI), the Reconnaissance Drought Index (RDI) and Deciles was first conducted to assess their suitability for the determination of drought conditions. The use of the Standardised Precipitation Index (SPI) was shown to be satisfactory for assessing and monitoring meteorological droughts in Australia. When applied to data, SPI was also successful in detecting the onset and the end of historical droughts.

Temporal changes in historic rainfall variability and the trend of SPI were investigated using non-parametric trend techniques to detect wet and dry periods across Victoria, Australia. The first part of the analysis was carried out to determine annual rainfall trends using Mann Kendall (MK) and Sen’s slope tests at five selected meteorological stations with long historical records (more than 100 years), as well as a short sub-set period (1949-2011) of the same data set. It was found that different trend results were obtained for the sub-set. For SPI trend analysis, it was observed that, although different results were obtained showing significant trends, SPI gave a trend direction similar to annual precipitation (downward and upward trends). In addition, temporal trends in the rate of occurrence of drought events (i.e. inter-arrival times) were examined. The fact that most of the stations showed negative slopes indicated that the intervals between events were becoming shorter and the frequency of events was temporarily increasing. Based on the results obtained from the preliminary analysis, the trend analyses were then carried out for the remaining 65 stations. The main conclusions from these analyses are summarized as follows; 1) the trend analysis was observed to be highly dependent on the start and end dates of analysis. It is recommended that in the selection of time period for the drought, trend analysis should consider the length
of available data sets. Longer data series would give more meaningful results, thus improving the understanding of droughts impacted by climate change. 2) From the SPI and inter-arrival drought trends, it was observed that some of the study areas in Victoria will face more frequent dry period leading to increased drought occurrence. Information similar to this would be very important to develop suitable strategies to mitigate the impacts of future droughts.

The main objective of this study was the development of a methodology to assess drought risk for each region based on a frequency analysis of the drought severity series using the SPI index calculated over a 12-month duration. A novel concept centric on drought severity-duration-frequency (SDF) curves was successfully derived for all the 70 stations using an innovative threshold approach. The methodology derived using extreme value analysis will assist in the characterization of droughts and provide useful information to policy makers and agencies developing drought response plans. Using regionalization techniques such as Cluster analysis and modified Andrews curve, the study area was separated into homogenous groups based on rainfall characteristics. In the current Victorian application the study area was separated into six homogeneous clusters with unique signatures. A set of mean SDF curves was developed for each cluster to identify the frequency and severity of the risk of drought events for various return periods in each cluster. The advantage of developing a mean SDF curve (as a signature) for each cluster is that it assists the understanding of drought conditions for an ungauged or unknown station, the characteristics of which fit existing cluster groups. Non-homogeneous Markov Chain modelling was used to estimate the probability of different drought severity classes and drought severity class predictions 1, 2 and 3 months ahead. The non-homogeneous formulation, which considers the seasonality of precipitation, is useful for understanding the evolution of drought events and for short-term planning. Overall, this model predicted drought situations 1 month ahead well. However, predictions 2 and 3 months ahead should be used with caution.

Many parts of Australia including Victoria have experienced their worst droughts on record over the last decade. With the threat of climate change potentially further exacerbating droughts in the years ahead, a clear understanding of the impact of droughts is vital. The information on the probability of occurrence and the anticipated severity of drought will be helpful for water resources managers, infrastructure planners and government policy-makers with future infrastructure planning and with the design and building of more resilient communities.
CHAPTER 1

INTRODUCTION

1.1 Background

Droughts occur over most parts of the world, in both dry and humid regions and affect human welfare and food security. In south-eastern Australia (Victoria, parts of New South Wales and South Australia), several major droughts have occurred in the past, including the Federation drought (1895 - 1903), the World War II drought (1937 - 1945), and in 1963-1968, 1982-1983 and from 1991-1995. In recent years (from 1997 to 2009), most of Australia suffered from precipitation deficit-driven drought over an extended period, which adversely impacted living standards, primary production, economic prosperity and environmental health (Ummenhofer et al., 2009). The twelve-year prolonged dry period included four major drought years covering 1997, 2002, 2006 and 2008. As a result, many aspects of drought have received much attention over the last decade in Australia.

Drought is referred to as a creeping phenomenon, as its effects often take time (weeks or months) to impact. This makes it challenging to determine when a drought begins and likewise, when a drought is over. Owing to the frequent occurrence of drought and its slowly developing nature, the development of a comprehensive drought monitoring system that can provide early warning of drought onset and its end should be given more attention. With such information, the economic, social and environment impacts of drought could be reduced. Drought indices are often used for detecting the early onset and end of droughts. Several drought indices have been used effectively as drought assessment tools in other parts of the world (Hayes et al., 1999; Tsakiris et al., 2007; Asadi Zarch et al., 2011; Barua et al., 2011). In Australia, the Bureau of Methodology (BoM) uses Deciles to assess the status of rainfall deficiency throughout Australia. Formal drought declarations and assistance are handled by state and Commonwealth governments. In Victoria for example, the Department of Environment and Primary Industries is responsible for the provision of information related to drought. The Commonwealth government is responsible for national policy and implementing national drought relief initiatives such as drought relief packages. Therefore,
the Commonwealth and the states would greatly benefit from the development of an appropriate drought assessment tool that could apply consistently across jurisdictions.

Drought forecasting is an important aspect of drought hydrology and it plays a major role in risk management, drought preparedness and the implementation of mitigation measures. Extensive work has been done on modelling various aspects of drought, such as the identification and prediction of its duration and severity. However, a major research challenge still remains, primarily requiring the application of suitable techniques for forecasting the onset and termination points of droughts, especially in Australia.

1.2 Research Questions

As vulnerability to drought has increased globally, greater attention has been directed to reducing the risks associated with its occurrence. The present study therefore seeks to answer the following questions:

- What is the most applicable meteorological drought index for Victoria?
- Are there any trends in the climatic data and inter-arrival times of droughts?
- Can drought forecasting tools provide information (severity, probability, duration) on future droughts?
- What is the probability of the occurrence of droughts?

1.3 Aims of the study

The main aim of this research project is to develop a methodology to assess drought frequency and severity and to forecast droughts in the future. The aim of the study was achieved by primarily undertaking the following tasks:

1) Reviewing drought indices
2) Selecting the most applicable meteorological drought index for Victoria.
3) Analysing rainfall and drought severity trends for selected locations.
4) Developing the drought severity-duration-frequency (SDF) curves for various return periods over the region.
5) Identifying homogeneous regions with similar drought characteristics.
6) Developing SDF curves for each homogenous region.
7) Forecasting future drought conditions using drought forecasting tools for short durations (less than or equal to 3 months).

1.4 Research significance

In this section, the significance of the research and the possible outcomes are discussed. These contributions are outlined below:

- As was mentioned in Section 1.1, to date, there have been no drought indices applied across Australia by any Commonwealth agency except the Bureau of Methodology (BoM), which uses Deciles to assess the status of rainfall deficiency throughout Australia. In Australia, state-based agencies are responsible for operational decision-making. They use independently-derived indices to assist operational planning. As there is no consistency between regions and states, comparison either within a state or between states in a region is difficult. Therefore, there is a need to select the most appropriate drought index and apply it consistently throughout Australia to provide essential information on droughts (e.g. lead time, duration, magnitude (or severity), the onset and end of drought, etc.) which would help state-based organisations and the Commonwealth to plan and implement responses and mitigation measures.

- Trend analysis will facilitate the identification of any possible trends in climatic parameters which directly influence the occurrence of drought. To date, no comprehensive research has been conducted on drought severity trends in the country. Hence, whether there is a possible trend in the risk of occurrence of drought events will be determined.

- Drought information is often too technical and difficult to understand by decision-makers and end-users. This study aims to initially derive information about drought and its recurrence using precipitation information which can be understood easily by ordinary users.

- Regionalization methods for catchment groupings will identify homogenous areas with respect to drought. That is, stations that depict similar drought characteristics will be identified. This will reduce the heterogeneity of the study area so that the
methodology developed can be used with greater confidence to predict vulnerability to drought at any location within a particular region. Regionalization methods have been used for the classification and comparison of different aspects of yield hydrology, but not for drought characterisation. This study aims to explore regionalisation techniques for droughts.

- The drought-forecasting model will also be applied in this study and it is a useful tool which can become part of an early warning system to provide early indication of future drought conditions. Short-term prediction of the drought severity for the following one, two and three months could be achieved.

### 1.5 Outline of the Thesis

Chapter 1 describes the background of the research, the aims and the research significance. It also formulates the research questions to be addressed and provides an overall picture of the research tasks undertaken in the thesis.

Chapter 2 presents a comprehensive critical review of research related to drought indices and drought forecasting techniques and history of Australian droughts. This chapter identifies the current state of knowledge and research gaps in drought management.

Chapter 3 provides a description of the study area, the climatic data used and relevant information on the selected rainfall stations. The procedures of gap filling of monthly rainfall data are also given. This chapter also presents results of preliminary analysis on the assessment of droughts using meteorological drought indices (i.e. Standardised Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Theory of Runs (ToR)) that paved the way for the subsequent analyses. The work presented here has been published in *Journal of Hydrological Reasearch*.

Chapter 4 investigates the trend by non-parametric tests and a change point analyses (to detect point of change) of rainfall data for shorter and longer data lengths. This chapter also examines the spatial and temporal distributions of identified trends. The work presented here has been published in *Journal of Water and Climate Change*. Similar to the above analysis, this chapter provides the trend of wet/dry periods using selected meteorological drought index, namely the SPI and the temporal trends in drought events.
Development of the drought severity-duration-frequency (SDF) curves is presented in Chapter 5. This chapter also applies multivariate statistical techniques to identify homogeneous regions based on climatic characteristics which are related to the selected drought index. An independent validation of the SDF curves is also presented.

Chapter 6 presents the use of Markov Chain modelling in order to estimate the probability of different drought severity classes and drought severity class predictions at one, two and three months ahead. Predictions of drought are also tested for historical drought events in Victoria and reported in this chapter.

Finally, Chapter 7 presents a summary and the main conclusions drawn from individual research components. Recommendations for future work are also presented.
Figure 1.1 Outline of the thesis
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the definition of drought and its classification. These aspects of droughts have been widely discussed in the literature and remain major research topics. Some findings that have been reported from other studies are also reviewed and discussed. Precipitation, temperature, wind and relative humidity are important factors to include in characterizing drought. Since these climatic parameters vary temporally and spatially, there is a need to consider these meteorological aspects to assess drought frequency and severity, and to forecast droughts in the future.

Drought means different things to different people, depending on their choice of the form of water and its related aspects of interest. Hence, it is important to characterise drought into meteorological, hydrological, agricultural and socio-economic droughts (Beran and Rodier, 1985; Wilhite and Glantz, 1985; Nalbantis and Tsakiris, 2009). Meteorological drought is commonly defined as lack of precipitation over a region over a period of time. The consequential impacts of a meteorological drought over time lead to other drought categories, i.e. agricultural, hydrological or socio-economic droughts (Dracup et al., 1980; Khalili et al., 2011), as shown in Figure 2.1. Many studies involving precipitation have been carried out for meteorological drought analysis (Hayes et al., 1999; Khan et al., 2008; Gocic and Trajkovic, 2014).

Hydrological drought is expressed based on the inadequacy of surface or sub-surface water supply in terms of streamflow, reservoir storage and groundwater depths. A number of studies have analysed streamflow to better understand hydrologic droughts (Tallaksen and van Lanen, 2004; Nalbantis, 2008; Sharma and Panu, 2012; Tabari et al., 2013). Agricultural drought is defined as a reduction in soil moisture due to a shortfall of precipitation coupled with high evaporation rates (Tallaksen and van Lanen, 2004). On the other hand, socio-economic drought is associated with failure of water resources to meet
water demands, thus associating droughts with supply and demand shortfalls. Economic impacts include both direct effects, such as lost income from crop yield reduction and secondary effects such as reduced spending in rural communities (American Meteorological Society, 2004).

**Figure 2.1** Sequence of drought occurrence (Source: National Drought Mitigation Center, University of Nebraska–Lincoln, USA; http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx)

In contrast to meteorological droughts, the other three types of droughts occur less frequently because it usually takes weeks or months before precipitation deficiencies cause soil moisture deficiencies, declines in streamflow, reduced reservoir levels and lower groundwater tables. Therefore, for drought monitoring and early warning purposes, the meteorological drought indices provide the best initial assessment. Once the meteorological indices indicate the onset of a drought, other non-meteorological indices
provide complementary information to the relevant sectors describing the severity and impact.

2.2 Drought history in Australia

In Australia, several significant droughts have occurred in the past, including 1864-1866, 1880-1886, 1895-1903, 1911-1916, 1918-1920, 1939-1945, 1963-1968, 1972-1973, 1982-1983 and 1991-1995 (refer to Table 2.1), costing the Australian economy billions of dollars (Bureau of Meteorology (BoM), 2011). Droughts have destroyed crops, decimated live stock numbers, drained rivers and dams, restricted urban consumption and industry demand, compromised water-dependent eco systems and created conditions suitable for catastrophic bushfires.

Table 2.1 Historic droughts in Australia (Bureau of Meteorology (BoM), 2011)

<table>
<thead>
<tr>
<th>Year(s)</th>
<th>Description</th>
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<tr>
<td>1864-66</td>
<td>All states affected except Tasmania</td>
</tr>
<tr>
<td>1880-86</td>
<td>Southern and eastern states affected</td>
</tr>
<tr>
<td>1895-1903</td>
<td>The Federation drought. Several years of generally below average rainfall followed immediately by one or two years of exceptionally low rainfall. Most devastating drought in terms of stock losses.</td>
</tr>
<tr>
<td>1911-16</td>
<td>Loss of 19 million sheep and 2 million cattle.</td>
</tr>
<tr>
<td>1918-20</td>
<td>Only parts of Western Australia free from drought.</td>
</tr>
<tr>
<td>1939-45</td>
<td>The Forties drought. Loss of nearly 30 million sheep between 1942 and 1945. 1940 was one of the driest years on record across southern Australia.</td>
</tr>
<tr>
<td>1963-68</td>
<td>Widespread drought. Also longest drought in arid central Australia: 1958-67. The last two years saw a 40 per cent drop in wheat harvest, a loss of 20 million sheep, and a decrease in farm income of $300-500 million.</td>
</tr>
<tr>
<td>1972-73</td>
<td>Mainly in eastern Australia</td>
</tr>
<tr>
<td>1982-83</td>
<td>Total loss estimated in excess of $3000 million. Most intense drought in terms of vast areas affected.</td>
</tr>
<tr>
<td>1991-95</td>
<td>Particularly dry in parts of Queensland, northern New South Wales and parts of central Australia. Average production by rural industries fell about 10 per cent, resulting in possible $5 billion cost to the Australian economy.</td>
</tr>
<tr>
<td>2002-07</td>
<td>Winter crop production declined sharply in 2002-03 and, after recovering, declined again in 2006-07. The Murray-Darling Basin inflows were the lowest on record, severely affecting irrigated agriculture.</td>
</tr>
</tbody>
</table>
In the most recent drought, south-eastern Australia (Victoria, parts of New South Wales and South Australia) experienced low rainfall from 1997 to 2009, known as the Big Dry or Millennium Drought (Ummenhofer et al., 2009; Potter et al., 2010; Verdon-Kidd et al., 2010). Figure 2.2 illustrates rainfall in the most recent 14-year period (from October 1996 to September 2010) was the lowest on record for areas shaded in solid red. The twelve-year prolonged dry period saw four major drought years beginning in late 1997, 2002, 2006 and 2008 (Gergis et al., 2012). Tan and Rhodes (2008) reported the 2006 annual inflow into four major water harvesting reservoirs supplying 4.5 million people in the greater Melbourne area to be the lowest on record. The Thomson reservoir built as Melbourne’s drought reserve supplying 4.5 million people went from almost full in 1996 to just 16% full in 2009 (Melbourne Water, 2010). This resulted in prolonged water restrictions applied across the city, adversely impacting industry, small business and lifestyle. This drought catalysed the building of the largest desalination plant in the southern hemisphere to provide back-up water supply for Melbourne. In 2010, even though widespread above-average rainfall fell across most of Australia, it did not end the long-term rainfall deficiencies affecting large parts of southern Australia (National Climate Centre, 2010).

Figure 2.2 Australian rainfall deciles for the 14 years from October 1996 to September 2010 (Bureau of Meteorology (BoM), 2010)
2.3 Review of Drought Indices (DIs)

The success of drought preparedness and mitigation depends, to a large extent, upon timely information on drought onset and its end. These types of information can be obtained from drought indices, which provide decision-makers with information on drought severity and can be used to prepare drought contingency plans. Drought indices (DIs) have also been commonly used to quantify rainfall deficits, soil moisture and water availability (Morid et al., 2006; Mishra and Singh, 2010). Many meteorological drought indices have been developed to date. Other indices that have been used widely include the Palmer Drought Severity Index (PDSI) (Palmer, 1965), Percent of Normal (PN), Deciles (Gibbs and Maher, 1967), Standardized Precipitation Index (SPI) (McKee et al., 1993), Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis, 2005), Aggregated Drought Index (ADI) (Keyantash and Dracup, 2004), Streamflow Drought Index (SDI) (Nalbantis and Tsakiris, 2009), Groundwater Resource Index (Mendicino et al., 2008) and Nonlinear Aggregated Drought Index (ADI) (Barua et al., 2012). The following section discusses commonly-used DIs, their usefulness and limitations.

2.3.1 Palmer Drought Severity Index (PDSI)

Palmer (1965) first introduced the Palmer Drought Severity Index (PDSI) in the United States. The objective of the PDSI was to provide measurements of moisture conditions that were standardized so that comparisons using the index values would have comparable meaning at all locations and times (Palmer, 1965). The PDSI has been well tested and verified. The PDSI responds to weather conditions that are abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by PDSI ends without taking into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts (Karl and Knight, 1985). The PDSI is calculated based on precipitation and temperature data, as well as the local available water content (AWC) of the soil. From the above input parameters, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff and moisture loss from the surface layer (Hayes, 2003). Despite its widespread use, PDSI has many limitations (Alley, 1984; Hayes, 2003).
Its limitations include the arbitrary assumptions related to the water balance models used in the computation of PDSI. For instance, there is no universally accepted method of computing potential evapotranspiration. Although the Thornthwaite (1948) technique has wide acceptance, it requires a great deal of data but is still considered to be an approximation (Alley, 1984; Hayes, 2003). The simple two-layer water budget model of Palmer (1965) is used to estimate the soil moisture content in a catchment if measured soil moisture data are not available. However, due to lack of data, the two soil layers within the water balance computation are often simplified, and thus may not accurately represent a particular location. Furthermore, the PDSI method is more suitable for the characterization of agricultural droughts, since the model focuses on soil moisture. The method used to calculate PDSI does not do well in regions where there is extreme variability of rainfall or runoff, such as in Australia and South Africa (Hayes, 2003).

2.3.2 Standardized Precipitation Index (SPI)

One of the most well-known and widely-used meteorological drought indices is the Standardized Precipitation Index (SPI). The SPI was designed by McKee et al. (1993) at Colorado State University to quantify the precipitation deficit for multiple time scales (i.e. 1, 3, 6, 12, 24 and 48 month cumulative moving values). However, Dogan et al. (2012) concluded that the 1-month time scale should not be used solely in comparison studies to present a drought index, unless there is a specific reason. The 1-month time step was found to be irrelevant in arid/semi-arid regions because seasonal rainfall deficiencies are common there.

The SPI is basically the transformation of the precipitation time series into a standardized normal distribution. The SPI has the following positive characteristics: (a) It is uniquely related to probability; (b) the precipitation used in the SPI can be used to calculate the precipitation deficit (c) the SPI is normally distributed, so it can be used to monitor wet as well as dry periods (Tsakiris et al., 2007). The SPI has been used extensively because it can be computed for a variety of time scales relatively easily. This versatility allows the SPI to be used as a surrogate to monitor short-term water supplies, such as soil moisture, which is important for agricultural production and long-term water
resources, such as groundwater, streamflow, and lake and reservoir levels (McKee et al., 1993).

Dogan et al. (2012) in their study to determine the effect of time scales for choosing an appropriate value using six drought indices concluded that the SPI was more consistent in detecting droughts for different time steps. In addition, the SPI requires only rainfall data which are usually available in most countries for many locations. It can also be applied consistently across jurisdictions as the methodology has inbuilt standardisation of the specific index. In addition, after a comprehensive review, the World Meteorological Organization (WMO) recommended the use of the SPI to determine meteorological droughts and to complement local meteorological drought indices (Hayes et al., 2011).

The SPI has found widespread application for describing and comparing actual drought events in the United States (Hayes et al., 1999; Heim Jr, 2002; Keyantash and Dracup, 2002), Turkey (Sonmez et al., 2005; Turkes and Tatli, 2009), the Mediterranean area (Lana et al., 2001; Tsakiris and Vangelis, 2004; Paulo and Pereira, 2006; Vicente-Serrano, 2006; Nalbantis and Tsakiris, 2009; Gocic and Trajkovic, 2014) and other parts of the world (Mishra et al., 2009; Khalili et al., 2011).

The length of the precipitation record plays an important role in calculating the SPI. Different lengths of record and similar gamma distributions over different time periods would give consistent results in the SPI. In contrast, the SPI values might be inconsistent when the distributions are different. Hence, it is recommended that the SPI user should be aware of the numerical differences in the SPI values if different lengths of records are used (Mishra and Singh, 2010). Further details of the SPI are given in Section 3.6.1.

2.3.3 Reconnaissance Drought Index (RDI)

Tsakiris and Vangelis (2005) observed that, as meteorological droughts manifest as a water deficit, the focus can be on the water balance (input - precipitation and output - potential evapotranspiration). Based on this, a new drought characterization index known as the Reconnaissance Drought Index (RDI) was proposed. RDI is based on the ratio between precipitation and potential evapotranspiration (Tsakiris and Vangelis, 2005).
Three expressions of RDI were given by Tsakiris and Vangelis (2005) as the initial, normalized and standardized values.

RDI has been successfully applied in several Mediterranean countries (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007; Pashiardis and Michaelides, 2008; Tigkas, 2008) and Iran (Asadi Zarch et al., 2011; Khalili et al., 2011). While a number of studies have been applied using the SPI, few studies have focused on the RDI. One reason may be the fact that the RDI requires much more analytical detail and information than SPI, i.e. the computation of potential evapotranspiration requires the long-term availability of a number of parameters and data for the site under study.

Some of the advantages of the RDI index are that it can be calculated for any period of time (e.g., 1, 2, 3 months etc.) and it is sensitive to drought events (Tsakiris et al., 2007). One of the limitations of this index is that it is calculated starting at the beginning of each year for all time scales. For shorter time scales, the RDI cannot identify all drought events that might occur within one whole year (i.e. 3- and 6-month time scales). Further details of RDI are given in Section 3.6.2.

2.3.4 Deciles

Gibbs and Maher (1967) suggested another drought-monitoring technique by arranging monthly precipitation data into deciles. The Deciles is commonly used by the Australian Bureau of Meteorology (BoM) to assess the status of rainfall deficiency throughout Australia. In calculating deciles, long-term monthly rainfall records are first ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is then split into 10 parts or deciles on the basis of equal probabilities (Gibbs and Maher, 1967). The deciles are grouped into five classifications. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences and so on, until the tenth decile, which is the largest one-tenth of precipitation amounts within the long-term record.
The application of Deciles is found in Tsakiris et al. (2007), Kanellou et al. (2008) and Behzadi (2013). Kanellou et al. (2008) summarise that Deciles can be used as an indication of drought but they do not provide information about the onset, the end and the severity of the drought, which are important features of drought monitoring. Another limitation is that droughts are defined arbitrarily based on a selected threshold and hence differ from one location to the other (Nazahiyah et al., 2014). Further details of Deciles are given in Section 3.6.3.

### 2.3.5 Other drought indices

Other drought indices that have been developed, and their advantages and drawbacks are presented in Table 2.2. The Surface Water Supply Index (SWSI) was developed by Shafer and Dezman (1982) to complement the Palmer Index for moisture conditions across the state of Colorado. The objective of SWSI was to incorporate both hydrological and climatological features into a single index value resembling the Palmer Index for each major river basin in the state of Colorado (Shafer and Dezman, 1982). Palmer (1965) developed the Palmer Hydrological Drought Index (PHDI), which is very similar to the PDSI, using the identical water balance assessment on a two-layer soil model. In 2008, Nalbantis (2008) proposed a much simpler two-dimensional relationship of severity versus frequency called the Streamflow Drought Index (SDI).

The Aggregate Drought Index (ADI) was developed by Keyantash and Dracup (2004). The ADI comprehensively considers all physical forms of drought (meteorological, hydrological, and agricultural) through the selection of variables that are related to each drought type. Barua et al. (2012) proposed a data-hungry complex Nonlinear Aggregate Drought Index (NADI) which counters the weaknesses of ADI.
Table 2.2 Major drought indices (DIs) in use

<table>
<thead>
<tr>
<th>Indices</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardized Precipitation Index (SPI)</td>
<td>• Simple. Based only on precipitation</td>
<td>• Access to a long, reliable temporal time series;</td>
</tr>
<tr>
<td>(McKee et al., 1993)</td>
<td>• Versatile: Can be computed for any time scale</td>
<td>• Regions with low precipitations can give misleading SPI values for short time periods (1, 2 month)</td>
</tr>
<tr>
<td></td>
<td>• Can provide early warning of drought and help assess drought severity</td>
<td></td>
</tr>
<tr>
<td>Percent of Normal</td>
<td>• Simplest measurements of rainfall</td>
<td>• Easily misunderstood as &quot;normal&quot; is a mathematical construct that does not necessarily correspond with what you should expect the weather to be</td>
</tr>
<tr>
<td>(Gibbs and Maher, 1967)</td>
<td>• Very effective when used for a single region or a single season</td>
<td></td>
</tr>
<tr>
<td>Deciles (Gibbs and Maher, 1967)</td>
<td>• Provides an accurate statistical measurement of precipitation</td>
<td>• Accurate calculations require a long climatic data record</td>
</tr>
<tr>
<td></td>
<td>• Its computational ease.</td>
<td>• Simplicity can lead to conceptual difficulties.</td>
</tr>
<tr>
<td>Reconnaissance Drought Index (RDI)</td>
<td>• It is physically based, since it calculates the aggregated deficit</td>
<td>• Should consider actual (is the real output) and not the potential evapotranspiration.</td>
</tr>
<tr>
<td>(Tsakiris and Vangelis, 2005)</td>
<td>between precipitation and the evaporative demand of the atmosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• It can be effectively associated with agricultural and hydrological</td>
<td></td>
</tr>
<tr>
<td></td>
<td>drought.</td>
<td></td>
</tr>
</tbody>
</table>
### Table 2.2 Major drought indices (DIs) in use (continued)

<table>
<thead>
<tr>
<th>Indices</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Water Supply Index (SWSI)</td>
<td>• Represents water supply conditions unique to each basin</td>
<td>• Changing a data collection station or water management requires that new algorithms be calculated, and the index is unique to each basin, which limits interbasin comparisons</td>
</tr>
<tr>
<td>(Shafer and Dezman, 1982)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palmer Hydrological Drought Index (PHDI)</td>
<td>• Accounts not only for precipitation totals, but also for temperature, evapotranspiration, soil runoff, and soil recharge</td>
<td>• Complex</td>
</tr>
<tr>
<td>(Palmer, 1965)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streamflow Drought Index (SDI)</td>
<td>• Its simplicity</td>
<td>• Requires streamflow data of high quality and of sufficient length to accurately estimate the frequency of rare drought phenomenon</td>
</tr>
<tr>
<td>(Nalbantis, 2008)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate Drought Index (ADI)</td>
<td>• Considers all physical forms of drought (meteorological, hydrological, and agricultural)</td>
<td>• It assumes linear relationships between variables in formulating principal components</td>
</tr>
<tr>
<td>(Keyantash and Dracup, 2004)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonlinear Aggregate Drought Index (NADI)</td>
<td>• Considers all potential hydro-meteorological variables</td>
<td>• Complex</td>
</tr>
<tr>
<td>(Barua et al., 2012)</td>
<td></td>
<td>• It is yet to be tested in other regions.</td>
</tr>
</tbody>
</table>
2.4 Comparison of Drought Indices (DIs)

Several studies have been carried out to compare indices to find the most appropriate indices for specific regions. There have been comparisons between SPI and RDI for drought monitoring. Khalili et al. (2011) concluded that both indices exhibit an overall similar behaviour; particularly, they follow the first order Markov chain dependency. Similarly, Asadi Zarch et al. (2011) found the SPI and RDI methods showed approximately similar results for the effect of drought in different regions of Iran. Guttman (1998) compared PDSI with SPI and concluded that special characteristics of PDI vary from site to site (1035 sites) throughout the US, while those of SPI do not vary from site to site. Also, PDI has a long-term moisture memory, is highly variable and complicated, making it hard to interpret the representation of the index. On the other hand, SPI is easy to interpret using a simple moving average process and is spatially consistent. Lloyd-Hughes and Saunders (2002) concluded that SPI provides a better spatial standardization than PDSI with respect to extreme drought events. Kanello et al. (2008) compared three indices, namely Deciles, Palmer-Z index (Palmer, 1965) and RDI, and concluded that these indices are satisfactory to describe drought conditions in Greece and they all show similar characteristics.

Morid et al. (2006) compared the performances of six drought indices in the Tehran province of Iran. The indices included Deciles index (DI), Percent of Normal (PN), Standard Precipitation Index (SPI), China-Z index (CZI), Modified CZI (MCZI), Z-Score, and Effective Drought Index (EDI). The results showed that SPI, CZI and Z-Score performed similarly with regard to drought identification and responded slowly to drought onset. SPI and EDI were able to detect the onset of a drought, its spatial and temporal variation consistently. Five drought indices, namely, Percent of Normal (PN), Deciles, Standardized Precipitation Index (SPI), Surface Water Supply Index (SWSI), and Aggregated Drought Index (ADI) were evaluated for the Yarra River catchment in Victoria, Australia (Barua et al., 2011). The study showed that PN, Deciles, and SPI have similarities in detecting historical droughts as was expected, because they were developed with rainfall as the single variable. Different results could have been obtained if different time scales were applied for each DI. In this study the authors used a monthly (1-month) time step. Both SWSI and ADI showed smoother transitional characteristics during droughts and from dry to wet spells and vice versa.
2.5 Theory of runs

Apart from the indices, the use of run analysis has been proposed as an objective method for identifying drought periods and for the evaluation of the statistical properties of drought. According to this method, a drought period coincides with a negative run, defined as a consecutive number of intervals where a selected hydrological variable remains below a chosen truncation level or threshold (Yevjevich, 1967). Such a threshold may be a fixed value in the case of a non-periodic (e.g., annual) stationary time series, or a seasonally varying truncation level in the case of a stationary periodic series.

The threshold level in each time interval is usually assumed to be equal to the long-period mean of the variable of interest, while other possible choices include a fraction of the mean (Clausen and Pearson, 1995), a value corresponding to a given non-exceedence probability (Zelenhasic and Salvai, 1987), or a level defined as one standard deviation below the mean (Ben-Zvi, 1987; Paulo and Pereira, 2006). In any case, the threshold should be chosen in such a way that it is considered representative of the water demand level (Rossi et al., 1992).

As discussed in Section 1.1, no drought indices are currently applied across Australia, and it is important to carry out a study in order to select the most appropriate drought index. The current study focuses on meteorological drought indices. Therefore, certain meteorological drought indices, namely Standardised Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Deciles, will be assessed in order to investigate how well these indices reflect drought conditions in Victoria, Australia. This will be discussed in Chapter 3.

2.6 Spatial and temporal variation of climatic variables and drought analysis

Droughts are regional in nature and often characterized by temporary departures from normal precipitation resulting in severe water shortage (Ganguli and Reddy, 2014). Variability in precipitation imposes a challenge for the sustainable management of water resources. Understanding this variability and the factors influencing this phenomenon is very important for water managers and policy-makers (Loch et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) (2007) reported that significant trends were observed in
precipitation in many regions from 1900 to 2005. Precipitation decreased on the Mediterranean coast and in southern Africa and parts of southern Asia, whereas precipitation increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia. Climate change projections for Victoria suggest that, although increases and decreases in rainfall are projected in the future, decreases dominate the overall pattern, especially in the south in winter and spring (Suppiah et al., 2007).

Other climatic variables that have an impact on drought are temperature, wind and relative humidity, and they need to be considered when characterizing drought. Suppiah et al. (2004) reported that there is a considerable spatial variability in temperature in different parts of Victoria. The study predicted that by 2070, the number of days with temperatures greater than 35°C will be 17 per year in Melbourne (south Victoria) and as high as 51 days per year in Mildura (north-west Victoria). This study also observed that the reduction in relative humidity would be 2% in west/north-west Victoria and 1% in south/south-east Victoria. Due to decreasing rainfall and increasing temperature projected, drought projections for Australia suggest that up to 20% more drought months will occur over most of Australia by 2030, with up to 40% more droughts by 2070 in eastern Australia, and up to 80% more in south-western Australia (Mpelasoka et al., 2008).

Overall, it is important to understand the varying characteristics of dryness and wetness for predicting and preventing disasters brought about by extreme events such as drought. For instance, Du et al. (2012) applied the Standardized Precipitation Index (SPI) to analyse dry/wet conditions and for drought/flood monitoring in Hunan Province, China, while in western India, Ganguli and Reddy (2014) carried out a study to detect potential trends in long-term time series of the SPI in order to seek climate change impacts. Monitoring changes in the occurrence and length of dry spells is of obvious importance, since it is directly relevant for food and water supplies. Subash and Ram Mohan (2011) investigated the possible trends in monsoon rainfall and frequency of droughts using the SPI covering a 100 year period (1906-2005) to assess rice-wheat productivity in India. In addition, the detection of changes in climatic variables is significant in planning climate change adaptation measures, hydrologic modelling studies, establishing the validity of the dataset for frequency analysis and infrastructure design. Changes in climatic variables may be in the form of
gradual trends over some period in time, a more abrupt change or in a more complex form (Kundzewicz and Robson, 2004).

Monitoring and forecasting drought are real challenges in water resources management. However, they are essential as droughts are becoming more common and severe due to the impact of climate change (Meehl et al., 2000; Alexander et al., 2009; Mishra et al., 2009). Analysing historical drought events is essential to determine the potential risk of droughts occurring in the future. Each drought event is unique in its intensity, duration, peak and spatial extent. An event might persist for few months, years, or even more. The frequency of droughts at various levels of severity, duration and peak provides the exposure risk of drought in a region. It is critical to understand the nature of drought risk in order to establish comprehensive and integrated drought management strategies. Appropriate management of droughts requires knowledge of the expected frequency of drought magnitude, which can be achieved by employing probabilistic approaches (Ganguli and Reddy, 2014).

Given that Australia is one of the most drought-prone continents in the world, such probability analyses would assist policy makers to plan mitigation measures. A methodology needs to be developed to assess drought risk in Victoria based on frequency analysis of drought severity. Moreover, derived drought information is too technical and difficult to understand by decision-makers and end-users. The present study aims to initially derive information about drought and its recurrence that can be understood easily by ordinary users. The methodology proposed will be discussed in Chapter 5.

Owing to high spatial and temporal climatic variability and frequent dry periods, causing water scarcity, rationale water management decision-making is complex (Raziei et al., 2008; Nikbakht et al., 2013). Therefore, it is important to identify homogeneous areas that depict similar drought characteristics to assist water resources planning and management. Raziei et al. (2008) carried out regionalization based on precipitation in western Iran using principal component analysis (PCA) and cluster analysis (CA) techniques. Raziei et al. (2009) analysed the temporal and spatial variability of hydrological drought by applying PCA to the Standardized Precipitation Index (SPI). These two methods of regionalisation (drought variability and precipitation variability), though conceptually different, complement each other and can contribute to better management of water resources in an area.
2.7 Drought Forecasting Techniques

Drought forecasting is of great importance in drought hydrology and plays a major role in drought preparedness. The input variables and drought indices for drought forecasting depend upon the different types of droughts to be forecast (Mishra and Singh, 2011). Precipitation data are needed for meteorological drought analysis, stream flow, reservoir and lake level data for hydrologic drought analysis, and soil moisture and crop yield for agricultural drought. However, there are several drought indices that have been derived that consider all potential hydro-meteorological variables and can also be used for forecasting.

Various drought indices and the studies which have applied them for drought forecasting include the following: the Standardised Precipitation Index (SPI) (Mishra and Desai, 2005; Mishra and Desai, 2006; Cancelliere et al., 2007; Bacanli et al., 2009; Durdu, 2010), the Palmer Drought Severity Index (PDSI) (Lohani et al., 1998), the Surface Water Supply Index (SWSI) (Araghinejad, 2011), the Aggregated Drought Index (ADI) (Barua et al., 2010), and the Non-linear Aggregated Drought Index (NADI) (Barua et al., 2012). In addition to the hydro-meteorological variables, there are climate indices such as the El Nino-Southern Oscillation (ENSO), Sea Surface Temperature (SST), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Inter-decadal Pacific Oscillation (IPO) and Atlantic Multi-decadal Oscillation (AMO) for long-lead drought forecasting (Mishra and Singh, 2011).

The drought indices mentioned above have been applied in several studies for drought forecasting and they give reasonably good results. For example, Durdu (2010) presented a methodology to develop adequate linear stochastic models, known as autoregressive integrated moving average (ARIMA) and multiplicative seasonal autoregressive integrated moving average (SARIMA), to predict droughts in western Turkey using the SPI as the drought index. The predicted data showed reasonably good agreement with the observed data. The ARIMA model developed to predict drought was found to give acceptable results up to 2 months ahead. Lohani et al. (1998) presented a non-homogeneous Markov chain approach for forecasting drought using the PDSI in Virginia, USA, and concluded that this approach can be construed as a satisfactory model for predicting drought up to 3 months ahead. The study of Barua et al. (2012), based on artificial neural network (ANN), developed a drought forecasting approach using the time series of the Non-linear Aggregated Drought Index.
(NADI) to forecast NADI values. The results showed that the developed drought forecasting models were capable of forecasting drought conditions reasonably well up to 6 months ahead.

2.8 Summary

In Australia, drought management has always been an important issue in the context of water resources management. Although Deciles is commonly used to assess the status of rainfall deficiency in Australia, it has many limitations. One of the disadvantages is that it does not indicate the onset and end of droughts, which are important features of drought monitoring (Nazahiyah et al., 2014). Another limitation is that droughts are defined arbitrarily based on a selected threshold and hence differ from one location to the other. Therefore, it is important to select a drought index or develop a model to forecast droughts that can be applied consistently across jurisdictions. Some of the current drought indices are discussed earlier in this chapter. As this study concerns drought monitoring and early warning, meteorological drought indices provide the best initial evaluation. Rainfall, evaporation, temperature, soil-moisture and other indicators have been used to calculate drought indices, but there is no doubt that the most useful and convenient single indicator is rainfall. Therefore, three indices, the Standardised Precipitation Index (SPI), the Reconnaissance Drought Index (RDI) and Deciles, were assessed to further investigate how well these indices reflect drought conditions in Victoria, Australia as a case study. This is discussed at length in Chapter 3.

It is important to identify trends in climatic variables as extreme events are becoming more common and severe due to climate change. Trend analysis will be carried out to determine any trend in annual rainfall which also includes the recent years’ conditions. A year when a trend begins and changes abruptly will also be identified. It is important to determine any possible causes or explanations of increasing or decreasing trends that are observed. Although several studies on trend analysis have been done in Australia, there have been few discussions of the selection of time period and abrupt changes. Victoria has experienced a number of drought events including a recent severe drought. Therefore, the trend analysis of droughts using appropriate indices will be carried out in this current study. The details of the trend tests, results and conclusions drawn are reported in Chapter 4.
The frequency analysis of drought is very important from the point of view of drought preparedness. Frequency curves will be developed to provide a comprehensive characterization of droughts in Australia. Each drought event is unique in intensity, severity and duration. Furthermore, the frequency of occurrence of a drought with a certain severity also varies. In this study, the study area was divided into homogenous areas based on drought characteristics and drought frequency curves were developed for each region. In addition to their practicality for water resources planning and management, these curves will also be very useful for ungauged locations so that water planners do not have to repeat the same method to develop new frequency curve relationships. The details of the development of the frequency curves and the clustering techniques will be discussed in Chapter 5.

Several drought forecasting techniques have been reviewed and discussed in this chapter to understand each of the drought forecasting modelling techniques. The selection of the most appropriate drought forecasting tool to forecast future drought conditions in Victoria is the main aim of this current study. The application of the method chosen is discussed in Chapter 6.
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