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Assessment of trends in point rainfall using Continuous Wavelet Transforms

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ABSTRACT

The existence of trends in hydro-climatic variables such as rainfall is an indication of potential climate variability and climate change and the identification of such trends in rainfall is essential for the planning and design of sustainable water resources. This study focuses on identifying existing trends in annual, seasonal and monthly rainfall at thirteen stations in the Onkaparinga catchment in South Australia during the period 1960–2010. A relatively new trend detection approach, which combines a Continuous Wavelet Transform (CWT) with the Mann Kendall (MK) test, was applied in this study. The original rainfall time series was decomposed to different periodic components using a CWT and then the MK test was applied to detect the trends. One station showed a statistically significant (at the 5% level) negative trend for annual rainfall. Winter rainfall exhibited significant positive trends at four stations. In the case of monthly rainfall, significant positive trends were observed in June (at seven stations), November (at one station) and December (at one station). The study showed that the periodic components might have significant trends even when there are no significant trends in the original data. The periodic component that dominates the trend in the original data varies from season to season. A sequential Mann–Kendall analysis was found useful for identifying the trend turning points. Most of the trends, whether positive or negative, started during the mid-1970s to mid-1980s. The technique developed in this study may also be applied for trend detection of other hydro-climatic variables in other catchments, particularly where temporal and spatial variabilities are high.

1. Introduction

Hydro-meteorological variables are useful for detecting changes in the climate over time [8]. Understanding significant trends in rainfall is vital for sustainable water resources management [59]. The existence of trends in hydro-climatic variables such as rainfall, temperature, humidity, evapotranspiration and stream flow is an indication of climatic variability and climate change [6]. Changes in the trends of observed rainfall are caused by variations in the climatic environment, rainfall intensity and seasons [7,18,53,56]. Investigation of rainfall trends is therefore essential for identification of the potential impacts of climate change on a region's water resources and this should be monitored regularly [2].

Australian rainfall has strong spatial and temporal variability [15,49]. Previous investigations of rainfall trends reveal a variety of results across Australia. Both positive (increasing) and negative (decreasing) trends have been observed in different parts of the continent [15,18,33,53]. Moreover, a strong spatial variation in rainfall trends has been observed even at the regional scale [14,16]. Taschetto and England [53] examined the trends in Australian rainfall from 1970 to 2006. They observed a pattern in annual rainfall trends as being positive across the west and negative over the east part of Australia and this east–west pattern is exhibited by the trends in summer and autumn rainfall. South Australian annual total rainfall shows evidence of a decreasing trend during the last half of the twentieth century [38]. Murphy and Timbal [33] described the impact of recent low rainfall from 1997 to 2006 on the overall trends of rainfall across South-eastern Australia since 1950. They also observed that most of the rainfall decline occurred during autumn (March–May). Increasing and decreasing trends in South Australian rainfall can be associated with changes in heavy rainfall and decreases in the density of low pressure systems in the region [53]. Because of reduced advection of moist warm air into South Australia from the northwest and moist cold air along the southern coastline, their interaction become limited which results in rainfall deficiencies in South Australia [18].

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Observed time series data are often used for historical trend analysis. The Mann–Kendall (MK) trend test [26,29] is the most widely used non-parametric test for detecting monotonic trends in rainfall, temperature, stream flow and water quality [3,12,13,24,31,37,46,58]. Non-parametric methods are less affected by the existence of outliers in the data series [28]. Previous studies have used the MK test for detecting trends in Australian rainfall [4,15,16]. The MK test is robust as its performance is not affected even if the time series has a skewed distribution [39]. Moreover, this test is resilient to non-stationarity, non-linearity and missing values [1,40,59]. A notable limitation of the MK test is that it cannot handle data that have serial correlation, which is often found in rainfall data [40,60,61]. Hamed and Rao [21] therefore proposed a modified MK test which can handle autocorrelated data. Sneyers [51] developed the sequential MK test which is a further advancement on the MK test as it is able to examine the changes of trend in rainfall data with time [35,40,41,58].

A relatively recent development in signal processing is the well-known wavelet transform. It is a powerful tool which is capable of providing simultaneous time and frequency representations of a signal. Wavelet transforms can decompose the original time series into several periodicities. Lower periodicities contain high frequency components (rapidly changing events) and higher periodicities represent the low frequency components (slowly changing events) of the original signal. The wavelet transform has been successfully used in the analysis of various hydrological and meteorological variables to determine the non-stationary trends and periodicities [4,27,34,41,52,57,62]. The results obtained from a wavelet analysis can be used to detect the trends in different periodic components as well as their contribution to the trends in the original time series. Partal and Küçük [40] used both the wavelet transform and the MK test to detect non-linear trends in different periodic components of annual total rainfall in Turkey. They observed that a 16 year periodic component was the dominating component for producing the trend in the original annual rainfall time series. Zume and Tarhule [63] observed inter-annual to decadal variability in annual precipitation when they applied wavelet transforms and the MK test to analyse the variability and trends in rainfall and stream flow in north western Oklahoma over the period 1983–2003. Nalley et al. [35] applied a wavelet transform and the MK test together to analyse the trends in annual, seasonal and monthly precipitation and stream flow in southern Ontario and Quebec over the period 1954–2008. They observed that the periodic components that affect the trend of the original series vary from one station to another. While a number of research studies have been performed to identify trends in the original rainfall data at different temporal resolutions in Australia [4,14–16,33,48,50,53], no studies have investigated the trends in various periodic components and their influence on the trend of the original observed rainfall time series.

In this study we have used a Continuous Wavelet Transform (CWT) and the MK test to investigate the existing trends in both the original series and in various periodic components of the annual, seasonal and monthly rainfall in the Onkaparinga catchment in South Australia (SA). CWT can be used to decompose a series into any scale or frequency while discrete wavelet transforms (DWTs) are limited to a discrete number of scales, which are mostly multiples of the power of two of the average sampling intervals [47]. Moreover, the CWT is capable of detecting, extracting and reconstructing non-linear long term trends making it suitable for hydrology and climate research [1]. Furthermore the development of the periodic components using CWT proposed in this study is useful over DWT when there is a necessity to construct a periodic component for a scale other than dyadic. In DWT, the signal is decomposed into two components, namely detail and approximation or residual. The literature shows that this approximation carries most of the trend components and in order to better represent the MK trend analysis, the respective approximation components need to be added [35,36]. Whereas in case of CWT, development of the periodic component is straightforward and the MK trend analysis can be applied directly to each periodic component. In addition, we investigate how annual, seasonal and monthly rainfall trends change over time which is useful to identify the non-stationarity in the trends.

2. Study area and data

This study focuses on identification of rainfall trends across the Onkaparinga catchment in SA. The catchment is approximately 25 km southeast of the city of Adelaide in the Mount Lofty Ranges (MLR) and has an area of 553 km^2. There is a significant gradient ranging from the low lying coastal plain to an elevation of 700 m in the upper catchment. It has been selected as the Application Test Bed for the Goyder Institute climate change project (https://www.goyderinstitute.org). The water resources of the Onkaparinga catchment are crucial in SA because they form a significant source of water supply for metropolitan Adelaide as well as providing water to farm dams and for the natural environment to maintain the bio-diversity. Heneker and Cresswell [23] studied the climate change impacts in the MLR and found that there was a 30% potential reduction in the annual runoff in the Onkaparinga catchment. Moreover, Teoh [54] identified that farm dams divert about 8–10% (4.5 GL) of the surface water and this was forecast to increase to around 7–10 GL under the current management policies, as at 2002. This would have a profound impact on water security for Adelaide. Therefore the results of this study will be useful for water managers and policy makers involved in sustainable water resource management and climate change adaptation for the Onkaparinga catchment.

Around 60% of Adelaide's municipal water is supplied from the Onkaparinga catchment. This catchment is also important for its valuable contribution for meeting local irrigation demand. The Onkaparinga catchment is hydrologically very well instrumented, partly because of its importance as a water supply catchment and partly because it includes the Willunga Basin Super Science Site, which is funded by the Australian Commonwealth Government's Super Science program for the development of scientific infrastructure. The median annual rainfall over the area is approximately 770 mm but this varies with a strong gradient from approximately 400 mm near the coast to 1170 mm in upstream areas [54]. The catchment has a strong seasonal rainfall variation with less rainfall in summer (December–February) and higher rainfall during winter (June–August) [5]. Thirteen rainfall stations were selected within and around the catchment as shown in Fig. 1. These rainfall stations were previously used by Teoh [54] who found that the temporal homogeneity of rainfall data at these stations was satisfactory. Seven out of these selected stations match with the stations selected by Heneker and Cresswell [23] who used a network of 20 stations for the assessment of potential climate change on the water resources across the MLR. Details of the stations used in this study are given in Table 1. Rainfall data from 1960 to 2010 at these stations were collected from the Bureau of Meteorology (BOM), Australia. For detail statistical properties of rainfall data used in this study, please refer to Rashid et al. [45].

3. Methodology

In this study, annual, seasonal and monthly rainfall have been analysed at thirteen rainfall stations in the Onkaparinga catchment in SA to identify the existence of trends. First, the original rainfall