Long-term rainfall variations and their impacts in the South West of Western Australia

Priya Philip

School of Engineering and Built Environment

Griffith University

Submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

March 2020

EXTENDED ABSTRACT

The South West of Western Australia (SWWA) has been of interest to research due to the decrease in rainfall over this region since the 1950s with a significant shift since the 1970s. SWWA depends on the winter rainfall for meeting its agricultural water requirements and town water supply. A decrease in rainfall has adverse impacts on these sectors. The decreasing trend has been attributed to the decrease in the magnitude and frequency of the westerlies which bring rainfall to this region and the major changes in the large-scale atmospheric phenomenon such as the Southern Annular Mode. The observed decline in water levels in the dams of this region indicates a decrease in runoff which is mostly a result of decrease in heavy rainfall. This suggests to the need to characterize the rainfall changes in SWWA both temporally and spatially.

Total rainfall can be decomposed into light, medium and heavy rainfalls, and the land responds differently to these rainfall classes. The light and medium rainfall is crucial in replenishing the soil moisture which is beneficial to vegetation. While heavy rainfall contributes mostly to runoff flowing into dams, it also poses a higher risk of soil erosion compared to light and medium rainfall. This study aims to quantify contributions from these rainfall classes to the decrease and interannual variations in rainfall, and to relate the decrease to station characteristics, i.e., latitude, elevation and the mean annual rainfall, and to the large-scale circulation pattern known as the Southern Annular Mode (SAM). The Southern Annular Mode (SAM) is the north south movement of the westerlies which are winds from west to east and occur in the midlatitudes between the 30˚ and 60˚ in the northern and southern hemispheres. Long-term data for 30 stations were used, and daily rainfall was divided into three classes in such a way that they contributed equally (one third of the total) to the total rainfall of each station. It was observed that the decrease in heavy rainfall was mainly responsible for the decrease in total rainfall, followed by the medium and light rainfalls. Stations with a higher rainfall along the coast were more likely to experience a decrease in rainfall than those in the drier inland areas. Stations, where rainfall was strongly correlated with SAM, were mostly concentrated along the west coast of SWWA and the SAM index explained 9% of the variation in heavy rainfall and 11% in total rainfall for the region.

Rainfall volume is a crucial aspect because the precipitation over an area such as a catchment largely determines water resources availability for that area. Changes in the rainfall volume have considerable implications for regional water resources planning and management. As the

rainfall volume is the product of the wet area, which is the area receiving rainfall and the rainfall depth, the change in rainfall volume is the result of change in rainfall depth or that in wet area or both. No study has yet been undertaken to examine the change in rainfall volume in SWWA. This study also aims to examine the spatial and temporal changes in rainfall volume and to attribute this change to that in the wet area and that in the average rainfall depth in SWWA. Gridded daily rainfall data at 0.05° resolution for the period from 1911 to 2018 were used for an area of 265,952 km2 in SWWA. The results showed that regions near the coast with mean annual rainfall ≥ 600 mm showed significant decreasing trends in rainfall volume, and 84% of which could be attributed to a decrease in the wet area, while the decrease in rainfall depth only played a minor role. The regions farther inland showed an increasing trend in rainfall volume although the trend was not statistically significant. The regions near the coast also showed a decreasing trend in wet area with a higher number of rain days while the regions farther inland showed an increasing trend in wet area with a lower number of rain days. In the coast, the rate of decrease in rainfall has been reduced, and heavy rainfall, in fact, has increased over past 30 years, although, there was no concurrent change in SAM.

The runoff in SWWA has been steadily decreasing which has led to reduction in the water available for water supply and agriculture. The study aimed to understand the role of rainfall changes in the decrease of runoff in the study area. Daily rainfall, potential evapotranspiration and runoff data for 10 catchments in SWWA were used. It was observed that all catchments exhibited a decreasing trend in runoff while the rainfall showed an increasing trend in some catchments. Further, the rate of change in runoff was found to be 2.6 times the rate of change in rainfall. The AWBM model overpredicted the runoff suggesting the presence of factors besides the decreasing rainfall in the observed decrease in runoff. The results indicated that the decrease in rainfall has led to a persistent decrease in groundwater table, which accelerated the decrease in streamflow in the region.

This study focused on the trend in rainfall of different intensities and their contribution to the total rainfall trend. It was found that the decreasing trend was mainly concentrated along the coastal region (high mean annual rainfall) while the inland region (low mean annual rainfall) experienced an increasing trend in rainfall. In other words, the wet regions were becoming drier and the dry regions were becoming wetter. The trend and variability in heavy rainfall was observed to be the major contributor to the variations in total rainfall. Rainfall volume along the coast also showed a significant decrease and this was mainly due to the decrease in wet area while the decrease in average daily rainfall depth only played a minor role. Although, in the long term, the rainfall shows a decreasing trend, in the recent period, the rate of decrease in the total rainfall has reduced and the heavy rainfall, in fact, has increased with no concurrent change in SAM. The decrease in runoff was not solely caused by the changes in rainfall, but the steady decline of groundwater levels in the region could also be contributing to the decreasing runoff. Although, in the recent years, the rate of decrease in rainfall has reduced, the groundwater in this region needs to first recover before we can observe any positive change in streamflow in this region.

STATEMENT OF ORIGINALITY

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

(Signed)[redacted]

Priya Philip

ACKNOWLEDGEMENTS

I would like to thank my principal supervisor, Prof Bofu Yu, for his valuable guidance, constant encouragement, support and understanding throughout my candidature. He constantly found time to check on the progress of my research amidst his very busy schedule. He always stood by me without judgements through the ups and downs of my PhD journey. His passion for research and his students always inspired me.

I also thank my associate supervisor, Assoc Prof Prasad Kaparaju for his encouraging words and constant support. His words always gave me the confidence to carry on.

I also wish to thank my dearest friends Zhuo Cheng and Jagriti Tiwari. They helped me to improve my skills in using the ArcGIS software. Most importantly, they gave me the emotional support which only friends can provide.

I also thank the university for providing the financial support for this research through the Griffith University Postgraduate Research Scholarship and Griffith University International Postgraduate Research Scholarship. I thank the Griffith Graduate Research School for helping me throughout the scholarship extension and the thesis submission processes.

I thank my husband for his encouragement and continuous support without whom this journey would not be possible. I also thank my family and friends for their prayers and support.

Above all, I thank God Almighty for giving me the wisdom and resources to complete this journey.

TABLE OF CONTENTS

LIST OF PUBLISHED AND UNPUBLISHED PAPERS

This thesis is prepared as a series of papers. Chapter 3 is a published paper; Chapter 4 is a submitted manuscript and Chapter 5 is a draft manuscript in the initial phase of submission.

- Philip, P. and Yu, B., 2019. Interannual variations in rainfall of different intensities in South West of Western Australia. International Journal of Climatology. (Published) DOI: 10.1002/joc.6382
- Philip, P. and Yu, B., 2020. Temporal variations in rainfall volume in South West of Western Australia. Journal of Applied Meteorology and Climatology. (Accepted for publication)
- Philip, P. Cheng, Z and Yu, B., (draft manuscript). Rainfall-runoff relationship for selected catchments in the southwest of Western Australia

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 – INTRODUCTION

1.1 The South West of Western Australia (SWWA)

Rainfall is a main source of freshwater replenishment and plays an integral role in the sustenance of life on earth. Variability in rainfall has adverse effects on flora, fauna and humans. Rainfall variability and trends are an important area of research as they reflect the ongoing changes in climate while also influencing the soil moisture and streamflow. The changes in soil moisture and streamflow in turn have detrimental effects on the agriculture and water supply sectors.

In this study, the area of interest is the South West of Western Australia (SWWA), which lies to the south of 30ºS and west of 120ºE (Figure 1.1). It covers an area of 265,952 km^2. More than 20 water supply dams mainly for domestic, agricultural and industrial uses are located in this area. The region also coincides with the Australian wheatbelt which produces wheat, barley, canola and other crops. Agricultural production of the wheat belt contributed to 59% of total gross value of agricultural production in Western Australia in 2017-2018 (Australian Bureau of Statistics). Perth, the capital of Western Australia and one of the fastest growing cities is located in this region (www.perthnow.com.au). The population of Perth was greater than two million in 2015 according to the Australian Bureau of Statistics and is still showing an increasing trend (www.abs.gov.au).

The region is unique as it receives a higher mean annual rainfall ranging between 300 mm and 1310 mm while the surrounding region receives less than 300 mm of mean annual rainfall (Figure 1.1). Since the 1950s, the rainfall of SWWA has been showing a decreasing pattern and since the 1970s the trend was significant (Li *et al*., 2005 and Fu *et al*., 2010). With the decrease in rainfall, the streamflow to the dams in the region decreases, supplying lesser water to the increasing demands of a fast-growing population.

Due to the decrease in water availability and higher demand for water, the urban areas of SWWA, now uses a combination of desalinated seawater, groundwater, groundwater replenishment and streamflow into dams for meeting their water requirements. The water in dams is not only from the inflows from rain, but they also store groundwater and desalinated water for use in hotter months. In 2019-2020, Perth's water sources consisted of 43% of desalinated water, 39% of groundwater, 15% of water from dams and 3% from groundwater replenishment (https://www.watercorporation.com.au).

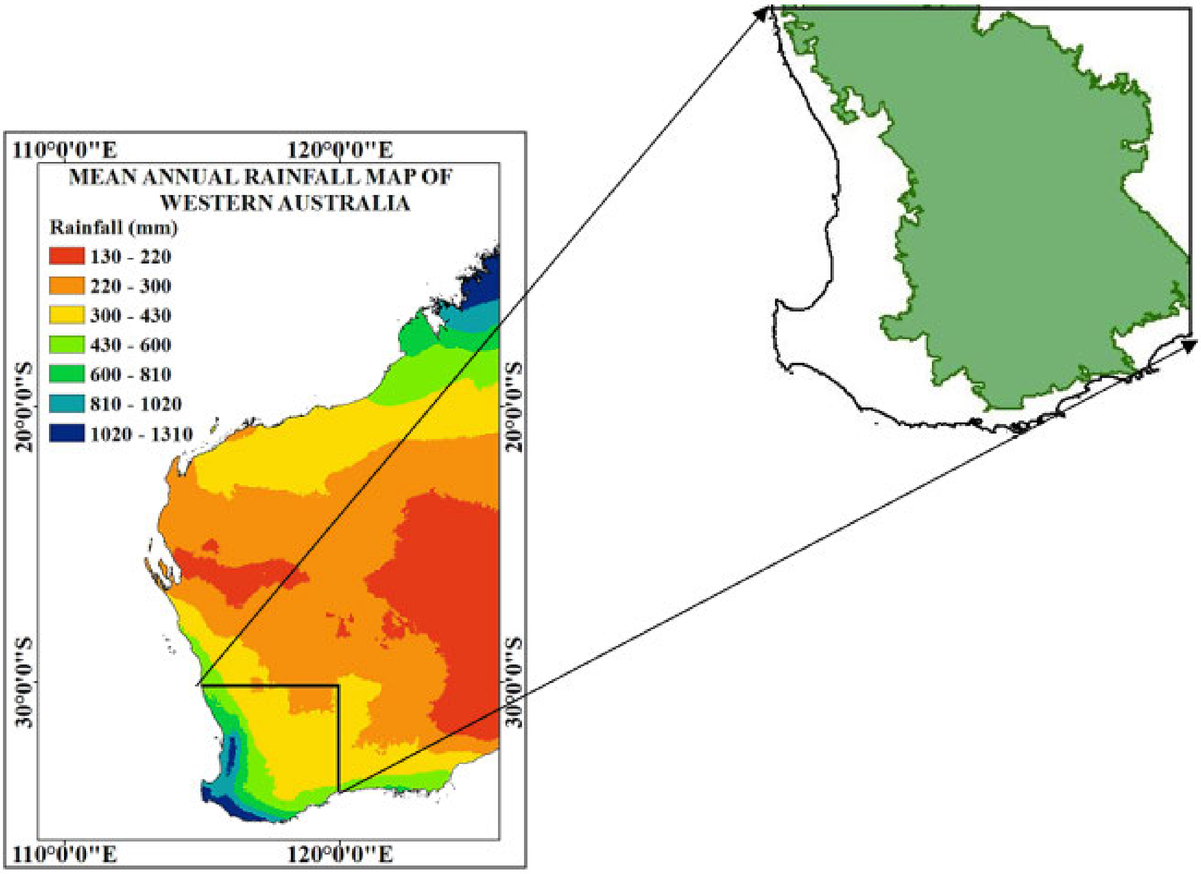

Figure 1. 1 Mean annual rainfall map of Western Australia sourced from http://www.bom.gov.au. The highlighted region indicates the study area and the green region represents the location of wheatbelt in SWWA sourced from https://catalogue.data.wa.gov.au..

1.2 Climate and weather drivers of SWWA

Figure 1.2 presents the climate zones of Australia according to the Koppen climate classification. The central part of Australia experiences desert climate with hot summers and hot winters. The northern part of Australia has tropical climate which is characterized by persistently wet monsoons. Western Australia has grassland climate which is persistently dry while Southwestern Australia experiences mediterranean climate. The eastern and southeastern part of Australia has subtropical and mediterranean climate respectively.

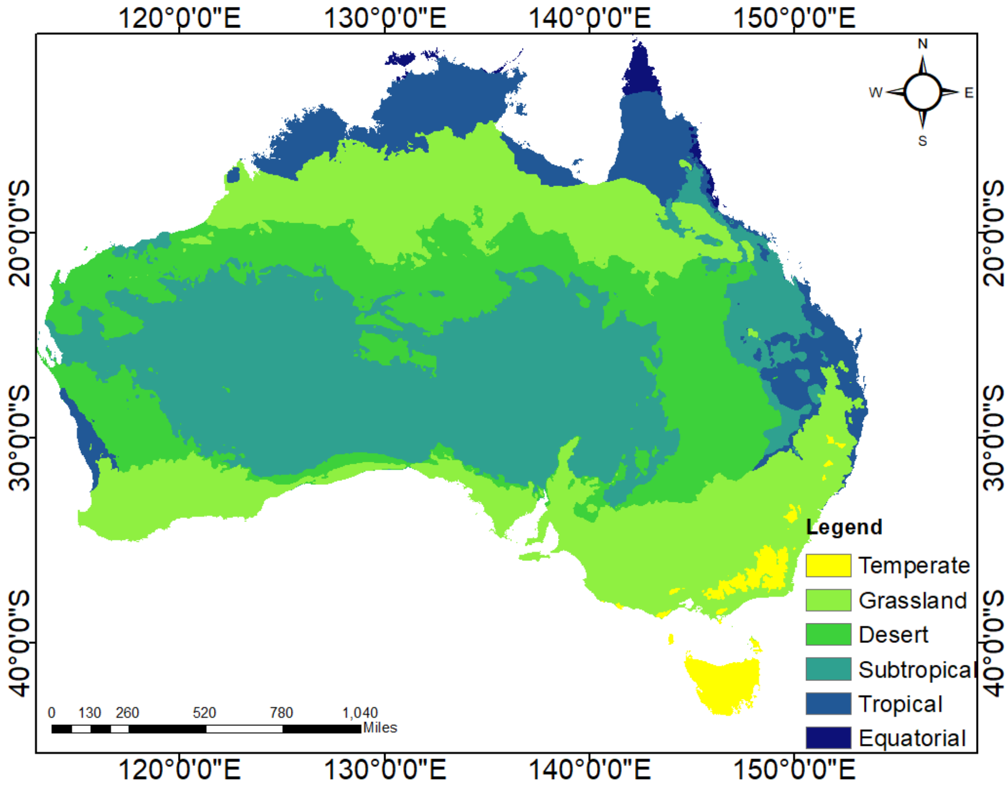

Figure 1. 2 Koppen Climate map of Australia (Bureau of Meteorology)

As mentioned above, SWWA has a Mediterranean climate with greater than 50% of the rain occurring during the winter months of June, July and August as shown in Figure 1.3.

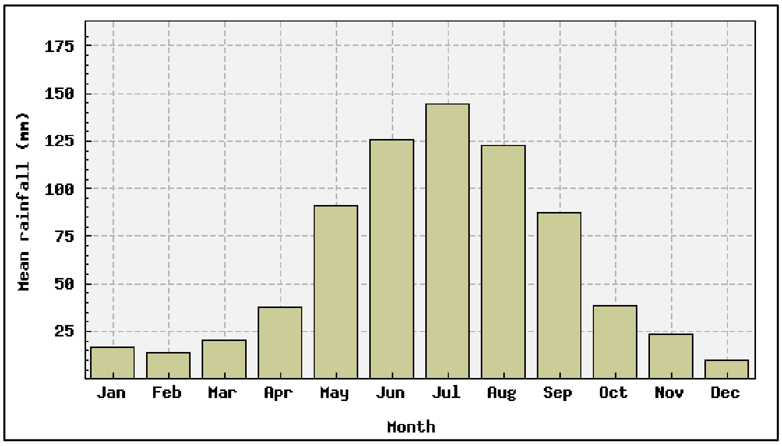

Figure 1. 3 Mean monthly rainfall at Perth (Source: www.bom.gov.au)

Figure 1.4 presents the various weather drivers affecting the rainfall of SWWA. The climate in SWWA is influenced by many factors like subtropical ridge, frontal systems, cut off lows, west coast trough, Southern Annular Mode (SAM), and Indian Ocean Dipole (IOD) (IOCI, 2002).

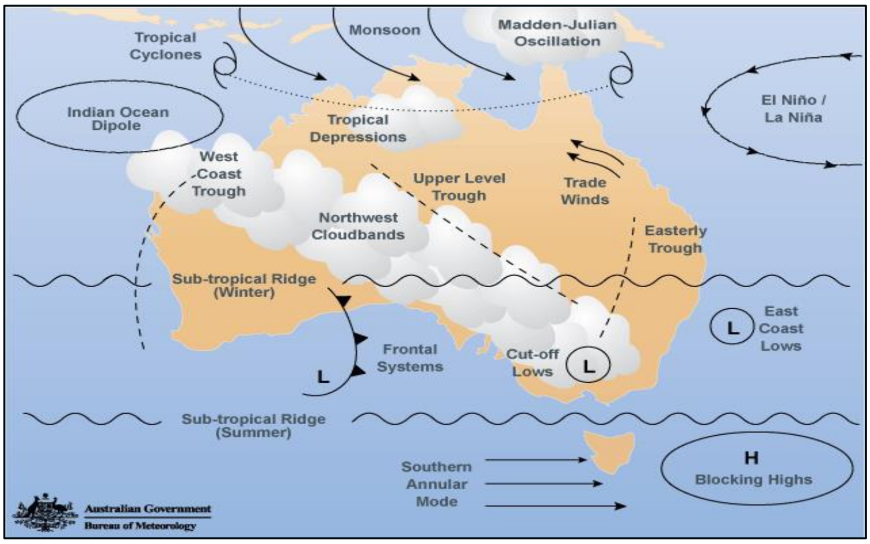

Figure 1. 4 Subtropical ridge in summer and winter (Source: http://www.bom.gov.au)

The relatively low rainfall experienced in SWWA is mainly caused by a cold water current, the West Australian current, which is a part of the Southern Indian Ocean current. The cold frontal systems which move from west to east across the Southern Ocean, varying in intensity and speed are generally associated with heavy rainfall in SWWA during the winter months. The low pressure systems, cut off lows, also bring sustained and often heavy rainfall to SWWA. The position of the subtropical ridge, a high pressure belt which encircles the earth at 30˚S and 30˚N plays a significant role in the climate of SWWA. During summer the subtropical ridge is located at the south of Australia thereby suppressing any cold frontal activity, while during winter the ridge moves up towards Central Australia giving way to cold fronts which bring rainfall to SWWA (Figure 1.4).

The westerlies which are winds blowing from west to east occur in the midlatitudes between the 30˚ and 60˚ latitudes in the northern and southern hemispheres. The Southern Annular Mode (SAM) is the north south movement of the westerlies. A positive value of SAM causes the belt of westerly winds to contract towards the South Pole and results in less rainfall and a negative SAM causes the westerly winds to expand towards the equator and results in strong storms and low pressure systems bringing more rainfall (Figure 1.5).

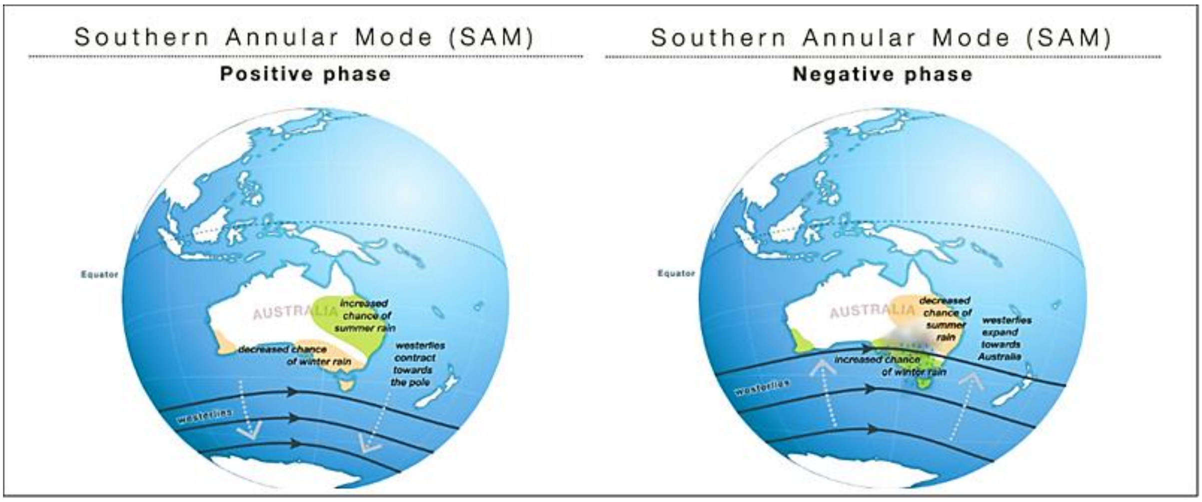

Figure 1. 5 Positive and negative phase of Southern Annular Mode (Source: http://www.bom.gov.au)

Indian Ocean Dipole (IOD) is a measure of the changes in sea surface temperature patterns in the northern Indian Ocean which has a significant impact on the rainfall of Australia. A positive IOD indicates reduced rainfall for Australia and a negative IOD indicates increase in rainfall. The role of the above mentioned weather drivers in the decreasing rainfall of SWWA is detailed in Section 2.2.

1.3 Decreasing rainfall of SWWA and its impacts

The rainfall trend has been examined for various regions of Australia and many researchers have concluded that the rainfall in Australia is showing large variability and significant change (Pittock, 1983, Yu and Neil, 1993, Hennessy, 1999, Smith, 2004). While the North East of Australia is experiencing an increasing trend in rainfall (Suppiah and Hennessy, 1998), SWWA has been showing a significant steady decline in its winter rainfall since the 1970s (Yu and Neil, 1993).

The two major sectors of SWWA that depend on rainfall are the agricultural and water supply sectors and these sectors respond differently to the decreasing rainfall pattern. The wheat grain yield in SWWA has not been much affected as the decrease in rainfall has mostly occurred during the months of June and July when the crop is relatively small with low water demand (Ludwig et al., 2009). This combined with the low evaporative demand and high humidity during winter suggests that the crop is not much impacted by a decrease in rainfall during June and July (Ward and Dunin, 2001). However, a decrease in rainfall during May and August can have detrimental effects on crop yield. In May, rainfall is required to wet the soil for suitable sowing conditions while in August, water demand is high due to increased water demand of the larger crop and increased temperature compared to previous months (Ludwig et al., 2009). The decrease in wheat production could be up to 50% of total wheat production by 2070 (Sprigg et al., 2014). Similarly, more hot days and less rainfall could also affect livestock due to greater heat stress (Hughes and McMichael, 2011). Figure 1.6 shows a wheat paddock under the dry spell in the South West of Western Australia.

Figure 1. 6 Wheat paddock with water tanks (Source: Bill Bunbury, 2015)

The low dam levels in SWWA is a significant indicator of the declining rainfall as presented in Figure 1.7 (Power et al., 2005, Hope and Ganter, 2010). Years of below average rainfall in the region has reduced the infiltration of rainfall to recharge the groundwater. Overtime this has led to disconnectivity between the surface water and groundwater leading to reduced streamflow (Kinal and Stoneman, 2012). This has resulted in a shift in hydrologic regime of streams from perennial to ephemeral (Petone et al., 2010). Extreme rainfall is required to re-establish the surface water - groundwater connectivity.

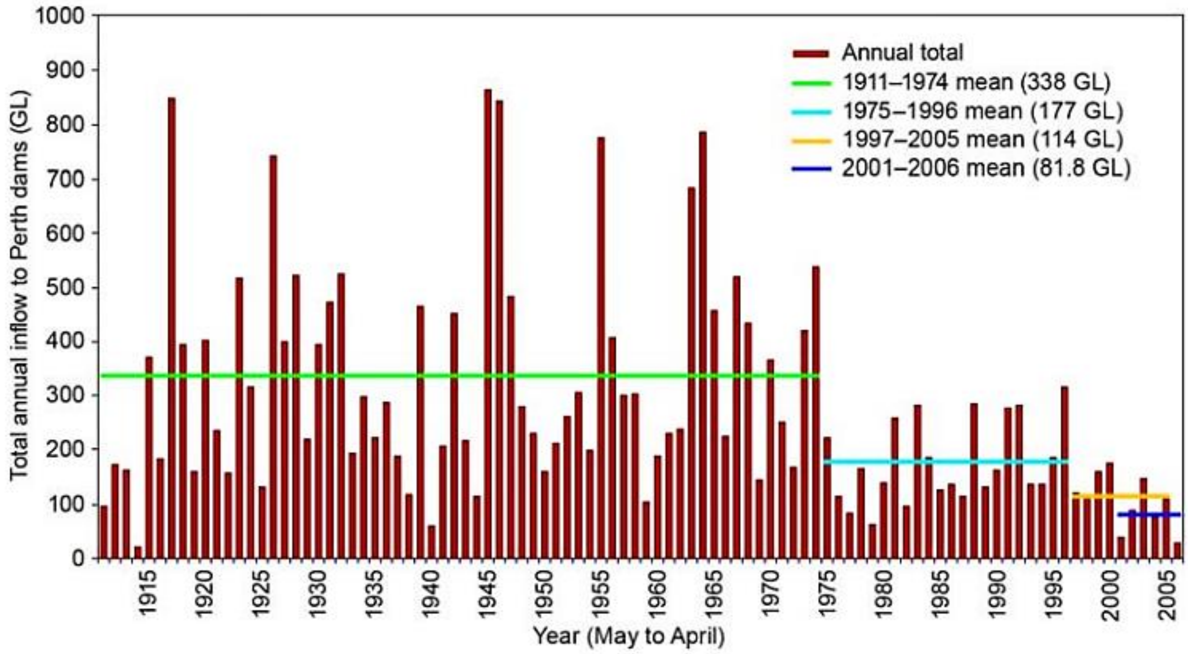

Figure 1. 7 Annual streamflow into Perth's water supply dams (Source: Reid et al., 2009)

The hypothesis is that the decline in water levels in the dams in the study area indicate a decrease in runoff which is mostly a result of decrease in heavy rainfall. This suggests to the need to characterise the rainfall changes in SWWA both temporally and spatially. No study has yet been done to understand the role of different classes of rainfall in the observed decrease of total rainfall in SWWA. Rainfall volume is a crucial aspect because the precipitation over an area such as a catchment largely determines water resources availability for that area. Changes in the rainfall volume have considerable implications for regional water resources planning and management. As the rainfall volume is the product of the wet area, which is the area receiving rainfall and the rainfall depth, the change in rainfall volume is the result of change in rainfall depth or that in wet area or both. No study has yet been undertaken to examine the change in rainfall volume in SWWA. This study also aims to examine the spatial and temporal changes in rainfall volume and to attribute this change to that in the wet area and that in the average rainfall depth in SWWA. The runoff in SWWA has been steadily decreasing which has led to reduction in the water available for water supply and agriculture. This study aimed to understand the role of rainfall changes in the decrease of runoff in the study area.

1.4 Aims and objectives

The aim of this study is to understand the changes in rainfall of SWWA by looking at the following objectives:

1) Identify the contribution of each of the different classes of rainfall, namely, light, medium and heavy rainfall, to the total decrease of rainfall.
2) Determine the changes in rainfall volume, wet area, average daily rainfall depth and the number of rain days.
3) Understand the rainfall-runoff relationship for selected catchments in the study area.

A flowchart presenting the aim, objectives and the methodology adopted to achieve the objectives is presented in Figure 1.8.

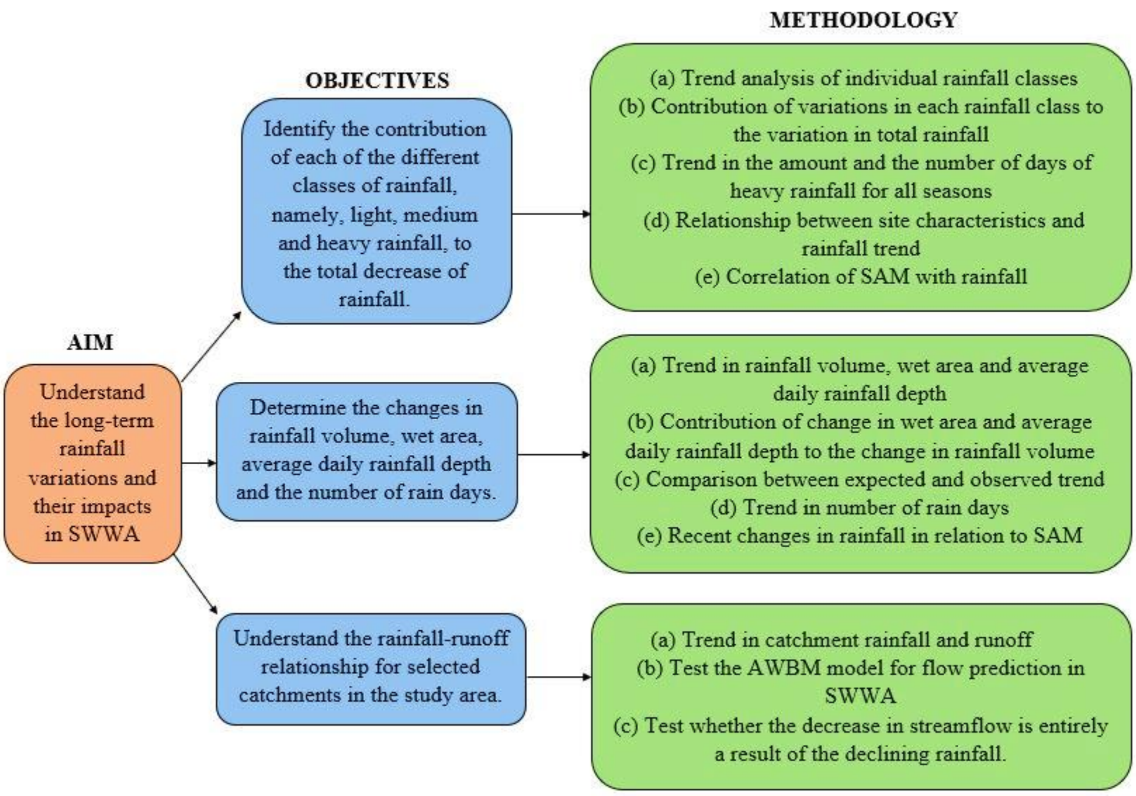

Figure 1. 8 Flowchart of the aim, objectives and methodology adopted in this study

1.5 Organisation of thesis

This thesis presents the research undertaken by the author between September 2016 and February 2020. This PhD thesis is presented as a series of papers. Chapter 1 describes the features of the study area and the climate drivers of the region. The effects of the decreasing rainfall and the aims and objectives of the study are also presented. Chapter 2 details the previous studies on global rainfall changes, rainfall and streamflow trend in SWWA and the causes of the observed trend. The knowledge gap and motivation for the study are also discussed. Chapters 3, 4 and 5 are research articles which are published, submitted and in initial stages of submission, respectively. Each research article explains the previous studies relating to the topic, data and methods followed by the results, discussion and conclusion. Chapter 3 discusses the interannual variations in light, medium and heavy rainfall in SWWA based on daily rainfall data from 30 rain gauge stations in the study area. Chapter 4 determines the changes in rainfall volume, wet area, average daily rainfall depth and number of rain days in SWWA using gridded daily rainfall data for the period 1911 - 2018. The rainfall-runoff relationship for selected catchments in the southwest of Western Australia was analysed in Chapter 5. Chapter 6 presents the key findings, limitations of the study and the future scope of study.

References

Bill Burnbury. 2015. Invisible country, southwest Australia: understanding a landscape. UWA Publishing:AU.

Fu, G., Viney, N. R., Charles, S. P., & Liu, J., 2010. Long-term temporal variation of extreme rainfall events in Australia: 1910-2006. J. Hydrometeorol. 11. 950-965. https://doi.org/10.1175/2010JHM1204.1

Hennessy, K.J., Suppiah, R. and Page, C.M. (1999) Australian rainfall changes, 1910-1995. Australian Meteorological Magazine, 48, 1–13.

Hughes, L. and McMichael, T., 2011. The critical decade: climate change and health. ACT Climate Commission Secretariat.

IOCI, C., 2002. Variability and change in south-west Western Australia. Indian Ocean Climate Initiative, 34p.

Li, Y., Cai, W., & Campbell, E. P., 2005. Statistical modeling of extreme rainfall in southwest Western Australia. J. Clim. 18(6), 852-863. https://doi.org/10.1175/JCLI-3296.1

Ludwig, F., Milroy, S.P. and Asseng, S., 2009. Impacts of recent climate change on wheat production systems in Western Australia. Climatic Change, 92(3-4), pp.495-517.

Petrone, K.C., Hughes, J.D., Van Niel, T.G. and Silberstein, R.P., 2010. Streamflow decline in southwestern Australia, 1950–2008. Geophys. Res. Lett. 37(11).

Pittock, A.B., 1983. Recent climatic change in Australia: Implications for a CO 2-warmed earth. Clim. Chang. 5, 321-340. doi:10.1007/BF02423529.

Smith, I., 2004. An assessment of recent trends in Australian rainfall. Aust. Met. Mag., 53, 163-173.

Sprigg, H., Belford, R., Milroy, S., Bennett, S.J. and Bowran, D., 2014. Adaptations for growing wheat in the drying climate of Western Australia. Crop and Pasture Science, 65(7), pp.627-644.

Suppiah, R. and Hennessy, K.J., 1998. Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. Int. J. Climatol. 18, 1141-1164. doi:10.1002/(SICI)1097-0088(199808)18:10<1141::AID-JOC286>3.0.CO;2-P.

Reid, M., Cheng, X., Banks, E., Jankowski, J., Jolly, I., Kumar, P., Lovell, D., Mitchell, M., Mudd, G., Richardson, S. and Silburn, M., 2009. Catalogue of conceptual models for groundwater–stream interaction in eastern Australia.

Ward, P.R. and Dunin, F.X., 2001. Growing season evapotranspiration from duplex soils in south-western Australia. Agricultural Water Management, 50(2), pp.141-159.

Yu, B. and Neil, D.T., 1993. Long-term variations in regional rainfall in the south-west of Western Australia and the difference between average and high intensity rainfalls. Int. J. Climatol. 13, 77-88. doi:10.1002/joc.3370130106.

CHAPTER 2 – LITERATURE REVIEW

2.1 Global rainfall changes

Rainfall shows considerable temporal and spatial variability around the world (Easterling *et al*., 2000). Yang et al. (2019), observed that 55% of the global land area exhibited either significant wetting or significant drying trends, with 38% of the global land area showing significant changes towards drier conditions. As a result of global warming, the frequency of extreme rainfall events have increased significantly by 12% globally compared to those expected due to natural multidecadal variability (Lehmann *et al.,* 2015). A warming climate allows the atmosphere to hold more water as suggested by the Clausius Clapeyron (C-C) relationship due to which there is an increase in regional precipitation events (IPCC, 2019). As global temperature increases, the hydrological cycle intensifies and circulation patterns change (Marvel and Bonfils, 2013). More intense rainfall causes redistribution of surface and groundwater resources. High intensity rainfall results in increased runoff and inflow into reservoirs (blue water) and decrease in water stored in soil which is available for plants (green water). In other words, extreme rainfall can cause surface flooding, soil erosion and water stress for plants (Eekhout *et al.,* 2018).

In the United States, the Northwest and Southwest shows decreasing trends on precipitation amount, while the Midwest, Northeast and parts of South show increasing trends during the period 1980 - 2010 (Prein *et al*., 2016). A significant decreasing trend has been reported, during the period 1910 - 2009, in the annual rainfall of the Mediterranean basin and a significant increasing trend in annual rainfall in Central and Northern Europe (Caloiero *et al*., 2018). In the Arab regions, a general warming trend has been observed since the 1970s. The western part of the region exhibits a wetting trend while the eastern part shows a drying trend (Donat *et a*l., 2014). Wang *et al*. (2015) studied the spatial and temporal variations of annual precipitation in China during the period 1960 - 2010 and found that there have been significant changes in rainfall in East, Northwest China, Northeast and Southwest China and the decadal changes of precipitation in East China were closely correlated with the East Asian summer monsoon and the atmospheric circulation. Saha *et al*. (2018) suggests that the trend of rainfall over different regions in India shows dissimilar pattern considering the rainfall during the period 1848 - 2006. The trend of rainfall in different seasons in North and Central India is closely related to the overall decreasing pattern of the country, Peninsular India shows slight similarity while North East India shows a different pattern to the overall decreasing pattern in rainfall.

In the southern hemisphere, a study conducted in New Zealand by Caloiero (2014) for the period 1951 - 2010, looked at the spatial and temporal patterns of daily precipitation concentration using the precipitation concentration index (CI) and the results showed the different behaviour of CI between the North Island and the South Island. The precipitation concentration index (CI) is used to examine the temporal heterogeneity of precipitation distribution by correlating the magnitude of precipitation events with the time of occurrence (Zhang et al., 2019). North Island showed most critical rainfall concentration and the eastern side of South Island showed comparable CI values to North Island while the western side of South Island showed lower CI values. In Australia, the average rainfall has increased in the northwest and southeast (Collins & Della-Marta, 1999; Suppiah and Hennessey, 1999), while there is a large significant decline of rainfall in Southern Australia and South West of Western Australia (Cai and Cowen, 2008; Wright, 1974; Yu and Neil, 1993, Choudhury *et al*., 2015).

These studies indicate that rainfall patterns are changing temporally and spatially around the world indicating that the weather drivers which bring rainfall to these regions may have altered in magnitude or the time of occurrence. These changes also suggest the importance of planning and allocating the available water irrigation and water supply.

2.2 Rainfall trend in SWWA

Many studies have been carried out to understand the variability of rainfall in Australia, mostly around the late 20th century. Almost all of them have concluded that the winter rainfall has steadily decreased in the South West of Western Australia. A decrease in the mean rainfall in the winter months in SWWA was observed by Pittock (1983). Yu and Neil (1993) associated the decrease in annual rainfall in SWWA to the decrease in the frequency of occurrence of all rainfall intensities in winter and that though the high intensity events (extreme events closely related to flooding, soil erosion and gully formation), show a decrease in winter, an increase in the summer rainfall was observed. The decline in winter rainfall in SWWA is caused by the significant decrease in both the intensity and frequency of high intensity rainfall (Hennessy *et al*., 1999 and Haylock and Nicholls, 2000). Hennessy *et al*. (1999) found a significant decrease of 19% in total rainfall and a 25 % decrease in winter rainfall. A significant decrease of 41 – 59% in the frequency of winter heavy rainfall and a 13% decline in the total winter rain days in SWWA were also observed. The change point of statistically significant decreasing trend in SWWA is identified to be around the time 1965 – 1970 (Li *et al*., 2005 and Fu *et al*., 2010). Gallant *et al*. (2007) analysed the trend in six Australian regions using 9 climatic indices which are related to the mean annual, seasonal and extreme daily rainfall and found that 8 out of the 9 indices in SWWA show a statistically significant decreasing trend. SWWA also exhibits a decrease in the occurrence and intensity of daily precipitation (Bates *et al*., 2010). Standard deviation of annual rainfall in coast of SWWA is higher compared to inland region indicating that the coast is more susceptible to periods of drought and flood (Dey *et al.*, 2019). There also has been a westward shift in rainfall zones by up to 100 km in SWWA (Guthrie *et al.*, 2015) as presented in Figure 2.1.

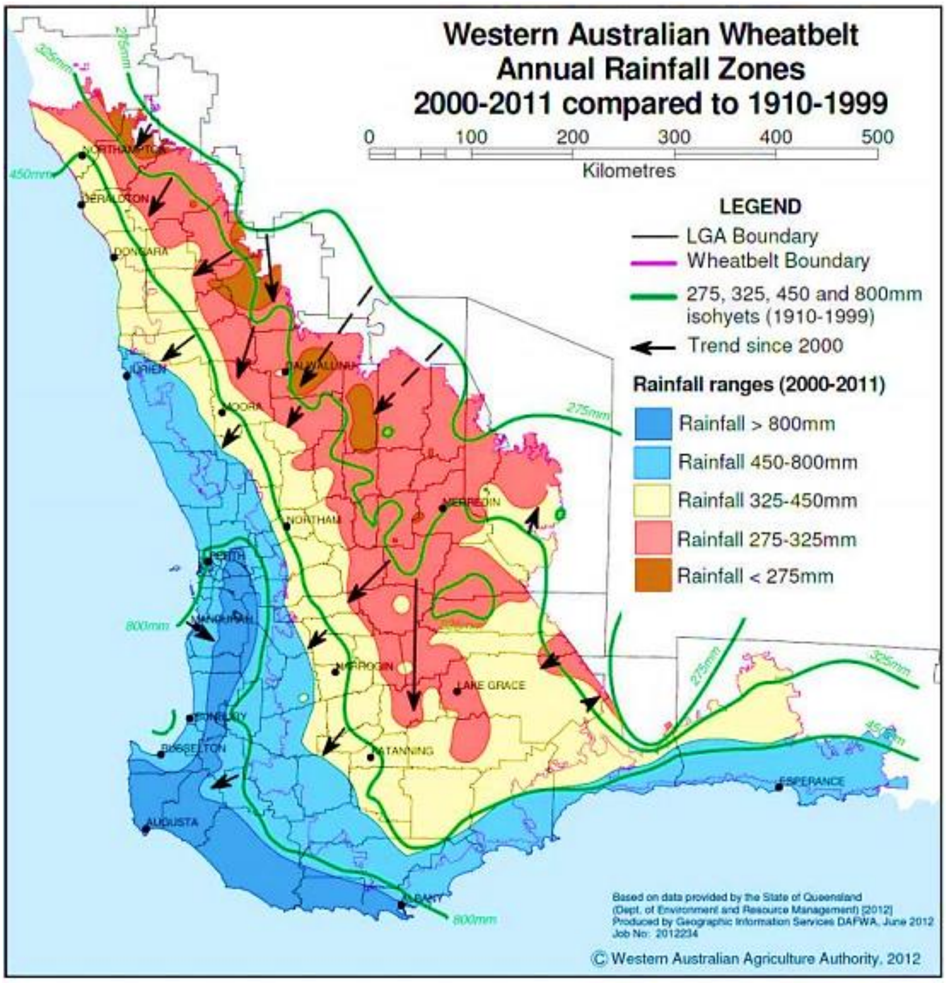

Figure 2.1 Shift in rainfall zones (Guthrie et al. 2015)

Research has hypothesised to relate decreasing rainfall trends with climate drivers and large-scale atmospheric phenomena like Southern Annular Mode (SAM), El Nino Southern Oscillation (ENSO) and Sea Surface Temperature (SST) (Hope et al., 2006, Raut et al., 2014). Beecham and Choudhury (2010) analysed the variability of point rainfall in Melbourne, Australia at different temporal scales and found a correlation between periodic intensity rainfall and ENSO. Samuel *et al*. (2006) observed that winter rainfall in SWWA is lower in the years when warm SSTs dominate the southern and tropical western Indian Ocean. They also observed a correlation between the SST anomalies and the sharp reduction in SWWA rainfall in the 1970s. Nicholls (2010), suggests that SST does not completely explain the variability in south Australian rainfall while the year to year variations of the Southern annular Mode is closely correlated to the year to year variation of rainfall. SAM is found to be inversely related to the SWWA winter rainfall (Hope *et al*., 2010 and Feng *et al*., 2015). SAM is exhibiting a significant increasing trend which has been caused by the ozone depletion over Australia and the greenhouse gas increase (Thompson *et al.*, 2011). As SAM is inversely related to SWWA rainfall, an increasing trend in SAM indicates further decrease in rainfall.

The decreasing frequency of westerly fronts in SWWA during June, July and August is also stated to be responsible for the declining winter rainfall (Hope *et al*., 2006 and Alexander *et al*., 2010). K means cluster analysis was used to find that the major decline in winter rainfall over SWWA is due to the overall reduction in frequency of westerly fronts and particularly strong fronts and it was also found that a positive phase of SAM resulted in reduced winter rainfall in all phase of ENSO (Raut et al., 2014). The region of maximum front frequency is projected to shift from 20˚S - 40˚S to 40˚S - 60˚S (Catto et al.,2014). The subtropical ridge has intensified over the recent decades due to an increase in the number of high pressure systems. This intensification, coupled with the southward shift of subtropical ridge prevents the cold fronts from reaching SWWA resulting in reduced rainfall (Timbal and Drosdowsky, 2013, Pepler et al.,2018). The step change in winter rainfall in SWWA after the 1970s is explained as a positive SAM in a neutral ENSO phase which was associated with a reduced rainfall from westerly fronts. Frederiksen and Frederiksen (2011), explains the reduction in winter rainfall in SWWA as a result of the reduction in the strength of the Southern hemispheric subtropical jet stream and the associated poleward displacement of the storm tracks. The concept of a monsoon like atmospheric circulation, South West Australian Circulation (SWAC) was put forward by Feng *et al*., (2015) and SWAC was found to explain clearly the interannual variability of rainfall in SWWA and also the long-term drying trend. Villarini and Denniston

(2016), found that Tropical Cyclones (TCs) play a significant role in extreme rainfall in much of Australia and in particular, Western Australia. They concluded that the vast majority of annual rainfall in excess of 100 mm over Western Australia can be associated with TC and that there is an increased probability of having a TC annual maximum rainfall and seasonal extreme rainfall during La Nina year rather than an El Nino year.

2.3 Streamflow trend in SWWA

In Australia, Zhang et al., (2016) analysed the pattern of streamflow from the 1950s for the whole country using streamflow data from 222 gauging stations which were not impacted by major developments or changes from bushfire and suitable to study changes of streamflow. It was found that annual streamflow in Australia has been showing a significant increasing trend in northern part of the Northern territory while a significant decreasing trend in South west of Western Australia (SWWA), Southern Australia, New South Wales, Victoria and South East Queensland. Petrone et al., (2010) observed that the inflow into the major water supply reservoirs of SWWA, have declined by more than 50% due to a 16% reduction in rainfall since the mid-1970s and the runoff coefficients have been progressively lower over the last 50 years. Model projections in SWWA indicate that the change in runoff is three times the change in rainfall (Islam et al., 2013, Silberstein et al., 2012). Based on the observed declining groundwater levels and declining runoff coefficients, it was suggested that the hydrological processes of this region could be non-stationary and that model calibrations from historical conditions may not be suitable for future projections (Silberstein et al., 2012). The study by Smith and Power (2014) suggests that the increasing temperature in SWWA do not have a direct influence on the declining inflow into the dams, rather temperature and rainfall are inversely related. In addition to the decreasing rainfall, the groundwater levels in SWWA has also been showing a declining trend and even the years of average rainfall does not satisfy the groundwater storage before contributing to runoff (Hughes et al.,2012). The variable rainfall in addition to the falling ground water levels could probably be the reason for the streamflow decline in SWWA (Petrone et al., 2010).

2.4 Knowledge gaps

Previous studies in SWWA have examined the decreasing trend in the rainfall in SWWA in terms of a decrease in extreme events or high intensity rainfall (Hennessy *et al*., 1999; Fu *et* *al*., 2010; McGree *et al*., 2014) and annual and seasonal trend analysis have also been carried out showing similar results (Choudhury *et al*., 2015). The total rainfall in an area can be considered to be the sum of light, medium and heavy rainfall. Classifying rainfall into heavy, medium and light rainfall would be advantageous to a better understanding of the rainfall-runoff relationship as catchments responds differently to different rainfall classes in terms of runoff generation and water availability. No study has been done yet to identify the contribution of each of the different classes of rainfall, namely, light, medium and heavy rainfall, to the total decrease of rainfall in SWWA. Examining the decrease in rainfall in SWWA from this perspective has two benefits. First, different rainfall classes may be associated with distinct precipitation mechanisms. For example, heavy winter rainfall in SWWA is mostly associated with north westerly winds while the late winter showery rainfall is mainly due to the south westerly winds (Wright, 1974). Examining the trend and the interannual variations of different rainfall classes could help identify the underlying cause for the decline in rainfall in SWWA. Second, identifying the trend of light, medium and heavy rainfall, helps in understanding the interannual and seasonal pattern of each of these classes and is useful for developing water management strategies. A decrease in heavy rainfall would imply a decrease in streamflow and consequent lowering of water level in reservoirs whereas a decrease in light or medium rainfall indicates lower water availability for soil moisture replenishment which is critical for crop growth.

Also, studies in this region have determined the change in rainfall in relation to the change in rainfall depth or frequency (Pittock, 1983; Yu and Neil, 1993; Hennessey *et al*., 1999; Smith, 2004; Gallant *et al*., 2007). Rainfall volume as distinct from rainfall depth is crucial because the precipitation over an area such as a river basin largely determines water resources availability for that area. Changes in the rainfall volume have considerable implications for regional water resources planning and management. As the rainfall volume is the product of the wet area, which is the area receiving rainfall and the rainfall depth, the change in rainfall volume is the result of change in rainfall depth or that in wet area or both. Previous studies which considered rainfall volume were concerned with the rainfall volume produced by tropical storms and their effects (Noguiera *et al*., 2010) and the relationship between rainfall volume and vegetation (La'zaro *et al*., 2000). To our knowledge, no research has been undertaken to examine the change in rainfall volume and the wet area in the context of a regional decline in rainfall in SWWA.

Studies indicate that the decreasing rainfall plays an important role in the declining runoff in SWWA. No study has yet been done to determine the impact of trends in different intensities of rainfall on the runoff trend in SWWA.

References

Alexander, L.V., Uotila, P., Nicholls, N. and Lynch, A., 2010. A new daily pressure dataset for Australia and its application to the assessment of changes in synoptic patterns during the last century. J. Clim. 23(5), pp.1111-1126.

Bates, B. C., Chandler, R. E., Charles, S. P., & Campbell, E. P. (2010). Assessment of apparent nonstationarity in time series of annual inflow, daily precipitation, and atmospheric circulation indices: a case study of south west Western Australia. Water Resour. Res. 46, W00H02. DOI: 10.1029/2010WR009509

Beecham, S., & Choudhury, R. K. 2010. Temporal characteristics and variability of point rainfall: a statistical and wavelet analysis. Int. J. of Climatol. 30, 458-473. DOI: 10.1002/joc.1901

Cai, W., & Cowan, T. (2008). Dynamics of late autumn rainfall reduction over southeastern Australia. Geophysical Research Letters, 35(9).

Caloiero, T., 2014. Analysis of daily rainfall concentration in New Zealand. Nat. Hazards. 72, 389-404. doi: 10.1007/s11069-013-1015-1.

Caloiero, T., Caloiero, P. and Frustaci, F., 2018. Long-term precipitation trend analysis in Europe and in the Mediterranean basin. Water Environ J. 32, 433-445. doi: 10.1111/wej.12346.

Catto, J.L., Nicholls, N., Jakob, C. and Shelton, K.L., 2014. Atmospheric fronts in current and future climates. Geophys. Res. Lett. 41(21), pp.7642-7650.

Chowdhury, R.K., Beecham, S., Boland, J. and Piantadosi, J., 2015. Understanding South Australian rainfall trends and step changes. Int. J. Climatol. 35, 348-360. doi: 10.1002/joc.3982.

Collins, D.A. and Della-Marta, P.M., 1999. Annual climate summary 1998: Australia's warmest year on record. Aust. Met. Mag. 48, 273-83.

Dey, R., Lewis, S.C., Arblaster, J.M. and Abram, N.J., 2019. A review of past and projected changes in Australia's rainfall. Wiley Interdisciplinary Reviews: Clim. Change. 10(3), p.e577.

Donat, M.G., Peterson, T.C., Brunet, M., King, A.D., Almazroui, M., Kolli, R.K., Boucherf, D., Al-Mulla, A.Y., Nour, A.Y., Aly, A.A. and Nada, T.A.A., 2014. Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO. Int. J. Climatol. 34, 581-592. doi:10.1002/joc.3707.

Dore, M.H., 2005. Climate change and changes in global precipitation patterns: what do we know?. Environ. Int. 31, 1167-1181. doi:10.1016/j.envint.2005.03.004.

Easterling, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E. and Ambenje, P., 2000. Observed variability and trends in extreme climate events: a brief review. Bull. Am. Meteorol. Soc. 81(3), pp.417-426.

Eekhout, J.P., Hunink, J.E., Terink, W. and de Vente, J., 2018. Why increased extreme precipitation under climate change negatively affects water security. Hydrol. Earth Syst. Sci. 22(11), pp.5935-5946.

Feng, J., Li, J., Li, Y., Zhu, J., & Xie, F., 2015. Relationships among the monsoon-like southwest Australian circulation, the southern annular mode, and winter rainfall over southwest Western Australia. Adv. Atmos. Sci. 32. 1063-1076. https://doi.org/10.1007/s00376-014-4142-z

Frederiksen, J. S., & Frederiksen, C. S., 2011. Twentieth century winter changes in southern hemisphere synoptic weather modes. ADV METEOROL. 2011: 1-16.

Fu, G., Viney, N. R., Charles, S. P., & Liu, J., 2010. Long-term temporal variation of extreme rainfall events in Australia: 1910-2006. J. Hydrometeorol. 11. 950-965. https://doi.org/10.1175/2010JHM1204.1

Gallant, A.J., Hennessy, K.J. and Risbey, J., 2007. Trends in rainfall indices for six Australian regions: 1910-2005. Aust. Met. Mag. 56, 223-241.

Guthrie, M., Evans, F., and Bowran D., 2015 The influence of climate change on Western Australian agriculture. 2015 Agribusiness Crop Updates. Grain Industry Association of Western Australia, viewed August 2015

Haylock, M., & Nicholls, N., 2000. Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. Int. J. Climatol. 20. 1533-1541.

Hennessy, K.J., 1999. Australian rainfall changes, 1910-1995. Aust. Met. Mag. 48, 1-13.

Hope, P.K., Drosdowsky, W. and Nicholls, N., 2006. Shifts in the synoptic systems influencing southwest Western Australia. Clim. Dyn. 26, 751-764.

Hope, P., Timbal, B. and Fawcett, R., 2010. Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. Int. J. of Climatol. 30(9), pp.1360-1371.

Hughes, J.D., Petrone, K.C. and Silberstein, R.P., 2012. Drought, groundwater storage and stream flow decline in southwestern Australia. Geophys. Res. Lett. 39(3).

Islam, S.A., Bari, M.A. and Anwar, A.H.M.F., 2013. Hydrologic impact of climate change on Murray Hotham catchment of Western Australia: a projection of rainfall-runoff for future water resources planning. Hydrology & Earth System Sciences Discussions, 10(10).

Lazaro, R., Rodrigo, F.S., Gutiérrez, L., Domingo, F. and Puigdefábregas, J., 2001. Analysis of a 30-year rainfall record (1967–1997) in semi–arid SE Spain for implications on vegetation. J. Arid Environ. 48, 373-395. doi:10.1006/jare.2000.0755.

Lehmann, J., Coumou, D. and Frieler, K., 2015. Increased record-breaking precipitation events under global warming. Clim. Chang. 132(4), pp.501-515.

Li, Y., Cai, W., & Campbell, E. P., 2005. Statistical modeling of extreme rainfall in southwest Western Australia. J. Clim. 18(6), 852-863. https://doi.org/10.1175/JCLI-3296.1

Marvel, K. and Bonfils, C., 2013. Identifying external influences on global precipitation. Proc. Natl. Acad. Sci. 110(48), pp.19301-19306.

McGree, S., Whan, K., Jones, D., Alexander, L. V., Imielska, A., Diamond, H., ... & Kumar, R., 2014. An updated assessment of trends and variability in total and extreme rainfall in the western Pacific. Int. J. Climatol. 34(8), 2775-2791. DOI: 10.1002/joc.3874

Nicholls, N., 2010. Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007. Climate dynamics, 34(6), pp.835-845.

Nogueira, R.C. and Keim, B.D., 2010. Annual volume and area variations in tropical cyclone rainfall over the eastern United States. J. Clim. 23, 4363-4374. doi:10.1175/2010JCLI3443.1.

Petrone, K.C., Hughes, J.D., Van Niel, T.G. and Silberstein, R.P., 2010. Streamflow decline in southwestern Australia, 1950–2008. Geophys. Res. Lett. 37(11).

Pepler, A., Dowdy, A. and Hope, P., 2019. A global climatology of surface anticyclones, their variability, associated drivers and long-term trends. Clim. Dyn. 52(9-10), pp.5397-5412.

Pittock, A.B., 1983. Recent climatic change in Australia: Implications for a CO 2-warmed earth. Clim. Chang. 5, 321-340. doi:10.1007/BF02423529.

Prein, A.F., Holland, G.J., Rasmussen, R.M., Clark, M.P. and Tye, M.R., 2016. Running dry: The US Southwest's drift into a drier climate state. Geophys. Res. Lett. 43, 1272-1279. doi:10.1002/2015GL066727.

Raut, B.A., Jakob, C. and Reeder, M.J., 2014. Rainfall changes over southwestern Australia and their relationship to the Southern Annular Mode and ENSO. J. Clim. 27(15), pp.5801-5814.

Saha, S., Chakraborty, D., Paul, R.K., Samanta, S. and Singh, S.B., 2018. Disparity in rainfall trend and patterns among different regions: analysis of 158 years' time series of rainfall dataset across India. Theor. Appl. Climatol. 1-15. doi:10.1007/s00704-017-2280-9.

Samuel, J. M., Verdon, D. C., Sivapalan, M., & Franks, S. W., 2006. Influence of Indian Ocean sea surface temperature variability on southwest Western Australian winter rainfall. Water Resour. Res. 42(8). DOI: 10.1029/2005WR004672

Silberstein, R.P., Aryal, S.K., Durrant, J., Pearcey, M., Braccia, M., Charles, S.P., Boniecka, L., Hodgson, G.A., Bari, M.A., Viney, N.R. and McFarlane, D.J., 2012. Climate change and runoff in south-western Australia. J. Hydrol. 475, pp.441-455.

Smith, I., 2004. An assessment of recent trends in Australian rainfall. Aust. Met. Mag., 53, 163-173.

Smith, I. and Power, S., 2014. Past and future changes to inflows into Perth (Western Australia) dams. J. Hydrol. Reg. Stud. 2, pp.84-96.

Suppiah, R. and Hennessy, K.J., 1998. Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. Int. J. Climatol. 18, 1141-1164. doi:10.1002/(SICI)1097-0088(199808)18:10<1141::AID-JOC286>3.0.CO;2-P.

Thompson, D.W., Solomon, S., Kushner, P.J., England, M.H., Grise, K.M. and Karoly, D.J., 2011. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. Nat. Geosci. 4(11), p.741.

Timbal B and Drosdowsky W., 2013. The relationship between the decline of Southeastern Australian rainfall and the strengthening of the subtropical ridge. Int. J. Climatol. 33, 1021-1034. DOI: 10.1002/joc.3492.

Villarini, G., & Denniston, R. F., 2016. Contribution of tropical cyclones to extreme rainfall in Australia. Int. J. Climatol. 36(2), 1019-1025. DOI: 10.1002/joc.4393

Wang, Y., Chen, X. and Yan, F., 2015. Spatial and temporal variations of annual precipitation during 1960–2010 in China. Quat. Int. 380, 5-13.

Wright, P.B., 1974. Seasonal rainfall in southwestern Australia and the general circulation. Mon. Weather Rev. 102, 219-232. doi:10.1175/1520-0493(1974)102<0219:SRISAA>2.0.CO;2.

Yang, T., Ding, J., Liu, D., Wang, X. and Wang, T., 2019. Combined use of multiple drought indices for global assessment of dry gets drier and wet gets wetter paradigm. Journal of Climate, 32(3), pp.737-748.

Yu, B. and Neil, D.T., 1993. Long-term variations in regional rainfall in the south-west of Western Australia and the difference between average and high intensity rainfalls. Int. J. Climatol. 13, 77-88. doi:10.1002/joc.3370130106.

CHAPTER 3 - Interannual variations in rainfall of different intensities in South West of Western Australia

STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

Chapter 3 is a pre-print of a co-authored paper titled "Interannual variations in rainfall of different intensities in South West of Western Australia" which was published in the International Journal of Climatology. My contribution as the lead author included data collection, modelling, analysis, and writing the manuscript.

Paper citation: Philip, P. and Yu, B., 2019. Interannual variations in rainfall of different intensities in South West of Western Australia. International Journal of Climatology. DOI:10.1002/joc.6382

(Signed) [redacted] Date: 24/03/2020

Priya Philip

(Countersigned) [redacted] Date: 24/03/2020

Corresponding author of paper: Bofu Yu

(Countersigned) [redacted] Date: 24/03/2020

Supervisor: Bofu Yu

3.1. Introduction

Rainfall is one of the most important weather variables as it is the primary source of fresh water, and regional rainfall variability and change are an integral part of the global concern with climate change as a result of the enhanced greenhouse effect (Folland et al., 2001). Examining rainfall trends helps to identify their underlying causes and develop adaption strategies for water resources management.

Studies have shown increased rainfall variability in most parts of the world over the years (Dore, 2005). In England and Wales, winters are becoming increasingly wet while summers are drier during the time period, 1766 to 2014. Since 1976 winter precipitation has shown no significant trend, but spring has become wetter with drier summers (Mills, 2016). Bavil et al. (2018) investigated the trend in the frequency of occurrence of precipitation in Urmia Lake basin in Iran and concluded that the frequency of occurrence of daily precipitation with small amounts (10 mm) is significantly decreasing resulting in reduced runoff to the lake. Significant decreasing trends are observed in the annual rainfall in West and North Africa with an abrupt reduction since 1968 (Nicholson et al., 2018). Based on annual and seasonal analyses in Nigeria, Akinsanola and Ogunjobi (2017) report an increasing trend in annual, monsoon, post- and pre-monsoon rainfalls and a decreasing trend in winter rainfall. Excessive monsoon flooding has become more frequent in South East Asia and understanding the shift and predicting changing trends of the monsoon may be central to managing the floods which have devastating impacts on millions of people in the region (Loo et al., 2015).

Rainfall has been examined for various regions of Australia and many have concluded that the rainfall in Australia is showing large interannual variability and significant change (Pittock, 1983; Yu and Neil, 1993; Hennessy et al., 1999; Smith, 2004). While some parts of Australia show a significant increasing trend in rainfall (Suppiah and Hennessy, 1998), the South West of Western Australia (SWWA) is showing a significant decreasing trend (Yu and Neil, 1993; Gallant et al., 2007; Bates et al., 2010). SWWA receives most of its rainfall in winter during the months of June, July and August and SWWA depends on the winter rainfall for meeting its agricultural water requirements and town water supply. These sectors have been adversely affected by the decrease in rainfall over recent decades. Wheat production in the area could decline by 7.3% by 2030 (Heyhoe et al., 2007) and the decrease of inflow into the dams due to lower rainfall has led to low water levels in the dams of this region while the demand for water supply has been rising continuously (Steffen et al., 2015).

A decrease in the mean rainfall in the winter months in SWWA was observed by Pittock (1983). Yu and Neil (1993) associated the decrease in annual rainfall in SWWA with the decrease in the frequency of occurrence of all rainfall intensities in winter and though the high-intensity events (extreme events closely related to flooding, soil erosion and gully formation) show a decrease in winter, this is offset by a corresponding increase during summer. The decline in winter rainfall in SWWA is caused by the significant decrease in both the intensity and frequency of high-intensity rainfall (Hennessy et al., 1999; Haylock and Nicholls, 2000). Hennessy et al. (1999) found a significant decrease of 19% in total rainfall and a 25% decrease in winter rainfall. A significant decrease of 41–59% in the frequency of winter heavy rainfall and a 13% decline in the total winter rain days in SWWA were also observed. The change point of the statistically significant decreasing trend in SWWA is identified to be around the time 1965–1970 (Li et al., 2005; Fu et al., 2010). Gallant et al. (2007) analysed the trend in six Australian regions using nine climatic indices which are related to the mean annual, seasonal and extreme daily rainfall and found that eight out of the nine indices in SWWA show a statistically significant decreasing trend. SWWA also exhibits a decrease in the occurrence and intensity of daily precipitation (Bates et al., 2010).

The climate of SWWA is influenced by various weather drivers including the frontal system, Indian Ocean Dipole (IOD), sea surface temperature (SST), El Nino Southern Oscillation (ENSO), Southern Annular Mode (SAM) and the Sub Tropical Ridge (Murphy and Timbal, 2008). The winter rainfall in SWWA is lower in years when warm SSTs dominate the southern and tropical western Indian Ocean and the SST anomalies show a strong negative correlation with the sharp reduction in SWWA rainfall in the 1970s (Samuel et al., 2006). SAM is observed to have an inverse relationship to the SWWA winter rainfall (Feng et al., 2010; Hope et al., 2010). The step change in winter rainfall in 1970 is thought to be the result of a positive SAM in a neutral ENSO phase accompanied by a reduction in rainfall from the westerly fronts (Raut et al., 2014). The decreasing frequency of westerly fronts in SWWA during June, July and August is also thought to be responsible for the declining winter rainfall (Hope, 2006; Alexander and Arblaster, 2009). Rainfall variability in SWWA is more closely linked to the mean sea level pressure (MSLP) than SST (Ansell et al., 2000). The decreasing trend is strongly associated with a decrease in atmospheric moisture and an increase in regionally averaged sea level pressure (Bates et al., 2010). The correlation between SST and winter rainfall in SWWA was found to be the highest during the time period 1950–1994 (Smith et al., 2000). The concept of a monsoon-like atmospheric circulation, the South West Australian Circulation (SWAC), put forward by Feng et al. (2015) explains clearly the interannual variability of rainfall in SWWA and the long term decreasing trend.

Previous studies in SWWA have examined the decreasing trend in the rainfall in SWWA in terms of a decrease in extreme events or high-intensity rainfall (Hennessy et al., 1999; Fu et al., 2010; McGree et al., 2014) and annual and seasonal trend analyses have also been carried out showing similar results (Choudhury et al., 2015). The total rainfall in an area can be considered to be the sum of light, medium and heavy rainfalls. Classifying rainfall into heavy, medium and light rainfall classes would be useful for a better understanding of the rainfall–runoff relationship as catchments responds differently to different rainfall classes in terms of runoff generation and water availability. No study has been done yet to identify the contribution of each of the different classes of rainfall, namely, light, medium and heavy rainfalls, to the total decrease of rainfall in SWWA. Examining the decrease in rainfall in SWWA from this perspective has two benefits. First, different rainfall classes may be associated with distinct precipitation mechanisms. For example, heavy winter rainfall in SWWA is mostly associated with north-westerly winds while the late winter showery rainfall is mainly due to the south-westerly winds (Wright, 1974). Examining the trend and the interannual variations of different rainfall classes could help identify the underlying cause for the decline in rainfall in SWWA. Second, identifying the trend of light, medium and heavy rainfalls helps in understanding the interannual and seasonal pattern of each of these classes and is useful for developing water management strategies. A decrease in heavy rainfall would imply a decrease in streamflow and consequent lowering of water level in reservoirs whereas a decrease in light or medium rainfall indicates lower water availability for general uses.

To classify light, medium and heavy rainfalls, absolute thresholds, common to all sites, were not used because rainfall classification irrespective of the site location may lead to different or even erroneous interpretations, as the rainfall considered extreme for one location may not be extreme at another due to differing climatic conditions (Gallant et al., 2007). It is more appropriate to use relative thresholds, which are site-specific thresholds, where the classification is based on the actual rainfall received at that particular station.

Previous studies which examined the pattern of extreme rainfall in the study area have used the peak over threshold approach (Li et al., 2005; Aryal et al., 2009) and the 95th percentile (Hennessy et al., 1999; Haylock and Nicholls, 2000; McGree et al., 2014) to develop the extreme rainfall series in the study area. This study used an alternate approach to classify rainfall as light, medium and heavy for each station. Two thresholds in mm·day−1 were selected for each site so that the total rain was separated into three equal components. Previous studies have established the inverse relationship between the large scale circulation pattern, the SAM and the winter rainfall in SWWA (Feng et al., 2010; Hope et al., 2010). The current study aims to further test the relationship between the SAM) and the trend in light, medium, heavy and total annual rainfalls. The study also aims to assess the effect of the local site characteristics such as latitude, elevation, distance from the coast and the mean annual rainfall on the observed rainfall trends.

The objectives of this study are (a) to quantify the change in each rainfall class as components of the overall decrease in rainfall in SWWA, (b) to evaluate the contribution from each rainfall class to the total rainfall in terms of interannual variations, (c) to determine the change in the amount and the number of days of heavy rainfall for all seasons, (d) to test whether site-specific characteristics such as latitude, elevation, distance from coast and the mean annual rainfall are significantly correlated with the change in the total rainfall and individual rainfall classes and (e) to determine whether observed changes in rainfall in SWWA could be explained by the large scale circulation pattern, the SAM.

3.2 Data and methodology

SWWA has a Mediterranean climate with rainfall mostly occurring in winter months. The region has a mean annual rainfall of 300–1,200 mm (Table 3.1) and receives more than half of its total rainfall during the months of June, July and August. Rainfall in this region is mostly associated with cold frontal systems, which are moving from west to east across the Southern Ocean. Other factors that affect the rainfall in this region include the Subtropical ridge, SAM, IOD, west coast trough and cloud bands (Murphy and Timbal, 2008).

The study area lies south of 30°S and west of 119°E (Figure 3.1). This area was chosen because it has the highest mean annual rainfall (300–1,310 mm) compared to the neighbouring regions with a lower mean annual rainfall (130–300 mm) (Figure 3.1). More importantly, previous studies (Yu and Neil, 1993; Hennessy et al., 1999; Gallant et al., 2007) show that significant decreases in rainfall have occurred in this area.

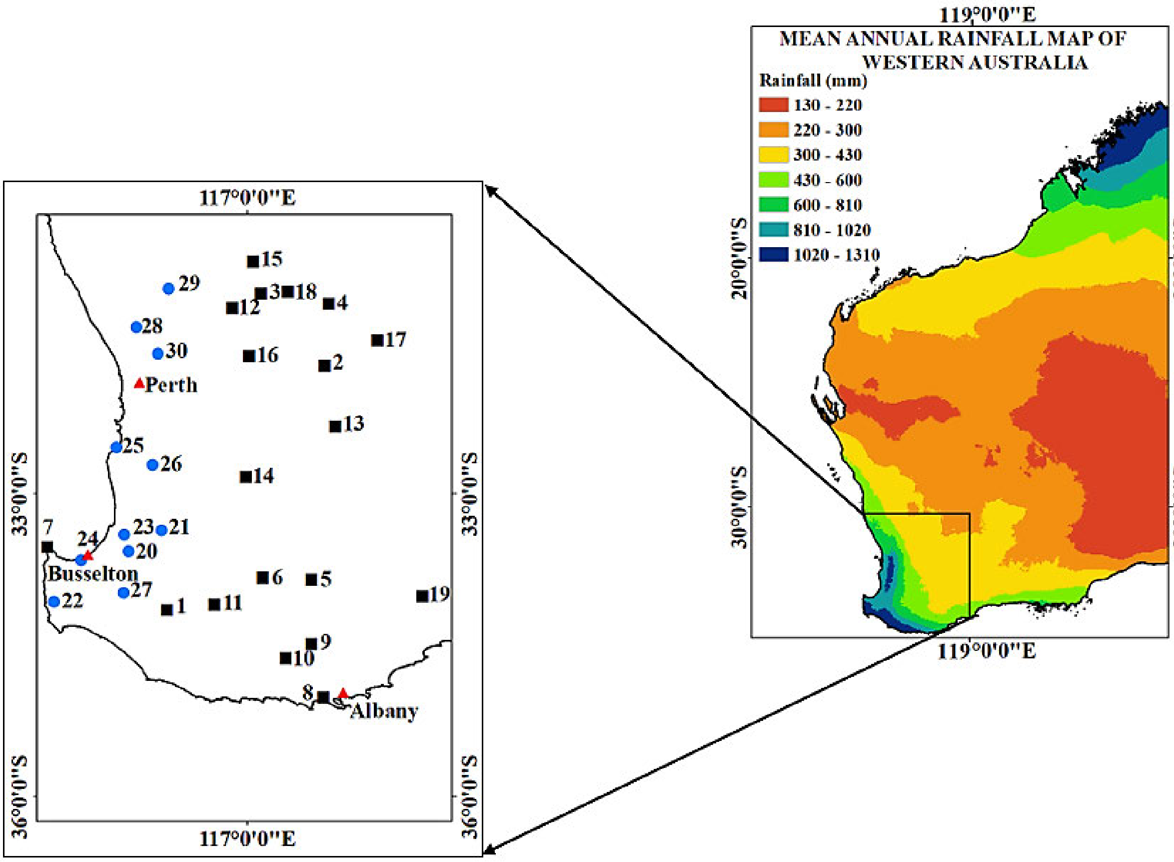

Figure 3. 1 The 30 rainfall stations in South West of Western Australia considered for this study. The squares represent stations regarded as high-quality stations (Lavery et al., 1992 and 1997), the circles represent additional stations for better spatial coverage, and the triangles represent major cities. The mean annual rainfall of Western Australia (130-1310 mm) was sourced from *http://www.bom.gov.au*. The station names corresponding to the sequential numbers indicated on map are given in Table 3.1.

Daily rainfall data for SWWA were obtained from the Bureau of Meteorology website for 30 stations in the study area. Nineteen of them were identified as high-quality rainfall stations (Lavery et al., 1992; 1997). The remaining 11 stations were selected for a better spatial coverage. Distribution of the stations in the study area is shown in (Figure 3.1 and details of the stations are given in Table 3.1.

Table 3. 1 Rainfall stations included in this study (Station number in bold indicates high quality stations as identified in Lavery et al., 1992 and 1997)

BoM Station Number	Station number on Fig.1	Location	Latitude	Longitude	Elevation (m)	Mean annual rainfall (mm)	Record length (years)
9619	1	Wilgarrup	-34.15	116.2	240	908	103
10037	2	Cuttening	-31.73	117.76	300	308	100
10045	3	Ejanding	-31.016	117.13	290	313	107
10126	4	Trayning	-31.116	117.8	290	319	99
10525	5	Broomehill	-33.85	117.63	328	446	103
10582	6	Kojonup	-33.83	117.15	305	533	85
9519	7	Cape Naturaliste	-33.53	115.016	109	807	106
9551	8	Grassmere	-35.016	117.75	10	1004	95
9561	9	Kendenup	-34.483	117.63	262	598	71
9591	10	Pardelup	-34.63	117.38	230	792	69
9616	11	Westbourne	-34.1	116.67	280	687	107
10024	12	Casuarina Vale	-31.16	116.85	275	376	84
10536	13	Corrigin	-32.33	117.866	295	372	104
10658	14	Cuballing	-32.833	116.983	300	504	99
8066	15	Kokardine	-30.7	117.05	310	327	104
10091	16	Meckering	-31.633	117.016	195	380	64
10092	17	Merredin	-31.483	118.283	315	330	105
10032	18	Cowcowing	-31	117.4	300	303	99
9520	19	Cape Riche	-34.016	118.73	40	561	101
9534	20	Donnybrook	-33.57	115.82	63	978	110
9628	21	Collie	-33.36	116.15	204	988	69
9547	22	Forest Grove	-34.07	115.08	60	1141	83
9527	23	Dardanup East	-33.4	115.78	40	914	81
9515	24	Busselton Shrine	-33.66	115.35	4	862	71
9572	25	Halls head	-32.54	115.7	366	866	92
9538	26	Dwellingup	-32.71	116.06	267	1226	80
9585	27	Nannup	-33.98	115.77	100	973	62
9018	28	Gingin	-31.35	115.9	92	760	67
9033	29	New Norcia	-30.97	116.22	220	548	68
9009	30	Lower Chittering	-31.61	116.11	113	848	59

A day with greater than or equal to 0.2 mm of rainfall was considered as a wet day. For stations with missing data, a station was accepted for a year if it had less than 10% of rain days missing and less than five consecutive rain days missing (Hennessy et al., 1999). Similarly, for stations with accumulated data (data which included rainfall of more than 1 day), a station was accepted for a year if it had less than 10% of accumulated rainfall and less than five consecutive accumulated rainfall records (Hennessy et al., 1999).

To classify rainfall into light, medium and heavy, relative thresholds were used. The method adopted here involved ranking the rainfall data at a station in a decreasing order and dividing this ranked series into three sets such that each set contributed to 1/3 (one third) of the total rainfall. The top set was defined as heavy rainfall for the station. Similarly, the bottom one third was defined light rainfall and the remaining values in the middle were the medium rainfall for the particular station. The thresholds that separate these rainfall classes would vary from site to site, but all the three classes contribute equally to the total rainfall for all sites. Annual time series of total, light, medium and heavy rainfall were prepared for each station in the study area using this relative threshold approach.

To determine the trend in total rainfall and in each of the three classes, linear regression was used to quantify how rainfall (the dependent variable) varies with time (the independent variable). The slope of the regression line was taken to indicate the rate of change in rainfall, and the trend was deemed to be statistically significant based on the p value if the slope differs from zero. As shown in Appendix 3.1, the sum of the rate of change for individual rainfall class equals the rate of change in the total rainfall, that is,

$$\beta_r = \beta_l + \beta_m + \beta_h \qquad (1)$$

where βr is the slope of the regression line for the annual rainfall, βl, βm and βh are the slopes for light, medium and heavy rainfalls, respectively. In addition, when each of the three rainfall classes contribute equally to the total rainfall, it can be shown that the slope for individual rainfall classes is identical. In other words, we have

$$\beta_l = \beta_m = \beta_h = \beta_r/3 \qquad (2)$$

as the null hypothesis to examine how each of these rainfall components varies in time in relation to variations in the annual rainfall.

To evaluate the contribution from each rainfall class to the variation in the total rainfall, the total variation in rainfall was decomposed as the sum of covariance of light, medium and heavy rainfalls with the total rainfall as shown in Appendix 3.2:

$$Var(T) = Cov\,(L,T) + Cov\,(M,T) + Cov\,(H,T)$$

To determine the variation in heavy rainfall for each season, time series of the total amount of heavy rainfall and the number of days with heavy rainfall for each season in each year were prepared for all the stations. The seasons considered for the analysis were summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November). Linear regression was used to determine the trend in heavy rainfall in each of the four seasons.

Pearson correlation coefficient between the site characteristics such as latitude, elevation, the mean annual rainfall and distance from the coastline and the trend in each rainfall class and that in total rainfall was used to examine the relationship between the site characteristics and the observed trends in rainfall. Latitude, elevation and the mean annual rainfall for each station were obtained from the Bureau of Meteorology website. Distance from the coastline was calculated as the shortest distance between the station and the coastline. Similarly, the correlation between SAM with the observed trend was also examined using the SAM index (source: http://www.lasg.ac.cn/staff/ljp/data-NAM-SAM-NAO/SAM(AAO).html). The SAM index is the difference between the normalized zonal MSLP at 40°S and at 65°S (Nan and Li, 2003). Linear models were developed to estimate the total and heavy rainfalls in the study area from the SAM index.

3.3. Results and Discussion

3.3.1 Trend analysis for individual rainfall classes

Table 3.2 shows results from trend analysis of the three rainfall classes and the total rainfall together with the long-term average annual rainfall for the 30 stations considered in this study. The average rainfall for each class is not included in Table 2 as it is just one third of the total average rainfall. Twenty seven of the 30 stations showed a decreasing trend in total rainfall, of which 12 stations showed a significant decrease at 5% significance level. Of the 12 stations, 10 showed a significant decrease at 1% significance level. The range of the decreasing trend for total rainfall varied from 0.84 (Cape Riche) to 38.3 mm·decade^{-1} (Wilgarrup).

Table 3. 2 Linear trends in the total, light, medium and heavy rainfall (values with '†' and '††' indicate statistical significance at 5% and 1% levels, respectively). The mean annual rainfall is also presented.

Station	Total		Light (mm/ decade)	Medium (mm/ decade)	Heavy (mm/ decade)
	Trend (mm/ decade)	Mean Rainfall (mm)			
Wilgarrup	-38.3††	907.8	-3.7††	-10.3††	-24.4††
Cuttening	-2.4	307.7	-0.2	-0.4	-1.8
Ejanding	1.5	312.5	0.4	1.1	0.1
Trayning	1.1	319.0	0.0	-0.2	1.2
Broomehill	-5.4	446.2	-0.3	-3.1†	-2.1
Kojonup	-14.6††	533.4	0.8	-7.3††	-8.1††
Cape Naturaliste	-13.3††	807.4	-3.5††	-5.6††	-4.2
Grassmere	-24.0††	1004.3	-0.2	-5.4†	-18.4††
Kendenup	-14.4†	597.8	0.9	-4.9	-10.4†
Pardelup	-25.7††	792.2	-4.5†	-9.2††	-12.0†
Westbourne	-10.4††	687.3	1.5	-3.8†	-8.1††
Casuarina Vale	-7.0	376.1	-6.8††	-1.0	0.9
Corrigin	-5.8†	371.9	-1.8†	-0.9	-3.1
Cuballing	-9.4††	504.2	0.1	-2.2	-7.3††
Kokardine	-0.9	326.7	-0.2	0.6	-1.3
Meckering	-11.9	380.2	-0.5	-6.4†	-5.0
Merredin	-1.5	329.7	-0.1	-3.0††	1.5
Cowcowing	-1.7	302.7	-0.6	-0.7	-0.3
Cape Riche	-0.8	561.5	6.1	-0.9	-6.0
Donnybrook	-18.2††	977.7	-4.3††	-6.9††	-7.1†
Collie	-13.0	988.4	-8.9††	-9.8	5.7
Forest Grove	-6.4	1141.2	11.1††	-2.8	-14.7†
Dardanup East	-26.1††	914.0	-0.2	-5.6	-20.2††
Busselton Shrine	-12.9	862.5	-5.9†	-2.5	-4.5
Halls head	-6.0	865.9	-2.6	-2.7	-0.7
Dwellingup	-32.7††	1225.7	-2.9	-11.4†	-18.5†
Nannup	0.5	973.2	6.0	1.7	-7.2
Gingin	-16.5	760.2	-2.3	1.0	-15.3†
New Norcia	-12.2	548.3	-7.5††	1.2	-5.9
Lower Chittering	-7.7	848.3	3.7	-0.2	-11.1

For three stations, namely Wilgarrup, Pardelup and Donnybrook, the significant decrease in total rainfall was accompanied by significant decreases in the light, medium and heavy rainfalls. For seven among the 12 stations that showed a significant decreasing trend in total rainfall, the total decrease was accompanied by a significant decrease in heavy rainfall only. Similarly, for five of the 12 stations, the decrease in total rainfall was accompanied by a significant decrease in the medium rainfall and at two stations, by a significant decrease in the light rainfall. For four stations, the decrease in the total rainfall was accompanied by a decrease in both the medium and heavy rainfalls and at one station the trend in total rainfall was accompanied by a decrease in both the medium and light rainfalls. These suggested that for a majority of the stations, the decreasing trend in total rainfall has been brought about by a concurrent decrease in heavy rainfall, followed by the medium and light rainfalls. For most stations, the rate of decrease in mm·decade^{-1} relative to the average rainfall (mm) was the highest for heavy rainfall followed by the medium and light rainfalls. For example, at Wilgarrup, the heavy rainfall decreased by 8% ([24.4 mm·decade^{-1}]/[907.8 mm/ 3]), the medium rainfall decreased by 3% ([10.3 mm·decade^{-1}]/[907.8 mm / 3]) and the light rainfall decreased by 1% ([3.7 mm·decade^{-1}]/[907.3 mm / 3]) from their respective long-term average.

Time series of the total and the three classes of rainfall at Wilgarrup station, where all classes showed a significant decreasing trend at 1% significance level is given in Figure 3.2 as an example. The decreasing trend in heavy rainfall (2.43 mm·year^{-1}) was higher than the decreasing trend in medium rainfall (1.03 mm·year^{-1}), followed by the decreasing trend in light rainfall (0.37 mm·year^{-1}). Thus, the trend in heavy rainfall is the largest (63%) contributor to the decrease in total rainfall (3.83 mm·year^{-1}) at Wilgarrup.

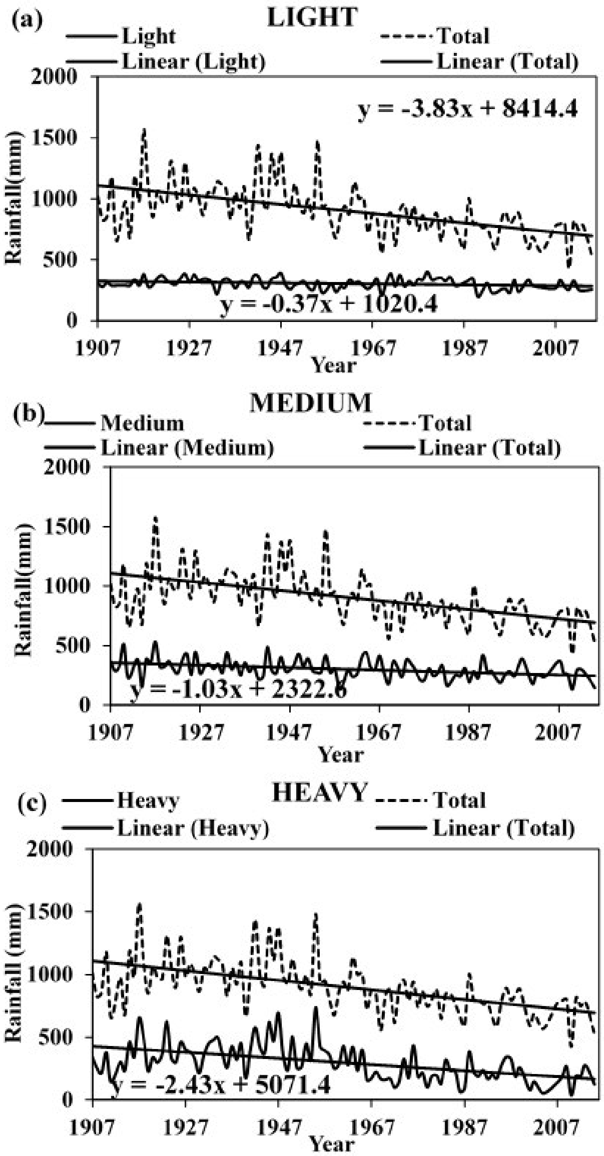

Figure 3. 2 Annual time series of (a) light, (b) medium, and (c) heavy rainfall in addition to the total rainfall at Wilgarrup in South West of Western Australia.

Significant positive correlation was found between the trends in total, light, medium and heavy rainfalls for the 30 stations in SWWA (Table 3.3). This indicated that the decrease in the total rainfall was contributed by the decreases in all three rainfall classes, although the degree of their contribution to the decrease in total rainfall differed. The trend in the medium (0.79) and the heavy rainfalls (0.78) was highly correlated with the trend in total rainfall and the correlation was weaker (0.37) for the light rainfall. Significant correlation was also observed between the trend in the medium rainfall and that in heavy rainfall (0.40). This suggests that both these rainfall classes could be produced by similar weather systems and the decrease in rainfall might be related to a weakening of these types of weather systems.

Table 3. 3 Correlation between the trend in total rainfall and the three distinct rainfall classes (values with '†' and '††' indicates significant correlation at 5% and 1% significance level, respectively)

	Total	Light	Medium	Heavy
Total	1	0.37†	0.79††	0.78††
Light		1	0.32	-0.21
Medium			1	0.40†
Heavy				1

Figure 3.3 shows the spatial distribution of stations with significant (at 5% significance level) and nonsignificant trends for all classes of rainfall and the total rainfall in the study area. It can be seen that for all rainfall classes and for total rainfall, most stations away from the coastline do not exhibit a significant decrease compared to those nearer to the coastline. In addition, more than 70% of stations with a significant trend, in all rainfall classes and total rainfall, were observed to be located south of 33°S. The relationship between the trend and latitude of a station will be further discussed in Section 3.2. For the heavy and total rainfalls, 75% of the stations which exhibited a significant decreasing trend were located near the south-west corner of the study area (Figure 3.3a,d). Sixty percent of the stations that showed a significant decrease in the light rainfall were mostly located along the west coast of the study area (Figure 3.3b). For stations with a significant decreasing trend in the medium rainfall, 73% of the stations were located in the southern half of the south of the study area (Figure 3.3c). Similar results were obtained for winter rainfall in SWWA (Raut et al., 2014). Rainfall in the coastal regions of SWWA showed a significant decreasing trend and this was found to be related to the predominantly positive phase of SAM in a neutral ENSO phase resulting in reduced rainfall from the rain-bearing westerly fronts in winter months (Raut et al., 2014)

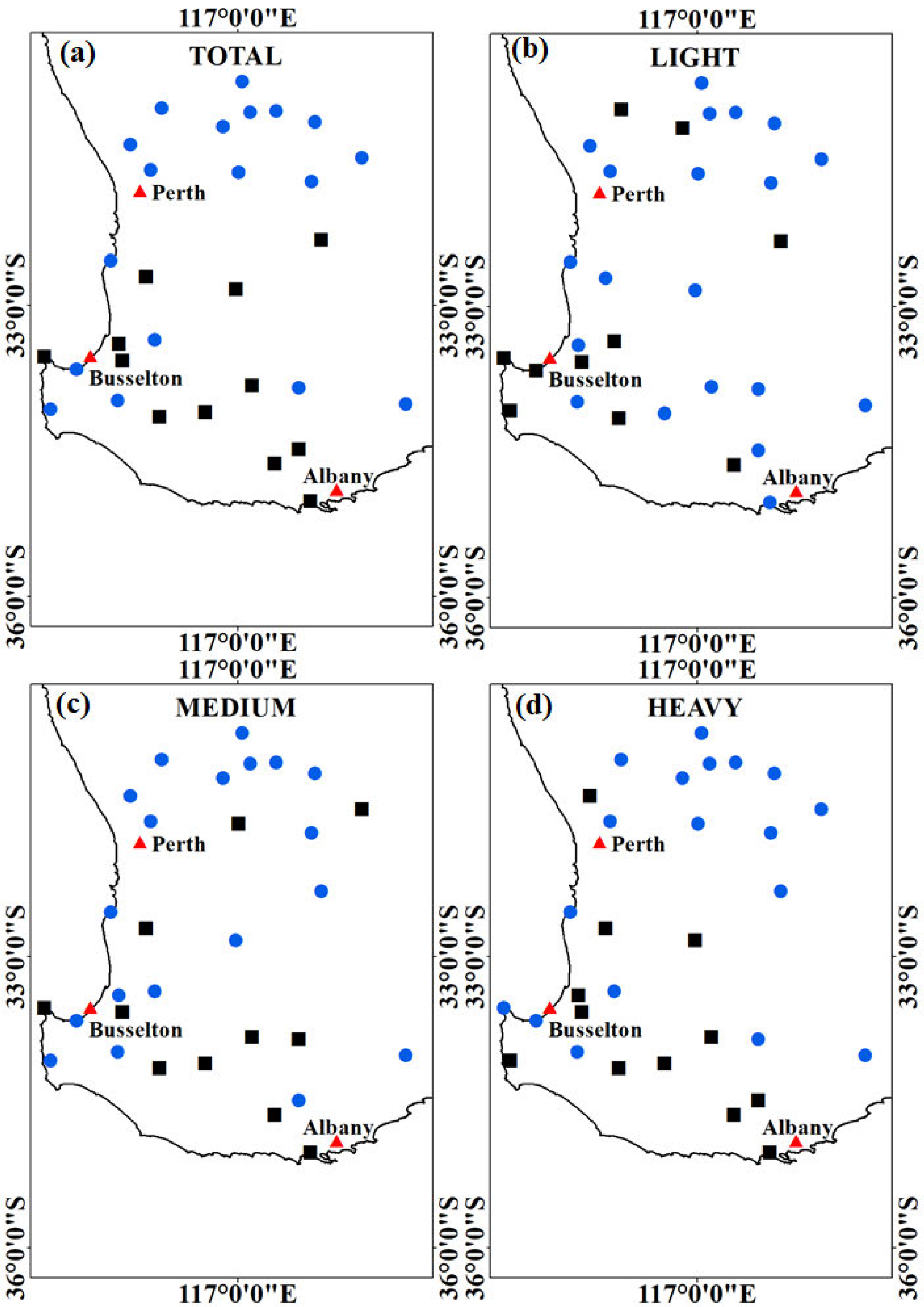

Figure 3. 3 Spatial distribution of rainfall stations with significant trends in (a) total, (b) light, (c) medium and (d) heavy rainfall (circles, squares and triangles represent stations with no significant changes, stations with significant decrease (p-value < 0.05) and major cities, respectively)

As the rainfall was classified into three classes such that each contributed to one third of the total rainfall for each station, in an ideal case, the rate of decrease in light, medium and heavy rainfalls should also be exactly one third of the total rainfall decrease at the particular station.

Our analysis showed that the rate of decline in heavy rainfall was 68% higher and the rate of decline in light rainfall was 55% lower than what was expected. The medium rainfall exhibited a trend that was closer (24%) to the expected trend compared to the other two classes. Figure 3.4 shows the observed trend versus expected trend (one third of the total) for three rainfall classes.

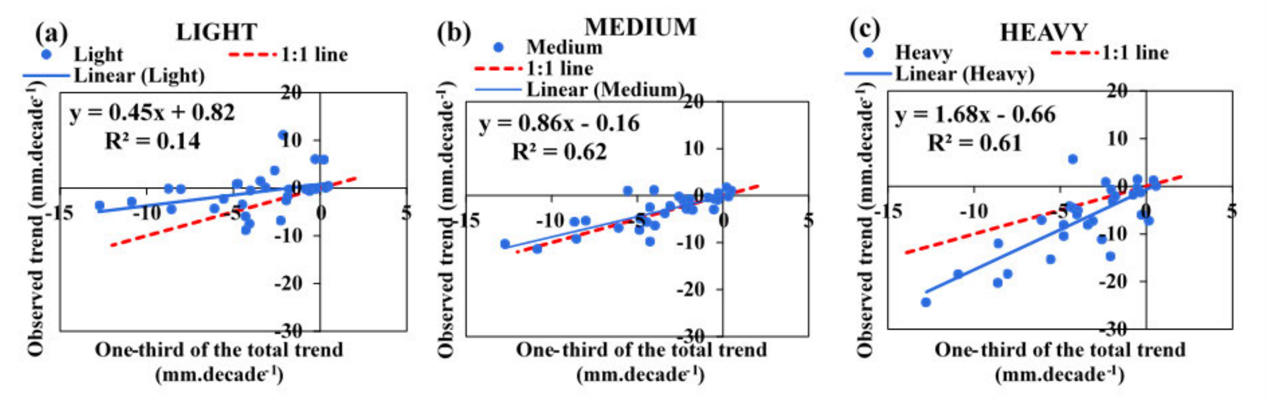

Figure 3. 4 Observed vs expected trends for (a) light, (b) medium and (c) heavy rainfall for the 30 sites selected. The dashed lines represent the expected trend.

The contribution of the three rainfall classes to the total rainfall in terms of the interannual variability was computed as the sum of the covariance between the light, medium, and heavy, and the total rainfalls (Equation 3 and Appendix 3.2) and is given in Table 3.4. The variation in heavy rainfall contributed to 57% of the total variation on average followed by medium and light rainfall which contributed to 30% and 13%, respectively. This shows that the interannual variation in heavy rainfall is largely responsible for the interannual variation in rainfall in SWWA. These results were congruent with the previous results shown in Figure 4, where the observed trend in heavy rainfall was higher than expected, the trend in light rainfall was lower than expected, while the observed trend in the medium rainfall was close to what was expected.

Table 3. 4 Covariance of light (L), medium (M) and heavy (H) rainfall expressed as a percentage of the variation of total rainfall.

Station number	Standard Deviation (mm)	L (%)	M (%)	H (%)
9619	207.5	9	29	63
10037	81.8	16	31	54
10045	79.5	16	23	61
10126	83.1	17	28	55
10525	93.7	15	26	60
10582	103.7	8	33	60
9519	138.0	13	29	58
9551	159.3	5	26	68
9561	110.4	9	34	56
9591	148.1	14	27	59
9616	121.4	11	29	60
10024	91.6	17	32	50
10536	85.7	15	26	59
10658	102.3	15	28	57
8066	79.9	22	24	54
10091	101.1	14	33	53
10092	80.0	19	22	59
10032	71.7	19	33	48
9520	129.9	6	22	72
9534	179.9	15	33	52
9628	191.0	14	30	56
9547	154.8	3	32	65
9527	168.8	14	30	56
9515	137.4	16	37	48
9572	151.5	7	36	56
9538	246.7	13	30	57
9585	151.5	14	32	54
9018	157.8	13	31	56
9033	135.2	15	33	52
9009	171.4	10	34	56
	Average	**13**	**30**	**57**

As the trend in the amount of heavy rainfall contributed most to the total trend in rainfall in SWWA compared to the other two classes, the trend in the number of days with heavy rainfall in a year and the seasonal distribution of heavy rainfall events were further examined. The average number of days with heavy rainfall in the study area ranged between 4.2 days·year^{-1} at Ejanding and 12 days·year^{-1} at Grassmere. Majority of the stations showed a decreasing trend in the number of days with heavy rainfall, of which, 12 stations showed a significant decreasing trend. All stations which had a significant decreasing trend in the amount of heavy rainfall (Table 3.2) also showed a significant decreasing trend (at 5% significance level) in the total number of days with heavy rainfall, except for Pardelup and Gingin. Significant decreasing trends in the total number of days with heavy rainfall were detected at Corrigin and Nannup, although there was no concurrent significant decrease in the total amount of heavy rainfall for the two sites.

The significant decreasing trend in the number of days with heavy rainfall ranged from 0.15 mm·decade^{-1} (or 3% of the average annual number of days with heavy rainfall) at Corrigin to 0.84 mm·decade^{-1} (or 8%) at Wilgarrup. It was worth noting that the significant decreasing trend in the total amount of heavy rainfall also showed a similar pattern ranging between 2% at Donnybrook and 8% at Wilgarrup. The similarity in terms of the relative magnitude of the decrease in heavy rain amount and heavy rain days suggests that weather systems associated with heavy rainfall in SWWA are weakening in both their intensity and frequency.

Since, the trend in the amount of heavy rainfall and number of days with heavy rainfall contributed most to the total decreasing trend in the study area, seasonal pattern of heavy rainfall was also examined. Patterns of the total amount of heavy rainfall and the number of heavy rain days in each season are presented in Tables 3.5 and 3.6, respectively. The results indicated that the decrease in the amount of heavy rainfall and the number of heavy rain days for most stations have occurred in winter. Fifteen stations showed a significant decreasing trend in the amount of heavy rainfall in winter and 13 stations had a significant decreasing trend in the number of heavy rain days in winter at 5% significance. In autumn, seven stations had a significant decreasing trend in the amount of heavy rainfall as well as a significant decreasing trend in the number of heavy rain days. Two stations (Nannup and Wilgarrup) had a significant decreasing trend in the amount of heavy rainfall and the number of heavy rain days in spring. In summer, no stations showed a significant decrease in heavy rainfall and the number of heavy rain days. Instead, significant increases (5% significance) in heavy rainfall occurred at two sites (Broomehill and Cuballing, Table 3.5) and significant increases (5% significance) in the number of heavy rain days also occurred at two sites (Broomehill and Merredin, Table 3.6). It is interesting to note that given the overwhelming decreasing trend in rainfall and heavy rainfall, significant increases in heavy rainfall in summer have occurred at some sites in SWWA.

Table 3. 5 Linear trend in the amount heavy rainfall for all seasons (values with '†' indicate statistical significance at 5% level). The mean heavy rainfall in a year for each season is also presented.

Station name	Autumn		Winter		Spring		Summer	
	Trend (mm/ decade)	Mean Rainfall (mm)	Trend (mm/ decade)	Mean Rainfall (mm)	Trend (mm/ decade)	Mean Rainfall (mm)	Trend (mm/ decade)	Mean Rainfall (mm)
Wilgarrup	-0.42†	75.20	-1.58†	164.34	-0.36†	42.85	-0.11	12.66
Cuttening	-0.08	36.43	-0.15	31.89	-0.05	10.99	0.08	23.01
Ejanding	-0.03	36.00	-0.10	36.74	0.06	9.28	0.07	21.70
Trayning	0.03	34.30	-0.04	38.20	0.09	12.93	0.01	16.61
Broomehill	-0.24†	45.19	-0.30†	56.45	0.07	24.23	0.25†	22.33
Kojonup	-0.32†	48.20	-0.55†	86.48	0.03	23.29	0.05	14.96
Cape Naturaliste	-0.13	69.39	-0.38	159.88	0.08	27.40	-0.01	6.93
Grassmere	-0.58†	90.73	-1.03†	152.80	-0.11	66.57	-0.14	17.66
Kendenup	-0.38	62.78	-0.54†	73.31	-0.16	40.92	0.04	14.89
Pardelup	-0.40	77.72	-0.74†	105.13	-0.02	53.93	-0.09	18.25
Westbourne	-0.26	62.90	-0.69†	111.44	0.00	32.16	0.02	17.13
Casuarina Vale	0.05	40.47	-0.15	53.81	0.08	8.72	0.08	21.70
Corrigin	-0.08	38.50	-0.34†	45.08	-0.08	15.78	0.23	20.14
Cuballing	-0.23†	38.56	-0.60†	90.77	-0.06	20.52	0.18†	13.58
Kokardine	-0.01	34.84	-0.17	41.86	-0.02	10.90	0.02	18.20
Meckering	-0.05	38.21	-0.55	60.65	-0.16	11.04	0.22	12.84
Merredin	0.04	37.60	-0.17†	34.80	0.06	12.89	0.16	16.63
Cowcowing	0.00	37.50	-0.14	34.09	0.09	9.83	0.02	19.03
Cape Riche	-0.50†	53.51	-0.04	62.77	-0.16	39.63	0.08	30.27
Donnybrook	-0.09	79.88	-0.58†	201.31	-0.09	33.85	-0.02	8.15
Collie	0.31	71.76	0.51	209.08	-0.24	33.67	-0.03	10.72
Forest Grove	-0.38	92.45	-1.02†	236.77	-0.03	41.55	-0.05	11.01
Dardanup East	-0.71†	77.13	-1.55†	187.39	0.06	25.53	0.07	7.58
Busselton Shrine	0.30	74.69	-0.81†	182.49	0.10	20.16	-0.06	8.90
Halls head	-0.01	74.29	-0.48	174.33	0.18	25.10	0.18	11.46
Dwellingup	0.26	89.07	-2.09†	244.73	0.09	57.72	-0.12	16.46
Nannup	0.20	80.50	-0.26	188.71	-0.51†	43.25	-0.15	9.60
Gingin	-0.21	54.51	-1.00	162.50	-0.29	26.32	0.04	7.21
New Norcia	-0.08	50.40	-0.32	100.97	-0.19	17.65	0.05	11.08
Lower Chittering	-0.15	62.03	-0.42	184.51	-0.42	24.53	0.20	7.02

Table 3. 6 Linear trend in the number of days with heavy rainfall for all seasons (values with '†' indicate statistical significance at 5% level). The mean annual number of days with heavy rainfall for each season is also presented.

Station name	Autumn		Winter		Spring		Summer	
	Trend (days/ decade)	Mean no. of days	Trend (days/ decade)	Mean no. of days	Trend (days/ decade)	Mean no. of days	Trend (days/ decade)	Mean no. of days
Wilgarrup	-0.02†	2.51	-0.05†	5.91	-0.01†	1.64	0.00	0.38
Cuttening	0.00	1.50	-0.01	1.59	0.00	0.49	0.00	0.83
Ejanding	0.00	1.34	-0.01	1.74	0.00	0.43	0.00	0.71
Trayning	0.00	1.41	0.00	1.90	0.00	0.65	0.00	0.58
Broomehill	-0.01†	1.98	-0.01†	2.86	0.00	1.12	0.01†	0.80
Kojonup	-0.01†	1.98	-0.02†	4.04	0.00	1.09	0.00	0.46
Cape Naturaliste	0.00	2.41	-0.01	5.80	0.00	1.07	0.00	0.22
Grassmere	-0.02†	3.22	-0.04†	6.00	0.00	2.68	0.00	0.59
Kendenup	-0.01	2.69	-0.02	3.73	-0.01	2.00	0.00	0.52
Pardelup	-0.01	3.03	-0.03	4.75	0.00	2.42	0.00	0.66
Westbourne	-0.01†	2.29	-0.03†	4.73	0.00	1.42	0.00	0.55
Casuarina Vale	0.00	1.56	-0.01	2.49	0.00	0.35	0.00	0.68
Corrigin	0.00	1.55	-0.01†	2.09	0.00	0.73	0.00	0.56
Cuballing	-0.01	1.46	-0.02†	3.70	0.00	0.89	0.00	0.39
Kokardine	0.00	1.40	-0.01†	1.98	0.00	0.55	0.00	0.77
Meckering	0.00	1.45	-0.01	2.56	-0.01	0.47	0.00	0.42
Merredin	0.00	1.49	-0.01†	1.74	0.00	0.61	0.01†	0.56
Cowcowing	0.00	1.52	-0.01†	1.74	0.00	0.48	0.00	0.77
Cape Riche	-0.01†	1.80	0.00	2.48	0.00	1.41	0.00	0.88
Donnybrook	0.00	2.21	-0.02	5.75	0.00	1.11	0.00	0.20
Collie	0.01	1.97	0.01	6.28	-0.01	1.07	0.00	0.26
Forest Grove	-0.01	2.78	-0.03†	7.08	0.00	1.36	0.00	0.30
Dardanup East	-0.02†	2.09	-0.04†	5.42	0.00	0.84	0.00	0.19
Busselton Shrine	0.01	2.20	-0.02	5.69	0.00	0.70	0.00	0.27
Halls head	0.00	2.18	-0.01	5.26	0.01	0.85	0.00	0.23
Dwellingup	0.01	2.09	-0.04†	5.91	0.00	1.51	0.00	0.30
Nannup	0.00	2.44	-0.02	6.42	-0.02†	1.61	0.00	0.27
Gingin	0.00	1.73	-0.03	5.42	-0.01	0.93	0.00	0.18
New Norcia	0.00	1.87	-0.01	4.09	-0.01	0.72	0.00	0.34
Lower Chittering	-0.01	1.88	-0.01	5.92	-0.01	0.81	0.00	0.17

Broadly, it was observed that there was a decreasing trend in the amount of heavy rainfall and the number of heavy rain days in the study area during winter and autumn. In spring, around 50% of the stations had a decreasing trend in the amount and in the number of heavy rain days, while the remaining stations showed an increasing trend in heavy rainfall, although, this increasing trend was not found to be significant for any of the stations. In summer, more than 60% of the stations had an increasing trend in the amount of heavy rainfall and the number of heavy rain days. This suggested that the heavy rainfall in the predominant rainy season (winter) in SWWA was decreasing, while the heavy rainfall during the dry season (summer) was increasing. These results are consistent with the findings of Yu and Neil (1993), who reported a decrease of high-intensity rainfall in winter and an increasing trend in summer in SWWA.

3.3.2 Relationship between site characteristics and rainfall trend

The effect of the station characteristics (latitude, elevation and the mean annual rainfall) on the observed trend total rainfall and the three intensity classes was considered using Pearson correlation analysis and the results are presented in Table 3.7. Initially, the distance from the coastline was also considered for the study but as the distance from the coastline and the mean annual rainfall of the study area was highly correlated (−0.85), only the mean annual rainfall was considered for further analysis. The mean annual rainfall showed a significantly negative correlation with the trend in the medium, heavy and total rainfalls. The results suggested that those stations with a high mean annual rainfall (stations near the coastline) were more likely to be associated with decreases in rainfall compared to those with a low mean annual rainfall (stations farther inland). Figure 3.5 shows the relationship between the mean annual rainfall and the trend in all three rainfall classes and that in the total rainfall.

Table 3. 7 Correlation between rainfall and station attributes (‘†’ and ‘††’ indicate statistical significance at 5% and 1%, respectively)

Rainfall class	Latitude	Elevation	Mean annual rainfall
Light	-0.18	-0.18	0.03
Medium	0.55††	0.04	-0.51††
Heavy	0.48††	0.44†	-0.61††
Total	0.48††	0.26	-0.62††

Latitude was found to be significantly and positively correlated with the trend in the medium, heavy and total rainfalls. Most stations (70%) at higher latitudes (south of 33°S) showed significant trends compared to those stations at lower latitudes (Figure 3.3). Site elevation was found to be significantly and positively correlated with the trend in heavy rainfall only. This suggested that stations at a lower elevation are more likely to be associated with decreasing trends compared to those at a higher elevation. This can be seen from the spatial distribution of stations in Figure 3.3, where most of the stations with a significant decreasing trend are located towards the coast with a lower elevation compared to the stations located farther inland with a higher elevation. The decrease in the light rainfall did not show significant correlations with any site characteristics examined in this study, whereas the decrease in the medium and heavy rainfalls was significantly correlated with site location characteristics.

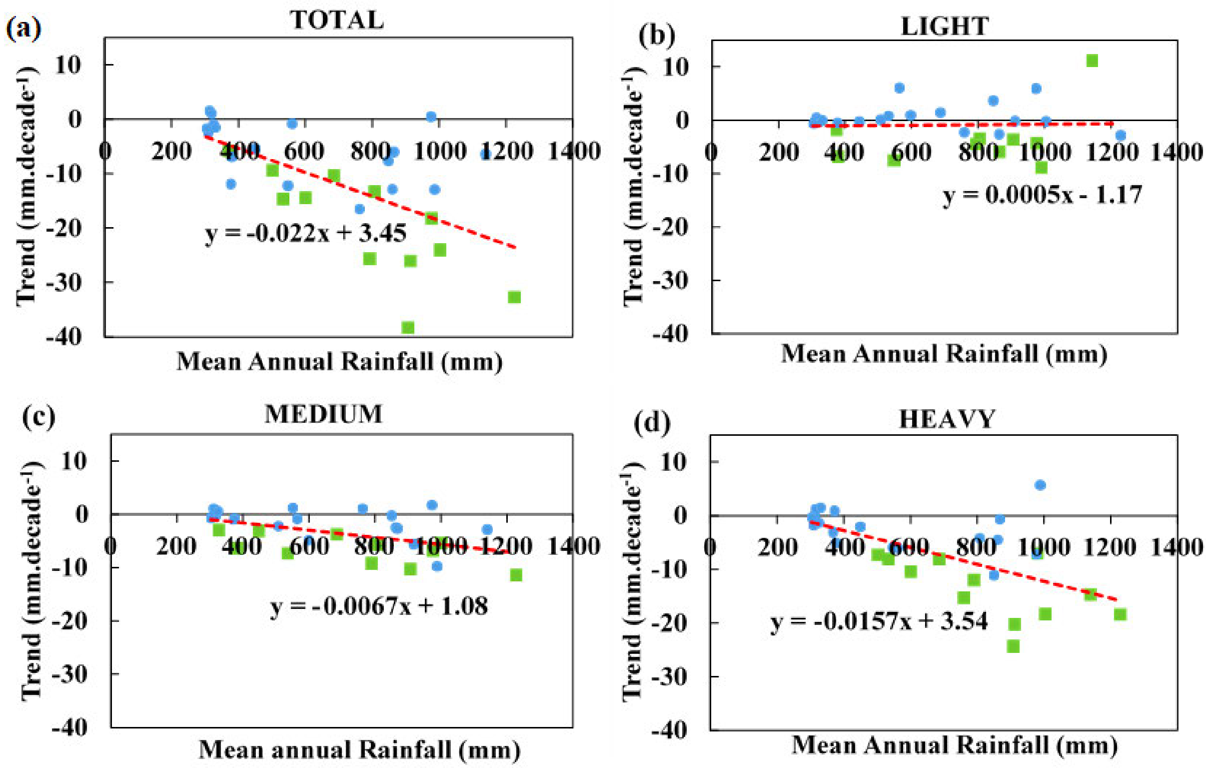

Figure 3. 5 Relationship between the mean annual rainfall and the linear trend in (a) total (b) light, (c) medium and (d) heavy rainfall (circles and squares denote non-significant and significant trend respectively and the dashed lines represent the trend line).

Using latitude, elevation and the mean annual rainfall as predictors, linear models were developed for the light, medium, heavy and total rainfalls. For the medium, heavy and total rainfalls, the models were found to be significant at 5% significance level and they were able to explain 30–40% of the variation in the dependent variables (Table 3.8). Latitude, elevation and the mean annual rainfall were found to be significant predictors for the medium rainfall whereas for total rainfall, the mean annual rainfall was found to be the only significant predictor. Although the linear model for heavy rainfall was significant, none of the independent variables was found to be significant predictors. Also, the model developed for the light rainfall was not significant at the 5% level. The observed trend versus the modelled trend using latitude, elevation and mean annual rainfall as predictors for the total rainfall and all the classes of rainfall are shown in Figure 3.6.

Table 3. 8 Partial regression coefficients ('††' indicate statistical significance at 1%)

Rainfall class	Latitude	Elevation	Mean annual rainfall	Adjusted R^2	p value
Light	-0.770	-0.009	-0.004	-0.020	>0.05
Medium	1.170††	-0.014††	-0.007††	0.420	<0.05
Heavy	0.920	0.008	-0.011	0.340	<0.05
Total	1.320	-0.016	-0.022††	0.350	<0.05

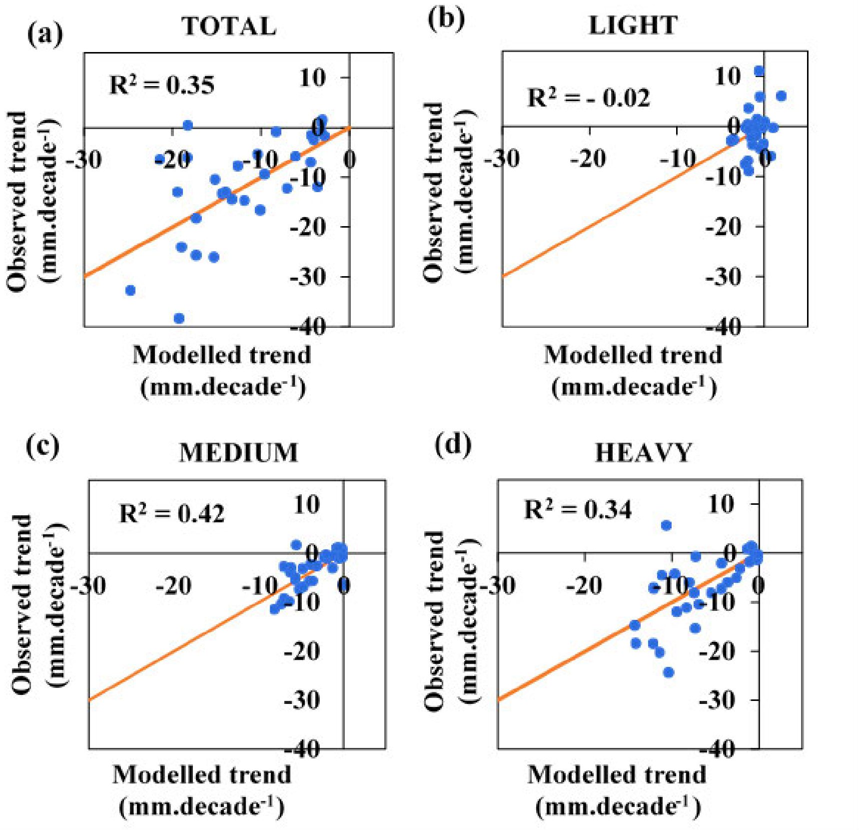

Figure 3. 6 Observed trend vs modelled trend using latitude, elevation and mean annual rainfall as predictors for (a) total (b) light (c) medium and (d) heavy rainfall. The straight line indicates the 1:1 line.

3.3.3 Correlation of SAM with rainfall

Results of Pearson correlation analysis, carried out to find possible associations between the total, light, medium and heavy rainfalls of all the stations and the SAM index, are presented in Table 3.9. The majority of the stations (73%) showed a negative correlation with SAM for the total rainfall. This result agreed with the findings of Feng et al. (2010) and Hope et al. (2010), which suggested an inverse relationship between SAM and winter rainfall in SWWA. Another interesting fact about the stations in the study area was that a significant decreasing trend was observed for all those stations where the medium, heavy and total rainfalls were significantly correlated to SAM.

Table 3. 9 Correlation between rainfall and SAM

Coefficient Range	SAM			
	Light	Medium	Heavy	Total
- 0.6 – - 0.31	5	1	5	3
- 0.30 – 0	12	21	15	19
0 – 0.30	12	8	10	8
0.31 – 0.6	1	0	0	0
No. of stations with significant correlation ($p<0.05$)	4	1	6	5

All five stations, for which the total rainfall showed correlation with SAM and had a significant decreasing trend in total rainfall, were found to be in the south-west corner of the study area as shown in Figure 3.7. In the case of the light, medium and heavy rainfalls, the stations which showed significant correlations with SAM and had a significant decreasing trend were also concentrated in this region. This region was defined by 32.25°S, 34.25°S and 116.5°E, and data for stations in this region were aggregated for further examination.

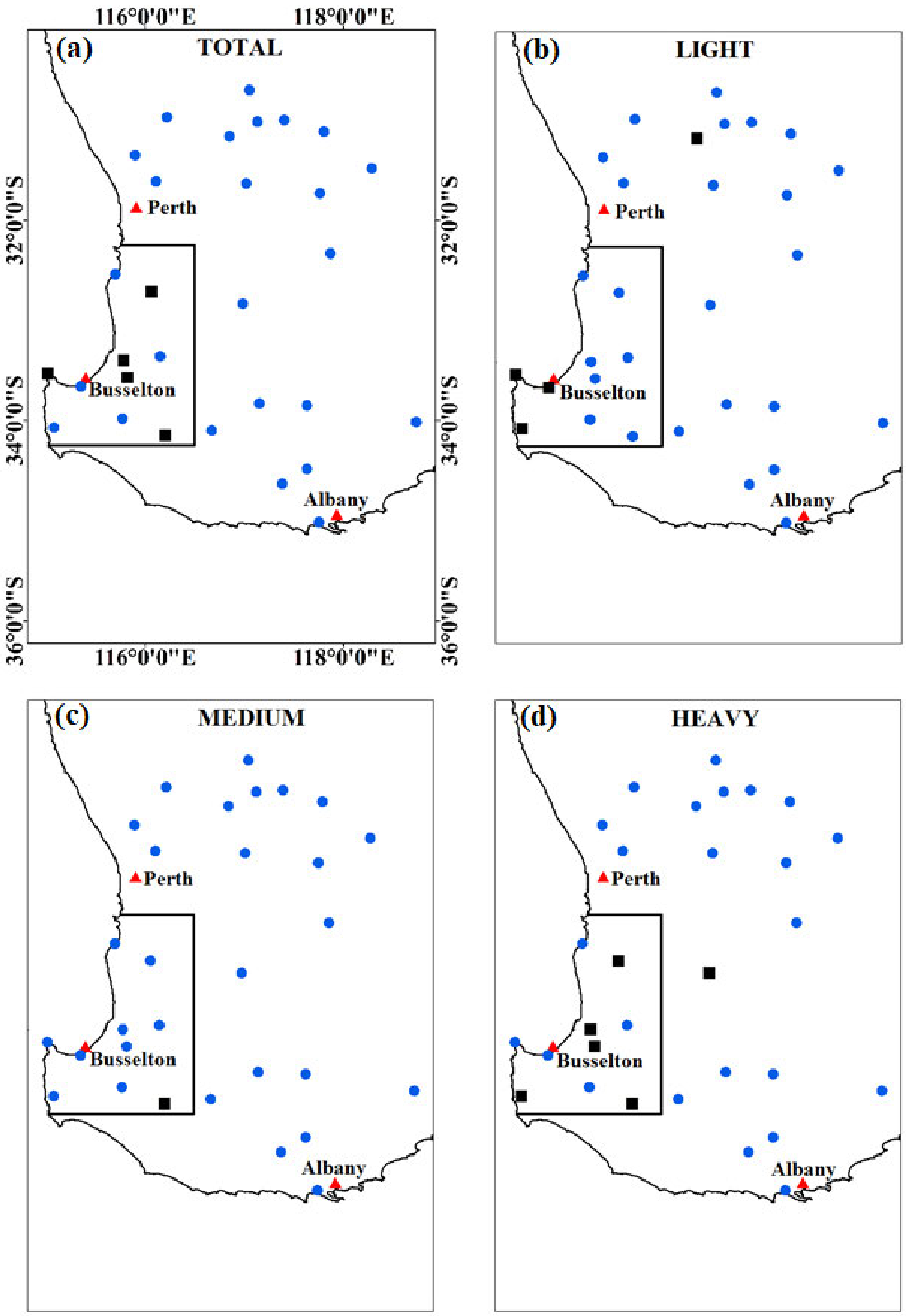

Figure 3. 7 Location of stations with significant correlations with SAM in (a) total (b) light (c) medium and (c) heavy rainfall. Squares represent stations with significant correlation with SAM and circles represent stations with non-significant correlations. The highlighted area is the region along the west coast where the sites, which showed significant correlations with both SAM and had significant decreasing trend, were more concentrated than elsewhere in the study area.

To evaluate whether SAM index could be used to predict the heavy and total rainfalls of this region, the correlation of SAM with the average rainfall in this region (highlighted in Figure 3.7) was computed. The annual time series of heavy and total rainfalls in the west coast region along with SAM are shown in Figure 3.8. The total and heavy rainfalls showed significant decreasing trends at the 5% level. SAM (1948–2010) showed a significant correlation coefficient of −0.34 with the heavy rainfall of the region and of −0.30 with the total rainfall.

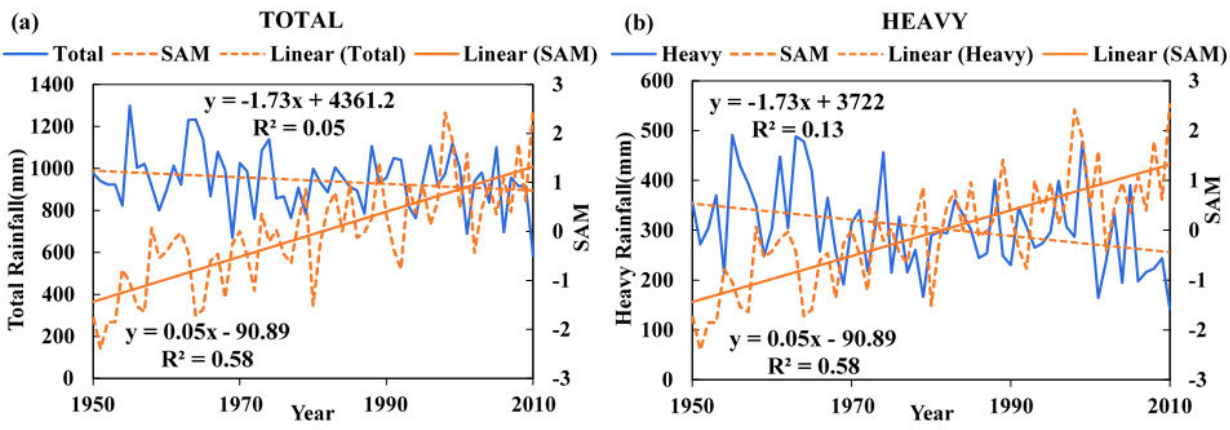

Figure 3. 8 Annual variation in SAM and (a) total rainfall and (b) heavy rainfall

Using the SAM index, linear regression models were developed, to test if the SAM index could be used to predict the heavy and total rainfalls in the highlighted region (Figure 3.7). It was found that the SAM index was capable of explaining 11% of the total variation in the total rainfall and 9% of the variation in the heavy rainfall at 5% level of significance (Figure 3.9a,b).

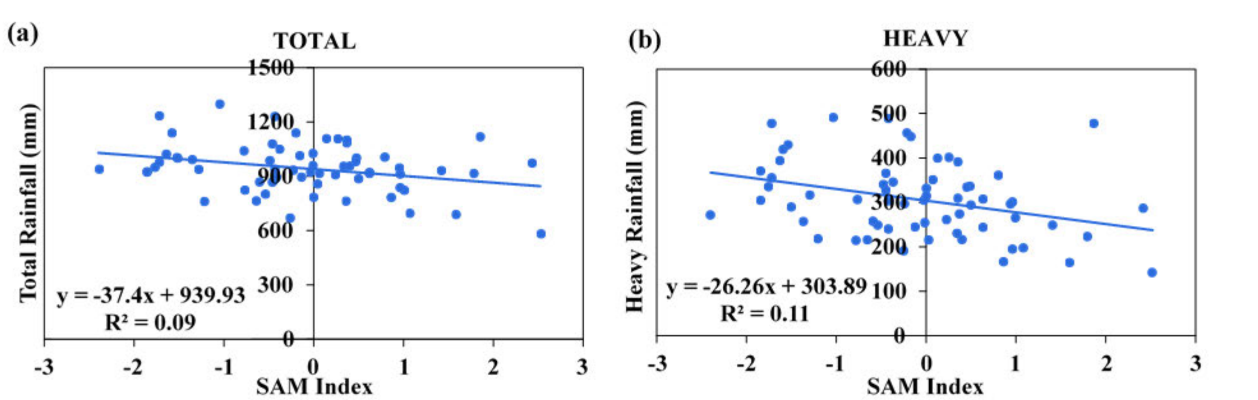

Figure 3. 9 The relationship between SAM and (a) annual total rainfall and (b) annual heavy rainfall for the west coastal region in SWWA as defined in Fig. 3.7.

While significant correlations between rainfall and SAM were found for the selected region along the west coast of Western Australia (Figure 3.7a), there are exceptions for individual stations. For example, some stations such as Kendenup, Pardelup and Corrigin showed a significant decrease in total rainfall, although rainfall for these stations was not significantly correlated with SAM. This indicated that the variability in rainfall in this region was not entirely and consistently dependent on the SAM.

Previous studies in SWWA investigated the annual and seasonal patterns in rainfall (Choudhury et al., 2015) as well as the pattern of extreme rainfall using other methods of classification such as the peak over threshold method (Li et al., 2005; Aryal et al., 2009). This study used a different method to classify rainfall as light, medium and heavy rainfalls. The results showed that the major contributor to the decrease in total annual rainfall was heavy rainfall followed by medium and light rainfalls. The results agreed with the previous findings in the study area (Hennessy et al., 1999; Haylock and Nicholls, 2000). This study also examined the contribution of each rainfall class to the total annual variation in rainfall in SWWA, showing the larger contribution of heavy rainfall to the total rainfall variability. The study also revealed the larger decline of the heavy rainfall in SWWA, compared to the other two classes considered in this study. The decrease in heavy rainfall was found to be mainly during winter and autumn while in summer it showed an increasing trend. This seasonal pattern of heavy rainfall is consistent with the findings of Yu and Neil (1993), which suggested a decrease in high-intensity rainfall in winter and an increase in summer. A significant correlation was observed between the trend in rainfall classes and the local site characteristics and the SAM, indicating the influence of these factors on the observed trend in rainfall of SWWA. SAM showed significant negative correlation to total and heavy rainfalls in the west coast of the study area which agrees with the findings of previous studies regarding the inverse relationship between SAM and winter rainfall in SWWA (Feng et al., 2010; Hope et al., 2010).

The larger rate of decline in heavy rainfall in the study area explains the marked lowering of water levels in the dams of this region as it is the heavy rainfall which causes runoff and inflow to dams. The results also indicate the significant weakening of the precipitation mechanisms or weather drivers causing heavy rainfall in this region.

3.4. Conclusion

The contributions of different rainfall classes to the decline in the total rainfall were examined using daily rainfall data from 30 stations in SWWA. Twelve, ten, eleven and twelve stations showed a significant decreasing trend in the total, light, medium and heavy rainfalls, respectively. The trends in all three rainfall classes were found to have significant positive correlation with the trend in the total rainfall, indicating that all three classes contributed to the overall decrease in rainfall in the region. The trends in the medium and heavy rainfalls were highly (0.78) correlated with the total trend compared to the correlation of trends in light rainfall with the total rainfall (0.37).

The decomposition analysis of the variation in the annual rainfall for the 30 stations showed that the variation in the heavy rainfall was the major contributor (57%) to the variation in the total rainfall, followed by the variation in the medium (30%) and light rainfalls (13%). Similar conclusions were supported given that more stations showed concurrent decreases in the heavy and total rainfalls, while there are fewer stations with concurrent decreases in both the light and total rainfalls in the study area. The rate of decrease in the heavy rainfall was 68% higher than the expected one third of the rate of decrease in the total rainfall and the rate of decrease in the light rainfall was 55% lower than the expected. The rate of decrease in medium rainfall was quite close to the expected rate. Majority of the stations which showed a significant decreasing trend in the amount of heavy rainfall also showed a significant decrease in the number of heavy rain days. The seasonal trend analysis of heavy rainfall indicated a significant decreasing trend in the amount of heavy rainfall and the number of heavy rain days in winter and autumn and for some stations an increasing trend in summer.

The observed trends in the total, medium and heavy rainfalls were found to be related to the mean annual rainfall, latitude and elevation. Majority of the stations which exhibited significant decreasing trends were those with a high mean annual rainfall and located near the coastline. It was also observed that more than 70% of stations with significant trends for all three rainfall classes and the total rainfall were located south 33°S latitude. Stations at a lower elevation were more likely to have a significant decreasing trend compared to the stations at a higher elevation. Trends in the light rainfall were not significantly correlated with any of the site characteristics examined.

The rainfall in the region showed significant negative correlation with the large scale circulation pattern, the SAM. All stations with significant correlation between SAM and the medium, heavy and total rainfalls showed a significant decreasing trend for these rain classes. The stations showing a significant decreasing trend in the total, light, medium and heavy rainfalls as well as significant correlation between these rainfall classes and SAM were all concentrated along the west coast of the study area. The linear models developed using the SAM index as a predictor for the total and heavy rainfalls of the west coast region of SWWA were able to explain 11% of the variation in total rainfall and 9% of the variation in heavy rainfall.

References

Akinsanola, A.A. and Ogunjobi, K.O. (2017) Recent homogeneity analysis and long-term spatio-temporal rainfall trends in Nigeria. Theoretical and Applied Climatology, 128(1–2), 275–289. https://doi.org/10.10 07/s00704-015-1701-x

Alexander, L.V. and Arblaster, J.M. (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. International Journal of Climatology, 29, 417–435. http s://doi.org/10.1002/joc.1730

Ansell, T.J., Reason, C.J.C., Smith, I.N. and Keay, K. (2000) Evidence for decadal variability in southern Australian rainfall and relationships with regional pressure and sea surface temperatures. International Journal of Climatology, 20, 1113–1129.

Aryal, S.K., Bates, B.C., Campbell, E.P., Li, Y., Palmer, M.J. and Viney, N.R. (2009) Characterizing and modeling temporal and spatial trends in rainfall extremes. Journal of Hydrometeorology, 10(1), 241–25 3. https://doi.org/10.1175/2008JHM1007.1

Bates, B.C., Chandler, R.E., Charles, S.P. and Campbell, E.P. (2010) Assessment of apparent nonstation arity in time series of annual inflow, daily precipitation, and atmospheric circulation indices: a case study of south west Western Australia. Water Resources Research, 46, W00H02. https://doi.org/10.1029/2010W R009509

Bavil, S.S., Zeinalzadeh, K. and Hessari, B. (2018) The changes in the frequency of daily precipitation in Urmia Lake basin, Iran. Theoretical and Applied Climatology, 133(1–2), 205–214. https://doi.org/10.100 7/s00704-017-2177-7

Choudhury, R.K., Beecham, S., Boland, J. and Piantadosi, J. (2015) Understanding south Australian rainfall trends and step changes. International Journal of Climatology, 35, 348–360. https://doi.org/10.100 2/joc.3982

Dore, M.H. (2005) Climate change and changes in global precipitation patterns: what do we know? Environment International, 31(8), 1167–1181.

Feng, J., Li, J., Li, Y., Zhu, J. and Xie, F. (2015) Relationships among the monsoon-like southwest Australian circulation, the southern annular mode, and winter rainfall over Southwest Western Australia. Advances in Atmospheric Sciences, 32, 1063–1076. https://doi.org/10.1007/s00376-014-4142-z

Feng, J., Li, J.P. and Li, Y. (2010) Is there a relationship between the SAM and Southwest Western Australian winter rainfall? Journal of Climate, 23, 6082–6089. https://doi.org/10.1175/2010JCLI3667.1

Folland, C.K., Karl,T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E.,Oerlemans, J., Salin ger, M.J. and Wang, S.W. (2001) Observed climate variability and change. Climate change, 2001, The Scientific Basis—Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp. 99– 181, Cambridge Univ. Press, New York.

Fu, G., Viney, N.R., Charles, S.P. and Liu, J. (2010) Long-term temporal variation of extreme rainfall events in Australia: 1910-2006. Journal of Hydrometeorology, 11, 950–965. https://doi.org/10.1175/2010J HM1204.1

Gallant, A.J.E., Hennessy, K.J. and Risbey, J. (2007) Trends in rainfall indices for six Australian region s: 1910-2005. Australian Meteorological Magazine, 56, 223–239.

Haylock, M. and Nicholls, N. (2000) Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. International Journal of Climatology, 20, 1533–1541.

Hennessy, K.J., Suppiah, R. and Page, C.M. (1999) Australian rainfall changes, 1910-1995. Australian Meteorological Magazine, 48, 1–13.

Heyhoe, E., Kim, Y., Kokic, P., Levantis, C., Ahammad, H., Schneider, K., Crimp, S., Nelson, R., Flo od, N. and Carter, J. (2007) Adapting to climate change-issues and challenges in the agriculture sector. Australian Commodities: Forecasts and Issues, 14, 167.

Hope, P., Timbal, B. and Fawcett, R. (2010) Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. International Journal of Climatology, 30, 136 0–1371.

Hope, P.K. (2006) Projected future changes in synoptic systems influencing Southwest Western Australia. Climate Dynamics, 26, 765–780. https://doi.org/10.1007/s00382-006-0116-x

Lavery, B., Joung, G. and Nicholls, N. (1997) An extended high-quality historical rainfall dataset for Australia. Australian Meteorological Magazine, 46(1), 27–38.

Lavery, B., Kariko, A. and Nicholls, N. (1992) A historical rainfall data set for Australia. Australian Meteorological Magazine, 40, 33–39.

Li, Y., Cai, W. and Campbell, E.P. (2005) Statistical modeling of extreme rainfall in Southwest Western Australia. Journal of Climate, 18(6), 852–863. https://doi.org/10.1175/JCLI-3296.1

Loo, Y.Y., Billa, L. and Singh, A. (2015) Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. Geoscience Frontiers, 6(6), 817–823.

McGree, S., Whan, K., Jones, D., Alexander, L.V., Imielska, A., Diamond, H., et al. (2014) An updated assessment of trends and variability in total and extreme rainfall in the western Pacific. International Journal of Climatology, 34(8), 2775–2791. https://doi.org/10.1002/joc.3874

Mills, T.C. (2016) Modelling rainfall trends in England and Wales. Cogent Geoscience, 2(1), 1133218. http s://doi.org/10.1080/23312041.2015.1133218

Murphy, B.F. and Timbal, B. (2008) A review of recent climate variability and climate change in southeastern Australia. International Journal of Climatology, 28(7), 859–879. https://doi.org/10.1002/joc.1627

Nan, S. and Li, J. (2003) The relationship between the summer precipitation in the Yangtze River valley and the boreal spring southern hemisphere annular mode. Geophysical Rese arch Letters, 30(24),2266. https://doi.org/10.1029/2003GL018381.

Nicholson, S.E., Funk, C. and Fink, A.H. (2018) Rainfall over the African continent from the 19th through the 21st century. Global and Planetary Change, 165, 114–127.

Pittock, A.B. (1983) Recent climatic change in Australia: implications for a CO2-warmed earth. Climatic Change, 5(4), 321–340. https://doi.org/10.1007/BF02423529

Raut, B.A., Jakob, C. and Reeder, M.J. (2014) Rainfall changes over southwestern Australia and their relationship to the southern annular mode and ENSO. Journal of Climate, 27(15), 5801–5814. https://doi.or g/10.1175/JCLI-D-13-00773.1

Samuel, J.M., Verdon, D.C., Sivapalan, M. and Franks, S.W. (2006) Influence of Indian Ocean Sea surface temperature variability on Southwest Western Australian winter rainfall. Water Resources Research, 42(8), W08402. https://doi.org/10.1029/2005WR004672

Smith, I. (2004) An assessment of recent trends in Australian rainfall. Australian Meteorological Magazine, 53(3), 163–173.

Smith, I.N., McIntosh, P., Ansell, T.J., Reason, C.J.C. and McInnes, K. (2000) Southwest Western Australian winter rainfall and its association with Indian Ocean climate variability. International Journal of Climatology, 20(15), 1913–1930.

Steffen, W., Hughes, L. and Pearce, A. (2015) Climate change 2015: Growing risks, critical choices. Climate Council of Australia, Sydney

Suppiah, R. and Hennessy, K.J. (1998) Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. International Journal of Climatology, 18(10), 1141–1164. https://doi.org/10.100 2/(SICI)1097-0088(199808)18:103.0.CO;2-P

Wright, P.B. (1974) Seasonal rainfall in southwestern Australia and the general circulation. Monthly Weather Review, 102(3), 219–232. https://doi.org/10.1175/1520-0493(1974)1022.0.CO;2

Yu, B. and Neil, D.T. (1993) Long-term variations in regional rainfall in the south-west of Western Australia and the difference between average and high intensity rainfalls. International Journal of Climatology, 1 3(1), 77–88. https://doi.org/10.1002/joc.3370130106

Appendix 3.1: Rate of change in total rainfall expressed as the sum of the rate of changes in light, medium and heavy rainfall

The equations for annual, light, medium and heavy rainfall are given by

$$Y_r = \alpha_r + \beta_r t \quad \text{(A1)}$$

$$Y_l = \alpha_l + \beta_l t \quad \text{(A2)}$$

$$Y_m = \alpha_m + \beta_m t \quad \text{(A3)}$$

$$Y_h = \alpha_h + \beta_h t \quad \text{(A4)}$$

where, Y_r, Y_l, Y_m and Y_h are the annual total rainfall, annual light rainfall, annual medium rainfall and annual heavy rainfall at a particular station. β_r,β_l, β_m and β_h are the slopes of total, light, medium and heavy rainfall and α_r,α_l, α_m and α_h are the respective intercepts. It can be shown that the rate of change in total rainfall (β_r) is the sum of the rates of change in light (β_l), medium (β_m) and heavy rainfall (β_h) as demonstrated below.

The slope of the regression equation is given by

$$\beta 1 = \frac{\sum_{i=1}^{n}(x_i y_i) - n\bar{x}_i\bar{y}_i}{\sum_{i=1}^{n}(x_i^2) - n\bar{x}_i{}^2} \quad \text{(A5)}$$

In this case x_i = the time, t and let the mean of time be $\bar{t}$. Also, let the mean of total, light, medium and heavy rainfall be denoted as $\overline{Y_r}$,$\overline{Y_l}$,$\overline{Y_m}$, and $\overline{Y_h}$.

$$\beta_l + \beta_m + \beta_h = \frac{\sum(tY_l) - n\bar{t}\overline{Y_l} + \sum(tY_m) - n\bar{t}\overline{Y_m} + \sum(tY_h) - n\bar{t}\overline{Y_h}}{\sum t^2 - n\bar{t}^2}$$

$$= \frac{\sum t(\mathrm{Y}_l + \mathrm{Y}_m + \mathrm{Y}_h) - n\bar{t}(\overline{Y_l} + \overline{Y_m} + \overline{Y_h})}{\sum t^2 - n\bar{t}^2}$$

But $\mathrm{Y}_l + \mathrm{Y}_m + \mathrm{Y}_h = Y_r$ and $\overline{Y_l} + \overline{Y_m} + \overline{Y_h} = \overline{Y_r}$

$$\beta_l + \beta_m + \beta_h = \frac{\sum tY - n\bar{t}\overline{Y_r}}{\sum t^2 - n\,\bar{t}^2}$$

$=\beta_r$, the slope of total rainfall.

Appendix 3.2: Variation in total rainfall expressed as the sum of covariance of light, medium, heavy and total rainfall

$$T_i = L_i + M_i + H_i \quad \text{(A6)}$$

$$\bar{T} = \bar{L} + \bar{M} + \bar{H} \quad \text{(A7)}$$

By definition,

$$Var\ (T) = \sum(T_i - \bar{T})^2 = \sum T_i^2 - N\bar{T}^2 \quad \text{(A8)}$$

$$Cov\ (L, T) = \sum(L_i - \bar{L})(T_i - \bar{T}) = \sum L_i T_i - N\bar{L}\bar{T} \quad \text{(A9)}$$

Similarly,

$$Cov\ (M, T) = \sum M_i T_i - N\bar{M}\bar{T} \quad \text{(A10)}$$

$$Cov\ (H, T) = \sum H_i T_i - N\bar{H}\bar{T} \quad \text{(A11)}$$

Therefore, we have

$$Cov\ (L,T) + Cov\ (M,T) + Cov\ (H,T) = \sum T_i(L_i + M_i + H_i) - N\bar{T}(\bar{L} + \bar{M} + \bar{H})$$
$$= \sum T_i^2 - N\bar{T}^2 = Var(T) \qquad \text{(A12)}$$

where T_i is the total annual rainfall for a station which is the sum of annual light (L_i), medium (M_i) and heavy (H_i) rainfall. Also, the mean annual rainfall ($\bar{T}$) is the sum of mean annual light ($\bar{L}$), medium ($\bar{M}$) and heavy ($\bar{H}$) rainfall

CHAPTER 4 - Temporal variations in rainfall volume in South West of Western Australia

STATEMENT OF CONTRIBUTION TO CO-AUTHORED MANUSCRIPT

Chapter 4 is a co-authored manuscript titled "Temporal variations in rainfall volume in South West of Western Australia" which has been accepted for publication by the Journal of Applied Meteorology and Climatology. My contribution as the lead author to the manuscript included data collection, modelling, analysis, and writing the manuscript.

Paper citation: Philip, P. and Yu, B., (accepted). Temporal variations in rainfall volume in South West of Western Australia. (Manuscript has been accepted for publication by the Journal of Applied Meteorology and Climatology on 05/11/2020)

(Signed) [redacted] Date: 24/03/2020

Priya Philip

(Countersigned) [redacted] Date: 24/03/2020

Corresponding author of paper: Bofu Yu

(Countersigned [redacted] Date: 24/03/2020

Supervisor: Bofu Yu

4.1 Introduction

Rainfall shows considerable temporal and spatial variability around the world (Easterling et al. 2000). Spatial variability in rainfall can provide vital information and insight which would be useful for adopting region-specific water management strategies. The global precipitation pattern indicates that the wet areas are becoming wetter and dry areas are becoming drier (Dore 2005). In the United States, the Northwest and Southwest shows decreasing trends on precipitation amount, while the Midwest, Northeast and parts of South shows increasing trends (Prein et al. 2016). A significant decreasing trend has been reported in the annual rainfall of the Mediterranean basin and a significant increasing trend in annual rainfall in Central and Northern Europe has been found (Caloiero et al. 2018). In the Arab regions, a general warming trend has been observed since the 1970s. The western part of the region exhibits a wetting trend while the eastern part shows a drying trend (Donat et al. 2014). Wang et al. (2015) studied the spatial and temporal variations of annual precipitation in China during the period 1960 – 2010 and showed that there have been significant changes in rainfall in East, Northwest China, Northeast and Southwest China and the decadal changes of precipitation in East China were closely correlated with the East Asian summer monsoon and the atmospheric circulation. Saha et al. (2018) suggests that the trend of rainfall over different regions in India shows dissimilar pattern. The trend of rainfall in different seasons in North and Central India is closely related to the overall decreasing pattern of the country, Peninsular India shows slight similarity while North East India shows a different pattern to the overall decreasing pattern in rainfall.

In the southern hemisphere, a study conducted in New Zealand by Caloiero (2014), looked at the spatial and temporal patterns of daily precipitation concentration using the precipitation concentration index (CI). The precipitation concentration index (CI) is used to examine the temporal heterogeneity of precipitation distribution by correlating the magnitude of precipitation events with the time of occurrence (Zhang et al., 2019). The results showed the different behaviour of CI between the North Island and the South Island. North Island and the eastern side of South Island showed higher CI values indicating critical rainfall concentration while the western side of South Island showed lower CI values. In Australia, the average rainfall has increased in the northwest and southeast (Collins & Della-Marta 1999; Suppiah and Hennessey 1999), while there is a large significant decline of rainfall in South West of Western Australia (SWWA) (Wright 1974; Yu and Neil 1993, Choudhury et al. 2015).

The decrease of rainfall in SWWA has been well studied and documented in previous studies. They have examined the change in rainfall in relation to the change in rainfall depth or frequency (Pittock 1983; Yu and Neil 1993; Hennessey et al. 1999; Smith et al. 2004; Gallant et al. 2007). Rainfall volume as distinct from rainfall depth is crucial because the precipitation depth over an area such as a river basin helps to determine the water resources availability for that area. Changes in the rainfall volume have considerable implications for regional water resources planning and management (Arai et al. 2012). As the rainfall volume is the product of rainfall depth and the wet area, the change in rainfall volume is the result of change in rainfall depth or that in wet area or both. Rainfall volume has significant applications in hydrologic applications or global circulations models (Kebe et al. 2005). Previous studies which considered rainfall volume were concerned with the rainfall volume produced by tropical storms and their effects (Noguiera et al. 2010) and the relationship between rainfall volume and vegetation (La'zaro et al. 2000). To our knowledge, no research has been undertaken to examine the change in rainfall volume and the wet area in the context of a regional decline in rainfall in SWWA.

The Southern Annular Mode (SAM) is the north-south movement of the westerly wind belt which dominates the middle to higher latitudes of the Southern Hemisphere (Thompson and Wallace, 2000). Previous studies suggest that a positive SAM in a neutral ENSO (El Nin˜o Southern Oscillation) phase is the cause of the decrease in rainfall along the coast of SWWA (Raut et al. 2014). The inverse relationship between SAM and SWWA winter rainfall has also been established in previous studies (Ansell et al. 2000 and Li et al. 2005). However, Feng et al. (2010) found that the positive and negative phases of SAM has negligible impact on SWWA winter rainfall if the year 1964, which was an extremely wet year, is excluded. Most rainfall trend studies, as in this study, are usually based on long term rainfall data which can overlook the recent climate variations of a region. As a 30-year period is the minimum duration required to define regional climatology, the period from 1989 to 2018 was analyzed to examine recent climate variations in SWWA.

The aim of this study is to obtain a better understanding of the changes in rainfall volume in SWWA during the period from 1911 to 2018. The objectives of this study are to 1) evaluate the rate of change in rainfall volume, wet area, and the average daily rainfall depth for different rainfall thresholds; 2) attribute changes in rainfall volume to that in the wet area and average daily rainfall depth, 3) compare the observed trend in rainfall volume and wet area with the expected trend; 4) map the change in areas having different number of rain days for different rainfall thresholds; 5) analyze and interpret the recent trend (1989 -2018) in rainfall and trend variations in relation to the SAM.

4.2 Material and methods

The study area (265,952 km^2) is the South West of Western Australia, which lies south of 30ºS and west of 120ºE. This area receives a mean annual rainfall (MAR) between 200 and 1258 mm (Fig. 4.1) and has a Mediterranean climate with more than 50% of the rainfall in winter (June-August). The daily gridded rainfall data from Bureau of Meteorology from 1911 – 2018 (108 years) was used for this study (http://www.bom.gov.au/climate/data-services/maps.shtml). The gridded rainfall data has been developed under the Australian Water Availability Project (AWAP) where the grids are interpolated from station rainfall data using a sophisticated analysis technique as detailed by Jones et al. (2009). Each grid cell covers an area of 0.05˚latitude by 0.05˚longitude.

Based on the mean annual rainfall in SWWA, the area was classified into four zones. Areas with the mean annual rainfall between 200 mm - 400 mm as Zone 1, 400 mm - 600 mm as Zone 2, 600 mm - 1000 mm as Zone 3, and greater than 1000 mm as Zone 4 (Fig. 4.1). Table 1 gives the details of each zone. It is worth noting that these zones lie at varying distances from the coast with Zone 4 being closest to the coast and Zone 1 farther inland. For each zone the change in rainfall volume, wet area, and average daily rainfall depth were determined using linear regression. The statistical significance of the trend was determined using the p-value. A p-value less than 5% was considered as statistically significant.

.

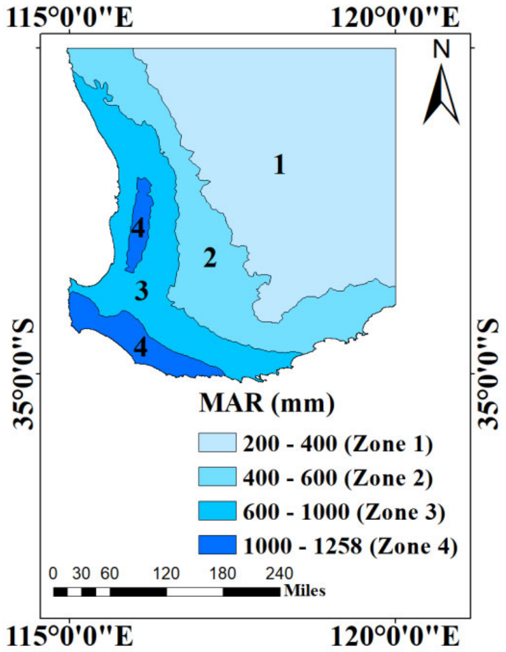

Figure 4. 1 Mean annual rainfall (MAR) in South West of Western Australia classified into four zones. Data sourced from *http://www.bom.gov.au* for the period, 1961-1990

Table 4. 1 The area and mean annual rainfall volume for the whole study area and the four zones for the period 1911 – 2018.

Region	**Area (km^2)**	**Mean Annual Rainfall Volume (TL year^{-1})**
Whole region	265952.2	131.7
Zone 1	140209.1	45.9
Zone 2	60738.7	29.3
Zone 3	49301.9	38.8
Zone 4	15702.4	17.6

A day with rainfall greater than or equal to 0.2 mm was considered as a wet day, a day with rainfall ≥ 10 mm as a heavy precipitation day, and a day with rainfall ≥ 30 mm as a very heavy precipitation day according to Australian Bureau of Meteorology (http://www.bom.gov.au/climate/change/about/extremes.shtml). In this study we define and investigate the following categories: daily rainfall ≥ 0.2 mm day^{-1} was considered as total rainfall, daily rainfall ≥ 10 mm day^{-1} was considered as heavy rainfall, and daily rainfall ≥ 30 mm day^{-1} was considered as very heavy rainfall. The rainfall volume, wet area, and average daily rainfall depth for each year were computed as follows:

1) The rainfall volume on a given day, V, was the sum of rainfall depths for all the grid cells with rainfall ≥ r (where r = 0.2, 10 and 30 mm day^{-1}) times average area of the grid cell (30.9103 km2). The annual rainfall volume was calculated as the sum of rainfall volumes for all days (rainfall ≥ r mm) in the year, given in TL (teralitres).
2) The wet area on a given day was the total number of cells with rainfall ≥ r times the average area of the grid cell. The average wet area for a year, A, was calculated as the average of all daily wet areas in a year, given in km^2.
3) The average daily rainfall depth, D, was the sum of rainfall depths for all grid cells with rainfall ≥ r in the year divided by the total number of cells with rainfall ≥ r in that year, given in mm.

The following conservation relationship among annual V (TL), A (km^2), and D (mm) values holds for all rainfall thresholds:

$$V = \frac{ADN}{10^6} \text{ for all r} \qquad (1)$$

where N is the number of days in a calendar year, and 106 just a factor for unit conversion. Eq. (1) allows decomposition of the total volume of water received at the ground level into the depth of precipitation, and the areal coverage.

Let V be the annual volume of rainfall of all grid cells with rainfall ≥ 0.2 mm day^{-1} and let V_r be the annual volume of rainfall of all grid cells with rainfall ≥ r (where r = 10 and 30 mm day^{-1}). For each threshold, r, let η be the ratio of the mean V_r to the mean V. As r increases, the contribution of V_r to total V would decrease or so would η. If V and V_r are perfectly correlated and proportional, i.e. $V_r(i) = \eta\, V(i)$ for each year i, one would expect that the rate of change in V_r, β_r, would be exactly ηβ, where β is the rate of change in V. Thus, we have a null hypothesis that $\beta_r = \eta\beta$, to test whether rainfall above a threshold varies in a similar fashion in comparison to that in total rainfall volume. In other word, we could compare the observed rate of change in V_r, i.e.β_r, with the expected rate of change, ηβ, for different rainfall thresholds. Similarly, the observed rate of change in wet area was compared to the expected rate of change in wet area for different daily rainfall thresholds.

To estimate the contribution of the change in wet area and depth to the rainfall volume, we regard the rain volume (V) as the product of the wet area (A) and rain depth (D), differentiating the equation V=AD with respect to time in finite difference form leads to:

$$\frac{\Delta V}{\Delta t} = D\frac{\Delta A}{\Delta t} + A\frac{\Delta D}{\Delta t} \qquad (2)$$

Or

$$\frac{\Delta V}{V\Delta t} = \frac{\Delta A}{A\Delta t} + \frac{\Delta D}{D\Delta t} \qquad (3)$$

The rate of change terms $\Delta V/\Delta t$, $\Delta A/\Delta t$ and $\Delta D/\Delta t$ in Eq. (2) and (3)can be approximated with linear trends in rainfall volume, wet area and average daily rainfall depth, respectively. The first term on the right-hand side of Eq. (3) can be used to represent the contribution from the change in wet area to change in rainfall volume. Likewise, the second term on the right-hand side, $\Delta D/D\Delta t$ represents the contribution from the change in rainfall depth to the overall change in rainfall volume. A similar approach has been used to partition the change in streamflow to climate and human factors (Wang et al. 2013).

The number of days with rainfall ≥ 0.2 mm and rainfall ≥ 10 mm in a year for each grid cell in the whole study area was determined and shown as maps for each decade. These maps help identify regions where the change in the number of rain days was most pronounced. The four zones based on the mean annual rainfall were not considered in the study of rate of change in number of rain days. Instead, new regions were identified throughout the study area based on the number of rain days and the rate of change in the area of these regions were calculated.

To determine the recent changes in rainfall and their relation to the SAM, the total annual rainfall was calculated for the 0.2 , 10, and 30 mm day^{-1} thresholds for the periods 1957 – 2018, 1957 - 1988, and 1989 – 2018, respectively. The trend in the SAM and rainfall for these periods were calculated for the whole region and the four zones. Pearson correlation was used to find the statistical relationships between SAM and rainfall in the study area. The SAM index was extracted for the period 1957 – 2018 from Marshall (2003).

4.3 Results

4.3.1 Trend in rainfall volume, wet area and average daily rainfall depth

The rainfall volume, wet area, and average daily rainfall depth were calculated for the whole area and the four zones separately for total rainfall (rainfall ≥ 0.2 mm day^{-1}), heavy rainfall (rainfall ≥ 10 mm day^{-1}), and very heavy rainfall (rainfall ≥ 30 mm day^{-1}), respectively, for the period 1911 – 2018. Figure 4.2(a) and 4.2(b) show an example of the time series of annual rainfall volume and the average wet area for Zone 4 (MAR ≥ 1000 mm) for the heavy rainfall (rainfall ≥ 10 mm day^{-1}). A decreasing pattern was observed in rainfall volume and wet area in Zone 4. Figure 4.2(c) represents the wet area (in km2) for heavy rainfall (rainfall ≥ 10 mm day^{-1}) in Zone 4 for each day of the year 1957. The average of these daily values (1586.25 km2 in 1957) was taken as the average wet area for the particular year.

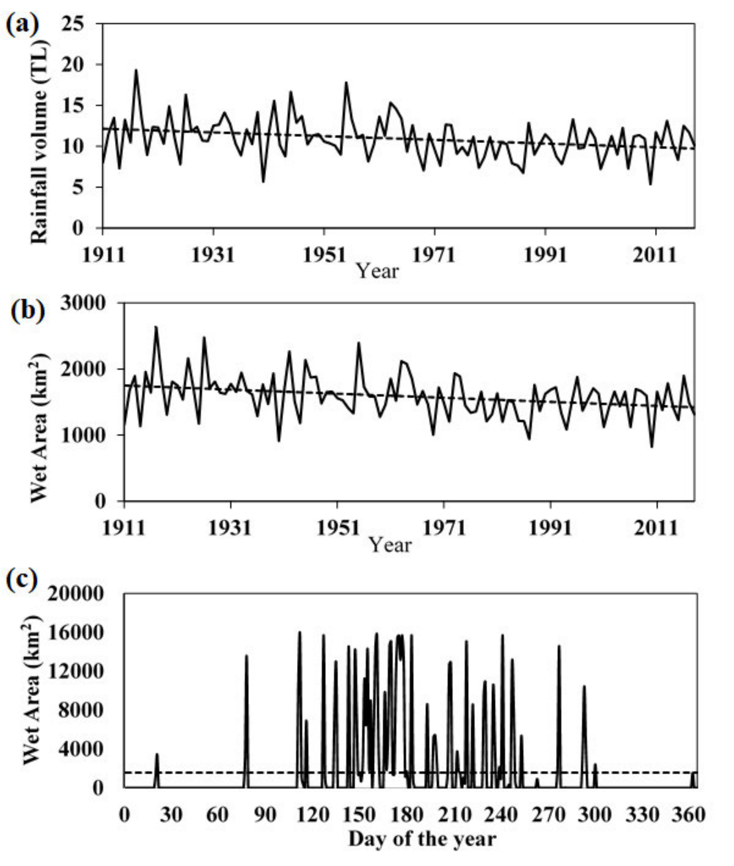

Figure 4. 2 Time series of (a) annual rainfall volume (b) annual wet area (c) daily wet area for 1957 in Zone 4 for daily rainfall intensity > 10 mm as an example. Dotted lines represent a decreasing trend of 0.23 TL per decade for rainfall volume and 31.04 km^2 per decade for wet area

a) Trend in rainfall volume

Figure 4.3 presents the results of trend analysis of the rainfall volume, for the whole study area and the four zones separately. The whole region showed a significant decreasing trend for the total rainfall (rainfall ≥ 0.2 mm day^{-1}). Zone 1 with a MAR of 200 to 400 mm, and which lies farther inland, showed an increasing trend in rainfall volume for total, heavy and very heavy rainfall (rainfall ≥ 0.2, 10 and 30 mm day^{-1}), although, the trend was not statistically significant for all thresholds. Zone 2 (400 mm ≤ MAR ≤ 600 mm) showed a significant decreasing trend in rainfall volume for total rainfall (rainfall ≥ 0.2 mm day^{-1}). Zone 3 (600 mm ≤ MAR ≤ 1000 mm) showed a significant decreasing trend in rainfall volume for total (rainfall ≥ 0.2 mm day^{-1}) and heavy rainfall (rainfall ≥ 10 mm day^{-1}) while Zone 4 showed significant decreasing trend for all thresholds. In general, the decreasing trend in rainfall volume was predominant in the coastal areas (Zone 3 and 4) while the inland area (Zone 1) showed an increasing trend although this trend was not statistically significant.

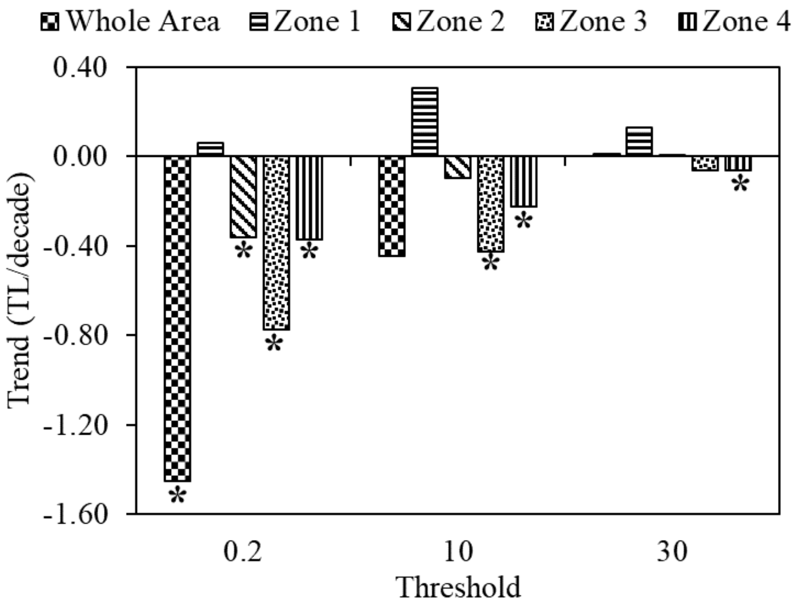

Figure 4. 3 The trend in the rainfall volume for the whole area and four zones with different daily rainfall thresholds. Columns with "*" indicates trend at 5% significance

b) Trend in wet area

Figure 4.4 presents the results of trend analysis of the average wet area for the region and for individual zones. Significant decreasing trend in wet area was observed for total rainfall (rainfall ≥ 0.2 mm day^{-1}) for the whole region and in all zones. Zone 1 showed an increasing trend in wet area for the heavy (rainfall ≥ 10 mm day^{-1}) and very heavy rainfall (rainfall ≥ 30 mm day^{-1}) although this trend was not significant. Zone 3 and 4 showed significant decrease in wet area with heavy rainfall (rainfall ≥ 10 mm day^{-1}) and Zone 4 had a significant decrease in wet area with very heavy rainfall than (rainfall ≥ 30 mm day^{-1}). These results suggested that the wet area has been shrinking in size for the study period (1911 – 2018) in the regions of high MAR (≥ 600 mm). This could be one of the reasons for the observed decreasing trend in rainfall in the study area. A net decrease in the wet area for the whole region was observed, even though there was an increase in the wet area farther inland, i.e. Zone 1, because this increase was more than off-set by the concurrent decrease in other zones.

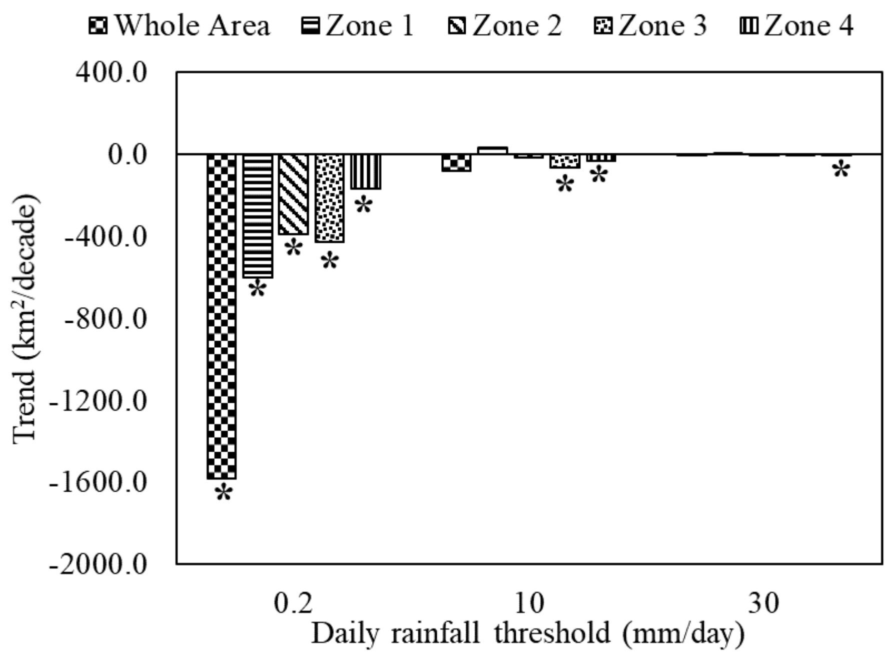

Figure 4. 4 The trend in the wet area for the whole study area and for four zones at different daily rainfall thresholds. Columns with "*" indicates trend at 5% significance

c) Trend in average daily rainfall depth

Figure 4.5 presents the trend in the average daily rainfall depth in the study area. The mean rainfall depth increases as the rainfall threshold increases. Significant trends were observed only for the total rainfall (rainfall ≥ 0.2 mm day^{-1}) for the whole region and in Zone 1. All three thresholds showed an insignificant increase in average daily rainfall depth for the whole region and all zones except for heavy rainfall (rainfall ≥ 10 mm day^{-1}) in Zone 4 and very heavy rainfall (rainfall ≥ 30 mm day^{-1}) in Zone 1.

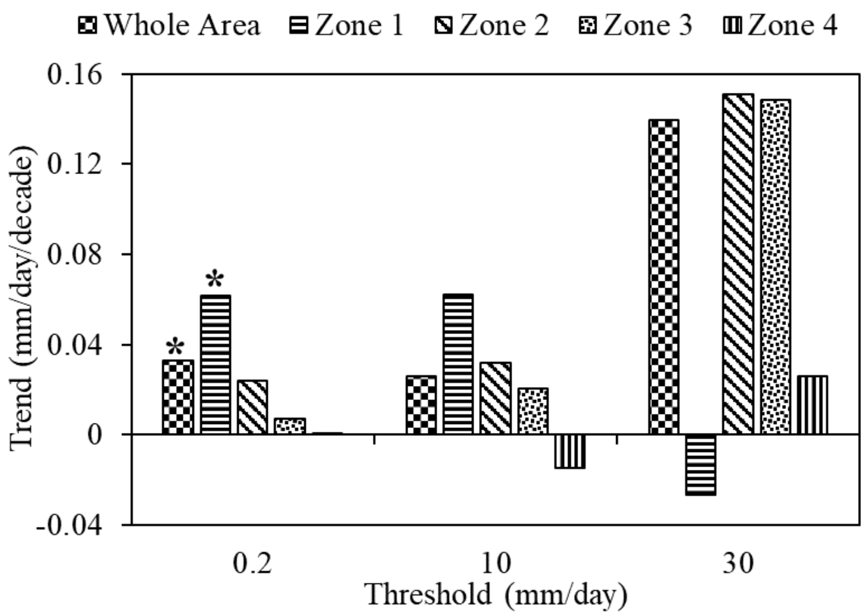

Figure 4. 5 The trend in the rainfall depth for the whole study area and for four zones with different daily rainfall thresholds. Columns with "*" indicates trend at 5% significance

To summarize, the total rainfall (rainfall ≥ 0.2 mm day^{-1}) showed a significant decreasing trend in rainfall volume and wet area, and an increasing trend in the average daily rainfall depth for the whole region and in most zones. For the heavy rainfall (rainfall ≥ 10 mm day^{-1}), a significant decreasing trend in rainfall volume and wet area was observed in the coastal regions (Zone 3 and 4) while an increasing trend was observed in the inland areas (Zone 1). The average daily rainfall depth for heavy rainfall showed an increasing trend in all zones except Zone 4. The very heavy rainfall (rainfall ≥ 30 mm day^{-1}), in the coastal region with MAR ≥ 1000 mm

(Zone 4) showed a significant decrease in rainfall volume and wet area and a non-significant increasing trend in the average daily rainfall depth in all zones except Zone 1.

4.3.2 Contribution of change in wet area and average daily rainfall depth to the change in rainfall volume

The rate of change in wet area contributed most to the rate of change in rainfall volume, while the rate of change in rainfall depth only played a minor role. Table 4.2 gives the range of percentage contribution of rate of change in wet area and average daily rainfall depth to the rate of change in rainfall volume. For the whole region, for all thresholds, more than 55% of the rate of change in volume was caused by a rate of change in wet area. In Zone 1, for the heavy (rainfall ≥ 10 mm day^{-1}) and very heavy rainfall (rainfall ≥ 30 mm day^{-1}), more than 77% of the rate of change in volume was due to the rate of change in wet area, while for total rainfall (rainfall ≥ 0.2 mm day^{-1}), 54% of the rate of change in volume was due to rate of change in average daily rainfall depth. In Zone 2, more than 50% of the rate of change in rainfall volume and in the coastal region (Zone 3 and 4), more than 84% of the rate of change in volume, was due to the rate of change in wet area. Generally, it was observed that for most regions, the rate of change in volume was caused mainly due to rate of change in wet area rather than the rate of change in average daily rainfall depth.

Table 4. 2 Percentage contribution of the rate of change in the wet area and that in the average daily rainfall depth to the rate of change in rainfall volume.

Zones	Wet Area (%)	Average daily rainfall depth (%)
Whole Area	56 - 85	15 - 44
Zone 1	46 - 98	2 - 54
Zone 2	52 - 84	16 -48
Zone 3	84 -94	6 - 16
Zone 4	98 – 99.7	0.3 - 2

4.3.3 Observed vs expected trends for rainfall volume and wet area

The observed trend was compared with the expected trend in rainfall volume and wet area as described in the Data and Methods Section. Figure 4.6 (a) and (b) show the observed and expected trends of rainfall volume for the heavy (rainfall $\geq$ 10 mm day^{-1}) and very heavy rainfall (rainfall $\geq$ 30 mm day^{-1}), respectively, for the whole region and the four zones considered for the study. The observed decreasing trend of rainfall volume for the heavy rainfall (rainfall $\geq$ 10 mm day^{-1}), as given in Figure 4.6 (a), was lower than the expected decreasing trend for the whole region, zones 2, 3 and 4, while in Zone 1, the observed increasing trend was higher than the expected increasing trend. For the whole region and Zone 2, a decreasing trend in the rainfall volume of very heavy rainfall (rainfall $\geq$ 30 mm day^{-1}), was expected but an increasing trend was observed instead (Figure. 4.6(b)). In Zone 1, the observed increasing trend was higher than the expected increasing trend, in Zone 3, the observed decreasing trend was lower than the expected decreasing trend while in Zone 4 the observed decreasing trend was higher than the expected decreasing trend.

Figure 4.6 (c) and (d) shows the observed and expected trends of wet area for the heavy (rainfall $\geq$ 10 mm day^{-1}) and very heavy rainfall (rainfall $\geq$ 30 mm day^{-1}) for the region and the four zones. The decreasing trend of wet area for the heavy rainfall (rainfall $\geq$ 10 mm day^{-1}) was lower than the expected decreasing trend for the whole region, zones 2, 3 and 4 (Fig. 4.6(c)) while in Zone 1, a decreasing trend was expected but an increasing trend was observed. For the very heavy rainfall (rainfall $\geq$ 30 mm day^{-1}), the observed decreasing trend in wet area for the whole region, zones 2 and 3 was lower than expected (Fig. 4.6(d)). In Zone 1, a decreasing trend was expected but an increasing trend was observed while in Zone 4, the observed decreasing trend was higher than the expected decreasing trend.

In general, in the inland region (Zone 1, 200 mm $\leq$ MAR $\leq$ 400 mm), the observed increasing trend in rainfall volume was higher than the expected increasing trend and for wet area, a decreasing trend was expected but an increasing trend was observed. In the coastal region (Zone 4, 1000 mm $\leq$ MAR $\leq$ 1258 mm), the observed decreasing trend in rainfall volume and wet area was higher than the expected decreasing trend.

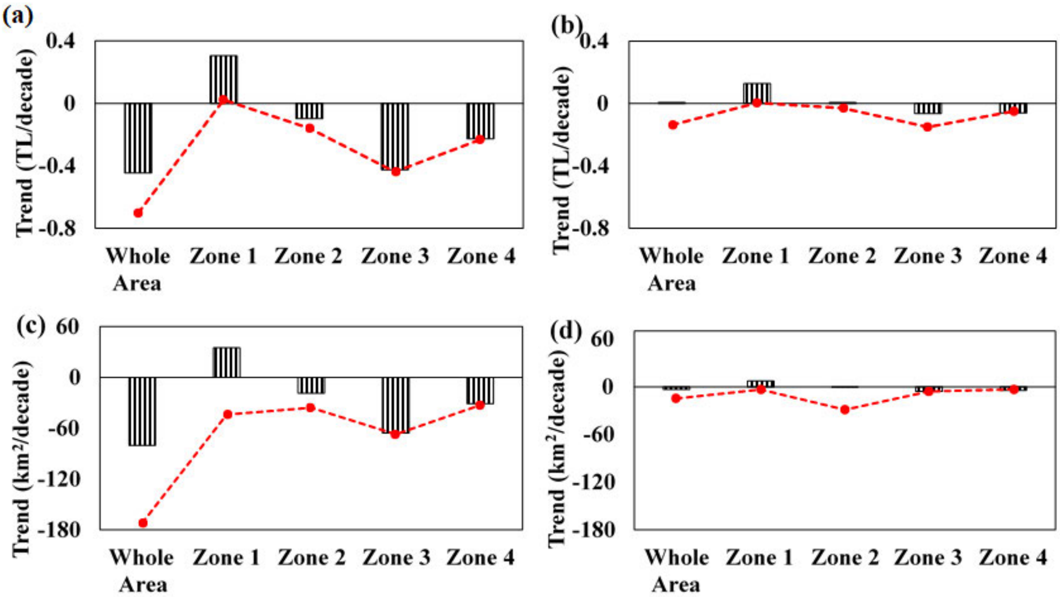

Figure 4. 6 The expected vs observed trends for (a, b) rainfall volume for the 10 and 30 mm/day threshold and (c, d) wet area for the 10 and 30 mm/day thresholds, respectively. In each plot, the dashed line indicates expected trend and the column indicates observed trend.

4.3.4 Trend in number of rain days

Figure 4.7 represents the change in the wet area corresponding to the number of days with rainfall greater than or equal to 0.2 mm day^{-1}.

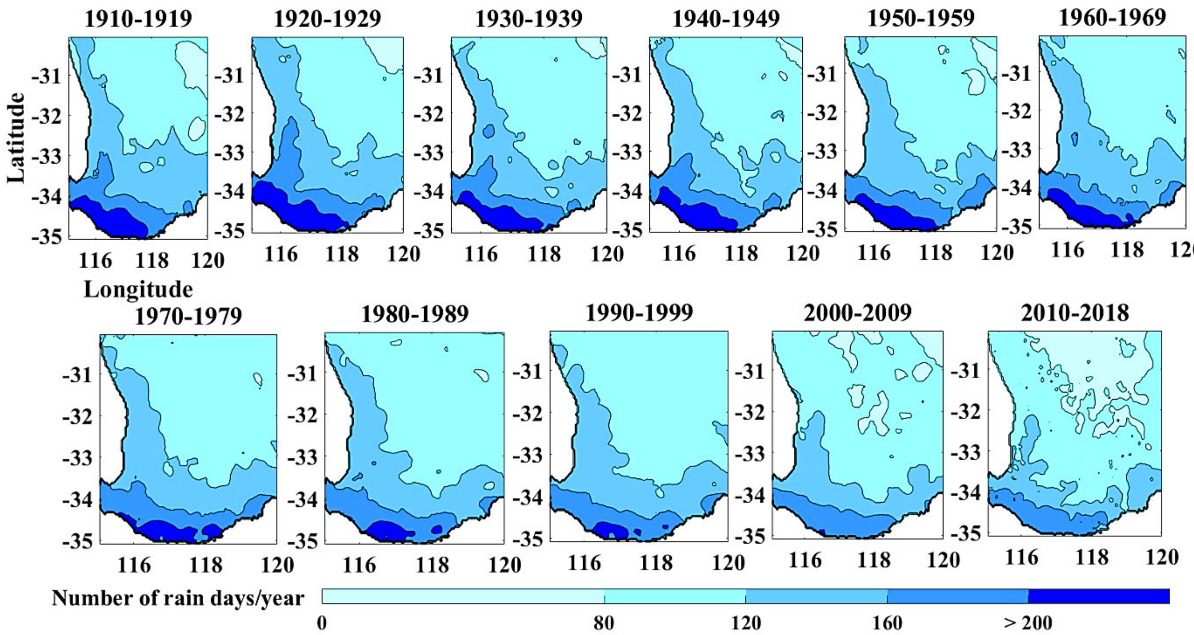

Figure 4. 7 Inter-decadal spatial variation in rain days with rain ≥ 0.2mm/day

The southern and western regions of the study area received more rain days compared to the northern and eastern parts of the study area (Fig. 4.7). Table 4.3 compares the fraction of the total area, receiving different classes of rain days for the first and last decade. The region in the south west coast receiving greater than or equal to 200 rain days year^{-1} which covered 6.5% of the study area in 1910s decreased to 0% by the 2010s (Table 4.3). The wet area with less than 120 rain days year^{-1}, in the north east of the study area, increased by 28% while the region in the south west receiving greater than or equal to 120 rain days year^{-1} decreased by 28%.

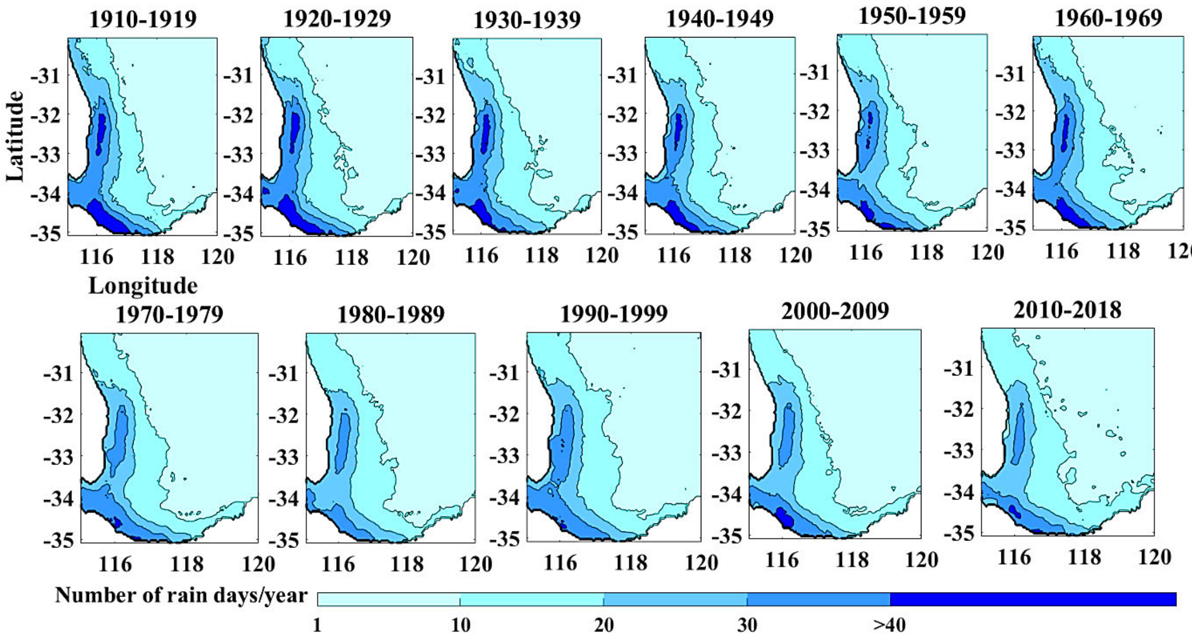

Figure 4. 8 Inter-decadal spatial variation in rain days with rain ≥10 mm/day

Figure 4.8 gives the change in wet area corresponding to the number of days with rainfall greater than or equal to 10 mm day^{-1}. Overrall, the west and south west of the study area received the highest number of days with rainfall greater than or equal to 10 mm day^{-1}. This region in the west and south west, with greater than or equal to 30 rain days year^{-1}, covered 12.8% of the total area in the 1910s but reduced to 6.5% in the 2010s. The area with less than 30 rain days year^{-1} which lies inland increased in area by 6.5% by the 2010s (Table 4.3). The region in the west which received greater than or equal to 40 rain days year^{-1} disappeared by the end of the study period while the region in the south with greater than or equal to 40 rain days year^{-1} gradually decreased in area.

Table 4. 3 Comparison of the fractional area in terms of the number of rain days per year between the 1910s and 2010s.

Rainfall ≥ 0.2 mm day^{-1}			**Rainfall ≥ 10 mm day^{-1}**		
No. of days year^{-1}	**% of total area**		**No. of days year^{-1}**	**% of total area**	
	1910s	**2010s**		**1910s**	**2010s**
1 - 80	6.3	24.2	1 - 10	56.7	56.4
80 - 120	41.8	51.9	10 - 20	19.6	26.7
120 - 160	34.7	15.8	20 - 30	10.9	11.4
160 - 200	10.7	8.1	30 - 40	9.5	5.1
≥ 200	6.5	0	≥ 40	3.3	0.4

Table 4. 4 Trend in the wet areas. Values with '†' indicates significance at 5%. (positive trends indicate that the wet area is expanding, and negative trends indicate that the wet area is contracting)

Rainfall ≥ 0.2 mm day^{-1}		**Rainfall ≥ 10 mm day^{-1}**	
No. of day year^{-1}	**Trend (km^2 year^{-1})**	**No. of day year^{-1}**	**Trend (km^2 year^{-1})**
1 - 80	40.4	1 - 10	113.6†
80 - 120	136.5†	10 - 20	47.4
120 - 160	- 93.5†	20 - 30	- 99.5†
160 - 200	- 37.1†	30- 40	- 48.3†
≥ 200	- 46.3†	≥ 40	- 13.2†

Table 4.4 gives the trend in wet area corresponding to the number of days with rainfall ≥ 0.2 mm day^{-1} and rainfall ≥ 10 mm day^{-1}, respectively. The wet area with rainfall greater than or equal to 0.2 mm day^{-1} and with less than 120 rain days year^{-1} showed a significant increasing trend while the region with more than 120 rain days year^{-1} showed a significant decreasing trend. The wet area with rainfall greater than or equal to 10 mm day^{-1} and less than 10 days of rainfall showed a decreasing trend. The wet area with 10 to 20 rain days year^{-1} showed an

increasing trend while the wet area with more than 20 rain days year^{-1} showed a decreasing trend. Mostly, the wet area with the higher number of rain days showed a significant decreasing trend in both the conditions considered while the wet area with lower number of rain days showed an increasing trend.

4.3.5 Recent changes in rainfall in relation to the Southern Annular Mode

Trend analysis for the last 30 years showed that in the coastal regions (zones 3 and 4), the decreasing trend has reduced in magnitude for the total annual rainfall (rainfall $\geq$0.2 mm day^{-1}), while, heavy rainfall (rainfall $\geq$10 mm day^{-1}) and very heavy rainfall (rainfall $\geq$30 mm day^{-1}) showed an increasing trend, with no concurrent change in SAM. The rate of increase in SAM over the past 30 years (1989 – 2018) was 0.54 decade^{-1}, which was similar to the long term rate of increase (0.55 decade^{-1}) (Fig. 4.9(a)). In the coast (zones 3 and 4), the total annual rainfall decreased over the whole period (1957 – 2018) and showed a negative correlation (-0.29) to the SAM. This is consistent with the findings of Li et al. (2005) and Hope et al., (2010) who suggested an inverse relation between the SAM and rainfall. However, it was observed that the rate of decrease in rainfall has substantially reduced in magnitude over the past 30 years (1989 – 2018) compared to the previous 32 years (1957 - 1988)(Fig. 4.9(b)). This was true for the coastal region (zones 3 and 4), for all rainfall thresholds as presented in Table 4.5. For some, the trend has been reversed, i.e. rainfall has in fact increased over the past 30 years. For example, in Zone 4, during the period 1957 to 1988, the heavy rainfall significantly decreased at the rate of 61.5 mm decade-1, while in the last 30 years, the heavy rainfall showed an increasing trend (15.8 mm decade-1) as presented in Fig. 4.9(c). This change in the way rainfall varied over the past 30 years suggests that the relationship between SAM and rainfall has changed over the recent years, and other mechanisms are needed to explain the recent rainfall trend and variations in coastal regions of SWWA.

Table 4. 5 Comparison of trends in the total, heavy, and very heavy annual rainfall in Zone 3 and 4 during the period 1957 – 1988 and 1989 - 2018. Values with '†' indicates significance at 5%.

Region	Period	Daily threshold (mm day^{-1})		
		0.2	10	30
Zone 3	1957 - 1988	-30.8	-30.2	0.2
	1989 - 2018	-24.6	-1.4	12.5
Zone 4	1957 - 1988	-59.6†	-61.5†	-18.9
	1989 - 2018	-5.3	15.8	26.6†

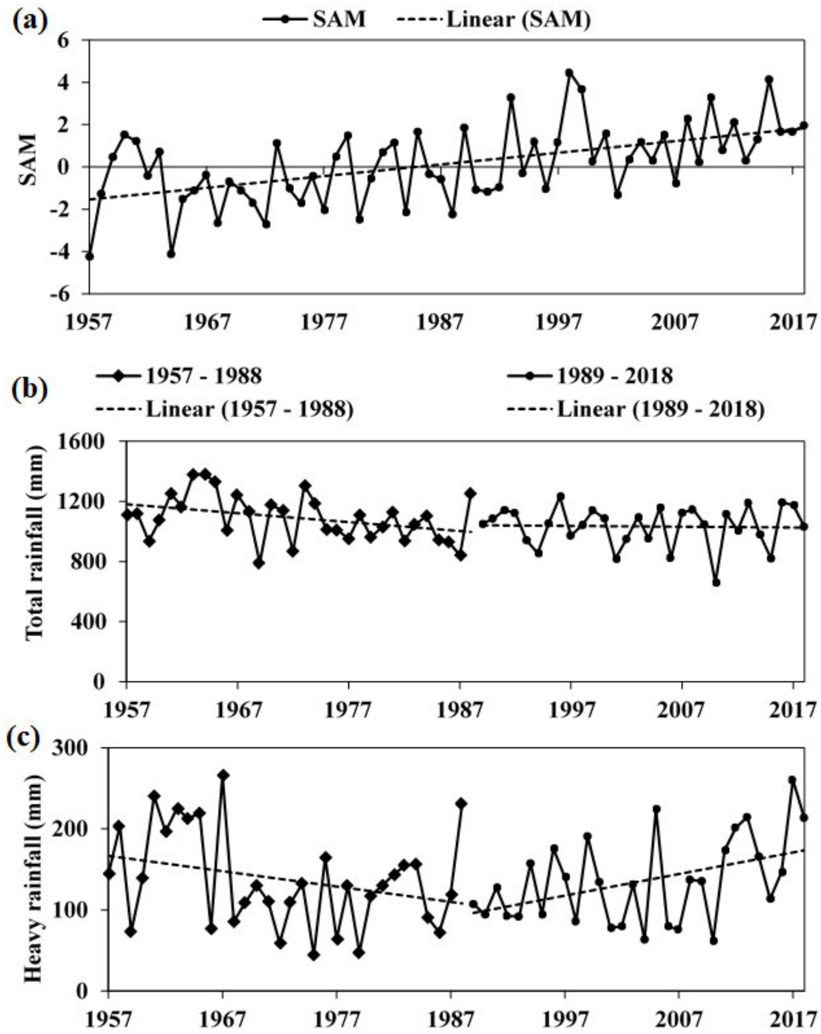

Figure 4.9 Time series of (a) SAM (b) total annual rainfall (0.2 mm day^{-1}) and (c) annual heavy rainfall (10 mm day^{-1}) for the period 1957 to 2018 in Zone 4. In each plot, the dashed line represents the trendline.

4.4 Discussion

In SWWA, the region of high rainfall near the coast (Zone 3 and Zone 4) with a larger number of rain days was observed to become drier due to a significantly decreasing trend in the wet area. On the other hand, the region farther inland (Zone 1) with low MAR and lower number of rain days was observed to become wetter due to an increasing trend in the wet area, although this trend was not significant. SWWA receives most of its rainfall from the frontal systems (Charles et al. 2010 and Pook et al. 2012), but since 1974, there has been fewer and weaker cold fronts (Frederiksen and Frederiksen 2007) which could explain the reduced wet area in SWWA. The decline in rainfall in the coastal regions has also been associated with the decrease in the frequency of strong westerly fronts (Nicholls 1997 and Hope et al. 2006). The observed decrease in wet area could also be attributed to the southward shift in synoptic circulations, associated with rain-bearing fronts, since the 1970s (Hope et al. 2006). The increasing trend in the inland region can be attributed to an increase in the frequency of easterly troughs in December, January and February in the inland region of the study area (Berry et al. 2011). Further, the positive phase of SAM in a neutral ENSO phase could cause the region to experience reduced rainfall from the westerly fronts and increased rainfall from easterly troughs (Raut et al. 2014).

Previous studies have suggested the role of the SAM in the decreasing pattern of rainfall in SWWA (Li et al. 2005 and Raut et al. 2014). However, in this study, it was observed that in the recent years (1989 – 2018), rate of decrease in rainfall has been reduced, and heavy rainfall in fact has increased in the coastal region of SWWA, while, there was no concurrent change in SAM index over the same period. This indicates that the relationship between SAM and rainfall has changed and other climate drivers could be the cause of the recent rainfall trend and variations in the coastal regions of SWWA.

4.5 Conclusion

This study aimed at determining the changes in rainfall volume, wet area, average daily rainfall depth, and the number of wet days in SWWA during the period 1911 - 2018. The study dealt with identifying the rainfall changes in four zones, classified based on the mean annual rainfall and located at varying distances away from the coast, with Zone 4 being the closest to the coast with the highest mean annual rainfall, while Zone 1 lied farther inland with the lowest mean annual rainfall. Also, in the study, rainfall at different intensities were considered to have a better understanding of the variation of heavy rainfall above certain threshold in relation to an overall decreasing trend in rainfall volume. Recent trend (1989 - 2018) in the total, heavy and very heavy rainfall were analyzed, and this was explained relative to the SAM. The key conclusions are given below:

- The significant decreasing trend in rainfall volume and wet area was predominant in coastal regions (Zone 3 and 4) while the inland region (Zone 1) showed an increasing trend although this trend was not statistically significant for all thresholds considered. In the inland region (Zone 1), the observed increasing trend in rainfall volume was greater than the expected increasing trend. A decreasing trend in wet area was expected but an increasing trend was observed. In the coastal region (Zone 4), observed decreasing trend in volume and wet area was greater than the expected decreasing trend.
- All three thresholds showed an increasing trend in average daily rainfall depth in the whole region and all zones except for heavy rainfall (rainfall $\geq$ 10 mm day^{-1}) in Zone 4 and very heavy rainfall (rainfall $\geq$ 30 mm day^{-1}) in Zone 1 where a decreasing trend was observed.
- More than 50% of the rate of change in rainfall volume in the whole region, Zone 1 and 2 was attributed to the change in wet area except the for the total rainfall (rainfall $\geq$ 0.2 mm day^{-1}) in Zone 1 where 54% of the rate of change in rainfall volume was due to the rate of change in average daily rainfall depth. In the coastal regions (Zone 3 and 4), more than 84% of the rate of change in rainfall volume was due to the rate of change in wet area.
- The region near the coast with a higher number of rain days per year showed a decreasing trend while the inland region with a lower number of rain days showed an increasing trend for rainfall $\geq$ 0.2 mm day^{-1} and rainfall $\geq$ 10 mm day^{-1}.
- The decreasing trend in total rainfall has reduced in magnitude, and heavy rainfall in fact has increased over the past 30 years in the coastal region of SWWA while there was no concurrent change in SAM index over the same period.

The study showed that the rainfall volume in coastal areas is showing a significant decreasing trend. This indicates the need for strategic planning in the management and allocation of the available water in a region of decreasing water availability. This study was done using gridded rainfall data which is interpolated from station data. In SWWA, the density of stations is higher towards the coast compared to the inland regions. This is a limitation of this work, as the data quality in the region with fewer stations would be less than the coastal region. Similarly, the number of rain days reported in this study will probably be higher than the actual number of rain days as the number of rain days is sensitive to the density of observations and as it takes only one station to record rainfall for surrounding grids to have an interpolated rainfall amount (Charles et al. 2010). Future studies could look into the effects of the observed decrease in rainfall volume and wet area on the water supply and agricultural sectors. Also, the changes in the climate drivers which influence the rainfall of SWWA could be further investigated to explain the recent changes in rainfall in the coastal regions of SWWA.

References

Ansell, T.J., Reason, C.J.C., Smith, I.N. and Keay, K., 2000. Evidence for decadal variability in southern Australian rainfall and relationships with regional pressure and sea surface temperature. *Int. J. Climatol*. ***20***, 1113-1129.

Berry, G., Jakob, C. and Reeder, M., 2011. Recent global trends in atmospheric fronts. *Geophys. Res. Lett.* ***38***, L21812.

Caloiero, T., 2014. Analysis of daily rainfall concentration in New Zealand. *Nat. Hazards.* ***72***, 389-404. doi: 10.1007/s11069-013-1015-1.

Caloiero, T., Caloiero, P. and Frustaci, F., 2018. Long-term precipitation trend analysis in Europe and in the Mediterranean basin. *Water Environ J.* ***32***, 433-445. doi: 10.1111/wej.12346.

Charles, S., Silberstein, R., Teng, J., Fu, G., Hodgson, G., Gabrovsek, C., Crute, J., Chiew, F., Smith, I., Kirono, D. and Bathols, J., 2010. Climate analyses for South-West Western Australia: A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project.

Chowdhury, R.K., Beecham, S., Boland, J. and Piantadosi, J., 2015. Understanding South Australian rainfall trends and step changes. *Int. J. Climatol*. ***35***, 348-360. doi: 10.1002/joc.3982.

Collins, D.A. and Della-Marta, P.M., 1999. Annual climate summary 1998: Australia's warmest year on record. *Aust. Met. Mag.* ***48***, 273-83.

Donat, M.G., Peterson, T.C., Brunet, M., King, A.D., Almazroui, M., Kolli, R.K., Boucherf, D., Al-Mulla, A.Y., Nour, A.Y., Aly, A.A. and Nada, T.A.A., 2014. Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO. *Int. J. Climatol*. ***34***, 581-592. doi:10.1002/joc.3707.

Dore, M.H., 2005. Climate change and changes in global precipitation patterns: what do we know?. *Environ. Int.* ***31***, 1167-1181. doi:10.1016/j.envint.2005.03.004.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. and Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. *Science.* ***289***, 2068-2074.

Feng, J., Li, J. and Li, Y., 2010. Is there a relationship between the SAM and southwest Western Australian winter rainfall?. *Journal of Climate*, ***23***(22), pp.6082-6089.

Frederiksen, J.S. and Frederiksen, C.S., 2007. Interdecadal changes in southern hemisphere winter storm track modes. *Tellus A.* ***59***, 599-617.

Gallant, A.J., Hennessy, K.J. and Risbey, J., 2007. Trends in rainfall indices for six Australian regions: 1910-2005. *Aust. Met. Mag.* ***56***, 223-241.

Hennessy, K.J., Suppiah, R. and Page, C.M. (1999) Australian rainfall changes, 1910-1995. Australian Meteorological Magazine, 48, 1–13.

Hope, P.K., Drosdowsky, W. and Nicholls, N., 2006. Shifts in the synoptic systems influencing southwest Western Australia. *Clim. Dyn.* ***26***, 751-764.

Hope, P. and Ganter, C., 2010, May. Recent and projected rainfall trends in south-west Australia and the associated shifts in weather systems. In Managing climate change: papers from the Greenhouse 2009 Conference. CSIRO, Collingwood, Victoria, Australia (pp. 53-63).

Hope, P., Timbal, B. and Fawcett, R., 2010. Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. *Int. J. Climatol.* ***30***(9), pp.1360-1371.

Islam, S.A., Bari, M.A. and Anwar, A.H.M.F., 2013. Hydrologic impact of climate change on Murray Hotham catchment of Western Australia: a projection of rainfall-runoff for future water resources planning. Hydrology & Earth System Sciences Discussions, 10(10).

Kebe, C.M.F., Sauvageot, H. and Nzeukou, A., 2005. The relation between rainfall and area–time integrals at the transition from an arid to an equatorial climate. *J. Clim.* ***18***, 3806-3819. doi:10.1175/JCLI3451.1.

Lazaro, R., Rodrigo, F.S., Gutiérrez, L., Domingo, F. and Puigdefábregas, J., 2001. Analysis of a 30-year rainfall record (1967–1997) in semi–arid SE Spain for implications on vegetation. *J. Arid Environ.* ***48***, 373-395. doi:10.1006/jare.2000.0755.

Nicholls, N., 2010. Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007. *Clim. Dyn.* ***34***(6), pp.835-845.

Nogueira, R.C. and Keim, B.D., 2010. Annual volume and area variations in tropical cyclone rainfall over the eastern United States. *J. Clim.* ***23***, 4363-4374. doi:10.1175/2010JCLI3443.1.

Pittock, A.B., 1983. Recent climatic change in Australia: Implications for a CO 2-warmed earth. *Clim. Chang.* ***5***, 321-340. doi:10.1007/BF02423529.

Pook, M.J., Risbey, J.S. and McIntosh, P.C., 2012. The synoptic climatology of cool-season rainfall in the central wheatbelt of Western Australia. *Mon. Weather Rev.* ***140***, 28-43. doi:10.1175/MWR-D-11-00048.1.

Prein, A.F., Holland, G.J., Rasmussen, R.M., Clark, M.P. and Tye, M.R., 2016. Running dry: The US Southwest's drift into a drier climate state. *Geophys. Res. Lett.* ***43***, 1272-1279. doi:10.1002/2015GL066727.

Raut, B.A., Jakob, C. and Reeder, M.J., 2014. Rainfall changes over southwestern Australia and their relationship to the Southern Annular Mode and ENSO. *J. Clim.* **27**(15), pp.5801-5814.

Risbey, J.S., Pook, M.J. and McIntosh, P.C., 2013. Spatial trends in synoptic rainfall in southern Australia. *Geophys. Res. Lett.* ***40***, 3781-3785. doi:10.1002/grl.50739.

Saha, S., Chakraborty, D., Paul, R.K., Samanta, S. and Singh, S.B., 2018. Disparity in rainfall trend and patterns among different regions: analysis of 158 years' time series of rainfall dataset across India. *Theor. Appl. Climatol.* 1-15. doi:10.1007/s00704-017-2280-9.

Smith, I., 2004. An assessment of recent trends in Australian rainfall. *Aust. Met. Mag*. ***53***, 163-173.

Suppiah, R. and Hennessy, K.J., 1998. Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. *Int. J. Climatol.* ***18***, 1141-1164. doi:10.1002/(SICI)1097-0088(199808)18:10<1141::AID-JOC286>3.0.CO;2-P.

Wang, Y., Chen, X. and Yan, F., 2015. Spatial and temporal variations of annual precipitation during 1960–2010 in China. *Quat. Int.* ***380***, 5-13.

Wang, Y., Ding, Y., Ye, B., Liu, F. and Wang, J., 2013. Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. *Sci. China Earth Sci*. ***56***, 1398-1412.

Wright, P.B., 1974. Seasonal rainfall in southwestern Australia and the general circulation. *Mon. Weather Rev*. ***102***, 219-232. doi:10.1175/1520-0493(1974)102<0219:SRISAA>2.0.CO;2.

Yu, B. and Neil, D.T., 1993. Long-term variations in regional rainfall in the south-west of Western Australia and the difference between average and high intensity rainfalls. *Int. J. Climatol*. ***13***, 77-88. doi:10.1002/joc.3370130106.

CHAPTER 5 - Rainfall-runoff relationship for selected catchments in the southwest of Western Australia

STATEMENT OF CONTRIBUTION TO CO-AUTHORED DRAFT MANUSCRIPT

Chapter 5 is a draft manuscript of a co-authored paper titled "Rainfall-runoff relationship for selected catchments in the southwest of Western Australia" which is in the initial stages of submission. My contribution as the lead author to the draft manuscript included data collection, modelling, analysis, and writing the manuscript.

Paper citation: Philip, P., Cheng, Z. and Yu, B., (preparing for submission), Rainfall-runoff relationship for selected catchments in the southwest of Western Australia. (Manuscript is in the initial stages of submission)

(Signed) [redacted] Date: 24/03/2020

Priya Philip

(Countersigned) [redacted] Date: 24/03/2020

Corresponding author of paper: Bofu Yu

(Countersigned) [redacted] Date: 24/03/2020

Supervisor: Bofu Yu

5.1 Introduction

Runoff is the catchment's response to rainfall, which contributes to inflow into water supply reservoirs. Runoff from a catchment is influenced by meteorological factors (rainfall, and potential evapotranspiration), physical factors (topography, soil, vegetation, and drainage pattern) and human activities (land use, urbanisation, dams and reservoirs operations) (Sengupta, 2017). While an increase in runoff can cause flooding and soil erosion, a decrease in runoff reduces the inflow into the dams and thereby directly impacts the water availability of a region. Several studies have been conducted on global and regional bases to understand the changes in runoff and how this is related to rainfall changes. Based on a study of 3558 catchments from around the world, Do et al. (2017) suggest that during the period from 1966 to 2005 more stations are showing decreasing trends (11.6%) in the annual maximum streamflow while 7.1% of the stations are showing increasing trends in the annual maximum streamflow. Specifically, for Australia, it was observed that there was a significant decreasing trend in streamflow along the west coast and east coast of the continent. Among the 79 stations chosen for study in Australia, 19% of the stations showed a significant decreasing trend and 2.5% of the stations showed an increasing trend in streamflow. In the 21st century, the mean streamflow has been projected to increase by 5% - 80% over most of Asia, northern Europe, northern and eastern North America, central and eastern Africa, south eastern and north western South America and central and northern Australia, but to decrease by 5% - 50% over the Mediterranean region, south western North America and Central America, northern and southern South America, Southern Africa and south western and south eastern Australia (Dai, 2016).

In Australia, Zhang et al. (2016) analysed the pattern of streamflow from the 1950s for the whole country using streamflow data from 222 unregulated gauging stations with minimal land use change and are suitable for trend analysis. It was found that the annual streamflow in Australia has been showing a significant increasing trend in the northern Australia including northern parts of Western Australia while a significant decreasing trend in South West of Western Australia (SWWA), South Australia, New South Wales, Victoria and South East Queensland. Petrone et al. (2010) observed that the inflow into the major water supply reservoirs in SWWA, have decreased by more than 50% due to a 16% reduction in rainfall since the mid-1970s and the runoff coefficients have been progressively getting lower over the last 50 years. Silberstein et al. (2013) integrated the Sacramento and IHACRES models to study the catchment behaviour of 106 catchments in SWWA. The possibility of a change in the state of the catchments which was not captured by the model was suggested. It is predicted that by 2030 there will be appreciable water deficit in SWWA if the current water consumption, population and economic growth and decrease in water yield continue (McFarlane et al., 2012). Model projections for SWWA indicate that the change in runoff is three times the change in rainfall (Islam et al., 2013, Silberstein et al., 2012). Smith and Power (2014) suggest that the increasing temperature in SWWA does not have a direct influence on the declining inflow into the dams, rather temperature and rainfall are inversely related. In addition to the decreasing rainfall, the groundwater levels in SWWA has also been showing a declining trend and even in years of average or above average rainfall, groundwater storage was insufficiently recharged (Hughes et al., 2012). The variable rainfall in addition to the falling groundwater table in the region could probably be the reason for the streamflow decline in SWWA (Petrone et al., 2010).

Previous studies indicate that the decreasing rainfall plays an important role in the declining runoff in SWWA. No study has yet examined the changes in the three classes of rainfall (light, medium and heavy rainfall) and how they are related to the declining runoff in the selected catchments in SWWA. The Australian Water Balance Model is a conceptual catchment water balance model that has been widely used in Australia and around the world (David and Richard, 2000, Boughton, 2006, Boughton and Chiew, 2007, Chiew 2010, Haque et al., 2014, Hughes and Vaze, 2015, Yu and Zhu, 2015). The model has a simple structure and high computational efficiency (Anshuman et al., 2018). The model uses rainfall and evapotranspiration as input to predict runoff. Previous studies have noted the disproportional reduction in runoff compared to rainfall in SWWA in the recent decades (Islam et al., 2013, Silberstein et al., 2012). The suitability of using the AWBM model in a region like SWWA with a consistently decreasing runoff needs to be investigated.

The aim of this study was to understand the rainfall-runoff relationship in SWWA using data from ten catchments with quality streamflow data in the study area. The objectives of this study were 1) to determine and compare the trend in light, medium, heavy and total rainfall and runoff; 2) to test the AWBM model, for flow prediction in SWWA; and 3) to test whether the decrease in streamflow is entirely a result of the declining rainfall.

5.2 Data and methodology

Ten catchments in SWWA were chosen for the study. All these catchments were identified by the Bureau of Meteorology as hydrologic reference stations which are well-maintained river gauges of long, high quality streamflow records (http://www.bom.gov.au/water/hrs/). The water data information obtained from Australian and State water agencies are collated and homogenised by the Bureau of Meteorology. The catchment area varied between 18.7 km^2 for Clarke Brook to 1834.5 km^2 for Kent River. The location of the catchments is given in Figure 5.1 and the site details given in Table 5.1.

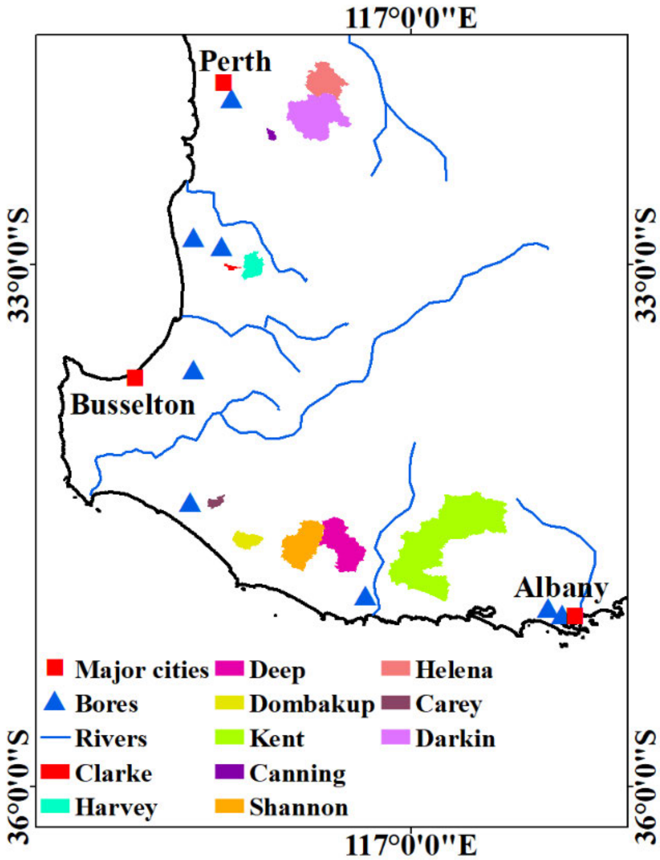

Figure 5. 1 Location of catchments and bores chosen for study in SWWA

Daily rainfall and potential evapotranspiration data for the catchments were extracted from the SILO database (https://www.longpaddock.qld.gov.au/). Daily runoff data were downloaded from the Bureau of Meteorology website (http://www.bom.gov.au/). Rainfall data ≥ 0.2 mm was considered for the study. Annual rainfall was computed for the water year which was defined as a 12-month period from May to April for SWWA (Bates et al., 2008). Groundwater levels for eight bores with most recent data in the study area were obtained from the Water Information Reporting website (http://wir.water.wa.gov.au/Pages/Water-Information-Reporting.aspx) as presented in Figure 5.1.

Table 5. 1 Site details

Station No.	Name	Latitude	Longitude	Catchment Area (km^2)	Period of Record
604053	Kent River at Styx Junction	-34.9	117.1	1834.5	1956 - 2018
606001	Deep River at Teds Pool	-34.8	116.6	467.8	1976 - 2018
606185	Shannon River at Dog Pool	-34.8	116.4	451.0	1964 - 2018
607155	Dombakup Brook at Malimup Track	-34.6	116.0	123.9	1962 - 2018
608002	Carey Brook at Staircase Road	-34.4	115.8	45.7	1975 - 2018
613002	Harvey River at Dingo Road	-33.1	116.0	147.2	1970 - 2018
613146	Clarke Brook at Hillview Farm	-33.0	115.9	18.7	1961 - 2018
616002	Darkin River at Pine Plantation	-32.1	116.3	667.1	1969 - 2018
616013	Helena River at Ngangaguringuring	-31.9	116.4	323.1	1972 - 2016
616065	Canning River at Glen Eagle	-32.2	116.2	521.8	1953 - 2018

To classify rainfall into light, medium and heavy, relative thresholds were used. The method adopted here involved ranking the rainfall data for each catchment in a decreasing order and dividing this ranked series into three sets such that each set contributed to 1/3 (one third) of the total rainfall. The top set was defined as heavy rainfall for the catchment. Similarly, the bottom one third was defined light rainfall and the remaining values in the middle were the medium rainfall for the particular station. The thresholds that separate these rainfall classes would vary from site to site, but all the three classes contribute equally to the total rainfall for all sites. Table 5.2 presents the relative thresholds chosen for each catchment. Linear regression was used to determine the trend for each rainfall class and runoff for each of the ten catchments. The correlation between the trend in runoff and rainfall were calculated based on Pearson correlation analysis.

Table 5. 2 Relative rainfall threshold for each catchment.

Catchment	Light (mm)	Medium (mm)	Heavy (mm)
Kent	< 5.3	5.3 – 11.8	≥ 11.8
Deep	< 7.3	7.3 – 15.4	≥ 15.4
Shannon	< 8.5	8.5 - 18	≥ 18
Dombakup	< 9.7	9.7 – 19.5	≥ 19.5
Carey	< 9.7	9.7 – 19.9	≥ 19.9
Harvey	< 12.2	12.2 – 24.4	≥ 24.4
Clarke	< 11.4	11.4 – 23.2	≥ 23.2
Darkin	< 8.5	8.5 – 18.1	≥ 18.1
Helena	< 8	8 – 16.9	≥ 16.9
Canning	< 10.4	10.4 – 22.5	≥ 22.5

The Australian Water Balance Model (AWBM) was used to test whether the model could predict the runoff and its variations over time in the study area. The model, developed by Walter Boughton, is a conceptual and lumped catchment water balance model which simulates runoff from daily or hourly rainfall and evapotranspiration data (Boughton, 1995). The model has 8 calibration parameters which accounts for catchment partial areas, surface storage capacities, baseflow and flow recession constants. The model uses three surface stores of differing capacities, C1, C2 and C3 to simulate partial area runoff. At each time step, rainfall is added to the existing moisture in the store and evapotranspiration subtracted according to the formula,

$$Store\_n = Store\_n + rain - evapotranspiration \ (n = 1 \text{ to } 3)$$

When the moisture in each store exceeds the store capacity, the excess becomes runoff and if the evapotranspiration demand is greater than the available moisture and the value of moisture in the store would become negative, this is reset to zero. The three parameters, A_1, A_2 and A_3 represent the proportions of the catchment area such that $A_1 + A_2 + A_3 = 1$. When A_1 and A_2 are changed, A_3 will be adjusted automatically.

When rainfall excess occurs from any store, part of this becomes recharge to the baseflow according to Base Flow Index (BFI) x excess and the remaining (1 – BFI) x excess becomes surface runoff. The surface store is depleted at the rate, $(1 - k_s)$ x Surface Store (SS) and baseflow is depleted at the rate, $(1 - k_b)$ x Baseflow Store (BS) (Boughton, 1995). The model is included in a software package called the Rainfall Runoff Library which was used in this study (Perraud *et al.*, 2003 and Podger, 2003). Figure 5.2 gives the structure of the AWBM model. The default minimum and maximum values of the parameters as used in the RRL model are given in Table 5.3.

Table 5. 3 Default values of calibration parameters in AWBM model

Parameter	Default value	Default minimum	Default maximum
A_1	0.134	0	1
A_2	0.433	0	1
BFI	0.35	0	1
C_1 (mm)	7	0	50
C_2 (mm)	70	0	200
C_3 (mm)	150	0	500
K_b	0.95	0	1
K_s	0.35	0	1

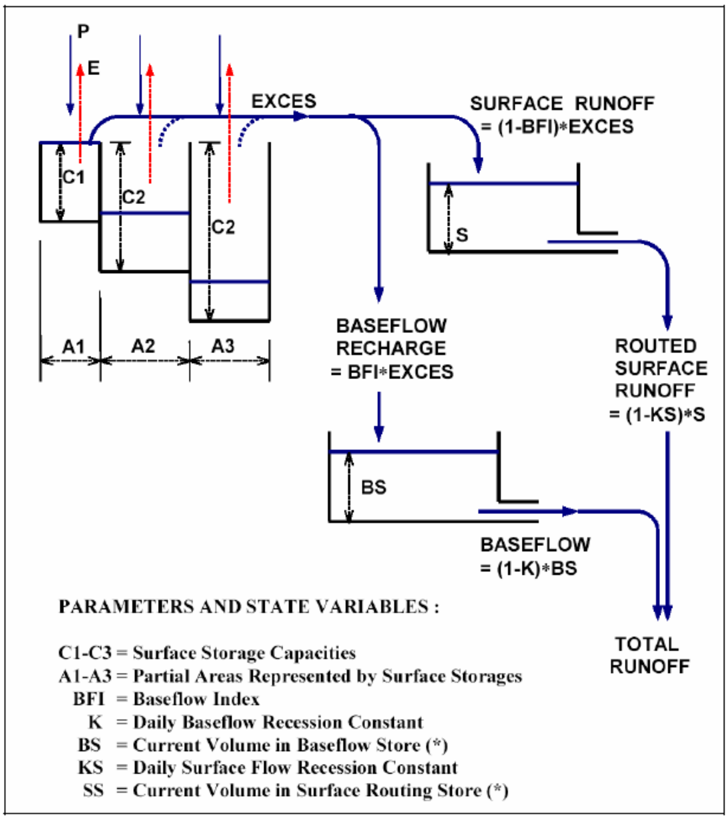

Figure 5. 2 Structure of AWBM rainfall runoff model (Source: Rainfall Runoff Library user guide)

In this study, for model calibration, the first 60% of the available data for each catchment was used and the remaining 40% of the data was used for model validation. The model was calibrated based on monthly streamflow values. For model calibration, the objective function was to minimise the sum of squares errors (SSE) (Kim *et al.,* 2005). For validation of the model results, the modelled runoff was compared with the observed streamflow using the Nash Sutcliffe Efficiency (NSE) (eqn. 5.1) and Pearson correlation analysis.

$$\text{Nash Sutcliffe Efficiency} = \frac{\sum_{i=1}^{n}(Q_{obs}-Q_{mod})^2}{\sum_{i=1}^{n}(Q_{obs}-Q_{ave})^2} \qquad (5.1)$$

where, n is total number of monthly observations in the validation period, Q_{obs} is the observed streamflow, Q_{mod} is the modelled runoff and Q_{ave} is the average observed streamflow for each catchment. Nash Sutcliffe Efficiency was chosen as it is the most commonly and widely used model evaluation statistic (Ewen, 2011, Guinot et al., 2011, Pushpalatha et al., 2012).

5.3 Results

5.3.1 Correlation between rainfall and runoff

Annual total and heavy rainfall for most catchments showed highest correlation to annual runoff as presented in Table 5.4. Total, medium and heavy rainfall for all catchments showed significant correlation with runoff. Light rainfall for all catchments except Carey, Clarke and Darkin showed significant correlation with runoff.

Table 5. 4 Pearson correlation coefficient between total light, medium, heavy rainfall and runoff (Values with '†' indicate significance at 5%)

Catchment	Total	Light	Medium	Heavy
Kent	0.63†	0.27†	0.49†	0.45†
Deep	0.72†	0.31†	0.46†	0.56†
Shannon	0.81†	0.29†	0.59†	0.65†
Dombakup	0.75†	0.36†	0.50†	0.59†
Carey	0.70†	0.20	0.35†	0.58†
Harvey	0.76†	0.29†	0.59†	0.54†
Clarke	0.81†	0.22	0.52†	0.66†
Darkin	0.63†	0.25	0.45†	0.53†
Helena	0.67†	0.43†	0.39†	0.62†
Canning	0.79†	0.38†	0.53†	0.68†
Average	**0.73**	**0.30**	**0.49**	**0.58**

5.3.2 Trend in catchment rainfall and runoff

Runoff for all the ten catchments showed significant decreasing trends while the rainfall did not decrease over the period considered for all catchments. Table 5.5 presents the trend in the total annual rainfall, runoff and volumetric runoff coefficient (ratio of runoff over rainfall) for the catchments during the time periods given in Table 5.1. All catchments exhibited decreasing trends in rainfall, except Deep and Carey, which exhibited increasing trends in annual rainfall totals. Figure 5.3 presents the time series of rainfall and runoff for the Harvey and Carey catchments as an example. The rate of decrease in runoff at Harvey was greater than the rate of decrease in rainfall (Fig. 5.3(a)). In Carey (Fig. 5.3 (b)), while the runoff decreased, the rainfall showed an increasing trend. The runoff coefficient for all catchments showed significant decreasing trend indicating that the fraction of rainfall becoming runoff in all these catchments has reduced.

Table 5. 5 Trend in total rainfall, runoff and runoff ratio ('†' indicates statistical significance at 5%)

Name	Rainfall		Runoff		Runoff Ratio	
	Trend (mm/decade)	Mean (mm)	Trend (mm/decade)	Mean (mm)	Trend	Mean
Kent	-8.6	721.5	-4.1†	40.3	-0.0005†	0.05
Deep	6.4	936.5	-12.9†	67.0	-0.001†	0.06
Shannon	-17.9	1046.9	-20.8†	145.3	-0.002†	0.13
Dombakup	-29.8†	1226.4	-38.3†	283.5	-0.002†	0.23
Carey	17.6	1199.6	-15.9†	142.2	-0.001†	0.12
Harvey	-21.6	1077.5	-41.7†	190.2	-0.003†	0.17
Clarke	-38.3†	1017.5	-53.5†	223.2	-0.004†	0.21
Darkin	-15.0	681.6	-1.7†	5.0	-0.0002†	0.006
Helena	-18.1	587.1	-1.4†	5.0	-0.0002†	0.008
Canning	-39.2†	888.6	-9.9†	33.9	-0.0008†	0.03

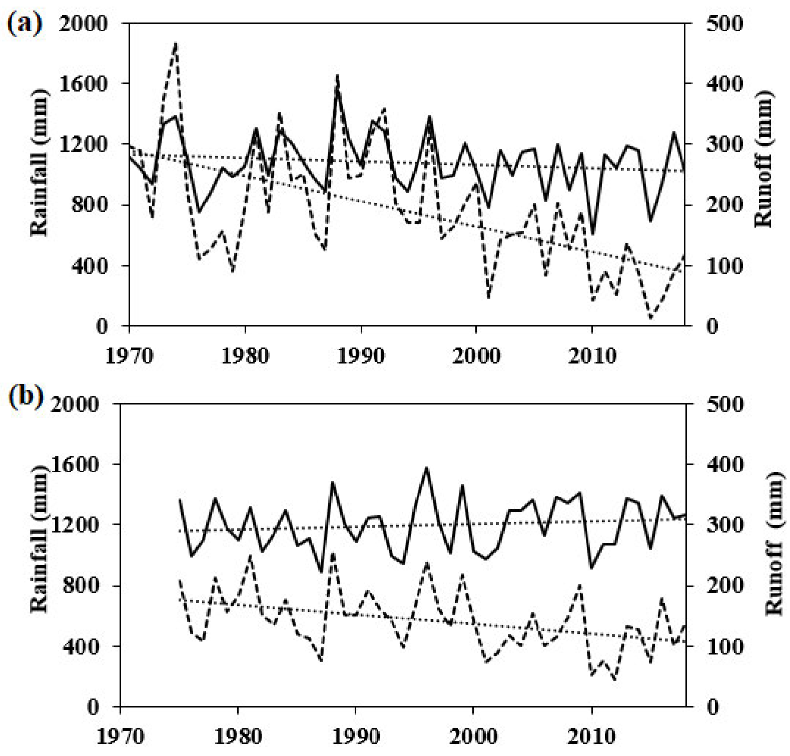

Figure 5. 3 Time series of rainfall and runoff in (a) Harvey and (b) Carey. Solid line, dashed line and dotted line represents rainfall, runoff and trendline, respectively.

Table 5.6 presents the trend in light, medium and heavy rainfall for the ten catchments during the time period given in Table 5.1. The light rainfall showed decreasing trends in all the ten catchments and significant decreasing trends for seven of the ten catchments. Medium rainfall showed decreasing trends for all catchments except Deep and Shannon where an increasing trend was observed. Heavy rainfall showed decreasing trends in 6 catchments and an increasing trend in the other 4 catchments (Kent, Deep, Carey and Harvey). Similar results were found, showing an increasing trend in the heavy (daily rainfall ≥ 10 mm day^{-1}) and the very heavy rainfall (daily rainfall ≥ 30 mm day^{-1}) for the recent years in Chapter 4. It was also observed that the catchments, Kent, Deep and Carey which showed an increasing trend in heavy rainfall and showed a significant decreasing trend in light rainfall, were concentrated to the south of the study area.

Table 5. 6 Trend in light, medium and heavy rainfall ('†' indicates statistical significance at 5%)

Catchment	Trend (mm/decade)		
	Light	**Medium**	**Heavy**
Kent	-8.3†	-2.8	2.5
Deep	-14.4†	7.8	12.6
Shannon	-8.1†	3.3	-13.4
Dombakup	-12.0†	-5.7	-12.1
Carey	-21.4†	16.4	22.4
Harvey	-8.7	-17.7	4.8
Clarke	-1.5	-10.2	-26.6†
Darkin	-6.0	-2.5	-6.6
Helena	-7.8†	-2.2	-8.2
Canning	-6.3†	-7.4	-25.9†

The Pearson correlation analysis between the rate of change in total rainfall, light, medium, heavy rainfall and runoff showed that the total (r = 0.58) and heavy rainfall (r = 0.54) were positively correlated to the rate of change in runoff followed by trend in the medium rainfall (r = 0.44). The trend in light rainfall showed a negative correlation (r = -0.39) with trend in runoff. Although the trend in total rainfall and that in heavy rainfall were positively correlated to runoff, the total and heavy rainfall showed increasing trend in most catchments where the runoff showed a significant decreasing trend. This suggests the role of additional factors in the observed decreasing trends in runoff for these ten catchments in SWWA.

Figure 5.4 presents the rate of change in runoff for all catchments plotted against the rate of change in each rainfall class during the time period given in Table 5.1. It was observed that the rate of change in runoff was 2.6 times the rate of change in total rainfall and could explain 34% of the variability in runoff. This is similar to findings in previous studies that the rate of change in runoff in SWWA is about three times the rate of change in rainfall (Islam et al., 2013, Silberstein et al., 2012). The rate of change in light, medium and heavy rainfall explained 15%, 20% and 30% of the variability in runoff, respectively.

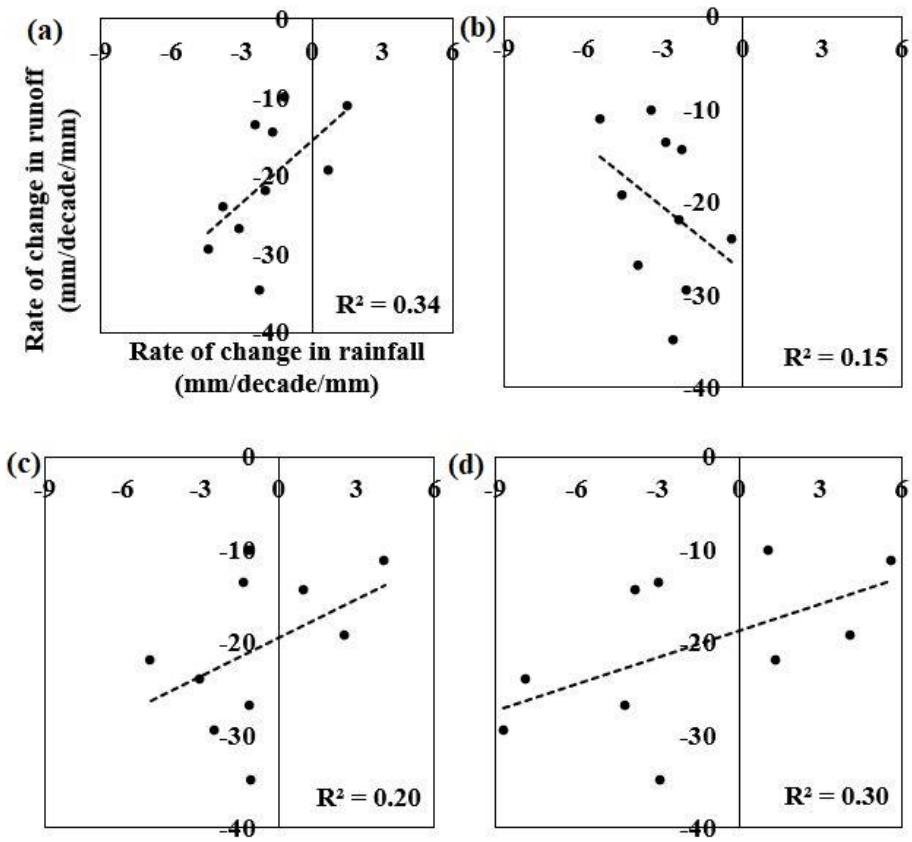

Figure 5. 4 Rate of change in runoff plotted against rate of change in (a) total; (b) light; (c) medium and (d) heavy rainfall.

5.3.3 AWBM model calibration and validation

Suitability of the AWBM model for flow prediction in SWWA was examined. Table 5.7 presents the calibrated parameter values and calibration efficiency for the ten catchments. All catchments had a calibration efficiency greater than 0.65 except Darkin (0.39). The Pearson correlation coefficient between the modelled runoff and observed monthly streamflow for the validation period varied between 0.75 and 0.89 for the catchments.

Table 5. 7 Calibrated parameter values and model performance for AWBM for the ten selected catchments

Catchment	**A1**	**A2**	**BFI**	**C1**	**C2**	**C3**	**Kb**	**Ks**	**Calibration efficiency**	**Validation efficiency**	**Pearson correlation coefficient**
Kent	0.03	0.3	0.6	0.1	178.8	416.5	0.97	0.82	0.68	0.55	0.79
Deep	0.001	0.4	0.4	49.9	199.7	499.3	0.99	0.92	0.74	0.28	0.79
Shannon	0.001	0.4	0.4	49.9	199.7	491.7	0.99	0.82	0.74	0.68	0.85
Dombakup	0.005	0.5	0.3	47.5	200.0	452.0	0.99	0.76	0.77	0.59	0.79
Carey	0.08	0.5	0.7	6.4	199.8	499.6	0.99	0.90	0.67	0.60	0.86
Harvey	0.009	0.3	0.6	49.9	158.5	499.6	0.99	0.85	0.72	0.32	0.84
Clarke	0.2	0.4	0.5	49.9	199.9	499.3	0.99	0.75	0.82	0.51	0.89
Darkin	0.0009	0.1	0.3	49.9	200.0	499.6	0.99	0.85	0.39	0.33	0.76
Helena	0.08	0.3	0.9	50.0	186.7	332.9	0.99	0.88	0.68	0.45	0.75
Canning	0.03	0.2	0.8	46.3	147.5	490.2	0.99	0.86	0.72	0.51	0.75

The estimated streamflow using the AWBM model was greater than the observed streamflow for 9 out the ten catchments considered in this study. Comparing the observed streamflow with modelled streamflow, it was observed that for all catchments, except Helena, the model overpredicted the streamflow. Figure 5.5 presents the time series of modelled streamflow and observed streamflow for the calibration and validation period in Harvey, as an example. It was observed that the departure of the observed streamflow from the modelled streamflow has been increasing towards the end of the validation period.

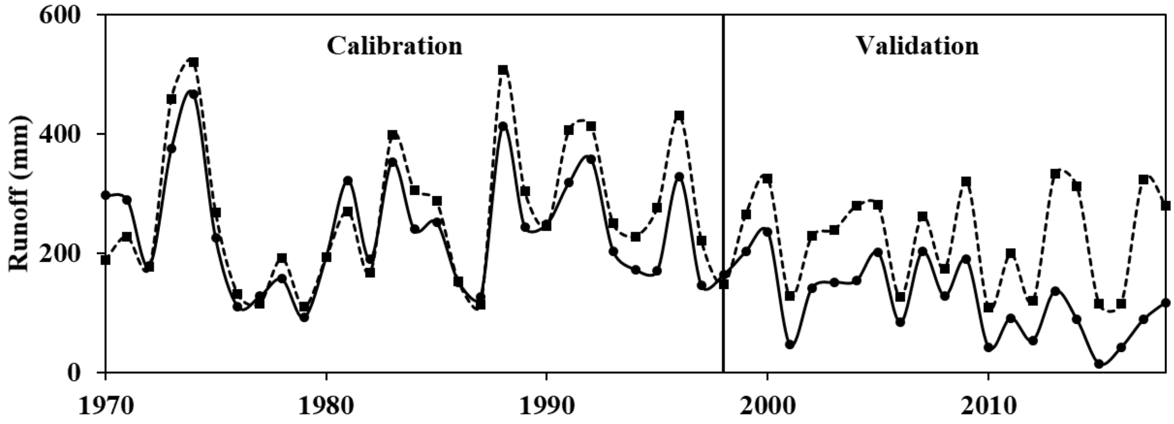

Figure 5. 5 Time series of modelled and observed streamflow for Harvey catchment. The dashed line represents modelled streamflow and the solid line represents the observed streamflow. The vertical line cuts the time series into calibration and validation periods.

Figure 5.6 presents the average annual observed streamflow plotted against the average annual modelled runoff for all catchments. During the calibration period (Fig. 5.6 (a)), the observed streamflow was similar to the runoff modelled by AWBM, but during the validation period (last 40% of the period of study), the observed streamflow was systematically lower than the modelled streamflow. In other words, the modelled flows were biased for the validation period as the model parameters were calibrated using the initial 60% of the period of study. This indicates that factors other than rainfall and the potential evapotranspiration (inputs to AWBM) could be changing in recent years causing a further decrease in runoff than expected, at least to the extent that was captured with calibrated parameter values for AWBM.

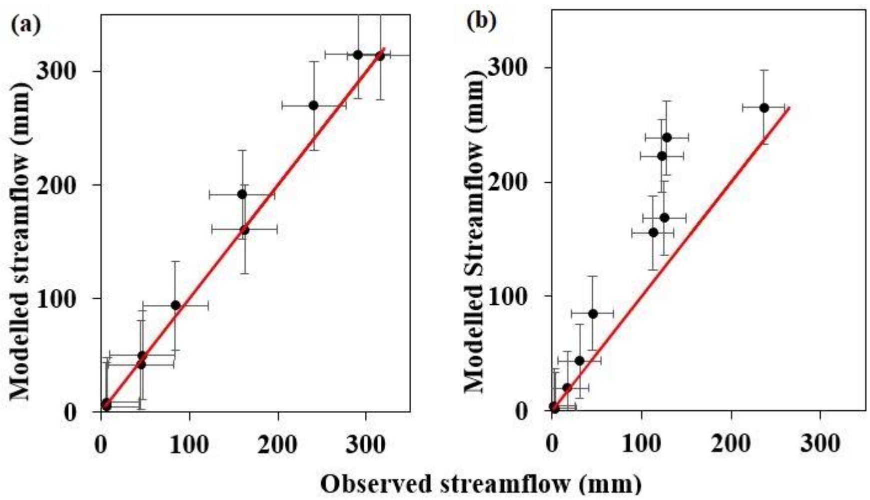

Figure 5. 6 Average annual observed streamflow vs modelled streamflow for all the ten catchments for (a) calibration period and (b) validation period. The 1:1 line in red indicates perfect agreement.

5.4 Discussion

As the rate of decrease in runoff was greater than the rate of decrease in rainfall and the AWBM model overestimated the runoff in recent years for the ten catchments in SWWA, additional factors could be involved in the decrease in runoff in SWWA. Previous studies in the region has found a steady decline in groundwater level of SWWA (Hughes et. al., 2012). Data from eight bores in the study area with most recent groundwater data were obtained as presented in Table 5.8 and Figure 5.1. It was found that the groundwater level has been steadily decreasing in all the bores. Figure 5.7 presents the reduced standing water levels at all the bores presented in Table 5.8.

Table 5. 8 Bore details and trend

No.	Bore id	Latitude	Longitude	Record length	Trend (m / decade)
(a)	61615051	-32.1	115.9	1985 - 2019	-4.99
(b)	61330024	-32.9	115.9	1982 - 2019	-1.46
(c)	61319142	-32.9	115.7	1979 - 2017	-0.14
(d)	61030066	-33.7	115.7	1987 - 2018	-0.14
(e)	60830007	-34.4	115.7	1993 - 2019	-0.30
(f)	ALBA0599	-35.0	117.7	2003 - 2018	-0.14
(g)	ALBAN298	-35.1	117.8	2002 - 2018	-0.18
(h)	WALPO105	-34.9	116.7	2012 - 2018	-0.17

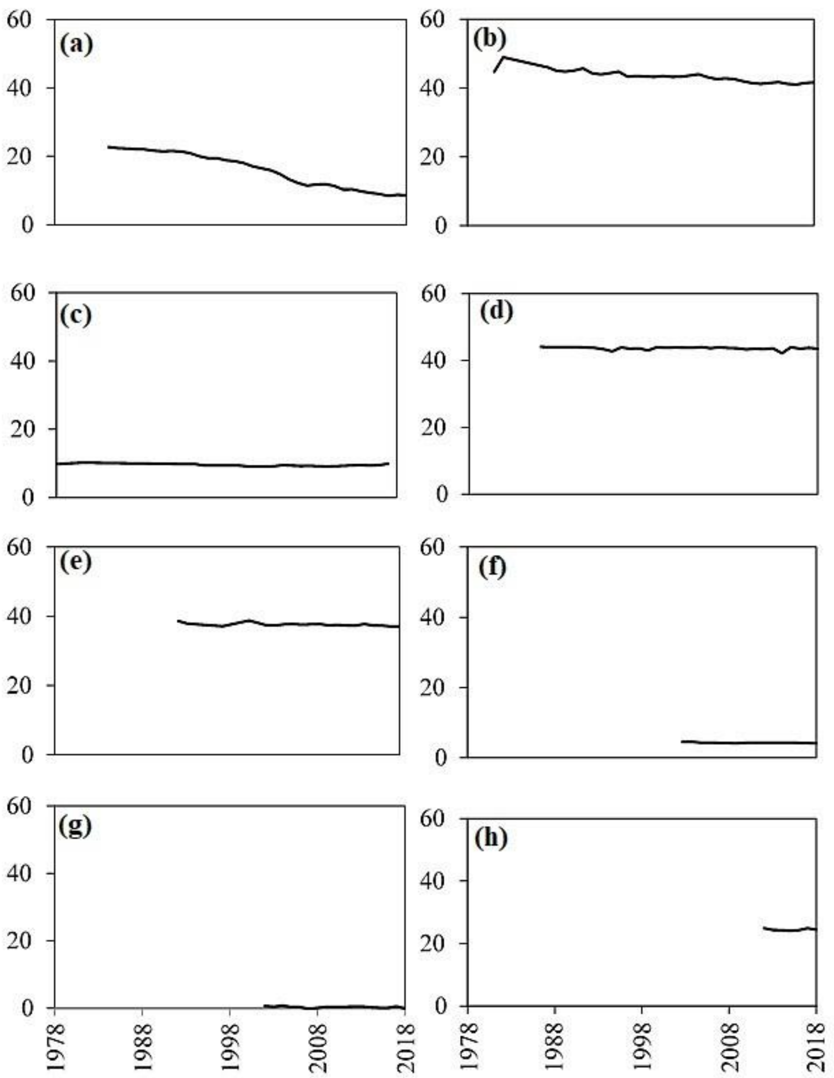

Figure 5. 7 Reduced standing water level (mm) of all the bores given in Table 5.8

In certain catchments, such as Deep and Carey, the streamflow showed a decreasing trend, even though the rainfall showed an increasing trend. This might be due to the high interannual variability of rainfall in these catchments. For the groundwater to be replenished and to contribute to streamflow, these catchments should receive above average rainfall regularly. The AWBM model parameters which were calibrated using the first 60% of the period of study was unable to capture the decrease in groundwater level for the validation period which caused the model to overpredict the runoff. As previously observed by Hughes et al., 2012 and Petrone et al., 2010, the groundwater in this region needs to first recover before we can observe any positive change in streamflow in this region. Similarly, from the simulated runoff, it may be inferred that in the recent years, the rainfall runoff relationship in SWWA has changed. A decrease or increase in rainfall no longer guarantees a respective change in runoff. This indicates the need to look at additional factors or processes such as groundwater level or land use changes and also using models which take into account these factors or processes.

This study was done using gridded rainfall data which is interpolated from station data. In SWWA, the density of stations is higher towards the coast compared to the inland regions. This is a limitation of this work, as the data quality in the region with fewer stations would be lower than the coastal region. Further, this study used the Morton's wet environment areal potential evapotranspiration as input to the AWBM model. It assumes upwind effects are negligible and local variations are ignored and hence the evapotranspiration estimate is an areal average (Wang et al., 2000). Future studies could use model evaluation techniques other than NSE as NSE tends to be sensitive to larger values in a time series whereas lower values are neglected (Legates and McCabe, 1999).

5.5 Conclusion

This study aimed to understand the rainfall-runoff relationship in SWWA based on data from ten catchments. Main conclusions from this study are:

- The total and heavy rainfall showed highest correlation with runoff for all catchments.
- All catchments showed significant decreasing trends in runoff while decrease in rainfall occurred in most catchments only while rainfall did increase occurred in a few. The rate of decrease in runoff was 2.6 times larger than the rate of decrease in rainfall.
- The trends in total and heavy rainfall showed positive correlation with runoff trend and explained 34% and 30%, respectively, of the variation in trends among the ten catchments.
- The modelled runoff from the AWBM model was found to be greater than the observed streamflow in recent years. The overpredicted runoff using parameters calibrated for earlier periods was likely to have occurred because of the decrease in groundwater level that was not adequately captured by the AWBM model.

Although, rainfall was showing an increasing trend for some of the catchments in SWWA, the groundwater should be replenished first in these dry catchments for runoff to recover.

References

Anshuman, A., Kunnath-Poovakka, A. and Eldho, T.I., 2018. Performance evaluation of conceptual rainfall-runoff models GR4J and AWBM. ISH Journal of Hydraulic Engineering, pp.1-10.

Bates, B.C., Hope, P., Ryan, B., Smith, I. and Charles, S., 2008. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Climatic Change*, **89**(3-4), pp.339-354.

Boughton, W.C., 1995. An Australian water balance model for semiarid watersheds. Journal of soil and water conservation, 50(5), pp.454-457.

Boughton, W. and Chiew, F., 2007. Estimating runoff in ungauged catchments from rainfall, PET and the AWBM model. Environmental Modelling & Software, 22(4), pp.476-487.

Dai, A., 2016. Historical and future changes in streamflow and continental runoff: A review. Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts, *Geophys. Monogr*, **221**, pp.17-37.

Do, H.X., Westra, S. and Leonard, M., 2017. A global-scale investigation of trends in annual maximum streamflow. *Journal of hydrology*, **552**, pp.28-43.

Ewen, J., 2011. Hydrograph matching method for measuring model performance. Journal of Hydrology, 408(1-2), pp.178-187.

Guinot, V., Cappelaere, B., Delenne, C., Ruelland, D., 2011. Towards improved criteria for hydrological model calibration: theoretical analysis of distance- and weak form-based functions. J. Hydrol. 401, 1–13.

Haque, M.M., Rahman, A., Hagare, D. and Kibria, G., 2015. Parameter uncertainty of the AWBM model when applied to an ungauged catchment. Hydrological processes, 29(6), pp.1493-1504.

Hughes, J.D., Petrone, K.C. and Silberstein, R.P., 2012. Drought, groundwater storage and stream flow decline in southwestern Australia. *Geophysical Research Letters,* **39**(3).

Islam, S.A., Bari, M.A. and Anwar, A.H.M.F., 2013. Hydrologic impact of climate change on Murray Hotham catchment of Western Australia: a projection of rainfall-runoff for future water resources planning. *Hydrology & Earth System Sciences Discussions*, **10**(10).

Kim, S., Vertessy, R.A., Perraud, J.M. and Sung, Y., 2005. Integration and application of the Rainfall Runoff Library. *Water science and technology*, **52**(9), pp.275-282.

Legates, D.R. and McCabe Jr, G.J., 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water resources research, 35(1), pp.233-241.

McFarlane, D., Stone, R., Martens, S., Thomas, J., Silberstein, R., Ali, R. and Hodgson, G., 2012. Climate change impacts on water yields and demands in south-western Australia. Journal of Hydrology, **475**, pp.488-498.

Perraud, J.M., Podger, G.M., Rahman, J.M. and Vertessy, R.A., 2003. A new rainfall-runoff software library. *In Proceedings of MODSIM* (Vol. 4, pp. 1733-1738).

Petrone, K.C., Hughes, J.D., Van Niel, T.G. and Silberstein, R.P., 2010. Streamflow decline in southwestern Australia, 1950–2008. *Geophysical Research Letters*, **37**(11).

Podger, G., 2004. Rainfall runoff library user guide. Cooperative Research Centre for Catchment Hydrology.

Pushpalatha, R., Perrin, C., Le Moine, N., Andréassian, V., 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. J. Hydrol. 420–421, 171–182.

Sengupta, P.K., 2017. Industrial Water Resource Management: Challenges and Opportunities for Corporate Water Stewardship. John Wiley & Sons.

Silberstein, R.P., Aryal, S.K., Braccia, M., Durrant, J. and Silberstein, R., 2013, December. Rainfall–runoff model performance suggests a change in flow regime and possible lack of catchment resilience. In Proceedings of the 20th International Congress on Modelling and Simulation (MODSIM2013), Adelaide, Australia (pp. 1-6).

Silberstein, R.P., Aryal, S.K., Durrant, J., Pearcey, M., Braccia, M., Charles, S.P., Boniecka, L., Hodgson, G.A., Bari, M.A., Viney, N.R. and McFarlane, D.J., 2012. Climate change and runoff in south-western Australia. *Journal of Hydrology*, **475**, pp.441-455.

Smith, I. and Power, S., 2014. Past and future changes to inflows into Perth (Western Australia) dams. *Journal of Hydrology: Regional Studies*, **2**, pp.84-96.

Wang, Q.J., McConachy, F.L.N., Chiew, F.H.S., James, R., deHoedt, G.C. and Wright, W.J., 2000. Climatic Atlas of Australia: Maps of Evapotranspiration. Australian Bureau of Meteorology.

Yu, B. and Zhu, Z., 2015. A comparative assessment of AWBM and SimHyd for forested watersheds. Hydrological sciences journal, 60(7-8), pp.1200-1212.

Zhang, X.S., Amirthanathan, G.E., Bari, M.A., Laugesen, R.M., Shin, D., Kent, D.M., MacDonald, A.M., Turner, M.E. and Tuteja, N.K., 2016. How streamflow has changed across Australia since the 1950s: evidence from the network of hydrologic reference stations. *Hydrology and Earth System Sciences*, **20**(9), p.3947.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

This chapter includes the key findings from the whole study, and recommendation because of the limitations and scope for future work.

This research study dealt with characterizing the rainfall changes in the South West of Western Australia during the period 1911 to 2018 in the context of decreasing runoff in this region. The rainfall in this region has showed significant decrease from the 1950s and the runoff coefficients have decreased progressively over the last 50 years (Petrone et al. (2010)).The decrease in runoff has resulted in lowering of dam water levels and limited water supply for irrigation, domestic and commercial and industry water use.

6.1 Conclusions

Based on data from 30 rain gauging stations in SWWA, the daily rainfall was classified into light, medium and heavy rainfall. For each station the light, medium and heavy rainfall were different as the heavy rainfall for one station may not be heavy for another. The results indicated that the variation in heavy rainfall was the major contributor (57%) of the variation in total annual rainfall followed by medium (30%) and light rainfall (13%). The rate of decrease in heavy rainfall was also higher (68%) than the expected rate of decrease. Seasonal trend analysis showed that amount of heavy rainfall and the number of days with heavy rainfall showed decreasing trend in winter and autumn while an increasing trend in summer. Stations with significant decreasing trend in total and heavy rainfall were mostly concentrated along the coast and had a higher mean annual rainfall. Rainfall in the region also showed significant negative correlation to the large-scale circulation pattern, the Southern Annular Mode (SAM).

To determine the changes in the rainfall volume, wet area, average daily rainfall depth and number of wet days in SWWA, gridded daily rainfall data for the period 1911 to 2018 was used. The study area was classified into four zones based on the mean annual rainfall and three daily rainfall thresholds (total, heavy and very heavy) were considered. Significant decreasing trend in rainfall volume and wet area was observed in the coastal regions while in the inland region an increasing trend was observed. The average daily rainfall depth showed an increasing trend for most thresholds. In the coastal region (mean annual rainfall $\geq$ 600 mm), more than

84% of the rate of change in rainfall volume was attributed to the changing extend of wet areas while the average daily rainfall depth only played a minor role. The region near the coast with a higher number of rain days showed a decreasing trend in area while an increasing trend was observed for the inland region with a lower number of rain days. Although, in long term the rainfall is decreasing in the coastal area, over the past 30 years, the rate of decrease in rainfall has reduced and the heavy rainfall, in fact, has increased with no concurrent change in the SAM index.

To understand the rainfall-runoff relationship in the study area, daily rainfall and runoff data for ten catchments in the study area was extracted, trends in rainfall and runoff were analysed and streamflow was estimated using hydrologic models. While the runoff in all the ten catchments showed a significant decreasing trend, the rainfall showed a decreasing trend in some catchments only and an increasing trend in others. The rate of decrease in runoff was found to be 2.6 times higher than the rate of change in rainfall. The trend in total and heavy rainfall showed positive correlation with runoff trend in the study area and explained 34% and 30% of the variation in runoff trends among the ten study catchments. The estimated runoff using the AWBM model was found to be higher than the observed streamflow indicating the presence of other factors such as the steady decline of groundwater levels in the region which was not adequately captured by the model.

The results of this research add to our understanding of the rainfall decrease in SWWA in that the trend and variability in heavy rainfall is the major contributor to the decrease in total rainfall of SWWA. The study examined changes in the rainfall volume and the wet area at different rainfall thresholds, an approach which has not been previously used to understand the decreasing rainfall in SWWA. It was found that the decrease in rainfall volume in the coastal region was mainly due to the decrease in wet area. It was also found that area with higher number of rain days in the coasts of SWWA has been decreasing while the area with lower number of rain days in the inland region has been increasing. In other words, wet areas are becoming drier and dry areas are becoming wetter. In the recent years, the rate of decrease in total rainfall has reduced and the heavy rainfall, in fact, has increased. It was also found that the AWBM model overpredicts the runoff in SWWA as it does not adequately capture the impact of factors other than rainfall, such as, the decreasing groundwater level, which contributes to the decline in runoff in the study area.

6.2 Recommendations for further study

This study used point rainfall data from the Bureau of Meteorology and gridded rainfall data from the SILO climate database for analysis. While using the point data, the years which had more than 10% of missing data or more than 10% of accumulated data were omitted. This meant that these years were not a part of the study while analyzing the rainfall trend for the region. Gridded rainfall data is interpolated from station data. The density of stations is higher towards the coasts compared to the inland regions, hence, the data quality in the inland region with fewer stations would be lower than that in the coastal regions.

This study used linear regression for trend analysis as the rainfall and runoff in this region has been steadily decreasing since the 1950s. Linear regression assumes a linear relation between the dependent variable and the independent variable. This could lead to omission of any nonlinear behavior in rainfall and runoff. This study used the AWBM model which is a simple conceptual model that uses rainfall and evapotranspiration as inputs to predict the runoff of a catchment. The model assumes similar soil conditions for the whole catchment which may not always hold true especially for the larger catchments. Future studies in the region could consider process-based models which better represent hydrologic responses and incorporates spatial variability in a catchment such as the Penn State Integrated Hydrologic Modeling System (PIHM) (Pechlivanidis et al., 2011). Process based models are built on the understanding of the physics related to the hydrological processes (Vaze, 2011). They are used when accurate data is available and the hydrological processes in the catchment are accurately understood (Sitterson et al., 2018). One of the limitations of such models is the large amounts of data required to run them (Uhlenbrook et al., 2004). Further, the use of coupled surface water-groundwater models such as MIKE SHE or MODFLOW, could also be beneficial to understand the interaction between the surface water and groundwater in the context of the declining runoff in SWWA.

APPENDIX A - REFERENCES

Akinsanola, A.A. and Ogunjobi, K.O., 2017. Recent homogeneity analysis and long-term spatio-temporal rainfall trends in Nigeria. Theoretical and Applied Climatology, 128(1–2), 275–289. https://doi.org/10.10 07/s00704-015-1701-x

Alexander, L.V. and Arblaster, J.M., 2009. Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. International Journal of Climatology, 29, 417–435. http s://doi.org/10.1002/joc.1730

Alexander, L.V., Uotila, P., Nicholls, N. and Lynch, A., 2010. A new daily pressure dataset for Australia and its application to the assessment of changes in synoptic patterns during the last century. J. Clim. 23(5), pp.1111-1126.

Ansell, T.J., Reason, C.J.C., Smith, I.N. and Keay, K., 2000. Evidence for decadal variability in southern Australian rainfall and relationships with regional pressure and sea surface temperatures. International Journal of Climatology, 20, 1113–1129.

Anshuman, A., Kunnath-Poovakka, A. and Eldho, T.I., 2018. Performance evaluation of conceptual rainfall-runoff models GR4J and AWBM. ISH Journal of Hydraulic Engineering, pp.1-10.

Aryal, S.K., Bates, B.C., Campbell, E.P., Li, Y., Palmer, M.J. and Viney, N.R.,2009. Characterizing and modeling temporal and spatial trends in rainfall extremes. Journal of Hydrometeorology, 10(1), 241–25 3. https://doi.org/10.1175/2008JHM1007.1

Bates, B. C., Chandler, R. E., Charles, S. P., & Campbell, E. P., 2010. Assessment of apparent nonstationarity in time series of annual inflow, daily precipitation, and atmospheric circulation indices: a case study of south west Western Australia. Water Resour. Res. 46, W00H02. DOI: 10.1029/2010WR009509

Bavil, S.S., Zeinalzadeh, K. and Hessari, B., 2018. The changes in the frequency of daily precipitation in Urmia Lake basin, Iran. Theoretical and Applied Climatology, 133(1–2), 205–214. https://doi.org/10.100 7/s00704-017-2177-7

Beecham, S., & Choudhury, R. K., 2010. Temporal characteristics and variability of point rainfall: a statistical and wavelet analysis. Int. J. of Climatol. 30, 458-473. DOI: 10.1002/joc.1901

Berry, G., Jakob, C. and Reeder, M., 2011. Recent global trends in atmospheric fronts. Geophys. Res. Lett. 38, L21812.

Boughton, W.C., 1995. An Australian water balance model for semiarid watersheds. Journal of soil and water conservation, 50(5), pp.454-457.

Bill Burnbury., 2015. Invisible country, southwest Australia: understanding a landscape. UWA Publishing:AU.

Cai, W., & Cowan, T., 2008. Dynamics of late autumn rainfall reduction over southeastern Australia. Geophysical Research Letters, 35(9).

Caloiero, T., 2014. Analysis of daily rainfall concentration in New Zealand. Nat. Hazards. 72, 389-404. doi: 10.1007/s11069-013-1015-1.

Caloiero, T., Caloiero, P. and Frustaci, F., 2018. Long-term precipitation trend analysis in Europe and in the Mediterranean basin. Water Environ J. 32, 433-445. doi: 10.1111/wej.12346.

Catto, J.L., Nicholls, N., Jakob, C. and Shelton, K.L., 2014. Atmospheric fronts in current and future climates. Geophys. Res. Lett. 41(21), pp.7642-7650.

Charles, S., Silberstein, R., Teng, J., Fu, G., Hodgson, G., Gabrovsek, C., Crute, J., Chiew, F., Smith, I., Kirono, D. and Bathols, J., 2010. Climate analyses for South-West Western Australia: A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project.

Chowdhury, R.K., Beecham, S., Boland, J. and Piantadosi, J., 2015. Understanding South Australian rainfall trends and step changes. Int. J. Climatol. 35, 348-360. doi: 10.1002/joc.3982.

Collins, D.A. and Della-Marta, P.M., 1999. Annual climate summary 1998: Australia's warmest year on record. Aust. Met. Mag. 48, 273-83.

Dai, A., 2016. Historical and future changes in streamflow and continental runoff: A review. Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts, Geophys. Monogr, 221, pp.17-37.

Dey, R., Lewis, S.C., Arblaster, J.M. and Abram, N.J., 2019. A review of past and projected changes in Australia's rainfall. Wiley Interdisciplinary Reviews: Clim. Change. 10(3), p.e577.

Do, H.X., Westra, S. and Leonard, M., 2017. A global-scale investigation of trends in annual maximum streamflow. Journal of hydrology, 552, pp.28-43.

Donat, M.G., Peterson, T.C., Brunet, M., King, A.D., Almazroui, M., Kolli, R.K., Boucherf, D., Al-Mulla, A.Y., Nour, A.Y., Aly, A.A. and Nada, T.A.A., 2014. Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO. Int. J. Climatol. 34, 581-592. doi:10.1002/joc.3707.

Dore, M.H., 2005. Climate change and changes in global precipitation patterns: what do we know?. Environ. Int. 31, 1167-1181. doi:10.1016/j.envint.2005.03.004.

Easterling, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E. and Ambenje, P., 2000. Observed variability and trends in extreme climate events: a brief review. Bull. Am. Meteorol. Soc. 81(3), pp.417-426.

Eekhout, J.P., Hunink, J.E., Terink, W. and de Vente, J., 2018. Why increased extreme precipitation under climate change negatively affects water security. Hydrol. Earth Syst. Sci. 22(11), pp.5935-5946.

Feng, J., Li, J., Li, Y., Zhu, J., & Xie, F., 2015. Relationships among the monsoon-like southwest Australian circulation, the southern annular mode, and winter rainfall over southwest Western Australia. Adv. Atmos. Sci. 32. 1063-1076. https://doi.org/10.1007/s00376-014-4142-z

Feng, J., Li, J.P. and Li, Y., 2010. Is there a relationship between the SAM and Southwest Western Australian winter rainfall? Journal of Climate, 23, 6082–6089. https://doi.org/10.1175/2010JCLI3667.1

Folland, C.K., Karl,T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E.,Oerlemans, J., Salin ger, M.J. and Wang, S.W., 2001. Observed climate variability and change. Climate change, 2001, The Scientific Basis—Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp. 99– 181, Cambridge Univ. Press, New York.

Frederiksen, J.S. and Frederiksen, C.S., 2007. Interdecadal changes in southern hemisphere winter storm track modes. Tellus A. 59, 599-617.

Frederiksen, J. S., & Frederiksen, C. S., 2011. Twentieth century winter changes in southern hemisphere synoptic weather modes. ADV METEOROL. 2011: 1-16.

Fu, G., Viney, N. R., Charles, S. P., & Liu, J., 2010. Long-term temporal variation of extreme rainfall events in Australia: 1910-2006. J. Hydrometeorol. 11. 950-965. https://doi.org/10.1175/2010JHM1204.1

Gallant, A.J., Hennessy, K.J. and Risbey, J., 2007. Trends in rainfall indices for six Australian regions: 1910-2005. Aust. Met. Mag. 56, 223-241.

Guthrie, M., Evans, F., and Bowran D., 2015 The influence of climate change on Western Australian agriculture. 2015 Agribusiness Crop Updates. Grain Industry Association of Western Australia, viewed August 2015

Haque, M.M., Rahman, A., Hagare, D. and Kibria, G., 2015. Parameter uncertainty of the AWBM model when applied to an ungauged catchment. Hydrological processes, 29(6), pp.1493-1504.

Haylock, M., & Nicholls, N., 2000. Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. Int. J. Climatol. 20. 1533-1541.

Hennessy, K.J., Suppiah, R. and Page, C.M., 1999. Australian rainfall changes, 1910-1995. Australian Meteorological Magazine, 48, 1–13.

Heyhoe, E., Kim, Y., Kokic, P., Levantis, C., Ahammad, H., Schneider, K., Crimp, S., Nelson, R., Flo od, N. and Carter, J., 2007. Adapting to climate change-issues and challenges in the agriculture sector. Australian Commodities: Forecasts and Issues, 14, 167.

Hope, P.K., Drosdowsky, W. and Nicholls, N., 2006. Shifts in the synoptic systems influencing southwest Western Australia. Clim. Dyn. 26, 751-764.

Hope, P. and Ganter, C., 2010, May. Recent and projected rainfall trends in south-west Australia and the associated shifts in weather systems. In Managing climate change: papers from the Greenhouse 2009 Conference. CSIRO, Collingwood, Victoria, Australia (pp. 53-63).

Hope, P., Timbal, B. and Fawcett, R., 2010. Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. Int. J. of Climatol. 30(9), pp.1360-1371.

Hughes, L. and McMichael, T., 2011. The critical decade: climate change and health. ACT Climate Commission Secretariat.

Hughes, J.D., Petrone, K.C. and Silberstein, R.P., 2012. Drought, groundwater storage and stream flow decline in southwestern Australia. Geophys. Res. Lett. 39(3).

Islam, S.A., Bari, M.A. and Anwar, A.H.M.F., 2013. Hydrologic impact of climate change on Murray Hotham catchment of Western Australia: a projection of rainfall-runoff for future water resources planning. Hydrology & Earth System Sciences Discussions, 10(10).

Kebe, C.M.F., Sauvageot, H. and Nzeukou, A., 2005. The relation between rainfall and area–time integrals at the transition from an arid to an equatorial climate. J. Clim. 18, 3806-3819. doi:10.1175/JCLI3451.1.

Kim, S., Vertessy, R.A., Perraud, J.M. and Sung, Y., 2005. Integration and application of the Rainfall Runoff Library. Water science and technology, 52(9), pp.275-282.

Kinal, J., & Stoneman, G. L. (2012). Disconnection of groundwater from surface water causes a fundamental change in hydrology in a forested catchment in south-western Australia. Journal of Hydrology, 472, 14-24.

Lavery, B., Joung, G. and Nicholls, N., 1997. An extended high-quality historical rainfall dataset for Australia. Australian Meteorological Magazine, 46(1), 27–38.

Lavery, B., Kariko, A. and Nicholls, N., 1992. A historical rainfall data set for Australia. Australian Meteorological Magazine, 40, 33–39.

Lazaro, R., Rodrigo, F.S., Gutiérrez, L., Domingo, F. and Puigdefábregas, J., 2001. Analysis of a 30-year rainfall record (1967–1997) in semi–arid SE Spain for implications on vegetation. J. Arid Environ. 48, 373-395. doi:10.1006/jare.2000.0755.

Lehmann, J., Coumou, D. and Frieler, K., 2015. Increased record-breaking precipitation events under global warming. Clim. Chang. 132(4), pp.501-515.

Li, Y., Cai, W., & Campbell, E. P., 2005. Statistical modeling of extreme rainfall in southwest Western Australia. J. Clim. 18(6), 852-863. https://doi.org/10.1175/JCLI-3296.1

Loo, Y.Y., Billa, L. and Singh, A., 2015. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. Geoscience Frontiers, 6(6), 817–823.

Ludwig, F., Milroy, S.P. and Asseng, S., 2009. Impacts of recent climate change on wheat production systems in Western Australia. Climatic Change, 92(3-4), pp.495-517.

Marvel, K. and Bonfils, C., 2013. Identifying external influences on global precipitation. Proc. Natl. Acad. Sci. 110(48), pp.19301-19306.

McFarlane, D., Stone, R., Martens, S., Thomas, J., Silberstein, R., Ali, R. and Hodgson, G., 2012. Climate change impacts on water yields and demands in south-western Australia. Journal of Hydrology, 475, pp.488-498.

McGree, S., Whan, K., Jones, D., Alexander, L. V., Imielska, A., Diamond, H., ... & Kumar, R., 2014. An updated assessment of trends and variability in total and extreme rainfall in the western Pacific. Int. J. Climatol. 34(8), 2775-2791. DOI: 10.1002/joc.3874

Mills, T.C., 2016. Modelling rainfall trends in England and Wales. Cogent Geoscience, 2(1), 1133218. http s://doi.org/10.1080/23312041.2015.1133218

Murphy, B.F. and Timbal, B., 2008. A review of recent climate variability and climate change in southeastern Australia. International Journal of Climatology, 28(7), 859–879. https://doi.org/10.1002/joc.1627

Nan, S. and Li, J., 2003. The relationship between the summer precipitation in the Yangtze River valley and the boreal spring southern hemisphere annular mode. Geophysical Rese arch Letters, 30(24),2266. https://doi.org/10.1029/2003GL018381.

Nicholson, S.E., Funk, C. and Fink, A.H., 2018. Rainfall over the African continent from the 19th through the 21st century. Global and Planetary Change, 165, 114–127.

Nicholls, N., 2010. Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007. Climate dynamics, 34(6), pp.835-845.

Nogueira, R.C. and Keim, B.D., 2010. Annual volume and area variations in tropical cyclone rainfall over the eastern United States. J. Clim. 23, 4363-4374. doi:10.1175/2010JCLI3443.1.

Pechlivanidis, I.G., Jackson, B.M., Mcintyre, N.R. and Wheater, H.S., 2011. Catchment scale hydrological modelling: a review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. Global NEST journal, 13(3), pp.193-214.

Pepler, A., Dowdy, A. and Hope, P., 2019. A global climatology of surface anticyclones, their variability, associated drivers and long-term trends. Clim. Dyn. 52(9-10), pp.5397-5412.

Perraud, J.M., Podger, G.M., Rahman, J.M. and Vertessy, R.A., 2003. A new rainfall-runoff software library. In Proceedings of MODSIM (Vol. 4, pp. 1733-1738).

Petrone, K.C., Hughes, J.D., Van Niel, T.G. and Silberstein, R.P., 2010. Streamflow decline in southwestern Australia, 1950–2008. Geophys. Res. Lett. 37(11).

Pepler, A., Dowdy, A. and Hope, P., 2019. A global climatology of surface anticyclones, their variability, associated drivers and long-term trends. Clim. Dyn. 52(9-10), pp.5397-5412.

Pittock, A.B., 1983. Recent climatic change in Australia: Implications for a CO 2-warmed earth. Clim. Chang. 5, 321-340. doi:10.1007/BF02423529.

Podger, G., 2004. Rainfall runoff library user guide. Cooperative Research Centre for Catchment Hydrology.

Pook, M.J., Risbey, J.S. and McIntosh, P.C., 2012. The synoptic climatology of cool-season rainfall in the central wheatbelt of Western Australia. Mon. Weather Rev. 140, 28-43. doi:10.1175/MWR-D-11-00048.1.

Prein, A.F., Holland, G.J., Rasmussen, R.M., Clark, M.P. and Tye, M.R., 2016. Running dry: The US Southwest's drift into a drier climate state. Geophys. Res. Lett. 43, 1272-1279. doi:10.1002/2015GL066727.

Pushpalatha, R., Perrin, C., Le Moine, N., Andréassian, V., 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. J. Hydrol. 420–421, 171–182.

Raut, B.A., Jakob, C. and Reeder, M.J., 2014. Rainfall changes over southwestern Australia and their relationship to the Southern Annular Mode and ENSO. J. Clim. 27(15), pp.5801-5814.

Reid, M., Cheng, X., Banks, E., Jankowski, J., Jolly, I., Kumar, P., Lovell, D., Mitchell, M., Mudd, G., Richardson, S. and Silburn, M., 2009. Catalogue of conceptual models for groundwater–stream interaction in eastern Australia.

Risbey, J.S., Pook, M.J. and McIntosh, P.C., 2013. Spatial trends in synoptic rainfall in southern Australia. Geophys. Res. Lett. 40, 3781-3785. doi:10.1002/grl.50739.

Saha, S., Chakraborty, D., Paul, R.K., Samanta, S. and Singh, S.B., 2018. Disparity in rainfall trend and patterns among different regions: analysis of 158 years' time series of rainfall dataset across India. Theor. Appl. Climatol. 1-15. doi:10.1007/s00704-017-2280-9.

Samuel, J. M., Verdon, D. C., Sivapalan, M., & Franks, S. W., 2006. Influence of Indian Ocean sea surface temperature variability on southwest Western Australian winter rainfall. Water Resour. Res. 42(8). DOI: 10.1029/2005WR004672

Sengupta, P.K., 2017. Industrial Water Resource Management: Challenges and Opportunities for Corporate Water Stewardship. John Wiley & Sons.

Sitterson, J., Knightes, C., Parmar, R., Wolfe, K., Avant, B. and Muche, M., 2018. An overview of rainfall-runoff model types.

Silberstein, R.P., Aryal, S.K., Braccia, M., Durrant, J. and Silberstein, R., 2013, December. Rainfall–runoff model performance suggests a change in flow regime and possible lack of catchment resilience. In Proceedings of the 20th International Congress on Modelling and Simulation (MODSIM2013), Adelaide, Australia (pp. 1-6).

Silberstein, R.P., Aryal, S.K., Durrant, J., Pearcey, M., Braccia, M., Charles, S.P., Boniecka, L., Hodgson, G.A., Bari, M.A., Viney, N.R. and McFarlane, D.J., 2012. Climate change and runoff in south-western Australia. J. Hydrol. 475, pp.441-455.

Smith, I., 2004. An assessment of recent trends in Australian rainfall. Aust. Met. Mag., 53, 163-173.

Smith, I.N., McIntosh, P., Ansell, T.J., Reason, C.J.C. and McInnes, K., 2000. Southwest Western Australian winter rainfall and its association with Indian Ocean climate variability. International Journal of Climatology, 20(15), 1913–1930.

Smith, I. and Power, S., 2014. Past and future changes to inflows into Perth (Western Australia) dams. J. Hydrol. Reg. Stud. 2, pp.84-96.

Sprigg, H., Belford, R., Milroy, S., Bennett, S.J. and Bowran, D., 2014. Adaptations for growing wheat in the drying climate of Western Australia. Crop and Pasture Science, 65(7), pp.627-644.

Steffen, W., Hughes, L. and Pearce, A., 2015. Climate change 2015: Gro wing risks, critical choices. Climate Council of Australia, Sydney

Suppiah, R. and Hennessy, K.J., 1998. Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. Int. J. Climatol. 18, 1141-1164. doi:10.1002/(SICI)1097-0088(199808)18:10<1141::AID-JOC286>3.0.CO;2-P.

Thompson, D.W., Solomon, S., Kushner, P.J., England, M.H., Grise, K.M. and Karoly, D.J., 2011. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. Nat. Geosci. 4(11), p.741.

Timbal B and Drosdowsky W., 2013. The relationship between the decline of Southeastern Australian rainfall and the strengthening of the subtropical ridge. Int. J. Climatol. 33, 1021-1034. DOI: 10.1002/joc.3492.

Uhlenbrook, S., Roser, S. and Tilch, N., 2004. Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. Journal of Hydrology, 291(3-4), pp.278-296.

Vaze, J., Jordan, P., Beecham, R., Frost, A. and Summerell, G., 2011. Guidelines for rainfall-runoff modelling: towards best practice model application. Australia: eWater Coopration Research Centre.

Villarini, G., & Denniston, R. F., 2016. Contribution of tropical cyclones to extreme rainfall in Australia. Int. J. Climatol. 36(2), 1019-1025. DOI: 10.1002/joc.4393

Wang, Q.J., McConachy, F.L.N., Chiew, F.H.S., James, R., deHoedt, G.C. and Wright, W.J., 2000. Climatic Atlas of Australia: Maps of Evapotranspiration. Australian Bureau of Meteorology.

Wang, Y., Chen, X. and Yan, F., 2015. Spatial and temporal variations of annual precipitation during 1960–2010 in China. Quat. Int. 380, 5-13.

Wang, Y., Ding, Y., Ye, B., Liu, F. and Wang, J., 2013. Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. Sci. China Earth Sci. 56, 1398-1412.

Ward, P.R. and Dunin, F.X., 2001. Growing season evapotranspiration from duplex soils in south-western Australia. Agricultural Water Management, 50(2), pp.141-159.

Wright, P.B., 1974. Seasonal rainfall in southwestern Australia and the general circulation. Mon. Weather Rev. 102, 219-232. doi:10.1175/1520-0493(1974)102<0219:SRISAA>2.0.CO;2.

Yang, T., Ding, J., Liu, D., Wang, X. and Wang, T., 2019. Combined use of multiple drought indices for global assessment of dry gets drier and wet gets wetter paradigm. Journal of Climate, 32(3), pp.737-748.

Yu, B. and Neil, D.T., 1993. Long-term variations in regional rainfall in the south-west of Western Australia and the difference between average and high intensity rainfalls. Int. J. Climatol. 13, 77-88. doi:10.1002/joc.3370130106.

Yu, B. and Zhu, Z., 2015. A comparative assessment of AWBM and SimHyd for forested watersheds. Hydrological sciences journal, 60(7-8), pp.1200-1212.

Zhang, X.S., Amirthanathan, G.E., Bari, M.A., Laugesen, R.M., Shin, D., Kent, D.M., MacDonald, A.M., Turner, M.E. and Tuteja, N.K., 2016. How streamflow has changed across Australia since the 1950s: evidence from the network of hydrologic reference stations. Hydrology and Earth System Sciences, 20(9), p.3947.

APPENDIX B - PUBLISHED PAPER

Received: 11 March 2018 | Revised: 17 May 2019 | Accepted: 25 October 2019
DOI: 10.1002/joc.6382

RESEARCH ARTICLE

International Journal of Climatology RMetS

Interannual variations in rainfall of different intensities in South West of Western Australia

Priya Philip | **Bofu Yu**

School of Engineering and Built Environment and Australian Rivers Institute, Griffith University, Brisbane, Queensland, Australia

Correspondence
Bofu Yu, School of Engineering and Built Environment, Nathan Campus, Griffith University, 170 Kessels Road, QLD 4111, Australia.
Email: b.yu@griffith.edu.au

Funding information
Griffith University

Abstract

Significant decreases in rainfall in South West of Western Australia (SWWA) over recent decades are of concern for water supply and agricultural production in the region. Total rainfall can be decomposed into light, medium and heavy rainfalls, and the land responds differently to these rainfall classes. Little, however, is known about changes in different rainfall classes in SWWA. The objective of this study is to quantify contributions from these rainfall classes to the decrease and interannual variations in rainfall, and to relate the decreases to station characteristics, that is, latitude, elevation and the mean annual rainfall, and to the large scale circulation pattern known as the Southern Annular Mode (SAM). Long-term data for 30 stations were used, and daily rainfall was divided into three classes in such a way that they contributed equally (one third of the total) for each station. Trend and correlation analysis was applied to these classes. The decrease in heavy rainfall was mainly responsible for the decrease in total rainfall, followed by the medium and light rainfalls. The rate of decrease in heavy rainfall was 68% higher than, while that in light rainfall was about half, of the expected trend. Heavy rainfall exhibited a significant decreasing trend in winter and autumn but mildly increasing trend in summer. The number of heavy rain days also showed a significant decreasing trend. The rate of decrease relative to the mean was similar for both heavy rainfall and number of heavy rain days. Stations with a higher rainfall were more likely to experience a decrease in rainfall than those in the drier inland areas. Stations where rainfall was strongly correlated with SAM were mostly concentrated along the west coast of SWWA. The SAM index explained 9% of the variation in heavy rainfall and 11% in total rainfall for the region.

KEYWORDS

heavy rainfall, relative threshold, site characteristics, South West of Western Australia, Southern Annular Mode, trend

1 | INTRODUCTION

Rainfall is one of the most important weather variables as it is the primary source of fresh water, and regional rainfall variability and change are an integral part of the global concern with climate change as a result of the enhanced greenhouse effect (Folland *et al.*, 2001). Examining rainfall trends helps to identify their underlying causes and develop adaption strategies for water resources management.

Studies have shown increased rainfall variability in most parts of the world over the years (Dore, 2005). In England and Wales, winters are becoming increasingly wet while summers are drier during the time period, 1766 to 2014. Since 1976 winter precipitation has shown no significant trend, but spring has become wetter with drier summers (Mills, 2016). Bavil *et al.* (2018) investigated the trend in the frequency of occurrence of precipitation in Urmia Lake basin in Iran and concluded that the frequency of occurrence of daily precipitation with small amounts (<5 mm) is showing a significant increasing trend while the frequency of occurrence for larger amounts (>10 mm) is significantly decreasing resulting in reduced runoff to the lake. Significant decreasing trends are observed in the annual rainfall in West and North Africa with an abrupt reduction since 1968 (Nicholson *et al.*, 2018). Based on annual and seasonal analyses in Nigeria, Akinsanola and Ogunjobi (2017) report an increasing trend in annual, monsoon, post- and pre-monsoon rainfalls and a decreasing trend in winter rainfall. Excessive monsoon flooding has become more frequent in South East Asia and understanding the shift and predicting changing trends of the monsoon may be central to managing the floods which have devastating impacts on millions of people in the region (Loo *et al.*, 2015).

Rainfall has been examined for various regions of Australia and many have concluded that the rainfall in Australia is showing large interannual variability and significant change (Pittock, 1983; Yu and Neil, 1993; Hennessy *et al.*, 1999; Smith, 2004). While some parts of Australia show a significant increasing trend in rainfall (Suppiah and Hennessy, 1998), the South West of Western Australia (SWWA) is showing a significant decreasing trend (Yu and Neil, 1993; Gallant *et al.*, 2007; Bates *et al.*, 2010). SWWA receives most of its rainfall in winter during the months of June, July and August and SWWA depends on the winter rainfall for meeting its agricultural water requirements and town water supply. These sectors have been adversely affected by the decrease in rainfall over recent decades. Wheat production in the area could decline by 7.3% by 2030 (Heyhoe *et al.*, 2007) and the decrease of inflow into the dams due to lower rainfall has led to low water levels in the dams of this region while the demand for water supply has been rising continuously (Steffen *et al.*, 2015).

A decrease in the mean rainfall in the winter months in SWWA was observed by Pittock (1983). Yu and Neil (1993) associated the decrease in annual rainfall in SWWA with the decrease in the frequency of occurrence of all rainfall intensities in winter and though the high-intensity events (extreme events closely related to flooding, soil erosion and gully formation) show a decrease in winter, this is offset by a corresponding increase during summer. The decline in winter rainfall in SWWA is caused by the significant decrease in both the intensity and frequency of high-intensity rainfall (Hennessy *et al.*, 1999; Haylock and Nicholls, 2000). Hennessy *et al.* (1999) found a significant decrease of 19% in total rainfall and a 25% decrease in winter rainfall. A significant decrease of 41–59% in the frequency of winter heavy rainfall and a 13% decline in the total winter rain days in SWWA were also observed. The change point of the statistically significant decreasing trend in SWWA is identified to be around the time 1965–1970 (Li *et al.*, 2005; Fu *et al.*, 2010). Gallant *et al.* (2007) analysed the trend in six Australian regions using nine climatic indices which are related to the mean annual, seasonal and extreme daily rainfall and found that eight out of the nine indices in SWWA show a statistically significant decreasing trend. SWWA also exhibits a decrease in the occurrence and intensity of daily precipitation (Bates *et al.*, 2010).

The climate of SWWA is influenced by various weather drivers including the frontal system, Indian Ocean Dipole (IOD), sea surface temperature (SST), El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM) and the Sub Tropical Ridge (Murphy and Timbal, 2008). The winter rainfall in SWWA is lower in years when warm SSTs dominate the southern and tropical western Indian Ocean and the SST anomalies show a strong negative correlation with the sharp reduction in SWWA rainfall in the 1970s (Samuel *et al.*, 2006). SAM is observed to have an inverse relationship to the SWWA winter rainfall (Feng *et al.*, 2010; Hope *et al.*, 2010). The step change in winter rainfall in 1970 is thought to be the result of a positive SAM in a neutral ENSO phase accompanied by a reduction in rainfall from the westerly fronts (Raut *et al.*, 2014). The decreasing frequency of westerly fronts in SWWA during June, July and August is also thought to be responsible for the declining winter rainfall (Hope, 2006; Alexander and Arblaster, 2009). Rainfall variability in SWWA is more closely linked to the mean sea level pressure (MSLP) than SST (Ansell *et al.*, 2000). The decreasing trend is strongly associated with a decrease in atmospheric moisture and an increase in regionally averaged sea level pressure (Bates *et al.*, 2010). The correlation between SST and winter rainfall in SWWA was found to be the highest during the time period 1950–1994 (Smith *et al.*, 2000). The concept of a monsoon-like atmospheric circulation, the South West Australian Circulation (SWAC), put forward by Feng *et al.* (2015) explains clearly the interannual variability of rainfall in SWWA and the long term decreasing trend.

Previous studies in SWWA have examined the decreasing trend in the rainfall in SWWA in terms of a decrease in extreme events or high-intensity rainfall (Hennessy *et al.*, 1999; Fu *et al.*, 2010; McGree *et al.*, 2014) and annual and seasonal trend analyses have also been carried out showing similar results (Choudhury *et al.*, 2015). The total rainfall in an area can be considered to be the sum of light, medium and heavy rainfalls. Classifying rainfall into heavy, medium and light rainfall classes would be useful for a better understanding of the rainfall–runoff relationship as catchments responds differently to different rainfall classes in terms of runoff generation and water availability. No study has been done yet to identify the contribution of each of the different classes of rainfall, namely, light, medium and heavy rainfalls, to the total decrease of rainfall in SWWA. Examining the decrease in rainfall in SWWA from this perspective has two benefits. First, different rainfall classes may be associated with distinct precipitation mechanisms. For example, heavy winter rainfall in SWWA is mostly associated with north-westerly winds while the late winter showery rainfall is mainly due to the south-westerly winds (Wright, 1974). Examining the trend and the interannual variations of different rainfall classes could help identify the underlying cause for the decline in rainfall in SWWA. Second, identifying the trend of light, medium and heavy rainfalls helps in understanding the interannual and seasonal pattern of each of these classes and is useful for developing water management strategies. A decrease in heavy rainfall would imply a decrease in streamflow and consequent lowering of water level in reservoirs whereas a decrease in light or medium rainfall indicates lower water availability for general uses.

To classify light, medium and heavy rainfalls, absolute thresholds, common to all sites, were not used because rainfall classification irrespective of the site location may lead to different or even erroneous interpretations, as the rainfall considered extreme for one location may not be extreme at another due to differing climatic conditions (Gallant *et al.*, 2007). It is more appropriate to use relative thresholds, which are site-specific thresholds, where the classification is based on the actual rainfall received at that particular station. Previous studies which examined the pattern of extreme rainfall in the study area have used the peak over threshold approach (Li *et al.*, 2005; Aryal *et al.*, 2009) and the 95th percentile (Hennessy *et al.*, 1999; Haylock and Nicholls, 2000; McGree *et al.*, 2014) to develop the extreme rainfall series in the study area. This study used an alternate approach to classify rainfall as light, medium and heavy for each station. Two thresholds in mm·day^{-1} were selected for each site so that the total rain was separated into three equal components.

Previous studies have established the inverse relationship between the large scale circulation pattern, the SAM and the winter rainfall in SWWA (Feng *et al.*, 2010; Hope *et al.*, 2010). The current study aims to further test the relationship between the SAM and the trend in light, medium, heavy and total annual rainfalls. The study also aims to assess the effect of the local site characteristics such as latitude, elevation, distance from the coast and the mean annual rainfall on the observed rainfall trends.

The objectives of this study are (a) to quantify the change in each rainfall class as components of the overall decrease in rainfall in SWWA, (b) to evaluate the contribution from each rainfall class to the total rainfall in terms of interannual variations, (c) to determine the change in the amount and the number of days of heavy rainfall for all seasons, (d) to test whether site-specific characteristics such as latitude, elevation, distance from coast and the mean annual rainfall are significantly correlated with the change in the total rainfall and individual rainfall classes and (e) to determine whether observed changes in rainfall in SWWA could be explained by the large scale circulation pattern, the SAM.

2 | DATA AND METHODOLOGY

SWWA has a Mediterranean climate with rainfall mostly occurring in winter months. The region has a mean annual rainfall of 300–1,200 mm (Table 1) and receives more than half of its total rainfall during the months of June, July and August. Rainfall in this region is mostly associated with cold frontal systems, which are moving from west to east across the Southern Ocean. Other factors that affect the rainfall in this region include the Subtropical ridge, SAM, IOD, west coast trough and cloud bands (Murphy and Timbal, 2008).

The study area lies south of 30°S and west of 119°E (Figure 1). This area was chosen because it has the highest mean annual rainfall (300–1,310 mm) compared to the neighbouring regions with a lower mean annual rainfall (130–300 mm) (Figure 1). More importantly, previous studies (Yu and Neil, 1993; Hennessy *et al.*, 1999; Gallant *et al.*, 2007) show that significant decreases in rainfall have occurred in this area.

Daily rainfall data for SWWA were obtained from the Bureau of Meteorology website for 30 stations in the study area. Nineteen of them were identified as high-quality rainfall stations (Lavery *et al.*, 1992; 1997). The remaining 11 stations were selected for a better spatial coverage. Distribution of the stations in the study area is shown in (Figure 1 and details of the stations are given in Table 1.

A day with greater than or equal to 0.2 mm of rainfall was considered as a wet day. For stations with missing

TABLE 1 Rainfall stations included in this study (station number in bold indicates high quality stations as identified in Lavery *et al.*, 1992; 1997)

BoM station number	Station number on Figure 1	Location	Latitude	Longitude	Elevation (m)	Mean annual rainfall (mm)	Record length (years)
9619	1	Wilgarrup	34.15	116.2	240	908	103
10037	2	Cuttening	31.73	117.76	300	308	100
10045	3	Ejanding	31.016	117.13	290	313	107
10126	4	Trayning	31.116	117.8	290	319	99
10525	5	Broomehill	33.85	117.63	328	446	103
10582	6	Kojonup	33.83	117.15	305	533	85
9519	7	Cape Naturaliste	33.53	115.016	109	807	106
9551	8	Grassmere	35.016	117.75	10	1,004	95
9561	9	Kendenup	34.483	117.63	262	598	71
9591	10	Pardelup	34.63	117.38	230	792	69
9616	11	Westbourne	34.1	116.67	280	687	107
10024	12	Casuarina Vale	31.16	116.85	275	376	84
10536	13	Corrigin	32.33	117.866	295	372	104
10658	14	Cuballing	32.833	116.983	300	504	99
8066	15	Kokardine	30.7	117.05	310	327	104
10091	16	Meckering	31.633	117.016	195	380	64
10092	17	Merredin	31.483	118.283	315	330	105
10032	18	Cowcowing	31	117.4	300	303	99
9520	19	Cape Riche	34.016	118.73	40	561	101
9534	20	Donnybrook	33.57	115.82	63	978	110
9628	21	Collie	33.36	116.15	204	988	69
9547	22	Forest Grove	34.07	115.08	60	1,141	83
9527	23	Dardanup East	33.4	115.78	40	914	81
9515	24	Busselton Shrine	33.66	115.35	4	862	71
9572	25	Halls head	32.54	115.7	366	866	92
9538	26	Dwellingup	32.71	116.06	267	1,226	80
9585	27	Nannup	33.98	115.77	100	973	62
9018	28	Gingin	31.35	115.9	92	760	67
9033	29	New Norcia	30.97	116.22	220	548	68
9009	30	Lower Chittering	31.61	116.11	113	848	59

data, a station was accepted for a year if it had less than 10% of rain days missing and less than five consecutive rain days missing (Hennessy *et al.*, 1999). Similarly, for stations with accumulated data (data which included rainfall of more than 1 day), a station was accepted for a year if it had less than 10% of accumulated rainfall and less than five consecutive accumulated rainfall records (Hennessy *et al.*, 1999).

To classify rainfall into light, medium and heavy, relative thresholds were used. The method adopted here involved ranking the rainfall data at a station in a decreasing order and dividing this ranked series into three sets such that each set contributed to 1/3 (one third) of the total rainfall. The top set was defined as heavy rainfall for the station. Similarly, the bottom one third was defined light rainfall and the remaining values in the middle were the medium rainfall for the particular station. The thresholds that separate these rainfall classes would vary from site to site, but all the three classes contribute equally to the total rainfall for all sites. Annual time series of total, light, medium and heavy rainfall were prepared for each station in the study area using this relative threshold approach.

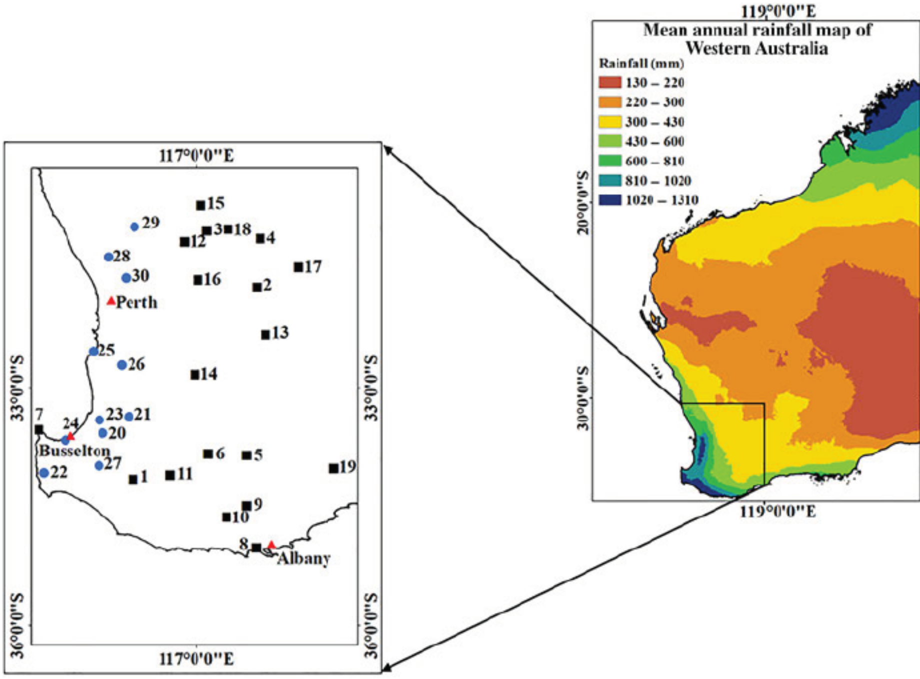

FIGURE 1 The 30 rainfall stations in South West of Western Australia considered for this study. The squares represent stations regarded as high quality stations (Lavery *et al.*, 1992; 1997), the circles represent additional stations for better spatial coverage, and the triangles represent major cities. The mean annual rainfall of Western Australia (130 1310 mm) was sourced from http://www.bom.gov.au [Colour figure can be viewed at wileyonlinelibrary.com]

To determine the trend in total rainfall and in each of the three classes, linear regression was used to quantify how rainfall (the dependent variable) varies with time (the independent variable). The slope of the regression line was taken to indicate the rate of change in rainfall, and the trend was deemed to be statistically significant based on the *p* value if the slope differs from zero. As shown in Appendix A, the sum of the rate of change for individual rainfall class equals the rate of change in the total rainfall, that is,

$$\beta_{\mathrm{r}}=\beta_{\mathrm{l}}+\beta_{\mathrm{m}}+\beta_{\mathrm{h}} \tag{1}$$

where β_{r} is the slope of the regression line for the annual rainfall, β_{l}, β_{m} and β_{h} are the slopes for light, medium and heavy rainfalls, respectively. In addition, when each of the three rainfall classes contribute equally to the total rainfall, it can be shown that the slope for individual rainfall classes is identical. In other words, we have

$$\beta_{\mathrm{l}}=\beta_{\mathrm{m}}=\beta_{\mathrm{h}}=\frac{\beta_{\mathrm{r}}}{3} \tag{2}$$

as the null hypothesis to examine how each of these rainfall components varies in time in relation to variations in the annual rainfall.

To evaluate the contribution from each rainfall class to the variation in the total rainfall, the total variation in rainfall was decomposed as the sum of covariance of light, medium and heavy rainfalls with the total rainfall as shown in Appendix B:

$$Var(T)=Cov(L,T)+Cov(M,T)+Cov(H,T) \tag{3}$$

To determine the variation in heavy rainfall for each season, time series of the total amount of heavy rainfall and the number of days with heavy rainfall for each season in each year were prepared for all the stations. The seasons considered for the analysis were summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November). Linear regression was used to determine the trend in heavy rainfall in each of the four seasons.

Pearson correlation coefficient between the site characteristics such as latitude, elevation, the mean annual rainfall and distance from the coastline and the trend in each rainfall class and that in total rainfall was used to examine the relationship between the site characteristics and the observed trends in rainfall. Latitude, elevation and the mean annual rainfall for each station were obtained from the Bureau of Meteorology website. Distance from the coastline was calculated as the shortest distance between the station and the coastline. Similarly, the correlation between SAM with the observed trend was also examined using the SAM index (source: http://www.lasg.ac.cn/staff/ljp/data-NAM-SAM-NAO/SAM(AAO).html). The SAM index is the difference between the normalized zonal MSLP at 40°S and at 65°S (Nan and Li, 2003). Linear models were developed to estimate the total and heavy rainfalls in the study area from the SAM index.

3 | RESULTS AND DISCUSSION

3.1 | Trend analysis for individual rainfall classes

Table 2 shows results from trend analysis of the three rainfall classes and the total rainfall together with the long-term average annual rainfall for the 30 stations considered in this study. The average rainfall for each class is not included in Table 2 as it is just one third of the total average rainfall. Twenty seven of the 30 stations showed a decreasing trend in total rainfall, of which 12 stations showed a significant decrease at 5% significance level. Of the 12 stations, 10 showed a significant decrease at 1% significance level. The range of the decreasing trend for total rainfall varied from 0.84 (Cape Riche) to 38.3 mm·decade^{-1} (Wilgarrup).

For three stations, namely Wilgarrup, Pardelup and Donnybrook, the significant decrease in total rainfall was accompanied by significant decreases in the light,

TABLE 2 Linear trends in the total, light, medium and heavy rainfalls (values with "†" and "††" indicate statistical significance at 5% and 1% levels, respectively)

Station	Total		Light (mm·decade^{-1})	Medium (mm·decade^{-1})	Heavy (mm·decade^{-1})
	Trend (mm·decade^{-1})	Mean rainfall (mm)			
Wilgarrup	38.3††	907.8	3.7††	10.3††	24.4††
Cuttening	2.4	307.7	0.2	0.4	1.8
Ejanding	1.5	312.5	0.4	1.1	0.1
Trayning	1.1	319.0	0.0	0.2	1.2
Broomehill	5.4	446.2	0.3	3.1†	2.1
Kojonup	14.6††	533.4	0.8	7.3††	8.1††
Cape Naturaliste	13.3††	807.4	3.5††	5.6††	4.2
Grassmere	24.0††	1,004.3	0.2	5.4†	18.4††
Kendenup	14.4†	597.8	0.9	4.9	10.4†
Pardelup	25.7††	792.2	4.5†	9.2††	12.0†
Westbourne	10.4††	687.3	1.5	3.8†	8.1††
Casuarina Vale	7.0	376.1	6.8††	1.0	0.9
Corrigin	5.8†	371.9	1.8†	0.9	3.1
Cuballing	9.4††	504.2	0.1	2.2	7.3††
Kokardine	0.9	326.7	0.2	0.6	1.3
Meckering	11.9	380.2	0.5	6.4†	5.0
Merredin	1.5	329.7	0.1	3.0††	1.5
Cowcowing	1.7	302.7	0.6	0.7	0.3
Cape Riche	0.8	561.5	6.1	0.9	6.0
Donnybrook	18.2††	977.7	4.3††	6.9††	7.1†
Collie	13.0	988.4	8.9††	9.8	5.7
Forest Grove	6.4	1,141.2	11.1††	2.8	14.7†
Dardanup East	26.1††	914.0	0.2	5.6	20.2††
Busselton Shrine	12.9	862.5	5.9†	2.5	4.5
Halls head	6.0	865.9	2.6	2.7	0.7
Dwelling up	32.7††	1,225.7	2.9	11.4†	18.5†
Nannup	0.5	973.2	6.0	1.7	7.2
Gingin	16.5	760.2	2.3	1.0	15.3†
New Norcia	12.2	548.3	7.5††	1.2	5.9
Lower Chittering	7.7	848.3	3.7	0.2	11.1

Note: The mean annual rainfall is also presented.

medium and heavy rainfalls. For seven among the 12 stations that showed a significant decreasing trend in total rainfall, the total decrease was accompanied by a significant decrease in heavy rainfall only. Similarly, for five of the 12 stations, the decrease in total rainfall was accompanied by a significant decrease in the medium rainfall and at two stations, by a significant decrease in the light rainfall. For four stations, the decrease in the total rainfall was accompanied by a decrease in both the medium and heavy rainfalls and at one station the trend in total rainfall was accompanied by a decrease in both the medium and light rainfalls. These suggested that for a majority of the stations, the decreasing trend in total rainfall has been brought about by a concurrent decrease in heavy rainfall, followed by the medium and light rainfalls. For most stations, the rate of decrease in mm·decade^{-1} relative to the average rainfall (mm) was the highest for heavy rainfall followed by the medium and light rainfalls. For example, at Wilgarrup, the heavy rainfall decreased by 8% ([24.4 mm·decade^{-1}]/[302.6 mm]), the medium rainfall decreased by 3% ([10.3 mm·decade^{-1}]/[302.6 mm]) and the light rainfall decreased by 1% ([3.7 mm·decade^{-1}]/[302.6 mm]) from their respective long-term average.

Time series of the total and the three classes of rainfall at Wilgarrup station, where all classes showed a significant decreasing trend at 1% significance level is given in Figure 2 as an example. The decreasing trend in heavy rainfall (2.43 mm·year^{-1}) was higher than the decreasing trend in medium rainfall (1.03 mm·year^{-1}), followed by the decreasing trend in light rainfall (0.37 mm·year^{-1}). Thus, the trend in heavy rainfall is the largest (63%) contributor to the decrease in total rainfall (3.83 mm·year^{-1}) at Wilgarrup.

Significant positive correlation was found between the trends in total, light, medium and heavy rainfalls for the 30 stations in SWWA (Table 3). This indicated that the decrease in the total rainfall was contributed by the decreases in all three rainfall classes, although the degree of their contribution to the decrease in total rainfall differed. The trend in the medium (0.79) and the heavy rainfalls (0.78) was highly correlated with the trend in total rainfall and the correlation was weaker (0.37) for the light rainfall. Significant correlation was also observed between the trend in the medium rainfall and that in heavy rainfall (0.40). This suggests that both these rainfall classes could be produced by similar weather systems and the decrease in rainfall might be related to a weakening of these types of weather systems.

Figure 3 shows the spatial distribution of stations with significant (at 5% significance level) and non-significant trends for all classes of rainfall and the total rainfall in the study area. It can be seen that for all rainfall classes and for total rainfall, most stations away from

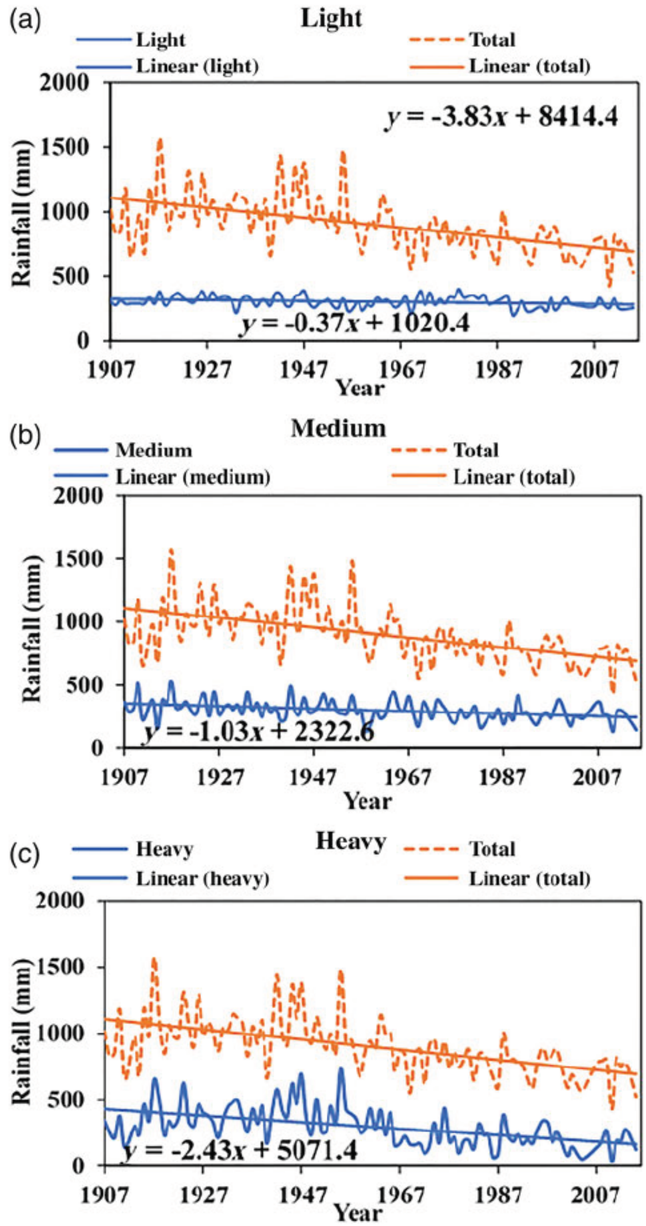

FIGURE 2 Annual time series of (a) light, (b) medium and (c) heavy rainfalls in addition to the rainfall total at Wilgarrup in South West of Western Australia [Colour figure can be viewed at wileyonlinelibrary.com]

the coastline do not exhibit a significant decrease compared to those nearer to the coastline. In addition, more than 70% of stations with a significant trend, in all rainfall classes and total rainfall, were observed to be located south of 33°S. The relationship between the trend and latitude of a station will be further discussed in Section 3.2. For the heavy and total rainfalls, 75% of the stations which exhibited a significant decreasing trend were located near the south-west corner of the study area (Figure 3a,d). Sixty percent of the stations that showed a significant decrease in the light rainfall were mostly located along the west coast of the study area (Figure 3b). For stations with a significant decreasing trend in the medium rainfall, 73% of the stations were located in the southern half of the south of the study area (Figure 3c). Similar results were obtained for winter rainfall in SWWA (Raut *et al*., 2014). Rainfall in the coastal regions of SWWA showed a significant decreasing trend and this was found to be related to the predominantly positive phase of SAM in a neutral ENSO phase resulting in reduced rainfall from the rain-bearing westerly fronts in winter months (Raut *et al*., 2014).

TABLE 3 Correlation between the trend in total rainfall and the three distinct rainfall classes (values with "†" and "††" indicates significant correlation at 5% and 1% significance level, respectively)

	Total	Light	Medium	Heavy
Total	1	0.37†	0.79††	0.78††
Light		1	0.32	0.21
Medium			1	0.40†
Heavy				1

As the rainfall was classified into three classes such that each contributed to one third of the total rainfall for each station, in an ideal case, the rate of decrease in light, medium and heavy rainfalls should also be exactly one third of the total rainfall decrease at the particular station. Our analysis showed that the rate of decline in heavy rainfall was 68% higher and the rate of decline in

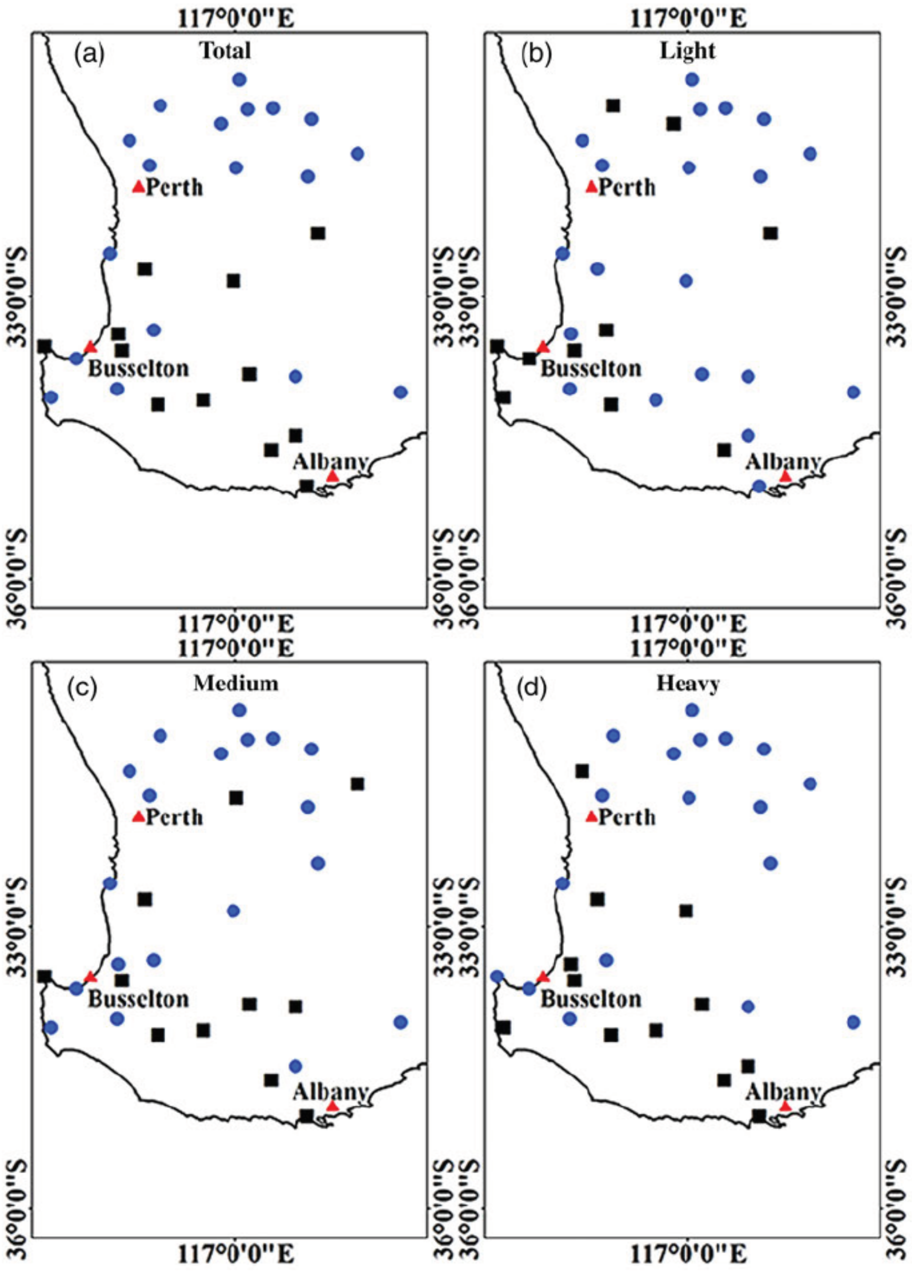

FIGURE 3 Spatial distribution of rainfall stations with significant trends in (a) total, (b) light, (c) medium and (d) heavy rainfalls (circles, squares and triangles represent stations with no significant changes, stations with significant decrease (p value < .05) and major cities, respectively) [Colour figure can be viewed at wileyonlinelibrary.com]

light rainfall was 55% lower than what was expected. The medium rainfall exhibited a trend that was closer (24%) to the expected trend compared to the other two classes. Figure 4 shows the observed trend versus expected trend (one third of the total) for three rainfall classes.

The contribution of the three rainfall classes to the total rainfall in terms of the interannual variability was computed as the sum of the covariance between the light, medium, and heavy, and the total rainfalls (Equation 3 and Appendix B) and is given in Table 4. The variation in heavy rainfall contributed to 57% of the total variation on average followed by medium and light rainfall which contributed to 30% and 13%, respectively. This shows that the interannual variation in heavy rainfall is largely responsible for the interannual variation in rainfall in SWWA. These results were congruent with the previous results shown in Figure 4, where the observed trend in heavy rainfall was higher than expected, the trend in light rainfall was lower than expected, while the observed trend in the medium rainfall was close to what was expected.

As the trend in the amount of heavy rainfall contributed most to the total trend in rainfall in SWWA compared to the other two classes, the trend in the number of days with heavy rainfall in a year and the seasonal distribution of heavy rainfall events were further examined. The average number of days with heavy rainfall in the study area ranged between 4.2 days·year^{-1} at Ejanding and 12 days·year^{-1} at Grassmere. Majority of the stations showed a decreasing trend in the number of days with heavy rainfall, of which, 12 stations showed a significant decreasing trend. All stations which had a significant decreasing trend in the amount of heavy rainfall (Table 2) also showed a significant decreasing trend (at 5% significance level) in the total number of days with heavy rainfall, except for Pardelup and Gingin. Significant decreasing trends in the total number of days with heavy rainfall were detected at Corrigin and Nannup, although there was no concurrent significant decrease in the total amount of heavy rainfall for the two sites.

The significant decreasing trend in the number of days with heavy rainfall ranged from 0.15 mm·decade^{-1} (or 3% of the average annual number of days with heavy rainfall) at Corrigin to 0.84 mm·decade^{-1} (or 8%) at Wilgarrup. It was worth noting that the significant decreasing trend in the total amount of heavy rainfall also showed a similar pattern ranging between 2% at Donnybrook and 8% at Wilgarrup. The similarity in terms of the relative magnitude of the decrease in heavy rain amount and heavy rain days suggests that weather systems associated with heavy rainfall in SWWA are weakening in both their intensity and frequency.

Since, the trend in the amount of heavy rainfall and number of days with heavy rainfall contributed most to the total decreasing trend in the study area, seasonal pattern of heavy rainfall was also examined. Patterns of the total amount of heavy rainfall and the number of heavy rain days in each season are presented in Tables 5 and 6, respectively. The results indicated that the decrease in the amount of heavy rainfall and the number of heavy rain days for most stations have occurred in winter. Fifteen stations showed a significant decreasing trend in the amount of heavy rainfall in winter and 13 stations had a significant decreasing trend in the number of heavy rain days in winter at 5% significance. In autumn, seven stations had a significant decreasing trend in the amount of heavy rainfall as well as a significant decreasing trend in the number of heavy rain days. Two stations (Nannup and Wilgarrup) had a significant decreasing trend in the amount of heavy rainfall and the number of heavy rain

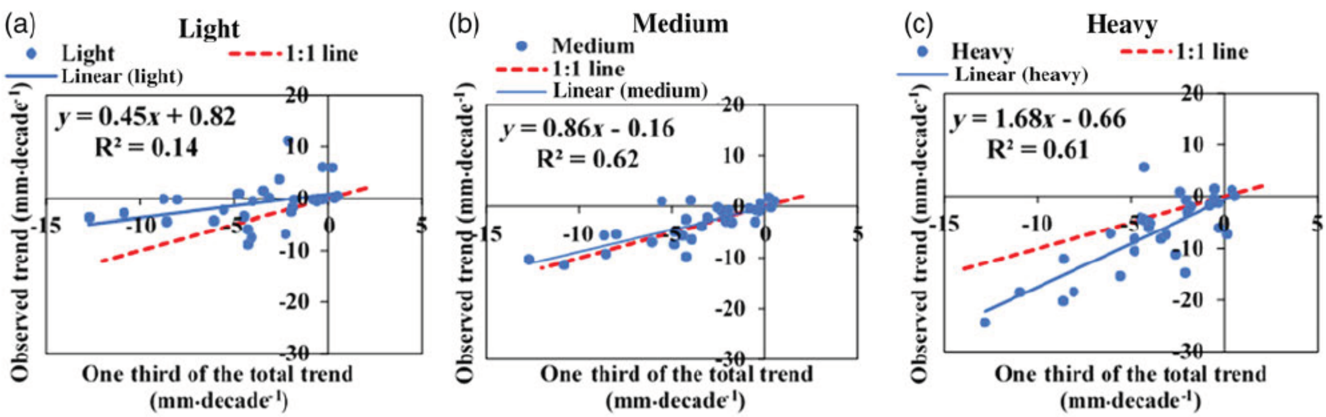

FIGURE 4 Observed versus expected trends for (a) light, (b) medium and (c) heavy rainfalls for the 30 sites selected. The dashed lines represent the expected trend [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Covariance of light (*L*), medium (*M*) and heavy (*H*) rainfalls expressed as a percentage of the variation of total rainfall

Station number	Standard deviation (mm)	*L* (%)	*M* (%)	*H* (%)
9619	207.5	9	29	63
10037	81.8	16	31	54
10045	79.5	16	23	61
10126	83.1	17	28	55
10525	93.7	15	26	60
10582	103.7	8	33	60
9519	138.0	13	29	58
9551	159.3	5	26	68
9561	110.4	9	34	56
9591	148.1	14	27	59
9616	121.4	11	29	60
10024	91.6	17	32	50
10536	85.7	15	26	59
10658	102.3	15	28	57
8066	79.9	22	24	54
10091	101.1	14	33	53
10092	80.0	19	22	59
10032	71.7	19	33	48
9520	129.9	6	22	72
9534	179.9	15	33	52
9628	191.0	14	30	56
9547	154.8	3	32	65
9527	168.8	14	30	56
9515	137.4	16	37	48
9572	151.5	7	36	56
9538	246.7	13	30	57
9585	151.5	14	32	54
9018	157.8	13	31	56
9033	135.2	15	33	52
9009	171.4	10	34	56
Average		*13*	*30*	*57*

days in spring. In summer, no stations showed a significant decrease in heavy rainfall and the number of heavy rain days. Instead, significant increases (5% significance) in heavy rainfall occurred at two sites (Broomehill and Cuballing, Table 5) and significant increases (5% significance) in the number of heavy rain days also occurred at two sites (Broomehill and Merredin, Table 6). It is interesting to note that given the overwhelming decreasing trend in rainfall and heavy rainfall, significant increases in heavy rainfall in summer have occurred at some sites in SWWA.

Broadly, it was observed that there was a decreasing trend in the amount of heavy rainfall and the number of heavy rain days in the study area during winter and autumn. In spring, around 50% of the stations had a decreasing trend in the amount and in the number of heavy rain days, while the remaining stations showed an increasing trend in heavy rainfall, although, this increasing trend was not found to be significant for any of the stations. In summer, more than 60% of the stations had an increasing trend in the amount of heavy rainfall and the number of heavy rain days. This suggested that the heavy rainfall in the predominant rainy season (winter) in SWWA was decreasing, while the heavy rainfall during the dry season (summer) was increasing. These results are consistent with the findings of Yu and Neil (1993), who reported a decrease of high-intensity rainfall in winter and an increasing trend in summer in SWWA.

TABLE 5 Linear trend in the amount heavy rainfall for all seasons (values with "†" indicate statistical significance at 5% level)

Station name	Autumn		Winter		Spring		Summer	
	Trend (mm·decade^{-1})	Mean rainfall (mm)	Trend (mm·decade^{-1})	Mean rainfall (mm)	Trend (mm·decade^{-1})	Mean rainfall (mm)	Trend (mm·decade^{-1})	Mean rainfall (mm)
Wilgarrup	−0.42†	75.20	−1.58†	164.34	−0.36†	42.85	−0.11	12.66
Cuttening	−0.08	36.43	−0.15	31.89	−0.05	10.99	0.08	23.01
Ejanding	−0.03	36.00	−0.10	36.74	0.06	9.28	0.07	21.70
Trayning	0.03	34.30	−0.04	38.20	0.09	12.93	0.01	16.61
Broomehill	−0.24†	45.19	−0.30†	56.45	0.07	24.23	0.25†	22.33
Kojonup	−0.32†	48.20	−0.55†	86.48	0.03	23.29	0.05	14.96
Cape Naturaliste	−0.13	69.39	−0.38	159.88	0.08	27.40	−0.01	6.93
Grassmere	−0.58†	90.73	−1.03†	152.80	−0.11	66.57	−0.14	17.66
Kendenup	−0.38	62.78	−0.54†	73.31	−0.16	40.92	0.04	14.89
Pardelup	−0.40	77.72	−0.74†	105.13	−0.02	53.93	−0.09	18.25
Westbourne	−0.26	62.90	−0.69†	111.44	0.00	32.16	0.02	17.13
Casuarina Vale	0.05	40.47	−0.15	53.81	0.08	8.72	0.08	21.70
Corrigin	−0.08	38.50	−0.34†	45.08	−0.08	15.78	0.23	20.14
Cuballing	−0.23†	38.56	−0.60†	90.77	−0.06	20.52	0.18†	13.58
Kokardine	−0.01	34.84	−0.17	41.86	−0.02	10.90	0.02	18.20
Meckering	−0.05	38.21	−0.55	60.65	−0.16	11.04	0.22	12.84
Merredin	0.04	37.60	−0.17†	34.80	0.06	12.89	0.16	16.63
Cowcowing	0.00	37.50	−0.14	34.09	0.09	9.83	0.02	19.03
Cape Riche	−0.50†	53.51	−0.04	62.77	−0.16	39.63	0.08	30.27
Donnybrook	−0.09	79.88	−0.58†	201.31	−0.09	33.85	−0.02	8.15
Collie	0.31	71.76	0.51	209.08	−0.24	33.67	−0.03	10.72
Forest Grove	−0.38	92.45	−1.02†	236.77	−0.03	41.55	−0.05	11.01
Dardanup East	−0.71†	77.13	−1.55†	187.39	0.06	25.53	0.07	7.58
Busselton Shrine	0.30	74.69	−0.81†	182.49	0.10	20.16	−0.06	8.90
Halls head	−0.01	74.29	−0.48	174.33	0.18	25.10	0.18	11.46
Dwelling up	0.26	89.07	−2.09†	244.73	0.09	57.72	−0.12	16.46
Nannup	0.20	80.50	−0.26	188.71	−0.51†	43.25	−0.15	9.60
Gingin	−0.21	54.51	−1.00	162.50	−0.29	26.32	0.04	7.21

(Continues)

TABLE 5 (Continued)

Station name	Autumn		Winter		Spring		Summer	
	Trend (mm·decade^{-1})	Mean rainfall (mm)	Trend (mm·decade^{-1})	Mean rainfall (mm)	Trend (mm·decade^{-1})	Mean rainfall (mm)	Trend (mm·decade^{-1})	Mean rainfall (mm)
New Norcia	−0.08	50.40	−0.32	100.97	−0.19	17.65	0.05	11.08
Lower Chittering	−0.15	62.03	−0.42	184.51	−0.42	24.53	0.20	7.02

Note The mean heavy rainfall in a year for each season is also presented.

3.2 | Relationship between site characteristics and rainfall trend

The effect of the station characteristics (latitude, elevation and the mean annual rainfall) on the observed trend total rainfall and the three intensity classes was considered using Pearson correlation analysis and the results are presented in Table 7. Initially, the distance from the coastline was also considered for the study but as the distance from the coastline and the mean annual rainfall of the study area was highly correlated (−0.85), only the mean annual rainfall was considered for further analysis. The mean annual rainfall showed a significantly negative correlation with the trend in the medium, heavy and total rainfalls. The results suggested that those stations with a high mean annual rainfall (stations near the coastline) were more likely to be associated with decreases in rainfall compared to those with a low mean annual rainfall (stations farther inland). Figure 5 shows the relationship between the mean annual rainfall and the trend in all three rainfall classes and that in the total rainfall.

Latitude was found to be significantly and positively correlated with the trend in the medium, heavy and total rainfalls. Most stations (70%) at higher latitudes (south of 33°S) showed significant trends compared to those stations at lower latitudes (Figure 3). Site elevation was found to be significantly and positively correlated with the trend in heavy rainfall only. This suggested that stations at a lower elevation are more likely to be associated with decreasing trends compared to those at a higher elevation. This can be seen from the spatial distribution of stations in Figure 3, where most of the stations with a significant decreasing trend are located towards the coast with a lower elevation compared to the stations located farther inland with a higher elevation. The decrease in the light rainfall did not show significant correlations with any site characteristics examined in this study, whereas the decrease in the medium and heavy rainfalls was significantly correlated with site location characteristics.

Using latitude, elevation and the mean annual rainfall as predictors, linear models were developed for the light, medium, heavy and total rainfalls. For the medium, heavy and total rainfalls, the models were found to be significant at 5% significance level and they were able to explain 30–40% of the variation in the dependent variables (Table 8). Latitude, elevation and the mean annual rainfall were found to be significant predictors for the medium rainfall whereas for total rainfall, the mean annual rainfall was found to be the only significant predictor. Although the linear model for heavy rainfall was significant, none of the independent variables was found to be significant predictors. Also, the model developed for the light rainfall was not significant at the 5% level. The observed trend versus

TABLE 6 Linear trend in the number of days with heavy rainfall for all seasons (values with "†" indicate statistical significance at 5% level)

Station name	Autumn		Winter		Spring		Summer	
	Trend (days·decade^{-1})	Mean no. of days	Trend (days·decade^{-1})	Mean no. of days	Trend (days·decade^{-1})	Mean no. of days	Trend (days·decade^{-1})	Mean no. of days
Wilgarrup	0.02†	2.51	0.05†	5.91	0.01†	1.64	0.00	0.38
Cuttening	0.00	1.50	0.01	1.59	0.00	0.49	0.00	0.83
Ejanding	0.00	1.34	0.01	1.74	0.00	0.43	0.00	0.71
Trayning	0.00	1.41	0.00	1.90	0.00	0.65	0.00	0.58
Broomehill	0.01†	1.98	0.01†	2.86	0.00	1.12	0.01†	0.80
Kojonup	0.01†	1.98	0.02†	4.04	0.00	1.09	0.00	0.46
Cape Naturaliste	0.00	2.41	0.01	5.80	0.00	1.07	0.00	0.22
Grassmere	0.02†	3.22	0.04†	6.00	0.00	2.68	0.00	0.59
Kendenup	0.01	2.69	0.02	3.73	0.01	2.00	0.00	0.52
Pardelup	0.01	3.03	0.03	4.75	0.00	2.42	0.00	0.66
Westbourne	0.01†	2.29	0.03†	4.73	0.00	1.42	0.00	0.55
Casuarina Vale	0.00	1.56	0.01	2.49	0.00	0.35	0.00	0.68
Corrigin	0.00	1.55	0.01†	2.09	0.00	0.73	0.00	0.56
Cuballing	0.01	1.46	0.02†	3.70	0.00	0.89	0.00	0.39
Kokardine	0.00	1.40	0.01†	1.98	0.00	0.55	0.00	0.77
Meckering	0.00	1.45	0.01	2.56	0.01	0.47	0.00	0.42
Merredin	0.00	1.49	0.01†	1.74	0.00	0.61	0.01†	0.56
Cowcowing	0.00	1.52	0.01†	1.74	0.00	0.48	0.00	0.77
Cape Riche	0.01†	1.80	0.00	2.48	0.00	1.41	0.00	0.88
Donnybrook	0.00	2.21	0.02	5.75	0.00	1.11	0.00	0.20
Collie	0.01	1.97	0.01	6.28	0.01	1.07	0.00	0.26
Forest Grove	0.01	2.78	0.03†	7.08	0.00	1.36	0.00	0.30
Dardanup East	0.02†	2.09	0.04†	5.42	0.00	0.84	0.00	0.19
Busselton Shrine	0.01	2.20	0.02	5.69	0.00	0.70	0.00	0.27
Halls head	0.00	2.18	0.01	5.26	0.01	0.85	0.00	0.23
Dwellingup	0.01	2.09	0.04†	5.91	0.00	1.51	0.00	0.30
Nannup	0.00	2.44	0.02	6.42	0.02†	1.61	0.00	0.27
Gingin	0.00	1.73	0.03	5.42	0.01	0.93	0.00	0.18
New Norcia	0.00	1.87	0.01	4.09	0.01	0.72	0.00	0.34
Lower Chittering	0.01	1.88	0.01	5.92	0.01	0.81	0.00	0.17

Note: The mean annual number of days with heavy rainfall for each season is also presented.

the modelled trend using latitude, elevation and mean annual rainfall as predictors for the total rainfall and all the classes of rainfall are shown in Figure 6.

3.3 | Correlation of SAM with rainfall

Results of Pearson correlation analysis, carried out to find possible associations between the total, light, medium and heavy rainfalls of all the stations and the SAM index, are presented in Table 9. The majority of the stations (73%) showed a negative correlation with SAM for the total rainfall. This result agreed with the findings of Feng *et al.* (2010) and Hope *et al.* (2010), which suggested an inverse relationship between SAM and winter rainfall in SWWA. Another interesting fact about the stations in the study area was that a significant decreasing trend was observed for all those

TABLE 7 Correlation between rainfall and station attributes ("†" and "††" indicate statistical significance at 5% and 1%, respectively)

Rainfall class	Latitude	Elevation	Mean annual rainfall
Light	0.18	0.18	0.03
Medium	0.55††	0.04	0.51††
Heavy	0.48††	0.44†	0.61††
Total	0.48††	0.26	0.62††

stations where the medium, heavy and total rainfalls were significantly correlated to SAM.

All five stations, for which the total rainfall showed correlation with SAM and had a significant decreasing trend in total rainfall, were found to be in the south-west corner of the study area as shown in Figure 7. In the case of the light, medium and heavy rainfalls, the stations which showed significant correlations with SAM and had a significant decreasing trend were also concentrated in this region. This region was defined by 32.25°S, 34.25°S and 116.5°E, and data for stations in this region were aggregated for further examination.

To evaluate whether SAM index could be used to predict the heavy and total rainfalls of this region, the correlation of SAM with the average rainfall in this region (highlighted in Figure 7) was computed. The annual time series of heavy and total rainfalls in the west coast region along with SAM are shown in Figure 8. The total and heavy rainfalls showed significant decreasing trends at the 5% level. SAM (1948–2010) showed a significant correlation coefficient of −0.34 with the heavy rainfall of the region and of −0.30 with the total rainfall.

Using the SAM index, linear regression models were developed, to test if the SAM index could be used to predict the heavy and total rainfalls in the highlighted region (Figure 7). It was found that the SAM index was capable of explaining 11% of the total variation in the total rainfall and 9% of the variation in the heavy rainfall at 5% level of significance (Figure 9a,b).

While significant correlations between rainfall and SAM were found for the selected region along the west coast of Western Australia (Figure 7a), there are exceptions for individual stations. For example, some stations such as Kendenup, Pardelup and Corrigin showed a significant decrease in total rainfall, although rainfall for these stations was not significantly correlated with

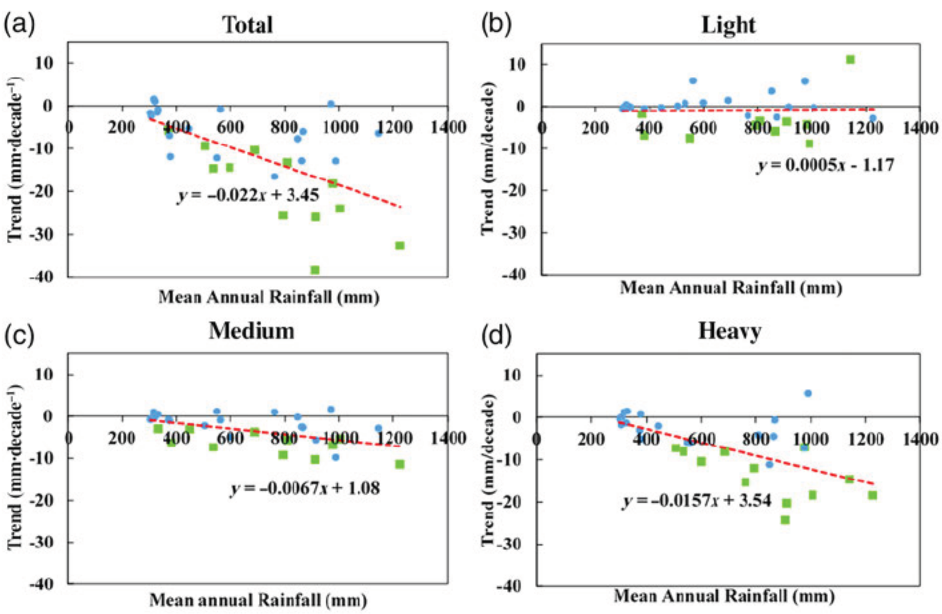

FIGURE 5 Relationship between the mean annual rainfall and the linear trend in (a) total, (b) light, (c) medium and (d) heavy rainfalls (circles and squares denote non significant and significant trend, respectively, and the dashed lines represent the trend line) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 8 Partial regression coefficients ("††" indicates statistical significance at 1%)

Rainfall class	Latitude	Elevation	Mean annual rainfall	Adjusted R^2	*p* value
Light	0.770	0.009	0.004	0.020	>0.05
Medium	1.170††	0.014††	0.007††	0.420	<0.05
Heavy	0.920	0.008	0.011	0.340	<0.05
Total	1.320	0.016	0.022††	0.350	<0.05

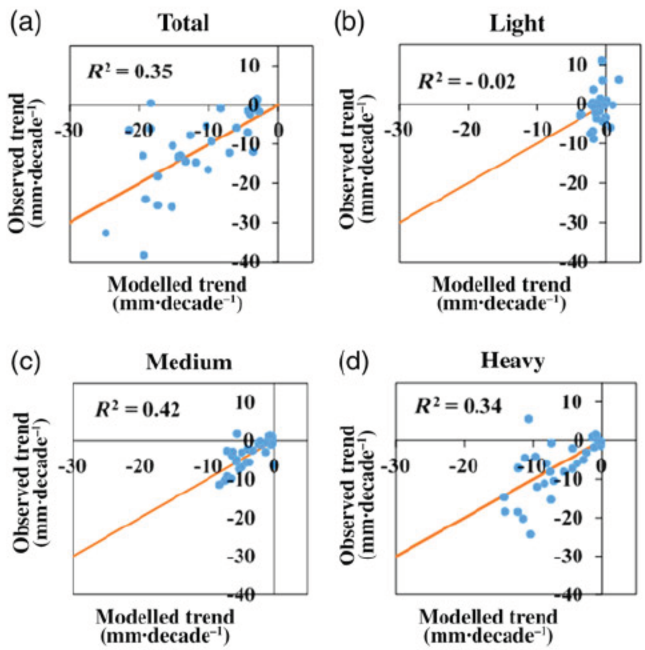

FIGURE 6 Observed trend versus modelled trend using latitude, elevation and mean annual rainfall as predictors for (a) total, (b) light, (c) medium and (d) heavy rainfalls. The straight line indicates the 1:1 line [Colour figure can be viewed at wileyonlinelibrary.com]

SAM. This indicated that the variability in rainfall in this region was not entirely and consistently dependent on the SAM.

Previous studies in SWWA investigated the annual and seasonal patterns in rainfall (Choudhury *et al*., 2015) as well as the pattern of extreme rainfall using other methods of classification such as the peak over threshold method (Li *et al*., 2005; Aryal *et al*., 2009). This study used a different method to classify rainfall as light, medium and heavy rainfalls. The results showed that the major contributor to the decrease in total annual rainfall was heavy rainfall followed by medium and light rainfalls. The results agreed with the previous findings in the study area (Hennessy *et al*., 1999; Haylock and Nicholls, 2000). This study also examined the contribution of each rainfall class to the total annual variation in rainfall in SWWA, showing the larger contribution of heavy rainfall to the total rainfall variability. The study also revealed the larger decline of the heavy rainfall in SWWA, compared to the other two classes considered in this study. The decrease in heavy rainfall was found to be mainly during winter and autumn while in summer it showed an increasing trend. This seasonal pattern of heavy rainfall is consistent with the findings of Yu and Neil (1993), which suggested a decrease in high-intensity rainfall in winter and an increase in summer. A significant correlation was observed between the trend in rainfall classes and the local site characteristics and the SAM, indicating the influence of these factors on the observed trend in rainfall of SWWA. SAM showed significant negative correlation to total and heavy rainfalls in the west coast of the study area which agrees with the findings of previous studies regarding the inverse relationship between SAM and winter rainfall in SWWA (Feng *et al*., 2010; Hope *et al*., 2010).

The larger rate of decline in heavy rainfall in the study area explains the marked lowering of water levels in the dams of this region as it is the heavy rainfall which causes runoff and inflow to dams. The results also indicate the significant weakening of the precipitation mechanisms or weather drivers causing heavy rainfall in this region.

4 | CONCLUSIONS

The contributions of different rainfall classes to the decline in the total rainfall were examined using daily rainfall data from 30 stations in SWWA. Twelve, ten, eleven and twelve stations showed a significant decreasing trend in the total, light, medium and heavy rainfalls, respectively. The trends in all three rainfall classes were found to have significant positive correlation with the trend in the total rainfall, indicating that all three classes contributed to the overall decrease in rainfall in the region. The trends in the medium and heavy rainfalls

TABLE 9 Correlation between rainfall and SAM

	SAM			
Coefficient range	Light	Medium	Heavy	Total
0.6 to 0.31	5	1	5	3
0.30 to 0	12	21	15	19
0 to 0.30	12	8	10	8
0.31 to 0.6	1	0	0	0
No. of stations with significant correlation ($p < .05$)	4	1	6	5

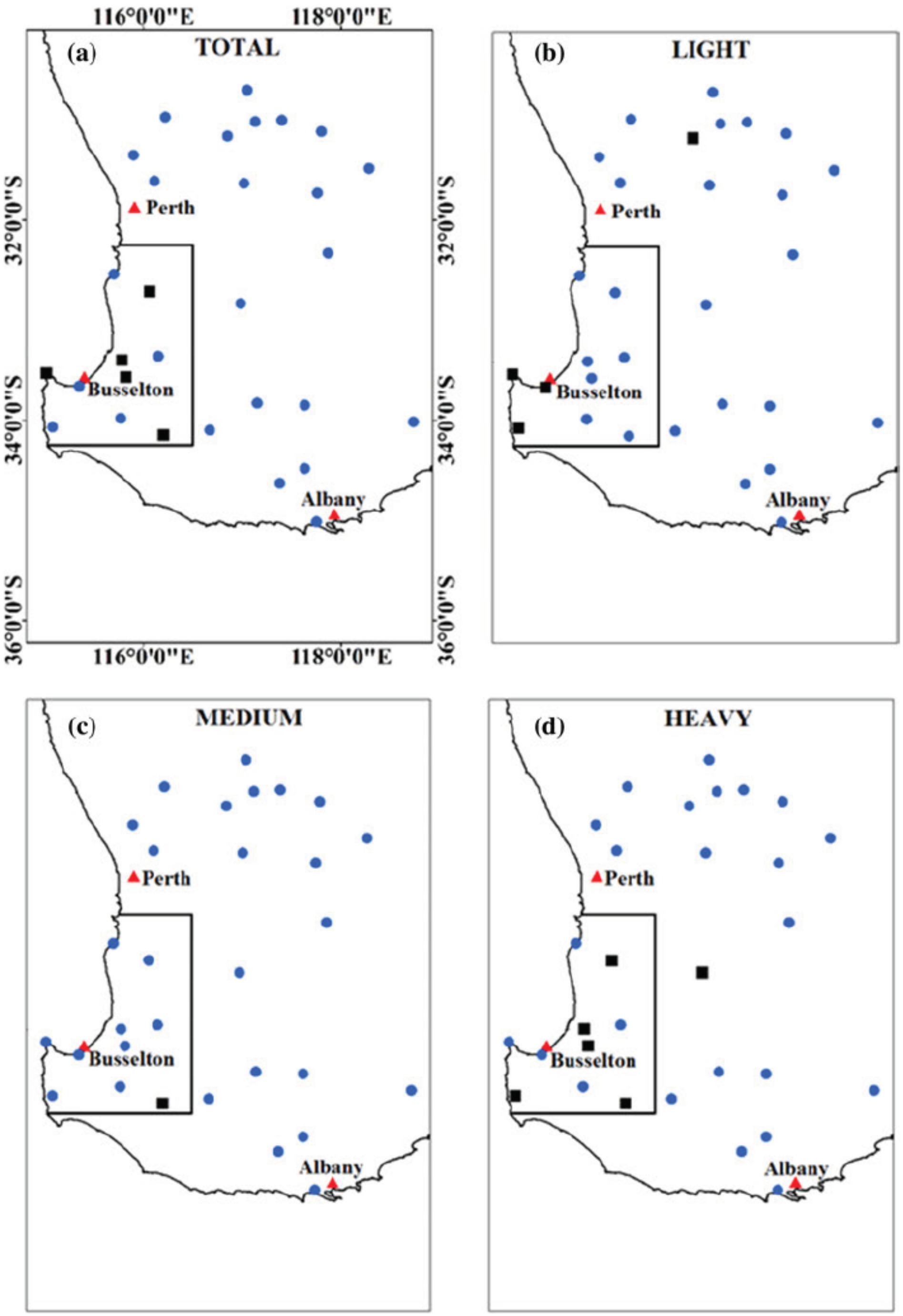

FIGURE 7 Location of stations with significant correlations with SAM in (a) total, (b) light, (c) medium and (c) heavy rainfalls. Squares represent stations with significant correlation with SAM and circles represent stations with non significant correlations. The highlighted area is the region along the west coast where the sites, which showed significant correlations with both SAM and had significant decreasing trend, were more concentrated than elsewhere in the study area [Colour figure can be viewed at wileyonlinelibrary.com]

were highly (0.78) correlated with the total trend compared to the correlation of trends in light rainfall with the total rainfall (0.37).

The decomposition analysis of the variation in the annual rainfall for the 30 stations showed that the variation in the heavy rainfall was the major contributor (57%) to the variation in the total rainfall, followed by the variation in the medium (30%) and light rainfalls (13%). Similar conclusions were supported given that more stations showed concurrent decreases in the heavy and total rainfalls, while there are fewer stations with concurrent decreases in both the light and total rainfalls in the study area. The rate of decrease in the heavy rainfall was 68% higher than the expected one third of the rate of decrease in the total rainfall and the rate of decrease in the light rainfall was 55% lower than the expected. The rate of decrease in medium rainfall was quite close to the expected rate. Majority of the stations which showed a significant decreasing trend in the amount of heavy rainfall also showed a significant decrease in the number of heavy rain days. The seasonal trend analysis of heavy rainfall indicated a significant decreasing trend in the amount of heavy rainfall and the number of

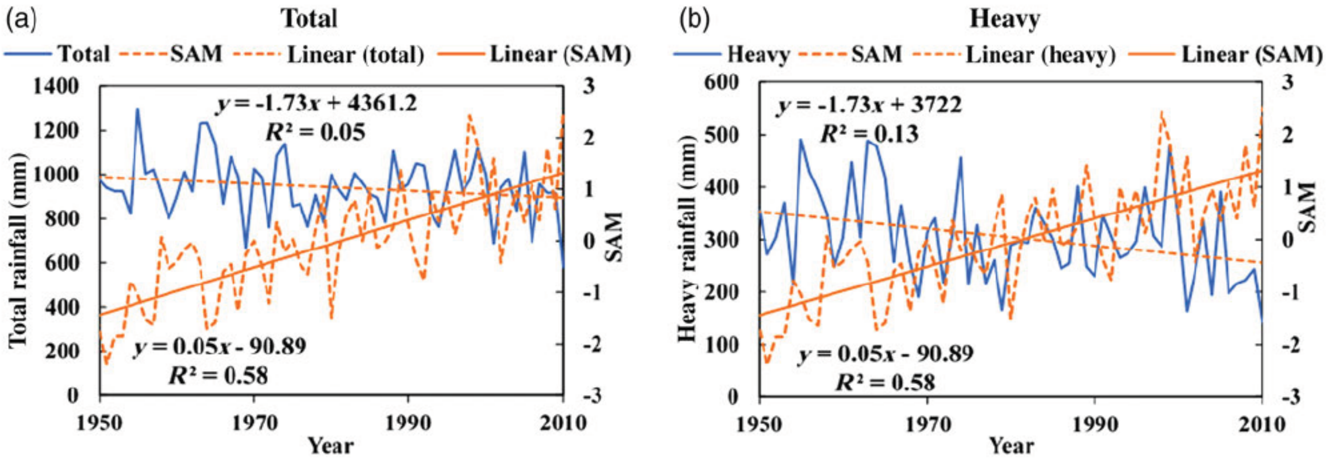

FIGURE 8 Annual variation in SAM and (a) total and (b) heavy rainfalls [Colour figure can be viewed at wileyonlinelibrary.com]

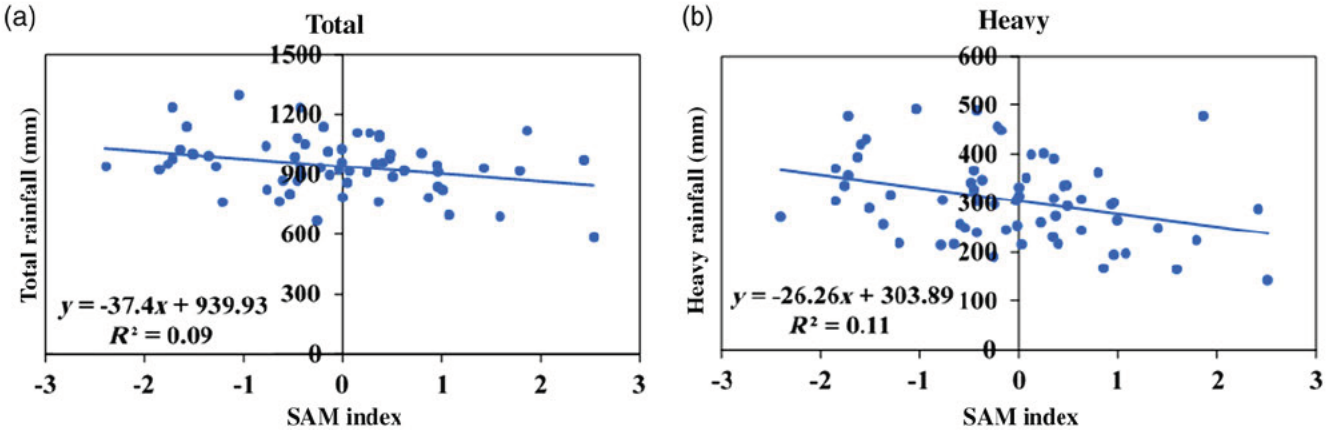

FIGURE 9 The relationship between SAM and (a) annual total rainfall and (b) annual heavy rainfall for the west coastal region in SWWA as defined in Figure 7 [Colour figure can be viewed at wileyonlinelibrary.com]

heavy rain days in winter and autumn and for some stations an increasing trend in summer.

The observed trends in the total, medium and heavy rainfalls were found to be related to the mean annual rainfall, latitude and elevation. Majority of the stations which exhibited significant decreasing trends were those with a high mean annual rainfall and located near the coastline. It was also observed that more than 70% of stations with significant trends for all three rainfall classes and the total rainfall were located south 33°S latitude. Stations at a lower elevation were more likely to have a significant decreasing trend compared to the stations at a higher elevation. Trends in the light rainfall were not significantly correlated with any of the site characteristics examined.

The rainfall in the region showed significant negative correlation with the large scale circulation pattern, the SAM. All stations with significant correlation between SAM and the medium, heavy and total rainfalls showed a significant decreasing trend for these rain classes. The stations showing a significant decreasing trend in the total, light, medium and heavy rainfalls as well as significant correlation between these rainfall classes and SAM were all concentrated along the west coast of the study area. The linear models developed using the SAM index as a predictor for the total and heavy rainfalls of the west coast region of SWWA were able to explain 11% of the variation in total rainfall and 9% of the variation in heavy rainfall.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Griffith University for the financial support provided through the Griffith University International Postgraduate Research Scholarship (GUIPRS) and the Griffith University Postgraduate Research Scholarship (GUPRS). The authors of the paper have no conflict of interest to declare. The authors also thank the reviewers for their valuable suggestions which helped in improving the quality of this paper.

ORCID

Bofu Yu https://orcid.org/0000-0001-7266-4197

REFERENCES

Akinsanola, A.A. and Ogunjobi, K.O. (2017) Recent homogeneity analysis and long term spatio temporal rainfall trends in Nigeria. *Theoretical and Applied Climatology*, 128(1 2), 275 289. https://doi.org/10.1007/s00704 015 1701 x

Alexander, L.V. and Arblaster, J.M. (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *International Journal of Climatology*, 29, 417 435. https://doi.org/10.1002/joc.1730

Ansell, T.J., Reason, C.J.C., Smith, I.N. and Keay, K. (2000) Evidence for decadal variability in southern Australian rainfall and relationships with regional pressure and sea surface temperatures. *International Journal of Climatology*, 20, 1113 1129.

Aryal, S.K., Bates, B.C., Campbell, E.P., Li, Y., Palmer, M.J. and Viney, N.R. (2009) Characterizing and modeling temporal and spatial trends in rainfall extremes. *Journal of Hydrometeorology*, 10(1), 241 253. https://doi.org/10.1175/2008JHM1007.1

Bates, B.C., Chandler, R.E., Charles, S.P. and Campbell, E.P. (2010) Assessment of apparent nonstationarity in time series of annual inflow, daily precipitation, and atmospheric circulation indices: a case study of south west Western Australia. *Water Resources Research*, 46, W00H02. https://doi.org/10.1029/2010WR009509

Bavil, S.S., Zeinalzadeh, K. and Hessari, B. (2018) The changes in the frequency of daily precipitation in Urmia Lake basin, Iran. *Theoretical and Applied Climatology*, 133(1 2), 205 214. https://doi.org/10.1007/s00704 017 2177 7

Choudhury, R.K., Beecham, S., Boland, J. and Piantadosi, J. (2015) Understanding south Australian rainfall trends and step changes. *International Journal of Climatology*, 35, 348 360. https://doi.org/10.1002/joc.3982

Dore, M.H. (2005) Climate change and changes in global precipitation patterns: what do we know? *Environment International*, 31 (8), 1167 1181.

Feng, J., Li, J., Li, Y., Zhu, J. and Xie, F. (2015) Relationships among the monsoon like southwest Australian circulation, the southern annular mode, and winter rainfall over Southwest Western Australia. *Advances in Atmospheric Sciences*, 32, 1063 1076. https://doi.org/10.1007/s00376 014 4142 z

Feng, J., Li, J.P. and Li, Y. (2010) Is there a relationship between the SAM and Southwest Western Australian winter rainfall? *Journal of Climate*, 23, 6082 6089. https://doi.org/10.1175/2010JCLI3667.1

Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E., Oerlemans, J., Salinger, M.J. and Wang, S.W. (2001) Observed climate variability and change. *Climate change, 2001, The Scientific Basis Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 99 181, Cambridge Univ. Press, New York.

Fu, G., Viney, N.R., Charles, S.P. and Liu, J. (2010) Long term temporal variation of extreme rainfall events in Australia: 1910 2006. *Journal of Hydrometeorology*, 11, 950 965. https://doi.org/10.1175/2010JHM1204.1

Gallant, A.J.E., Hennessy, K.J. and Risbey, J. (2007) Trends in rainfall indices for six Australian regions: 1910 2005. *Australian Meteorological Magazine*, 56, 223 239.

Haylock, M. and Nicholls, N. (2000) Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910 1998. *International Journal of Climatology*, 20, 1533 1541.

Hennessy, K.J., Suppiah, R. and Page, C.M. (1999) Australian rainfall changes, 1910 1995. *Australian Meteorological Magazine*, 48, 1 13.

Heyhoe, E., Kim, Y., Kokic, P., Levantis, C., Ahammad, H., Schneider, K., Crimp, S., Nelson, R., Flood, N. and Carter, J. (2007) Adapting to climate change issues and challenges in the agriculture sector. *Australian Commodities: Forecasts and Issues*, 14, 167.

Hope, P., Timbal, B. and Fawcett, R. (2010) Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. *International Journal of Climatology*, 30, 1360 1371.

Hope, P.K. (2006) Projected future changes in synoptic systems influencing Southwest Western Australia. *Climate Dynamics*, 26, 765 780. https://doi.org/10.1007/s00382 006 0116 x

Lavery, B., Joung, G. and Nicholls, N. (1997) An extended high quality historical rainfall dataset for Australia. *Australian Meteorological Magazine*, 46(1), 27 38.

Lavery, B., Kariko, A. and Nicholls, N. (1992) A historical rainfall data set for Australia. *Australian Meterological Magazine*, 40, 33 39.

Li, Y., Cai, W. and Campbell, E.P. (2005) Statistical modeling of extreme rainfall in Southwest Western Australia. *Journal of Climate*, 18(6), 852 863. https://doi.org/10.1175/JCLI 3296.1

Loo, Y.Y., Billa, L. and Singh, A. (2015) Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, 6(6), 817 823.

McGree, S., Whan, K., Jones, D., Alexander, L.V., Imielska, A., Diamond, H., et al. (2014) An updated assessment of trends and variability in total and extreme rainfall in the western Pacific. *International Journal of Climatology*, 34(8), 2775 2791. https://doi.org/10.1002/joc.3874

Mills, T.C. (2016) Modelling rainfall trends in England and Wales. *Cogent Geoscience*, 2(1), 1133218. https://doi.org/10.1080/23312041.2015.1133218

Murphy, B.F. and Timbal, B. (2008) A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology*, 28(7), 859 879. https://doi.org/10.1002/joc.1627

Nan, S. and Li, J. (2003) The relationship between the summer precipitation in the Yangtze River valley and the boreal spring southern hemisphere annular mode. *Geophysical Research Letters*, 30(24), 2266. https://doi.org/10.1029/2003GL018381

Nicholson, S.E., Funk, C. and Fink, A.H. (2018) Rainfall over the African continent from the 19th through the 21st century. *Global and Planetary Change*, 165, 114 127.

Pittock, A.B. (1983) Recent climatic change in Australia: implications for a CO_2 warmed earth. *Climatic Change*, 5(4), 321 340. https://doi.org/10.1007/BF02423529

Raut, B.A., Jakob, C. and Reeder, M.J. (2014) Rainfall changes over southwestern Australia and their relationship to the southern annular mode and ENSO. *Journal of Climate*, 27(15), 5801 5814. https://doi.org/10.1175/JCLI D 13 00773.1

Samuel, J.M., Verdon, D.C., Sivapalan, M. and Franks, S.W. (2006) Influence of Indian Ocean Sea surface temperature variability on Southwest Western Australian winter rainfall. *Water Resources Research*, 42(8), W08402. https://doi.org/10.1029/2005WR004672

Smith, I. (2004) An assessment of recent trends in Australian rain fall. *Australian Meteorological Magazine*, 53(3), 163 173.

Smith, I.N., McIntosh, P., Ansell, T.J., Reason, C.J.C. and McInnes, K. (2000) Southwest Western Australian winter rain fall and its association with Indian Ocean climate variability. *International Journal of Climatology*, 20(15), 1913 1930.

Steffen, W., Hughes, L. and Pearce, A. (2015) *Climate change 2015: Growing risks, critical choices*. Climate Council of Australia, Sydney.

Suppiah, R. and Hennessy, K.J. (1998) Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910 1990. *International Journal of Climatology*, 18(10), 1141 1164. https://doi.org/10.1002/(SICI)1097 0088(199808)18:10<1141::AID JOC286>3.0.CO;2 P

Wright, P.B. (1974) Seasonal rainfall in southwestern Australia and the general circulation. *Monthly Weather Review*, 102(3), 219 232. https://doi.org/10.1175/1520 0493(1974)102<0219:SRISAA>2.0.CO;2

Yu, B. and Neil, D.T. (1993) Long term variations in regional rain fall in the south west of Western Australia and the difference between average and high intensity rainfalls. *International Journal of Climatology*, 13(1), 77 88. https://doi.org/10.1002/joc.3370130106

How to cite this article: Philip P, Yu B. Interannual variations in rainfall of different intensities in South West of Western Australia. *Int J Climatol*. 2019;1–20. https://doi.org/10.1002/joc.6382

APPENDIX A

RATE OF CHANGE IN TOTAL RAINFALL EXPRESSED AS THE SUM OF THE RATE OF CHANGES IN LIGHT, MEDIUM AND HEAVY RAINFALLS

The equations for annual, light, medium and heavy rainfalls are given by

$$Y_r=\alpha_r+\beta_r t \tag{A1}$$

$$Y_l=\alpha_l+\beta_l t \tag{A2}$$

$$Y_m=\alpha_m+\beta_m t \tag{A3}$$

$$Y_h=\alpha_h+\beta_h t \tag{A4}$$

where Y_r, Y_l, Y_m and Y_h are the annual total rainfall, annual light rainfall, annual medium rainfall and annual heavy rainfall at a particular station, respectively. β_r, β_l, β_m and β_h are the slopes of total, light, medium and heavy rainfalls and α_r,α_l, α_m and α_h are the respective intercepts. It can be shown that the rate of change in total rainfall (β_r) is the sum of the rates of change in light (β_l), medium (β_m) and heavy rainfalls (β_h) as demonstrated below.

The slope of the regression equation is given by

$$\beta 1=\frac{\sum_{i=1}^{n}(x_i y_i)-n\bar{x}_i\bar{y}_i}{\sum_{i=1}^{n}(x_i^2)-n\bar{x}_i{}^2} \tag{A5}$$

In this case x_i is the time, t, and let the mean of time be $\bar{t}$. Also, let the mean of total, light, medium and heavy rainfalls be denoted as $\bar{Y}_r$, $\bar{Y}_l$, $\bar{Y}_m$ and $\bar{Y}_h$.

$$\begin{aligned}\beta_l+\beta_m+\beta_h &= \frac{\sum(tY_l)-n\bar{t}\bar{Y}_l+\sum(tY_m)-n\bar{t}\bar{Y}_m+\sum(tY_h)-n\bar{t}\bar{Y}_h}{\sum t^2-n\bar{t}^2}\\ &=\frac{\sum t(Y_l+Y_m+Y_h)-n\bar{t}(\bar{Y}_l+\bar{Y}_m+\bar{Y}_h)}{\sum t^2-n\bar{t}^2}\end{aligned}$$

But $Y_l + Y_m + Y_h = Y_r$ and $\bar{Y}_l+\bar{Y}_m+\bar{Y}_h=\bar{Y}_r$

$$\beta_l+\beta_m+\beta_h=\frac{\sum tY-n\bar{t}\bar{Y}_r}{\sum t^2-n\,\bar{t}^2}$$

the right hand side of the equation is β_r, the slope of total rainfall.

APPENDIX B

VARIATION IN TOTAL RAINFALL EXPRESSED AS THE SUM OF COVARIANCE OF LIGHT, MEDIUM, HEAVY AND TOTAL RAINFALLS

$$T_i=L_i+M_i+H_i \tag{A6}$$

$$\bar{T}=\bar{L}+\bar{M}+\bar{H} \tag{A7}$$

By definition,

$$Var(T) = \sum (T_i - \bar{T})^2 = \sum T_i^2 - N\bar{T}^2 \tag{A8}$$

$$Cov(L,T) = \sum (L_i - \bar{L})(T_i - \bar{T}) = \sum L_i T_i - N\bar{L}\bar{T} \tag{A9}$$

Similarly,

$$Cov(M,T) = \sum M_i T_i - N\bar{M}\bar{T} \tag{A10}$$

$$Cov(H,T) = \sum H_i T_i - N\bar{H}\bar{T} \tag{A11}$$

Therefore, we have

$$\begin{aligned} Cov(L,T) + Cov(M,T) + Cov(H,T) &= \sum T_i(L_i + M_i + H_i) \\ &\quad - N\bar{T}(\bar{L} + \bar{M} + \bar{H}) \\ &= \sum T_i^2 - N\bar{T}^2 = Var(T) \end{aligned} \tag{A12}$$

where T_i is the total annual rainfall for a station which is the sum of annual light (L_i), medium (M_i) and heavy (H_i) rainfalls. Also, the mean annual rainfall ($\bar{T}$) is the sum of mean annual light ($\bar{L}$), medium ($\bar{M}$) and heavy ($\bar{H}$) rainfalls.