UNIVERSITY OF KWAZULU-NATAL

THE CONTRIBUTION OF FOG TO THE WATER BALANCE ALONG THE EASTERN ESCARPMENT OF SOUTH AFRICA

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Environmental Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Agricultural Campus, South Africa. The research was financially supported by DST-NRF and the Water Research Commission (WRC) of South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: ………………..
Tiffany Aldworth

Supervisor: ………………..	Co-supervisor: ………………..
Dr Michele L. Toucher	Dr Alistair D. Clulow

DECLARATION 1: PLAGIARISM

I, **Tiffany A Aldworth**, declare that:

- (i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;
- (ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;
- (iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;
- (iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    - a) their words have been re-written but the general information attributed to them has been referenced;
    - b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;
- (v) where I have used material for which publications followed, I have indicated in detail my role in the work;
- (vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;
- (vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: ………………..

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DECLARATION 2: PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part of/or include research presented in this dissertation (including publications submitted and published, giving details of the contributions of each author to the research and writing each publication):

Publication 1 – Chapter 2 of this dissertation
Aldworth TA, Toucher ML, Clulow AD. 2016. Temporal and spatial variations of fog along the eastern escarpment of South Africa.

The analysis for this publication was conducted by TA Aldworth with technical advice from ML Toucher and AD Clulow. The publication was written in its entirety by TA Aldworth and all figures, tables and graphs were produced by the same unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by ML Toucher and AD Clulow.

Publication 2 – Chapter 3 of this dissertation
Aldworth TA, Toucher ML, Clulow AD. 2016. The contribution of fog to the water balance of a commercial forestry plantation situated in the KwaZulu-Natal Midlands, South Africa.

The analysis for this publication was conducted by TA Aldworth with technical advice from ML Toucher and AD Clulow. The publication was written in its entirety by TA Aldworth and all figures, tables and graphs were produced by the same unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by ML Toucher and AD Clulow.

ABSTRACT

Fog is a frequent phenomenon in South Africa, occurring mostly on the west coast and along the mountains forming the southern and eastern escarpments. Fog measurements are, however, neglected in water balance studies, resulting in an underestimate of the precipitation input to catchments that experience frequent fog occurrences. World-wide, tropical montane cloud forest (TMCF) studies have proven that fog deposition, facilitated via the interception of fog droplets by vegetation, can represent a significant fraction of the total hydrological input. In South Africa, limited literature exists on the contribution of fog to the country's water yielding catchments. In particular, information on fog patterns and its contribution to the water balance is extremely scarce in the mountains forming South Africa's eastern escarpment, where only one study has been previously conducted. Additionally, no forestry studies in the country have attempted to quantify fog. Thus, the aim of this study was to determine the contribution of fog to the water balance of two research catchments of different land use types and altitudes, situated along South Africa's eastern escarpment. These sites included the Cathedral Peak research catchments and Two Streams; Cathedral Peak is a high altitude montane grassland catchment, whereas Two Streams is at a lower altitude and afforested by exotic plantations. At Two Streams, fog and the climatic conditions were monitored over a 16-month period (July 2015 to October 2016) and additional measurements of throughfall, stemflow and soil water content were carried out in an *Acacia mearnsii* plantation, to further determine the fog contribution in a forest plantation. At the Cathedral Peak research catchments, fog and the climatic conditions were monitored at three sites, including Mike's Pass Meteorological Station, Catchment VI and a High Altitude site. Monitoring was conducted over a 14-month period (September 2015 to October 2016) at Mike's Pass and over a two-month period (August 2015 to September 2015) at Catchment VI and the High Altitude site. Fog was found to be prevalent, occurring frequently and for long durations, potentially contributing fairly substantial amounts of water to the water balance. It occurred all year round, but was predominantly a summer phenomenon, however, it comprised a greater proportion of the total precipitation during the dry winter season. At Mike's Pass, fog represented a contribution of almost 30 % during several drier months. At Two Streams, during the driest month of August 2015, fog represented a contribution of approximately 38 % of the total precipitation. Fog increased with altitude as a whole, but changes in other topographic features (i.e. hillslope orientation and slope) over short distances, meant that the delivery of fog was not uniform from one point to another at the same altitude. Fog occurrence and water yield increased with wind speed, although this was not found to be a very significant relationship. A stronger relationship between wind direction and fog was observed, particularly at Mike's Pass, the higher altitude site, which was better exposed to fog-bearing winds. At Two Streams, fog did not facilitate throughfall of rainfall or contribute to soil water. The indirect effects of limiting wet canopy evaporation and transpiration rates were suggested to be a more relevant effect of fog on the water balance. These findings further the understanding of the contribution of fog to the water balance along the eastern escarpment of South Africa and will assist in future long-term climatological studies of fog and low cloud occurrence in the region.

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I would like to sincerely acknowledge the following:

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CHAPTER 1: INTRODUCTION

1.1 Research Rationale and Motivation

Fog is essentially a cloud in the vicinity of the earth's surface, comprising of an aggregate of microscopic water droplets suspended in the air (Herschy and Fairbridge, 1999; Klemm *et al.*, 2012; Degefie *et al*., 2015). Its formation occurs when the air contains sufficient moisture and there is a process of cooling and/or lifting (Croft, 2003). The air temperature cools until it equals the dew point temperature, which is followed by the condensation of water vapour, resulting in the formation of fog (Herschy and Fairbridge, 1999; Glickman, 2000; Fessehaye *et al.*, 2014). Various types of fog exist, classified according to their location of occurrence and by the processes of their formation (i.e. radiation, sea, steam and advection fog) and based on geographical terms (i.e. coastal, valley and orographic fog) (Fessehaye *et al*., 2014; Degefie *et al*., 2015). Fog also commonly occurs when a low-lying stratus cloud intersects the ground surface (Carbone *et al*., 2013; Degefie *et al*., 2015). Dominant fog types differ substantially between different land uses and terrains and a combination of fog types may occur in a region, with no one type dominating (Olivier, 2002; Akimoto and Kusaka, 2015).

Fog is a frequent phenomenon in South Africa, occurring mostly on the west coast and along the mountains forming the southern and eastern escarpments (Kotzé, 2014). However, studies conducted in the country's water yielding catchments only consider the precipitation that can be measured with the standard rain gauge, such as rain, drizzle and snow, in their annual water balances. This usually produces satisfactory results, but where fog episodes and low-level cloud cover occur frequently, this absence of incorporating fog as a form of precipitation, may result in an underestimate of the water input (Schemenauer and Cereceda, 1994). Thus, fog should be quantified before an accurate prediction of the surface water balance can be carried out (Katata *et al*., 2010).

A number of fog studies have been conducted in South Africa, most of which have looked at the potential of fog water harvesting for domestic use and small-scale farming (Louw *et al.*, 1998). In terms of fog as a hydrological factor, some of the world's earliest scientific fog publications have been produced on Table Mountain's renowned "tablecloth" (Fessehaye *et al*., 2014; Kotzé, 2014). In 1905, Dr Rudolf Marloth conducted a fog experiment in which he measured the amount of fog water intercepted by the vegetation on Table Mountain, using two rain gauges, one standard rain gauge and one with reed bundles suspended above, to catch horizontally windblown fog droplets (Marloth, 1905). He discovered that the gauge with the reed bundles measured considerably more water than that measured by the standard rain gauge (Nagel, 1956). Subsequent to Marloth's experiment, a number of fog studies have been conducted in the Table Mountain area, including those by Nagel (1956), Snow (1985), and in more recent years, South Africa's Earth Observation Network (SAEON) of the Fynbos Node (de Buys, 2014). SAEON have investigated the influence of fog on fynbos vegetation at two high elevation sites, namely, the Table Mountain National Park and the Jonkershoek Nature Reserve. They measured fog using brass mesh cylindrical fog gauges, and over a study period of a year, they found that it averaged approximately 100 mm per month at both of the sites. During dry months, fog was shown to be the dominant form of precipitation, representing up to 86 % (153 mm) of the total water input. At the Jonkershoek high elevation site, SAEON measured 1234 mm of fog in the absence of rainfall over a one-year period, which was almost a third of what the raingauge measured (de Buys, 2014; Kotzé, 2014). On the country's eastern escarpment, only one hydrological study has been conducted. This study was completed by Schmidt and Schulze (1989) in the Cedara Catchments, Kwazulu-Natal Midlands. Schmidt and Schulze (1989) measured fog over a period of 11 years at seven sites, ranging in altitude between 1058 m.a.s.l and 1445 m.a.s.l. Fog was found to be predominantly a summer phenomenon, occurring mostly in the wet season months. Additionally, it was found that higher sites were more affected by fog, with fog yields being directly proportional to altitude. At their highest station, the fog gauge measured an average of over 2500 mm of fog and wind driven rainfall per annum, which was twice that caught by the rain gauge. Schmidt and Schulze (1989) even suggested that fog could deposit onto the soil at the sites situated at higher elevations.

Most international research regarding fog has been conducted in tropical montane cloud forests (TMCF). Researchers have recognised that fog water deposition, facilitated via the interception of fog droplets by vegetation, is an important hydrological input to the water balance of these ecosystems, particularly those in arid environments (Holder, 2004; Prada *et al*., 2009; Ebner *et al*., 2011). It has also been acknowledged that fog indirectly contributes to the water balance of TMCF's, due to the fact that its occurrence results in decreased air temperatures, vapour pressure deficit and insolation, thus moderating evaporation from the soil and transpiration losses during photosynthesis (Yin and Arp, 1994; Dawson, 1998; Keppeler, 2007; Klemm *et al*., 2012; Carbone *et al*., 2013). Attempts to measure fog in TMCF's have been conducted for many years, with reports of varying proportions of fog contributing to their annual water inputs (Ritter *et al*., 2008). The majority of studies found that fog represented a significant fraction of the total hydrological input. One of the world's most extensively-studied ecosystems includes the coastal redwood forests of northern California, where Dawson (1998) found that there was on average 447 mm of fog drip or throughfall each year, equating to over one-third of the total precipitation input. On the extreme high end of reported values, a study of a montane forest on Madeira Island in Portugal measured 5100 mm of fog per year, representing a 73 % contribution (Prada *et al.*, 2009). This study, as well as another study conducted in Guatemala by Holder (2004), found significant fog contributions to soil water and even reported evidence of groundwater recharge by fog. Several sites have, however, found fog contributions to be insignificant and one study, conducted in an elfin cloud forest on the Luquillo Mountains of north-eastern Puerto Rico, even suggested the indirect effects of fog at the site to be more important than fog deposition (Eugster *et al*., 2006). These studies concur that fog tends to exhibit high temporal and spatial variability (Hansen and Juvik, 2010). Temporally, fog was found to vary greatly between wet and dry seasons, with fog episodes being more frequent, persisting for longer durations and containing greater amounts of water in dry seasons when rainfall is low (Liu *et al*., 2004; Marzol, 2008; Ponette-González *et al*., 2010). Spatially, mountainous areas were found to be more affected by fog compared to low-lying areas (Shimadera *et al*., 2008).

Rainfall is evidently not the only source of precipitation contributing to the water balance of fog-affected ecosystems. This has been proven by studies conducted in TMCF's all over the world that have, for the most part, found the fog input to be significant. This is shown by two studies even reporting evidence of groundwater recharge by fog. There is, therefore, a strong argument for understanding, and including in the water balance, the additional moisture intercepted by vegetation in fog-affected ecosystems. In South Africa, fog occurs frequently, however, limited literature exists on the contribution of fog to the country's water yielding catchments. The studies that have been conducted in the country all agreed that fog contributed significantly to their local water balances, but a limited understanding of the hydrological impacts of fog still exists. In particular, information on fog and its contribution is extremely scarce in the mountains forming South Africa's eastern escarpment. Only one study has been conducted on the eastern escarpment, despite the significance of fog at higher altitudes, and the suggestion that it could contribute to the soil water content (Schmidt and Schulze, 1989). Further investigations along the country's eastern escarpment thus need to be conducted, to more fully understand the contribution of fog to the water balance. International TMCF studies also found the fog input to be highly variable according to seasons and regions, and thus, these are important factors to be considered in further investigations. Additionally, no attempts to measure the fog input to forest ecosystems in South Africa have been conducted.

1.2 Research Approach

The study was conducted at two sites situated on the eastern escarpment of South Africa in the KwaZulu-Natal Province, namely, the Cathedral Peak research catchments and the Two Streams catchment (Figure 1.1). The catchments are of different land use types and altitudes; Cathedral Peak is a high altitude montane grassland catchment, whereas Two Streams is at a lower altitude and afforested by exotic plantations. These catchments are both long-term hydrological research and monitoring catchments, where frequent fog occurrences have been observed. The contribution of fog to their water balances was, however, unknown.

Field measurements were conducted at four sites over a 16-month period, from July 2015 to October 2016. Three of the sites were at the Cathedral Peak research catchments, including Mike's Pass Meteorological Station, Catchment VI and a High Altitude site. The fourth site was an Automatic Weather station (AWS) in a grassland at Two Streams, located near the forestry plantations. Fog was measured using Juvik-type fog gauges that were installed alongside existing AWS's, to determine the contribution of fog to their water balances. The sites are all located at different altitudes, and thus, the variation of fog occurrence and water yields with altitude was investigated. At Two Streams, additional measurements of throughfall, stemflow and soil water content were carried out in an *Acacia mearnsii* plantation, to further determine the fog contribution in a forest plantation.

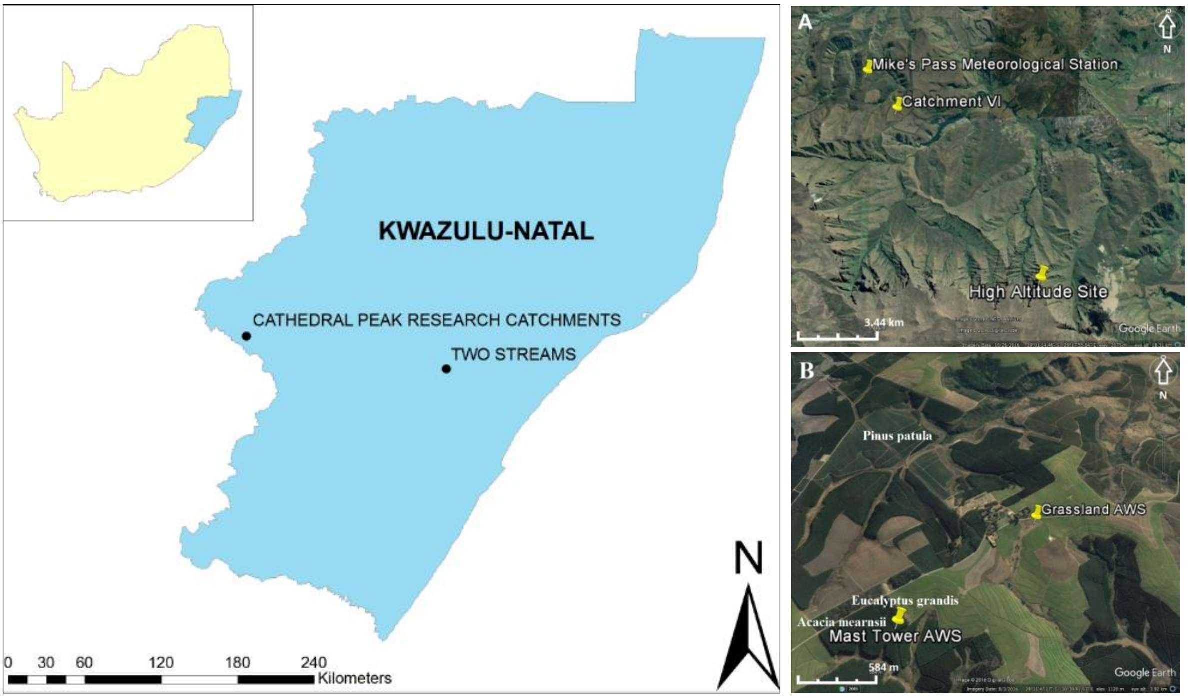

Figure 1.1 Map of the location of the Two Streams and Cathedral Peak research catchments, both situated along the eastern escarpment of South Africa in the KwaZulu-Natal Province. The top right figure (A) shows the positions of Mike's Pass Meteorological Station, Catchment VI and a High Altitude site at the Cathedral Peak research catchments and the bottom right figure (B) shows the positions of the Grassland Automatic Weather station at Two Streams (Google Earth, 2016)

1.3 Aim and Research Questions

The overall aim of the study was to determine the contribution of fog to the water balance of two research catchments of different vegetation types and altitudes situated along South Africa's eastern escarpment.

The study aimed to address the following research questions:

- What is the significance of the contribution of fog to the water balance?
- Is the fog contribution seasonal and is the importance of fog relative to the total precipitation?
- Does altitude influence fog occurrence and measured fog water yields?
- Do wind speed and direction influence fog occurrence and measured fog water yields?

- Is there evidence of fog drip in the *Acacia mearnsii* plantation? Does fog interception assist in bringing the canopy closer to saturation, so that when rainfall occurs, there are quicker and greater responses in throughfall and stemflow?
- What is the significance of the fog contribution to the soil water content?

From the outcomes of the research, the aim was to be able to advise on whether there is a need to consider fog as a contributor to the catchment water balance.

1.4 Outline of Dissertation Structure

This dissertation consists of two research papers, which include relevant literature, materials and methods, results, discussion and conclusion sections. Due to the fact that both papers share study sites and similar methodologies and equipment used, there is considerable repetition of information over these sections. As outlined in the University of KwaZulu-Natal's dissertation guidelines, the referencing style for each of the research papers adhere to the journal to which the paper is intended to be submitted to.

Chapter 2, the first paper, focused on identifying the temporal and spatial variations of fog along South Africa's eastern escarpment. Specific focus was on the seasonal and diurnal patterns of fog, as well as its spatial distribution in relation to altitude. Fog and the climatic conditions were measured over a 16-month period at four sites that vary in altitude and vegetation type in the Cathedral Peak research catchments and at Two Streams.

Chapter 3 investigated the importance of fog as a precipitation source and whether it contributed to net precipitation and soil water at Two Streams, a fog-affected commercial forestry catchment. Over a 16-month period, the precipitation, fog, throughfall, stemflow and soil water content were measured.

Chapter 4 is a final synthesis, which includes the conclusions, uncertainties and challenges of the research, as well as the recommendations for future research.

The structure and research approach of Chapters 2-4 is depicted in Figure 1.2.

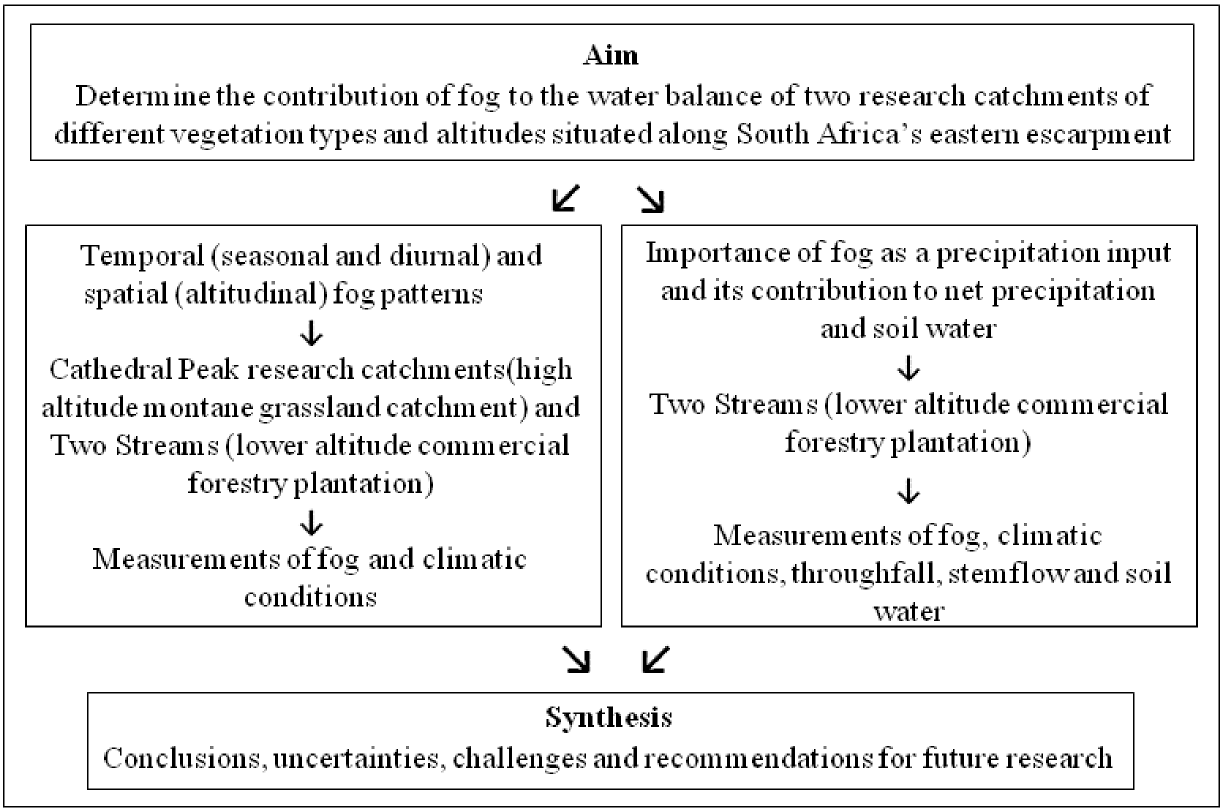

Figure 1.2 The structure and research approach of Chapters 2-4

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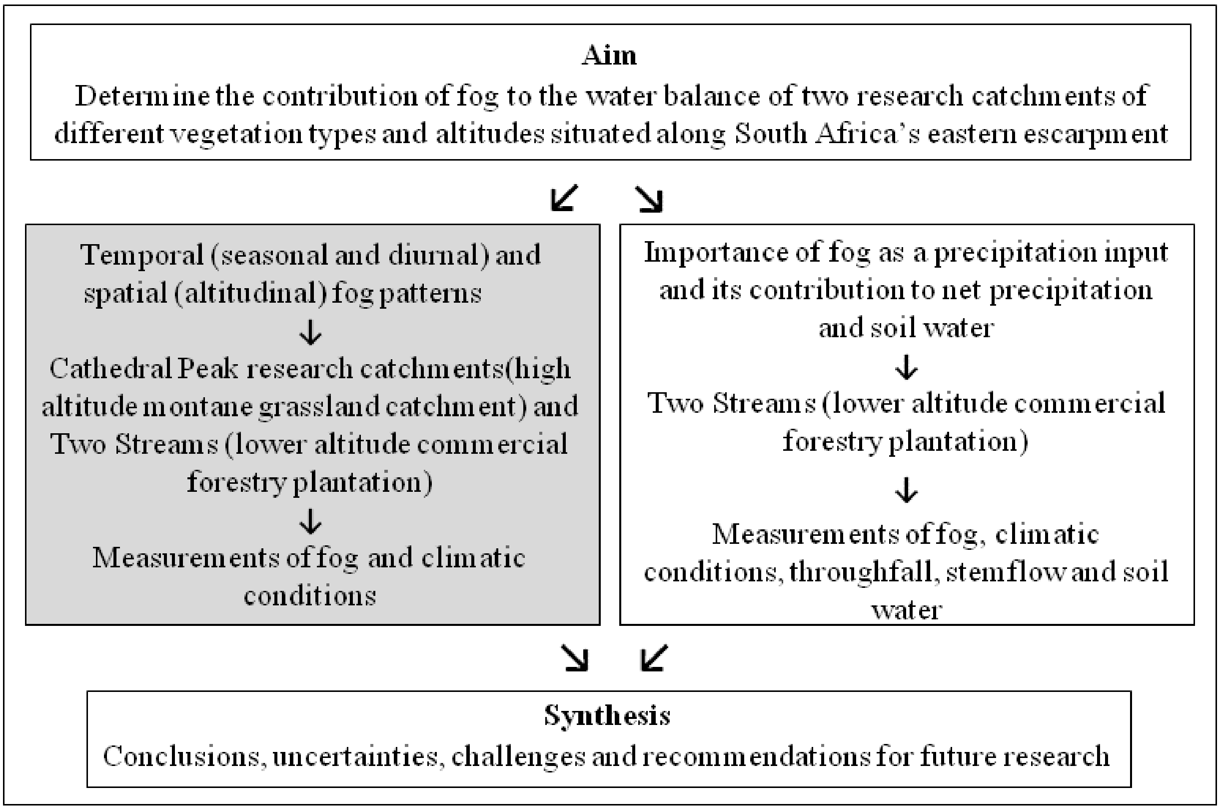
Lead into Chapter 2

Chapter 2 focuses on understanding the temporal and spatial variations of fog along South Africa's eastern escarpment. Specific focus was on the seasonal and diurnal patterns of fog as well as its spatial distribution in relation to altitude. Fog and the climatic conditions were measured at two sites that vary in altitude and vegetation type, namely, the Cathedral Peak research catchments and Two Streams.



CHAPTER 2: TEMPORAL AND SPATIAL VARIATIONS OF FOG ALONG THE EASTERN ESCARPMENT OF SOUTH AFRICA

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ABSTRACT

The scientific interest to study and measure fog started in South Africa in the early 1900's, yet knowledge of the dynamics regarding the country's temporal and spatial fog patterns is still poor and few fog monitoring sites currently exist. Information on fog is particularly scarce in the mountains forming South Africa's eastern escarpment. This study aims to identify the seasonal and diurnal patterns of fog as well as its spatial distribution in relation to altitude along South Africa's eastern escarpment. Over a 16-month period, fog and climatic conditions were measured at four sites of varying altitudes; three at Cathedral Peak and one at Two Streams. Fog was found to have a substantial contribution to the water balance, however, its occurrence and water yield patterns have proven to be highly variable over both time and space. Temporally, fog is mostly confined to the cooler hours of the day and the wet season of the year, although it does have a greater contribution, relative to the total precipitation, during the dry season. Spatially, the distribution of fog is explained by the important role that the altitude plays. Other topographic features, such as the hillslope orientation and slope are believed to play an equally important role in spatial fog variability and further studies on the influence of these features on fog are recommended.

Keywords: *fog, eastern escarpment, seasonality, altitude, wind speed and direction.*

2.1 Introduction

The scientific interest to study and measure fog started in South Africa, with some of the world’s earliest fog publications having been conducted in the early 1900’s on Table Mountain in the Western Cape Province (Olivier, 2002). Despite this early interest, knowledge of the dynamics regarding temporal and spatial fog patterns in South Africa is still poor and this is only exacerbated by the fact that very few fog monitoring sites currently exist in the country (Olivier, 2002). In South Africa, fog and low clouds occur frequently, mostly along the west coast and in the mountains forming the southern and eastern escarpments (Kotzé, 2014). Particularly in these mountainous regions, fog can be extremely variable over time and space. This is due to the fact that the climatic and topographic conditions, that influence the distribution and frequency of fog, can vary considerably in these environments, and thus, these variations need to be more fully defined (Keppeler, 2007).

Information on fog is particularly scarce in the mountains forming South Africa’s eastern escarpment. One of the few hydrological studies conducted here, was that by Schmidt and Schulze (1989) in the Cedara Catchments, Kwazulu-Natal Midlands. Schmidt and Schulze (1989) measured fog over a period of eleven years at seven sites, ranging in altitude between 1058 m.a.s.l and 1445 m.a.s.l. Further north in the Soutpansberg Mountains in the Limpopo province, Louw *et al*. (1998) investigated the synoptic and meteorological factors associated with fog water collection at several high altitude sites. Olivier and Rautenbach (2002) have also conducted a fog water harvesting study here. These studies agreed that although fog occurs frequently during the dry winter months, it is predominantly a summer phenomenon, occurring mostly in the wet season months. Studies conducted on South Africa’s west coast also confirmed these findings. van Schalkwyk and Dyson (2013) found that at Cape Town International airport, fog is most prevalent in the wet season and Olivier *et al*. (2015) established that at Steenbokfontein, near Lamberts Bay, the fog season began towards the end of the wet season. Topographically, it was found that higher sites are more affected by fog. For example, Schmidt and Schulze (1989) found that fog yields are directly proportional to altitude in the Cedara Catchments. At their highest station, the fog gauge measured an average of over 2500 mm of fog and wind driven rainfall per annum, which was twice that caught by the rain gauge. Schmidt and Schulze (1989) even suggested that fog could deposit onto the soil at the higher elevated sites.

Worldwide, studies have found that fog is highly variable over time, with distinct seasonal and hourly variations (Marzol, 2008). These studies agreed with studies conducted in South Africa that fog varies greatly between wet and dry seasons, however, they found that fog episodes are more frequent, persist for longer durations and contain greater amounts of water in dry seasons when there is low rainfall (Liu *et al*., 2004; Marzol, 2008; Ponette-González *et al*., 2010). For example, in a tropical seasonal rainforest in south-west China, fog contributed a very small proportion of only 5 % to the annual precipitation, however, 86 % of this fog occurred during the dry season (Liu *et al*., 2005). Using stable isotopes at the site, more fog drip water was detected in the soil water in the dry season than that detected in the wet season. In the Andean forest of El Zumbador, fog water accounted for 3 % of the total precipitation during the wettest month, however, during the driest month it had a contribution of up to 19 % (Cavelier and Goldstein, 1989). In the Canary Islands in Spain, the volume of fog water collected in the three summer months was of great importance for the survival of vegetation, not only because of the significant amount of water, but because it was the driest season of the year (Marzol, 2008). On average, 28 days per month experienced fog during the dry season compared to only 13 days per month in the wet season. Thus, throughout the dry season, fog occurred almost every day, while in the wet season, only every second or third day experienced fog. The hourly changes in air temperatures determine the development and dissipation of fog, with most fog occurring during the cooler nocturnal hours (Olivier, 2002; Estrela *et al*., 2008). As temperatures increase, evaporation occurs and fog thins, lifts and dissipates (Louw *et al.*, 1998; Newton, 2003).

Spatial differences in fog occurrence and its water content can be explained by the local topography of a site, most importantly by its altitude (Olivier and Rautenbach, 2002; Marzol, 2008; Olivier *et al*., 2015). Mountainous areas are more affected by fog, compared to low-lying areas, and this has been attributed to increased wind speeds, better exposure to dominant winds and greater fog liquid water contents at higher sites (Cavelier and Goldstein, 1989; Olivier and Rautenbach, 2002; Shimadera *et al*., 2008; Pryet *et al*., 2012; Olivier *et al*., 2015). High altitude orographic fog contains the highest levels of moisture, because the upward movement of air from lower to upper sites enhances saturation of the air and increases wind speeds, as well as the number and size of fog water droplets (Cavelier *et al*., 1996; Ritter *et al*., 2008). High altitudes can also intersect clouds, which contain more water than surfacegenerated fogs (Yin and Arp, 1994). Fog, however, may vary from one point to another at sites with the same altitude, due to additional topographic features, such as the hillslope orientation and proximity to the coastline (Fessehaye *et al*., 2014; Olivier *et al*., 2015). A hillslope oriented toward the prevailing wind direction is more exposed towards winds that carry fog (Cavelier *et al*., 1996; Olivier *et al*., 2015). Furthermore, fog frequencies decrease with increasing distance from the coast, due to the fact that fog and moisture bearing winds come from the ocean and evaporation of fog droplets takes place with inland travel (Kidron, 1999; Cereceda *et al*., 2008; Marzol, 2008). There have, however, been several studies that found that fog occurrence and yield did not increase with altitude and that the other factors mentioned above, such as the hillslope orientation and proximity to coastline, played a more important role. For example, in Germany, Zimmermann and Zimmermann (2002) found that higher sites, which were not in a ridge position, had a lower fog frequency than lower lying stations that were situated in ridge positions. On Santa Cruz Island, Carbone *et al*. (2013) found that fog did not increase with altitude; proximity to the ocean was a more important factor, as the lower site situated closer to the coastline, experienced more fog.

Research shows that fog occurrence and the amount of water produced can vary significantly over short periods of time and over short distances across the landscape (Cavelier *et* al., 1996). For these reasons, results cannot be extrapolated from one site to another and site specific studies are required. Therefore, this study aims to identify the seasonal and diurnal patterns of fog, as well as its spatial distribution in relation to altitude along South Africa’s eastern escarpment. Due to the site-dependent nature of fog, and the fact that limited information is known regarding its occurrence and yield patterns on the country’s eastern escarpment, it is evident that further studies need to be conducted here, in order to determine the contribution of fog to the precipitation input of the water balance. Additionally, identifying these fog patterns will establish potential areas where these fog studies need to be conducted. With the demand for freshwater supplies on the eastern escarpment of South Africa rapidly escalating, it is vital that our water resources are managed as efficiently as possible, but this is only achievable if the total precipitation contribution is fully understood.

2.2 Materials and Methods

2.2.1 Study sites

The study was conducted at two sites situated on the eastern escarpment of South Africa in proximity to Pietermaritzburg in the KwaZulu-Natal Province, namely, the Cathedral Peak research catchments and Two Streams (Figure 2.1). These sites are both long-term monitoring and ongoing hydrological research catchments, where frequent fog occurrences have been observed.

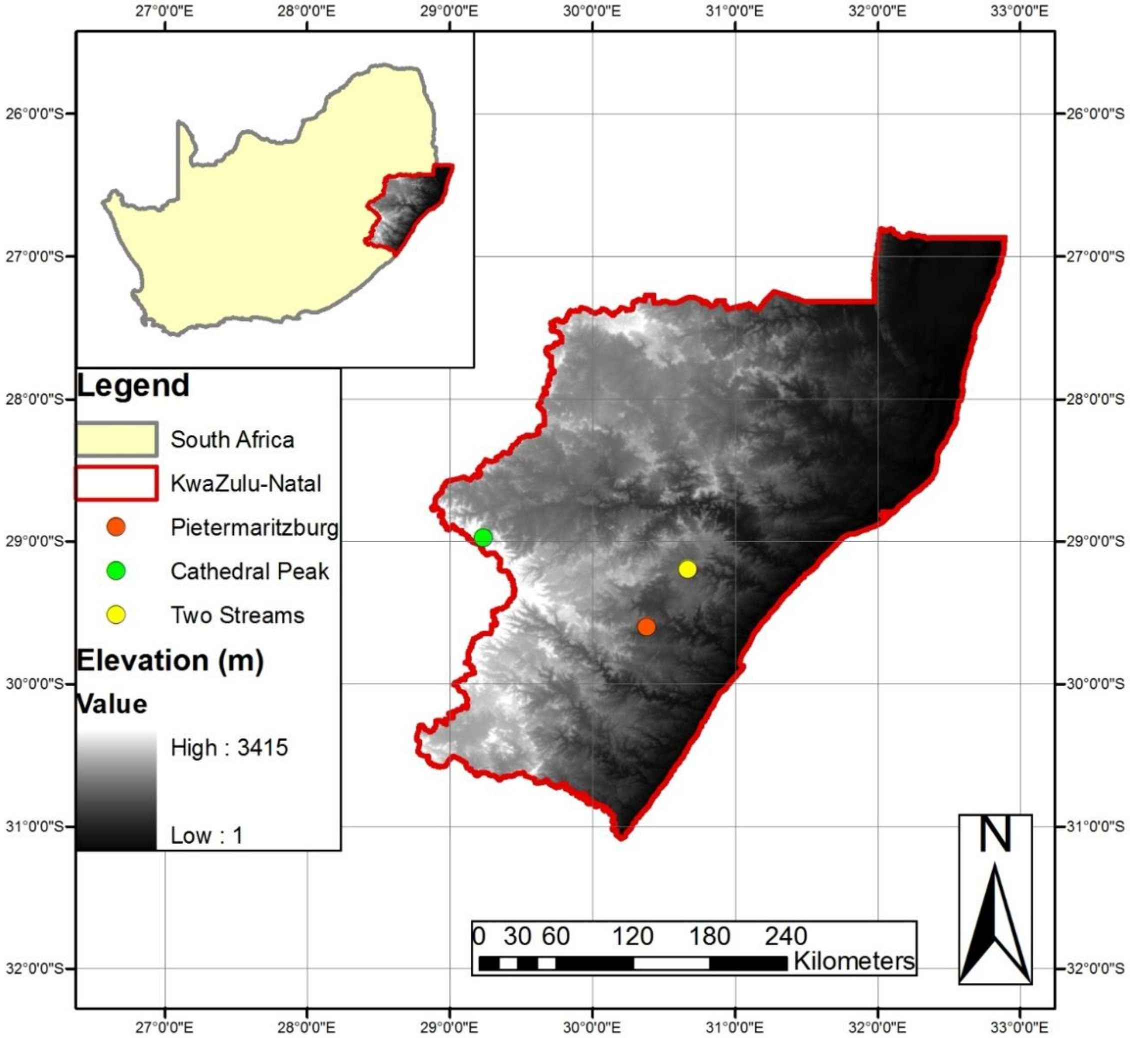

Figure 2.1 Map of the location and elevation of the Two Streams and Cathedral Peak research catchments, both situated along the eastern escarpment of South Africa in the KwaZulu-Natal Province close to Pietermaritzburg

2.2.1.1 Cathedral Peak research catchments

The Cathedral Peak research catchments (29°00’S, 29°15’E) are located on the Little Berg plateau in the northern uKhahlamba Drakensberg, bordering the north-eastern side of Lesotho (Figure 2.1). Rainfall in the Drakensberg has a strong seasonality, with 85 % of its rainfall occurring between the months of October and March (Nänni, 1956). The wettest months are January, February and March, while the driest include June and July (Nänni, 1956). The catchments experience a mean annual rainfall of 1400 mm (Warburton *et al.,* 2014), with precipitation events being dominated by thunderstorms, which occur most often during the afternoons and evenings in summer (Nänni, 1956). Dense fog and stratus clouds are frequently seen on the catchment slopes (Louw *et al.,* 1998). Cathedral Peak experiences a mean annual temperature of 13.8 °C (le Roux *et al*., 2011). Winters are cold and dry, with snowfalls not being uncommon (Warburton *et al.,* 2014). In winter, winds are predominantly stronger, coming from the west, while summer experiences occasional gusts from the east (Nänni, 1956).

The catchments are naturally vegetated by *Themeda triandra* grassland, with *Leucosidea sericea* and *Buddleia salvifolia* frequently found along stream banks (Gush *et al.,* 2002). The terrain is steep, ranging in altitude between 1 820 m.a.s.l. and 2 463 m.a.s.l (Warburton *et al.,* 2014).The catchments are underlain by basaltic lavas overlying Clarens sandstone (Nänni, 1956). The soils are acidic, highly leached and consist predominantly of silty clays derived from basalt (Gush *et al.,* 2002). On the gentler slopes, soils consist of Huttons and Griffins, while Katspruit and Champagne forms are commonly found along stream banks (Warburton *et al.,* 2014).

2.2.1.2 Two Streams

The Two Streams catchment is situated on Mondi Forest’s Mistley-Canema Estate (29°11’S, 30°39’E) in Seven Oaks on the Greytown road, approximately 70 km from Pietermaritzburg (Figure 2.1). The catchment experiences an annual rainfall of between 659 and 1139 mm, with most of this rainfall coming from summer thunderstorms and winter cold fronts (Everson *et al*., 2014). Seven Oaks lies in a “moist midlands mist belt grassland”, according to the South African Bioresource Group (BRG) classification system, thus mist can be heavy and frequent in the catchment (Bulcock and Jewitt, 2012). The mean temperature of the area is 17 ^{o}C. The area is prone to occasional droughts, hail and frost, while berg winds occur frequently in the area (Everson *et al*., 2014).

The area was previously a natural *Themeda triandra* grassland, however, due to invasion of native *Aristida junciformis,* only a few relic patches of this grassland remain (Everson *et al*., 2007; Everson and Clulow, 2011). The catchment has since been converted to commercial forest plantations of *Acacia mearnsii*, *Eucalyptus grandis* and *Pinus patula,* as well as a small area of sugarcane, due to its high percentage of arable land. The terrain consists of gentle slopes and rolling landscapes, with the elevation ranging from 1071 m.a.s.l to 1170 m.a.s.l at the highest point (le Roux *et al*., 2011; Everson *et al*., 2014; Everson and Clulow, 2011). The geology consists mainly of sandstone of the Natal group with small areas of dolerite (le Roux *et al*., 2011). The soils are highly leached as a result of the moist climate, thus promoting the genesis of dystrophic soils (Everson *et al*., 2007; le Roux *et al*., 2011). They are mostly apedal and plinthic, derived mainly from the Ecca group with dolerite dykes and sills (Everson *et al*., 2014; Everson and Clulow, 2011).

2.2.2 Field measurements

Field measurements were conducted over a 16-month period, from July 2015 to October 2016. There were four sites in total, of which three were in Cathedral Peak; Mike's Pass Meteorological Station, Catchment VI and a nearby High Altitude site. The Grasslands-Forests-Wetlands Node, South African Environmental Observation Network (SAEON) was responsible for collecting this data. The site at Two Streams was an Automatic Weather station (AWS) in a grassland area located near the forestry plantations. At all four sites, fog was measured using fog gauges that were installed alongside AWS's, to determine the temporal and spatial variations of fog occurrence and its water yields. The location of the instrumentation setup at the sites is shown in Figure 2.2 and their coordinates and elevations are shown in Table 2.1.

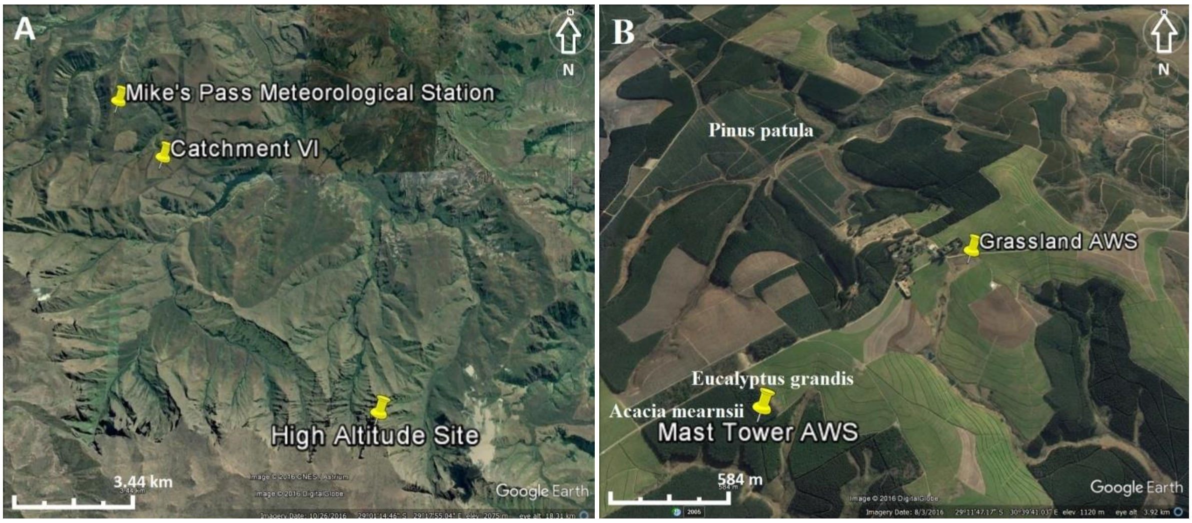

Figure 2.2 Map of the location of the instrumentation setup at a) the Cathedral Peak research catchments and b) Two Streams (Google Earth, 2016)

Table 2.1 Co-ordinates and elevations of the study sites at the Cathedral Peak research catchments and Two Streams

Study sites	Latitude (S)	Longitude (E)	Elevation (m.a.s.l)
Mike's Pass	28°58'32.18"	29°14'8.77"	1859
Catchment VI	28°59'35.12"	29°15'6.43"	1923
High Altitude site	29° 3'52.24"	29°19'17.17"	2911
Two Streams grassland AWS	29°11'48.03"	30°39'58.40"	1109

The climatic conditions at the sites were monitored by similar AWS's. At Two Streams, a second AWS exists at the top of a 24 m tall lattice mast above an *Acacia mearnsii* canopy, close to the centre of the stand. Instrumentation at the AWS's were installed at a measurement height of 2 m above the short grass surface, except for the rain gauge (TE525, Texas Electronics Inc., Dallas, Texas, USA) that was installed with the orifice at 1.2 m above the surface. Instrumentation included wind vanes and 3-cup anemometers (Model 03001, R.M. Young, Traverse city, Michigan, USA), pyranometers (LI200x, LI-Cor, Lincoln, Nebraska, USA) and air temperature and relative humidity sensors (HMP60, Vaisala Inc., Helsinki, Finland). These instruments were connected to Campbell Scientific data-loggers, recording data at event-based, 5-minute, 10-minute, 20-minute, hourly and daily intervals.

Fog was measured using Juvik-type fog gauges, installed at a height of two metres above the ground. The fog gauges consist of a louvered brass mesh cylindrical screen attached to a Texas rain gauge, based on the design by Juvik and Ekern (1978). The fog collection process occurs when horizontally wind-blown fog water droplets collect on the mesh screen, where they coalesce until they are heavy enough to flow down into a funnel connected to a rain gauge. On top of the cylindrical screen, there is an extra funnel connected to a PVC pipe, to drain away rain water. Due to its cylindrical design, the Juvik gauge represents the same silhouette and catch surface area to the prevailing wind, independent of the wind direction, providing consistent and comparable fog measurements in all environments (Frumau *et al.*, 2006; Estrela *et al.*, 2008). The Juvik gauge also has good drainage characteristics, is of a durable construction and is inexpensive to construct and maintain (Hansen and Juvik. 2010). However, the Juvik gauges have no mechanism to separate fog from drizzle and rainfall and have been found to over-estimate fog water deposition to vegetation, due to artificial collecting surfaces of fog gauges and natural plant surfaces differing in their rates of fog water collection (Frumau *et al.*, 2011).

To convert fog gauge output to a “unit vertical catch” equivalent to a rain gauge in units of depth (mm), the manufacturer’s calibration of 0.254 mm was accepted, and a ratio between the collection area (cm^2) of the standard Texas rain gauge orifice to the collection area of the fog gauge mesh was calculated.

2.2.3 Data analysis and collection problems

A number of terms were used in the analysis of data and these terms were defined as follows: The maximum monthly fog yield refers to the greatest amount of fog water (mm) that occurred within a month, while the maximum daily fog yield refers to the greatest amount of fog water (mm) that occurred within a day. A day was considered to be a fog day when during a 24-hour period, starting at midnight, the fog gauge measured at least 0.1 mm in the absence of rainfall. A rain day was determined in the same manner, provided the rain gauge measured at least 0.2 mm. A fog event was defined as a period in which fog occurred over a number of consecutive hours, with a fogless interval of no more than one hour within this period.

During the measurement period, several issues with the instrumentation arose, leading to gaps in the data records. At Cathedral Peak, there were blockages of the fog gauge at Mike’s Pass Meteorological Station, vandalism in Catchment 6 and extreme winds at the High Altitude site. At Two Streams, a number of gaps existed in the grassland AWS data record, due to technical problems, but some of these gaps were patched with data from the second lattice mast AWS located above the *Acacia mearnsii* plantation. A timeline table illustrating when data was available for these sites is shown in Table 2.2.

Table 2.2 A timeline table illustrating when data was available for the Mike’s Pass Meteorological Station, Catchment VI, High Altitude and Two Streams sites

	2015						**2016**									
	J	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**
Mike's Pass			■	■	■		■	■	■	■	■	■	■	■	■	■
Catchment VI		■	■													
High Altitude site		■	■													
Two Streams	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

2.3 Results

The results are presented for a 16-month period from July 2015 to October 2016. Specific focus was given to fog water yields, monthly frequency of fog occurrence, daily temporal character of fog, fog event duration and the influence of wind speed and direction on fog occurrence and yields. Comparison between the Mike’s Pass and Two Streams sites was emphasised, due to the overlap periods and completeness of their data records. An additional comparison between the High Altitude site, Catchment VI and Two Streams sites was carried out when there was an overlap of data at these sites, to determine the variation of fog with altitude.

2.3.1 Fog water yields

Fog occurred all year round at Mike’s Pass and Two Streams, but greater monthly fog yields were experienced at Mike’s Pass, the more elevated site (Figure 2.3 and 2.4). At both sites, greater fog yields were experienced mostly over the wet summer season, generally from

September through to April. At Mike's Pass, the maximum monthly fog yield occurred in October 2015 and measured approximately 18.5 mm. At Two Streams, the maximum monthly fog yield occurred in January 2016 and measured approximately 6 mm. When considering the monthly percent ratio of fog to the total precipitation received, the fog contribution varied between wet and dry seasons. Generally, there were greater fog contributions in the drier months when less rainfall occurred. For several months at Mike's Pass, fog represented a contribution of almost 30 %. During the driest month of August 2015 at Two Streams, fog represented a contribution of approximately 38 % of the total precipitation.

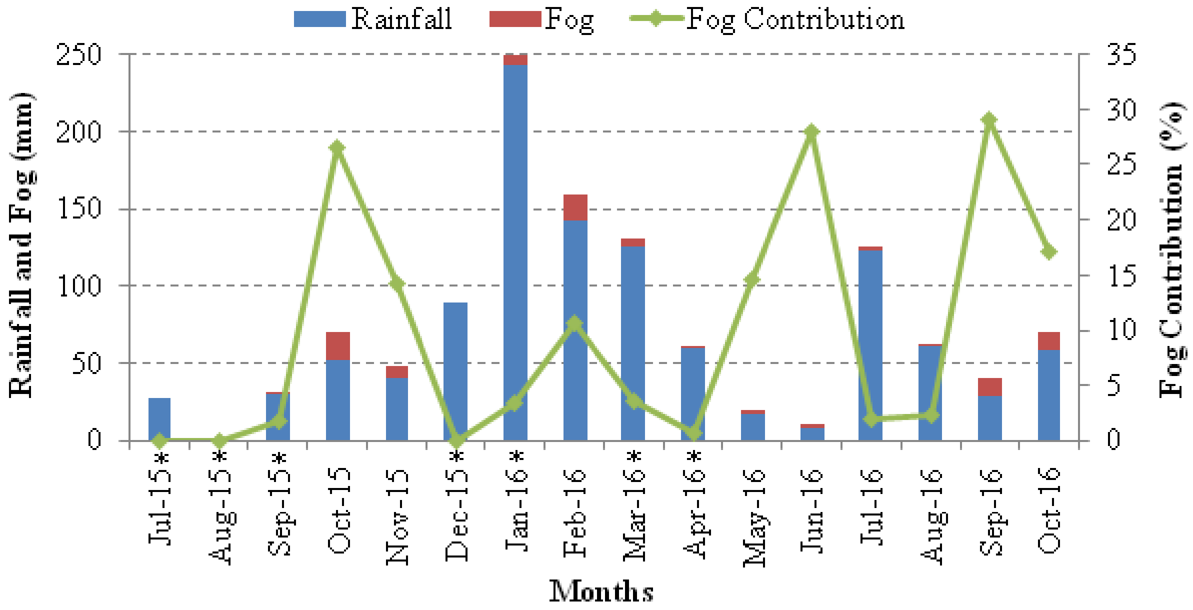

Figure 2.3 Monthly rainfall and fog yields when rainfall was absent (represented by the bar graph) and the ratio of fog to total precipitation (represented by the line graph) at Mike's Pass from July 2015 to October 2016. The stars (*) indicate the months when there was missing data

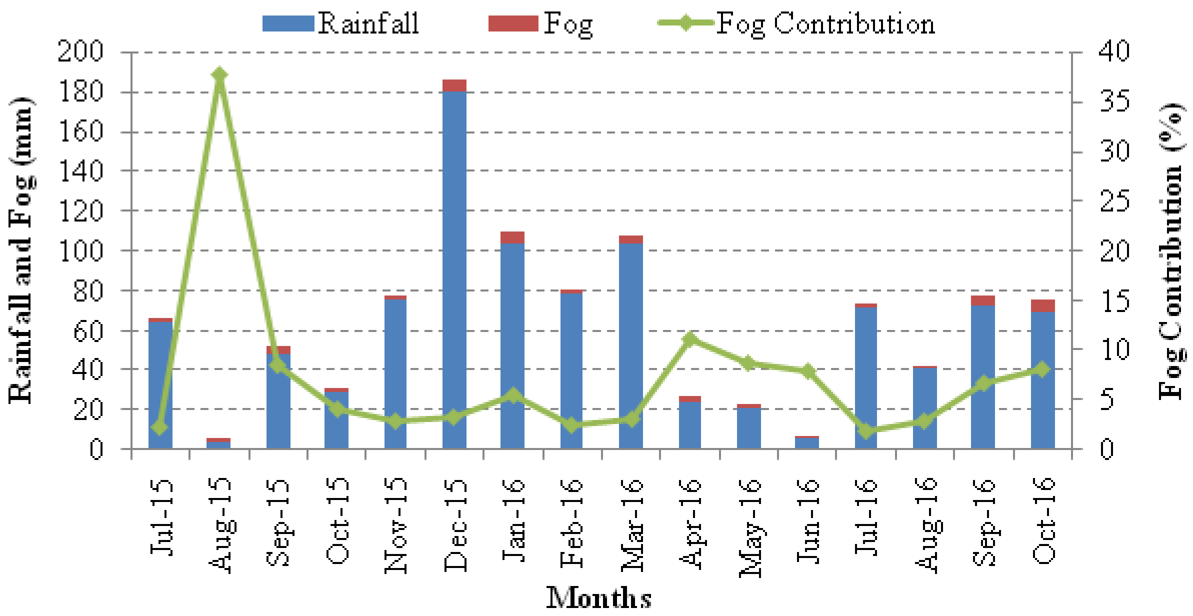

Figure 2.4 Monthly rainfall and fog yields when rainfall was absent (represented by the bar graph) and the ratio of fog to total precipitation (represented by the line graph) at Two Streams from July 2015 to October 2016

The daily fog yields, measured in the absence of rainfall at Mike's Pass and Two Streams (Figure 2.5), also show that the more elevated site, Mike's Pass, experienced greater daily fog yields than the lower site, Two Steams. At both sites, there were more fog events and larger daily fog yields in the wet summer season, while fewer fog events and lower daily fog yields occurred in the dry winter season. At Mike's Pass, the maximum daily yield occurred in February 2016 and measured approximately 8.5 mm. At Two Streams, the maximum daily yield occurred in September 2016 and measured approximately 2.7 mm.

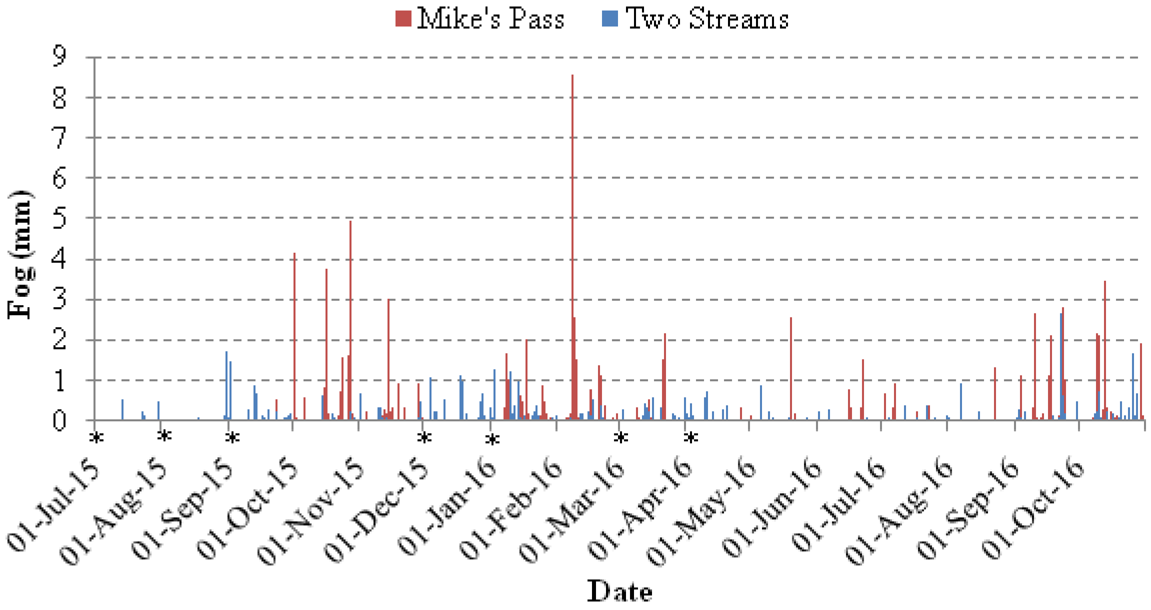

Figure 2.5 Daily fog yields (when rainfall was absent) from July 2015 to October 2016. The stars (*) indicate the months when there was missing data at Mike's Pass

Comparing daily fog yields in relation to altitude over a short period where there was an overlap of data at the High Altitude site, Catchment VI and Two Streams, shows that generally greater fog yields were measured at the more elevated sites, but this was not always the case (Figure 2.6). On some days, including September 13th 2015, the High Altitude site didn't experience any fog, while the lower sites, Catchment VI and Two Streams did. On other days, including August 10th 2015, September 3rd 2015 and September 12th 2015, the lower site at Cathedral Peak, Catchment VI, experienced greater daily fog yields than the High Altitude site.

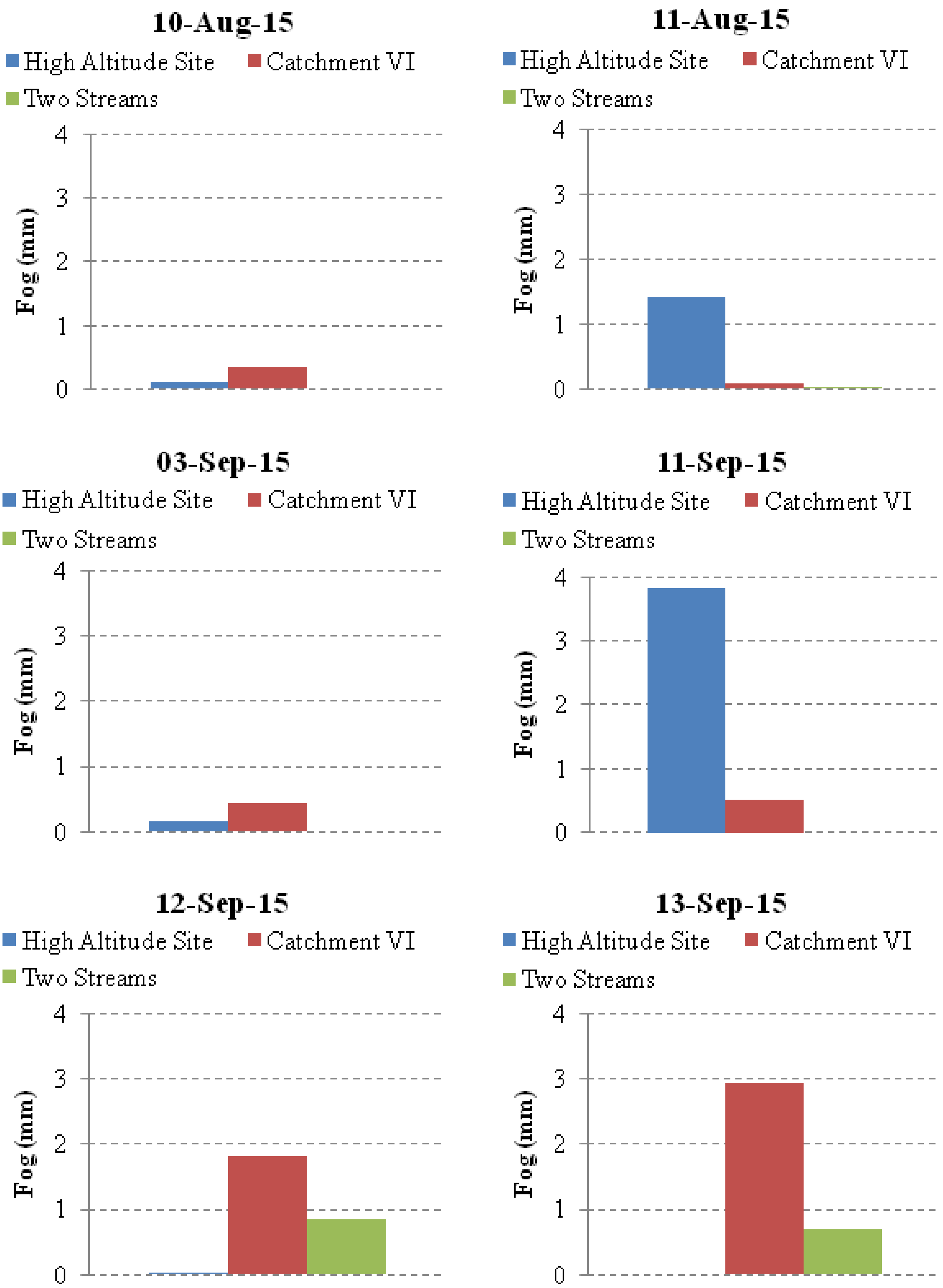

Figure 2.6 Daily fog yields (when rainfall was absent) at the High Altitude, Catchment VI and Two Streams sites

2.3.2 Monthly frequency of fog occurrence

Total precipitation was divided into four categories (Figure 2.7 and 2.8). The four categories in the graph represent the percentage of days each month that experienced fog-only, rainfall and fog, rainfall-only or no precipitation at all. Generally, a higher distribution of rain days occurred than fog days during a month, except for one month at Two Streams (April 2016) and three months at Mike's Pass (October 2015, June 2016 and September 2016) when a slightly higher distribution of fog days than rain days occurred. Overall, a greater distribution of fog days occurred at the more elevated site, Mike's Pass than at Two Streams, except for the month of August 2016. At both sites, a greater number of days experienced fog during the wet summer months from September through to April, corresponding to the higher fog water yields measured over these months (Figure 2.3 and 2.4). At Mike's Pass, up to 38 % of days during a month experienced fog (January 2016), and at Two Streams, up to 36 % of days during a month experienced fog (December 2015, January 2016 and October 2016).

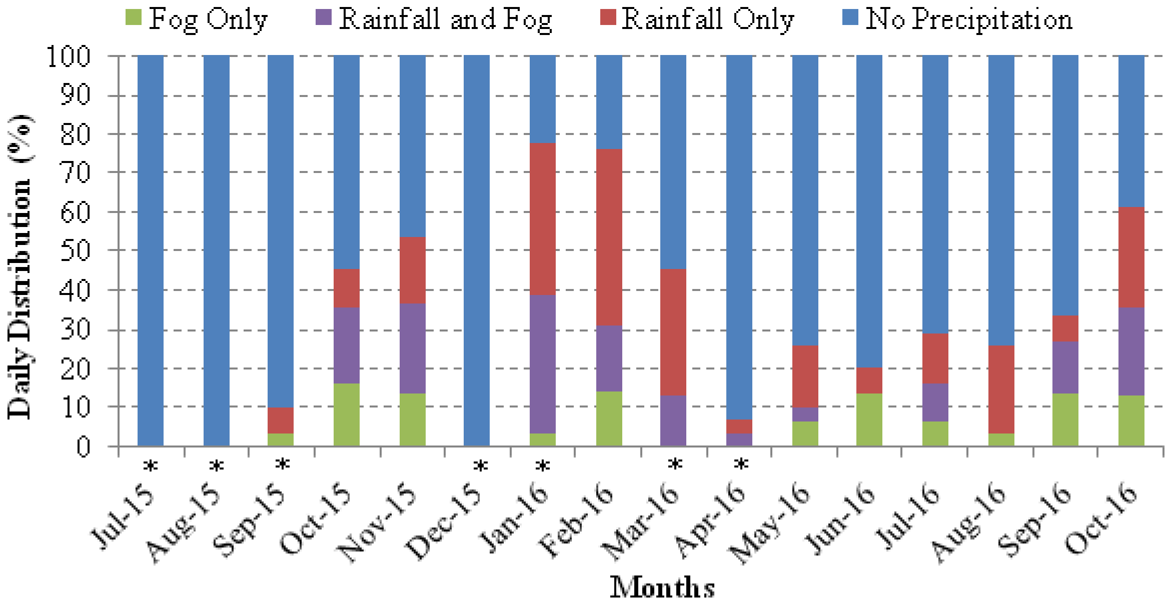

Figure 2.7 Distribution of precipitation at Mike's Pass from July 2015 to October 2016. The stars (*) indicate the months when there was missing data

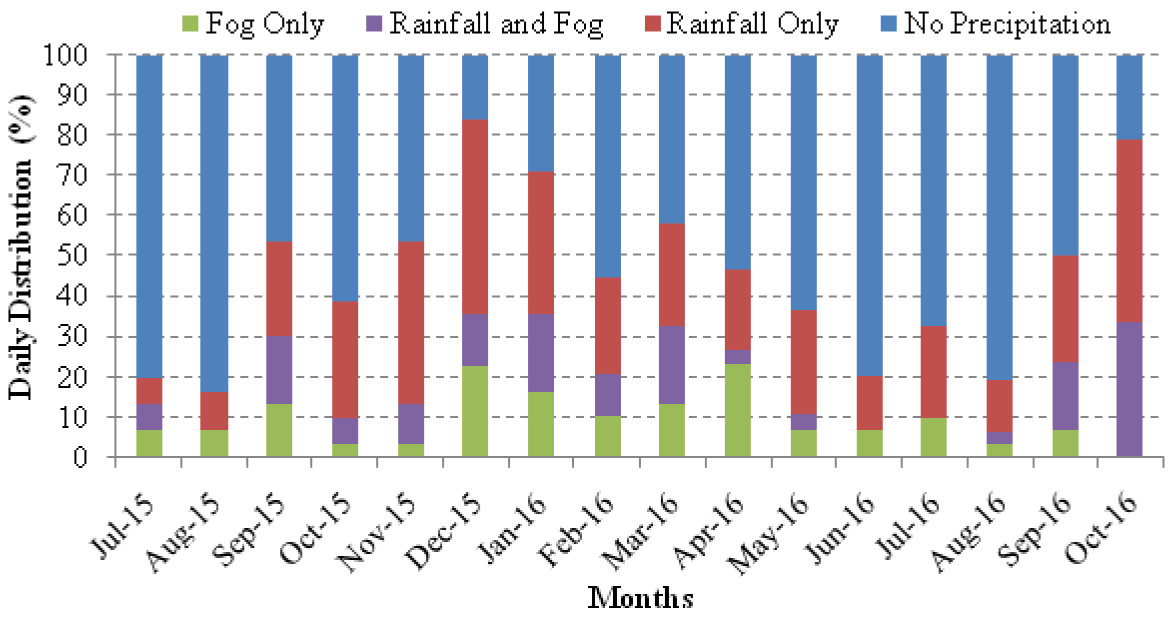

Figure 2.8 Distribution of precipitation at Two Streams from July 2015 to October 2016

2.3.3 Daily temporal character of fog

Fog shows a clear diurnal pattern, occurring mostly during the cooler hours (Figure 2.9). At Two Streams, it appears late afternoon, followed by a steady increase at night, where most fog occurs in the early morning hours when temperatures are generally low. It disappears in the later morning hours after sunrise when diurnal warming leads to rapid fog dissipation. Fog does not occur at midday when some of the highest temperatures can be reached. At Mike’s Pass, fog shows a similar pattern, however, it is able to persist throughout the day as it is generally cooler at this site.

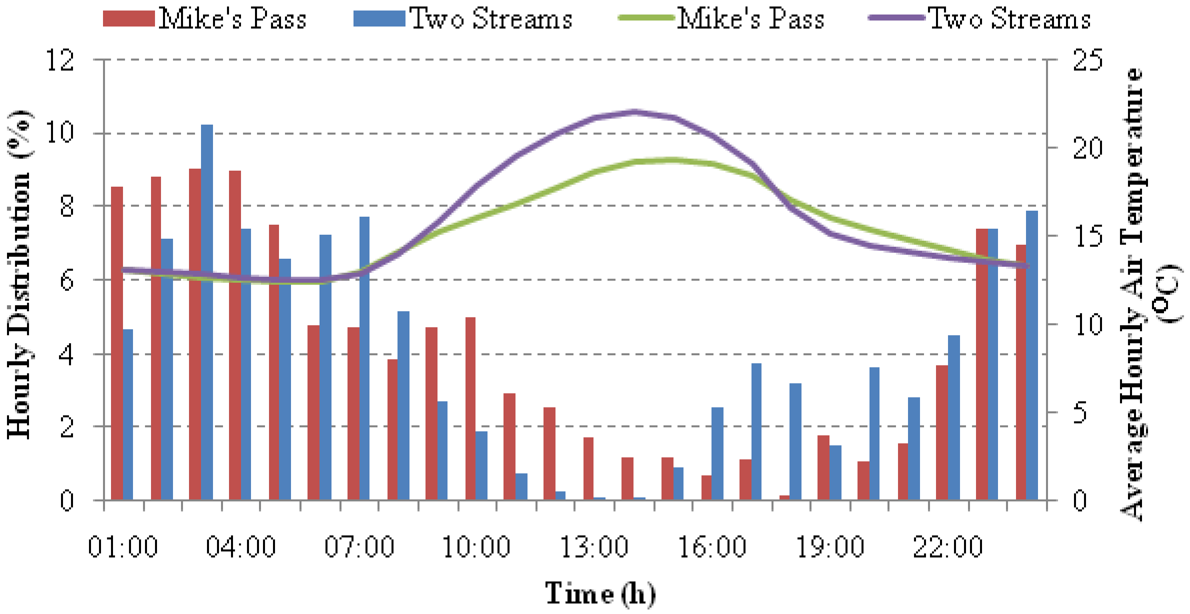

Figure 2.9 Average hourly distribution of fog (represented by the bar graph) and average hourly air temperature (represented by the line graph) observed from July 2015 to October 2016

2.3.4 Fog event duration

At both sites, fog-only events occurred frequently, but the majority of events persisted for short durations of less than four hours (Figure 2.10). At both sites, more than 50 % of events had durations of four hours or less. Events also persisted for longer durations, with several exceeding 9 hours; approximately 12 % of events at Mike's Pass and 7 % of events at Two Streams persisted for longer than 9 hours. At Mike's Pass, the maximum event duration persisted for 13 hours and 30 minutes, the minimum for 15 minutes and the mean for 4 hours and 17 minutes. At Two Streams, the maximum event duration persisted for 13 hours and 39 minutes, the minimum for 38 minutes and the mean for 4 hours and 28 minutes.

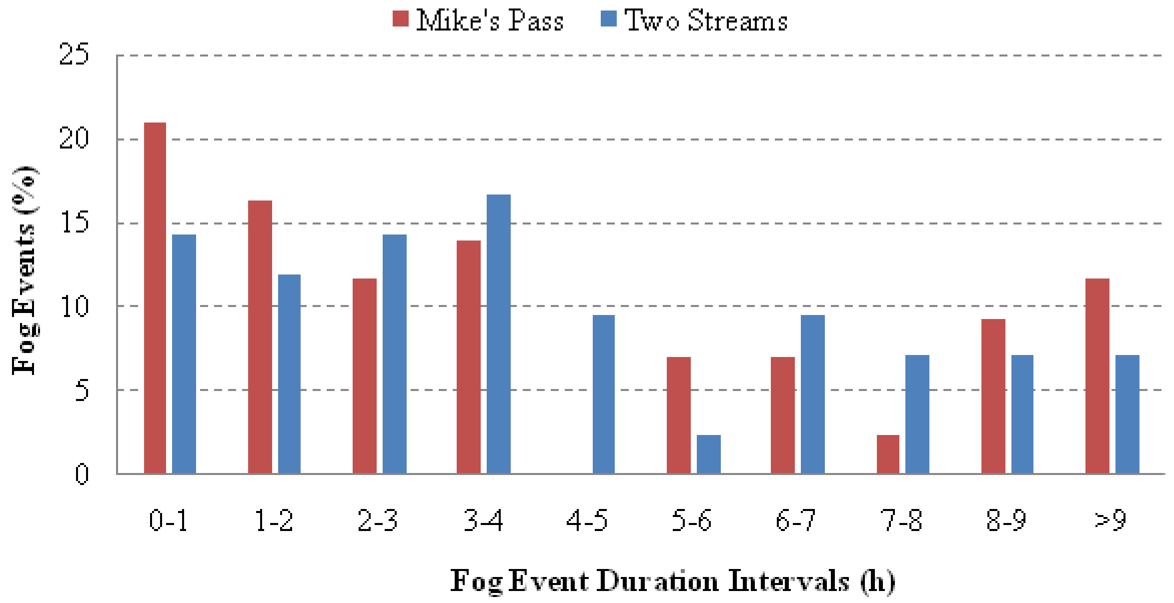

Figure 2.10 Percentage of fog events from July 2015 to October 2016 that occurred within specified duration intervals

2.3.5 Influence of wind speed and direction on fog

Plotting the average daily wind speed for fog days and non-fog days at Mike’s Pass and Two Streams (Figure 2.11 and 2.12) indicated that overall, slightly stronger wind speeds were experienced at Mike’s Pass, where greater fog yields were experienced (Figure 2.3). Additionally, at both sites, daily wind speeds were stronger in the wet summer season when greater fog yields occurred. However, it appears that winds were the same for fog days and non-fog days and no significant difference in wind speed between these days could be established. Analysing the influence of wind speed on fog yields, shows that at both sites, most fog occurred when wind speeds were low; approximately 24 % of total fog yields at Mike’s Pass and approximately 51 % of total fog yields at Two Streams occurred when wind speeds were less than 0.5 m s^{-1} (Figure 2.13). At Mike’s Pass, fog yields increased with wind speed up until 2.5 m s^{-1}, whereafter they decreased and fog rarely occurred when wind speeds exceeded 3.5 m s^{-1}. At Two Streams, greater fog yields occurred when there were lower wind speeds of less than 2.5 m s^{-1}.

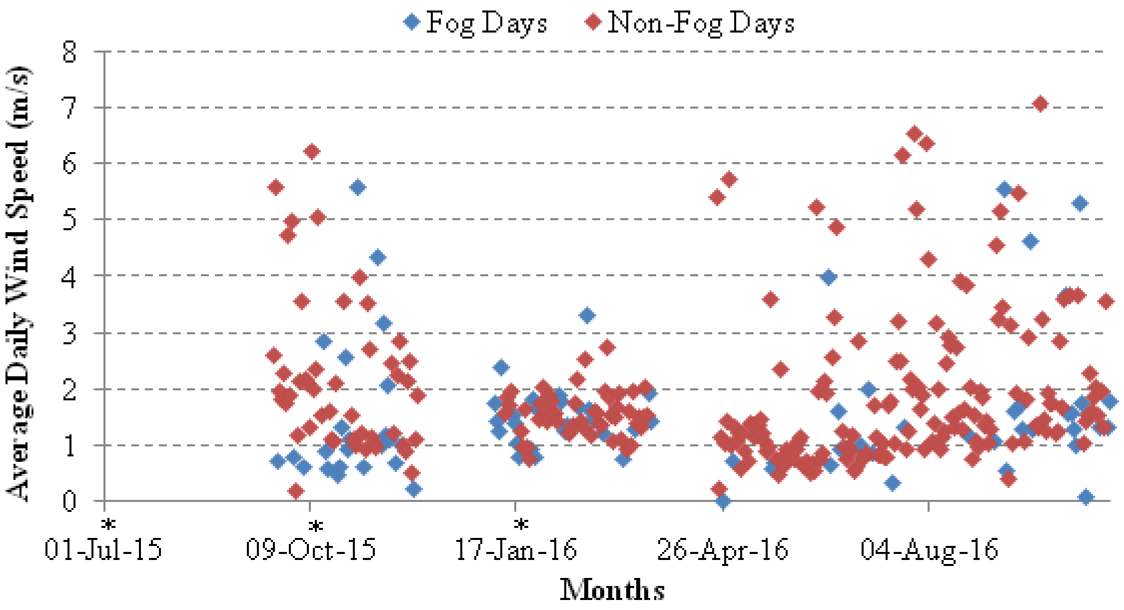

Figure 2.11 Average daily wind speeds on fog days and non-fog days at Mike’s Pass from July 2015 to October 2016. The stars (*) indicate the months when there was missing data

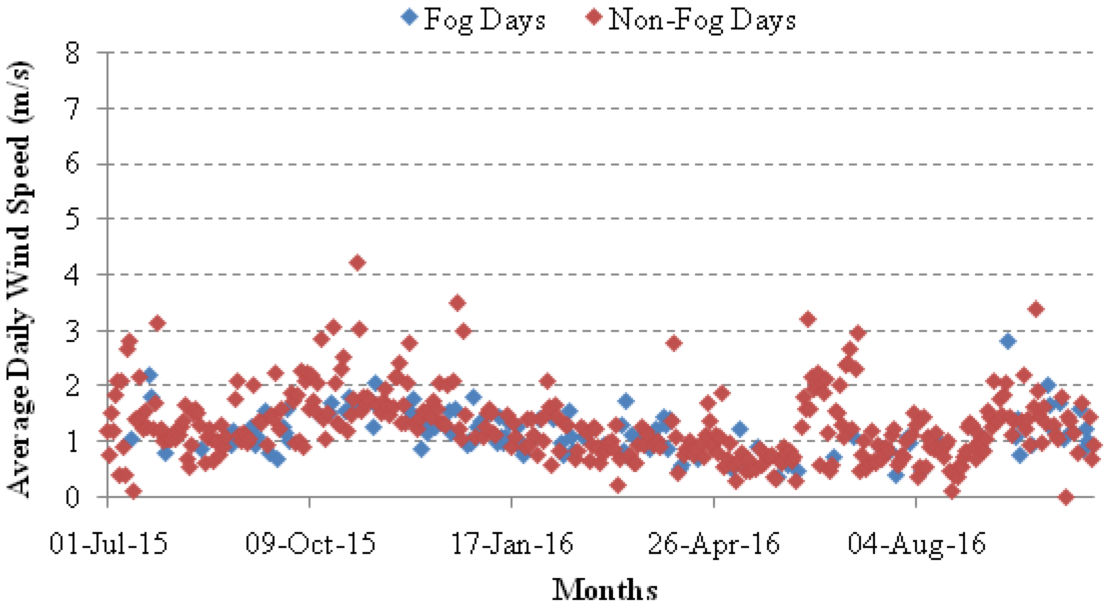

Figure 2.12 Average daily wind speeds on fog days and non-fog days at Two Streams from July 2015 to October 2016

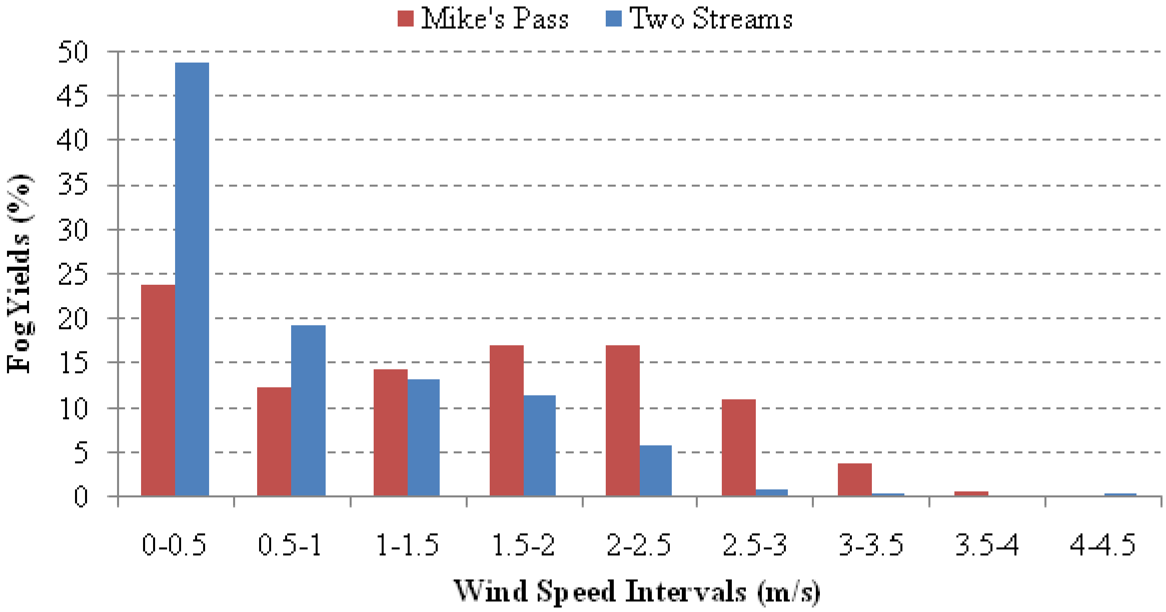

Figure 2.13 Fog yields from July 2015 to October 2016 for specified wind speed intervals

A stronger relationship between wind direction and fog was observed at Mike's Pass and Two Streams (Figure 2.14). At Two Streams, northerly, north-easterly and north-westerly winds prevailed all year round when fog occurred. Fog rarely occurred when any other wind directions prevailed. In the wet summer season when greater fog yields occurred, the northerly and north-easterly winds were most dominant. At Two Streams when fog occurred, eastely and south easterly winds prevailed in the summer, with a stronger westerly and southerly component during winter (Figure 2.15).

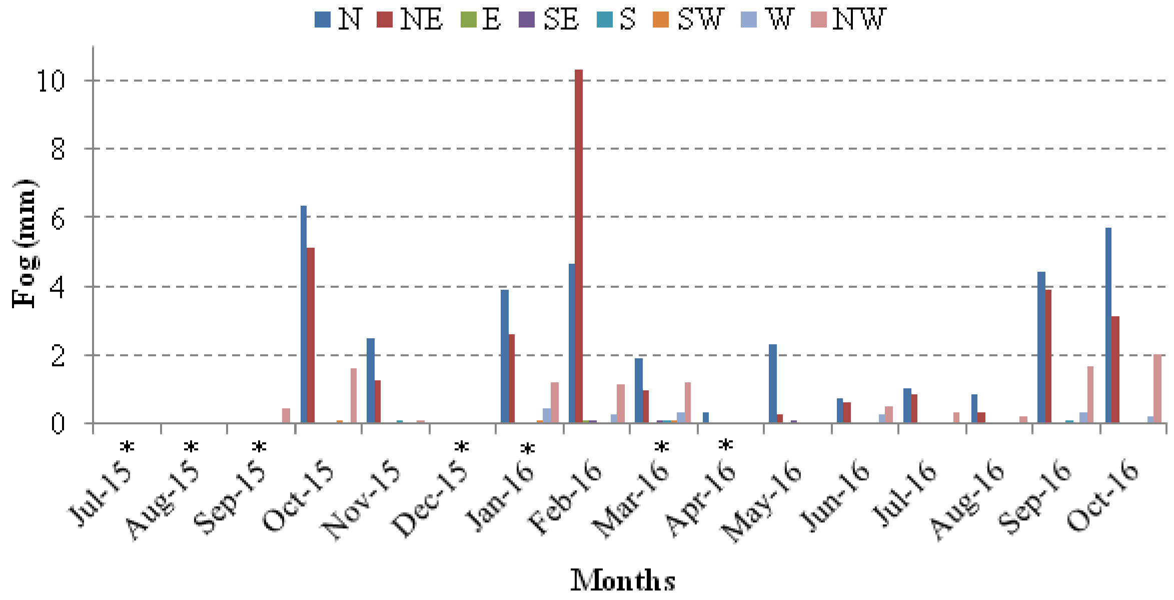

Figure 2.14 Fog yields measured per wind direction at Mike's Pass from July 2015 to October 2016. The stars (*) indicate the months when there was missing data

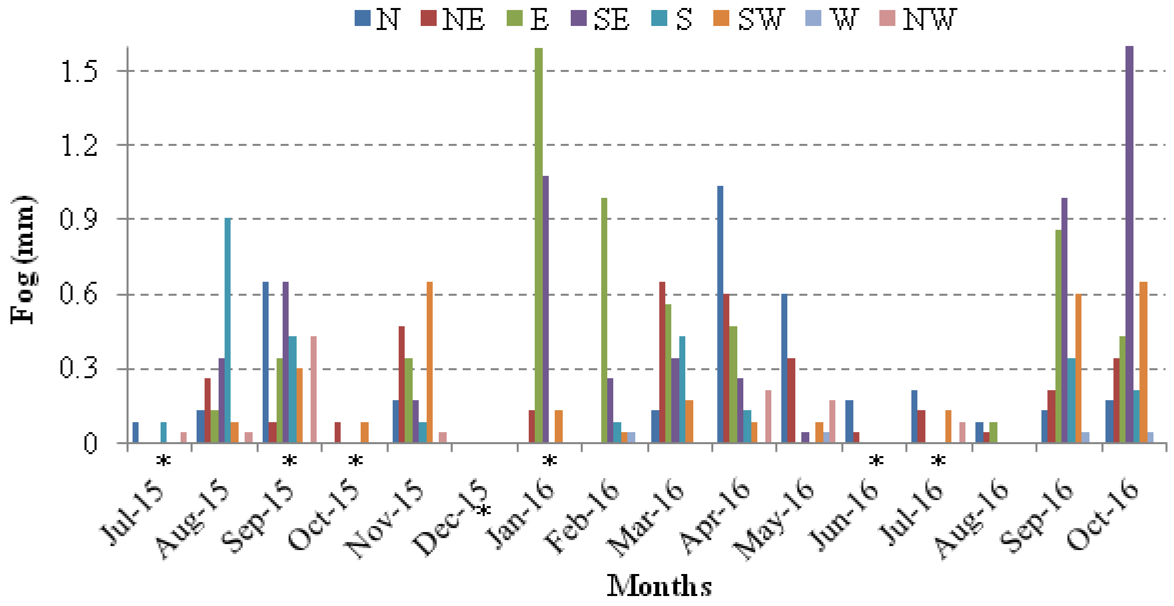

Figure 2.15 Fog yields measured per wind direction at Two Streams from July 2015 to October 2016. The stars (*) indicate the months when there was missing data

2.4 Discussion

The mountains forming South Africa's eastern escarpment experience some of the country's highest fog frequencies, yet very few fog studies have been conducted in this region (Kotzé, 2014). Past research has shown that particularly in mountainous environments, fog occurrence and the amount of water it produces can be extremely variable over time and space (Keppeler, 2007). Thus, this study attempted to characterize these temporal and spatial variations of fog at two sites located at different altitudes along South Africa's eastern escarpment.

Fog was found to exhibit distinct seasonal and diurnal patterns. Seasonally, fog occurred most frequently and contributed greater water yields during the wet summer season, confirming the findings of previous studies conducted along South Africa's eastern escarpment and west coast (Schmidt and Schulze, 1989; Louw *et al.*, 1998; van Schalkwyk and Dyson, 2013; Olivier *et al*., 2015). When considering the monthly percent ratio of fog to the total precipitation amount received, there were, however, greater fog contributions in most dry months when less rainfall occurred. This seasonal pattern agrees with other South African studies, however, differs from the findings of international studies, such as Liu *et al*. (2005), Marzol (2008) and Cavelier and Goldstein (1989), who have found greater fog frequencies and water yields during the dry season. There could be a number of reasons for this dissimilarity, most likely different climatological conditions, but could also include the presence of higher wind speeds promoting fog occurrence and more frequent fog-bearing winds that occur during the wet summer season along South Africa's eastern escarpment. Diurnally, fog was mostly confined to the cooler hours of the evening and early morning. At Two Streams, fog did not occur at midday when some of the highest temperatures are reached, but fog was able to occur throughout the day at Mike's Pass. This could be attributed to the lower air temperatures experienced at midday at Mike's Pass. Orographic fog and stratus clouds that occur here may also be more persistent than other fog types.

Spatial differences in fog occurrence and its water yield can be explained in terms of the important role that the topography plays, such as the altitude and hillslope orientation. This study only investigated the variation of fog with altitude; hillslope orientation was not considered, because fog gauges were not installed on the same mountain slope, and thus, accurate comparisons could not be made. On the whole, there were more frequent fog occurrences and greater daily and monthly fog water yields at the more elevated site, Mike's Pass than at the lower site, Two Streams. These significant differences in fog between the two sites point to the important role that altitude plays in the promotion of fog. The more frequent fog occurrences and greater fog water yields at Mike's Pass can be explained by a number of other reasons. Literature has emphasised that wind speed and direction are some of the most important factors influencing fog (Olivier and van Heerden, 2003; Olivier *et al.*, 2015). Although fog was not found to have a significant relationship with wind speed as found by much of the literature, wind speeds were substantially higher at Mike's Pass. A stronger relationship between wind direction and fog was observed, particularly at Mike's Pass, as a more elevated site is more exposed to fog-bearing winds. Orographic fog and stratus clouds that occur at Mike's Pass also contain higher liquid water contents than other fog types that form at lower altitudes, such as radiation and advection fog (Cavelier *et al.*, 1996; Ritter *et al.*, 2008). To further study the variation of fog with altitude, daily fog yields were compared over a short period where there was an overlap of data at the High Altitude site, Catchment VI and Two Streams. Generally, fog yields increased with altitude, however, this was not always found to be true. There were days where fog would occur at lower altitudes, but not at higher altitudes, as well as days where greater fog yields were measured at lower altitudes than at higher altitudes. It is thus evident that fog increases with altitude as a whole, however, literature has highlighted the fact that changes in other topographic features, such as the hillslope orientation and slope, over short distances, can mean that the delivery of fog is not uniform with elevation. Further investigation is required to determine whether this is also true for South Africa's eastern escarpment.

A number of uncertainties regarding this study must be acknowledged. Firstly, the Juvik-type fog gauges used in this study exhibit many design limitations and have no mechanism to differentiate between fog and wind-blown drizzle and rainfall (Hansen and Juvik, 2010; Frumau *et al.*, 2011). The fog gauges were, however, a useful indicator of fog conditions, such as its frequency, timing and amount. Secondly, there was only one gauge at each site, despite the high spatial variability of fog at these mountainous sites. This study may thus be insufficient as a regional assessment, but will assist in establishing where further studies need to be conducted. Thirdly, the literature states that a site situated closer to the coast has more fog, however, this study found that altitude was a more important factor and the site situated closer to the coast had less fog than the site further away. Finally, the study was conducted during a period of severe drought in South Africa and these hot and dry conditions may have affected fog occurrence and water yields.

2.5 Conclusion

Fog was found to be prevalent along the eastern escarpment of South Africa, potentially contributing significantly to the water balance, however, its occurrence and water yield patterns have proven to be highly variable over both time and space. Temporally, fog was mostly confined to the cooler hours of the day and the wet season of the year, although fog did have a greater contribution, relative to the total precipitation, during the dry season. Spatially, the distribution of fog must be explained in terms of the important role that the local topography plays. Fog was generally found to increase with altitude, however, other topographic features, such as the hillslope orientation and slope are believed to play an equally important role in spatial fog variability. Further studies into the influence of these topographic features on fog are recommended. The findings of this study may be useful in assisting in future long-term climatological studies of fog and low cloud occurrence along South Africa's eastern escarpment.

2.6 Acknowledgements

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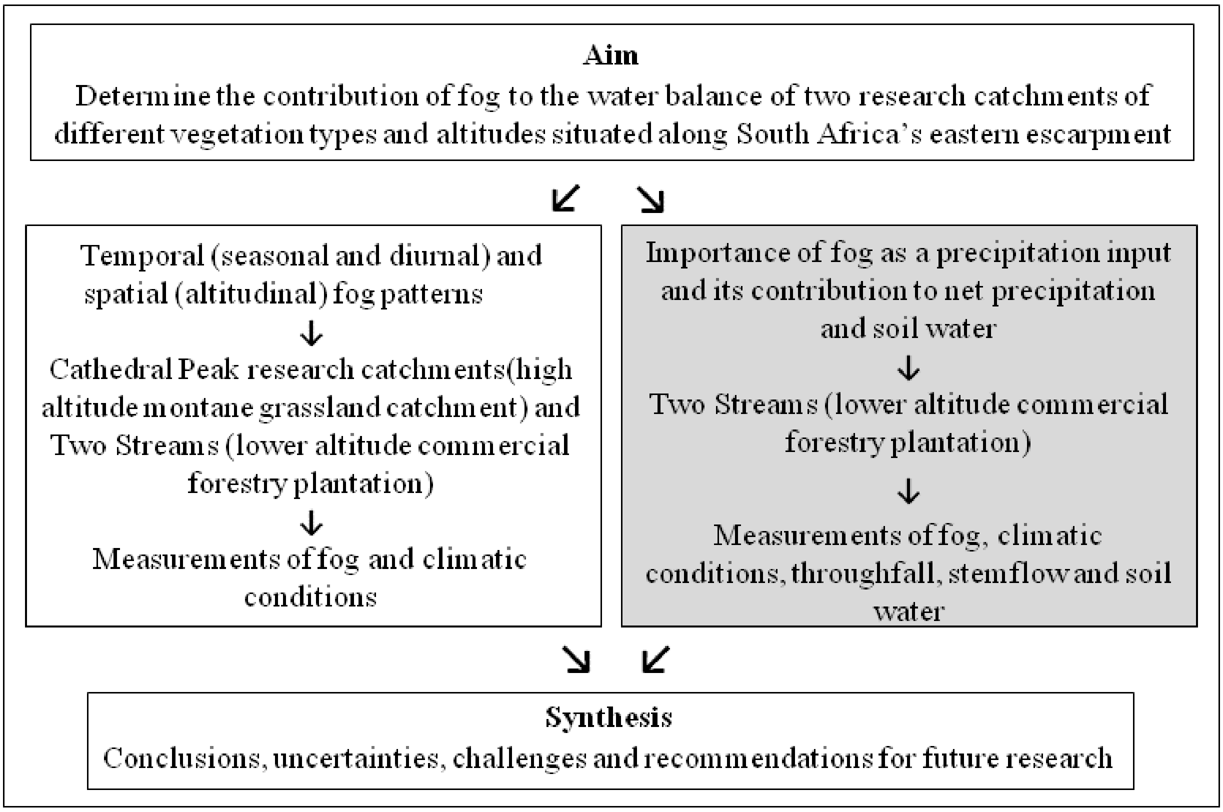
Lead into Chapter 3

Chapter 3 investigates the importance of fog as a precipitation source and whether it contributes to net precipitation and soil water at Two Streams, a fog-affected commercial forestry catchment. Measurements of the precipitation, fog, throughfall, stemflow and soil water content were conducted.



CHAPTER 3: THE CONTRIBUTION OF FOG TO THE WATER BALANCE OF A COMMERCIAL FORESTRY CATCHMENT SITUATED IN THE KWAZULU-NATAL MIDLANDS, SOUTH AFRICA

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ABSTRACT

Wind-driven, horizontal fog water interception by vegetation has widely been recognised as an important component in the hydrology and ecology of indigenous forests, where fog occurs frequently. In South Africa, no forestry studies have attempted to quantify fog and no information exists on the relative dependence of these ecosystems on this precipitation input. This study aims to investigate the importance of fog as a precipitation source and whether it contributes to net precipitation and soil water at Two Streams, a fog-affected commercial forestry catchment. Over a 16-month period, the precipitation, fog, throughfall, stemflow and soil water content were measured. Fog was found to represent 4.6 % of the total precipitation input, occurring mostly over the wet summer season. Fog, however, comprised a larger proportion of the total precipitation during the dry winter season. During fog-only events, evidence of throughfall and stemflow was found, but fog did not facilitate throughfall of rainfall or contribute to soil water. Due to the high frequency of fog occurrence noted at Two Streams, the indirect effects of limiting wet canopy evaporation and transpiration rates were suggested to be a more relevant effect on the water balance.

Keywords: *cloud forest, mist, interception, soil water*

3.1 Introduction

The interception of wind-blown fog water droplets by vegetation has widely been recognized as an important component in the hydrology and ecology of indigenous forests, where fog episodes and low-level cloud cover occur frequently (Chang *et al.*, 2006; Keppeler, 2007; Ritter *et al.*, 2008; Hansen and Juvik, 2010). In addition to reducing evapotranspiration rates, moderating temperatures and playing a role in nutrient cycling, fog has been proven to provide an additional moisture input when droplets are intercepted by the forest canopy and drip to the ground (Yin and Arp, 1994; Chang *et al.*, 2002; Prada *et al.*, 2009). The significance of fog as a precipitation source has been proven in cloud forests world-wide that are thriving in water-scarce environments (Fessehaye *et al.*, 2014). For example, on the American Pacific Coast, there is only sufficient rainfall for Mediterranean scrubby vegetation, but due to high fog occurrence, tall coniferous redwood forests exist (Dawson, 1998). The northern coastal hills of Chile and Peru also experience low rainfall, but their forests survive almost exclusively on high amounts of advection sea fog (Pinto *et al.*, 2001).

Over the last two decades a number of cloud forest studies have attempted to quantify fog, reporting varying proportions to their annual inputs (Keppeler, 2007; Ritter *et al.*, 2008). One of the world's most extensively-studied ecosystems includes the coastal redwood forests of northern California, where Dawson (1998) found that there was on average 447 mm of fog drip each year. This equated to over one-third of the total precipitation input. On the extreme high end of reported values, a study of a montane forest on Madeira Island in Portugal measured 5100 mm of fog per year, representing a 73 % contribution (Prada *et al.*, 2009). This study even reported evidence of groundwater recharge by fog. In a montane forest in Taiwan, fog measured an average of 328 mm per year, occurring frequently, with the number of annual fog days often exceeding 350. High rainfall, however, reduced the importance of fog to the water supply and fog only contributed to 10 % of the annual total hydrological input (Chang *et al.*, 2006). Generally, studies found that the fog contribution to the monthly water supply varied greatly between seasons, with fog being more frequent, lasting longer durations and constituting a larger proportion of the total precipitation in the dry season (Liu *et al.*, 2004; Marzol, 2008; Ponette-González *et al.*, 2010). In a tropical seasonal rainforest in south-west China, fog contributed a very small proportion of 89.4 mm, only 5 % to the annual precipitation. However, 86 % of this fog occurred during the dry season, representing 49 % of the total precipitation in the same period. Using stable isotope analysis at this site, shallow soil water was found to contain more fog than rainfall in the dry season (Liu *et al*., 2004).

Trees are good fog collectors and those with a larger surface area (i.e. taller canopies, greater leaf area index’s and small needle-like leaf structures) are more efficient fog interceptors (Prada *et al*., 2009; Holwerda *et al*., 2013; Fessehaye *et al*., 2014). For this reason, as well as the fact that forests have rougher surface areas, water input and soil moisture contributions by fog have been found to be measurably higher in forest stands than in grasslands (Dawson, 1998; Liu *et al*., 2007). In the coastal redwood forests of northern California, Dawson (1998) found that approximately 34 % of the annual hydrologic input came from fog drip off of the trees, when the trees were removed from the catchment the average annual input from fog was only 17 %. Regarding climatic factors, the intensity of fog interception increases with greater frequencies and durations of fog events, larger droplet size distributions, higher wind speeds and wind exposure from all directions (Cavelier and Goldstein, 1989; Ritter *et al*., 2008; Villegas *et al*., 2008; Prada *et al.*, 2009; Klemm *et al*., 2012). Terrain factors promoting fog interception include higher elevations and hill slopes oriented toward winds that bring fog (Cavelier and Goldstein, 1989; Marzol, 2008; Ritter *et al*., 2008; Prada *et al*., 2009).

Quantifying the fog deposition rate in forested ecosystems has been proved challenging (Frumau *et al*., 2006; Holwerda *et al*., 2010). Not only is it difficult to measure horizontal fog water interception by tall vegetation, separating fog from the horizontal component of wind-driven rainfall is not an easy task (Hansen and Juvik, 2010). Furthermore, where measurements have been made, it is impossible to quantitatively compare results at different locations, due to the wide range of collection devices that have been used (Schemenauer and Cereceda, 1994). The most common method is the use of fog gauges (Villegas *et al*., 2008). Fog gauges are able to estimate the frequency and amount of fog that can be potentially captured by nearby vegetative surfaces, but they do not represent vegetative surfaces and fail to provide a direct quantification of fog water interception by vegetation (Gabriel and Jauze, 2008; Pryet *et al.*, 2012). There have, however, been good relationships found between fog gauges and fog-induced canopy throughfall, making it possible to use open-site fog gauge measurements to predict adjacent forest canopy throughfall (Cavelier and Goldstein, 1989; Holwerda *et al*., 2011). Fog can also be measured indirectly, through comparison of rainfall and net precipitation for periods with and without fog (Holwerda *et al*., 2006; Schmid *et al*., 2011; Pryet *et al*., 2012). This method, however, only provides a minimum estimate of fog, as it fails to consider canopy interception and its subsequent evaporation, and fog is only quantified when net precipitation exceeds gross precipitation (Liu *et al*., 2004; Holwerda *et al*., 2006; Prada *et al*., 2009; Schmid *et al*., 2011). Stable isotopes have been explored as a useful tool in tracing fog water movement, and in more recent years, more sophisticated instruments have been introduced, including cloud droplet spectrometers and the eddy covariance technique (Chang *et al*., 2006; Frumau *et al*., 2006; Scholl *et al*., 2010; Frumau et al., 2011). Thus, debate remains on how best to quantify fog interception in cloud forests and a reliable, convenient and inexpensive method is yet to be developed (Fessehaye *et al*., 2014).

In South Africa, no forestry studies have attempted to quantify fog and there is no information available on the relative dependence of these ecosystems on this precipitation source. One of the country's most intensively studied long-term forestry monitoring catchments includes Two Streams. Two Streams is not an indigenous cloud forest, although it is situated in a 'moist midlands mist belt' and experiences frequent fog occurrences. Questions regarding the fog input have arisen in the past, but the extent to which it contributes to the catchments water balance has not been investigated. A study by Burger (1999) found that the annual evapotranspiration measured above the *Acacia mearnsii* plantation exceeded the annual rainfall by 45 % during the exponential growth phase. Everson *et al.* (2014) suggested that the unaccounted for water in the water balance could be due to the absence of incorporating fog as a form of precipitation. Bulcock and Jewitt (2012) recently conducted an interception study at Two Streams, but didn't consider fog in their measurements. This study, therefore, aims to investigate the importance of fog as a precipitation source and whether fog contributes to net precipitation and soil water in a fog-affected commercial forestry catchment, where rainfall is highly seasonal.

3.2 Materials and Methods

3.2.1 Site description

The Two Streams catchment is situated on Mondi Forest's Mistley-Canema Estate (30.67"S, 29.19"E) in Seven Oaks on the Greytown road, approximately 70 km from Pietermaritzburg in the KwaZulu-Natal Province of South Africa (Figure 3.1). It is one of South Africa's most intensely studied long-term forestry research catchments, with 15 years of detailed hydrological process observations. Research in the Catchment has contributed significantly to scientific advances in riparian zone management and groundwater/surface water interactions (Everson *et al*., 2014).

The catchment is located in the summer rainfall zone of South Africa, experiencing an annual rainfall of between 659 and 1139 mm. Most of this rainfall comes from summer thunderstorms and cold fronts (Everson *et al*., 2014). Seven Oaks lies in a “moist midlands mist belt grassland” according to the South African Bioresource Group (BRG) classification system, and thus, mist can be heavy and frequent in the catchment (Bulcock and Jewitt, 2012). The mean temperature of the area is 17 °C. The area is prone to occasional droughts, hail and frost, while berg winds occur frequently in the area (Everson *et al*., 2014).

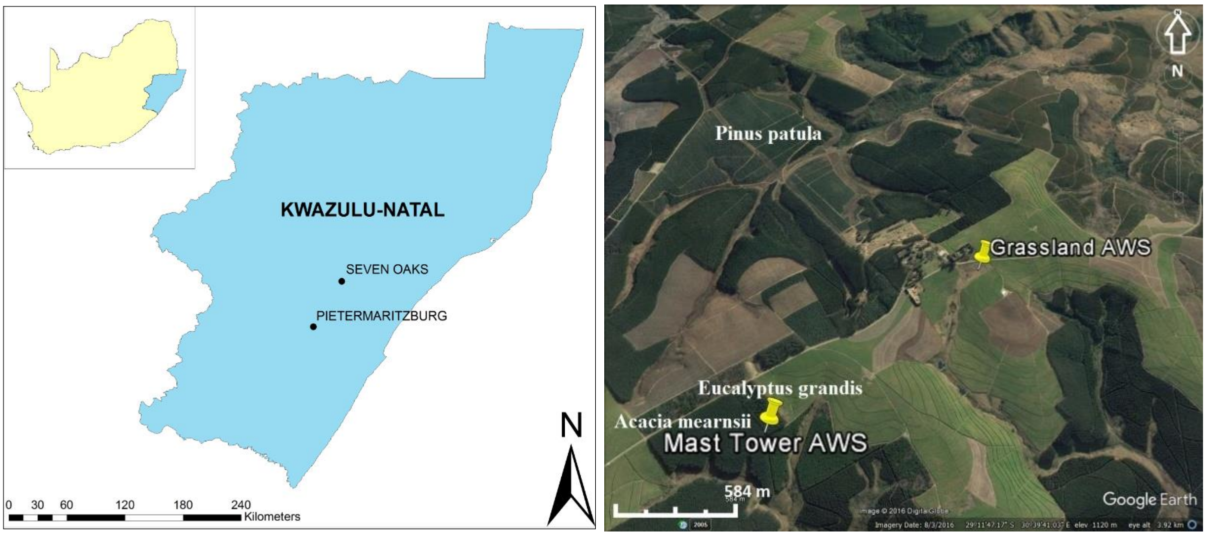

Figure 3.1 Map of the location of Seven Oaks, situated in the KwaZulu-Natal Province, South Africa and the location of the instrumentation setup in the *Acacia mearnsii* stand at Two Streams

The area was previously a natural *Themeda triandra* grassland; however, due to invasion of native *Aristida junciformis,* only a few relic patches of this grassland remain (Everson *et al*., 2007; Everson and Clulow, 2011). The catchment has since been converted to commercial forest plantations of *Acacia mearnsii*, *Eucalyptus grandis* and *Pinus patula,* as well as a small area of sugarcane, due to its high percentage of arable land. The terrain consists of gentle slopes and rolling landscapes, with the elevation ranging from 1071 m.a.s.l to 1170 m.a.s.l at the highest point (le Roux *et al*., 2011; Everson *et al*., 2014; Everson and Clulow, 2011). The geology consists mainly of sandstone of the Natal group with small areas of dolerite (le Roux *et al*., 2011). The soils are highly leached as a result of the moist climate, thus promoting the genesis of dystrophic soils (Everson *et al*., 2007; le Roux *et al*., 2011). They are mostly apedal and plinthic, derived mainly from the Ecca group with dolerite dykes and sills (Everson *et al*., 2014; Everson and Clulow, 2011).

3.2.2 Field instrumentation

Field measurements were conducted over a period of 16 months, from July 2015 to October 2016. The precipitation, fog, throughfall (the precipitation that passes through or drips from the canopy to the forest floor), stemflow (the intercepted precipitation that flows down the branches and trunk of the tree to the forest floor) and soil water content were measured to estimate the contribution of fog to the water balance of the catchment. Instrumentation was set up in the *Acacia mearnsii* plantation and at the Automatic Weather Station (AWS) in an open grassland area near the forestry plantations. These study sites and the location of the instrumentation setup is shown in Figure 3.1.

The climatic conditions at Two Streams were monitored by the AWS in the open grassland and a second AWS at the top of a 24 m tall lattice mast above the *Acacia mearnsii* canopy, close to the centre of the stand. Instrumentation at the AWS was installed at a measurement height of 2 m above the short grass surface, except for the rain gauge (TE525, Texas Electronics Inc., Dallas, Texas, USA) that was installed with the orifice at 1.2 m above the surface. Sensors included a wind vane and 3-cup anemometer (Model 03001, R. M Young, Traverse city, Michigan, USA), a pyranometer (LI200x, LI-Cor, Lincoln, Nebraska, USA) and air temperature and relative humidity (HMP50, Vaisala Inc., Helsinki, Finland). These instruments were connected to central receiving loggers (Campbell Scientific Inc. (CS) data loggers (CR1000 and CR23X)) recording data at event-based, 5-minute, 10-minute, 20-minute, hourly and daily intervals.

Fog was measured using a Juvik-type fog gauge, installed at the grassland AWS at a height of two metres above the ground. The fog gauge consists of a louvered brass mesh cylindrical screen of 44.4 cm height and 25 cm diameter (1109.5 cm^2 cross-sectional area), based on the design by Juvik and Ekern (1978). The fog collection process occurs when horizontally wind-blown fog water droplets collect on the mesh screen, where they coalesce until they are heavy enough to flow down into a funnel connected to a Texas rain gauge. On top of the cylindrical screen, there is an extra funnel connected to a PVC pipe, to drain away rain water. Due to its cylindrical design, the Juvik gauge represents the same silhouette and catch surface area to the prevailing wind, independent of the wind direction, providing consistent and comparable fog measurements in all environments (Frumau *et al*., 2006; Estrela *et al*., 2008). The Juvik gauge also has good drainage characteristics, is of a durable construction and is inexpensive to construct and maintain (Hansen and Juvik. 2010). They, however, have no mechanism to separate fog from drizzle and rainfall and have been found to over-estimate fog water deposition to vegetation, due to artificial collecting surfaces of fog gauges and natural plant surfaces differing in their rates of fog water collection (Frumau *et al*., 2011).

To convert fog gauge output to a "unit vertical catch" equivalent to a rain gauge in units of depth (mm), the manufacturer's calibration of 0.254 mm was accepted, and a ratio between the collection area (cm^2) of the standard Texas rain gauge orifice to the collection area of the fog gauge mesh was calculated.

Two sets of throughfall and stemflow collectors were set up in the *Acacia mearnsii* plantation, to determine whether there was any indication of fog drip beneath the canopy. These collectors were placed at randomly chosen trees, one set towards the centre of the plantation and one on the windward edge. The throughfall collectors consist of a nest of three "V"-shaped troughs made from galvanised iron sheeting, 0.1 m wide and 2.0 m long, based on the design of Cuartus *et al.* (2007). The troughs were installed at an angle of between 15 and 20 ^{o} to facilitate drainage and their radial arrangement accounted for the linear variability within the canopy. The design of the steep "V"-shaped sides helps to minimise splash out and the troughs were covered with mosquito netting, to decrease the entry of debris. Stemflow was measured using spiral-type collectors attached around the trunk of the tree between 1 and 1.5 m above the ground. They are made of PVC tubing (internal diameter = 20 mm), which are cut open lengthwise and any remaining gaps between the tubing and the trunk were sealed with silicone sealant. Both the throughfall and stemflow collectors were connected to Davis single tipping bucket rain gauges, where each tip on an event basis was recorded with a HOBO pendent event logger.

Soil water probes were additionally setup beneath the *Acacia mearnsii* plantation, to determine whether fog contributes to the soil water content. Four soil water probes (CS616, Campbell Scientific) were horizontally installed in the surface soil layers at depths of 25 and 50 mm, with one set placed close to the trunk of the tree and the other placed between the rows of trees. Soil water probes measure the volumetric water content from 0 % to saturation and have high accuracy, high precision and a fast response time. They were connected to a CR1000 logger, recording data at 5 minutes intervals.

3.2.3 Data collection problems

Due to technical problems, a number of gaps existed in the grassland AWS data record, but they were patched with data from the second AWS in the *Acacia mearnsii* plantation. A number of gaps also existed in the throughfall and stemflow data, as the small compound leaves of *Acacia mearnsii* lead to occasional blockages of the Davis tipping bucket gauges that were connected to the collectors. This excluded a larger subset of data, particularly during the rainy season.

3.3 Results

The results are presented over a 16-month period from July 2015 to October 2016. Focus was on evaluating the efficiency of the fog gauge, the contribution of fog to the precipitation input, the frequency of fog occurrence and whether any evidence of fog could be found in throughfall, stemflow and soil water content measurements.

3.3.1 Fog gauge collection efficiency

The raw data of monthly fog yields measured by the fog gauge was plotted against the monthly rainfall (Figure 3.2). The monthly fog yields were highly exaggerated, even exceeding the rainfall during some months, including October 2015, November 2015 and April 2016. This is due to the Juvik gauge measuring fog and windblown rainfall combined, having no mechanism to separate the two. Due to the impossibility of differentiating the origin of water collected by the fog gauge during rainfall episodes, this study chose to eliminate all data collected from the fog gauge within an hour of any rainfall being recorded. This, however, leads to an underestimation of fog when rainfall was present.

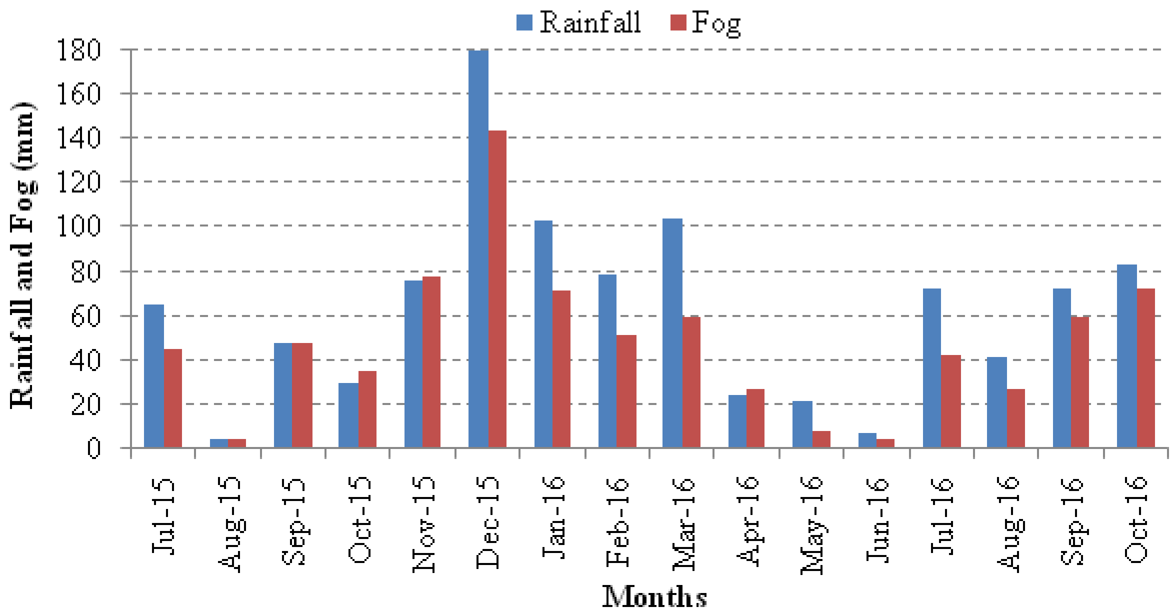

Figure 3.2 Monthly rainfall and fog using raw data from July 2015 to October 2016

3.3.2 Contributions of fog to the precipitation input of the catchment

Over the 16-month measurement period, the rain gauge recorded a total of 1006.3 mm, while the fog gauge measured 48.4 mm in the absence of rainfall. Thus, fog represented 4.6 % of the total precipitation input over this period. Fog occurred all year round, with higher fog yields experienced mostly over the wet summer season, generally from September through to April (Figure 3.3). In particular, the months of December 2015, January 2016 and October 2016 had the highest fog water yields, with these months also having some of the highest total rainfalls during the measurement period. When considering the monthly percent ratio of fog to the total precipitation amount received, the fog contribution varied between wet and dry seasons. Although more fog was received in the wet summer months, the fog contribution relative to the rainfall was greater in the dry winter months. During the driest month of August 2015, fog represented a contribution of more than one third of the total precipitation. Unusually high rainfall occurred in the dry season months of July 2015 and July 2016, resulting in a lesser contribution to the water balance than in the other dry season months.

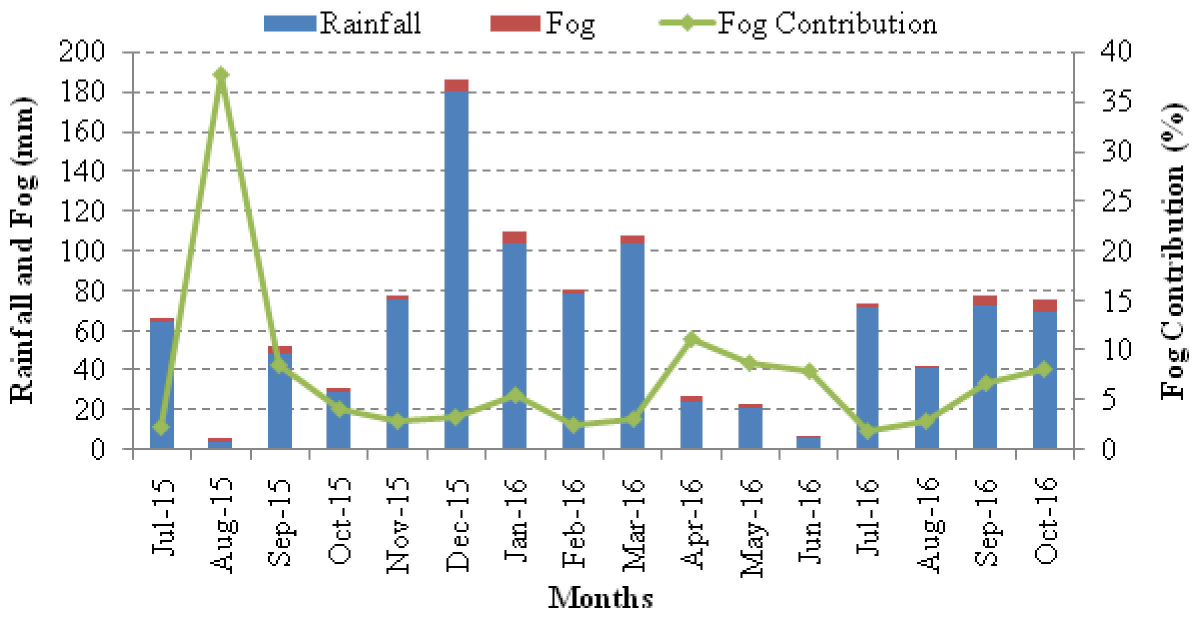

Figure 3.3 Monthly rainfall and fog yields when rainfall was absent (represented by the bar graph) and the ratio of fog to total precipitation (represented by the line graph) from July 2015 to October 2016

The daily fog yields measured in the absence of rainfall (Figure 3.4) show that there were more fog events and larger daily fog yields in the wet summer season, while fewer fog events and lower daily fog yields occurred in the dry winter season. Generally, most days experienced very low fog yields of less than 0.5 mm, however, some days in the wet summer season measured up to approximately 1.7 mm of fog per day. The highest daily fog yield occurred towards the end of September 2016 and measured approximately 2.6 mm.

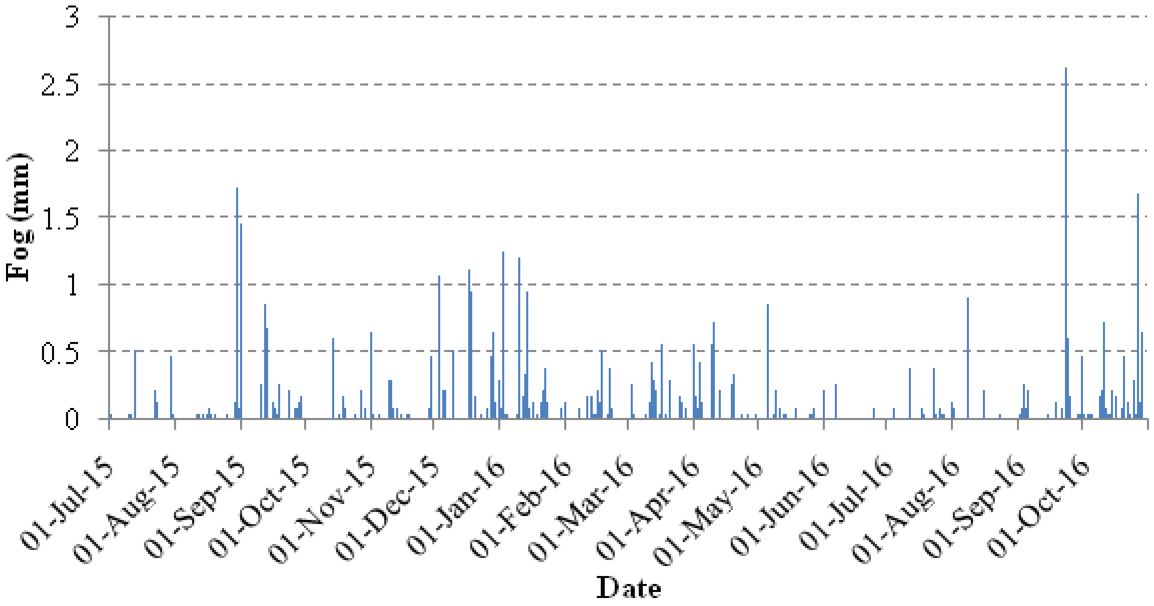

Figure 3.4 Daily fog yields (when rainfall was absent) from July 2015 to October 2016

3.3.3 Frequency of fog occurrence

Total precipitation was divided into four categories (Figure 3.5). The four categories in the graph represent the percentage of days each month that experienced fog-only, rainfall and fog, rainfall-only or no precipitation at all. A day was considered to be a fog day when during a 24-hour period, starting at midnight, the fog gauge measured atleast 0.1 mm in the absence of rainfall. A rain day was determined in the same manner, provided the rain gauge measured atleast 0.2 mm. Generally, a higher distribution of rain days occurred than fog days during a month, except for April 2016 when a slightly higher distribution fog days than rain days occurred. Between 5 and 36 % of days during a month experienced fog, either alone or accompanied by rainfall. During the wet summer months, particularly December 2015, January 2016 and October 2016, a higher number of days experienced fog, corresponding to the higher fog water yields measured over these months (Figure 3.3). Fog-only events occurred frequently at Two Streams, with the maximum event duration persisting for 13 hours and 39 minutes, the minimum for 38 minutes and the average for 4 hours and 18 minutes.

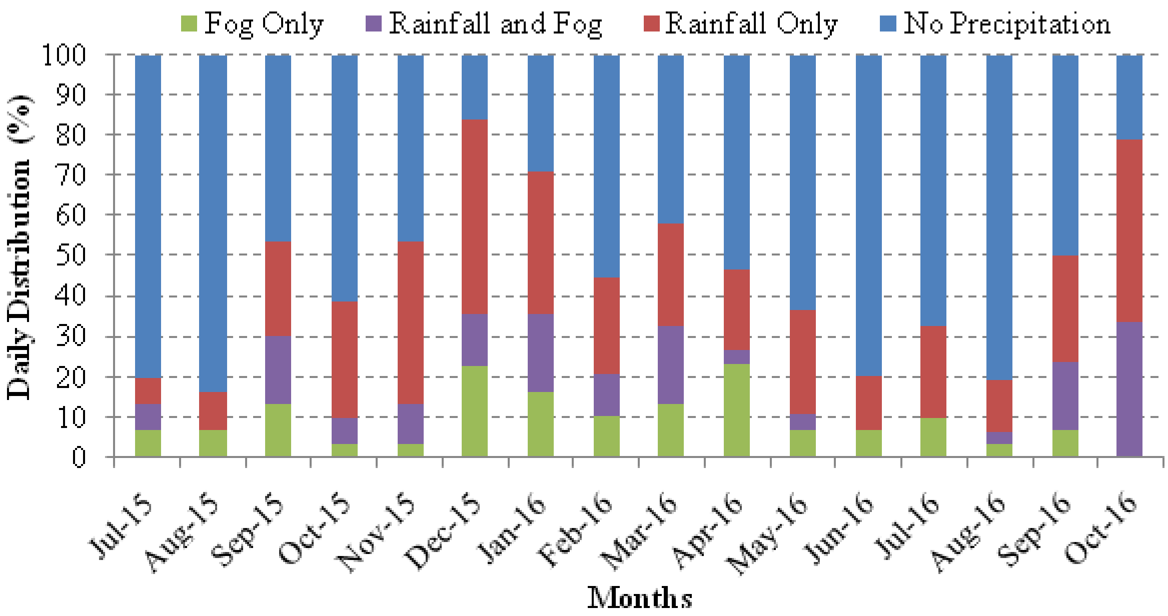

Figure 3.5 Distribution of precipitation at Two Streams from July 2015 to October 2016

3.3.4 Evidence of fog drip

When analysing fog-only events that occurred in the absence of rainfall, several events indicated evidence of throughfall and stemflow volumes in collectors. It was noted during this analysis that these were the fog events that had the longest durations and highest water yields. It was also investigated whether fog water interception assisted in bringing the canopy closer to saturation, so that when rainfall occurred, there were quicker and greater responses in throughfall. This was done by plotting open-site rainfall against *Acacia mearnsii* throughfall for two series: 1) mixed fog and rainfall events, and 2) rainfall-only events (Figure 3.6). Rainfall events that were less than 20 mm and of lower intensities were only included in the comparison against mixed fog and rainfall events, as fog does not occur with heavy rainfall or thunderstorm downpours that occur often in summer at Two Streams. As rainfall increased, throughfall increased, and throughfall was about half that of the rainfall. Both series showed a similar relationship with an almost identical linear regression line and fitted equation, indicating that fog does not play a significant role in filling the canopy storage capacity and facilitating greater throughfall amounts.

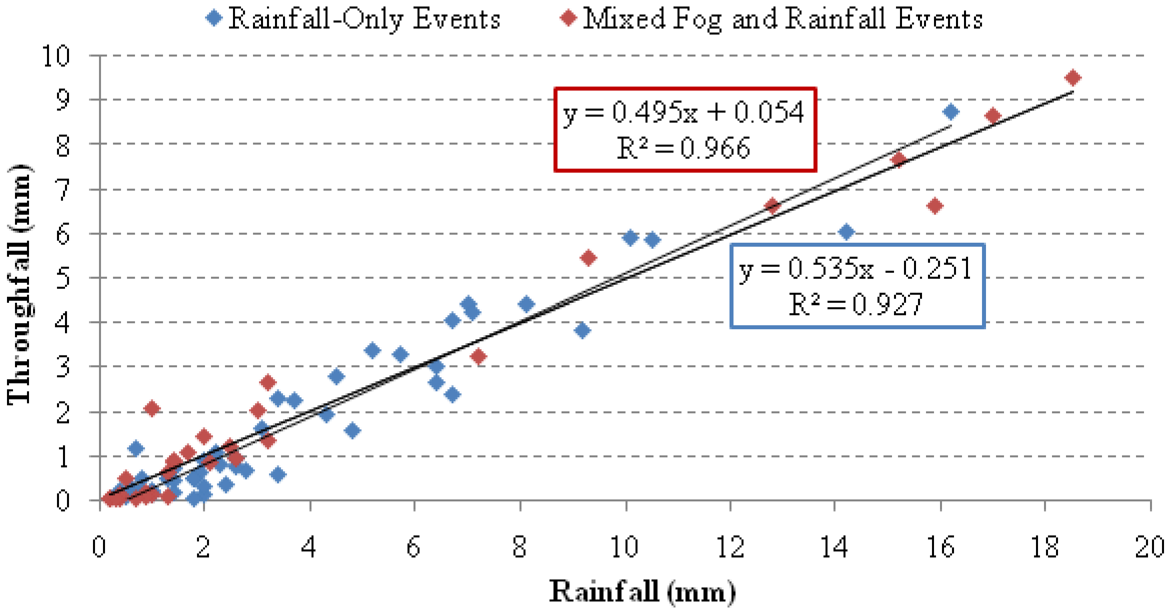

Figure 3.6 Open-site rainfall vs. *Acacia mearnsii* throughfall for mixed rainfall and fog events and rainfall-only events

Regarding the soil water content, no change was detected during fog-only events. Figure 3.7 shows three events of the highest water yields and longest durations, where fog accumulations were plotted against the change in soil water content. No spikes occurred in the 25 or 50 mm sensors placed at the trunks of the trees and between the rows of trees during any of these events. The second fog event had an over 2.5 mm water yield, but this was not detected in the soil.

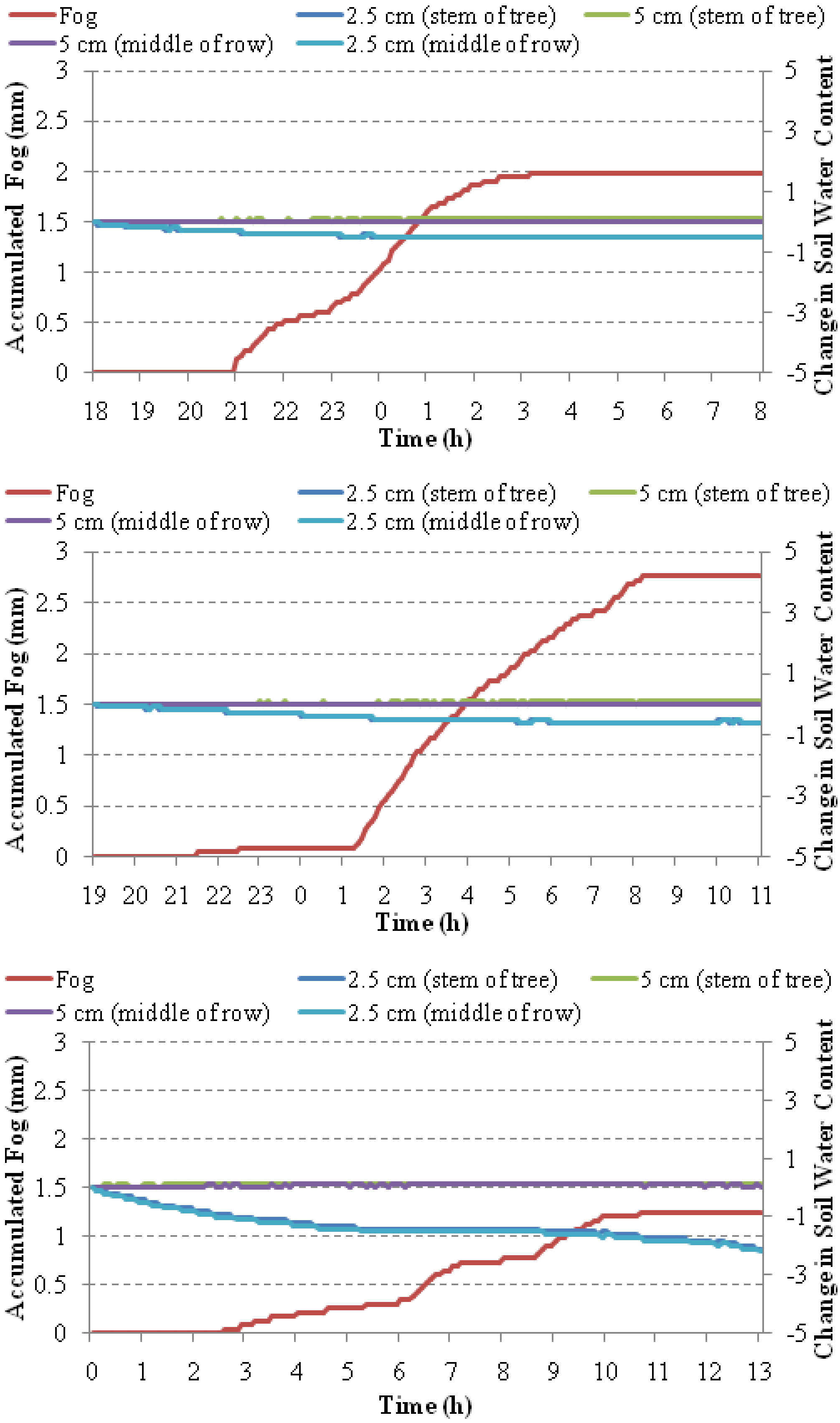

Figure 3.7 Fog accumulations and the percentage change in soil water content over time for three of the largest fog-only events

3.4 Discussion

Past studies have suggested that horizontal precipitation via fog interception can provide a significant hydrological input to cloud forests worldwide, particularly those in drier ecosystems, where fog events occur regularly (Holder, 2004; Ebner *et al*., 2011). Up until now, no studies in South Africa have quantified fog and its contribution to the water balance of a forested ecosystem, this being the first attempt.

Quantifying fog deposition rates in forested ecosystems has proved difficult and a variety of methods have been used at different sites, making it impossible to compare collection results (Hansen and Juvik, 2010; Holwerda *et al*., 2010). This study used a Juvik-type fog gauge to determine the amount, timing and duration of fog occurrence. This data was also monitored concurrently with stemflow, throughfall and soil water to establish whether fog contributed to net precipitation and soil water content. The fundamental problem in attempting to quantify fog using any type of fog gauge is that these instruments have no mechanism to differentiate between fog and wind-blown drizzle and rainfall. Fog frequently occurred simultaneously with drizzle and rainfall, thus fog yields measured by the fog gauge were highly exaggerated (Figure 3.2). For this reason, this study had no choice but to ignore fog gauge data when rainfall occurred during the same period. In the past, studies have made several attempts to correct fog measurements contaminated by rainfall. Schemenauer and Cereceda (1994), Hansen and Juvik (2010) and Estrela *et al*. (2008) all attempted to eliminate the simultaneous rainfall component from fog measurements with similar data reduction techniques using rainfall, wind speed, and event drop size estimates, but these correction factors only lead to more uncertainty in results. Frumau *et al*. (2006) shielded their fog gauge from rainfall with a 'hat' and Schemenauer and Cereceda (1994) also mentioned a previous study that had placed louvers on the screen of a cylindrical fog gauge, however, these additions only partly prevented the collection of rainfall. Fog gauges do not mimic forest structure, and the problem of relating results given by this instrument to fog water intercepted by an actual canopy, has still not been solved.

After an analysis of fog accumulations recorded during the absence of rainfall, it could be confirmed that fog accounted for approximately 4.6 % of the total precipitation amount received over a 16-month period at Two Streams. Although this number is not comparable to other studies, as similar comparative studies for forestry catchments in South Africa are non-existent and different methodologies and various collection devices have been used by international cloud forest studies, this is a fairly small contribution at the lower range of reported values. It must be noted that the actual fog amount is believed to be larger than reported, as the fog gauge data was excluded when rainfall occurred. Fog was found to be fairly seasonal, occurring most frequently and contributing greater yields during the wet summer period, from September through to April. This contradicts the results of other international studies that have found fog to be more frequent and supply greater water yields during the dry season, however, fog constituted a larger proportion of the total precipitation during most dry season months, due to the low amount of rainfall that occurred. It must be acknowledged that the study was conducted during a period of severe drought in South Africa, which may have affected fog occurrence and water yields.

When the fog gauge suggested fog occurrence in the absence of rainfall, evidence of throughfall and stemflow was found, but for the most part, fog remained trapped in the forest canopy. These fog events may have been of too short duration and their water content too low to result in any measurable net precipitation. According to Bulcock and Jewitt (2012), interception is a threshold process, in that "a certain amount of precipitation is required to saturate the canopy, as well as the litter storage capacity deficit before successive processes can take place". Bulcock and Jewitt (2012) measured the canopy storage capacity for *Acacia mearnsii* to be 1.2 mm. According to Figure 3.4, this amount of fog was only exceeded on 4 - 5 days during the study period, thus the majority of events would have been intercepted by the canopy and not have contributed to throughfall. This study also investigated whether fog water interception assisted in bringing the canopy closer to saturation, so that when rainfall occurred, there were quicker and greater responses in throughfall. No evidence of this was found and mixed fog and rainfall events and rainfall-only events had very similar relationships with throughfall amounts. No increase in soil water content was found when fog occurred in the absence of rainfall. *Acacia mearnsii* has a thick litter layer with a high interception capacity of approximately 1.8 mm according to Bulcock and Jewitt (2012). Fog would have also had to pass through the canopy, and thus, would require an event of atleast 3 mm to pass through the litter layer and make its way to the soil. However, the biggest fog-only event measured approximately 2.7 mm.

These results imply that fog may not be providing moisture to the vegetation and soil at Two Streams. However, the high frequency of fog occurrence, even during the dry season (Figure 3.5) and the persistence of long fog event durations, indicates that the indirect effects of fog may be a more relevant effect on the water balance. Enhanced humidity, reduced insolation and decreased air temperatures resulting from fog occurrence can limit wet canopy evaporation and actual plant transpiration rates. An increase in leaf surface water by fog may also cause direct evaporation from the leaf surface water, resulting in restricted transpiration from the stomata.

3.5 Conclusion

Given the fact that commercial forestry is a streamflow reduction activity, water resource management in these catchments is vital, and thus, accurate water balances that incorporate all precipitations inputs are required. Although fog was not found to be a very significant moisture input to the water balance at Two Streams, its frequent occurrence suggests that it may play a more important role in reducing evapotranspiration rates. Further studies in other fog-affected commercial forests are, however, still recommended, due to the site-dependent nature of fog.

3.6 Acknowledgements

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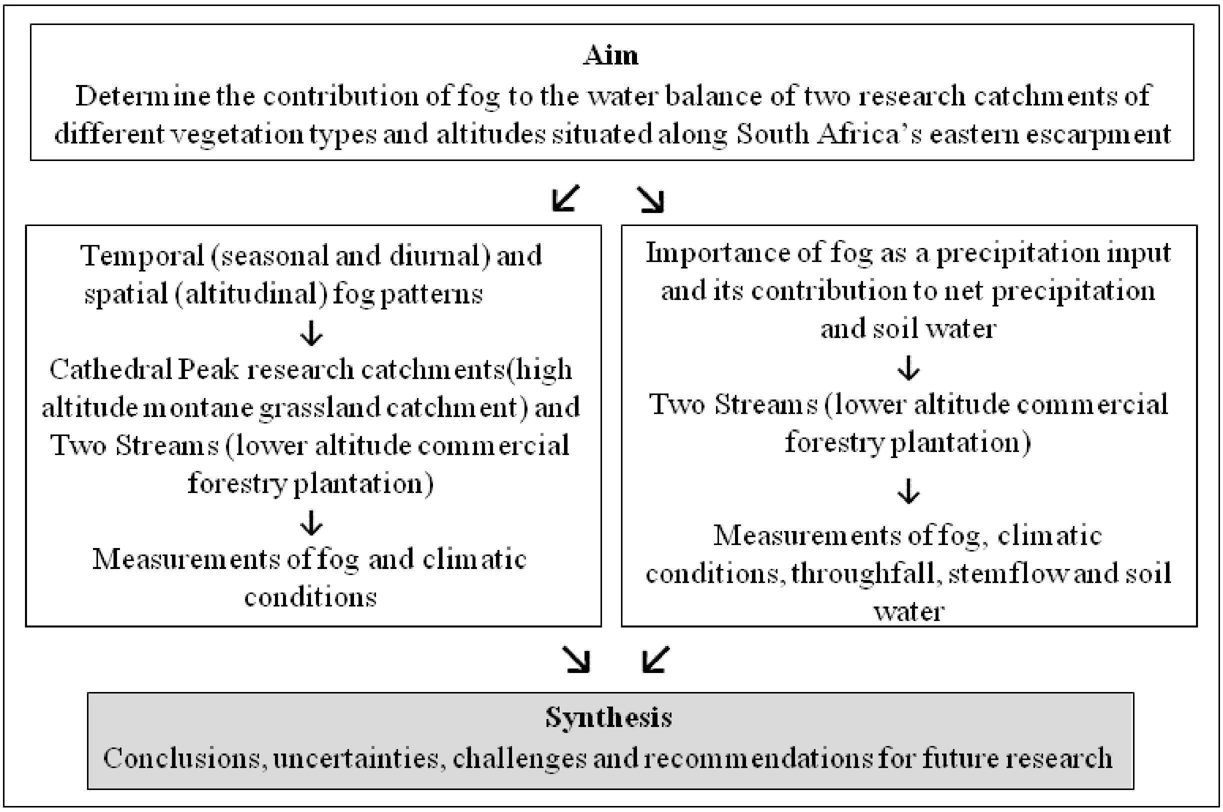
Lead into Chapter 4

Finally, Chapter 4 is a synthesis, which includes the conclusions, uncertainties and challenges of the research, as well as the recommendations for future research.



CHAPTER 4: SYNTHESIS

Fog measurements are neglected in water balance studies, resulting in underestimation of the precipitation input to catchments that experience frequent fog occurrences (Schemenauer and Cereceda, 1994). World-wide, TMCF studies have proven that fog deposition, facilitated via the interception of fog droplets by vegetation, can represent a significant fraction of the total precipitation input, particularly in arid environments (Holder, 2004; Prada *et al*., 2009; Ebner *et al*., 2011). Understanding, and including in the water balance, the additional moisture intercepted by vegetation is thus crucial in fog-affected catchments. In South Africa, fog is a frequent phenomenon, yet knowledge of fog patterns and its contribution to the water balance is poor, particularly in the mountains forming the eastern escarpment. Additionally, no forestry studies in the country have attempted to quantify fog and its contribution and no information exists on the relative dependence of these ecosystems on this precipitation input.

4.1 Summary of the Research

The overall aim of the research was to determine the contribution of fog to the water balance of two research catchments of different vegetation types and altitudes situated along South Africa's eastern escarpment.

The research aimed to address the following research questions:

- What is the significance of the contribution of fog to the water balance?
- Is the fog contribution seasonal and is the importance of fog relative to the total precipitation?
- Does altitude influence fog occurrence and measured fog water yields?
- Do wind speed and direction influence fog occurrence and measured fog water yields?
- Is there evidence of fog drip in an *Acacia mearnsii* plantation? Does fog interception assist in bringing the canopy closer to saturation, so that when rainfall occurs, there are quicker and greater responses in throughfall and stemflow?
- What is the significance of the fog contribution to the soil water content?

From the outcomes of the research, the aim was to be able to advise on whether there is a need to consider fog as a contributor to the catchment water balance.

The research was conducted at two long-term monitoring catchments, where frequent fog occurrences have been observed, yet the contribution of fog to their water balances was unknown. The catchments are of different land use types and altitudes; Cathedral Peak is a high altitude montane grassland catchment, whereas Two Streams is at a lower altitude and afforested by exotic plantations. At both sites, fog and the climatic conditions were monitored over a 16-month period from July 2015 to October 2016. At Two Streams, additional measurements of throughfall, stemflow and soil water content were carried out in an *Acacia mearnsii* plantation, to further determine the fog contribution in a forest plantation. The first paper (Chapter 2) investigated the temporal and spatial variation of fog occurrence and its water yield in both the Cathedral Peak research catchments and Two Streams. Temporally, the focus was on diurnal and seasonal variation, and spatially, the focus was on altitudinal variation. The second paper (Chapter 3) attempted to establish the importance of fog as a precipitation source and whether it contributed to net precipitation and soil water content fluctuations at Two Streams, a fog-affected commercial forestry catchment.

4.2 Key Findings of the Research

Key findings of the research regarding fog along the eastern escarpment of South Africa included:

- Fog was found to be prevalent, occurring frequently and for long durations, potentially contributing fairly substantial amounts of water to the water balance.
- Fog occurred all year round, but was predominantly a summer phenomenon, occurring most frequently and contributing greater water yields during the wet summer season. It, however, comprised a greater proportion of the total precipitation during the dry winter season when there is low rainfall.
- Fog increased with altitude as a whole, but changes in other topographic features (i.e. hillslope orientation and slope) over short distances, meant that the delivery of fog was not uniform from one point to another at the same altitude.
- Fog occurrence and water yield increased with wind speed, but this was not found to be a very significant relationship. A stronger relationship between wind direction and fog was observed, particularly at Mike’s Pass, the higher altitude site. Northerly, north-easterly and north-westerly winds prevailed all year round when fog occurred

here. In the wet summer season when most fog occurred, the northerly and north-easterly winds were most dominant.

- Evidence of throughfall and stemflow during fog-only events was found, but fog did not facilitate throughfall of rainfall.
- Fog did not contribute to soil water, but it is still thought to have a contribution at higher altitude sites, where greater fog yields occur.
- In low-lying forestry plantations, the indirect effects of fog limiting wet canopy evaporation and transpiration rates were suggested to be a more relevant effect on the water balance than contributing to interception and throughfall.

These findings further the understanding of the contribution of fog to the water balance along the eastern escarpment of South Africa, which will assist in future long-term climatological studies of fog and low cloud occurrence.

4.3 Uncertainties of the Research

Uncertainties encountered during the course of the research included:

- The fog gauges used in this study had no mechanism to differentiate between fog and wind-blown drizzle and rainfall. For this reason, this study chose to ignore fog gauge data when rainfall occurred during the same time period. However, fog frequently occurred simultaneously with drizzle and rainfall and the contribution of fog to the water balance is thus believed to be highly underestimated.
- Most fog measurements in international research were based on fog gauge interception and not vegetation interception, however, fog gauges do not mimic the complex structure of vegetation.
- The high spatial variability of fog occurrence and water yields, particularly in mountainous environments, was demonstrated in the research, however, with only three fog gauges installed over a wide area in the Cathedral Peak research catchments, and only one at Two Streams, spatial variation could not be accounted for accurately.
- The study was conducted during a period of severe drought and these dry conditions could result in less fog occurrence and lower fog water yields.
- The soil water sensors used to measure the soil water content may not have had the precision to measure very small fluctuations in soil water.

4.4 Challenges of the Research

Challenges faced during the course of the research included:

- In the Cathedral Peak research catchments, field instrumentation was setup in remote and inaccessible areas. As a result, monitoring and maintenance of field instrumentation was costly, time-consuming and challenging.
- Vandalism and theft of field instrumentation resulted in a loss of valuable data at the Cathedral Peak research catchments.

4.5 Recommendations for Future Research

It is evident that further fog studies are required on the eastern escarpment of South Africa, to improve the understanding of the contribution of fog to the water balance. Recommendations for future research should include:

- Research into more reliable, accurate and inexpensive methods of measuring fog that should be suitable for use in mountainous terrain and complex vegetation types. Additionally, methods should be able to separate fog from wind-driven drizzle and rainfall. A standard method to measure fog would also be useful so that results at different locations can be accurately compared.
- At high altitudes, where fog likely contributes to soil water, this contribution should be measured.
- A fog gauge to soil water conversion factor could be useful in relating the amount of fog water intercepted by a fog gauge to the amount of fog water reaching the soil and contributing to the water balance.
- A reasonable number of fog gauges should be set up at a site, to account for spatial variability. Additionally, remote sensing could be a valuable tool in monitoring fog over large areas in complex terrain.
- The role of hillslope orientation on spatial fog variability requires investigation by comparing fog gauge data on windward and leeward slopes.

In addition to the specific research areas described above, literature frequently referred to the possibility that fog occurrence may be affected in the future by climate change. The impacts of climate change on fog occurrence and yield thus need to be investigated, especially given the water scarce nature of southern Africa and the likely increases in precipitation variability in the near future.

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