The effect of fire on hydrological response and the subsequent effect on streamflow

Hermanus Petrus van Zyl

Thesis presented in fulfilment of the requirements for the degree of
Master of Engineering in Civil Engineering in the Faculty of Engineering at Stellenbosch University

Supervisor: Prof. J A Du Plessis

March 2018

Stellenbosch University https://scholar.sun.ac.za

Declaration

I, Hermanus Petrus van Zyl, declare that the entire body of work contained in this research assignment is my own, original work; that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2018

Copyright © 2018 Stellenbosch University
All rights reserved

Stellenbosch University https://scholar.sun.ac.za

Acknowledgements

I would first like to acknowledge my parents, who have supported me throughout my entire academic career. Without their support and encouragement, I would not have been able to achieve what I have. Secondly, I would like to thank Nadia Fouche. She put in much effort and gave me a lot of encouragement. Lastly, I would like to thank Prof Du Plessis, who has been a kind and wise supervisor. I know that there is still so much more to learn.

Stellenbosch University https://scholar.sun.ac.za

Abstract

Fire is a destructive force that destroys thousands of hectares of both urban and rural vegetation in South Africa every year. Fire not only destroys vegetation, but also affects the infiltration and percolation capacity of soil. With fire destroying vegetation and changing soil characteristics, it is therefore within reason to assume that the hydrological response of a catchment could be affected by fire. The main aim of this research was to investigate the hydrological changes caused by fire on a catchment scale. On the 9th of March 2015, a wildfire started in Jonkershoek nature reserve, which destroyed indigenous fynbos vegetation and afforested areas. Within the nature reserve, there are multiple rainfall and runoff stations, which provided a means of measuring possible hydrological changes caused by the fire event on different catchments. There were four catchments used for the research, one main catchment (fynbos area) and three sub-catchments (afforested areas). Fifty-six percent of the main catchment burned, while two sub-catchments were completely burned and the other was primarily unaffected by the fire. The main catchment's hydrological response due to rainfall events were analysed by comparing the hydrographs of comparable pre- and post-fire rainfall events. Eighteen comparable events were used for the analysis. The mean runoff volume increased by 6.8% and mean peak flow by 50%, after the fire. The Wilcoxon signed ranked test confirmed that the increase in volume was significant ($p < 0.05$), however the increase in peak flow was not significant ($p = 0.053$).

Since all of the sub-catchments were similar in size and were close to the same rainfall station, there were two affected catchments and one control catchment identified for further comparison. Before the fire, the average daily streamflow over the control and burned sub-catchments was similar, however after the fire the average daily streamflow of the burned sub-catchments in comparison to the control catchment, had increased by 45% and 50% respectively. The two-way mixed Analyses of Variance (ANOVA) confirmed that the differences were statistically significant ($p < 0.01$). The mean volume runoff, after the fire for individual events increased with 72.4% and 54.7% for the two burned -sub-catchments respectively, in comparison to the control sub-catchment. The mean peak flows increased with 116.7% and 183.3% in the burned-sub-catchments respectively, in comparison to the control sub-catchment. The paired catchment method was used to test whether the results were significant by using multiple linear regression. The runoff volume before the fire was statistically significant ($p < 0.05$) when comparing the control and affected sub-catchments. With the addition of an interaction term (F) for indicating the effect of fire, the predictability of the model did not increase, which indicates that fire was not a significant term. By using the same approach on the peak flows, it was found that with the addition of an interaction term (F), fire did increase the predictability of the model.

Key words: Hydrological change, fire, runoff response

Stellenbosch University https://scholar.sun.ac.za

Opsomming

Vuur is ‘n verwoestende krag wat jaarliks duisende hektar vernietig in beide stedelike en landelike gebiede in Suid-Afrika. Vuur vernietig nie net plantegroei nie, maar beïnvloed ook die infiltrasie en deurlaatbaarheidskapasiteit van die grond. Met vuur wat plantegroei vernietig en grond se eienskappe verander is dit verstaanbaar dat die hidrologiese reaksie van die opvanggebied beïnvloed sal word word deur vuur. Die doel van hierdie navorsing was om die hidrologiese veranderinge te bestudeer wat deur ‘n vuur veroorsaak word in opvanggebied.

Op die 9de Maart 2015 het ‘n veldbrand begin in die Jonkershoek natuur reservaat wat inheemse fynbos sowel as plantasies vernietig het. Binne die natuur reservaat was daar verskeie reënval- en afloop stasis wat dit moontlik gemaak het om die hidrologiese veranderinge te ondersoek wat deur die brand veroorsaak was in verskeie opvanggebiede. Vier opvanggebiede is gebruik vir die navorsing, een was die hoof opvanggebied (fynbos area) en die ander drie was sub-opvanggebiede (plantasies). Ses en vyftig persent van die hoof opvanggebied het afgebrand, terwyl twee van die drie sub-opvanggebiede volledig afgebrand het. Die derde sub-opvanggebied was min beïnvloed deur die vuur. Die hoof opvangebied se hidrologiese reaksie as gevolg van reënval gebeurtenisse was ontleed deur die voor en na brand hidrograwe te bestudeer. Agtien vergelykbare reënval gebeurtenisse is gebruik vir die ontleding. Na die brand het die gemiddelde afloop volume toegeneem met 6.8% en die gemiddelde piek afloop met 50. Die Wilcoxon toets het bevestig dat die toename in afloop volume statisties beduidend was ($p<0.05$), maar dat die toename in piek vloei nie statisties beduidend was nie ($p = 0.053$).

Aangesien al die sub-opvanggebiede ongeveer dieselfde grootte is, en naby aan die selfde reënval stasie geleë is, is daar besluit om die twee gebrande sub-opvanggebiede, sowel as die kontrole sub-opvanggebied, te gebruik vir die analiese. Voor die vuur was die gemiddelde daaglikse afloop tussen die kontrole en gebrande sub-opvanggebiede dieselfde, maar na die brand het die daaglikese afloop van die gebrande sub-opvanggebiede in vergelyking met die kontrole sub-opvanggebied toegeneem met 45% en 50% onderskeidelik. Die ‘*two-way mixed Analysis of Variance*’ (ANOVA) metode het bevestig dat die verskille beduidend was ($p < 0.01$). Die gemiddelde volume afloop na die vuur vir die afsonderlike reënval gebeurtenisse het toe geneem met 72.4% en 54.7% in die twee sub-opvanggebiede onderskeidelik in vergelyking met die afloop van die kontrole sub-opvanggebied. Die gemiddelde piek vloei waardes het met onderskeidelik 116.7% en 183.3% toegeneem in die gebrande sub-opvanggebiede in vergelyking met die kontrole. Die ‘*paired catchment’* metode was gebruik om te toets of die resultate statisties beduidend was, deur veelvuldige lineêre regressie tegnieke te gebruik. Die volume afloop voor die brand was statisties beduidend ($p < 0.05$) indien die kontrole sub-opvangebiede vergelyk was met die gebrande sub-opvanggebiede. Met die byvoeging van ‘n interaksie term (F), wat die gevolge van brand in agneem, het die voorspelbaarheid van die model nie toegeneem nie, wat beteken dat die brand nie ‘n beduidende interaksie term was nie.

Stellenbosch University https://scholar.sun.ac.za

Wanneer die selfde metode toegepas is op die piek vloeie was daar gevind dat die interaksie term (F) die voorspelbaarheid van die model verbeter het.

Sleutel woorde: Hidrologiese verandering, vuur, afloop reaksie

Stellenbosch University https://scholar.sun.ac.za

Table of contents

Declaration		**ii**
Acknowledgements		**iii**
Abstract		**iv**
Opsomming		**iv**
List of Tables		**ixx**
List of Figures		**xii**
CHAPTER 1 INTRODUCTION		**1**
CHAPTER 2 LITERATURE REVIEW		**4**
2.1	BEHAVIOUR & CHARACTERISTICS OF FIRE	4
2.1.1	Fire intensity	6
2.1.2	Fire and burn severity	7
2.1.3	Ecosystem response and societal impact	7
2.2	EFFECT THAT FIRE HAS ON SOIL (WATER REPELLENCY & SOIL BURN SEVERITY)	8
2.2.1	Fire-induced soil water repellency	8
2.2.2	Soil burn severity	10
2.3	HYDROLOGICAL EFFECT THAT FIRE HAS ON RUNOFF	13
2.3.1	Hydrograph changes due to fire	13
2.3.2	Recovery time	18
2.4	POST-FIRE HYDROLOGICAL MEASURING METHODS IN A CATCHMENT	18
2.4.1	Paired catchment method	19
2.4.2	Computer based simulation models	20
2.5	RESEARCH CONDUCTED IN SOUTH AFRICA	21
2.6	DAMAGE CAUSED BY POST-FIRE RAINFALL	25
2.6.1	Switzerland	25
2.6.2	Greece	26
2.6.3	United States	26
2.7	CONCLUSION DRAWN FROM LITERATURE	26
2.8	FORMULATION OF AN HYPOTHESIS AND A RESEARCH PLAN	27
CHAPTER 3 RESEARCH METHODOLOGY		**29**
3.1	CATCHMENT DESCRIPTION	30
3.2	JONKERSHOEK FIRE TREATMENTS	33
3.3	METHODS	35
3.3.1	Variables needed for methods	35
3.3.2	Pre- and post-fire storm comparison method	39
3.3.3	Two way mixed ANOVA	41
3.3.4	Paired catchment method	41

Stellenbosch University https://scholar.sun.ac.za

3.3.5 Overview of methods 43

CHAPTER 4 ANALYSIS: MAIN CATCHMENT 44

4.1 CUMULATIVE RAINFALL AND RUNOFF FLOW 44

4.2 COMPARABLE RAINFALL EVENTS 46

4.3 HYDROGRAPHS 47

4.4 VOLUME RUNOFF BEFORE AND AFTER FIRES 48

4.5 PEAK FLOW VALUES BEFORE AND AFTER FIRES 51

4.6 TIME TO PEAK BEFORE AND AFTER FIRES 54

4.7 CONCLUSION 57

CHAPTER 5 ANALYSIS: SUB-CATCHMENTS 59

5.1 LONG-TERM STREAMFLOW 59

5.1.1 Two way mixed ANOVA 64

5.2 STORMFLOW 69

5.2.1 Paired catchment method 76

5.3 CONCLUSION 87

CHAPTER 6 RESEARCH CONCLUSION AND DISCUSSION 91

CHAPTER 7 FUTURE RESEARCH 95

REFERENCES 96

APPENDIX A: COMPARATIVE RAINFALL EVENTS TABLE A-1

APPENDIX B: ASSUMTIONS FOR TWO WAY MIXED ANOVA B-1

APPENDIX C: ASSUMPTIONS TESTED FOR PAIRED CATCHMENT METHOD C-1

APPENDIX D: MIXED ANOVA ANALYSIS BETWEEN BOSBOUKLOOF AND LAMBRECHTSBOS A D-1

APPENDIX E: APPLICATION OF THE PAIRED CATCHMENT REGRESSION MODEL E-1

.

Stellenbosch University https://scholar.sun.ac.za

List of Tables

Table 2.1: Environmental factors affecting behaviour of fire 5
Table 2.2: Fire severity and description (Keeley, 2009) 7
Table 2.3: Classes of soil burn severity with different vegetation (Parsons *et al.*, 2010) 11
Table 2.4: Hypothetical responses of fynbos after a fire (Bosch et al., 1986) 22
Table 2.5: Streamflow responses one year following fires (Scott, 1993) 23
Table 3.1: Catchment description 30
Table 3.2: Rainfall and streamflow stations 32
Table 3.3: Age of vegetation in catchment 34
Table 3.4: Number of rainfall events pre- and post-fire 39
Table 3.5: Descriptive statistics of pre- and post-fire 40
Table 3.6: Group allocation 40
Table 4.1: Dates of analysis 44
Table 4.2: Runoff/rainfall ratio 45
Table 4.3: Group 1 pre- and post-fire rainfall events 46
Table 4.4: Characteristics of two events 47
Table 4.5: Rainfall and runoff before and after fire 48
Table 4.6: Statistical values obtained with test 50
Table 4.7: Peak flow pre- and post-fire 51
Table 4.8: Statistical values from test 52
Table 4.9: Time to peak pre- and post-fire 55
Table 4.10: Statistical values for test 56
Table 5.1 Rainfall and runoff accumulated during July-September before and after the fire 62
Table 5.2 Average daily runoff values for the control and affected catchments with their ratios before and after the fire 64
Table 5.3: Test of within subjects effects between Bosboukloof and Lambrechtsbos B 66
Table 5.4: Test of within subjects effects between Bosboukloof and Lambrechtsbos B before fire 66
Table 5.5: Descriptive Statistics of Runoff before the fire 67
Table 5.6: Test of within subjects effects between Bosboukloof and Lambrechtsbos B after fire ... 67
Table 5.7: Descriptive Statistics of Runoff after the fire 68
Table 5.8: Rainfall events before and after fire for all the sub-catchments 69
Table 5.9: Key characteristic values of the hydrographs before and after fire 69
Table 5.10: Model summary of two sub-catchments 78
Table 5.11: Coefficients of before and after fire 79
Table 5.12: Model summary (peak flow) 80
Table 5.13: Coefficients peak flow 80

Stellenbosch University https://scholar.sun.ac.za

Table 5.14: Simple slope analysis coefficients Lambrechtsbos A 82
Table 5.15 Simple slope analysis coefficients Lambrechtsbos A 84
Table 5.16: Relation between control and affected catchment's runoff volume before and after the fire 89
Table 5.17: Relation between control and affected catchment's peak flow before and after the fire 89
Table 6.1: Summary of burned catchments 94
Table A.1: Comparable rainfall events before and after the fire for the main catchment A-2
Table D.1: Test of within subjects effects between Bosboukloof and Lambrechtsbos A D-1
Table D.2: Test of within subjects effects between Bosboukloof and Lambrechtsbos A before fire ... D-1
Table D.3: Descriptive statistics of runoff before fire for the affected (Lambrechtsbos A) and control catchment D-2
Table D.4: Test of within subjects effects between Bosboukloof and Lambrechtsbos A after fire D-2
Table D.5: Descriptive Statistics on Runoff after the fire D-3

Stellenbosch University https://scholar.sun.ac.za

List of Figures

Figure 2.1: Layers of the effect of fire (Keely, 2009) 6
Figure 2.2: Process of fire-induced soil water repellency (DeBano *et al*, 1998) 9
Figure 2.3: Visual illustration of soil burn severity (Parsons *et al., 2010*) 12
Figure 2.4: Simple representation of a hydrograph 17
Figure 2.5: Sprouter:seeder ratio (Bosch *et al., 1986*) 21
Figure 2.6: Runoff due to rainfall of 157 mm/h on plots (Strydom *et al.,* 2014) 24
Figure 2.7: Runoff due to rainfall of 200 mm/h on plots (Strydom *et al.,* 2014) 25
Figure 3.1: Jonkershoek (main and sub-catchments) 31
Figure 3.2: Thiessenspolygon on main catchment 33
Figure 3.3: Jonkershoek area burned March 2015 34
Figure 3.4: Determining volume of runoff 38
Figure 3.5: Research outline 43
Figure 4.1: Cumulative runoff/rainfall for main catchment 45
Figure 4.2: Pre- and post-fire comparable hydrograph 47
Figure 4.3: Histogram of Wilcoxon signed-rank test (Volume runoff) 49
Figure 4.4: Rainfall vs runoff pre-fire 50
Figure 4.5: Rainfall vs runoff post-fire 50
Figure 4.6: Histogram of Wilcoxon signed-rank test (Peak flows) 52
Figure 4.7: Rainfall vs peak flow for pre-fire storms 53
Figure 4.8: Rainfall vs peak flow for post-fire storms 53
Figure 4.9: Peak flow pre- and post-fire 54
Figure 4.10: Time to peak flow pre- and post-fire 54
Figure 4.11: Histogram of signed test (Time to peak) 56
Figure 4.12: Rainfall vs time to peak pre-fire 57
Figure 4.13: Rainfall vs time to peak pre-fire 57
Figure 5.1: Double mass plot of Lambrechtsbos A against Bosboukloof 60
Figure 5.2: Double mass plot of Lambrechtsbos B against Bosboukloof 61
Figure 5.3: Rainfall and runoff (Jul-Sep 2014) before fire 63
Figure 5.4: Rainfall and runoff (Jul-Sep 2015) after fire 63
Figure 5.5: Response time of Bosboukloof and Lambrechtsbos B 71
Figure 5.6: Bosboukloof and Lambrechtsbos B rainfall vs runoff before and after fire 72
Figure 5.7: Bosboukloof and Lambrechtsbos B rainfall vs peak flow before and after the fire 74
Figure 5.8: Hydrographs of three sub-catchments on the 2015/07/17 with their hyetograph 75
Figure 5.9: Runoff peak Lambrechtsbos A vs Bosboukloof before and after the fire 82
Figure 5.10: Runoff peak Lambrechtsbos A vs Bosboukloof before and after the fire 83

Stellenbosch University https://scholar.sun.ac.za

Figure 5.11 Runoff peak of Lambrechtsbos B against rainfall 85
Figure 5.12 Runoff peak of Lambrechtsbos A against rainfall 86
Figure 5.13: Runoff peak of Lambrechtsbos A against rainfall........ 87
Figure B.1: Normal Q-Q plot Bosboukloof B-1
Figure B.2: Normal Q-Q plot Lambrechtsbos A B-1
Figure B.3: Normal Q-Q plot Lambrechtsbos B B-1
Figure C.1: Testing for linearity volume runoff........ C-2
Figure C.2: Homoscedacity test Lambrechtsbos A and Bosboukloof volume runoff C-3
Figure C.3: Homoscedacity test Lambrechtsbos B and Bosboukloof volume runoff C-3
Figure C.4: Testing for normality Lambrechtsbos A volume runoff C-4
Figure C.5: Testing for normality Lambrechtsbos B volume runoff C-4
Figure C.6: Testing for linearity peak flow C-5
Figure C.7: Homoscedacity test Lambrechtsbos A and Bosboukloof peak flow........ C-6
Figure C.8: Homoscedacity test Lambrechtsbos B and Bosboukloof peak flow........ C-7
Figure C.9: Testing for normality peak flow C-8

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

In South Africa there are a considerable number of fire events that occur in catchments. Some of these catchments drain into channels, which flow through urban areas. The peak flows that drain into these channels can be determined through hydrological methods such as the Rational method or the Soil Conservation method (SCS). These deterministic methods take into consideration certain catchment characteristics such as the catchment size, the average slope of the longest watercourse, type of vegetation cover and type of soil. The effect that fire has on the runoff is generally not taken into consideration when conducting a hydrological analysis. When a fire event occurs in a catchment, it destroys vegetation and burns the soil, which may affect the absorption of precipitation into the soil and increase overland flow. Fire has the ability to hinder the process of infiltration and percolation (the movement of water through soil), not only by destroying the root systems, but also through changing the characteristics of the soil. The heat from a fire can change the chemical, physical and biological properties of the soil (Wagenbrenner, 2013). A key physical change occurs when fire creates, or expands a pre-existing, water repellent layer on top of the soil. This process is referred to as fire-induced soil water repellency (Debano, 2000). Soil water repellency is a reduction in the rate of wetting and retention of water in soil, caused by the presence of hydrophobic coatings on soil particles. Water repellent soils decrease the process of infiltration and percolation in soil, which can result in the rise of overland flow (Debano, 2000; Scott, 1993).

The degree of fire-induced soil water repellency is dependent primarily on the severity of the fire. Soil burn severity is a term, which categorises the effects that fire has on soil into different classes (low, medium and high). The higher the class of soil burn severity, the greater the effect that fire has on the soil. It is important to understand that the intensity reached by a fire is dependent on the available fuel that it can consume. A wildfire can only reach high intensity when the density of the fuel is sufficient. The density of vegetation differs; a forest-like vegetation has a much greater density than that of for, example, grasslands. Therefore, it can be expected that when a fire consumes different vegetation types, under the same climatic conditions, the vegetation with greater density will result in a higher class of soil burn severity than would the less dense vegetation.

Since there are different classes of soil burn severity, overland runoff will be different for each of the classes, which result from burning different types of vegetation. In hydrological practice, it is known that characteristic elements of catchments (such as their size, slope, vegetation type and climate) also affect overland flow. Large catchments with steep slopes generally produce more runoff than similarly sized catchments with flatter slopes, while having the same vegetation and climatic properties. The results of research on the effect that fire has on overland flow on a catchment scale

Stellenbosch University https://scholar.sun.ac.za

varies considerably. It is therefore important to investigate the effect that fire has on the hydrological response of a catchment and to determine whether it has a significant influence on the runoff in a catchment. Furthermore it is important to investigate to what extent overland flow changes after a fire, in terms of long-term flow and flow produced during a rainfall event (by means of analysing hydrographs).

1.2 AIMS/OBJECTIVES

The aim of the research was to test the effect that fire has on overland flow within suitable research catchments, taking the variables that affect overland flow into account. It was hypothesised that the observed hydrological changes caused by fire were linked to the level of soil burn severity, which is determined by the type of vegetation cover and its density, the soil profile, as well as the intensity of the fire.

1.3 SCOPE AND LIMITATIONS

The biggest challenge of conducting this research is to identify the variables which affect overland flow before a fire event and how to manage them efficiently after the event to ensure that fire is the only additional variable which alters the runoff response in a catchment. Methods used in the past to determine changes in runoff due to fire provide important guidelines, since background on the most efficient methods used for testing the effect of fire on runoff is provided. Furthermore past methods provide information on how to identify and manage the variables which affect the outcome of the results. Investigating previous research conducted in South Africa is important, since it can provide suitable comparisons to the results of this research, given that the research catchments have similar vegetation cover and catchment characteristics.

It was important that the research catchments should have accurate streamflow and rainfall data, both before and after a fire event. Identifying catchments with different vegetation covers, which had been burned by the same fire, would be ideal for calculating the effect that fire has on overland flow by comparing the effect that fire had had on these different types of vegetation.

After identifying suitable research catchments, methods were outlined in the methodology to test the effect that fire had on runoff within these catchments. The methods consisted of mainly analysing long-term runoff from an unburned catchment and then to compare the long-term runoff after the catchment burned. Another approach was to identify the effect that fire had on runoff during rainfall events by utilizing hydrographs. It is important when comparing hydrographs of a catchment (before and after a fire) that the rainfall events should be similar in both duration and intensity, furthermore to take into consideration the antecedent soil moisture before rainfall events. The antecedent soil moisture could have an effect on the infiltration capacity of the soil, which might affect the overland flow and thus change the outcome of the analyses.

Stellenbosch University https://scholar.sun.ac.za

Where there were suitable control (unburned) and affected (burned) catchments the analysis would consist of finding a relationship between the affected and control catchments runoff before the fire and then to compare it with the relationship after the fire. The control and affected catchments would have to have similar catchment characteristics such as size, slope and vegetation. Since the control and affected catchments would fall within the same rainfall area, it was assumed that they would experience similar rainfall. In order for any of the results to be relevant, the data had to undergo statistical tests to determine whether the results were statistically significant. Finally, the results were compared to previous research (the similarities and differences) to either validate or disprove the hypothesis.

1.4 THESIS LAYOUT

The literature study chapter follows the Introduction. The Methodology is the third chapter in the dissertation; this chapter describes catchment characteristics and methods used for the purpose of this research. The fourth and fifth chapters provide comprehensive description of the analysis and results of the hydrological response due to fire on the main catchment and sub-catchments respectively. Conclusion and discussion are presented in the six chapter. The last chapter will focus on providing suggestions for future research.

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 2
LITERATURE REVIEW

In South Africa, wildfire is a frequent and most devastating event. Wildfire destroyed 122 700 hectares of vegetation in the Western Cape during the first two months of 2017 (De Villiers, 2017). Not only does fire destroy the surrounding vegetation, but it also poses a substantial threat to wildlife and the surrounding communities. Fire also has the ability to affect the characteristic chemical, physical and biological properties of soil (Wagenbrenner, 2013).

Physically, fire changes the soil's ability to absorb water, through a process known as soil-water-repellency (Debano, 2000). This phenomenon, paired with the destruction of vegetation, should, theoretically, have an impact on the hydrological response of a catchment.

Quantifying the response in a catchment is difficult, due to the various factors including, but not limited to intensity of the fire, area of the burn, type of vegetation, soil type and shape of the catchment (Beschta, 1990). The challenge is further aggravated due to the lack of accurate rainfall and streamflow data within a particular affected catchment.

It is therefore understandable that despite the significant amount of research which has been done, no single set of clear results is available. The main objective of most available research was to understand the dynamics of the change in overland flow that was due to fire. The research encompasses the extent of runoff increase, quantifying the temporal changes in runoff dynamics as well as the change in the shape of storm hydrographs. Research was conducted on different methods and models used in the past to quantify the hydrological changes caused by fire.

To fully understanding the characteristic changes of runoff due to fire, the behaviour and characteristic classification of fire itself has to be studied, which will help to understand the effect fire has on the soil and vegetation. How fire affects the landscape in a physical and biological manner, might give a more concise insight into how fire alters the ecosystem's response to runoff.

2.1 BEHAVIOUR & CHARACTERISTICS OF FIRE

To understand what effect fire will have on runoff, it is important first to understand fire's physical processes and also how it is categorised, according to severity and intensity. Three main elements are needed for a fire to ignite, energy, fuel and an oxidising agent (Bickerton, 2012). With all these elements in place, a wildfire can occur in an ecosystem. The occurrence of a wildfire within an ecosystem releases varying amounts of thermal energy during the combustion of fuels (DeBano, Neary & Ffolliott, 1998), which is transferred by means of radiation, convection and conduction. Understanding the various environmental components that affect the behaviour of a fire can shed some light on its characteristic drivers.

Stellenbosch University https://scholar.sun.ac.za

According to Whelan (1995), various environmental components affect the behaviour of fire. Table 2.1, displays some of these components and the specific effect that each of these components have on the behaviour of fire.

Table 2.1: Environmental factors affecting behaviour of fire

Component	Effects
Fuel load	Determines maximum energy available to a fire.
	Arrangements affect aeration, vertical and horizontal spread of a fire.
	Size distribution can affect likelihood of initial ignition.
	Chemistry can increase (for example, resins or oils) or decrease (mineral content) flammability
Climate	Determine vegetative productivities and, therefore, the rate of fuel accumulation
Precipitation-humidity	Increase fuel moisture, combined with high relative humidity, decrease likelihood of ignition and rates of combustion and spread of a fire.
Wind	Causes drying of fuel.
	Increases oxygen available for combustion.
	Preheats and ignites fuel in advance of a fire front and can produce ignition ahead of the front.
	Changes in direction can increase the fire front.
Topography	Causes variation in local climate.
	Permits preheating and ignition for a fire burning uphill.
	Can provide natural firebreaks.
	Partially determines distribution of vegetative communities of varying flammabilities.

DeBano *et al*. (1998) suggest that interactions exist between the variable factors such as topography, weather and fuel, which determine the behaviour of fire. It is therefore understandable that the behaviour of fire varies with air temperature, relative humidity, and wind speed. Relative humidity and air temperature affect the ability of the vegetation to ignite, while wind speed affects the tempo at which the fire spreads. All these factors contribute to the size, intensity, and duration of the fire.

To understand the effect that fire has on an ecosystem, it is important first to characterise the fire in terms of fire intensity, fire severity, burn severity, the ecosystem response and societal impacts that accompany the fire (Keeley, 2009).

This characterisation can be perceived as layers of cause and effect between the fire and the ecosystem. Figure 2.1 provides a simplified illustration of the characterisation as proposed by Keeley (2009).

Stellenbosch University https://scholar.sun.ac.za

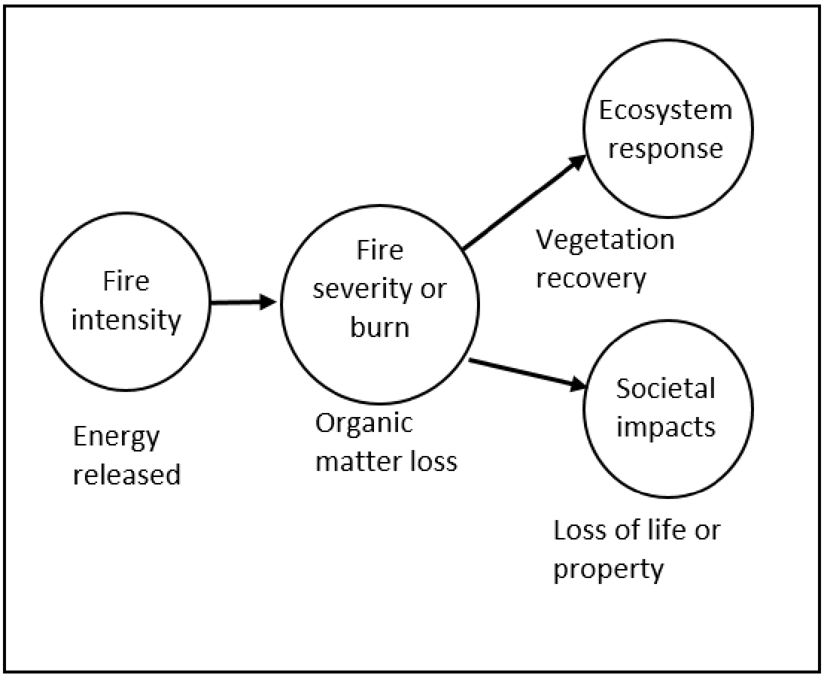


Figure 2.1: Layers of the effect of fire (Keely, 2009)

Figure 2.1 illustrates the initial release of energy represented by the fire intensity. This in turn, destroys organic material; the level of destruction can then be classified in terms of fire severity or burn severity. The effect of the severity of the fire is observed by the ability of the ecosystem to recover from a fire and by the impact that fire has on society.

2.1.1 Fire intensity

Fire intensity is the physical combustion process of the release of energy from organic matter, which represents the energy released during a wildfire (Keeley, 2009). The intensity is numerically equal to the product of the available fuel energy and the fire's rate of advance (Alexander, 1982). The intensity of fire is measured as illustrated in Equation 2.1:

$$I = Hwr \qquad \text{…(2.1)}$$

where,

- I is the fire intensity measured in kW/m
- H is the fuel of low heat of combustion in kJ/kg
- W is the weight of the fuel per unit area in kg/m^2
- r is the rate of spread in m/s.

Alexander (1982) stated that the intensity of a fire seldom reaches a value greater than 50 000 kW/m and that most forest fires range within 10 000 kW/m and 30 000 kW/m.

Stellenbosch University https://scholar.sun.ac.za

2.1.2 Fire and burn severity

The term *fire severity*, was created out of the need to provide a description of how fire intensity affects an ecosystem (Keeley, 2009). Fire severity is a term used particularly to describe wildfires, where there is normally a lack of information regarding the intensity. Keeley (2009) adapted a matrix, originally from Ryan & Noste (1985), to find a measurement for the fire severity. Table 2.2 displays the reconstructed matrix with the levels of fire severity as well as the description of how the severity affects the vegetation, taken from Keeley (2009).

Table 2.2: Fire severity and description (Keeley, 2009)

Fire severity	Description
Unburned	Plant parts green and unaltered, no direct effect from heat
Scorched	Unburned but plants exhibit leaf loss from radiated heat
Light	Canopy trees with green needles although stems scorched
	Surface litter, mosses, and herbs charred or consumed
	Soil organic layer largely intact and charring limited to a few mm depth
Moderate or severe surface burn	Trees with some canopy cover killed, but needles not consumed
	All understory plants charred or consumed
	Fine dead twigs on soil surface consumed and logs charred
	Pre-fire soil organic layer largely consumed
Deep burning or crown fire	Canopy trees killed and needles consumed
	Surface litter of all sizes and soil organic layer largely consumed
	White ash deposition and charred organic matter to several cm depth

Burn severity is another term for fire severity, which is used to qualitatively assess the impact of the heat pulse that is directed towards the ground during a fire (Forest, 2013).

Soil burn severity describes classes of fire-caused changes to the soil (Parsons, 2003). These changes include the loss of organic matter, alteration to the colour and structure of the soil, as well as a reduction in water infiltration (Parsons, Robichaud, Lewis, Napper & Clark, 2010) (Parsons *et al.*, 2010).

Vegetation burn severity, on the other hand, is the direct effect that fire has on the vegetative properties of the ecosystem, which has often been defined by the degree of consumption, scorch, and mortality of vegetation (Parsons *et al.*, 2010).

2.1.3 Ecosystem response and societal impact

The reason why fire is characterised, in such a manner as fire intensity, fire severity and burn severity, is to predict what would happen to the surrounding ecosystem and society (Keeley, 2009). The effect that fire has on ecosystems is related to the frequency and intensity of the fire, as well as the type of ecosystems that are affected (Stoof, 2011). The response of the ecosystem after a fire

Stellenbosch University https://scholar.sun.ac.za

differs according to the different vegetation, since some are more adaptable to post-fire restoration than others.

Fire has both a direct and an indirect impact on society. Directly, it has the potential to cause loss of life, destruction of crops and homes (Rábade & Aragoneses, 2008). Indirectly, it affects society by changing the landscape, resulting in a large amount of soil erosion, mainly caused by increased runoff. Understanding the dynamics of the hydrological changes to the ecosystem after a fire is important, because, with a proper post-fire prediction the severity of a flood event could be predicted and a great deal of damage averted.

The most fundamental contributing factor to fire-induced runoff is the absorption capabilities of the affected soil (Scott, 1994). The next section will discuss how fire alters soils by inducing water repellency and how to categorise the level of repellency according to the soil burn severity.

2.2 EFFECT THAT FIRE HAS ON SOIL (WATER REPELLENCY & SOIL BURN SEVERITY)

2.2.1 Fire-induced soil water repellency

The ability of soil to store water is called soil water retention; which is a measurement of the amount of water that can be stored in the soil and which, together with infiltration, determines what happens to the precipitation (Stoof, 2011). Fire has the ability to alter the soil's water retention and increase overland runoff (Scott, 1994).

Soils are typically assumed to draw water through the matrix of pores, that exist between soil particles, through attraction (Hillel, 1980). This attraction between water and soil particles (the soil's 'sorptivity'), can be altered as a result of the effects of fire (Scott, Lapp & Hegedus, 2013). High soil temperatures at the surface cause the charring of soil and, in turn, the charring of the soil coats the soil with organic material (Scott *et al.*, 2013). The organic material which coats the soil due to fire, such as plant litter or fungal mycella (Jex *et al.*, 1985), can contain hydrophobic compounds.

The coating of soil particles with these hydrophobic organic substances, reduces the attraction between the soil and water particles, this process is referred to as 'fire-induced water repellency' (Debano, 2000).

Water repellent soils impair the infiltration and percolation (the movement of water into and through soil) processess in soil, and this can result in the rise of overland flow (Debano, 2000) and the restriction of percolation to preferred pathways in the soil profile (Burch, Moore & Burns, 1989; Scott, 1993). Figure 2.1 displays a redrawn figure from DeBano *et al.* (1998), which illustrates the process of fire-induced soil water repellency.

Stellenbosch University https://scholar.sun.ac.za

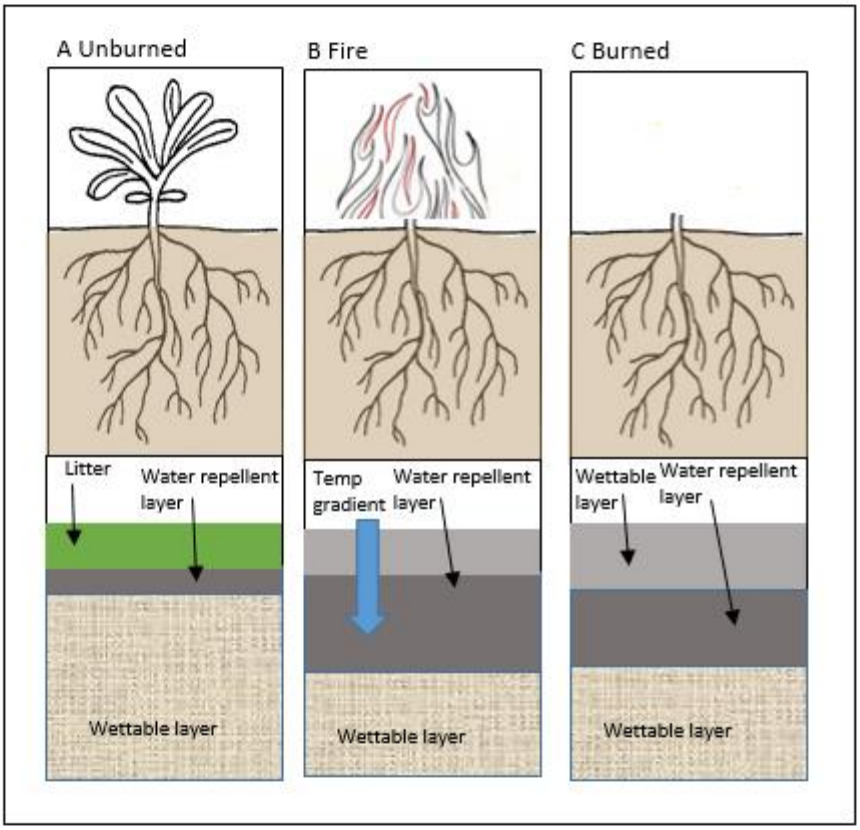


Figure 2.2: Process of fire-induced soil water repellency (DeBano *et al*, 1998)

Section A of Figure 2.2 shows a shrub like vegetation, with a naturally occurring water repellent layer covered by a litter layer, which contains hydrophobic material. A wildfire (section B), destroys some parts (or components) of the water repellent material, while others are volatilised and are forced to move downward into the soil,. After the fire (section C), there are three observable layers. The topmost layer is a wettable layer, which contains the remains of the destroyed litter layer. This layer does not support vegetation and will most likely be washed away during the first high intensity rainfall event. Underneath this layer is the enlarged water repellent layer. The deepest layer is the undamaged wettable soil.

Some soils, as in Figure 2.2, have a naturally occurring water repellent layer, which is most noticeable during dry conditions. Some of these soils are found under canopies of individual bushes. As observed in Figure 2.2, wildfire has the ability not only to create water-repellent soil, but also to exacerbate pre-existing water-repellent soil conditions (Parsons *et al.*, 2010; Scott, Pike & Moore, 2003).

With the increase in soil moisture, the effect of the water-repellent layer diminishes (Scott *et al.*, 2003). This means that the soils ability to absorb water increases with the increase in moisture. This is contradictory to the behaviour of normal soil, where the infiltration decreases with soil moisture increase (Scott *et al.*, 2013). The size of the soil particles is also a factor in the degree of water

Stellenbosch University https://scholar.sun.ac.za

repellency. Parsons (2010) found that coarse-grained soils are more prone to fire-induced water repellency than fine-grained soils.

It is reasonable to assume that effects of fire induced soil water repellency will be most noticeable during the first few rainfall events after a fire, which Scott *et al.* (2013) found to be true; however, with the regrowth of vegetation and recovery of soil, the effects will reduce over time. Dyrness (1976) found that six years after a fire the effects would no longer be noticeable. It is understandable that the temperature reached during a fire event plays a significant role in the level of soil water repellency.

DeBano (1981) studied the effects of different temperatures on the water repellent layer in a laboratory. He found that with temperatures below 175℃ there was no noticeable change in the water repellent layer. Between 175℃ and 200℃, the water repellent layer increased, and at over 280℃ the water repellent layer closest to the surface was destroyed. It is comprehensible that with the higher temperatures the surface repellent layer would be destroyed, however, the repellent layer will become greater at lower depths of the soil profile (Letey, 2001). Thus, wildfires with lower temperatures will cause water repellency in the surface layer and hotter fires with higher intensities will cause a water repellent layer at greater depths. The longer the soil is exposed to the high temperatures the greater is the effect (Neary, 2009). It is important to measure and classify the extent of the water repellency after the fire. Since measuring the temperature at the surface during a wildfire is difficult; another means of classification is needed. In Section 2.1.3 soil burn severity was introduced, which is a means of classifying the effect that fire has on the soil through historical empirical observations.

2.2.2 Soil burn severity

The USDA (United States Department of Agriculture) created a system which categorises the changes in the soil according to the level of soil burn severity (Parsons *et al.*, 2010). The soil-burn severity index was created by empirical observations of different vegetation types with varying densities. Table 2.3 displays such a classification matrix, redrawn from Parsons *et al.* (2010), of the different vegetation types with their varying densities.

Stellenbosch University https://scholar.sun.ac.za

Table 2.3: Classes of soil burn severity with different vegetation (Parsons *et al.*, 2010)

Vegetation type	Density model	Soil burn severity classes		
		Low	Moderate	High
Chaparral	Sparse	C	U	
	Medium	C	C	U
	High	C	C	U
Forest	Sparse	C	U	
	Medium	C	C	U
	High	C	C	C
Sagebush	Sparse	C	U	
	Medium	C	C	U
	High	C	C	U
Grass	Sparse	C		
	Medium	C	U	
	High	C	C	

C - Common, U - Uncommon

Table 2.3 displays different types of vegetation, which are categorised into different soil burn severity classes and different types of density. While most of the vegetation types will fall into a low soil burn severity class under a particular density, only certain types of vegetation will be capable of reaching a high enough temperature to cause a correspondingly high level of soil burn severity. It is likely that when a densely populated forest experiences a wildfire, it will attain a high level of soil burn severity. Other vegetation types are less likely to experience the same degree of severity. The most likely reason for this would be the relative weight of the available fuel and the availability of litter on the surface layer. Equation 2.1 shows that with an increase in fuel load the intensity of a fire rises. Forested areas are more prone to higher fuel loads than bush or grass. It is then reasonable that a forested area would have a higher soil burn severity and, in turn, a greater water repellent layer, after a severe fire.

The soil burn severity classification system applies not only to water repellency, but also to ground cover, ash colour, soil structure and root structure, which are all affected by the fire. However, for this research the focus is on classifying the fire-induced water repellency, since this is the factor that has a profound effect on the infiltration capabilities of the soil. Figure 2.3 is a visual representation of water repellency in the different soil burn severity classes, redrawn from Parsons *et al.* (2010).

Stellenbosch University https://scholar.sun.ac.za

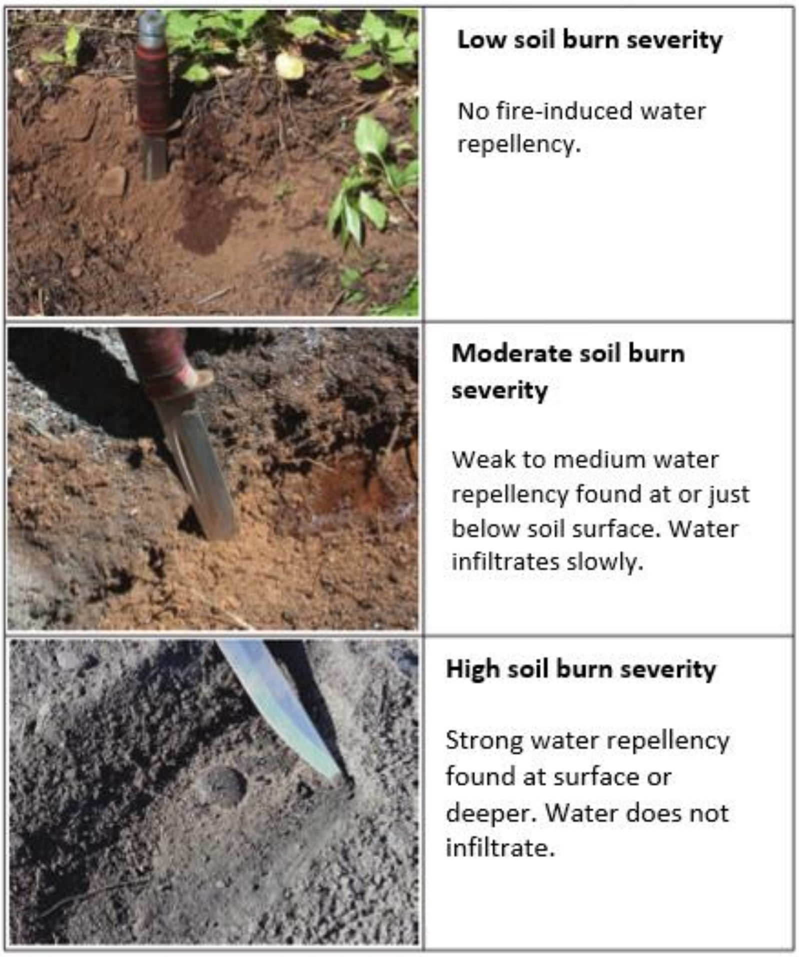


Figure 2.3: Visual illustration of soil burn severity (Parsons *et al., 2010*)

Figure 2.3 illustrates that the level of soil water repellency increases with the severity of the fire. With a low soil burn severity, water absorption is not altered. A moderate burn induces a weak to medium water repellency, which delays infiltration. During a high intensity soil burn, the water repellent soil layer is formed, which impedes water infiltration.

It is important to understand the dynamics behind fire-induced soil water repellency, because this understanding is validated by the resulting greater insight into the increase in overland flow and sediment loss after fires (Scott, 1994). Using a classification system such as the soil burn severity index (Table 2.3), provides a methodology to understand the extent to which the soil is damaged under different types of vegetation. Forest (2013) stated that the main reason for the classification of soil burn severity is to predict the extent of the increase in flow after a fire.

After gaining an understanding of the role that fire plays in changing the soil infiltration characteristics, it is important to understand the extent to which it could affect the overland flow in a catchment. The evaluation of the shape of a hydrograph provides an effective way to understand the effect that fire has on the hydrological changes within a catchment.

Stellenbosch University https://scholar.sun.ac.za

2.3 HYDROLOGICAL EFFECT THAT FIRE HAS ON RUNOFF

Numerous factors affect pre- and post-fire runoff in a catchment, including the shape, size, soil properties, vegetation cover, slope, soil moisture and rainfall intensities of the catchment (Johansen, Hakonson & Breshears, 2001; The South African National Roads Agency SOC, 2013). With fire having such a profound effect on two of these factors, vegetation cover and soil properties, a lot of research has been done to try to quantify the hydrological changes caused by a fire.

Before looking at some of the findings of previous research, it is necessary to classify the different hydrological features that are important to enable catchment managers to protect the biodiversity and to manage water systems downstream. There are two main components: (1) volumes of runoff over a period of time, and flood events caused by large rainfall events; (2) the time it takes for a catchment to recover and normal hydrological conditions to resume. Changes in flood characteristics due to fire, on the other hand, can have extremely detrimental effects on life and property. The next section will cover the comparison of hydrographs before and after fires. This will provide an understanding of what would change during a flood event.

2.3.1 Hydrograph changes due to fire

After a fire, the shape of hydrographs may be altered. The degree of alteration would depend on the severity of the fire and how it has affected the vegetation and the soil properties. Larger and more intense forest fires may change a hydrograph by increasing the volume of runoff and flood peaks (Le Maitre, Kotzee & O'Farrell, 2014). In large catchments (after a fire) there appears to be increased patchiness in vegetation that did not burn, in comparison to smaller catchments. This means that larger catchments would display less of a decrease in water storage than smaller catchments (Stoof *et al.*, 2012). The increased patches of unburned vegetation in large catchments in comparison to small catchments would mean that fire-induced soil water repellency would have less of an effect on large catchments and thus not show such a prominent change in runoff as with smaller catchments.

It is know that hydrological processes are highly affected by scale, in both burned and unburned systems (Stoof *et al.*, 2012). The changes that are observed at the plot-scale tend to overestimate the changes that occur at the hillslope- or catchment scale (Doerr, Ferreira, Walsh, Shakesby, Leighton-Boyce & Coelho, 2003). In large catchments the flood peaks increase has been between 45% (Anderson, Hoover & Reinhart, 1976) and 100% (Abramson *et al.*, 2009), and up to 1100% (Scott, 1993) in small catchments. Table 2.4 displays the results of various changes that have been measured or modelled in different parts of the world, including what has been done in South Africa.

Stellenbosch University https://scholar.sun.ac.za

Table 2.4: Research done in the past on fire's effect on runoff

Location	Catchment	Area (ha)	MAP (mm)	Description	Treatment	Stream-flow responses TF = Total flow PF = Peak flow SF = Storm flow	Reference
Mediterranean	Rimbaud basin	140	1164	Vegetation: Totally forested by maquis and degraded forest of cork trees and chestnuts	Wildfire that burned 85% of the catchment (August 1990)	TF: 30% increase in runoff yield during first year; PF: 62% increase	(Lavabre, Torres & Cernesson, 1993)
Portugal	Serra da Lousa	9.7		Vegetation: dense heathland dominated by Erica; Soil: schist or quartzite	High intensity experimental fire (2009)	Streamflow volume was 1.6 times higher than predicted	(Stoof *et al.*, 2012)
France	Gisele watershed	23400		Vegetation: Quercus suber (cork oak), Pinus pinaster(pine`), and Quercus pubescens are the dominant trees.	Fire simulation using HEC-HMS	PF: 10% to 50% increase	(Shital Dhakal & Dennis M. Fox, 2014)

United States, California	Mission Creek	3000		Vegetation: chaparra; Soil: sandstone and shale	Large fire scenario created for analysis	SF: 400% increase in runoff during a 2-year storm; TF: 124 %increase; PF: 100%	(Abramson *et al.*, 2009)
United States, San Gabriel Mountains	Auburn catchment			Vegetation: shrubs and bushes	Fire simulation using 45 years of data	PF: 105% increase	(Rulli & Rosso, 2007)
	Bailey	155				PF: 53% increase	
	Bradbury	176				PF: 100% increase	
	Spinks	113				PF: 91% increase	
United States	Rendija Canyon	2480			Wildfire (May 2000)	PF: increased up to 6 fold	(Moody & Martin, 2001)
United States	Wilson River	40800		Vegetation: Temperature Rainforest	Wildfire (1945)	TF: 11% increase; PF:45% increase	(Anderson *et al.*, 1976)
Australia	Snowy Mountains	4350		Vegetation: forest; Geology: siltstone, sandstone	High intensity fire (March 1965)	TF: sharp increase; PF: large increase	(Brown, 1972)
Australia	Slippery Rock Creek	136	1800	Native eucalyptus forest	Wildfire (2003)	TF: 65 - 75% increase	(Lane, Sheridan & Noske, 2006)
	Springs Creek	244				TF: 76-94% increase	

Stellenbosch University https://scholar.sun.ac.za

South Africa, Jonkershoek	Bosboukloof catchment	200	1296	Vegetation: Afforested (Pinus radiata)	High intensity wildfire (March 1987)	TF:12% increase; SF: 62% increase; PF:290% increase (1st year)	(Scott, 1993)
	Langrivier	245.8	2261	Vegetation: Tall mountain fybos	High intensity wildfire (October 1987)	TF:9.4% increase; SF: 3.8% increase; PF:8.4% increase (1st year)	
South Africa, Drakensburg	Ntabamhlope	132	838	Vegetation: Afforested (Eucalyptus fastigata)	High intensity wildfire (August 1989)	PF:1100% increase (1st year)	
South Africa, Klein drakenstein	Zachariashoek	324	1443	Vegetation: Mountain fynbos	Prescribed burns	TF: 15% increase in first year	(Lindley, Bosch & Van Wyk, 1988)

From Table 2.4 it is clear that, the results vary considerably. From having almost no effect on streamflow responses, such as the fynbos fire in Langrivier in Jonkershoek (Scott, 1993) and up to a 290% increase in peak flow during the first year after a fire (Bosboukloof sub-catchment), which is situated inside the same main catchment as Langrivier. Scott (1993) found that in the Drakensberg area the peak flow can increase up to 1100% during the first year after the fire.

From this it can be concluded that hydrographs can be altered remarkably by a fire, specifically in small catchments, with a forest like vegetation (Myronidis, n.d.). Figure 2.4 displays some key characteristics of a hydrograph.

Stellenbosch University https://scholar.sun.ac.za

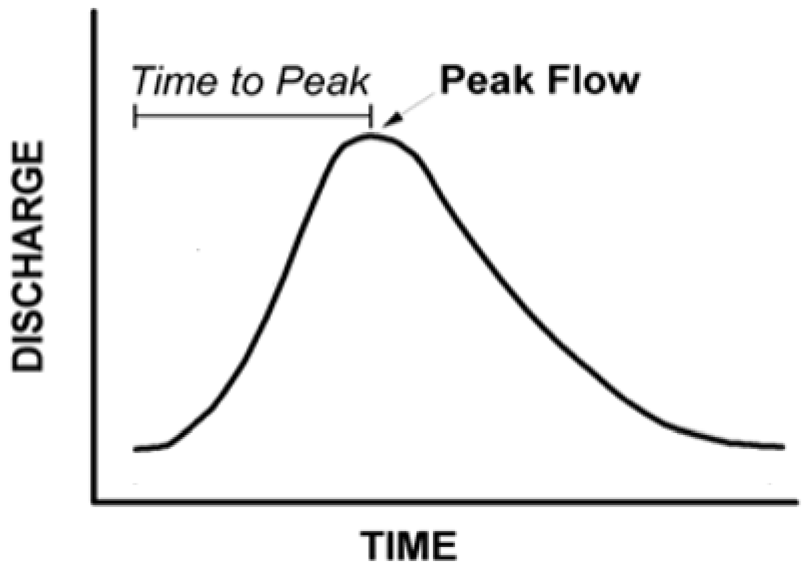


Figure 2.4: Simple representation of a hydrograph

The time to the peak runoff discharge is important when forecasting floods. It is especially true for burned areas in mountainous terrain where land managers and emergency managers need advance warning, and where the time to peak discharge is regularly shortened by the effects of wildfire (Moody & Martin, 2015).

According to Sugihara *et al.* (2006), fires shorten the lag time in hydrographs. A 40% reduction in post-fire lag time has been used for modeling purposes in previous studies (Cydzik & Hogue, 2009; Miller, *et al.*, 2014).The main reason for such a dramatic reduction is likely to be the lack of ground cover and the low water absorption capabilities. Ground cover such as vegetation and duff, aids infiltration by inhibiting overland flow, thereby increasing the frequency, as well as the depth, of ponding and also protecting the soil surface (Johansen *et al.*, 2001; Strydom, *et al.*, 2014).

The shape of a hydrograph is thus affected by both infiltration and surface features, such as depression storage and ground cover that impedes flow (Frasier, Weltz & Weltz, 1998). With a decrease in water infiltration through the soil, the result is a steeper slope of the rising portion of the hydrograph, which reflects the shorter time from the start of the storm until its peak.

Before runoff can begin, the rainfall must satisfy the ‘initial losses’ which are related to interception, surface depression storage, and any travel time from a source area (Moody & Martin, 2015). The initial abstraction (I_a) represents these initial losses. When rain falls, it must satisfy the initial abstraction before overland runoff can occur. The lack of vegetation for facilitation of soil infiltration can shift the rainfall response from an infiltration-dominated process to surface runoff-dominated processes (Yochum, 2015). It is thus important to quantify

Stellenbosch University https://scholar.sun.ac.za

the degree of change in initial abstraction due to fire. There have been few measurements of I_a in burned areas; however, Elliott *et al.* (2004) found a conservative 1 mm value which is the minimum rainfall that needs to occur to generate runoff in a burnt catchment. A post-fire model by Cydzik & Hogue (2009) showed that 19.6 mm of precipitation was needed to satisfy the initial abstraction. The difference between these values is due to the various factors that affect the initial abstraction, such as the antecedent soil moisture, the severity of soil burn, the vegetation cover, and the slope. It is important to know how long the hydrological changes will last and when the catchment is likely to return to normal.

2.3.2 Recovery time

The recovery time for streamflow to be restored varies, depending on the time that has passed after the fire event. Lavabre *et al.* (1993) found that the annual runoff could increase by as much as 30% in the first year after a fire. Scott (1993) found a 200% increase in runoff and up to 290% peak discharges a year after a forest fire in Jonkershoek.

The runoff and infiltration changes are determined mainly by the gradual recovery of vegetation, and thus the relationship between runoff and vegetation cover changes throughout the recovery period (Cerdá, 1998). Cerdá (1998) found that the increase in runoff coefficient caused by a wildfire decreased from 45% in the first winter to 6%, five and a half years later. This would depend on the time it takes for the soil water repellent layer to have an effect or the vegetation to recover. Dyrness (1976) found that after six years a forest catchment would usually recover fully. It all depends on the burn severity, the type of soil profile and the type of vegetation.

There are three main approaches to measuring the differences in runoff caused by wildfire. The first and most commonly used is to examine what happens on plot scale (small areas set out for research). The other two are by focusing on catchment scale. On a catchment scale, the paired catchment method and a computer based simulation model, which will be described below, are frequently used to quantify the changes in a catchment. Since this research was focused on understanding the changes in hydrological dynamics on a catchment scale, the next section will look at these two approaches.

2.4 POST-FIRE HYDROLOGICAL MEASURING METHODS IN A CATCHMENT

The literature is consistent in agreement that it is possible for changes to occur in storm hydrographs as a result of fire; however, the precise changes are difficult to measure. Research highlights two methods. The first is one of the oldest and most trusted methods, which is the paired catchment method. The second method is simulating the hydrological response of a catchment through computer modelling.

Stellenbosch University https://scholar.sun.ac.za

2.4.1 Paired catchment method

The method tries to establish a relationship between streamflow and peak flows in two similar catchments, during a calibration period where the vegetation cover remains unaltered. It is important that these catchments are close to each other, have similar vegetation cover and rainfall; otherwise, it is unlikely that the method will work (Zégre *et al.*, 2010).

One of the standard approaches using the paired catchment method is to use ordinary least squares (OLS) regression to detect changes between the runoff on the control and the affectedaffected catchments. In its most simple form, it can be expressed as follows:

$$T_j = \beta_0 + \beta_1 C_j + \epsilon_j \qquad \text{…(2.2)}$$

where,

- T_j is the burned catchment's runoff at time j
- j is the time interval
- β is a coefficient needed to create a regression equation
- C_j is the control catchment runoff at time j
- ϵ_j is the error at time j.

Adding other independent variables, such as: soil moisture, rainfall volume, rainfall duration and peak intensity, can improve the regression model. After the fire event, the regression model is run again calculating new coefficients. The regression model produces a p-value (probability value), when this value is smaller than the chosen significant level (α) it suggests that the data is sufficiently inconsistent with the null hypothesis. This illustrates that the data is statistically significant. The significant level cut-off for the regression model used in the paired catchment method is 5%. Thus, when the p-value calculated in the model is smaller than 0.05 it indicates that the data is statistically significant and then the deviations in the coefficients could be calculated.

Using this approach is functional only if an affected and control area are available close to each other (Folton, Andréassian & Duperray, 2015). Even then, the spatial variation in rainfall can cause anomalies in the results, and the paired catchment model is therefore only applicable to small catchments. The use of computer based simulation models makes it unnecessary to have a control catchment. The programs try to simulate the response of a catchment post-fire.

Stellenbosch University https://scholar.sun.ac.za

2.4.2 Computer based simulation models

There is a variety of software available, which simulates runoff from a catchment. Some of the most popular of these are WinTR-55, Wildcat5, HEC-HMS, HBV and ACRU. These models vary with input parameters, constraints and development interface (Kinoshita, Hogue & Napper, 2014; Scott, 1994). The most important aspect of the model is how well it is calibrated; this determines the accuracy of its prediction of streamflow.

The way in which software detects hydrological changes can be briefly explained in two steps. First the model is calibrated by looking at pre-fire conditions; these include streamflow, precipitation and various different catchment characteristics. If the calibration falls within acceptable statistical bounds, then the same model is used to simulate post-fire runoff, by simply adjusting certain parameters of the model. The parameters most likely to change in a post-fire model will be the vegetation cover and permeability of the soil, as highlighted in the previous chapters.

- The Curve Number (CN) is a parameter in the Soil Conservation Services (SCS) method, which incorporates the type of vegetation and the soil profile. Since the CN incorporates both of these parameters, it is therefore an attractive method for use in hydrological programs to estimate change in runoff after a fire (Forest, 2013; Yochum, 2015). The CN categorises soils as being either A, B, C or D type, where A allows the most infiltration and least runoff, while D allows the least infiltration and greatest runoff (South African National Roads Agency SOC Ltd, 2013). The soil is then further grouped according to the type of vegetation coversuch as wetland, bush, or pine. Higginson & Jarnecke (2007) proposed a general approximation for CN numbers according to the level of soil burn severity, which are:CN + 5 for low burn severity,
- CN + 10 for moderate burn severity,
- CN + 15 for high burn severity.

Kinoshita (2012) did an analysis on the HEC-HMS, WinTR-55 and Wildcat5 models, with the CN adjustments proposed by Higginson & Jarnecke (2007). She found that the CN models generally tend to over-estimate discharge, which stems from the CN over-estimation. It is thus important to give attention to the limitations of a model (i.e. geography, climate, watershed size), which must be considered when selecting an appropriate framework for the simulation of pre- and post-fire runoff.

Understanding the limitations of both the paired catchment method, as well as computer-based simulation programs, is important when computing the effect that fire has on the

Stellenbosch University https://scholar.sun.ac.za

hydrological response of a catchment. The next section examines different research, which was conducted in South Africa, and the methods used to analyse the effects of fire on runoff.

2.5 RESEARCH CONDUCTED IN SOUTH AFRICA

Various research has been done in South Africa regarding the effect of fire on runoff. Most of the research was conducted in the Western Cape region, with varying results and utilising different methodologies. The rest of this section will demonstrate some of the most fundamental work done in South Africa on the subject; briefly discussing the methodologies and results of each study.

Bosch, van Wilgen & Bands (1986) created a model that estimates the differences in water yield from different burning cycles of fynbos by using empirical data from two catchment experiments (Bosch, Schulze & Kruger, 1984). They tried to find a relationship between how the reduction in water yield affected the recovery of fynbos for different species. They assumed that a relationship exists between the sprouter:seeder ratio in the vegetation and the annual rate of change in water yield (k) following a fire. By looking at two catchments that had experienced fires, Langrivier (seeding dominated by fynbos) and Zachariashoek (sprouting dominated by fynbos), they observed an annual rate of water recovery yield for each catchment after the fire. This was done by determining the annual change in streamflow caused by the fire Q_m and observing the recovery rate of the streamflow on an annual basis.

Figure 2.5 displays a graph depicting the two catchments with their annual recovery yield and their sprouter:seeder ratio. It is clear from the graph that the more the fynbos sprouts from its seeds, the greater the likelihood of recovery of the water yield will be.

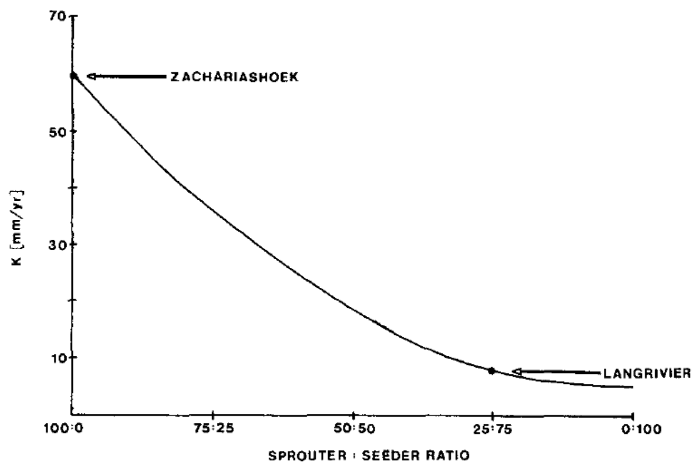


Figure 2.5: Sprouter:seeder ratio (Bosch *et al., 1986*)

Stellenbosch University https://scholar.sun.ac.za

Following the observation of these two catchments, they estimated recovery rate responses for different types of fynbos from sparse data. They hypothesised that the Q_m is mainly a function of the biomass of the fynbos. An expected post-fire maximum increase in water yield was assigned to different types of fynbos according to their assumed biomass. Table 2.5 displays the hypothetical responses of different types of fynbos after fire.

Table 2.5 Hypothetical responses of fynbos after a fire (Bosch *et al., 1986*)

Structural formation	Biomass rank†	Expected max. post-fire increase in streamflow/year (Qm) (in mm)	Sprouter :* seeder ratio	Expected rate of post-fire decrease in water yield/year (k) (in mm a^{-1})
Tall closed shrubland	1	180	0:100	4
Tall mid-dense shrubland	2	130	0:100	4
Mid-high closed shrubland	2	130	0:100	4
Tall open shrubland	3	90	25:75	8
Mid-high mid-dense shrubland	3	90	0:100	4
Low closed shrubland	3	90	50:50	19
Closed graminoid shrubland	3	90	75:25	37
Tall closed herbland	3	90	100:0	60
Tall sparse shrubland	4	60	50:50	19
Mid-high open shrubland	4	60	25:75	8
Low mid-dense shrubland	4	60	50:50	19
Dwarf closed shrubland	4	60	50:50	19
Mid-dense graminoid shrubland	4	60	75:25	37
Tall mid-dense herbland	4	60	100:0	60
Closed herbland	4	60	100:0	60
Mid-high sparse shrubland	5	35	50:50	35
Low open shrubland	5	35	75:25	35
Dwarf mid-dense shrubland	5	35	50:50	35
Open graminoid shrubland	5	35	75:25	35
Tall open herbland	5	35	100:0	35
Mid-dense herbland	5	35	100:0	35
Low sparse shrubland	6	18	75:25	18
Dwarf open shrubland	6	18	75:25	18
Sparse graminoid shrubland	6	18	100:0	18
Tall sparse herbland	6	18	100:0	18
Open herbland	6	18	100:0	18
Dwarf sparse shrubland	7	0	75:25	0
Sparse herbland	7	0	100:0	0

*† Represents the biomass rank. *The sprouter:seeder ratio is only a rough guide.*

By using the hypothetical Table 2.5 as a rough estimate of the expected post-fire increase (Q_m) and of the decrease (k) in runoff/year, a recovery period for runoff could be determined. Equation 2.3 displays the calculation for determining the time it takes a catchment to recover after a fire:

$$T = \frac{Q_m}{k} \qquad ...(2.3)$$

where,

- T is the time it takes for the streamflow to return to normal (years)
- Q_m is the maximum annual yield increase (mm/year)
- k is the annual yield recovery rate (mm/year).

Stellenbosch University https://scholar.sun.ac.za

Lindley, Bosch & Van Wyk (1988) looked at three sub-catchments in the Zachariashoek area to observe the effect of prescribed burns on streamflow by using a paired catchment experimental approach. Two catchments underwent prescribed burns. The Kasteelkloof catchment burned with six-year-old fynbos, while Zachariashoek burned with 12-year-old fynbos. With the use of the paired catchment response method for the Kasteelkloof catchment, the mean monthly streamflow increased by 7.1 mm for the first year after the burn. The second and third years did not result in significant changes in the streamflow.

The burn did not significantly alter the Zachariashoek streamflow. There was only a marginal 2 mm increase in the mean monthly streamflow in the first year after the fire. The following years showed no alteration in streamflow. Lindley *et al.* (1988) attributed the primary lack of change in the Zachariashoek streamflow due to the type of vegetation (veld type fynbos), which according to Bosch *et al.* (1986) has an ability to regenerate rapidly after a fire.

Scott (1993) also used the paired catchment response method in four mountainous catchments to analyse the catchments' responses to fire. Two of the catchments (Swartboskloof and Langrivier) were fynbos catchments in the Jonkershoek area, which did not display a significant increase in streamflow after the first year since the fire. The other catchments (Bosboukloof and Ntabamhlope) were afforested catchments. Bosboukloof is in the Jonkershoek area, while Ntabamhlope catchment is in the Drakensberg area. Both of these catchments showed a significant increase in streamflow one year following the fire.

Table 2.6 displays the changes in the streamflow characteristics of all four catchments a year after the fire, reconstructed from Scott (1993).

Table 2.6: Streamflow responses one year following fires (Scott, 1993)

Characteristic	Swartboskloof	Langrivier	Bosboukloof	Ntabamhlope
Annual flow change (mm)	1246	1389	733	106
	15%	9%	12%	-6%
Storm-flow change (mm)	16.1	30.3	6.4	n.m.
	-2%	4%	62%	
Quick-flow change (mm)	7.2	20.6	3.6	2.1
	22%	50%	201%	92%
Peak discharge change (mm/day)	15.4	42.2	32.3	78.5
	19%	8%	290%	1100%
Response ratio change (%)	11.9	36	7.5	6.5
	7%	11%	242%	319%

The annual flow of the catchments increased after the fire for most of the catchments. The peak discharges of the measured storms showed a dramatic increase in afforested areas, while the fynbos catchments did not display the same result. Scott (1993) attributes these big

Stellenbosch University https://scholar.sun.ac.za

differences between the two catchments with different types of vegetation to a number of factors. First, the intensity of the fires in the fynbos areas was not as great as that of the fires in the afforested area. This could have been due mainly to the pre-fire soil moisture content and the variance in biomass. Secondly, the timber plantations have less low-growing vegetation than fynbos, which leaves the soil at the surface more exposed to fire, thus creating a greater risk of soil water repellency.

Strydom *et al.* (2014) conducted plot experiments in the Kruger National Park to see what effects fire has on soil dynamics and water runoff on grassland vegetation. She recreated high intensity rainfall events by means of a sprayer nozzle above the plots. A 1 m x 1 m calibration frame was placed under the nozzle on the ground to collect water runoff and sediment. An initial rainfall intensity of 157 mm/h for 10 minutes was recreated for two unburned sites. After 24 hours, another 200 mm/h of ‘rain’ fell for 10 minutes on the same sites. The additional stimulus of water was to assess the effect of increased soil moisture, a day after a significant rainfall event. The same process was repeated after the plots had been burned.

Figure 2.6 displays the results of the rainfall due to the 157 mm/h event on the burned and unburned plots. The solid lines represent the post fire runoff, while the dotted lines represent the pre fire runoff.

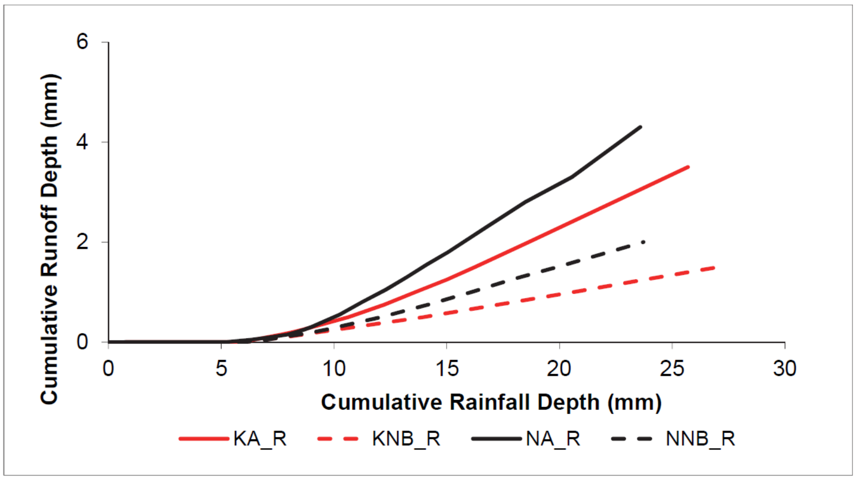


Figure 2.6: Runoff due to rainfall of 157 mm/h on plots (Strydom *et al.*, 2014)

As observed in the Figure 2.6 there is a prominent increase in runoff depth after the fire when compared with that before a fire, for both sites. Figure 2.7 displays the 200 mm/h event 24 hours after the initial event.

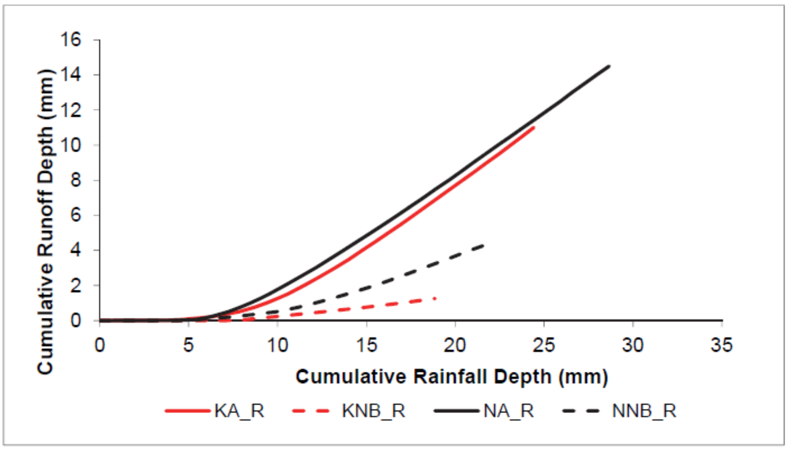


Figure 2.7: Runoff due to rainfall of 200 mm/h on plots (Strydom *et al.,* 2014)

A more prominent change was observed in the post-fire runoff in Figure 2.7 than in Figure 2.6. Figure 2.7 illustrates that runoff curves after the fire are more similar and have significantly increased, while the pre-fire runoff did not change significantly. This change can be attributed to the increased soil moisture and the intensity of the rainfall. These finding illustrate that an increase in the soil moisture before a fire has an effect on the runoff after a fire.

The research conducted in South Africa is crucial in understanding the work that has been done on the subject nationally. It also provides valuable guidelines for future research. The next section looks at the historical damage caused by post-fire floods.

2.6 DAMAGE CAUSED BY POST-FIRE RAINFALL

From the previous sections, it is clear that fire has the ability to have an effect on the hydrological responses of a catchment. The magnitude of the hydrological change depends on various factors, such as the type of soil and vegetation, and the intensity of the fire. When these factors contribute to a high soil burn severity, it is possible that flood events may occur, with even small rainfall events. In a limited number of cases flood events have occurred primarily due to a fire event; however, the following events illustrate how damaging these fire-induced floods can be.

2.6.1 Switzerland

In Switzerland, a fire burned an area in the town of Ronco on the 15th of March 1997; on the evening of the 28th of August 1997, a heavy rainstorm triggered a debris flow that overtopped the torrent channel in the inhabited area of the town. A considerable amount of damage was

Stellenbosch University https://scholar.sun.ac.za

caused by the flood and it was only by chance that there were no serious injuries or deaths (Conedera *et al.*, 2003)

2.6.2 Greece

In the Kassandra Peninsula (northern Greece), on 21 August 2006 a wildfire burned 77 km^2 of the 353 km^2 peninsula. Directly after the fire, a series of log erosion barriers (LEBs) were constructed on the hillslopes of the burnt area. Most of the necessary safety dams on the river channels, however, were not established during the critical first year after the fire. Just over a year later, on the 2nd of September 2007, a rainfall event occurred, with a precipitation of 59.4 mm. This event caused a flood event which provoked countless cases of damage and threatened human lives in the surrounding area (Myronidis, n.d.).

2.6.3 United States

In Mission Creek, California, a fire occurred in 1964. After the fire, a flood followed, which destroyed twelve homes and six bridges. The estimated public and private damages were around $300,000 (Abramson *et al.*, 2009).

In Southern California (2003), a post-wildfire flood caused considerable damage. The debris flows killed 16 people and caused tens of millions of dollars in damages (Abramson *et al.*, 2009).

It is clear that these have been floods which are due to the hydrological effect of fire on watersheds. Floods are considered one of the most damaging natural disasters. Increasing the likelihood of floods after a fire can have serious consequences on society.

2.7 CONCLUSION DRAWN FROM LITERATURE

Fire-induced flooding is possible, and examples of the devastating effects have been discussed in the previous section. It is therefore important to understand the dynamics behind the hydrological changes caused by fire.

The hydrological effect of fire can be traced back to the intensity of the fire. Since measuring fire intensity is difficult, and the effect that fire has differs considerably according to vegetation cover and soil profile, it is important to classify the fire by the severity of its nature. Fire severity is a categorisation according to the effect that fire has on vegetation and soil by using empirical data.

Vegetation cover is important in the gathering of water from rainfall. Vegetation not only captures the rainfall through its root system, but also helps prevent soil erosion. After the

Stellenbosch University https://scholar.sun.ac.za

destruction of vegetation through fire, there is naturally a bigger risk of erosion and runoff. The literature shows that the most fundamental predictor for increase in runoff after a fire is the changes that occur in the soil. Fire has the ability to affect the absorption capacity of soils. Fire burns the soil; in the process, the soil is coated with hydrophobic organic substances, which reduce the attraction between the water and soil molecules. These hydrophobic substances create or enlarge an existing water repellent layer. The extent of the fire-induced soil water repellent layer depends on the soil burn severity. The higher the soil burn severity, the deeper the water repellent layer, and thus the greater chance of increased runoff during a storm event. According to the USDA (Parsons *et al.*, 2010) a densely populated forest has a higher probability of reaching a high class of soil burn severity than either grass or sagebush. This is understandable, since the biomass of forest-like vegetation is greater than that of most other vegetation, which means that higher intensity fires are possible.

Much research has been done in an attempt to quantify the hydrological effect that fire has on runoff with varying results. The burn severity is not the only factor, which determines how catchments will respond to fire; the size of the research site is also a factor to consider. Plot size studies tend to overestimate the response of a catchment (Doerr *et al.*, 2003). Larger catchments also tend to have hydrological responses that change less after a fire than do those of small catchments; this could be due to the distribution of the burn and the shape of the catchment.

The effect that a severely burned catchment has on a hydrograph is thus increased flow volume and peak flows, while also shortening the response time, time to peak, lag time and time of concentration (Moody & Martin, 2015). The hydrological effects of a fire will last until the vegetation and soil has fully recovered. After six years, Dyrness (1976) found that a catchment would have fully recovered and runoff would be back to normal.

With this knowledge, the formulation of a hypothesis was possible, and a research plan to test the hypothesis followed.

2.8 FORMULATION OF AN HYPOTHESIS AND A RESEARCH PLAN

Based on the literature study, it was hypothesised that the observed hydrological changes caused by fire were linked to the level of soil burn severity, which is determined by the type of vegetation cover and its density, the soil profile, as well as the intensity of the fire. The more profound the soil burn severity, the deeper the fire-induced soil water repellent layer. The repellency layer hinders percolation and infiltration of water, which could increase overland flow. The growth in the overland flow can lead to an increase in the hydrological response of a catchment, in terms of runoff volume and peak discharge.

Stellenbosch University https://scholar.sun.ac.za

The research was planned to test the above hypothesis on the effect that fire has on the hydrological responses of a catchment, and included the following:

a) find suitable catchments that had undergone a high intensity wildfire, with the availability of adequate precipitation data;

b) detect possible long term changes in runoff after the fire event;

c) analyse the hydrological responses of rainfall events pre- and post-fire by using acceptable methods;

d) use the literature to validate results.

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 3
RESEARCH METHODOLOGY

The research was undertaken in four gauged catchments, composing one main catchment and three sub catchments inside the Jonkershoek nature reserve, in the Western Cape region of South Africa (33°57' S, 18°15' E). This chapter provides a description of these catchments, the fire affects that they had undergone and the methods that were used to test the hypothesis.

The main catchment was partially burned, while two of the sub-catchments (Lambrechtsbos A and B) were completely burned, which were both taken as affected catchments. The other sub-catchment (Bosboukloof) was largely un-affected by the fire and thus used as a control catchment for the two affected sub-catchments.

Two statistical methods were used for analyses on the sub-catchments. Both of these approaches were possible, since there was a control catchment with similar rainfall and vegetation cover.

The mixed Analyses of Variance (ANOVA) test was used to test if there was significant long-term change on streamflow. The method tests the mean differences between the streamflow volume before the fire, between the control catchment and both the affected catchments, and then compares the post-fire mean differences between the catchments. The paired catchment method (Section 2.4.1) was then used to analyse the effects of fire on runoff.

Since the size of the main catchment was too large to have another control catchment alongside it, with similar rainfall and vegetation properties, another approach was used for its analysis. Pre- and post-fire storms that had similar characteristics regarding storm duration and rainfall were compared using hydrographs. The Wilcoxon test was used to assess the validity of the descriptive statistics. The mixed ANOVA test, paired catchment method and Wilcoxon tests were conducted using a statistical software package, Statistical Package for Social Sciences (SPSS) (Field, 2009). The methods used for both the main catchment and the sub-catchments will be discussed in detail in the section hereafter.

Stellenbosch University https://scholar.sun.ac.za

3.1 CATCHMENT DESCRIPTION

The catchments are all mountainous catchments. The climate in Jonkershoek is mild, with hot dry summers and wet cold winters. The majority of precipitation occurs between April and October, with rainfall events being generally of low intensity and long duration. Jonkershoek area receives a Mean Annual Precipitation (MAP) of more than 1200 mm a year.

The vegetation in Jonkershoek is predominantly fynbos; it also contains afforested areas. Fynbos is a species indigenous to the area, which is a sclerophyllous scrub dominated by *Ericaceae, Proteaceae* and *Restionaceae* (Scott, 1994). The control and affected sub-catchments were predominantly afforested with *Pinus radiata*. A company called MTO uses the afforested areas as timber-crop. Table 3.1 supplies a summary of each catchment.

Table 3.1: Catchment description

Catchment	Area (ha)	Vegetation	Channel slope (%)	MAP (mm)	MAR (mm)
Main	2527.7	Tall mountain fynbos	9.6	1813	914
Bosboukloof	200.9	Pinus radiata	26	1127⁺	568⁺
Lambrechtsbos A	65.5	Pinus radiata	45	1145⁺	331⁺
Lambrechtsbos B	31.2	Pinus radiata	46	1145⁺	510⁺

⁺MAP = Mean Annual Precipitaiton and MAR = Mean Annual Runoff from (Scott *et al.*, 2000) from 1938-1998; Main catchment: MAP from 2011-2016, MAR from 1989-2016 (Department of Water and Sanitation)

The main catchment is much larger than the sub catchments; its channel slope is also less steep. Figure 3.1 is a visual representation of the main and sub catchments.

Stellenbosch University https://scholar.sun.ac.za

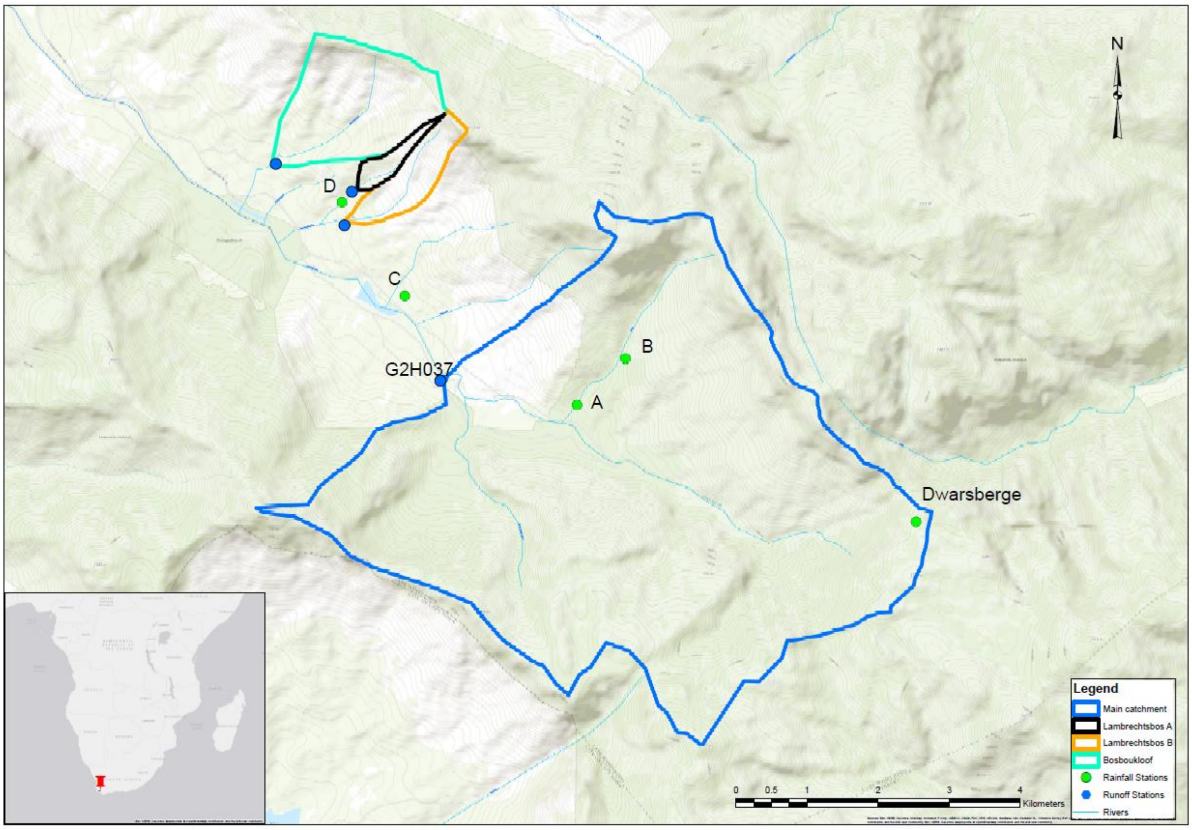


Figure 3.1: Jonkershoek (main and sub-catchments)

In Figure 3.1 the large area enclosed by a blue line is the main catchment. The sub catchment enclosed by turquoise is Bosboukloof, black is Lambrechtsbos A, and orange is Lambrechtsbos B.

There are also eight rainfall stations located in the Jonkershoek area; five of these stations were used for analysis. Three of these rainfall stations are located inside the main catchment (A, B and Dwarsberge), which are indicated in Figure 3.1. Rainfall station C is located at Tierkloof sub-catchment, which is a sub-catchment located next to the main catchment, while rainfall station D is located in the Lambrechtsbos stream. Each of these catchments contains a V-notched weir at the foot of the catchment, which measures streamflow. Table 3.2 provides the position, elevation, description and data source for the streamflow and rainfall data obtained for analysis.

Stellenbosch University https://scholar.sun.ac.za

Table 3.2: Rainfall and streamflow stations

Station		Latitude	Longitude	Elevation (m)	Start date	End date	Description & measuring interval	Data source
Streamflow	**Main (G2H037)**	-33.9847	18.9533	302	1989/06/15	2016/11/30	V-weir (12 minutes)	DWS
	Bosboukloof	-33.9617	18.9320	274	2011/09/05	2017/03/31	V-weir (1 hour)	SAEON
	Lambrechtsbos A	-33.9649	18.9429	362	2011/09/05	2017/03/31	V-weir (1 hour)	SAEON
	Lambrechtsbos B	-33.9682	18.9406	300	2011/09/05	2017/03/31	V-weir (1 hour)	SAEON
Rainfall	**A**	-33.9876	18.9700	366	2011/09/05	2016/09/20	Tipping gauge (event)	SAEON
	B	-33.9827	18.9762	472	2011/09/05	2016/09/20	Tipping gauge (event)	SAEON
	C	-33.9760	18.9483	298	2011/09/05	2016/09/20	Tipping gauge (event)	SAEON
	D	-33.9663	18.9404	310	2011/09/05	2017/03/31	Tipping gauge (event)	SAEON
	Dwarsberge	-33.9997	19.0130	1214	2013/03/12	2016/09/20	Weather station (1 hour)	SAEON

The stations measuring streamflow had different measuring time intervals; the main catchment's weir measured every 12 minutes, while the sub catchments' stream gauges measured flow every hour. The majority of the rainfall stations (A, B, C, D) measured rain every time 0.2 mm of rain fell. The weather station at Dwarsberge, however, measured rainfall every hour. There were two sources from which data was obtained: (1) Department of Water and Sanitation (DWS) and (2) South African Environmental Observation Network (SAEON).

Since the sub-catchments are situated so close to each other and have similar MAP (1145 mm and 1127 mm), rainfall station D was taken as representing the three sub-catchments. These sub-catchments were thus ideal for utilising the paired catchment and mixed ANOVA method, since there is a single rainfall station (D), which proportionally represents the rainfall of all the sub-catchments.

The contribution of the four stations (A, B, C and Dwarsberge) to the catchment rainfall was calculated, by means of the Theissenpolygon method (The South African National Roads Agency SOC Ltd, 2013). Figure 3.2 displays the contribution of the rainfall stations using the Theissenpolygon method.

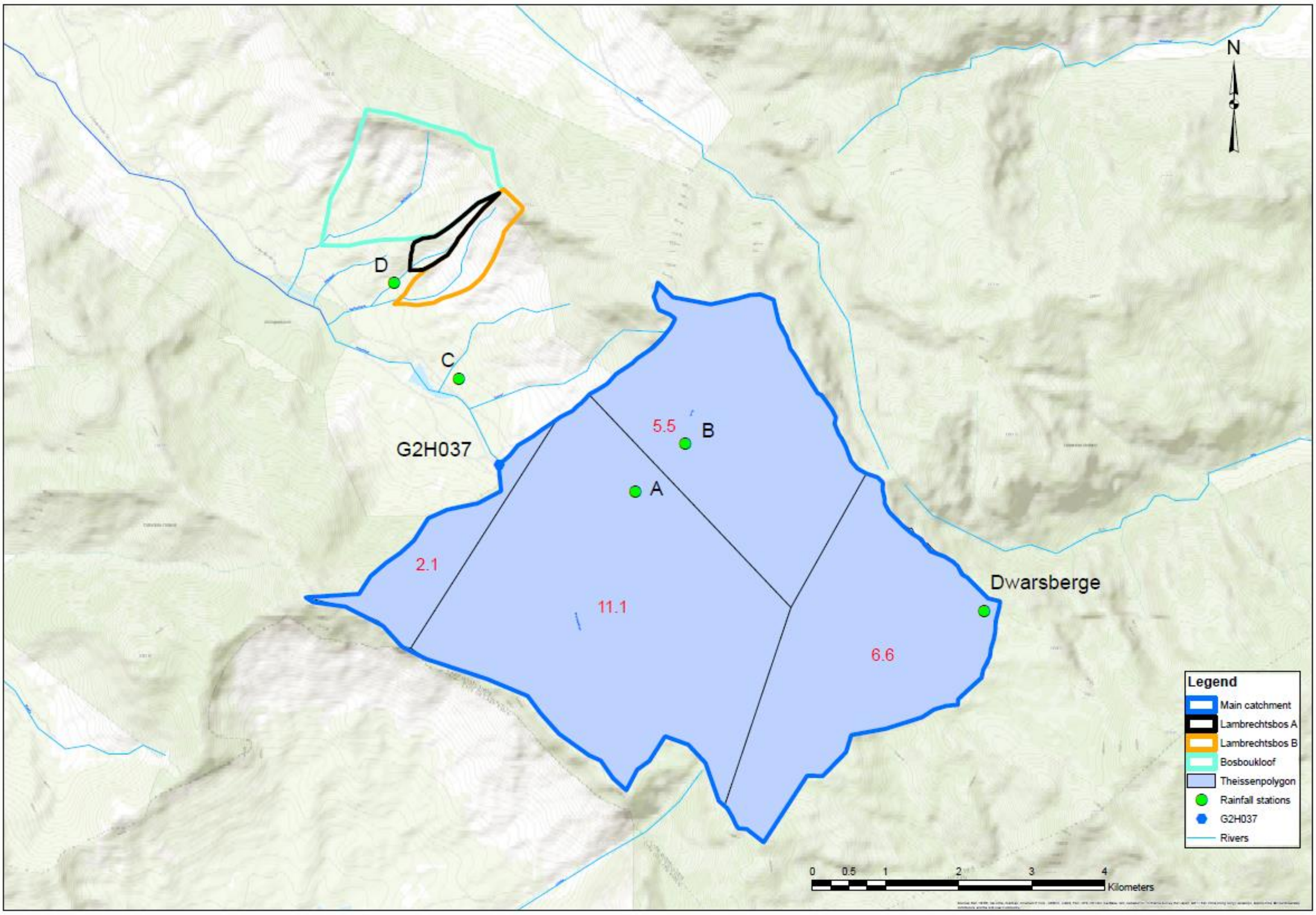


Figure 3.2: Thiessenspolygon on main catchment

The numbers inside the enclosed main catchment represent the area that each rainfall station contributes to the total area of the catchment. Rainfall station A added the highest contribution to the main catchments rainfall, 11.1 km^2 of the 25.3 km^2, which is 43.87%.

Since these catchments have adequate rainfall and runoff data, they are ideal for analysing the effect that fire has on the runoff.

3.2 JONKERSHOEK FIRE

There have been many fire events at Jonkershoek in the past. Most of the fires were wildfires, however there have also been prescribed burns in the nature reserve. On the 9th of March 2015, a high intensity wildfire started in Jonkershoek, which lasted until the 13th of March. The fire destroyed more than 4000 ha of both indigenous fynbos and afforested areas. Figure 3.3 displays a map similar to Figure 3.1 but showing the areas that were affected by the fire.

Stellenbosch University https://scholar.sun.ac.za

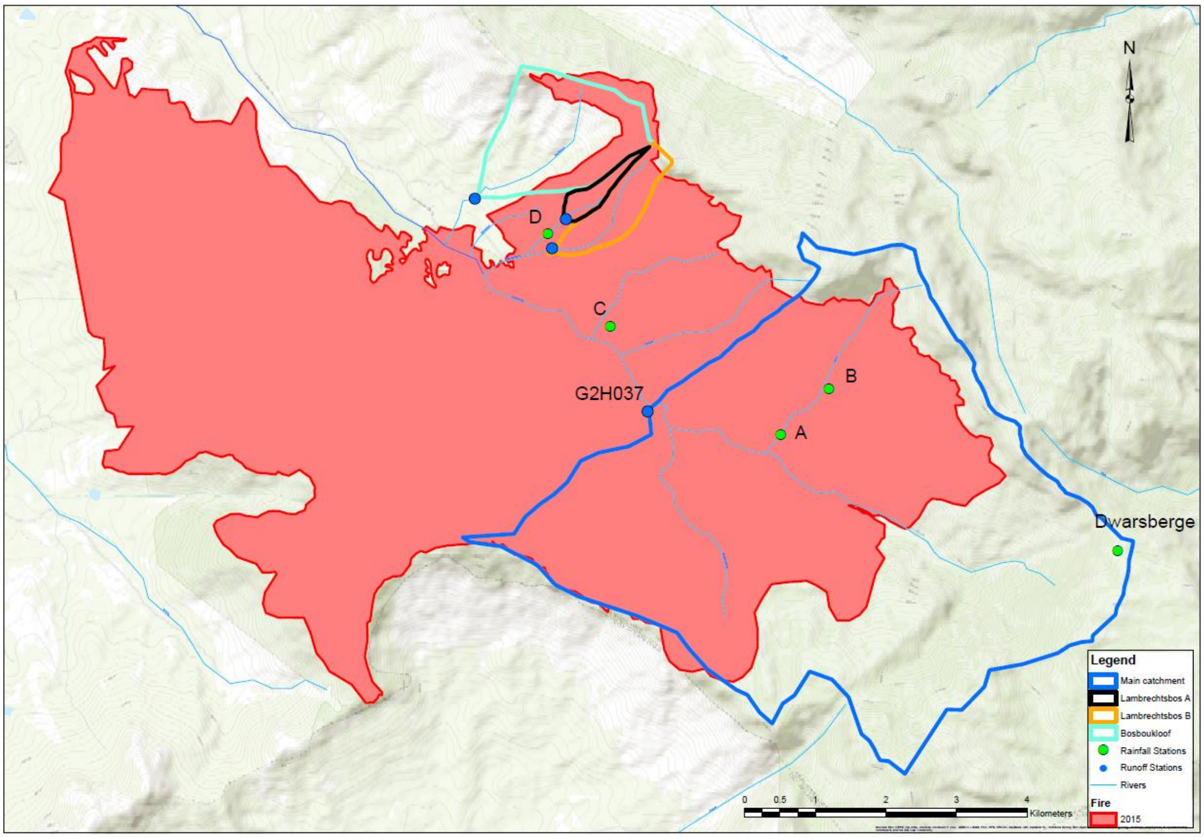


Figure 3.3: Jonkershoek area burned March 2015

The figure shows that the fire affected all the catchments in the research area. Only 56% of the main catchment was burned, while the fire affected 100% of the Lambrechtbos A and B catchments. Bosboukloof was only partially burned (30%) and could be used as a control catchment, since the majority of the catchment was unaffected by the fire.

Table 3.3 shows the age of vegetation for each catchment, and the percentage burned during the fire event in 2015.

Table 3.3: Age of vegetation in catchment

Catchment	Date of previous fire	Average vegetation age (years)	% Burned in 2015 fire
Main	2009/02/28	6	56
Bosboukloof	1986/02/18	29	30
Lambrechtsbos A	1986/02/18	29	100
Lambrechtsbos B	1986/02/18	29	100

The catchments have adequate data on fire, rainfall and runoff, which therefore can be used for analyses. The next section focuses on the different methods that were used for analysing the effects that the fire had on runoff in these catchments.

Stellenbosch University https://scholar.sun.ac.za

3.3 METHODS

The analyses of the main catchment and sub-catchments required different methods. The method for analysing the main catchment was by comparing pre- and post-fire rainfall events. These events had to have similar rainfall durations in order to be grouped together and a similar amount of rainfall to be matched. Hydrographs were then constructed for the matched pre- and post-fire rainfall events. The antecedent soil moisture of each event was also calculated by using an adaptation of the Antecedent Precipitation Index (API). The API is a means of estimating the soil moisture by using antecedent precipitation (Ali, Ghosh & Singh, 2010). The hydrographs were then compared with one another and possible relationships between the events were then determined by use of descriptive statistics and the Wilcoxon method.

Two methods were used to test the effect that fire has on the runoff in the sub-catchments. The mixed ANOVA method and the paired catchment method. The mixed ANOVA method establishes a relationship between the storm events of two similar catchments in terms of runoff (pre-fire), by using regression. After a relationship is established, the same regression method is applied post-fire. A hierarchical multiple regression analysis was used to determine whether there was a significant change in the relationship between the runoff in the control catchments, and the runoff in the burned catchment, before and after the fire. A full description of the model will be presented in Section 3.3.3. Other independent variables, such as API, rainfall volume, rainfall duration and peak intensity were added to the regression to see whether they had an effect on the model. This approach was possible in the sub-catchments, since there was a control catchment (Bosboukloof) and an affected (burned) catchment (Lambrechtsbos).

Before any of these methods can be applied, it is important to calculate the variables that are needed for each method.

3.3.1 Variables needed for methods

Certain parameters are needed for each of the methods used in the main and sub-catchments. The mixed ANOVA method uses the mean daily streamflow record, which was obtained from SAEON (Section 3.1). The paired catchment method and the technique for comparing the pre- and post-fire hydrographs, require similar parameters. The parameters that both methods require are the rainfall events (duration, amount and intensity), soil moisture before the event, and the runoff produced by the rainfall event, which all affect the shape of a hydrograph.

Stellenbosch University https://scholar.sun.ac.za

3.3.1.1 Rainfall events

Scott (1994) proposed that for a rainfall event to be included in his analysis at least 20 mm of cumulative rain would have to fall without interruption for more than six hours. Using the same approach, however, would not be sufficient in this analysis. Frontal events are the dominant source of precipitation in the Western Cape during the rainy season. These frontal events can continue for weeks, which means that different storm events may occur on a semi regular basis during this continuous rainfall period. Since storm events occur on a semi regular basis during this period, including a six-hour period of no rainfall in the analysis provides the possibility to include more than one rainfall event, which will result in multiple peak flow values. This would make it difficult to find comparable rainfall events, and therefore further complicate the analyses of hydrographs. Since the objective is to focus on single rainfall events, it was decided that an interruption of only one hour (of no rainfall) would be allowed for a rainfall event to be considered as a separate event. Therefore, a rainfall event in this research was classified when (1) there was a continuous cumulative amount of more than 10 mm and (2) without an interruption of more than one hour.

Since frontal storms continue for a prolonged period, soil moisture plays an important role in overland flow in this area.

3.3.1.2 Antecedent Precipitation Index (API)

Antecedent precipitation is precipitation falling before, and also influencing the runoff of, a given rainfall event (Ali *et al.*, 2010). The runoff from a rainfall event on an initially dry watershed is less than the runoff from the same rainfall event on the same watershed, which has already been wetted by earlier rainfall. This higher runoff is conceptually explainable as resulting from a reduction of the infiltration capacity (Heggen, 2001). The infiltration capacity is directly correlated with soil moisture.

Kohler & Linsley (1951) created the Antecedent Precipitation Index (API) model for calculating soil moisture by using antecedent precipitation data. The model is presented as follows:

$$API = \sum_{t=-1}^{-i} P_t k^{-t} \qquad \ldots(3.1)$$

where:

- *i* is the number of antecedent days,
- k is a decay constant (usually between 0.8 and 0.98 (Viessman, Lewis & Knapp, 2002)),
- P_t is precipitation during day t.

Stellenbosch University https://scholar.sun.ac.za

The decay factor k is a recession coefficient from the hydrograph of a receding rainfall event. A decay factor of 0.9 was chosen for determining API, since it is within the limits of Viessman *et al.*, (2002). The original API equation (Equation 3.1) does not include antecedent precipitation of rainfall in the day before the analysed event, which makes it difficult to predict the soil moisture in a semi continuous frontal storm system. The API was adapted to include the antecedent precipitation during the day just before the event:

$$API = \sum_{t=0}^{-i} P_t k^{-t} \qquad \text{...(3.2)}$$

The only difference between Equation 3.1 and 3.2 is that in Equation 3.1 *t* (day) starts on the day of the event and not a day before. Viessman *et al.*, (2002) discovered that after a sufficient amount of time (*i*), API would not show any further significant increase. Viessman *et al.*, (2002) found that seven days (*i* = 7) is an adequate amount of time for determining the API.

The same number of antecedent days (*i* = 7) was used for each catchment for determining each storm's API. The final API equation used in the analyses is Equation 3.3.

$$API = \sum_{t=0}^{-7} P_t 0.9^{-t} \qquad \text{…(3.3)}$$

3.3.1.3 Hydrographs

Runoff volume, peak flows, and the time from start of the hydrograph until its peak flow are all features important for discovering any possible physical changes in a catchment. Time to peak is the time it takes from the start of a change in runoff, during a rainfall event, until its peak flow. The peak flow value is the maximum flow that is reached as a result of a rainfall event. The volume of a hydrograph plays an integral part in understanding the change in runoff due to the destruction of vegetation caused by fire during a rainfall event. Figure 3.4 is a simple representation of how the runoff volume was determined for a hydrograph.

Stellenbosch University https://scholar.sun.ac.za

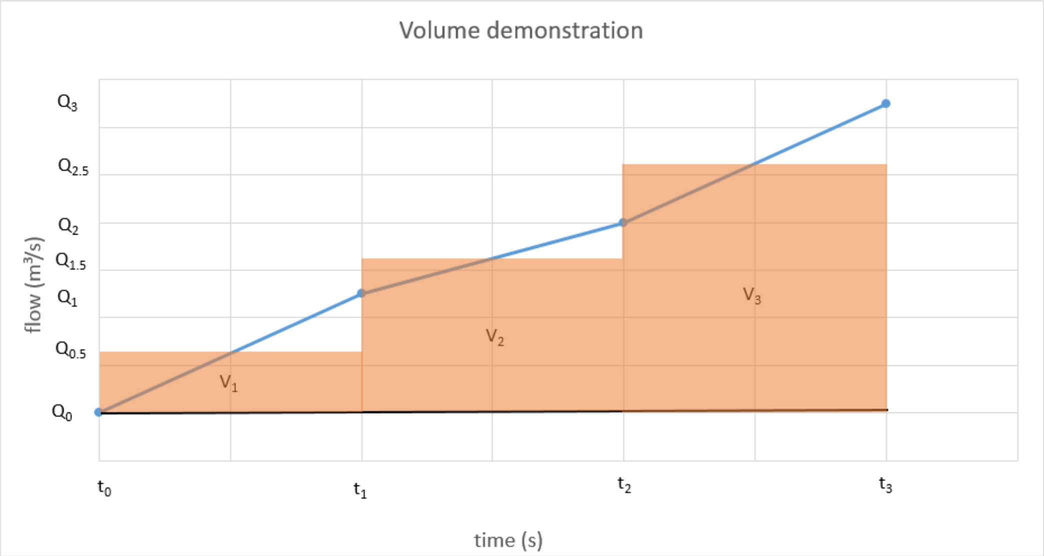


Figure 3.4: Determining volume of runoff

Figure 3.4 displays a rising hydrograph (blue line) with base flow Q_0 at time of t_0. The next measured flow is at Q_1 at t_1 and it continues to Q_3 at t_3. The volume between two succeeding flow values is displayed in terms of V_n. V_1 is the volume (m^3) between the starting flow (Q_0) and the following measured flow (Q_1).

The volume is determined using Equation 3.4.

$$\sum_{i=0}^{n} V_n = \left[\left|\frac{(Q_n - Q_{n-1})}{2}\right| + Q_{n-1} - Q_0\right] * \Delta t \,/(Area(km^2) * 1000) \qquad \ldots(3.4)$$

where:

- V_n is volume (mm),
- Q_n is flow (m^3/s),
- Δt is time between measured flows (s).

The volume produced by baseflow was excluded from Equation 3.4. The constant discharge method (Brodie & Hostetler, 2005), which assumes that the baseflow (Q_0) is constant regardless of stream height discharge was used for excluding baseflow. Flow was converted to mm/h to ensure that the runoff would be comparable between the sub-catchments.

Knowing the different variables that were needed for each of the methods, the different methods could be used. The pre- and post-fire storm comparison method was the first method applied.

Stellenbosch University https://scholar.sun.ac.za

3.3.2 Pre- and post-fire storm comparison method

Comparing rainfall events before and after a fire event is difficult, since certain key features of the events have to be compatible. Two rainfall events that both deliver the same quantity of precipitation, but within different time spans are two different events. One event will have a shorter duration with a higher intensity, while the other has a longer duration, but a lower intensity.

When a high intensity rainfall event of short duration takes place, the rising limb of its hydrograph will be steeper than that of a low intensity rainfall event and will generally produce a higher peak flow. A low intensity rainfall of long duration, on the other hand, will result in a more gradually rising limb, with longer duration runoff and generally a slower decline from peak flow until base flow. It is thus clear that, although they have similar quantities of precipitation, the hydrographs resulting from the rainfall events will be considerably different in both shape and duration.

To compare pre- and post-fire hydrographs, both the amount and the duration of the rainfall should be approximately the same for each event. Otherwise, the analyses will deliver inconsistent results. To ensure this is the case, the rainfall events should be grouped according to duration and rainfall. For that purpose, the individual events will be analysed.

Table 3.4 illustrates the limited number of rainfall events that were available for analysis.

Table 3.4: Number of rainfall events pre- and post-fire

Period	Number of rainfall events
Pre-fire	147
Post-fire	55

There were only 55 rainfall events after the fire, while there were 147 before the fire. Table 3.5 shows some of the descriptive statistics for the duration and rainfall of these rainfall events.

Stellenbosch University https://scholar.sun.ac.za

Table 3.5: Descriptive statistics of pre- and post-fire

Descriptive statistics	Duration (hours)			Rainfall (mm)		
	Pre-fire	Post-fire	All events	Pre-fire	Post-fire	All events
Minimum	4.0	7.0	4.0	10.0	10.5	10.0
1st Quartile	12.0	12.5	12.0	14.9	15.1	14.9
Median	17.0	18.0	17.5	25.3	21.9	24.2
3nd Quartile	26.0	22.0	25.8	40.8	35.4	39.4
Maximum	79.0	53.0	79.0	176.9	78.5	176.9
Mean	21.0	19.1	21.0	32.4	27.5	31.1
Standard deviation	13.0	9.7	13.0	25.1	16.2	23.2

The pre- and post-fire rainfall events had similar descriptive statistics. The difference in mean duration was less than two hours and difference in mean rainfall only 5.98 mm. The difference between the third quartile and the maximum value was quite substantial for both the pre- and post-fire events. This means that the longest 25% of the recorded rainfall events had a much greater distribution than the other 75% of rainfall events.

To obtain comparable storm events, it was important to ensure that the rainfall and duration were similar. Therefore, groupings of the rainfall duration were made to categorise similar duration events. The groupings were made by using the quartiles of the rainfall duration for all the events as illustrated in Table 3.5. These groupings used presented in Table 3.6.

Table 3.6: Group allocation

Group	Group 1	Group 2	Group 3	Group 4
Duration (hours)	4 – 12	12 – 17	17 – 26	26 – 79

Furthermore in order for rainfall events to be matched in the same duration group, the quantity of rainfall in each event needed to be within ±0.5 *mean std.dev of its corresponding event. This was to ensure that the events had a similar rainfall intensity.

When compatible rainfall events were found within the allocated groups, hydrographs were constructed. The pre- and post-fire hydrological characteristics of each event were then compared. Antecedent soil moisture was also used in the analyses of comparable rainfall

The Wilcoxon test was incorporated in the analysis to be used as a guide when analysing the differences in the pre- and post-fire runoff (Field, Miles & Field, 2013). The test is a non-parametric statistical test which is used when testing differences between two conditions (burned and unburned) while different participants (pre- and post-fire rainfall events) have been used in each condition (Field *et al.*, 2013). In the Wilcoxon tests the null hypothesis

Stellenbosch University https://scholar.sun.ac.za

[median difference between the pre-fire conditions (volume runoff, peak flow) and same post-fire conditions]. When the null hypothesis is rejected it demonstrates that there is a statistical significant likelihood of an increase in runoff from the post-fire conditions compared to the pre-fire conditions. The Wilcoxon method assumes that the difference is symmetrical; when the data is not symmetrical the Sign test was used (Field *et al.*, 2013). Both the Wilcoxon method and the Sign tests test the null hypothesis; the Sign test makes no assumptions, but the Wilcoxon test assumes that the difference is symmetrical.

3.3.3 Two way mixed ANOVA

The availability of the long-term streamflow records of the sub-catchments before and after the fires, supplied an opportunity to examine the effect that fire has on the streamflow in its totality. Bosboukloof was taken as the control sun-catchment, while the Lambrechtsbos A and B were the affected catchments.

The two way mixed Analysis of Variance (ANOVA) was used to test whether there was a significant interaction effect, both before and after the fire, between the volume of runoff from the affected catchments and the control catchment.

The two way mixed ANOVA compares the mean differences between groups that have been spilt into two ’factors’; the ’within-subjects’ factor and the ’between-subjects’ factor (Field *et al.*, 2013). The between-subjects factor is the treatment (before/after fires), while the within-subjects factor is the volume runoff of the two catchments (affected and control).

The method is first used to determine whether there has been an interaction between the catchments both before and after the fire. After establishing an interaction, it was then necessary to determine whether there was a significant difference between the catchments in volume runoff before the fire, and again after the fire.

3.3.4 Paired catchment method

The paired catchment method was used in this research to test for any possible hydrological changes that had occurred due to the effects of the wildfire on the sub-catchments. There were two affected catchments (Lambrechtsbos A and B) and a control catchment (Bosboukloof).

The method requires the calibration of the stream-flow (pre-burn) of a catchment with that of a similar control catchment. A hierarchical multiple regression analysis was run to determine whether the relationship between the runoff variables (volume runoff and runoff peak) of the affected catchment and control catchment before and after the fire differed. A different relationship between the treatment catchment and control catchment variables before (model 1) and after the fire (model 2) would be indicative of fire-related change in the runoff

Stellenbosch University https://scholar.sun.ac.za

variables, and the runoff in the treatment catchment being different from that of the control catchment. The full hierarchical multiple regression model was adapted from Scott (1994), and is represented by the following equation:

$$T' = \alpha_0 + \beta_0 F + \alpha_1 C' + \beta_1 FC' + \alpha_2 D' + \beta_2 FD' + \alpha_3 P' + \beta_3 FP' + \alpha_4 I' + \beta_4 FI' + \alpha_5 API' + \beta_5 FAPI' + \epsilon' \qquad \ldots(3.5)$$

where:

T	=	treatment catchment variable,
C	=	control catchment variable,
D	=	rainfall duration (hours),
P	=	precipitation (mm),
I	=	maximum 1 hour intensity of the storm (mm/h),
API	=	Antecedent Precipitation Index for each storm (mm),
F	=	Fire dummy variable
ϵ	=	model error term,
$\alpha_0 - \alpha_5$	=	fitted regression coefficients (pre-fire state if F=1 represents post-fire)
$\beta_0 - \beta_5$	=	fitted regression coefficients (moderation effect).

The inclusion of an accent (‘) shows that the variables were log transformed prior to analysis. Appendix E explains the application of this regression model.

3.3.5 Overview of methods

The method of analysing the possible change in runoff from the main catchment was different to the analyses of the sub-catchments. The approach to analyse the main catchment was focused on observing the change in runoff within the catchment by comparing pre- and post-fire rainfall events, which adhered to requirements set in Section 3.3.2.

Since there was also a control sub-catchment and two affected sub-catchments a different approach was used to test whether fire had an impact on the runoff, by comparing the control sub-catchment (Bosboukloof) with the affected catchments (Lambrechtsbos A and B) both before and after the fire event. Since two fundamentally different approaches were used for this research, the main catchment's analyses and results have been reported in a separate section of the thesis, while the sub-catchments in another as illustrated in Figure 3.5.

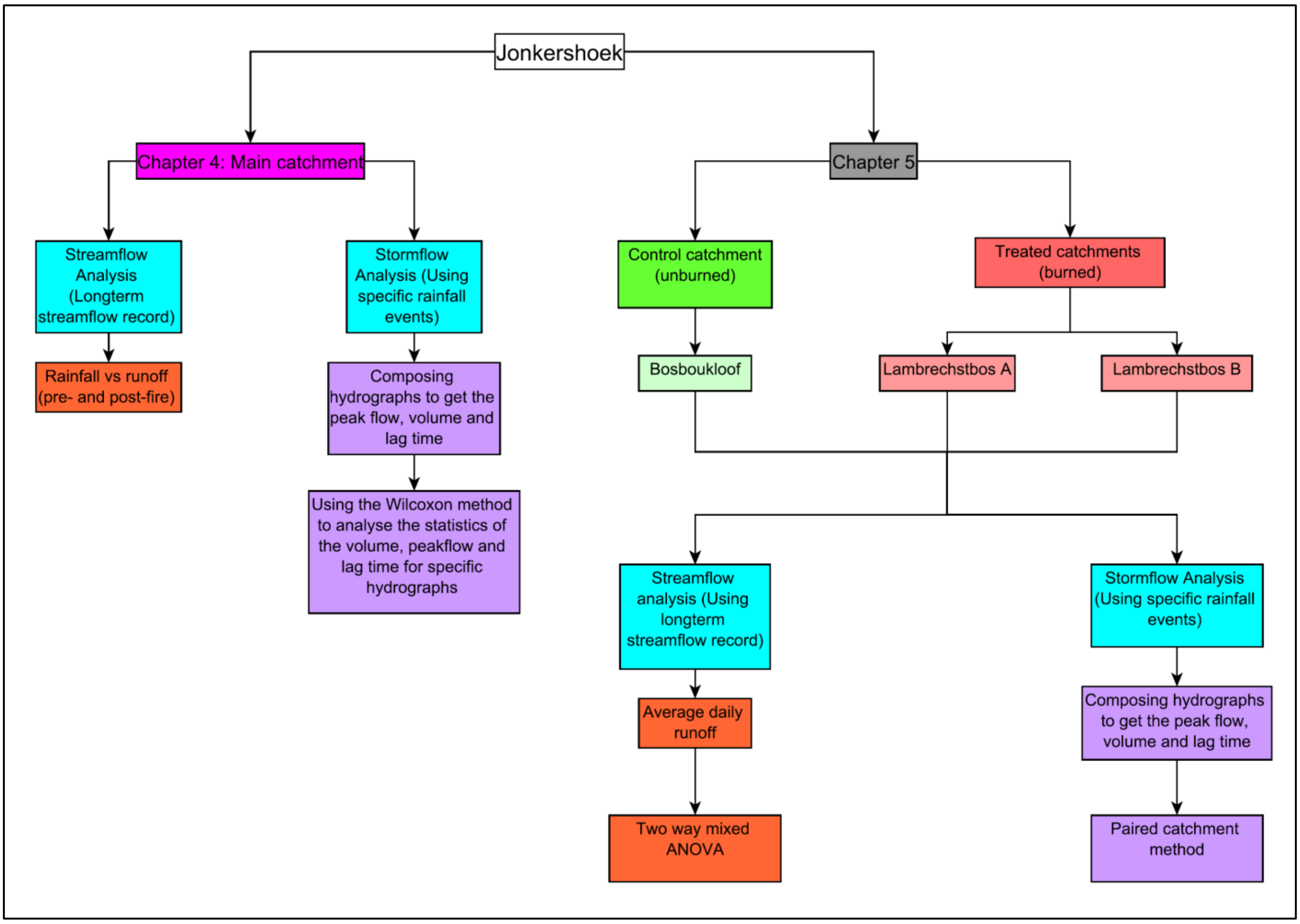


Figure 3.5: Research outline

From Figure 3.5 it can be seen that the main catchment and sub-catchments were both analysed on the characteristic changes of streamflow and stormflow due to the fire.

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 4
ANALYSIS: MAIN CATCHMENT

For the main catchment, the first part of the analysis was observing the long-term runoff and rainfall before and after the fire event. The second part consisted of comparing specific rainfall events before and after the fire. The historic data for this catchment was limited, since the rainfall gauges started recording only on the 20th of June 2011. The fire event happened three years and nine months later. The post-fire period was one year and six months.

The time lapse between the fire event and the recorded rainfall, in this case, is the ideal time from a research point of view, since the greatest hydrological change, according to the literature (Bosch *et al.*, 1986; Scott, 1993), happens within the first year after the fire.

Table 4.1 displays the date range for the main catchment analysis.

Table 4.1: Dates of analysis

Period	Date (start)	Date (end)
Pre-fire	2011/06/20	2015/03/09
Post-fire	2015/03/09	2016/09/20

4.1 CUMULATIVE RAINFALL AND RUNOFF FLOW

The cumulative rainfall was plotted against the cumulative runoff for the entire period; to determine whether the total flow was affected by the fire event. The results are plotted in Figure 4.1.

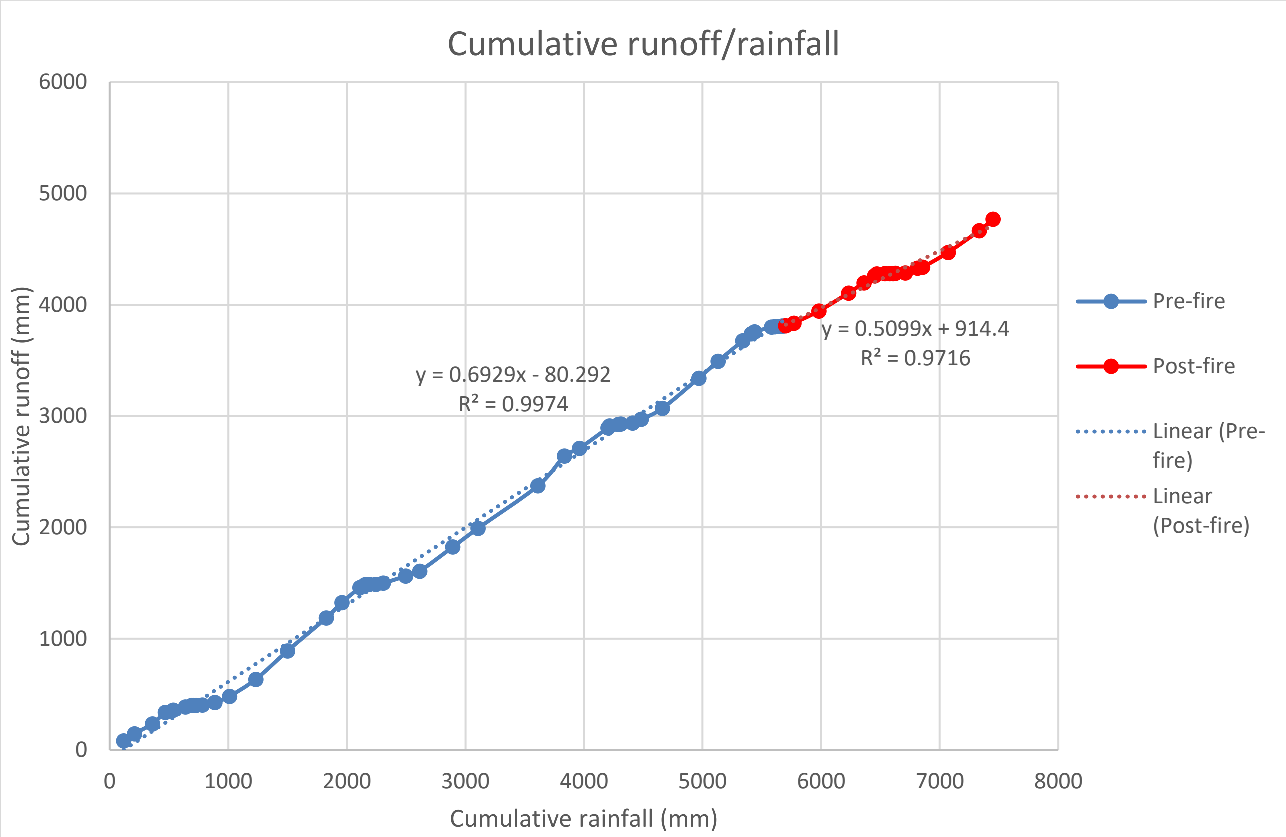


Figure 4.1: Cumulative runoff/rainfall for main catchment

The graph clearly shows that the slope of the cumulative rainfall and runoff plot is 0.6929 before the fire with a R^2 of 0.9974, while the slope of the cumulative rainfall and runoff plot is 0.5099 after the fire with a R^2 of 0.9716. The differences in runoff/rainfall ratios before and after the fire are presented in Table 4.2; the table contains the mean monthly rainfall and runoff for full period of data available, which is before and after the fire event, as well as the ratio of runoff to rainfall accumulated for these two periods. The rainfall intensity was not taken into account when comparing the average rainfall and runoff.

Table 4.2: Runoff/rainfall ratio

Period	Rainfall average (mm)	Runoff average (mm)	Runoff/rainfall ratio
Pre-fire	123	83	67%
Post-fire	104	56	54%

It is important to note that the mean monthly rainfall after the fire was 104 mm, while before the fire it was 123 mm. It is to be expected that when there is a higher quantity of rainfall the accumulated runoff should also be higher, in comparison to what it would be if there were a smaller quantity of rainfall. Although the mean rainfall was less after the fire than before, the runoff/rainfall ratio should show an increase after the fire, due to the fire induced water repellency of the soil. The ratio after the fire is smaller, which indicates that fire did not

Stellenbosch University https://scholar.sun.ac.za

increase the long-term streamflow. It is important to determine whether the streamflow had or had not also changed when analysing comparable rainfall events before and after the fire.

4.2 COMPARABLE RAINFALL EVENTS

Rainfall events were previously (Section 3.3.2) subdivided into four groups, or rainfall ranges. Rainfall events of similar magnitudes (from the same groupings) were selected, one from the before fire grouping and the other from the post fire grouping. These events were then compared with each other.

When matching two events, which complied with the specific requirements (Section 3.3.2) it was important to take into, account that there were still other factors which affected hydrographs. Antecedent soil moisture (API) and the temporal distribution of rainfall are factors which were considered in the results; however, they were not taken as a requirement for finding comparable rainfall events, given the limited data set.

Eighteen comparable rainfall events which adhered to the requirements were identified. Table 4.3 shows five pre- and post-fire rainfall events from Group 1.

Table 4.3: Group 1 pre- and post-fire rainfall events

Group	Events		Date	Time of start	Time without rain (hours)	Rain event (hours)	Rainfall (mm)	Intensity (mm/h)	API (mm)
1	1	Pre-fire	2014/06/14	6:00:00 AM	85	12	36.98	3.08	71.83
		Post-fire	2016/07/25	3:00:00 PM	53	13	42.62	3.28	52.34
	2	Pre-fire	2013/09/02	10:00:00 PM	32	9	22.49	2.50	202.27
		Post-fire	2015/07/23	4:00:00 PM	6	10	24.62	2.46	85.01
	3	Pre-fire	2013/10/30	1:00:00 AM	84	8	12.14	1.52	9.83
		Post-fire	2015/07/23	3:00:00 AM	17	7	12.73	1.82	72.28
	4	Pre-fire	2014/08/21	4:00:00 AM	5	8	10.20	1.27	49.57
		Post-fire	2015/07/23	3:00:00 AM	17	7	12.73	1.82	72.28
	5	Pre-fire	2011/09/15	4:00:00 AM	31	8	10.87	1.36	21.33
		Post-fire	2016/06/30	9:00:00 PM	77	8	11.06	1.38	20.51

Table 4.3 illustrates the selected rainfall events have more or less the same characteristics: rainfall duration (hours), rainfall quantity (mm) and average rainfall intensity (mm/h). The antecedent soil moisture (API) is different for each rainfall event. However, all of the rainfall events displayed in Group 1, had experienced rainfall within the seven days prior to the event itself, since the API is not zero for any event. Table A.1Table A.1 in Appendix A presents the comparable rainfall events for all the different group classifications.

After finding for each pre-fire rainfall event, a post-fire rainfall event, hydrographs were constructed for each of these rainfall events.

Stellenbosch University https://scholar.sun.ac.za

4.3 HYDROGRAPHS

Hydrographs provided an easy to use way of comparing pre- and post-fire rainfall events. Figure 4.2 displays a pre- and post-fire hydrograph with the cumulative rainfall of each event.

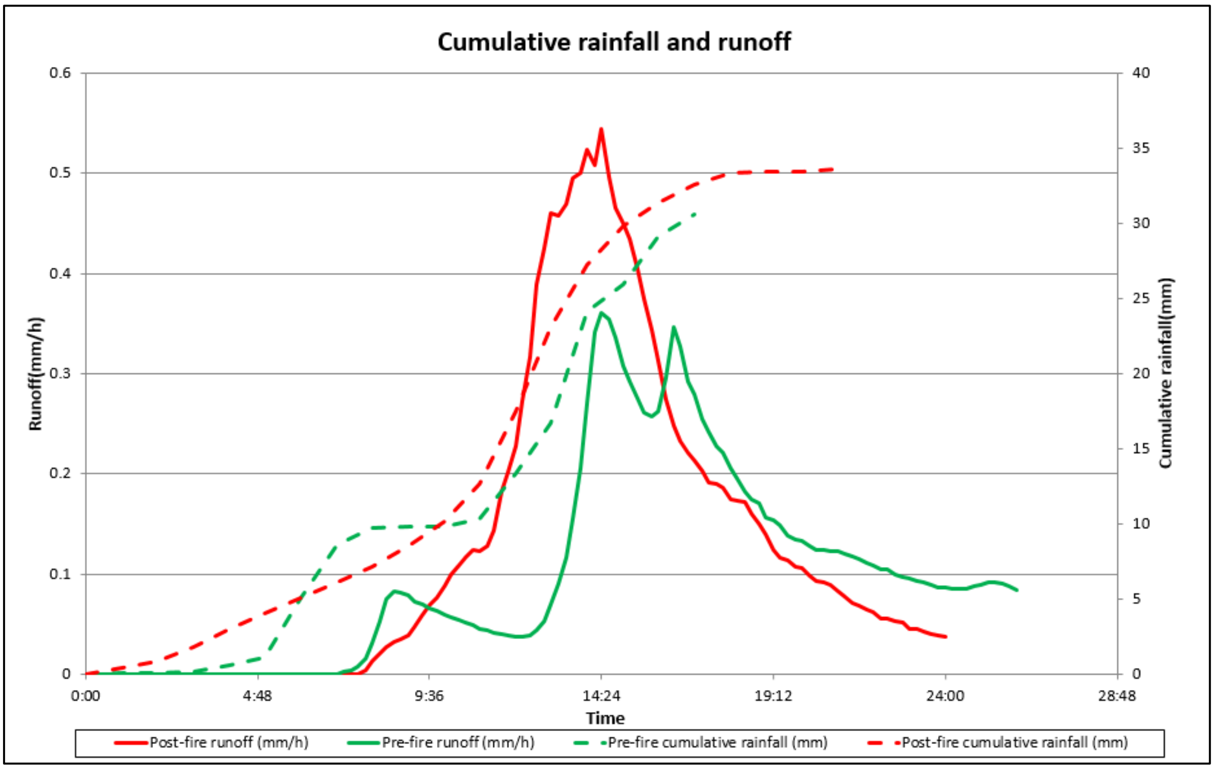


Figure 4.2: Pre- and post-fire comparable hydrograph

In Figure 4.2 the dotted lines represent the cumulative rainfall and the solid lines the runoff. The post-fire event is represented by the dark red lines, the pre-fire event by the light green lines. The runoff for the pre- and post-fire events at each catchment starts at the same value and the time axis was set at zero to illustrate duration, rather than actual time. The pre-fire rainfall event produced two peak flows, while the post-fire rainfall event only had one peak. The difference in shape of the two hydrographs was caused mainly by the temporal distribution of rainfall. The characteristic elements of each rainfall event and the flow that it produced is summarised in Table 4.4

Table 4.4: Characteristics of two events

Events	Date	Rain event (hours)	Rainfall (mm)	API (mm)	Qpeak (mm/h)	Time to Peak	Volume (mm)
Pre-fire	2014/08/26	17	30.61	35.60	0.36	6:12:00	13.0
Post-fire	2016/04/28	21	33.58	37.85	0.59	7:00:00	20.0
				Difference	**0.23**	**00:48:00**	**7**

Both events had approximately the same amount of rainfall, and the same intensity and antecedent soil moisture values. The post-fire event, however, produced a peak flow of

Stellenbosch University https://scholar.sun.ac.za

0.59 mm/h, while the value of the pre-fire event was recorded as 0.36 mm/h. The peak flow from the post-fire event represents a 63% increase on that of the pre-fire event. A similar result was obtained when examining the volume of runoff; 54% increase in runoff volume was recorded in the post-fire rainfall event, compared to that of the pre-fire rainfall event.

The time to peak flow in this example did not display a great difference between the events, with the post fire time to peak actually being greater than the pre-fire time to peak (contrary to what is expected). The same can be said for the slope of the rising limb of each of the hydrographs. Both of these results are dependent on the catchments time of response, which in this case seems to be unaffected.

While the example above illustrates some of the results expected; this is only a single event analysis, which cannot be used in isolation to illustrate hydrological change caused by the fire on the catchment. To provide a more comprehensive understanding of the changes experienced by the catchment because of fire, all the results need to be evaluated. These results will be presented and discussed in the next section.

4.4 VOLUME RUNOFF BEFORE AND AFTER FIRES

Table 4.5 displays the rainfall (mm) with the corresponding runoff (mm) as well as the API (mm), average rainfall intensity (mm/h) and runoff/rainfall response for all the comparable rainfall events.

Table 4.5: Rainfall and runoff before and after fire

Events	Pre-fire					Post-fire				
	Rainfall (mm)	Volume runoff (mm)	API (mm)	Intensity (mm/h)	Runoff/rainfall	Rainfall (mm)	Volume runoff (mm)	API (mm)	Intensity (mm/h)	Runoff/rainfall
1	37.0	9.8	71.8	3.1	26.4%	42.6	9.3	52.3	3.0	21.8%
2	22.5	2.7	202.3	2.5	12.2%	24.6	5.2	85.0	2.5	21.3%
3	12.1	0.4	9.8	1.5	3.6%	12.7	2.7	72.3	1.8	21.1%
4	10.2	2.8	49.6	1.3	27.4%	12.7	2.7	72.3	1.8	21.1%
5	10.9	0.5	21.3	1.4	4.7%	11.1	2.7	20.5	1.4	24.0%
6	41.0	1.6	0.0	2.3	3.9%	40.9	9.3	0.0	2.0	22.7%
7	39.3	7.0	0.0	2.3	17.8%	39.1	13.8	68.7	2.2	35.3%
8	36.4	12.2	45.3	1.9	33.5%	36.4	8.6	39.9	1.7	23.6%
9	30.6	13.0	35.6	1.8	42.6%	33.6	20.0	37.8	1.6	59.4%
10	28.0	8.6	31.9	2.2	30.5%	30.0	14.6	35.2	1.5	48.8%
11	85.4	31.3	52.4	3.4	36.7%	78.5	30.9	24.9	3.4	39.3%
12	44.6	14.4	14.5	1.5	32.2%	50.8	16.5	13.3	2.0	32.4%
13	23.1	6.1	69.1	0.7	26.2%	23.3	5.6	1.5	0.9	24.1%
14	22.5	11.9	43.6	1.0	52.7%	27.1	4.5	2.0	0.8	16.6%
15	61.7	12.9	0.0	1.4	20.9%	59.4	25.1	47.6	1.8	42.3%
16	52.4	20.8	2.3	1.3	39.7%	51.9	25.9	11.1	1.0	49.9%
17	46.3	20.8	35.6	1.2	44.9%	47.3	23.5	44.3	1.1	49.7%
18	55.3	11.9	0.0	1.0	21.5%	57.9	27.2	76.9	1.6	46.9%
Sum	659.3	188.6				680.0	247.9			
Average	36.6	10.5	38.1	1.8	26.5%	37.8	13.8	39.2	1.8	33.3%
Std.dev	18.9	7.9	46.1	0.7	14.0%	17.6	9.3	27.1	0.7	12.9%

The total rainfall in all the pre-fire events was 659.3 mm, while the post-fire rainfall was 680.0 mm. Before the fire, the average rainfall per event was 36.6 mm, which produced an average runoff of 10.5 mm. The average runoff/rainfall ratio was 26.5% pre-fire and after the

Stellenbosch University https://scholar.sun.ac.za

fire, the average runoff/rainfall ratio increased to 33.3%. This means that there was an average increase of 6.8% in the runoff/rainfall ratio after the fires for these 18 events. The runoff/rainfall ratio for the pre-fire events varied between 3.6% and 52.7%, while the post-fire events varied between 16.6% and 59.4%.

Five events had a greater runoff/rainfall ratio before the fire than after the fire. The API for four of these events were greater in the before fire rainfall events than the post-fire rainfall events. The average rainfall intensity from four of these events were slightly higher pre-fire than post-fire, this in conjunction with the higher API values could explain why the runoff/rainfall ratios were higher in the pre-fire events.

There were however three comparable events, which had higher API values pre-fire than post-fire and which had similar average rainfall intensities. For these events, the runoff/rainfall ratios were higher for the post-fire events than the pre-fire events.

Even though the antecedent soil moisture for some events were higher for the pre-fire events, the runoff/rainfall ratio produced was still higher for the post-fire events. This is further indication that fire had an impact on the runoff from the catchment.

The Wilcoxon signed-rank test was then used to determine if there was a statistically significant median difference between the volumes of the pre-fire rainfall events and the post-fire rainfall events. In order to use the Wilcoxon signed-rank test, the shape of the distribution of the differences needed to be approximately symmetrical. Figure 4.3 displays the histogram of the Wilcoxon signed-rank test. The histogram plots the differences between the post and pre-fire volume runoff (mm) for all of the comparable events and displaying the frequency of this distribution.

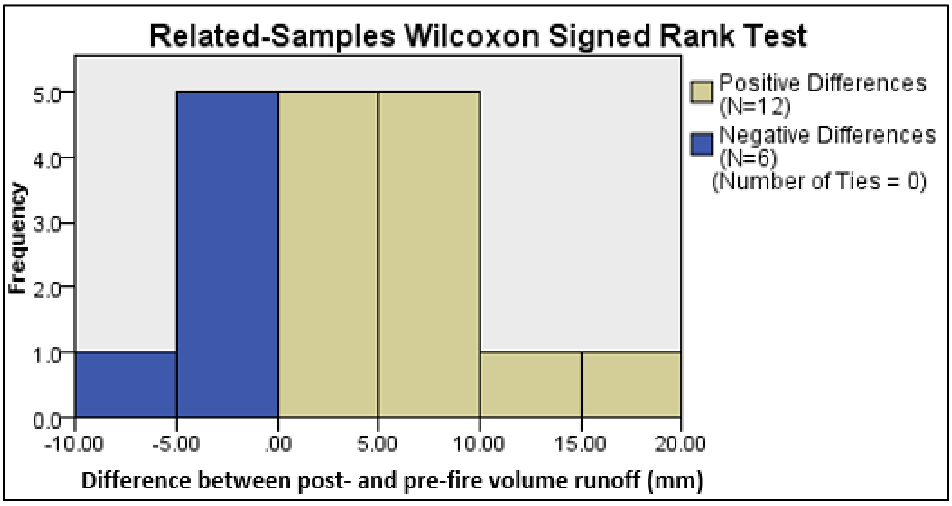


Figure 4.3: Histogram of Wilcoxon signed-rank test (Volume runoff)

Stellenbosch University https://scholar.sun.ac.za

Visually inspecting the shape of the distribution of differences recorded runoff volumes, reveals a reasonably symmetrical distribution. The histogram in Figure 4.3 thus displays the number of events for which volume runoff increased, remained the same, or decreased, after the fire. The histogram shows that in 12 events the volume runoff was higher after the fires compared to before the fires. In six events, the volume runoff was higher before the fires compared to after the fires.

Table 4.6 displays the statistical values obtained with the test.

Table 4.6: Statistical values obtained with test

Total N	18
Standard Error	22.96
Standardised Test Statistic	2.20
Significant value (p-value)	0.028

Table 4.6 shows that after the fires there was a statistically significant ($p < 0.05$) median increase in the volume runoff (mm) compared to before the fires. The p-value is the significant standard cut-off level of 5%. It means that when this value is smaller than the 0.05, it suggests that the data is sufficiently inconsistent with the null hypothesis which illustrates that the data is statistically significant.

From the results of the Wilcoxon signed rank test it can be deduced that the volume runoff displayed a statistically significant change ($p < 0.05$) from before to after the fire. The change can also be observed through inspecting Figure 4.4 and Figure 4.5, which shows the volume runoff (mm) plotted against the rainfall (mm), of the pre- and post-fire rainfall events.

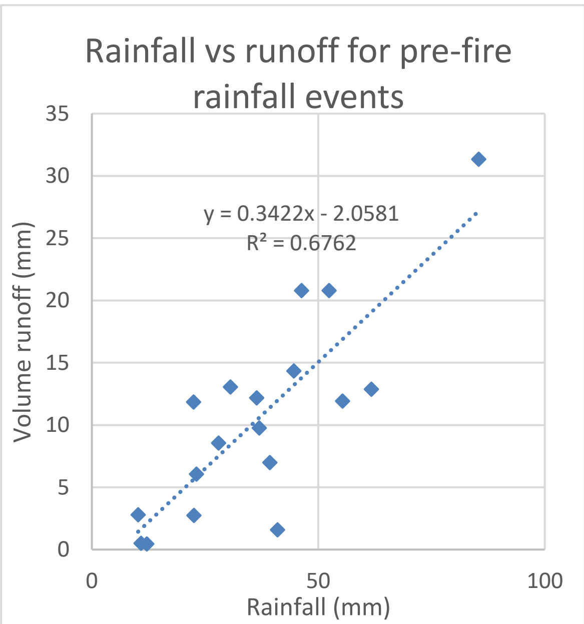


Figure 4.4: Rainfall vs runoff pre-fire

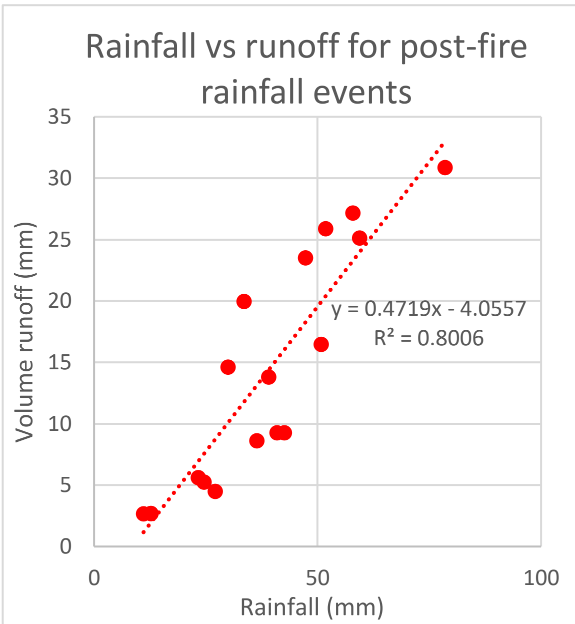


Figure 4.5: Rainfall vs runoff post-fire

Stellenbosch University https://scholar.sun.ac.za

Figure 4.4 and Figure 4.5 show that the runoff response from rainfall after the fire is greater than before the fire. Using simple linear regression, the slope for the pre-fire rainfall events is 0.3422 with an R^2 of 0.6762, while after the fire the slope is 0.4719 with an R^2 of 0.8006. The slope difference is 0.1297, which means a 37.9% increase in slope after the fire. This is a greater increase rainfall/response than the average runoff/rainfall response in Table 4.5, because in Table 4.5 averages were looked at. Therefore, by looking at the events responses in their totality the effect of fire is more prominent on the volume runoff than just taking the averages.

The increase in runoff volume delivered a different result than did the long-term cumulative runoff/rainfall volume discussed in Section 4.1, which implies that in this catchment the change in runoff volume is evident only by observing individual rainfall events, and not from long-term data.

4.5 PEAK FLOW VALUES BEFORE AND AFTER FIRES

Determining any change in the peak flow of rainfall events is important for flood managers. Table 4.7 displays the peak values of the comparable pre- and post-fire events, with the corresponding rainfall.

Table 4.7: Peak flow pre- and post-fire

Events	Pre-fire				Post-fire			
	Rainfall (mm)	API (mm)	Intensity (mm/h)	Qpeak pre(mm/h)	Rainfall (mm)	API (mm)	Intensity (mm/h)	Qpeak post(mm/h)
1	37.0	71.8	3.1	0.52	42.6	52.3	3.0	0.20
2	22.5	202.3	2.5	0.11	24.6	85.0	2.5	0.20
3	12.1	9.8	1.5	0.02	12.7	72.3	1.8	0.12
4	10.2	49.6	1.3	0.11	12.7	72.3	1.8	0.12
5	10.9	21.3	1.4	0.02	11.1	20.5	1.4	0.15
6	41.0	0.0	2.3	0.03	40.9	0.0	2.0	0.25
7	39.3	0.0	2.3	0.09	39.1	68.7	2.2	0.17
8	36.4	45.3	1.9	0.20	36.4	39.9	1.7	0.21
9	30.6	35.6	1.8	0.36	33.6	37.8	1.6	0.59
10	28.0	31.9	2.2	0.28	30.0	35.2	1.5	0.29
11	85.4	52.4	3.4	0.71	78.5	24.9	3.4	1.13
12	44.6	14.5	1.5	0.24	50.8	13.3	2.0	0.20
13	23.1	69.1	0.7	0.33	23.3	1.5	0.9	0.58
14	22.5	43.6	1.0	0.26	27.1	2.0	0.8	0.06
15	61.7	0.0	1.4	0.13	59.4	47.6	1.8	0.63
16	52.4	2.3	1.3	0.13	51.9	11.1	1.0	0.11
17	46.3	35.6	1.2	0.38	47.3	44.3	1.1	0.36
18	55.3	0.0	1.0	0.11	57.9	76.9	1.6	0.52
Average	36.6	38.1	1.8	0.22	37.8	39.2	1.8	0.33
Std.dev	18.9	46.1	0.7	0.18	17.6	27.1	0.7	0.26

The peak flow values were on average 0.11 mm/h greater after the fire than before the fire, which is a mean increase of 50%. An increase in peak flows were not observed for all the rainfall events. The first event showed that the runoff from the pre-fire storm had a peak value

Stellenbosch University https://scholar.sun.ac.za

of 0.52 mm/h, while the post-fire storm only managed 0.20 mm/h. The same was observed for event 14, where the pre-fire storm had a peak value of 0.26 mm/h, while the post-fire storm only managed 0.06 mm/h.

There were five anomalies in the data set (Events: 1, 12, 14, 16 and 17). Three of the events (Events: 1, 12 and 14) had greater API values for the pre-fire events. With the other two events (Events: 16 and 17), the average rainfall intensity was marginally larger in the pre-fire events than the post-fire events.

The Wilcoxon test was again used as a guide to determine whether the change shown by the descriptive statistics was significant.

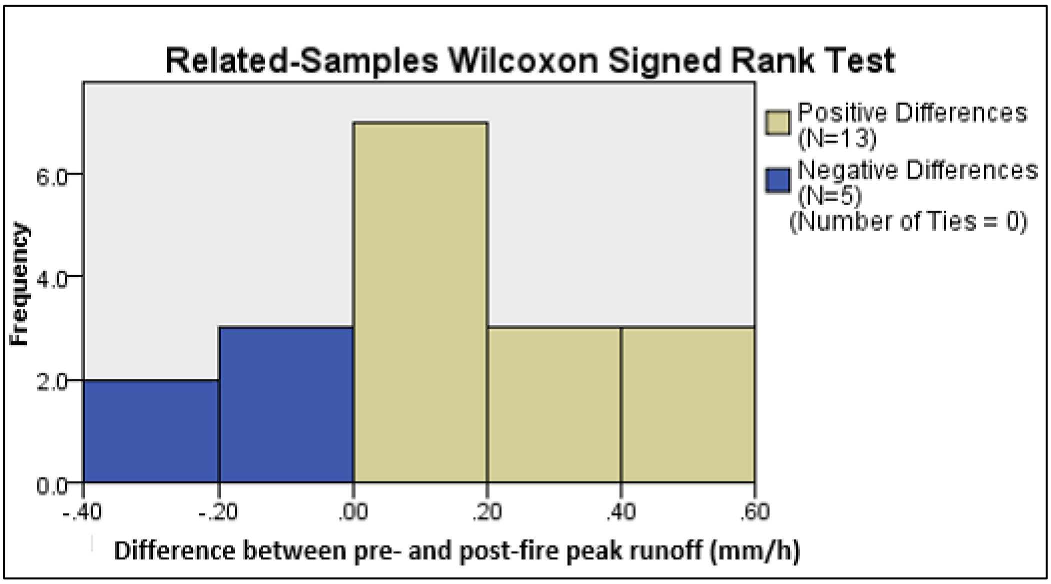


Figure 4.6: Histogram for Wilcoxon singed rank test (Peak flows)

Visual inspection of the shape of the distribution of differences recorded in runoff peaks reveals a reasonably symmetrical distribution; the same as that seen in Section 4.4.

From the histogram in Figure 4.6 it can be seen how the volume runoff in the events differed before the fires compared to after the fires. The histogram displays, thus, the number of events in which the peak flow increased, remained the same, or decreased, after the fire. The histogram shows that for 13 events, runoff peaks were higher after the fires than they had been before the fires. Table 4.8 displays the statistical values obtained with the test.

Table 4.8: Statistical values from test

Total N	18
Standard Error	22.96
Standardised Test Statistic	1.94
Significant value (p-value)	0.053

Stellenbosch University https://scholar.sun.ac.za

From Table 4.8 it can be seen that after the fires there was not a statistically significant ($p < 0.05$) median increase in the runoff peaks (mm) compared to those before the fires. However, it should be noted that this result closely approached statistical significance ($p = 0.053$).

The peak flow values in the main catchment changed after the fire in comparison to those recorded before the fire, by a mean increase of 50%, as could be seen by inspecting the descriptive statistics of Table 4.7.

The peak flow was plotted against rainfall for both the pre-fire and post-fire events. The peak flow from the pre-fire events displayed weak correlation with the amount of rainfall with an R^2 of 0.3388. The post-fire events, however displayed a greater correlation (R^2 of 0.6409). The slope of the linear regression line increased from 0.0055 pre-fire to 0.0119 post-fire. This is a 116% increase in slope after the fire. However, since the correlation value for the pre-fire events was so low it is not reasonable to make a comparison between Figure 4.7 and Figure 4.8.

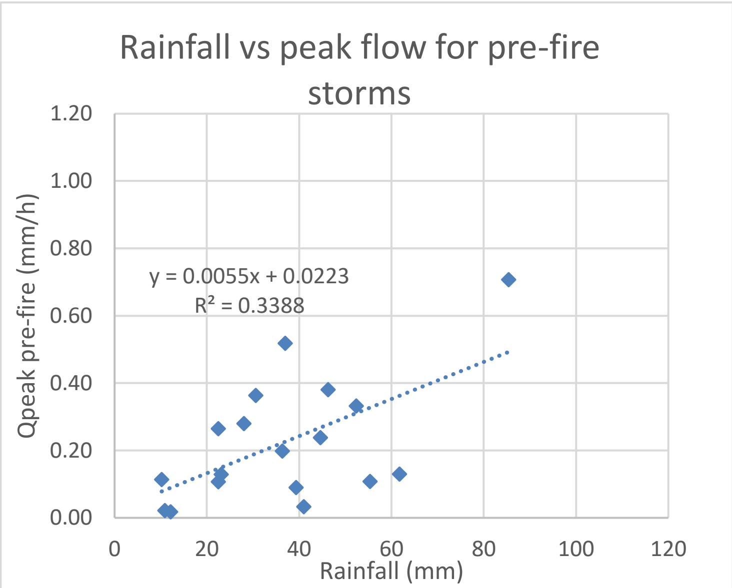


Figure 4.7 Rainfall vs peak flow for pre-fire storms

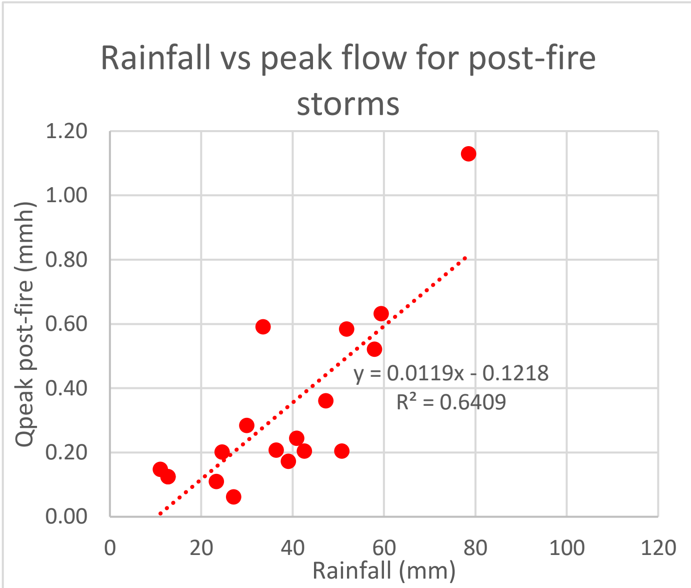


Figure 4.8 Rainfall vs peak flow for post-fire storms

Another visual illustration was needed and therefore Figure 4.9 was plotted to illustrate the peak flow values of the pre-fire rainfall events plotted against the peak flow of the post-fire rainfall events.

Stellenbosch University https://scholar.sun.ac.za

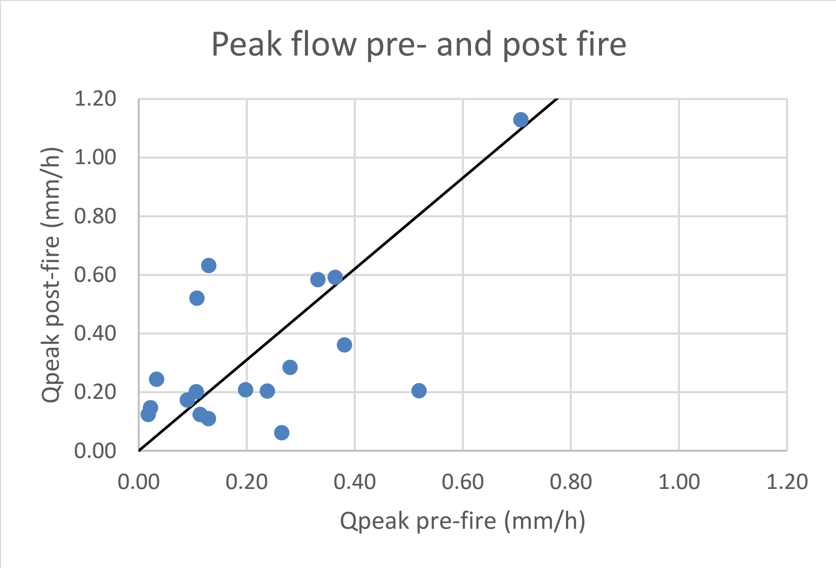


Figure 4.9: Peak flow pre- and post-fire

Figure 4.9 above illustrates that the distributions of the pre- and post-fire events were different. The majority of the post-fire events produced higher peak flow values in comparison to the pre-fire events.

4.6 TIME TO PEAK BEFORE AND AFTER FIRES

Another important characteristic of a hydrograph is the time that elapses from the start of the rainfall to the peak flow. Figure 4.10 displays the time to peak values of the pre- and post-fire events plotted against each other.

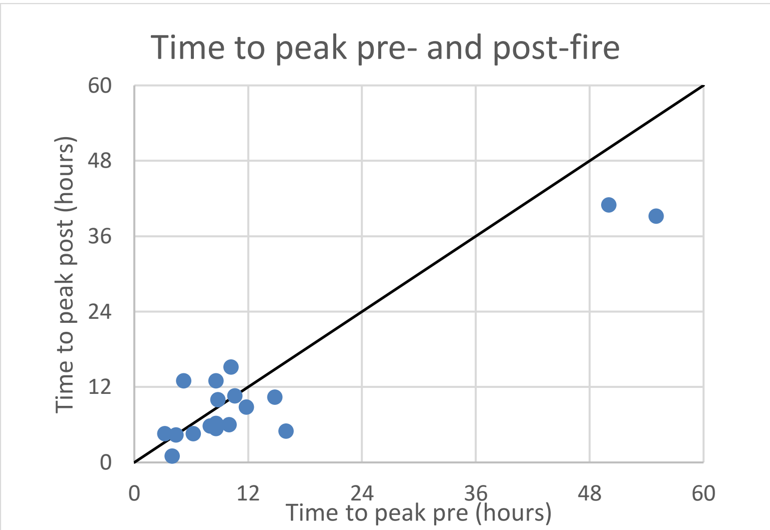


Figure 4.10: Time to peak flow pre- and post-fire

From observing Figure 4.9, it can be seen that there were two outliers (event 2 and 5) identified. Jonkershoek is in an area where rain can fall continuously for days on end and therefore it is understandable that the time to peak could take 48 hours, since the start of the rainfall event. However, the two events were removed from the time to peak analyses since they are more than four times longer than the mean time to peak values. After removing these two outliers, the mean time to peak of the pre- and post-fire events were calculated and displayed in Table 4.9.

Table 4.9: Time to peak pre- and post-fire

Events	Time to peak (pre-fire)	Time to peak (post-fire)
1	4:00	1:00
3	10:00	6:00
4	8:48	10:00
6	10:12	15:12
7	11:48	8:48
8	10:36	10:36
9	16:00	5:00
10	8:36	5:24
11	8:36	6:12
12	8:36	13:00
13	5:12	13:00
14	14:48	10:24
15	4:24	4:24
16	6:12	4:36
17	3:12	4:36
18	8:00	5:48
Average	8:41	7:45
Std.dev	3:30	3:47

Observing Table 4.9, the average time to peak values were shorter after the fire than they were before the fire, by approximately 56 minutes. The Signed rank test was used to test whether the difference between the pre- and post-fire times to peak values were statistically significant. The Wilcoxon signed rank test could only be used with an even distributed histogram, and therefore the Signed rank test was used, which could analyse an asymmetrical distribution. Figure 4.11 displays the Sign test.

Stellenbosch University https://scholar.sun.ac.za

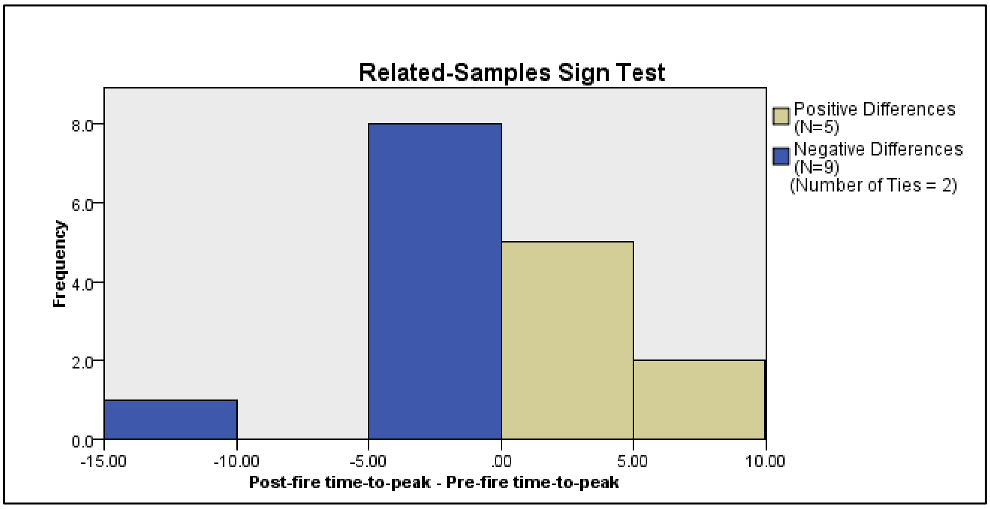


Figure 4.11: Histogram signed test (Time to peak)

In Figure 4.11 the time-to-peak events before the fire differed from those after the fire. In other words, it illustrates the number of the events in which time-to-peak values increased after the fire, remained the same after the fire, or decreased after the fire. The histogram shows that for five events, the time-to-peak values were higher after the fire than they had been before the fire. In nine events, the time-to-peak values were higher before the fire than they were after the fire. For two events the time-to-peak values were the same both before and after the fire.

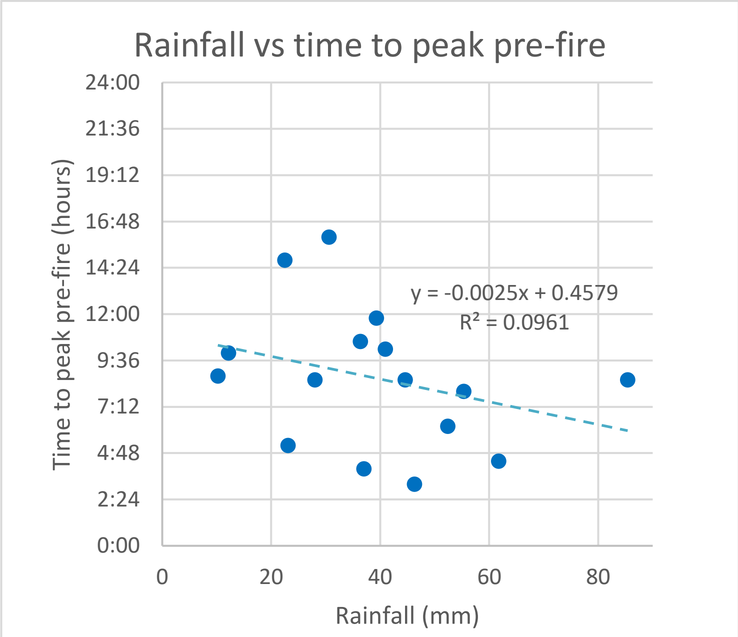
Table 4.10: Statistical values for test

Total N	16
Standard Error	1.87
Standardised Test Statistic	-0.80
Significant value (p-value)	0.43

Table 4.10 illustrates, by using the Sign test, that the fire did not statistically significantly ($p > 0.05$) alter the median change in the time-to-peak values recorded before the fire to those recorded after the fire. As in Section 4.4 and Section 4.5 the hydrograph characteristic under consideration was plotted against quantity of rainfall for both the pre-fire and post-fire events.

Figure 4.12 and Figure 4.13 displays the time to peak value of the pre- and post-fire events plotted against rainfall, which excludes the two outliers.

Stellenbosch University https://scholar.sun.ac.za



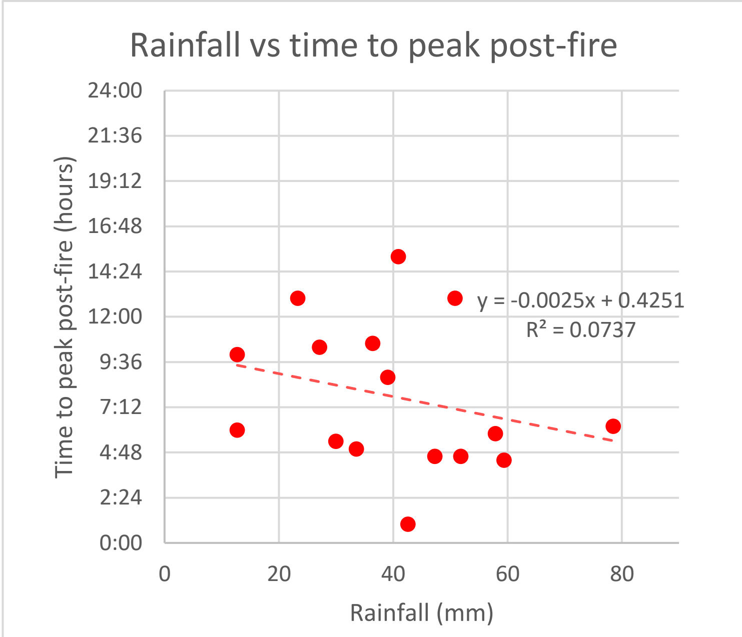


Figure 4.12: Rainfall vs time to peak pre-

Figure 4.13: Rainfall vs time to peak

In Figure 4.12 and Figure 4.13 it can be seen that the time to peak values show a similar scatter distribution when plotted against rainfall and by drawing a simple linear regression line through both Figure 4.12 and Figure 4.13 did not deliver a good correlation coefficient (R^2).

4.7 CONCLUSION

The cumulative rainfall and cumulative runoff was analysed for the entire period (pre- and post-fire); from observing Figure 4.1 it was found that there was not any increase in runoff after the fire in comparison to before the fire. The mean monthly runoff/rainfall ratio decreased after the fire from 67% to 54%. This decrease in the ratio indicates that fire did not affect the cumulative streamflow after the fire. Rainfall events were then analysed to see whether there was any significant change in runoff after the fires.

Eighteen compatible rainfall events were found, before and after the fire, which adhered to the requirements set in Section 3.3.2. Hydrographs were then constructed for each event and the characteristics of the rainfall and runoff of each event were tabulated (Table 4.5). By taking the mean volume runoff before and after the fire, a mean increase of 6.8% of the runoff/rainfall ratio was determined after the fire. The Wilcoxon signed ranked test confirmed that fire had a statistically significant impact on the runoff volume ($p = 0.028$). From plotting the rainfall and runoff volumes for both the pre- and post-fire events, the increase in the runoff/rainfall slope after the fire was determined to be 37.9%.

Stellenbosch University https://scholar.sun.ac.za

The mean peak flow before the fire was 0.22 mm/h, while after the fire the mean peak flow increased to 0.33 mm/h. Thus, after the fire the mean peak flow value for the compatible events increased by 50%. The Wilcoxon signed ranked test was used to test if the differences in peak flow values before and after the fire were statistically significant. The test showed that although fire did not have an impact on the peak flow values ($p = 0.053$), the p-value was close to being statistically significant ($p < 0.05$). The statistical test illustrates that although the mean runoff peak values changed after the fire; it was still not statistically significant.

The mean time-to-peak values changed after removing the two outliers, the mean time-to-peak value before the fire was 8 hours and 41 minutes and after the fire, it was 7 hours and 45 minutes, which indicates a reduction of 56 minutes in time-to-peak after the fire. The Wilcoxon sign ranked test was used to validate whether the reduction was statistically significant ($p<0.05$). Since the distribution of the test was not symmetrical, the Wilcoxon signed rank test could not be used and the Sign test was preferable to use for the analysis. The Sign test showed that there was no statistically significant ($p > 0.05$) difference in the time-to-peak values before and after the fire.

The hydrological changes observed in the catchment due to the fire, was just on a partially burned catchment (56% was burned). The outcome of the results should be more prominent if the fire affected the whole catchment.

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 5
ANALYSIS: SUB-CATCHMENTS

Two of the sub-catchments burned completely (Lambrechtsbos A & B), while Bosboukloof was only partially burned. The Lambrechtsbos catchments were thus the affected catchments, while Bosboukloof was designated to be the control catchment. This section will focus on how fire affected the affected catchments' stream flows, in comparison with its effect on the control catchment by comparing long-term streamflow data of the sub-catchments. The next section thereafter will focus on the effect that fire has on runoff produced by individual rainfall events by using the same control and affected catchments through different methods.

There was a number of data gaps between the sub-catchments between April and June 2015 and this data was excluded from the analysis.

5.1 LONG-TERM STREAMFLOW

The first step in the analyses of the sub-catchments was to compare the long-term streamflow of the control with those of the affected catchments. A good visual representation of long-term streamflow is obtained by using a double mass plot. The double mass plot represents the accumulated streamflow of the affected catchment plotted against that of the control catchment. Figure 5.1 represents the double mass plot of Lambrechtsbos A and Bosboukloof.

Stellenbosch University https://scholar.sun.ac.za

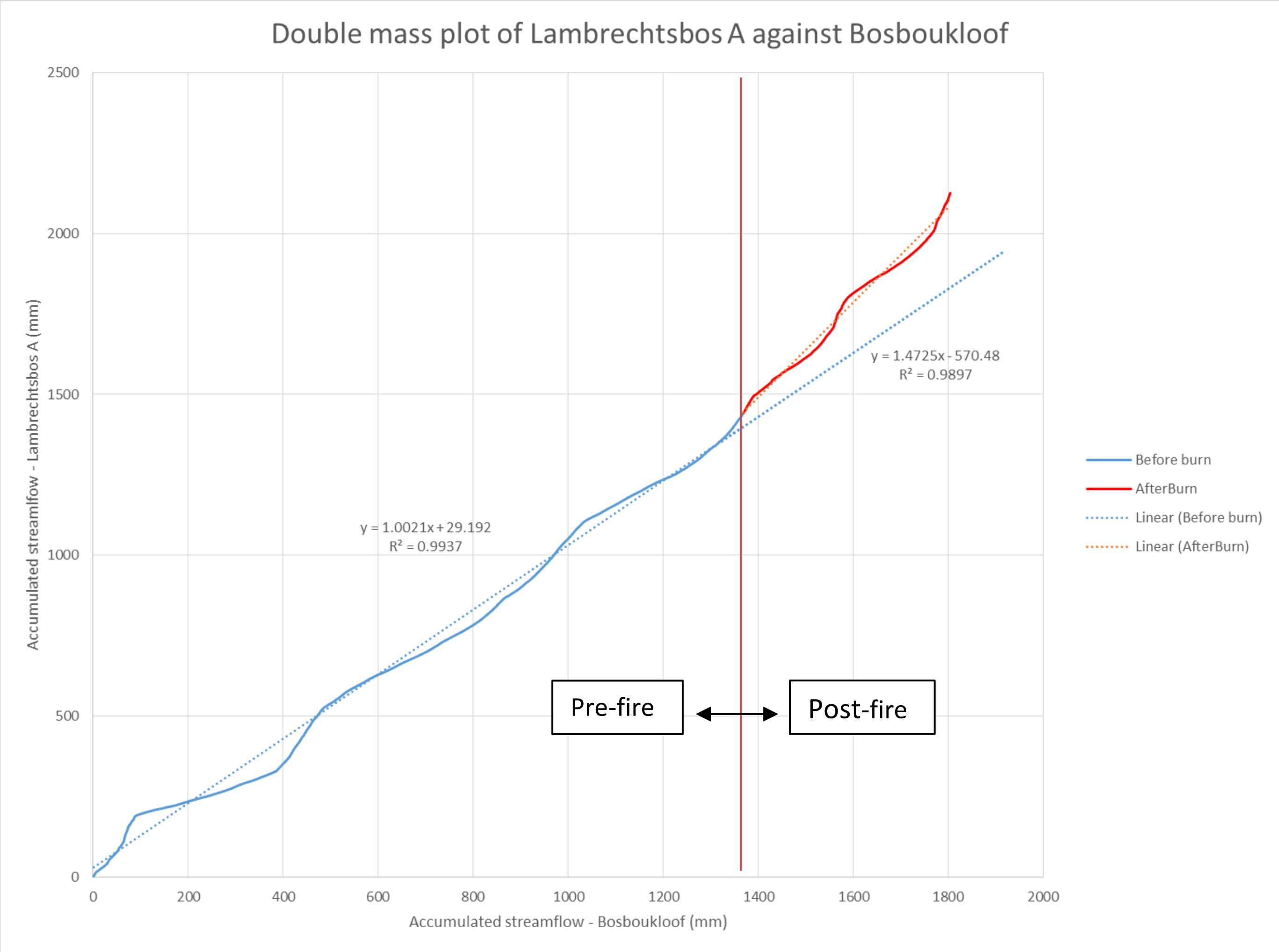


Figure 5.1: Double mass plot of Lambrechtsbos A against Bosboukloof

In Figure 5.1 it can be seen that the accumulated streamflow of the two catchments before the fire event was approximately the same; constructing a linear regression model and plotting its trendline revealed that the slope was 1.00 before the fire, with a R^2 of 0.9937. After the fire, however the slope increased in favour of the affected catchment (Lambrechtsbos A); the slope was 1.47 with an R^2 of 0.9897. The increase in slope indicates that there was a higher runoff rate at the affected catchment (Lambrechtsbos A) in comparison to the control catchment. Figure 5.2 displays a similar result for the catchment Lambrechtsbos B.

Stellenbosch University https://scholar.sun.ac.za

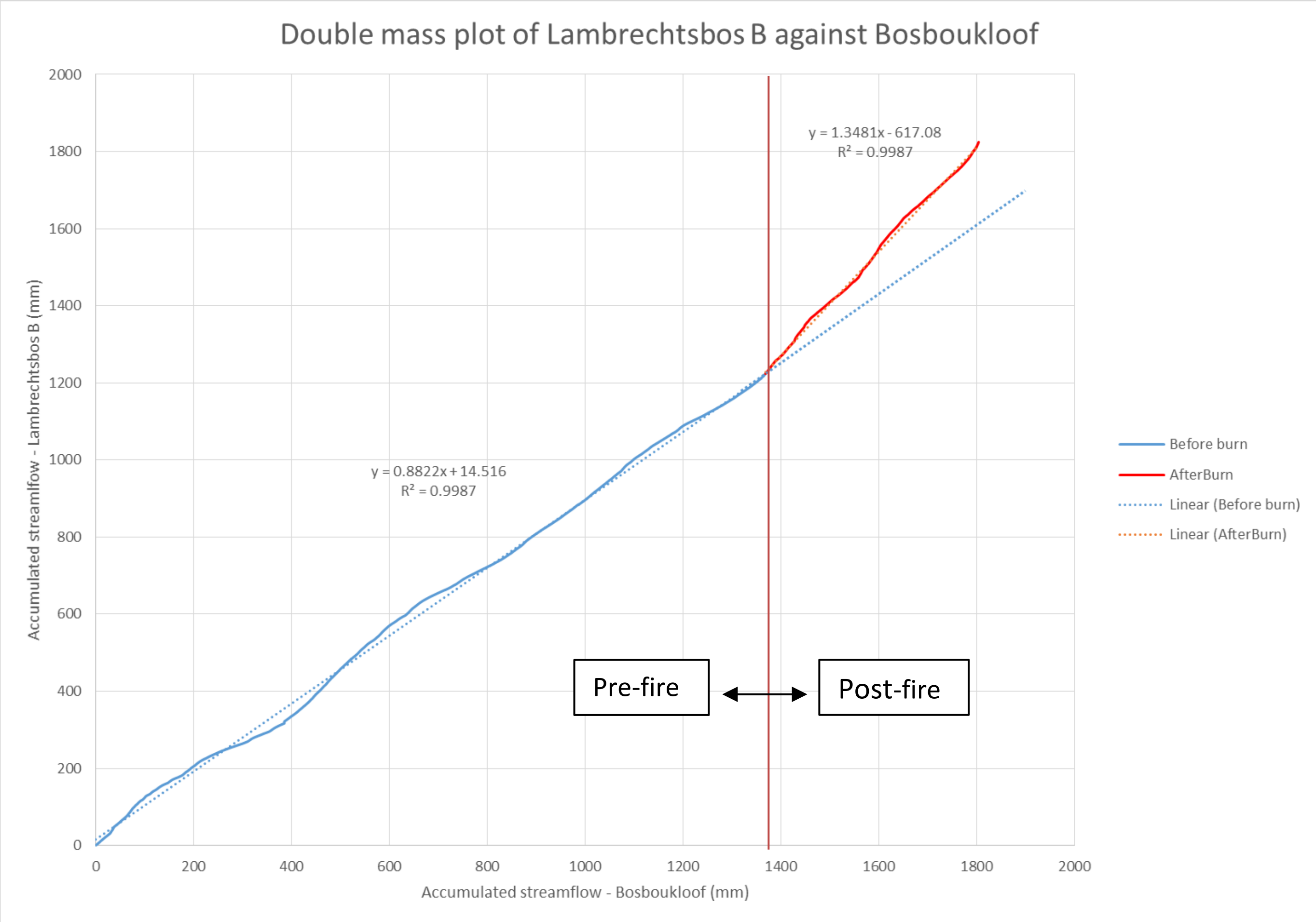


Figure 5.2: Double mass plot of Lambrechtsbos B against Bosboukloof

In Figure 5.2 it can be seen that there was a change in the runoff from the control catchment in comparison to the affected catchment (Lambrechtsbos B). Before the fire, the slope was 0.8822 with an R^2 of 0.9987, which indicates that more streamflow was generated in the control catchment (Bosboukloof) in comparison with Lambrechtsbos B for the same rainfall events. After the fire, however the slope increased to 1.3481 with an R^2 of 0.9987. The increase in slope after the fire indicates that the fire did have an impact on the accumulated streamflow.

The change in streamflow can also be observed when focusing on the monthly runoff for some of the wettest months, June–September, before and after the fire. Since there were gaps in runoff data for the period between April and June 2015, the analysis for the wettest months was only calculated between July and September pre- and post-fire. Table 5.1 shows the rainfall and runoff for these months for the three years before the fire and the two years after the fire.

Stellenbosch University https://scholar.sun.ac.za

Table 5.1 Rainfall and runoff accumulated during July-September before and after the fire

Year	Rainfall (mm) @ Station D	Runoff (mm)		
		Bosboukloof (C)	Lambrechtsbos B (T)	Lambrechtsbos A (T)
2012	638.8	203.2	137.7	88.9
2013	519.0	262.1	230.2	207.9
2014	375.2	174.7	140.5	138.2
Average	511.0	213.3	169.5	145.0
Fire event				
2015	278.4	97.4	130.2	106.9
2016	255.2	119.2	147.4	119.3
Average	266.8	108.3	138.8	113.1

C – Control catchment, T – Affected catchment

In Table 5.1 it can be seen that the average runoff for July-September (2012-2014) was higher in the control catchment (Bosboukloof) than in the affected catchments (Lambrechtsbos A&B) before the fire; however, after the fire the accumulated runoff for the control catchment was less than that of the affected catchments. To illustrate the difference, Figure 5.3 shows the daily rainfall and runoff values for the July-September the year before the fire (2014), while Figure 5.4 displays the same months a year after the fire (2015).

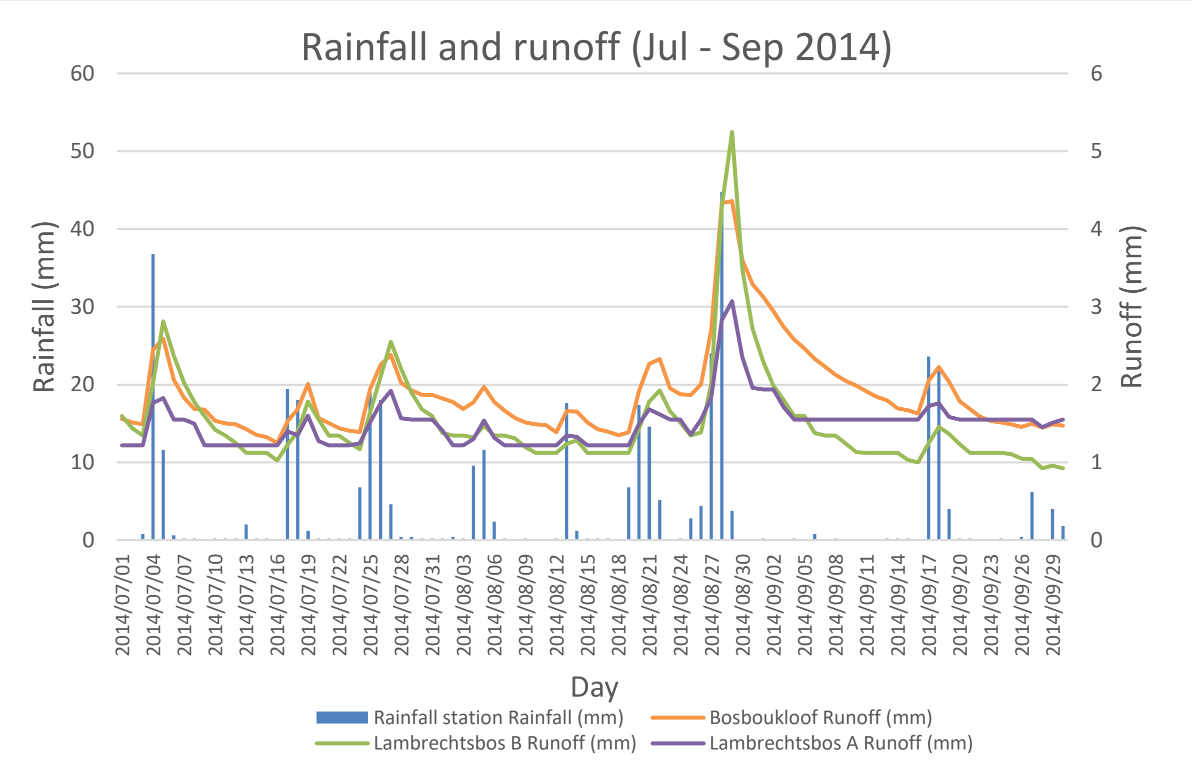


Figure 5.3: Rainfall and runoff (Jul-Sep 2014) before fire

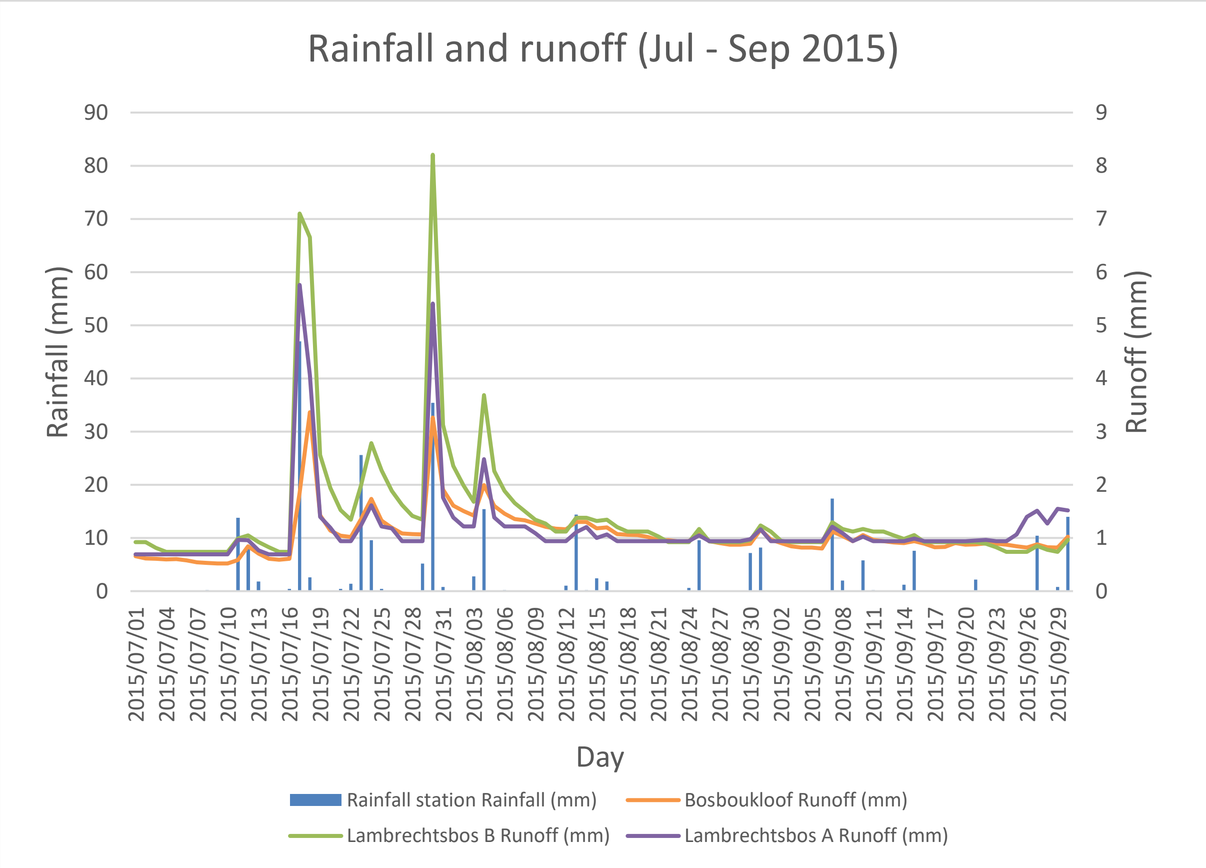


Figure 5.4: Rainfall and runoff (Jul-Sep 2015) after fire

Stellenbosch University https://scholar.sun.ac.za

From observing Figure 5.3 it can be seen that Bosboukloof tends to have slightly higher flow values than the affected catchments; however, there does not seem to be a prominent difference between the catchments. Figure 5.4, however illustrates that three months after the fire, there was a prominent difference between the control and affected catchments. The affected catchments displayed higher daily peak flow values than the control catchment.

The change in flow is less apparent when observing low rainfall conditions. This observation is important, because it demonstrates that the more intense a rainfall event is, the greater the observed change in runoff between the control and affected catchments will be. Table 5.2 displays the average daily runoff values for the control and affected catchments before the fire, the year after the fire, and the second year after the fire.

Table 5.2 Average daily runoff values for the control and affected catchments with their ratios before and after the fire

Period	Average daily runoff (mm)			Ratio	
	Bosboukloof (C)	Lambrechtsbos B (T)	Lambrechtsbos A (T)	Bosb : Lam B	Bosb : Lam A
Before fire	1.05	0.95	1.12	1 : 0.90	1 : 1.06
Year after	0.55	0.74	0.86	1 : 1.35	1 : 1.56
Two years after	0.64	0.90	1.02	1 : 1.41	1 : 1.59

In Table 5.2 it can be seen that before the fire the average daily runoff was approximately equal for all the sub-catchments, with approximately 1 mm daily runoff. We can thus assume an approximate 1:1 ratio for the period before the fire. The first year after the fire, however, the average daily runoff changed between the control and affected catchments. Lambrechtsbos B produced on average 45% more runoff than Bosboukloof during the first year of the fire. Lambrechtsbos A had on average 50% more runoff than Bosboukloof the first year after the fire. The second year after the fire the affected catchments showed a slight increase in relation to flow of the previous year.

The statistical significant change in streamflow needed to be verified and the mixed two way Analyses of Variance (ANOVA) method was used for this purpose.

5.1.1 Two way mixed ANOVA

The two way mixed ANOVA method was used to test the statistical significance ($p < 0.01$) of the difference between the control and affected catchments regarding the change in average daily streamflow that was observed due to the fire.

Stellenbosch University https://scholar.sun.ac.za

Since rainfall station D was the only station which was used for the affected and control catchments, it was therefore assumed that the amount of rainfall was constant for all the sub-catchments.

There are a few assumptions that have to be met in order to apply the two way mixed ANOVA method:

(1) that outliers have been identified,

(2) that residuals are approximately normally distributed,

(3) that there are equal variances between the categories of the between-subjects factor (before and after fire), at each category of the within-subjects factor, (catchments), for the dependent variable, runoff.

(4) that there are similar covariance's.

These assumptions were tested for the differences in the data between the affected catchments and the control catchments. Log transformations were applied to the runoff data in each catchment to enhance the normal distribution of residuals and increase homoscedasticity. Appendix 9.2 gives a more detailed explanation of how these assumptions were verified for the two way mixed ANOVA.

The data comparison between Bosboukloof and Lambrechtbos A did not satisfy the homogeneity of variance for the co-variances assumption. Even though this assumption had been violated, the two way mixed ANOVA test was nonetheless performed for this data set. Since the test was performed without all the basic requirements it assumes to be present, the results should be interpreted with caution. The data comparison between Bosboukloof and Lambrechtsbos B did satisfy all the assumptions required for the two way mixed ANOVA and the data can thus be assumed to be appropriate for this method. The dependent variable for the method is daily runoff (mm). The within-subjects factor is the catchments and the between-subjects factor is the before and after fire periods. The interaction between Bosboukloof and Lambrechtsbos B was first completed, because the data did not violate any of the required assumptions.

Stellenbosch University https://scholar.sun.ac.za

Table 5.3: Test of within subjects effects between Bosboukloof and Lambrechtsbos B

Test of Within-Subjects effects	
Type 3 Sum of Squares	4.534
df	1.000
Mean Square	4.534
F	425.936
Significant	0.001
Effect Size	0.200

The Significant row in Table 5.3 represents the p-value for the two-way interaction effect in the two-way mixed ANOVA. From Table 5.3 it can be seen that the p-value for the two-way interaction effect is 0.001. This is less than .01 (that means that it satisfies $p < .01$), which means that there is a statistically significant two-way interaction effect between the runoff from the control and the affected catchments. In addition, an effect size (a measure of practical significance) shows a large effect (0.200).

From this large effect size, a deduction was made that the difference in the daily runoff of the catchments was present for the whole research period.

To see what the difference truly entailed, a simple main effect was calculated. The simple main effect is a means of evaluating the difference in the runoffs of the catchments before the fire, and then to compare it with the differences in the runoff after the fire. Table 5.4 displays the difference in runoff of the catchments before the fire.

Table 5.4: Test of within subjects effects between Bosboukloof and Lambrechtsbos B before fire

Test of Within-Subjects effects	
Type 3 Sum of Squares	0.184
df	1.000
Mean Square	0.184
F	16.725
Significant	0.001
Effect Size	0.013

From the Significant row in Table 5.4 it can be seen that there was a significant difference in the volume runoff (mm) between the Bosboukloof and Lambrechtsbos B catchment before the fire ($p < 0.01$). However, due to the large sample size, the statistical significance should be interpreted with caution, and special attention should be paid to the effect size. From the descriptive statistics table below (Table 5.5) it can be seen that, before the fire, the mean volume runoff (mm) for Bosboukloof (1.08 mm) was very close to that of Lambrechtsbos B

Stellenbosch University https://scholar.sun.ac.za

(0.96 mm). This slight difference is confirmed by the effect size statistic in Table 5.4 above (Effect size = 0.013, indicating a small effect).

Table 5.5: Descriptive Statistics of Runoff before the fire

Descriptive Statistics_Runoff (mm)					
	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Average runoff per day in mm for Bosboukloof	1249	0	7.629	1.079	1.022
Average runoff per day in mm for Lambrechtsbos B	1249	0	9.880	0.964	0.899

The same procedure was then completed after the fire (Table 5.6).

Table 5.6: Test of within subjects effects between Bosboukloof and Lambrechtsbos B after fire

Test of Within-Subjects effects	
Type 3 Sum of Squares	7.580
df	1.000
Mean Square	7.580
F	783.163
Significant	0.0005
Effect size	0.629

From the Significant row in Table 5.6 above, it can be seen that there was a significant difference in the volumes of runoff (mm) from the Bosboukloof and from the Lambrechtsbos B catchment after the fire ($p < 0.01$). Due to the large sample size, the effect sizes are of great importance, since statistical significance is highly dependent on sample size. The effect size of the difference in volume runoff between the catchments was much greater than that shown before the fire (Effect size = 0.629 after the fire, compared to only 0.013 before the fire). From the descriptive statistics in Table 5.7, it can be seen that, after the fire, the mean volume runoff (mm) for Bosboukloof (0.598 mm) was considerably smaller than that of Lambrechtsbos B (0.825 mm), confirming the large effect size that was found.

Stellenbosch University https://scholar.sun.ac.za

Table 5.7: Descriptive Statistics of Runoff after the fire

Descriptive Statistics_Runoff (mm)					
	N	Minimum	Maximum	Mean	Std. Deviation
Average runoff per day in mm for Bosboukloof	462	0	3.586	0.598	0.543
Average runoff per day in mm for Lambrechtsbos B	462	0	8.207	0.825	0.823

In conclusion, the difference in average daily runoff (mm) between Bosboukloof and Lambrechtsbos B after the fire was not comparable to the difference before the fire. Before the fire, the runoff was very similar at Bosboukloof and Lambrechtsbos B, with an effect size of only 0.013. However, after the fire, the average daily runoff in Lambrechtsbos B was nearly double that reported in Bosboukloof, with a much greater effect size of 0.629.

The same analysis was completed for the interaction effect between the runoff from Lambrechtsbos A and Bosboukloof, keeping in mind that the data did not satisfy all the necessary assumptions (see Appendix B for the full analysis).

When the mixed ANOVA was executed between Bosboukloof and Lambrechtsbos A there was a significant interaction effect ($p < 0.01$) for both the within and the between subject factors. However, since there were a large number of data points it was important to analyse the effect size. The within subjects factor's effect size was small (Effect size = 0.043) in comparison to the within subjects factor of Lambrechtsbos B and Bosboukloof. Therefore, there was less of an interaction effect between Lambrechtsbos A and Bosboukloof's daily runoff, which confirms the assumptions tested for the method. There was still an effect when observing the daily volume runoff (mm) between catchments Bosboukloof and Lambrechtsbos A. The effect size before the fire was 0.595, which indicates that there was a difference between the daily runoff from the two catchments. However, after the fire, the effect size increased to 0.767, which indicates an even greater increase in runoff after the fire for the affected catchment compared to the control catchment.

The two-way Mixed ANOVA test thus verified that there was a statistically significant difference between the daily streamflow of the control catchment and the affected catchments as a result of the fire. Analysing the streamflow due to rainfall events will provide a better understanding of the nature of change in streamflow due to fire in the affected sub-catchments.

Stellenbosch University https://scholar.sun.ac.za

5.2 STORMFLOW

Table 5.8 shows the mean and standard deviation of the characteristic values from the rainfall events before and after the fire, including the antecedent soil moisture (API). The control and affected catchments received the same rainfall and thus there was only a distinction made between the pre- and post-fire rainfall events.

Table 5.8: Rainfall events before and after fire for all the sub-catchments

Period	N	Statistical parameter	Rainfall duration (hour)	Rainfall (mm)	API (mm)	Average intensity (mm/h)	Max hour intensity (mm/h)
Pre-fire	64	Mean	28.3	38.0	20.4	1.6	8.2
		Standard deviation	21.0	25.7	26.7	0.9	6.3
Post-fire	33	Mean	17.2	23.6	9.9	1.5	6.6
		Standard deviation	8.5	15.3	12.1	1.1	4.3

From Table 5.8 it can be seen that there were 64 pre-fire rainfall events and 33 post-fire rainfall events, which were considered for the analysis. The average rainfall for the analysed pre-fire rainfall events was 38.0 mm, with an average duration of 28 hours and API of 20.4 mm. The post-fire rainfall events delivered on average 23.6 mm rain; with an average duration of 17 hours and API of 9.9 mm. Hydrographs were constructed for each of these rainfall events to identify possible hydrological differences between the control and affected catchments, both before and after the fire event. Table 5.9 displays the values of some important characteristics of the hydrographs for both the pre- and post-fire rainfall events.

Table 5.9: Key characteristic values of the hydrographs before and after fire

Period	Catchment	N	Statistical parameter	Runoff volume (mm)	Runoff peak (mm/h)	Time to peak	Time between peak rainfall and runoff	Response time
Pre-fire	Bosboukloof (control)	64	Mean	1.75	0.12	12:31	6:32	3:24
			Standard deviation	2.94	0.11	12:35	9:42	2:02
	Lambrechtsbos B (treated)	64	Mean	2.03	0.11	12:36	7:17	4:45
			Standard deviation	3.80	0.11	12:47	10:24	2:53
	Lambrechtsbos A (treated)	64	Mean	1.03	0.07	9:46	5:44	4:41
			Standard deviation	2.08	0.07	12:24	9:55	2:52
Post-fire	Bosboukloof (control)	33	Mean	0.95	0.12	8:43	4:56	3:29
			Standard deviation	0.99	0.14	7:05	5:50	2:09
	Lambrechtsbos B (treated)	33	Mean	1.79	0.33	7:45	4:52	4:16
			Standard deviation	2.30	0.43	7:52	7:34	2:44
	Lambrechtsbos A (treated)	33	Mean	1.05	0.21	6:41	3:49	4:25
			Standard deviation	1.53	0.38	6:44	5:55	2:54

From Table 5.9 it can be seen that there were differences between the calculated mean values from the hydrographs (time-to-peak, response time, runoff volume and runoff peak) before the fire, in comparison with after the fire.

The calculated mean time variables (time to peak (t_c) and response time) from the hydrographs (Table 5.9) displayed different values for both the control and affected catchments before and

Stellenbosch University https://scholar.sun.ac.za

after the fire. The time to peak and response time is highly dependent on the rainfall intensity. In Table 5.8 it can be seen that the average rainfall intensity before the fire (1.6 mm/h) was approximately similar to after the fire (1.5 mm/h). However, it is important to take into account that the rainfall duration (hours) and rainfall quantity (mm) was greater before the fire than after the fire. This indicates that there were on average shorter storms with less rainfall after the fire than before the fire.

Before the fire, the time to peak value was approximately 12 and a half hours for Bosboukloof and Lambrechtsbos B, while Lambrechtsbos A was approximately 10 hours. The control catchment's t_c reduced by four hours after the fire, while Lambrechstbos B t_c reduced by five hours and Lambrechtsbos A by three hours. The response times changed slightly after the fire; Bosboukloof increased by 5 minutes, while Lambrechtsbos A decreased by 16 minutes and Lambrechtsbos B by 29 minutes. The reduction in the time variables could be due to the shorter duration storms after the fire, which had approximately the same average rainfall intensity than the longer storms before the fire. Figure 5.5 (a and b) display the difference between the control catchment and affected catchment's time to peak values, while Figure 5.5 (c and d) show the response time differences.

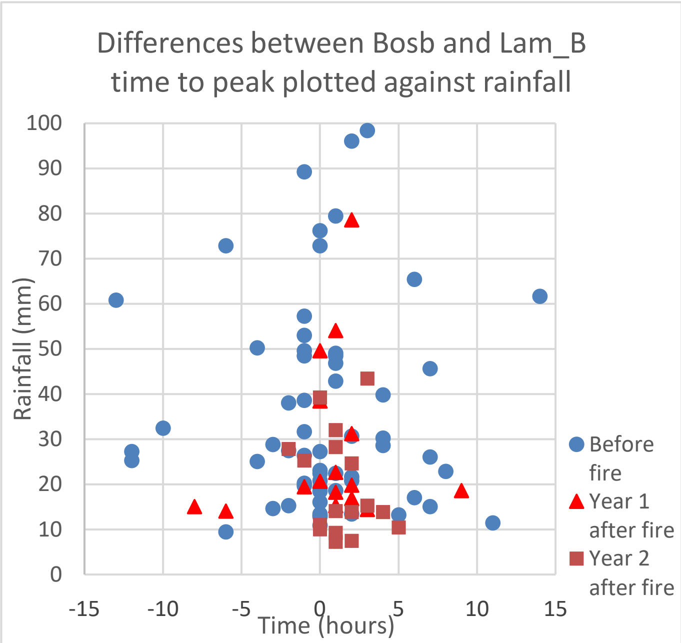


Figure 5.5 (a): Δ Time to peak of Bosboukloof and Lambrechtsbos B

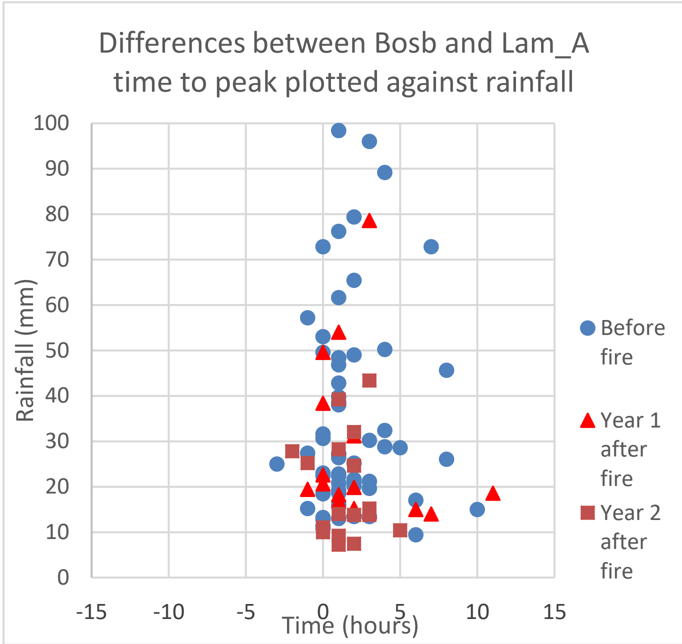


Figure 5.5 (b): Δ Time to peak of Bosboukloof and Lambrechtsbos A

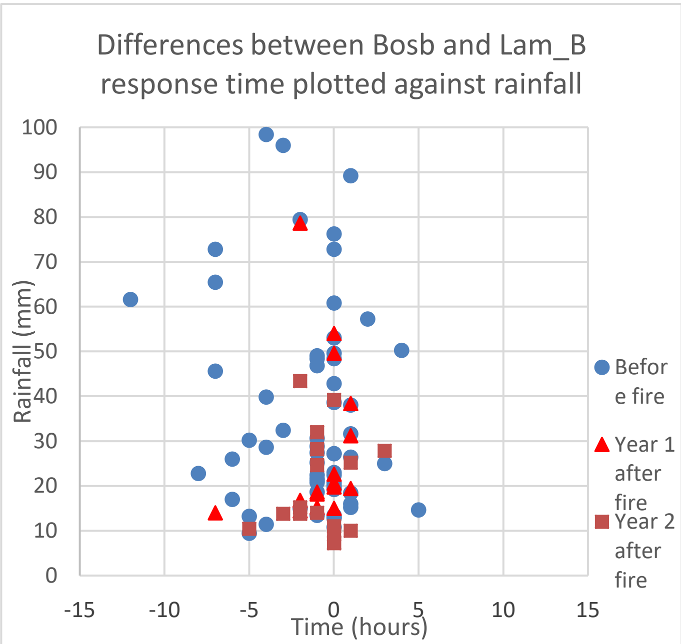


Figure 5.5 (c): Δ Response time of Bosboukloof and Lambrechtsbos B

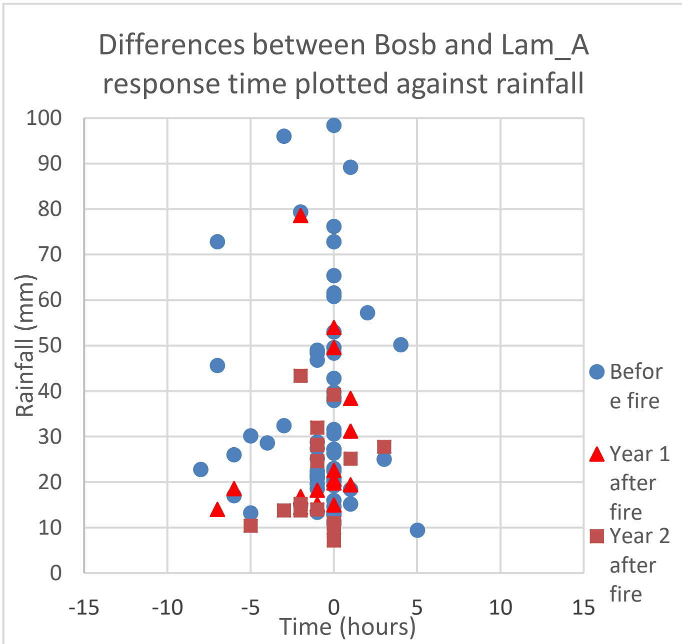


Figure 5.5 (d): Δ Response time of Bosboukloof and Lambrechtsbos A

Stellenbosch University https://scholar.sun.ac.za

The data points of Figure 5.5 (a-d) are approximately evenly distributed before and after the fire, which means that the difference between the control catchment and affected catchments data did not show changes after the fire. Since the time variables of the affected catchments were not showing any significant differences to those of the control catchment before or after the fire, it was assumed that fire did not change the time variables on the affected sub-catchments.

The mean volume runoff for the affected catchments did not change after the fire in relation to what it had been before the fire. Lambrechtsbos A's mean runoff stayed approximately 1 mm, while Lambrechtsbos B's went from 2 mm to 1.8 mm. It is important to recognise that the mean volume runoff for the control catchment decreased significantly after the fire, from a mean of 1.75 mm down to 0.95 mm. The reduction in runoff volume of the control catchment, and little to no change in the affected catchments, could be due to the rainfall event's characteristic differences before and after the fire (Table 5.8).

Figure 5.6 (a-d) display the rainfall plotted against volume runoff for the different rainfall events of both the control and affected catchment (Lambrechtsbos B). Before the fire (a,c) the control and affected catchments displayed a similar distribution in data points. After the fire, Bosboukloof remained relatively constant, while Lambrechtsbos B displayed a increase in volume of runoff.

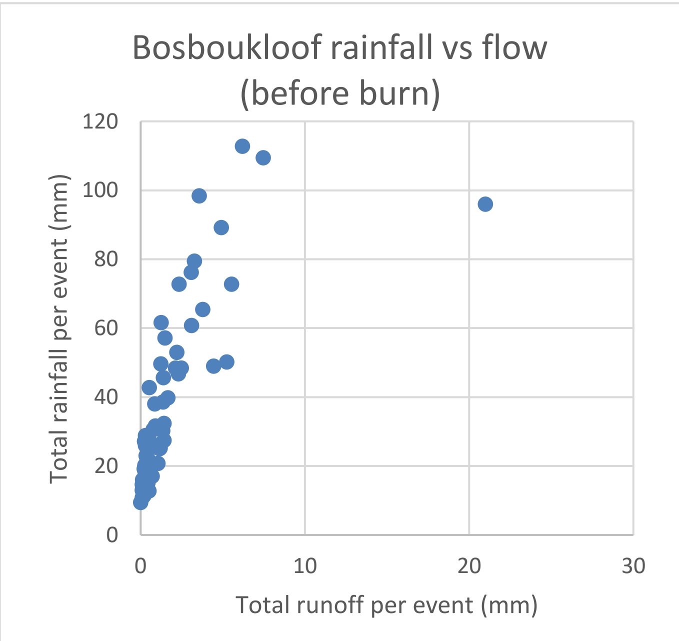


Figure 5.6 (a): Bosboukloof rainfall vs runoff before fire

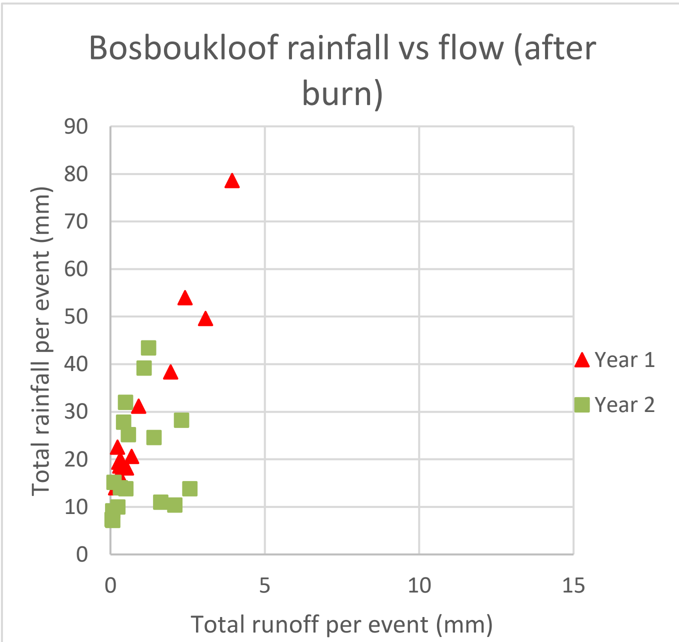


Figure 5.6 (b): Bosboukloof rainfall vs runoff (1st and 2nd year after fire)

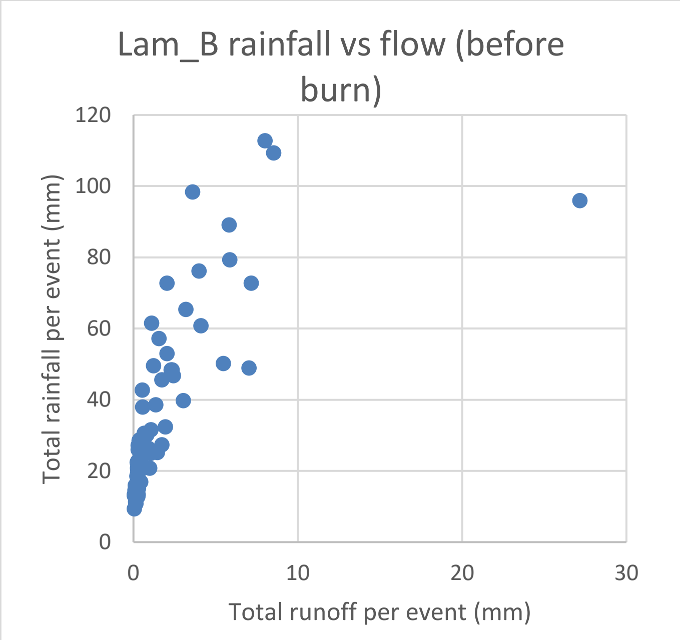


Figure 5.6 (c) Lambrechtsbos B rainfall vs runoff before fire

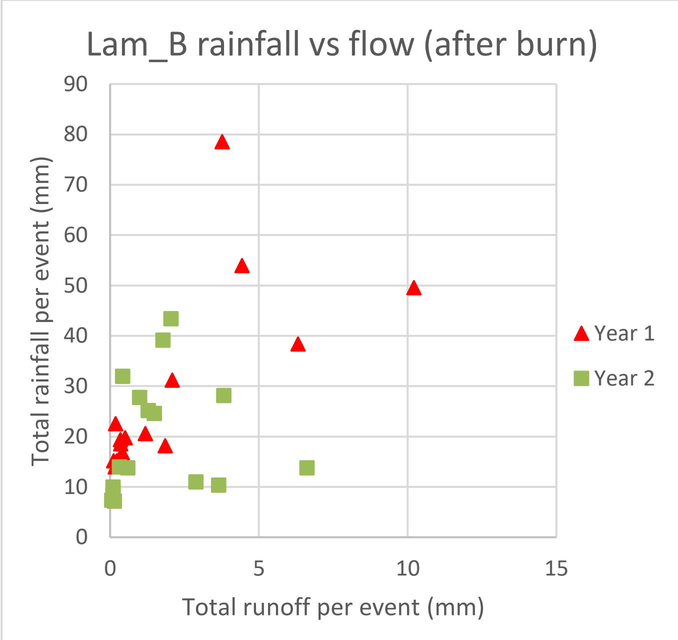


Figure 5.6 (d) Lambrechtsbos B rainfall vs runoff (1st and 2nd year after fire)

The mean peak flow reached during rainfall events did not change significantly after the fire for the control catchment (Table 5.9), however the mean peak flow did change for the affected catchments. Bosboukloof's peak discharge remained the same at 0.12 mm/h (before and after the fire). Lambrechstbos B mean peak discharge increased from 0.11 mm/h to 0.33 mm/h, which is a 200% increase. The Lambrechtbos A peak discharge increased from 0.07 mm/h to 0.21 mm/h, which is also a 200% increase in peak discharge. Figure 5.7 (a-d) display the rainfall plotted against the peak flow values for the different rainfall events of both the control and affected catchment (Lambrechtsbos B).

Stellenbosch University https://scholar.sun.ac.za

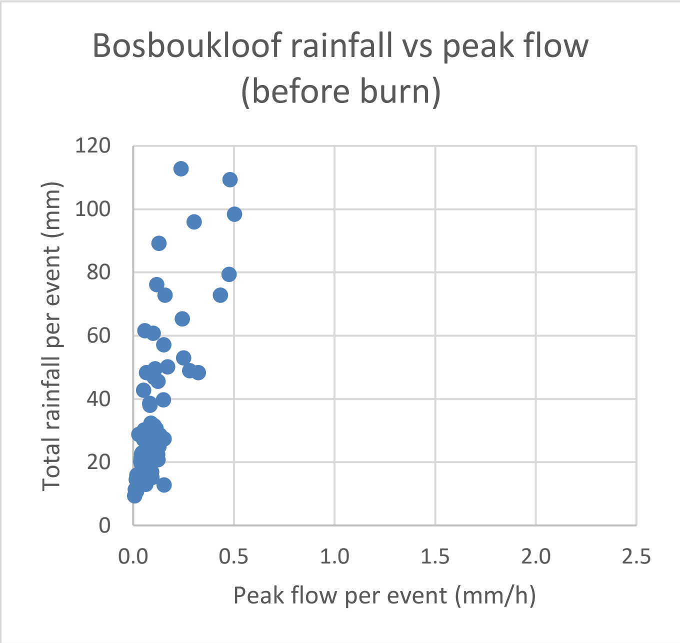


Figure 5.7 (a): Bosboukloof rainfall vs peak flow before the fire

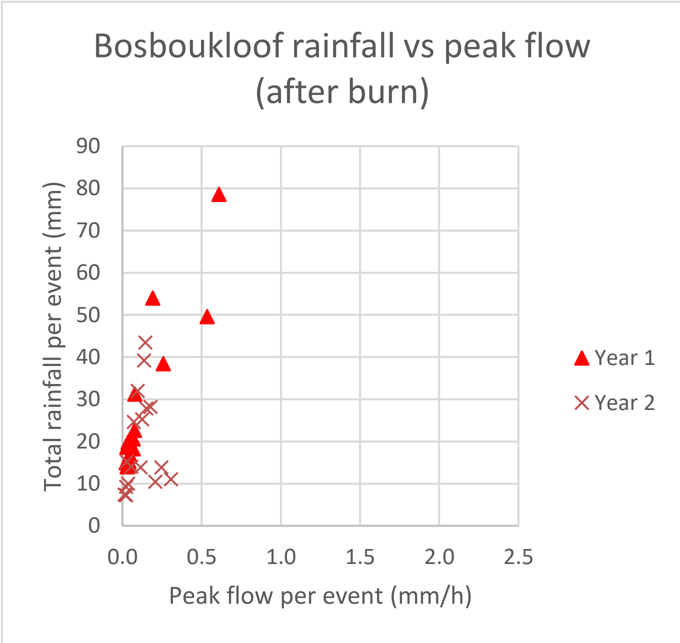


Figure 5.7 (b): Bosboukloof rainfall vs peak flow (1st and 2nd year after the fire)

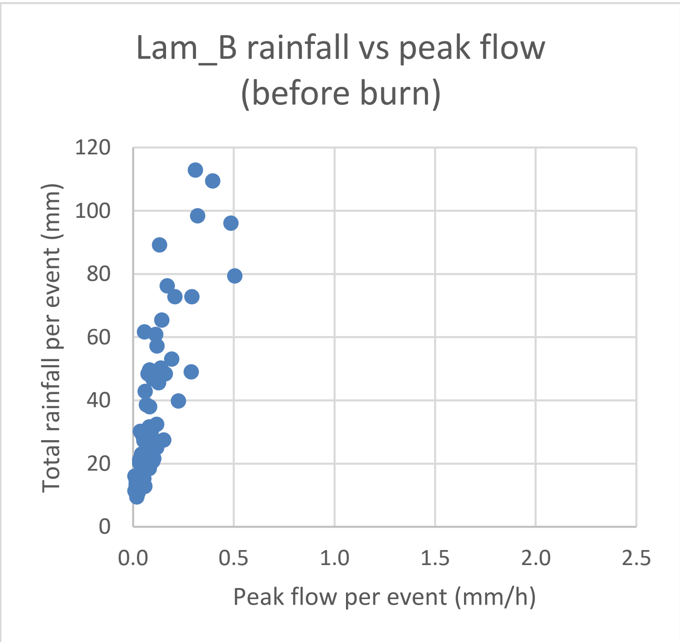


Figure 5.7 (c): Lambrechtsbos rainfall vs peak flow before the fire

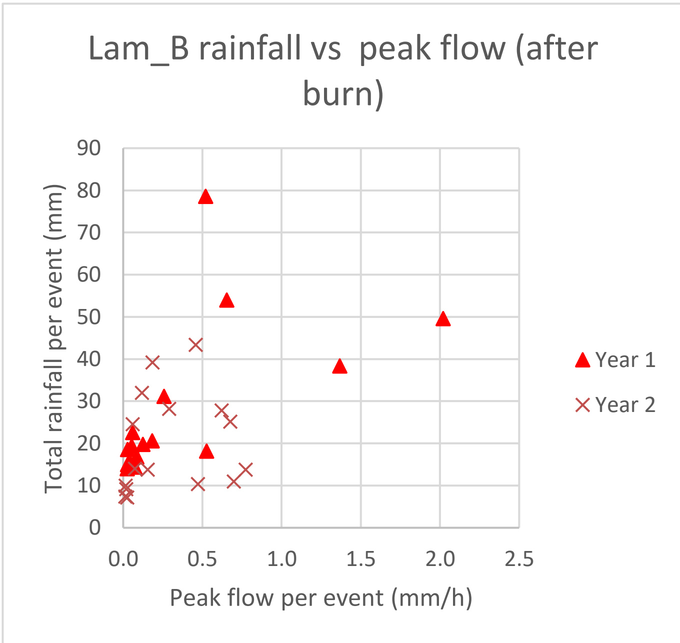


Figure 5.7 (d): Lambrechtsbos B rainfall vs peak flow (1st and 2nd year after the fire)

Stellenbosch University https://scholar.sun.ac.za

From Figure 5.7 (a,b) it can be seen that the control and affected catchments displayed a similar distribution of data points before the fire. After the fire, however, the affected catchment exhibited significantly larger peak flows in comparison to the control catchment. The biggest difference was observed in a rainfall event that took place on the 17th of July 2015. Rainfall of 49.6 mm during a period of 19 hours, with a peak intensity of 11.4 mm/h, was recorded. The soil moisture (API) was calculated as 15.75 mm before the event. Figure 5.8 illustrates the hydrological responses of the sub-catchments due to the rainfall event in the form of a hydrograph and hyetograph. From observing Figure 5.8, it can be seen that both affected catchments displayed similar runoff responses; forming double peaks with the highest approximately 2 mm/h, 14 hours into the event. The Bosboukloof sub-catchment reached its peak flow at the same time as the affected catchments and only managed 0.56 mm/h as its peak flow. Both the affected sub-catchments thus produced peaks approximately 300% greater than the control catchment. The runoff volume produced by the affected catchments were also greater than the control catchment. The weir at Bosboukloof received 3.1 mm of runoff, while at Lambrechtsbos B 10.2 mm and Lambrechstbos A 7.5 mm.

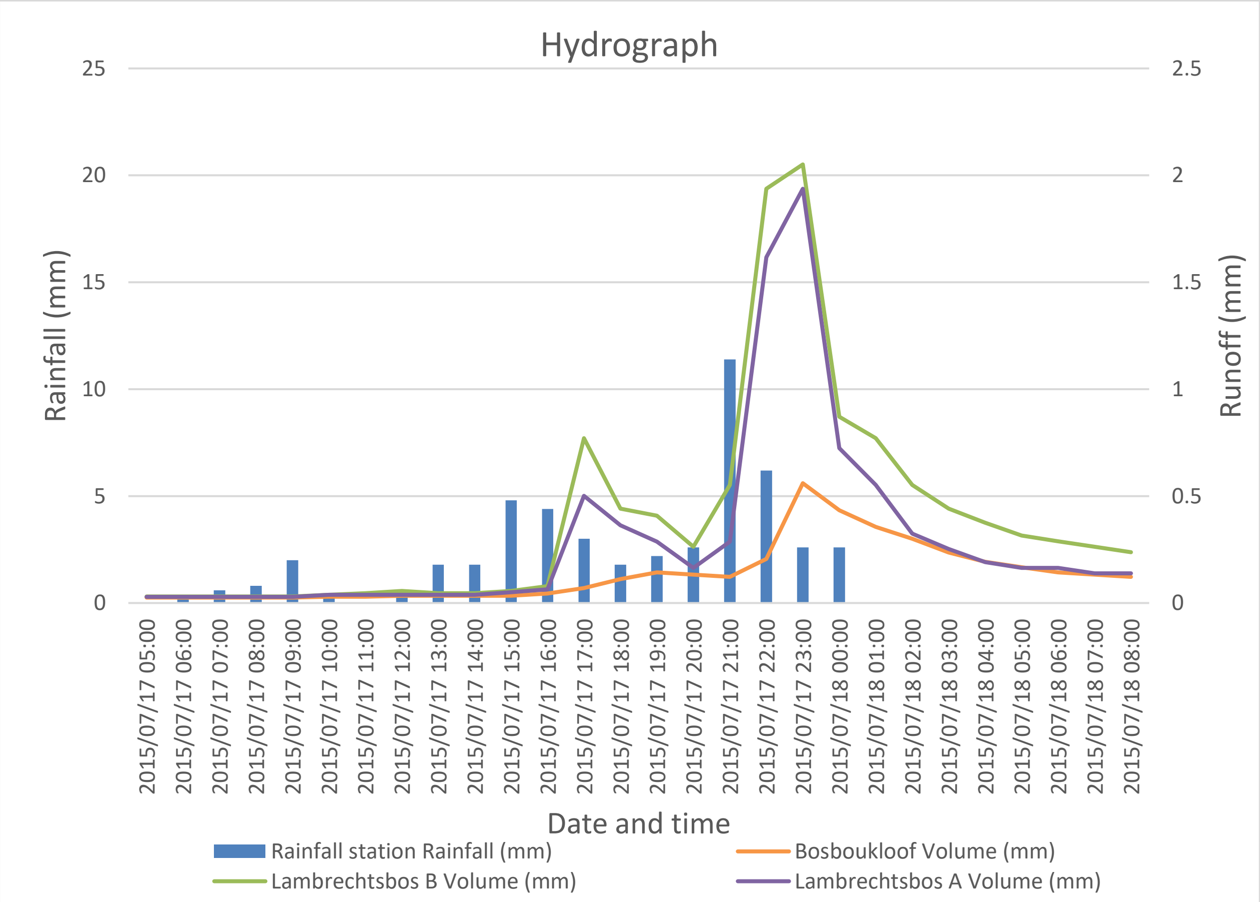


Figure 5.8: Hydrographs of three sub-catchments on the 2015/07/17 with their hyetograph

Stellenbosch University https://scholar.sun.ac.za

The runoff due to a rainfall event illustrated in Figure 5.8 demonstrates the significant changes that fire can bring to the hydrological response of a catchment. Determining whether there were any specific significant factors responsible for these runoff values is an important next procedure to fully assess the changes caused by the fire. The paired catchment method was used to validate whether the changes in runoff were statistically significant and to identify the key components responsible for the change in runoff.

5.2.1 Paired catchment method

The paired catchment method was applied to the analysis of the volume runoff produced by the rainfall events illustrated in Table 5.8, as well as for the peak discharges produced by these rainfall events, through the use of a hierarchical multiple regression-analysis. Before a hierarchical multiple analysis could be conducted, the data had to comply with certain assumptions:

(1) the independent variables had to be linearly related to the dependent variable,

(2) outliers needed to be identified and removed (if applicable),

(3) leverage points needed to be identified and removed,

(4) highly influential values needed to be identified and removed,

(5) the requirement of homoscedasticity should be met,

(6) data should be normally distributed.

Appendix C provides a detailed description of how the assumptions were verified for both the runoff volume and the peak flow values in the paired catchment method. The runoff data (volume and peak flow) from the dependent (Lambrechtsbos A and B) and independent variables were all log transformed to allow for better meeting the assumptions.

It is important to refer back to Equation 3.5, which displays the variables used for the paired catchment method. In Equation 3.5, there is one dependent variable, five independent variables, one dummy variable, an error term and fitted regression coefficients. Below is the variables, which were used in the analyses for both the volume runoff and peak flows.

Dependent variable:

T = treatment catchment variable (volume runoff/peak flow).

Independent variables:

C = control catchment variable (volume runoff/peak flow),

D = rainfall duration (hours),

Stellenbosch University https://scholar.sun.ac.za

P = precipitation (mm),

I = maximum 1 hour intensity of the storm (mm/h),

API = Antecedent Precipitation Index for each storm (mm).

Dummy variable:

F = Fire dummy variable.

After the data (dependent and independent) met the necessary requirements, two multiple regression models were created for the analysis. The first model is where the regression model is run without the interaction effect of fire (F = 0), while the second model includes the interaction effect of fire (F = 1) in the analysis.

A different relationship between the affected catchment and control catchment variables from the first and second models would be an indication that fire had an effect on the runoff variables and that the runoff (volume and peak flow) in the treatment catchment would be different from that of the control catchment.

The next section discusses the results from the paired catchment method used on runoff volume.

5.2.1.1 Runoff volume

The data points between the dependent variable (Lambrechtsbos A runoff volume) and the independent variables met the required assumptions, when eliminating a highly influential data point (2015/07/11). This data point was identified as both a leverage and highly influential value and was thus removed from the analysis.

All the assumptions were also met for the data points between the dependent variable (Lambrechtsbos B runoff volume) and the independent variables. A highly influential data point (2015/10/09) was also removed from this analysis since this data point was also identified as an outlier, because it was beyond the ±2 standard deviation range.

When the necessary assumptions were met, two moderated multiple regression models were compiled to assess the difference in relationship between the runoff and other input parameters before the fire vs the relationship after the fire for both the affected catchments (Lambrechtsbos A and B). Table 5.10 displays the summary of the two models.

Stellenbosch University https://scholar.sun.ac.za

Table 5.10: Model summary of two sub-catchments

Model Summary							
Sub-catchment	Model	R^2	Change Statistics				
			R^2 Change	F	df1	df2	Significant (p value)
Lam_A	1	0.903	0.903	93.479	6	60	< 0.001
	2	0.920	0.016	2.237	5	55	0.063
Lam_B	1	0.939	0.939	155.481	6	61	< 0.001
	2	0.943	0.005	0.923	5	56	0.473

The first model displayed a statistically significant relationship ($p < 0.05$) with a R^2 change of approximately 0.9, which was evident for both Lambrechtsbos A and B.

From the values of Model 2 in Table 5.10 it can be seen that the addition of the interaction terms (F=1) did not statistically significantly add to the prediction of volume runoff in Lambrechtsbos A or Lambrechtsbos B. This can be seen by an increase in total variation explained for a volume runoff of only 1.6 % (R^2 change) for Lambrechtsbos A, which was not statistically significant (F = 2.237, p = 0.063). Lambrechtsbos B displayed an increase in total variation explained for volume runoff of only 0.5% (R^2 change), which was also not statistically significant (F = 0.923, p = 0.473).

The result is confirmed when observing Table 5.11, which shows the coefficients for all the variables in both models. From the coefficients table (Table 5.11) it can be seen that none of the interaction effects between the Fire dummy variable (F) and each of the independent variables were statistically significant. Therefore, the relationship between the independent variables: D (hours), P (mm), API (mm/h), I (mm/h) and C (Runoff-volume Bosboukloof (mm) and the dependent variable T (runoff volume Lambrechtsbos A and B (mm)) did not differ before and after the fire. Of particular interest for this research is the non-significant interaction effect between the runoff volume of Bosboukloof with the addition of the Fire dummy variable with runoff volume in both Lambrecthsbos A and B, p = 0.698 (Lambrechtbos A), and p = 0.374 (Lambrechtsbos B). The non-significance of this interaction effect shows that the relationship between the runoff volume in Bosboukloof and the runoff volume in both Lambrechtsbos A and B did not differ before and after the fire.

Stellenbosch University https://scholar.sun.ac.za

Table 5.11: Coefficients of before and after fire

Coefficients					
Sub-catchments		Lambrechtsbos A		Lambrechtsbos B	
Model		Coefficients	Significant (p value)	Coefficients	Significant (p value)
1	Constant	-0.263	0.386	-0.056	0.817
	D (hours)	-0.174	0.233	-0.012	0.918
	P (mm)	0.271	0.222	0.020	0.910
	API (mm)	-0.037	0.135	0.008	0.678
	I (mm/h)	-0.213	0.156	0.009	0.940
	C (Runoff Volume (mm) Bosboukloof)	1.106	> 0.001	1.137	> 0.001
2	Constant	-0.135	0.762	-0.311	0.409
	D (hours)	-0.234	0.248	-0.174	0.310
	P (mm)	0.370	0.254	0.418	0.129
	API (mm)	-0.051	0.052	0.005	0.814
	I (mm/h)	-0.447	0.018	-0.139	0.372
	C (Runoff Volume (mm) Bosboukloof)	1.087	> 0.001	1.065	> 0.001
	DxF (hours)	0.205	0.511	0.215	0.413
	PxF (mm)	-0.482	0.284	-0.784	0.065
	APIxF (mm)	0.260	0.067	0.015	0.744
	IxF (mm/h)	0.915	0.072	0.405	0.133
	CxF (Runoff Volume (mm) Bosboukloof)	0.082	0.698	0.155	0.374

5.2.1.2 Peak values

The data points between the dependent variable (Lambrechtsbos A & B's peak flow) and the independent variables met the required assumptions. An outlier was removed from the data set for both Lambrechtsbos A and B (2015-07-11), because it was beyond the ±2 standard deviation range and since it was also identified as a highly influential data point.

Table 5.12 displays the model summary of the two sub-catchments with and without the interaction terms.

Stellenbosch University https://scholar.sun.ac.za

Table 5.12: Model summary (peak flow)

Model Summary							
			Change Statistics				
Sub-catchments	Model	R^2	R^2 Change	F	df1	df2	Sig. F Change
Lam_A	1	0.776	0.776	35.745	6	62	< 0.001
	2	0.814	0.038	2.337	5	57	0.053
Lam_B	1	0.823	0.823	48.013	6	62	< 0.001
	2	0.881	0.058	5.564	5	57	< 0.001

The first model displayed a statistically significant ($p < 0.05$) relationship for both sub-catchments, with a R^2 change of approximatly 0.8. This indicates that there was a significant relationship between the dependent and independent variables before the fire.

From the values in Table 5.12 it can be seen that the addition of the interaction terms (F=1) did add statistical significance to the prediction of Lambrechtsbos B (p = > 0.001) and approached statistical significance to Lambrechtbos A peak flow (p = 0.053)

The addition of the interaction terms led to an increase of total variation explained in peak flow of by 3.8 % for Lambrechtbos A and 5.8% for Lambrechtsbos B. Therefore, to determine which of the interaction effects contributed to this significant result, coefficients were looked at for clarification, which are displayed in Table 5.13.

Table 5.13: Coefficients peak flow

Coefficients					
Sub-catchments		Lambrechtsbos A		Lambrechtsbos B	
Model		Coefficients	Significant (p value)	Coefficients	Significant (p value)
1	Constant	-0.273	0.415	-0.578	0.070
	C (Runoff peak (mm) Bosboukloof)	1.001	> 0.001	0.920	> 0.001
	D (hours)	-0.195	0.204	-0.026	0.855
	P (mm)	0.220	0.333	0.237	0.267
	I (mm/h)	0.002	0.991	0.125	0.459
	API (mm)	-0.029	0.285	0.026	0.307
2	Constant	-0.577	0.187	-1.204	0.002
	C (Runoff peak (mm/h) Bosboukloof)	0.807	> 0.001	0.683	> 0.001
	D (hours)	-0.053	0.809	-0.261	0.164
	P (mm)	0.116	0.702	0.776	0.004
	I (mm/h)	0.041	0.864	-0.033	0.872
	API (mm)	0.001	0.983	0.040	0.109
	C x F (Runoff peak (mm/h) Bosboukloof)	0.489	0.033	0.743	> 0.001
	D x F(hours)	0.035	0.920	0.674	0.024
	P x F (mm)	-0.099	0.830	-1.531	> 0.001
	I x F (mm/h)	0.125	0.740	0.595	0.065
	API x F (mm)	-0.130	0.046	-0.090	0.100

Stellenbosch University https://scholar.sun.ac.za

In Table 5.13 it can be seen that the interaction terms between a number of independent variables and the fire dummy variable were statistically significant ($p < 0.05$) for both the affected sub-catchments. According to the paired catchment method for Lambrechtsbos A, there were two significant interaction terms, which influenced the runoff peaks: (1) C x F (runoff peaks of Bosboukloof (mm/h)) and (2) API x F (mm). In Lambrechtsbos B there were three significant interaction terms, which influenced its runoff peaks: (1) C x F (runoff peaks of Bosboukloof (mm/h)), (2) P x F (mm) and (3) D x F (hours).

The following interaction effects were thus further analysed:

- interaction between the runoff peaks (mm/h) of the control (Bosboukloof) and affected (Lambrechtsbos A & B) catchments,
- interaction between rainfall (mm) and the runoff peaks (mm/h) from all the sub-catchments.

A Simple slope analysis was done on the interaction terms, which influenced the runoff peaks of the affected catchments. Essentially a Simple slope analysis is conducting the same multiple regression as in Equation 3.5, but by only using the independent and the dependent variables.

Interaction between Bosboukloof and Lambrechtsbos A peak runoff:

Figure 5.9 displays the runoff peaks from Lambrechtsbos A plotted against Bosboukloof's runoff peaks.

Stellenbosch University https://scholar.sun.ac.za

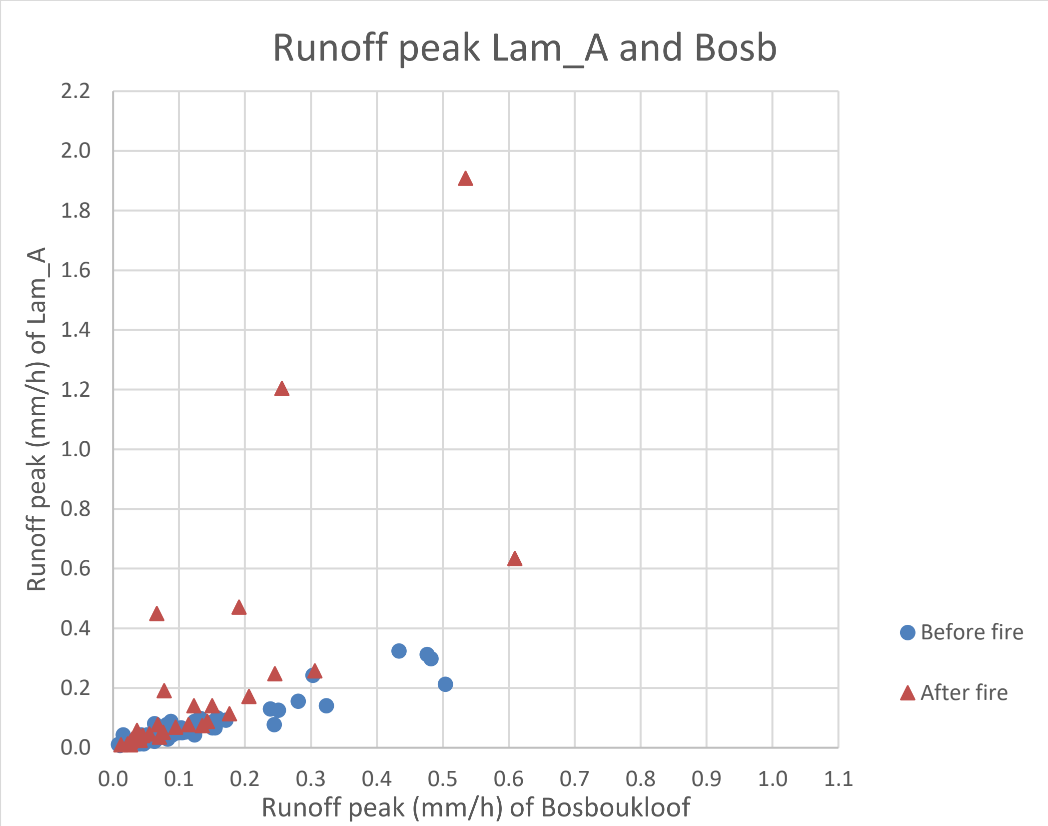


Figure 5.9: Runoff peak Lambrechtsbos A vs Bosboukloof before and after the fire

In Figure 5.9 it can be seen that there was a significant increase in runoff peaks after the fire at Lambrectsbos A in comparison to Bosboukloof.

Simple slope analysis was used to determine the relationship between the runoff peaks in Bosboukloof and in Lambrechtsbos A before and after the fire. Table 5.14 displays the following Simple slope analysis coefficients: the constant value produced by regression and runoff peak from Bosboukloof (mm).

In Figure 5.14 it can be seen that both before and after the fire, there was a statistically significant positive relationship between the runoff peaks in Bosboukloof and the runoff peaks in the affected catchment Lambrechtsbos A ($p < 0.05$).

Table 5.14: Simple slope analysis coefficients Lambrechtsbos A

Model	Before fire		After fire	
	Coefficients	Significant (p value)	Coefficients	Significant (p value)
Constant	-0.375	>0.001	0.263	0.009
C (Runoff peak (mm/h) Bosboukloof)	0.848	>0.001	1.243	>0.001

Stellenbosch University https://scholar.sun.ac.za

A one-unit increase in runoff peak (mm/h) in Bosboukloof was associated with a 0.848 unit increase in runoff peak (mm/h) Lambrechtsbos A before the fire and 1.243 after the fire. There was thus in increase of 46.5%.

Interaction between Bosboukloof and Lambrechtsbos B peak runoff:

Figure 5.10 displays the runoff peaks from Lambrechtsbos B plotted against Bosboukloof's runoff peaks.

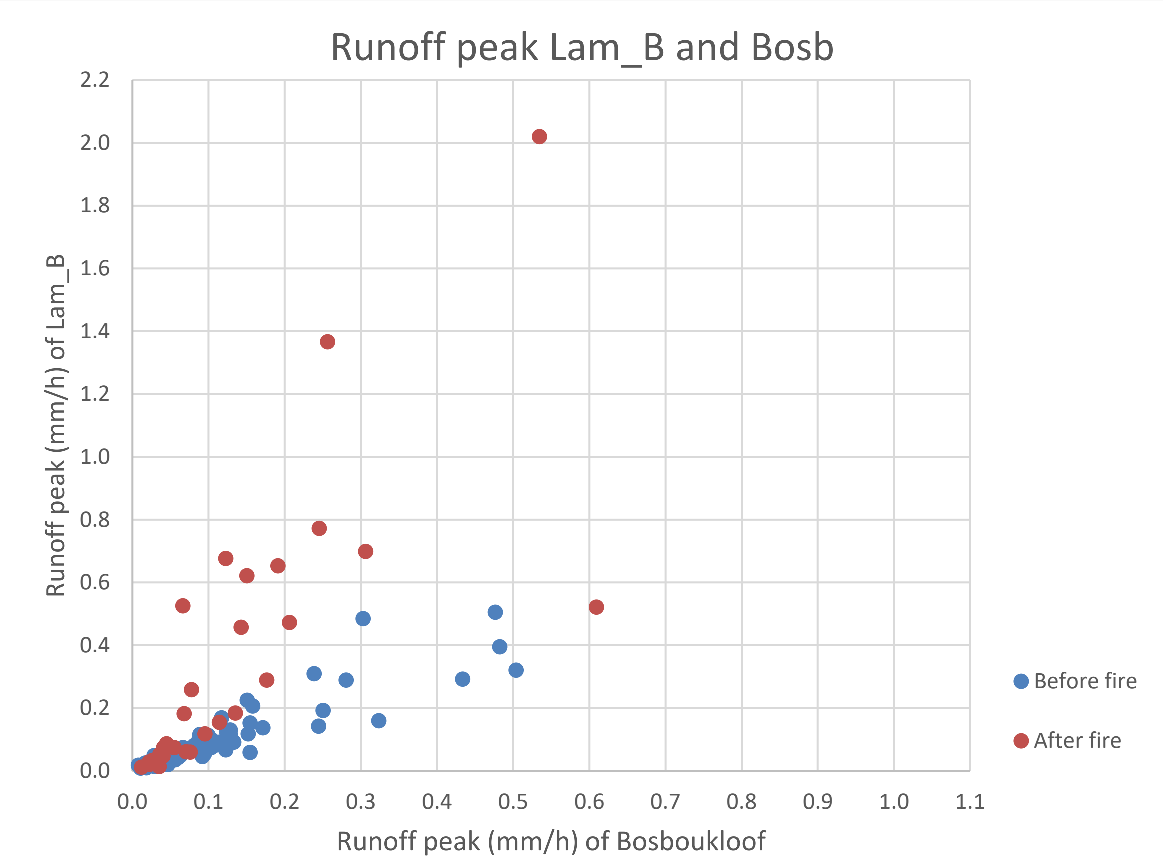


Figure 5.10: Runoff peak Lambrechtsbos B vs Bosboukloof before and after the fire

In Figure 5.10 it can be seen that there was a significant increase in runoff peaks after the fire at Lambrectsbos B in comparison to Bosboukloof, which is the same result as in Figure 5.9.

Simple slope analysis was used to determine the relationship between the runoff peaks in Bosboukloof and in Lambrechtsbos B before and after the fire. Table 5.15 displays the following Simple slope analysis coefficients: the constant value produced by regression and runoff peak from Bosboukloof (mm).

Stellenbosch University https://scholar.sun.ac.za

Table 5.15 Simple slope analysis coefficients Lambrechtsbos B

Model	Before fire		After fire	
	Coefficients	Significant (p value)	Coefficients	Significant (p value)
Constant	-0.119	0.102	0.610	>0.001
C (Runoff peak (mm/h) Bosboukloof)	0.941	>0.001	1.331	>0.001

Table 5.15 shows that both before and after the fire, there was a statistically significant positive relationship between the runoff peaks in Bosboukloof and the runoff peaks in the affected catchment Lambrechtsbos B ($p < 0.05$). A one-unit increase in runoff peak (mm/h) in Bosboukloof was associated with a 0.941 unit increase in runoff peak (mm/h) of Lambrechtsbos B before the fire and 1.331 after the fire. There was therefore an increase 41.4% from before the fire to after it, similar to Lambrecthsbos A.

From the results above it can be seen that the relationship between runoff peaks in Bosboukloof and runoff peaks in the affected catchments were somewhat different before and after the fire. An increase in runoff peak in Bosboukloof led to a greater increase in runoff peak at Lambrechtsbos A and Lambrechtsbos B after the fire in comparison to before the fire.

Stellenbosch University https://scholar.sun.ac.za

Interaction between rainfall (mm) and peak runoff (mm/h) for all the sub-catchments:

Rainfall (mm) showed a significant interaction on the runoff peaks in Lambrechtsbos B, according to the results of the paired catchment method. Figure 5.11 displays the runoff peaks from Lambrechtsbos B plotted against rainfall.

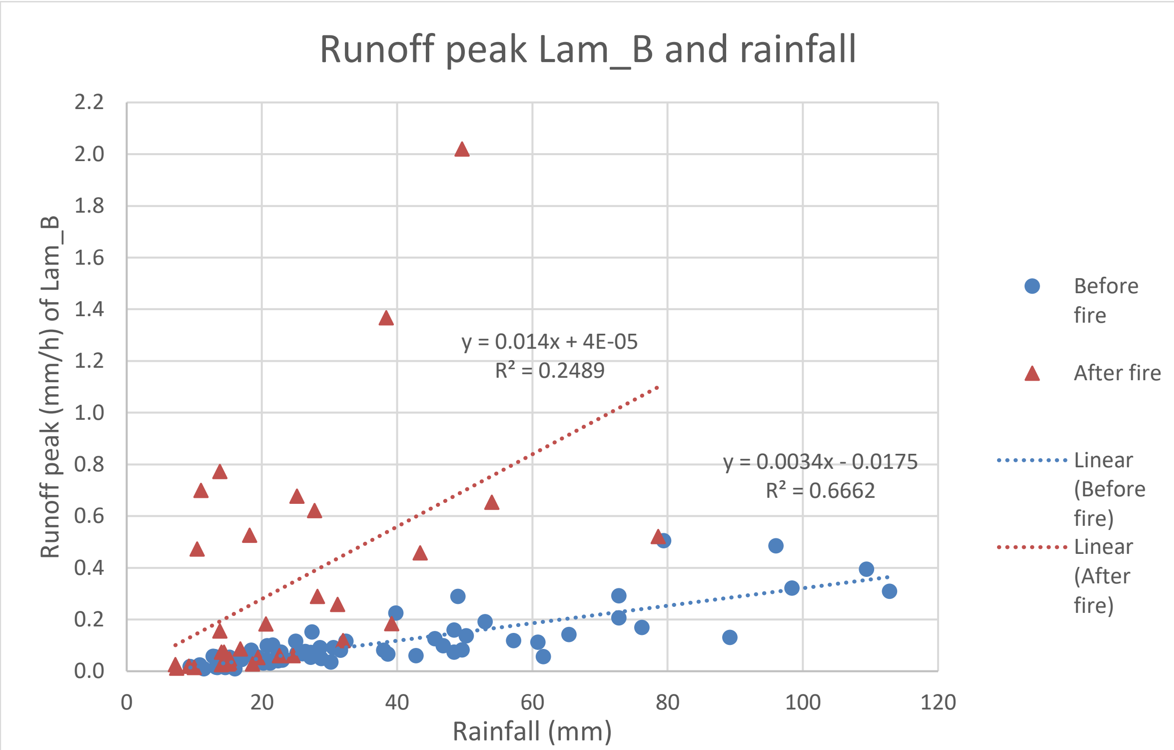


Figure 5.11 Runoff peak of Lambrechtsbos B against rainfall

Figure 5.11 illustrates that the quantity of rainfall had a greater effect on the peak runoff for Lambrechtsbos B after the fire than before the fire. By plotting a linear regression line it can be seen that before the fire the slope was significantly less than after the fire, however the R^2 value also decreased. In Figure 5.11 it can be seen that the majority of the peak flows produced by rainfall events after the fire fell within the same distribution as before the fire. The rainfall intensity could not be accommodated in Figure 5.11 and therefore it was important to plot the same graph for the other sub-catchments.

Stellenbosch University https://scholar.sun.ac.za

Figure 5.12 displays the runoff peaks from Lambrechtsbos A plotted against rainfall.

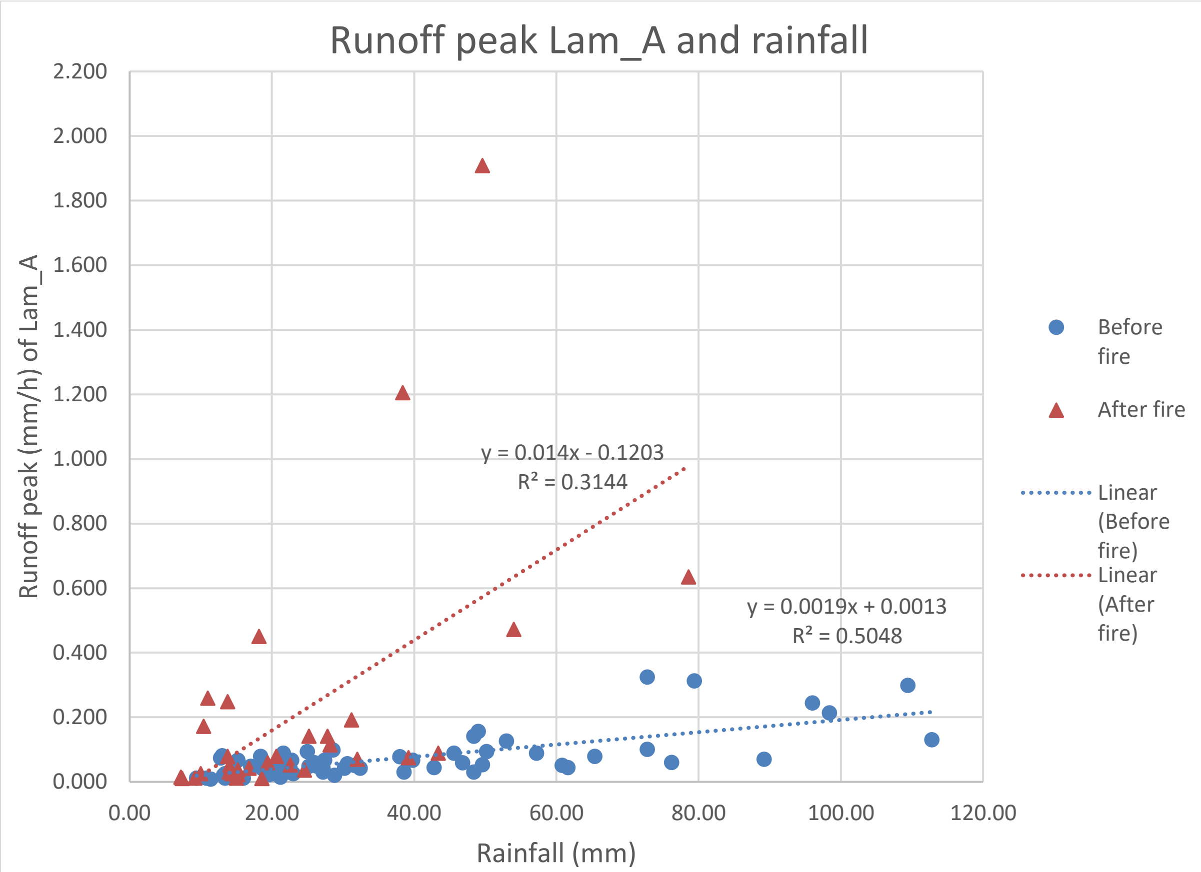


Figure 5.12 Runoff peak of Lambrechtsbos A against rainfall

In Figure 5.12 it can be seen that rainfall had a similar impact on Lambrechtsbos A's peak runoff before and after the fire, as it had with Lambrechtsbos B. The slope was similar for both the affected catchments after the fire and had relatively the same distribution of data points.

Figure 5.13 displays the runoff peaks from Bosboukloof plotted against rainfall.

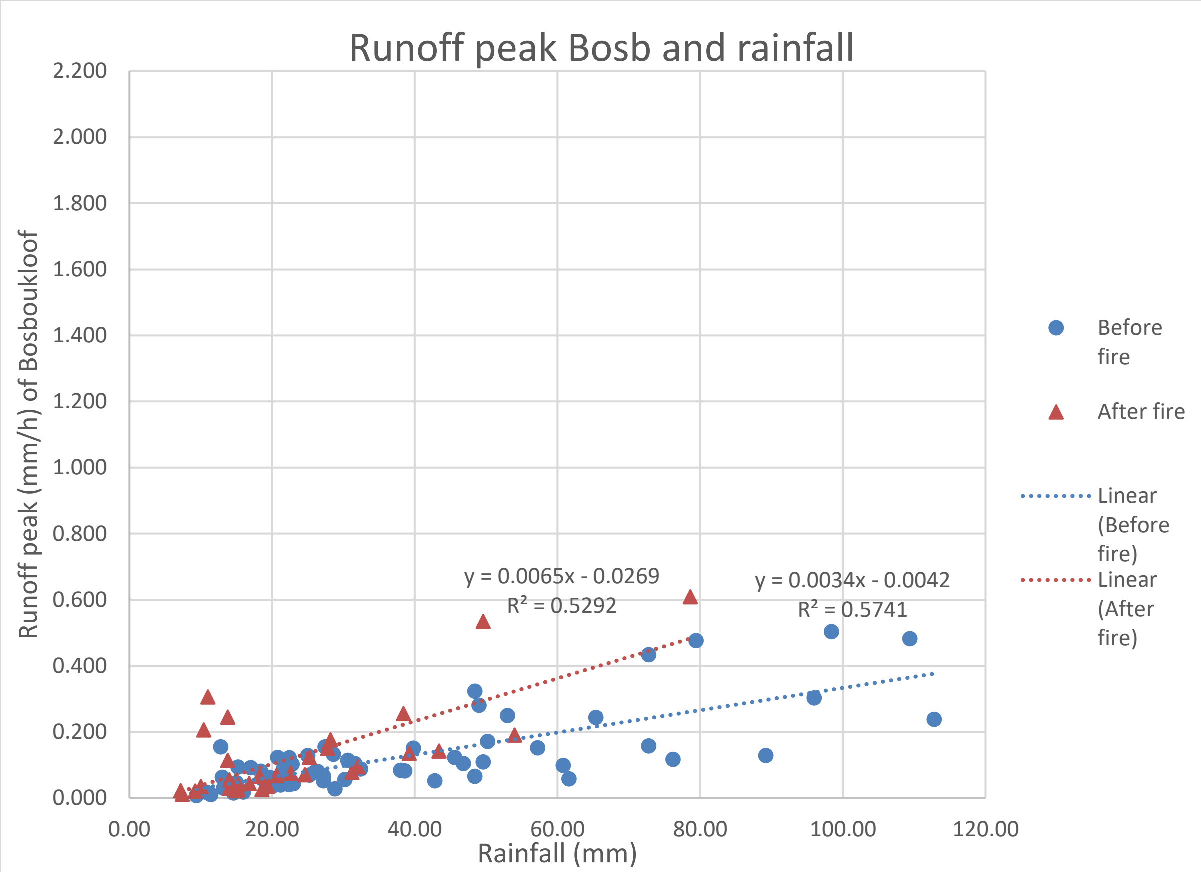


Figure 5.13: Runoff peak of Lambrechtsbos A against rainfall

In Figure 5.13 it can be seen that the amount of peak flows produced from rainfall also increased after the fire as in the affected catchments. The effect that it had was however less prominent than for the affected catchments.

5.3 CONCLUSION

This chapter determined whether fire had an impact on the affected catchments in relation to the control catchment. The runoff was assessed by observing the changes during a rainfall event and analysing the long-term flow.

Double mass plots were used to observe changes in the accumulated streamflow between the affected (Lambrechtsbos A & B) and control (Bosboukloof) catchments. Before the fire event, the average daily streamflow ratio between the affected and control catchments was approximately the same (1:1). After the fire, however, the streamflow responses changed substantially; a year after the fire the average daily runoff was 50% greater for Lambrechtsbos A in comparison to Bosboukloof. The other affected catchment (Lambrechtsbos B), had an average daily streamflow that also increased after the fire, and the first year after the fire an increase of 45% was found. The increase in runoff did not, however, change during the second year after the fire.

Stellenbosch University https://scholar.sun.ac.za

The two-way mixed ANOVA method was then used to test whether there had been a statistically significant change in streamflow between the control and affected catchments before and after the fire. The method establishes a relationship between the control and affected catchments average daily streamflow before the fire, and then calculates any possible changes after the fire. Before the method could be used, the data was tested to see if it met the needed requirements of the method. The only assumption that was violated was that the daily runoff data between Bosboukloof and Lambrechtbos A did not satisfy the homogeneity of variance of the covariance-assumptions. This violation, however, did not impede the use of the chosen method; although the results should be interpreted with caution.

The method showed that there was a significant difference ($p < 0.01$) between the streamflow of the control and affected catchments, before and after the fire. The difference between Lambrechtsbos A and Bosboukloof Effect size changed from 0.595 to 0.767; the Effect size between Lambrechtsbos B and Bosboukloof also changed after the fire, from 0.013 to 0.629. The two way mixed ANOVA method showed that there was a significant change in streamflow between the affected catchments and the control catchment after the fire. Rainfall events were also assessed for changes in streamflow dynamics, between the control and affected catchments.

Ninety-seven rainfall events met the requirements set in Section 3.3.1.1. Sixty-four rainfall events before the fire and 33 after were used in the analysis. The mean duration and rainfall quantities of these events differed, before and after the fires. The duration and quantity of rainfall was greater in the pre-fire rainfall events than the post-fire rainfall events. The average intensity, however, stayed the same (±1.5 mm/h).

Hydrographs were constructed for all these rainfall events, in both the affected catchments and the control catchment. The mean time-to-peak values (t_c) shortened after the fire, for both the control and the affected catchments. The response times changed slightly after the fires, where Bosboukloof increased by five minutes and Lambrechtsbos A decreased by 16 minutes and Lambrechtsbos B by 29 minutes. The mean reduction in the time variables (time to peak and response time) could be due to the mean reduction in rainfall duration after the fire (11 hours), while still maintaining the same average rainfall intensity. By observing the differences in t_c and response time between the control and affected catchments (Figure 5.5 (a-d)) it was concluded that the distribution was evenly spread before and after the fire. It was thus assumed that fire did not change the time variables (time to peak and response time) in the affected catchment in relation to the control catchment.

Stellenbosch University https://scholar.sun.ac.za

After the fire, the average runoff volumes changed slightly for the affected catchments (2.03 mm to 1.79 mm for Lambrechtsbos B and 1.03 mm to 1.05 mm for Lambrechtsbos A); however, the control catchment's volume decreased from 1.75 mm to 0.95 mm. Table 5.16 displays the comparison between control and affected catchment's runoff volume before and after the fire.

Table 5.16: Relation between control and affected catchment's runoff volume before and after the fire

Period	N	Mean runoff volume (mm)			Bosb:Lam_B	Bosb:Lam_A
		Bosb	Lam B	Lam A		
Before fire	64	1.75	2.03	1.03	1 : 1.16	1 : 0.59
After fire	33	0.95	1.79	1.05	1 : 1.88	1 : 1.11
				Difference	72.42%	51.67%

In Table 5.16 it can be seen that the runoff volume for both the affected catchments increased after the fire in comparison to the control catchment. Lambrechtsbos B increased by 72.42% and Lambrechtsbos A by 51.67% in comparison to Bosboukloof.

The runoff peak values displayed similar means before and after the fire for the control catchment. The mean peak flow values of both the affected catchments, however, increased by 183.33% for Lambrechtsbos B and 116.67% for Lambrechtsbos A in relation to Bosboukloof, which can be observed in Table 5.17.

Table 5.17: Relation between control and affected catchment's peak flow before and after the fire

Period	N	Mean peak flow (mm/h)			Bosb:Lam_B	Bosb:Lam_A
		Bosb	Lam B	Lam A		
Before fire	64	0.12	0.11	0.07	1 : 0.92	1 : 0.58
After fire	33	0.12	0.33	0.21	1 : 2.75	1 : 1.75
				Difference	183.33%	116.67%

The paired catchment method was applied to validate the changes in volume runoff and peak flows between the control and affected catchments. The data met the required assumptions after a few outliers and highly influential values were removed. When the effect of fire was not taken into account (model 1), the independent variables showed a statistically significant ($p < 0.05$) effect on predicting the runoff volumes of the affected catchments. By including the interaction effects (model 2), which is used to test whether the relationship between the independent variables and runoff volume had changed from what they were before to after the fire, it was found not to be statistically significant ($p > 0.05$).

Stellenbosch University https://scholar.sun.ac.za

The same model was calculated for the runoff peaks and, when the effect of fire was not taken into account (model 1), the independent variables showed a statistically significant ($p < 0.05$) effect on predicting the runoff peaks of the affected catchments. By including the interaction effects (model 2) the model showed in this case a statistically significant effect ($p < 0.05$). An increase in total variation was explained by 3.8% for Lambrechtsbos A and 5.8% for Lambrechtsbos B, by including the interaction effect.

Several independent variables had a significant impact on the peak flows of the threated catchments. Simple slope analysis was conducted for each of these independent variables in relation to the affected catchments peak flows. The runoff peaks of Bosboukloof displayed a significant interaction ($p < 0.05$) with the runoff peaks of both the affected catchments. Before the fire, for every mm increase in the Bosboukloof runoff peak, Lambrechtsbos A increased by 0.848 mm and Lambrechtsbos B by 0.941 mm. After the fire, a one mm increase in runoff peak from Bosboukloof resulted in 1.243 mm increase for the Lambrechtsbos A runoff peak and 1.331 mm for the Lambrectsbos B runoff peak. This is a 46.58% increase after the fire for Lambrecthsbos A, and 41.44% increase for Lambrecthbos B.

Rainfall (mm) displayed a significant interaction with Lambrectsbos B peak values both before and after the fire. By plotting the rainfall (mm) against the peak flows for all the sub-catchments it was observed that the affected catchments displayed significantly higher peak flow values than the control catchment after the fire.

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 6
RESEARCH CONCLUSION AND DISCUSSION

Different analysis methods were used to establish whether fire had any hydrological impact on a catchment and two sub-catchments, which were affected by fire in March 2015 in the Jonkershoek area. Fifty six per cent of the main catchment was burnt, while the vegetation in the two sub-catchments had been completely burned. The main catchment and sub-catchments were analysed by observing any changes in the long-term streamflow and any characteristic changes in streamflow during rainfall events.

The main catchment had an area of 25 277.7 ha, consisting primarily of indigenous tall mountain fynbos. This catchment, according to the long-term streamflow records alone, was not affected by the fire despite its 56% burned area. After the fire, the monthly average runoff/rainfall ratio actually decreased from 67.13 % to 54.01 %. The decrease is attributed to the decrease in average monthly rainfall from 123.39 mm to 104.41 mm. The literature does indicate that catchments with vegetation of similar type (fynbos) have displayed an increase in total flow after a fire. Scott (1994) discovered a 9.4% increase in total flow during the first year after a fire in the Langrivier catchment (an area of 245.8 ha) and 15.3% for the Swartboskloof catchment. Lindley *et al.* (1988) reported an increase of 15% in total flow during the first year after the fire in the Zachariashoek catchment (an area of 324 ha). Both of these burned catchments (Langrivier and Zachariashoek), however, were significantly smaller than the main catchment in this study, and were completely burned by a fire. From the research reported in Section 2.3.1 it was found that the size of the burned catchment generally has a significant effect on the change in the streamflow responses; where smaller catchments experience a greater increase in streamflow, while larger catchments exhibit a smaller response (e.g. due to more variable extent of burnt area). It is thus understandable that no effect on the long-term streamflow was observed in the large main catchment.

The streamflow responses of the main catchment during rainfall events did show significant changes in characteristics after the March 2015 fire. There were 18 pre- and post-fire rainfall events that displayed characteristics similar to each other. The mean volume of the runoff/rainfall response increased by 6.8% after the fire. The Wilcoxon signed ranked test confirmed that the increase in volume runoff was significant ($p < 0.05$). Scott (1994) discovered a 11% response ratio in the Langrivier catchment in the first year after the fire, which is in line with the response ratio of the main catchment in this study. The mean peak flow increased by 50% after the fire for the main catchment. The result of the Wilcoxon signed ranked test for

Stellenbosch University https://scholar.sun.ac.za

this catchment approached significance ($p = 0.053$), but was, however, not statistically significant ($p > 0.05$). Scott (1994) attained an 8.4% increase in peak daily discharge for the Langrivier catchment and 19% for Swartboskloof catchment. Scott (1994) used the paired catchment method, which meant that he had a greater number of rainfall events before and after the fire for analysis. The mean time to peak value decreased after the fire to 56 minutes, however, this difference was found not to be statistically significant ($p=0.423$).

Two sub-catchments (Lambrechtsbos A and B) were completely burned by the March 2015 fire, and one sub-catchment (Bosboukloof) was only partially (30%) burned. The partially burned sub-catchment was taken as the control catchment, since it consisted of the same vegetation cover (afforested Pinus radiata) as the fully burned catchments, and had similar rainfall.

The long-term streamflow of the affected catchments changed considerably in comparison to the control catchments. Before the fire, the ratio between the control and affected catchments for daily runoff was approximately 1:1, while for the first year after the fire it increased to 1:1.56 for the differences between the runoff of Bosboukloof and Lambrechtsbos A, and 1:1.35 for the differences between Bosboukloof and Lambrechtsbos B. The two-way mixed ANOVA method was used to determine whether there were any statistically significant changes in the long-term streamflow between the control and affected catchments. The method confirmed that there was indeed a significant difference ($p < 0.01$) between the pre- and post-fire streamflow between both the affected catchments and the control catchment. The increase in flows (45% and 50%) within the first year after the fire is within the acceptable range of increase for similar sized catchments from forested vegetation. Lane *et al.* (2006) discovered a 65-94% increase in total flow for two catchments planted with eucalyptus forest, which were 136 ha, and 244 ha in size. In 1987, Bosboukloof was burnt, and Scott (1993) discovered a 12% increase in streamflow within the first year after the fire.

The streamflow responses during rainfall events were analysed by comparing the control catchment's responses with the burned catchments' responses. There was no visible change in the time variables (time to peak, response time) from before to after the fire. Although the mean values of the burned catchments decreased, there was no significant change between the control and affected catchments time variables. This is a similar result to the time to peak value of the main catchment's, which did not deliver any observable change. The literature, however suggests that there should be a reduction in the time variables shown on hydrographs after the fire (Cydzik & Hogue, 2009; Sugihara *et al.*, 2006). Since the sub-catchments are small research catchments it was speculated that the change in the time variables were too small to be observed, and thus insignificant. The main catchment is a larger catchment, but it

Stellenbosch University https://scholar.sun.ac.za

is still relatively small and in a mountainous region where it is difficult to observe significant change in the time variables of hydrographs.

The mean volume runoff for the affected catchments remained approximately the same after the fire in comparison to what they were before the fire; however, the control catchments' volume runoff decreased after the fire event. The difference between the Lambrechtsbos B volume runoff in comparison with that of Bosboukloof, both before and after the fire, was 72.42% and of Lambrechtsbos A in comparison to Bosboukloof was 51.67%.

The paired catchment method displayed that there were no significant interaction variables, which contributed to the predictability of runoff volume due to the fire ($p > 0.05$). Scott (1994), however, had found a 62% increase in storm-flow by applying the same method in the Bosboukloof catchment, and found that fire was a significant interaction term. The reason that the paired catchment model did not, in this case, display any significant improvement in predicting streamflow after including the dummy variable, could be due to the limited number of data points available after the fire (33 rainfall events). Nevertheless the observed increase in mean runoff volumes for the affected catchments still support the findings of Scott (1994).

The peak flow values displayed similar means before and after the fire for the control catchment. The mean peak flow values of both affected catchments', however, increased by 183.33% for Lambrechtsbos B and 116.67% for Lambrechtsbos A, in relation to that of Bosboukloof after the fire.

The same model (paired catchment) was calculated for the runoff peaks, and when the effect of fire was not taken into account (model 1), the independent variables showed a statistically significant ($p < 0.05$) effect on accurately predicting the runoff peaks of the burned catchments. When including the interaction effects (model 2), the model also showed a statistically significant effect ($p < 0.05$) in this case.

Significant predictor terms were found between the peak flow values of the affected catchments and the independent variables. The Lambrechtsbos B peak flow values were significantly correlated with the Bosboukloof peak flow, rainfall duration and rainfall. The Lambrechtsbos A peak flow values were significantly correlated with the Bosboukloof's peak flow and soil moisture API. Scott's 1994 paired catchment method also displayed a significant interaction with fire in terms of the peak flow values. His significant predictor terms were the control catchment's peak flow values and the maximum rainfall intensity.

The results of the analysis confirmed the hypothesis of this study, which was that hydrological changes caused by the fire are linked to the level of soil burn severity. The main catchment, which was fynbos dominated, did not show change in its long-term flow after the fire in

Stellenbosch University https://scholar.sun.ac.za

comparison with that before the fire. The catchment did display changes in runoff volume during rainfall events before and after the fire. The time variable responses and peak flow values accumulated during rainfall events did not display changes between before and after the fire for the main catchment. From Table 2.3 it can be seen that a shrub-like vegetation (fynbos) does not have the ability to reach a high level of heat during a fire event, and therefore of soil burn severity. Therefore, only a moderate soil burn severity was experienced for the main catchment.

In contrast, by observing the effects of fire on the afforested catchments (Lambrechtsbos A and B), it can be seen that fire had a significantly larger effect on the hydrological response of the afforested catchments than it did on the fynbos catchment. Both the long-term streamflow and the peak flow values that were due to rainfall events were statistically-significantly altered by the fire in the afforested catchments. From Table 2.3 it can be seen that a forest-like vegetation, when it burns, has the ability to reach high soil burn severity, which is confirmed by the results in the afforested catchments in comparison to the fynbos catchment, as well as referring back to the results from the same area of Scott's 1994 study.

To conclude, fire has the ability to affect the hydrological response of a catchment. The analysis was of a one-fire event, which had burned catchments with different types of vegetation, which was an ideal situation, because it ensured that the fire on the catchments was subjected to the same climatic conditions, and the vegetation was the only changing factor in this case. Table 6.1 displays a summary of the streamflow changes due to fire for this research study.

Table 6.1: Summary of burned catchments

Characteristic	Main catchment	Lambrechtsbos A	Lambrechtsbos B
Long-term flow change (%)	-13.0*	50.0	45.0
Stormflow volume change (%)	6.8	51.7	72.4
Peak flow change (%)	50.0	116.7	183.3

(* - due to decrease in rainfall)

Stellenbosch University https://scholar.sun.ac.za

CHAPTER 7
FUTURE RESEARCH

The problem with conducting this research is that there are quite a number of factors, which influences the outcome of the results, such as the severity of the fire, vegetation cover and catchment characteristics. There is more in-depth research needed on quantifying these factors in more detail, specifically the effects that different severity fires have on the soil absorption capabilities of different local vegetation covers. Under a controlled environment different vegetation's can be burned and the soil absorption tested. It is important that the research should be conducted on catchment scale and not on plots, since the literature showed that the two delivered significantly different results.

Research should be conducted on more areas with different vegetation cover and catchment characteristics (size and slope). Further data and research from more fire events (not just one) as well as long term monitoring (up to six years) should be compiled. The information can be used to build up an archive of different circumstances, which can then be used to change the infiltration coefficients in the deterministic methods used in practice.

Stellenbosch University https://scholar.sun.ac.za

REFERENCES

Abramson, L., Chennell, M., Eisch, E., Glassco, A. & Holley, T. 2009. Post-fire sedimentation and flood risk potential in the Mission Creek watershed of Santa Barbara. *Management*. 79.

Alexander, M. 1982. Calculating and interpreting forest fire intensities. *Canadian Journal of Botanyt*. 60(4):349-357.

Ali, S., Ghosh, N.C. & Singh, R. 2010. Rainfall–runoff simulation using a normalized antecedent precipitation index. *Hydrological Sciences Journal*. 55(2):266–274.

Anderson, H.W., Hoover, M. & Reinhart, K.G. 1976. *Forests and water: Effects of forest management on floods, sedimentation, and water supply*.

Beschta, R.. 1990. *Effects of fire on water quantity and quality*. J.D. Walstad, S.R. Radosevich, & D.V. Sandberg (eds.).

Bickerton, J. 2012. The fire triangle. *Loss Prevention Bulletin*. 6–11.

Bosch, J.M., Schulze, R.E. & Kruger, F.J. 1984. The effects of fire on water yield.

Bosch, J.M., van Wilgen, B.W. & Bands, D.P. 1986. A model for comparing water yield from fynbos catchments burnt at different intervals. *Water SA*. 12:192–196.

Brodie, R.S. & Hostetler, S. 2005. a Review of Techniques for Analysing Baseflow From Stream Hydrographs. *Components*. 28:1–13. [Online], Available: http://www.connectedwater.gov.au/documents/IAH05_Baseflow.pdf.

Burch, G.J., Moore, I.D. & Burns, J. 1989. Soil hydrophobic effects on infiltration and catchment runoff. *Hydrological Processes*. 3(3):211–222.

Cerdá, A. 1998. Changes in overland flow and infiltration after a rangeland fire in a Mediterranean scrubland. *Hydrological Processes*. 12(7):1031–1042.

Conedera, M., Peter, L., Marxer, P., Forster, F., Rickenmann, D. & Re, L. 2003. Consequences of forest fires on the hydrogeological response of mountain catchments: A case study of the Riale Buffaga, Ticino, Switzerland. *Earth Surface Processes and Landforms*. 28(2):117–129.

Cydzik, K. & Hogue, T.S. 2009. Modeling postfire response and recovery using the hydrologic engineering center hydrologic modeling system (HEC-HMS). *Journal of the American Water Resources Association*. 45(3):702–714.

Debano, L.F. 2000. Water repellency in soils: A historical overview. In Vols 231–232 *Journal of Hydrology*. 4–32.

DeBano, L.F. 1981. *Water repellent soils: a state-of-the-art*.

DeBano, L.F., Neary, D.G. & Ffolliott, P.F. 1998. *Fire's Effects on Ecosystems*. New York (USA): John Wiley & Sons.

Doerr, S.H., Ferreira, A.J.D., Walsh, R.P.D., Shakesby, R.A., Leighton-Boyce, G. & Coelho, C.O.A. 2003. Soil water repellency as a potential parameter in rainfall-runoff modelling: Experimental evidence at point to catchment scales from Portugal. *Hydrological Processes*. 17(2):363–377.

Elliott, J.G., Smith, M.E., Friedel, M.J., Stevens, M.R., Bossong, C.R., Litke, D.W., Parker, R.S., Costello, C., et al. 2004. Analysis and mapping of post-fire hydrologic hazards for the 2002 Hayman, Coal Seam, and Missionary Ridge Wildfires, Colorado. *US Geological Scientific Investigations Report*. 5300:1–109.

Field, A. 2009. *Discovering statistics using SPSS*.

Field, A., Miles, J. & Field, Z. 2013. *Discovering Statistics Using SPSS*. Vol. 81.

Folton, N., Andréassian, V. & Duperray, R. 2015. Hydrological impact of forest-fire from paired-catchment and rainfall – runoff modelling perspectives. *Hydrological Sciences Journal*. 6667(January 2016).

Forest, G.N. 2013. Hydrologic Analyses of Post-Wildfire Conditions. (June).

Frasier, G.W., Weltz, M. & Weltz, L. 1998. Rainfall simulator runoff hydrograph analysis. *Range Manage*. 531–535.

Heggen, R.J. 2001. Normalized Antecedent Precipitation Index. *Journal of Hydrologic Engineering*. 6(October):377–381.

Stellenbosch University https://scholar.sun.ac.za

Higginson, B. & Jarnecke, J. 2007. Salt Creek BAER-2007 Burned Area Emergency Response. *Hydrology Specialist Report*. 11.

Hillel, D. 1980. *Fundamentals of soil physics*.

Jex, G.W., Bleakley, B.H., Hubbell, D.H. & Munro, L.L. 1985. High Humidity-induced Increase in Water Repellency in Some Sandy Soils1. *Soil Sci. Soc. Am. J.* 49(5):1177–1182.

Johansen, M.P., Hakonson, T.E. & Breshears, D.D. 2001. Post-fire runoff and erosion from rainfall simulation: Contrasting forests with shrublands and grasslands. *Hydrological Processes*. 15(15):2953–2965.

Keeley, J.E. 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire*. 18(1):116–126.

Kinoshita, A.M. 2012. Post-fire hydrologic behavior and recovery : Advancing spatial and temporal prediction with an emphasis on remote sensing. UCLA.

Kinoshita, A.M., Hogue, T.S. & Napper, C. 2014. Evaluating Pre- and Post-Fire Peak Discharge Predictions across Western U.S. Watersheds. *Journal of the American Water Resources Association*. 50(6):1540–1557.

Kohler, M.. & Linsley, R.. 1951. Predicting the runoff from storm rainfall. *Weather Bureau Research Paper No. 34*. (September):10.

Lane, P.N.J., Sheridan, G.J. & Noske, P.J. 2006. Changes in sediment loads and discharge from small mountain catchments following wildfire in south eastern Australia. *Journal of Hydrology*. 331(3–4):495–510.

Lavabre, J., Torres, D.S. & Cernesson, F. 1993. Changes in the hydrological response of a small Mediterranean basin a year after a wildfire. *Journal of Hydrology*. 142(1–4):279–299.

Letey, J. 2001. Causes and consequences of fire-induced soil water repellency. *Hydrological Processes*. 15(15):2867–2875.

Lindley, A.J. 1986. Effects of veld burning on water yield. 384–395.

Lindley, A.J., Bosch, J.M. & Van Wyk, D.B. 1988. Changes in water yield after fire in fynbos catchments. *Water SA*. 14:7–12.

Le Maitre, D.C., Kotzee, I.M. & O'Farrell, P.J. 2014. Impacts of land-cover change on the water flow regulation ecosystem service: Invasive alien plants, fire and their policy implications. *Land Use Policy*. 36:171–181.

Miller, M.E., Elliot, W.J., Endsley, K.A., Robichaud, P.R. & Billmire, M. 2014. Rapid response tools and datasets for post-fire erosion modeling: Linking remote sensing and process-based hydrological models to support post-fire remediation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. 40(1):257–263.

Moody, J.A. & Martin, R.G. 2015. Measurements of the initiation of post-wildfire runoff during rainstorms using in situ overland flow detectors. *Earth Surface Processes and Landforms*. 40(8):1043–1056.

Myronidis, D. n.d. an Assessment of Wildland Fire Effect on Storm Hydrograph and Sediment Yield. 1308–1317.

Neary, D.G. 2009. P ost- W ildland f ire D esertification : C an R ehabilitation T reatments M ake a D ifference ? 5(1):129–144.

Parsons, A. 2003. Soil Burn Severity Definitions and Mapping Guidelines BURNED AREA EMERGENCY REHABILITATION (BAER) SOIL BURN SEVERITY DEFINITIONS And MAPPING GUIDELINES DRAFT Soil Burn Severity Definitions and Mapping Guidelines. *Service Region USDA Forest Service Region USDA Forest Service Rocky Mountain Research Station*. 6(6).

Parsons, A., Robichaud, P.R., Lewis, S.A., Napper, C. & Clark, J.T. 2010. Field Guide for Mapping Post-Fire Soil Burn Severity.

Rábade, J.M. & Aragoneses, C. 2008. Social Impact of Large-Scale Forest Fires. 19–22.

Ryan, K. & Noste, N. 1985. Evaluating prescribed fires. *Symposium and Workshop on Wilderness Fire*. 230–238. [Online], Available: http://digitalcommons.usu.edu/barkbeetles/170/.

Stellenbosch University https://scholar.sun.ac.za

Scott, D.F. 1993. The Hydrological Effects of Fire in South-African Mountain Catchments. *Journal of Hydrology*. 150(2–4):409–432.

Scott, D.F. 1994. The hydrological effects of fire in south african catchments. University of Natal.

Scott, D., Pike, R. & Moore, D. 2003. Wildfires and watershed effects in the southern B. C. interior. *Streamline Watershed Management Bulletin*. 7(3):1–4.

Scott, D.F., Prinsloo, F.W., Moses, G., Mehlomakulu, M. & Simmers, A.D.A. 2000. A re-analysis of the South African catchment afforestation experimental data. (810):1–138.

Scott, D.F., Lapp, S. & Hegedus, S.A. 2013. Water Repellent Soils and their Assessment in the Field. *Streamline Watershed Management Bulletin*. 15(2):21–27.

Stoof, C.. 2011. Fire effects on soil and hydrology.

Stoof, C.R., Vervoort, R.W., Iwema, J., van den Elsen, E., Ferreira, a. J.D. & Ritsema, C.J. 2012. Hydrological response of a small catchment burned by experimental fire. *Hydrology and Earth System Sciences*. 16:267–285.

Strydom, T., Rowe, T., Riddell, E., Govender, N. & Lorentz, S. 2014. *Pyrohydrology in African savannas*.

Sugihara, N.G.N.G., van Wagtendonk, J.W., Fites-Kaufmann, J., Fites-Kaufman, J., Wagtendonk, J.W. Van & Fites-Kaufmann, J. 2006. Fire as an ecological process. *Fire in California's Ecosystems*. (1916):58–74. [Online], Available: http://books.google.com/books?hl=en&lr=&id=Fw2twMZE_-oC&oi=fnd&pg=PA57&dq=Fire+as+an+Ecological+Process&ots=l69PV-FRjP&sig=gWbNhv068zAcdTb_5z1ZNPi4Cuo%5Cnhttp://www.werc.usgs.gov/fileHandler.ashx?File=/Lists/Products/Attachments/.

The South African National Roads Agency SOC Ltd. 2013. *Drainage Manual*.

Viessman, W., Lewis, G.L. & Knapp, J.W. 2002. Introduction to hydrology. *Introduction to hydrology*. 780.

De Villiers, J. 2017. *Western Cape wildfires destroy 122 700 hectares*. [Online], Available: http://www.news24.com/SouthAfrica/News/western-cape-wildfires-destroy-122-700-hectares-20170228.

Wagenbrenner, J.W. 2013. Post-fire stream channel processes: changes in runoff rates, sediment delivery across spatial scales, and mitigation effectiveness. Washington State University.

Whelan, R.J. 1995. *The ecology of fire*.

Yochum, S.E. 2015. Wildfire-induced flooding and erosion-potential modeling: examples from Colorado, 2012 and 2013. (Figure 1).

Zégre, N., Skaugset, A.E., Som, N.A., Mcdonnell, J.J. & Ganio, L.M. 2010. In lieu of the paired catchment approach : Hydrologic model change detection at the catchment scale. 46(1):1–20.

Stellenbosch University https://scholar.sun.ac.za

APPENDIX A: COMPARATIVE RAINFALL EVENTS TABLE

On the next page the comparative rainfall events for the main catchment both before and after the fire event are shown in Table A.1.

Table A.1: Comparable rainfall events before and after the fire for the main catchment

Group	Events		Date	Time of start	Time without rain (hours)	Rain event (hours)	Rainfall (mm)	Intensity (mm/h)	API (mm)	Qmax (m^3/s)	Qbase (m^3/s)	Qmax-Qbase (m^3/s)	Qmax-Qbase (mm/h)	Time to Peak	Volume runoff (mm)	%Precipitation/Runoff
1	1	Pre-fire	2014/06/14	6:00:00 AM	85	12	36.98	3.08	71.83	18.9	0.7	18.2	0.52	14:48	9.8	26.41%
		Post-fire	2016/07/25	3:00:00 PM	53	13	42.62	3.00	52.34	7.9	0.8	7.2	0.20	10:24	9.3	21.76%
										11.0	-0.1	11.0	0.31	4:24	0.5	4.66%
	2	Pre-fire	2013/09/02	10:00:00 PM	32	9	22.49	2.50	202.27	6.9	3.1	3.7	0.11	4:24	2.7	12.18%
		Post-fire	2015/07/23	4:00:00 PM	6	10	24.62	2.46	85.01	9.8	2.7	7.1	0.20	4:24	5.2	21.30%
										-2.9	0.5	-3.4	-0.10	0:00	-2.5	-9.12%
	3	Pre-fire	2013/10/30	1:00:00 AM	84	8	12.14	1.52	9.83	0.9	0.3	0.6	0.02	6:12	0.4	3.61%
		Post-fire	2015/07/23	3:00:00 AM	17	7	12.73	1.82	72.28	5.8	1.4	4.4	0.12	4:36	2.7	21.08%
										-4.9	-1.1	-3.8	-0.11	1:36	-2.2	-17.46%
	4	Pre-fire	2014/08/21	4:00:00 AM	5	8	10.20	1.27	49.57	6.0	2.0	4.0	0.11	3:12	2.8	27.41%
		Post-fire	2015/07/23	3:00:00 AM	17	7	12.73	1.82	72.28	5.8	1.4	4.4	0.12	4:36	2.7	21.08%
										0.2	0.6	-0.4	-0.01	1:24	0.1	6.34%
	5	Pre-fire	2011/09/15	4:00:00 AM	31	8	10.87	1.36	21.33	1.6	0.8	0.8	0.02	8:00	0.5	4.72%
		Post-fire	2016/06/30	9:00:00 PM	77	8	11.06	1.38	20.51	5.8	0.6	5.2	0.15	5:48	2.7	23.97%
										-4.3	0.2	-4.4	-0.13	2:12	-2.1	-19.25%
2	6	Pre-fire	2012/03/29	3:00:00 PM	608	18	40.96	2.28	0.00	1.2	0.0	1.2	0.03	16:00	1.6	3.89%
		Post-fire	2015/06/23	6:00:00 PM	158	20	40.93	2.05	0.00	8.7	0.1	8.6	0.25	5:00	9.3	22.66%
										-7.6	-0.1	-7.4	-0.21	11:00	-7.7	-18.77%
	7	Pre-fire	2013/03/08	3:00:00 AM	191	17	39.30	2.31	0.00	3.2	0.0	3.2	0.09	8:36	7.0	17.77%
		Post-fire	2016/08/02	6:00:00 PM	113	18	39.07	2.17	68.75	7.2	1.1	6.1	0.17	5:24	13.8	35.34%
										-4.0	-1.1	-2.9	-0.08	3:12	-6.8	-17.57%
	8	Pre-fire	2012/05/03	2:00:00 AM	51	19	36.37	1.91	45.30	7.1	0.1	7.0	0.20	8:36	12.2	33.45%
		Post-fire	2015/08/03	6:00:00 PM	84	22	36.40	1.65	39.91	8.1	0.8	7.3	0.21	6:12	8.6	23.64%
										-1.0	-0.7	-0.4	-0.01	2:24	3.6	9.81%
	9	Pre-fire	2014/08/26	8:00:00 PM	7	17	30.61	1.80	35.60	14.4	1.6	12.8	0.36	8:36	13.0	42.62%
		Post-fire	2016/04/28	5:00:00 PM	79	21	33.58	1.60	37.85	20.8	0.0	20.8	0.59	13:00	20.0	59.44%
										-6.4	1.6	-8.0	-0.23	4:24	-6.9	-16.82%
	10	Pre-fire	2012/06/24	11:00:00 AM	29	16	28.00	2.16	31.93	10.0	0.2	9.8	0.28	5:12	8.5	30.52%
		Post-fire	2016/07/05	10:00:00 AM	69	20	29.99	1.50	35.21	10.3	0.3	10.0	0.29	13:00	14.6	48.75%
										-0.3	-0.1	-0.2	0.00	7:48	-6.1	-18.23%
4	11	Pre-fire	2013/08/12	4:00:00 PM	2	25	85.40	3.42	52.40	25.7	0.9	24.9	0.71	10:12	31.3	36.69%
		Post-fire	2015/07/17	3:00:00 AM	2	23	78.53	3.41	24.91	39.8	0.1	39.7	1.13	15:12	30.9	39.29%
										-14.1	0.7	-14.8	-0.42	5:00	0.5	-2.60%
	12	Pre-fire	2013/06/24	2:00:00 PM	61	30	44.60	1.49	14.51	8.8	0.5	8.4	0.24	11:48	14.3	32.16%
		Post-fire	2015/06/16	2:00:00 AM	7	33	50.83	1.95	13.32	7.5	0.3	7.2	0.20	8:48	16.5	32.40%
										1.4	0.2	1.2	0.03	3:00	-2.1	-0.23%
	13	Pre-fire	2014/06/03	11:00:00 AM	7	33	23.10	0.70	69.11	7.1	2.6	4.5	0.13	10:36	6.1	26.20%
		Post-fire	2015/08/13	5:00:00 AM	2	25	23.31	0.93	1.50	4.3	0.4	3.9	0.11	10:36	5.6	24.09%
										2.9	2.2	0.7	0.02	0:00	0.4	2.11%
	14	Pre-fire	2013/05/29	4:00:00 PM	28	36	22.48	1.02	43.65	9.9	0.6	9.3	0.26	4:00	11.9	52.71%
		Post-fire	2015/07/11	7:00:00 PM	2	36	27.14	0.75	1.98	2.201	0.024	2.2	0.06	1:00	4.5	16.56%
										7.699	0.576	7.1	0.20	3:00	7.4	36.15%
	15	Pre-fire	2013/08/06	9:00:00 PM	222	44	61.72	1.40	0.00	5.249	0.702	4.5	0.13	50:00	12.9	20.85%
		Post-fire	2015/07/29	8:00:00 AM	101	33	59.40	1.80	47.61	22.923	0.702	22.2	0.63	41:00	25.1	42.28%
										-17.674	0	-17.7	-0.50	9:00	-12.2	-21.43%
	16	Pre-fire	2014/06/03	11:00:00 AM	7	40	52.38	1.31	2.30	13.286	1.627	11.7	0.33	10:00	20.8	39.71%
		Post-fire	2016/07/19	2:00:00 AM	79	53	51.85	0.98	11.15	20.811	0.281	20.5	0.58	6:00	25.9	49.94%
										-7.525	1.346	-8.9	-0.25	4:00	-5.1	-10.22%
	17	Pre-fire	2014/08/27	10:00:00 PM	5	38	46.29	1.22	35.60	17.766	4.383	13.4	0.38	8:48	20.8	44.93%
		Post-fire	2016/06/13	6:00:00 PM	81	45	47.30	1.05	44.26	12.792	0.1	12.7	0.36	10:00	23.5	49.73%
										4.974	4.283	0.7	0.02	1:12	-2.7	-4.79%
	18	Pre-fire	2014/09/17	10:00:00 AM	258	55	55.34	1.01	0.00	4.02	0.241	3.8	0.11	55:00	11.9	21.54%
		Post-fire	2016/06/18	2:00:00 PM	53	36	57.91	1.61	76.89	18.786	0.466	18.3	0.52	39:12	27.2	46.92%
										-14.766	-0.225	-14.5	-0.41	15:48	-15.2	-25.37%

Stellenbosch University https://scholar.sun.ac.za

APPENDIX B: ASSUMTIONS FOR TWO WAY MIXED ANOVA

Testing for outliers

There were a few outliers in both cases, as assessed by examination of residuals for values greater than ±3. Since these outliers represented actual data points, it was decided not to delete these cases from the analysis.

Testing the assumption of normality

The two-way mixed ANOVA assumes that the residuals are approximately normally distributed within each cell of the design. After log transformations were carried out on the dependent variable, residuals were approximately normally distributed, as can be seen from the points in the Normal Q-Q Plots in Figure B.1, Figure B.2 and Figure B.3, which approximately follow the diagonal line. The assumption of normality was thus met.

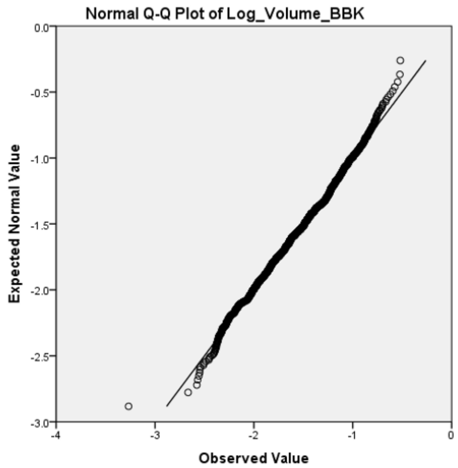


Figure B.1: Normal Q-Q plot Bosboukloof

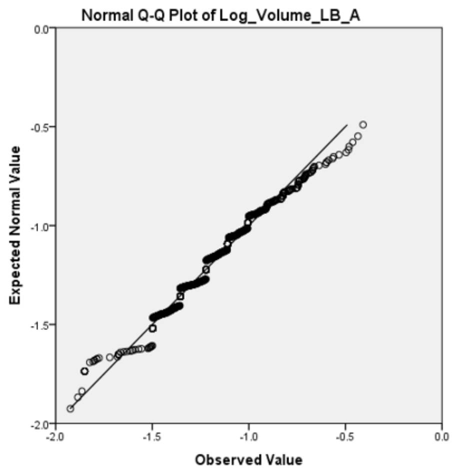


Figure B.2: Normal Q-Q plot Lambrechtsbos A

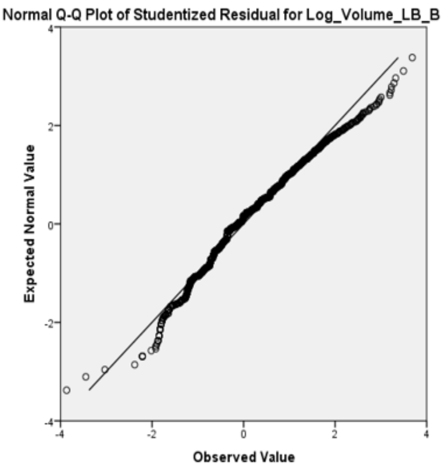


Figure B.3: Normal Q-Q plot Lambrechtsbos B

Stellenbosch University https://scholar.sun.ac.za

Testing the assumption of homogeneity of variances

Levene's test of equality of error variances tests the assumption of homogeneity of variances and the results of this test are presented in the Levene's Test of Equality of Error Variances table, as shown in Table B.1.

Table B.1: Levene's test

Levene's Test of Equality of Error Variances				
	F	df1	df2	p
Log_Runoff_BBK	1.278	1	1709	0.258
Log_Runoff_LB_A	17.527	1	1709	0.000
Log_Runoff_LB_B	5.563	1	1709	0.018

If this test is statistically significant (i.e., $p < .001$), you do not have equal co-variances, but if the test is not statistically significant, you have equal co-variances and you have not violated the assumption of homogeneity of co-variances. As can be seen from the table above, Bosboukloof and Lambrechtsbos B have p greater than 0.001, which indicates that the co-variances are equal for these two catchments. Lambrechtsbos A on the other hand violates the assumption of homogeneity.

Testing the assumption of similar co-variances

The Box's test of equality of covariance matrices is a method for testing whether there are similar co-variances between the control and affected catchments. Table B.2 displays the Box test.

Table B.2: Box's test

Box's Test of Equality of Covariance Matrices		
	BBK & LB_A	BBK & LB_B
Box's M	104.075	6.636
F	34.632	2.208
df1	3.000	3.000
df2	13555064.017	13555064.017
p	0.000	0.085

The Box's test is similar to Levene's test; if this test is statistically significant (i.e., $p < .001$), there are no equal co-variances, but if the test is not statistically significant, there are co-variances and the assumption of homogeneity of co-variances has not been violated. From Table B. it can be seen that the p value for the BBK & LB_A column is smaller than 0.001, which indicates that the co-variances are not equal. The p value for the BBK & LB_B column

Stellenbosch University https://scholar.sun.ac.za

on the other hand is 0.085, which indicates that co-variances are equal and that the assumption of homogeneity of co-variances has not been violated.

Stellenbosch University https://scholar.sun.ac.za

APPENDIX C: ASSUMPTIONS TESTED FOR PAIRED CATCHMENT METHOD

Volume runoff

Testing for linearity

After the variables had been transformed, all independent variables were linearly related to the dependent variable, within each level of the moderator variable, as can be seen from the scatterplots in Figure C.1 for Lambrechtsbos A with the independent variables and Lambrechtsbos B with the independent variables.

Stellenbosch University https://scholar.sun.ac.za

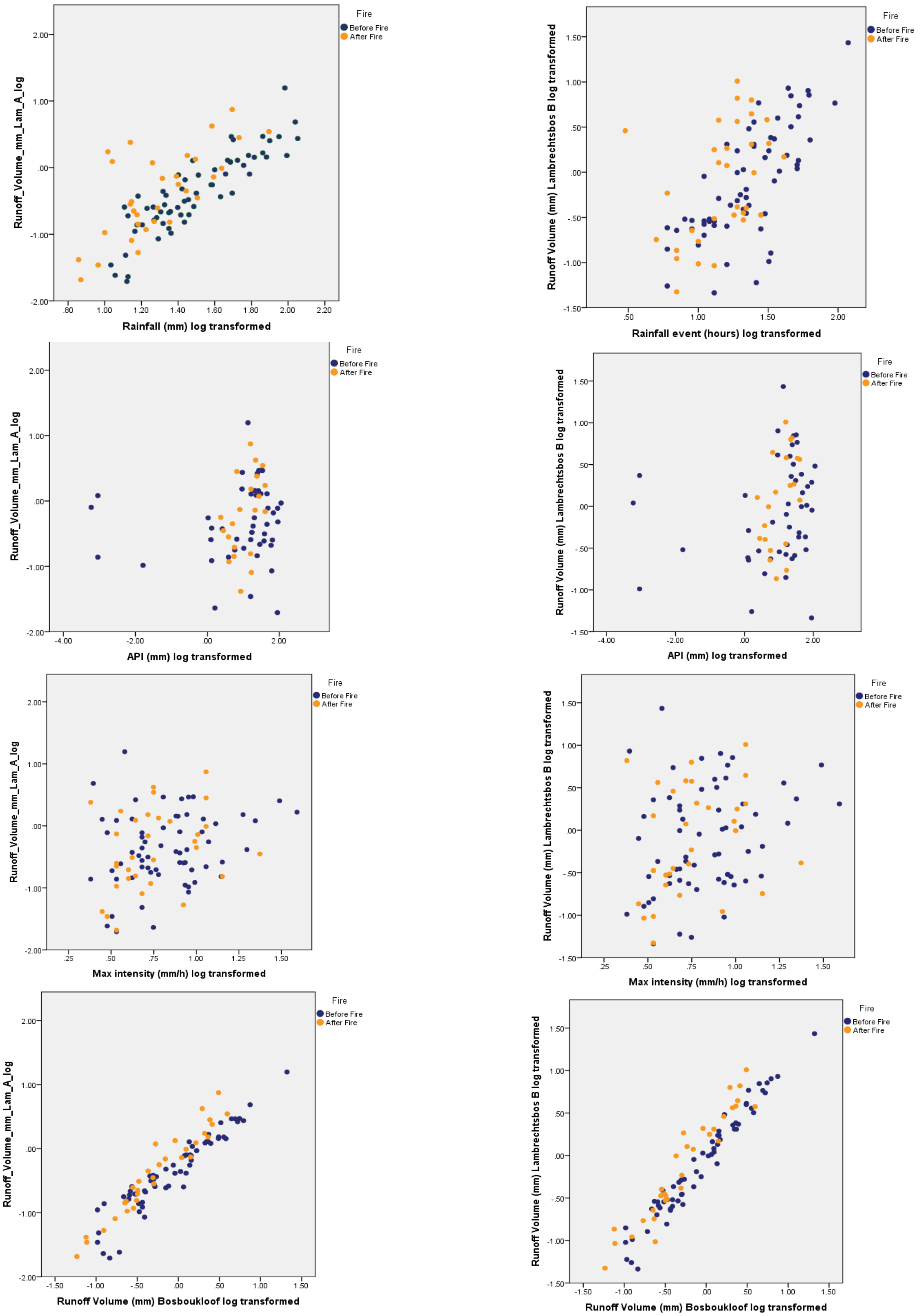


Figure C.1: Testing for linearity volume runoff

Stellenbosch University https://scholar.sun.ac.za

Testing for outliers

Only one outlier was identified for the Lambrechstbos B paired catchment method (2012/10/09), which was also a highly influential value. Lambrechtsbos A, however, did not contain any outliers.

Detecting leverage points

Leverage points were detected by calculating a cut-off value based on the following formula: 3p/n, where p = number of parameters plus the intercept and n = sample size. The cut-off value was 0.375. Thus, any values greater than 0.375 would be considered high leverage values. There were no high leverage values in the data for Lambrechtsbos B, however, a number were detected for Lambrechtsbos A. These values were then checked to detect whether or not they were highly influential values.

Detecting highly influential values

There were two highly influential cases in the dataset, with Cook's Distance value greater than 1. Both of these values were removed from the data set (rainfall event 2015/07/11 and *2012/10/09).*

Testing for homoscedasticity

Figure C.2 and C.3 displays the test for homoscedasticity for both the affected catchments.

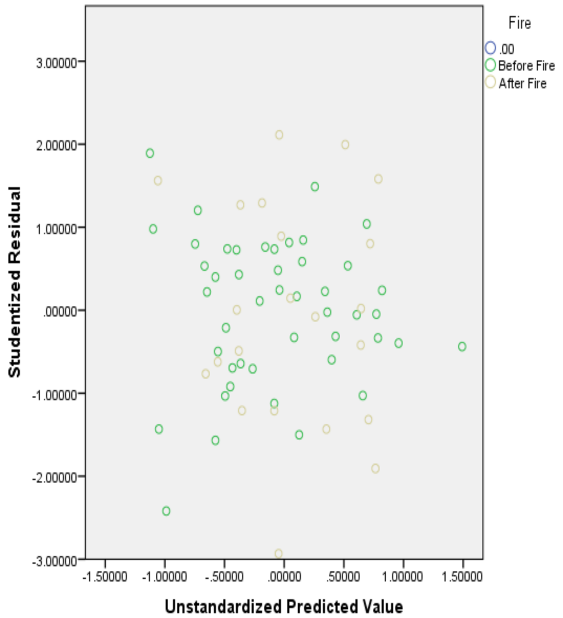


Figure C.2: Homoscedasticity test Lambrechtsbos A and Bosboukloof

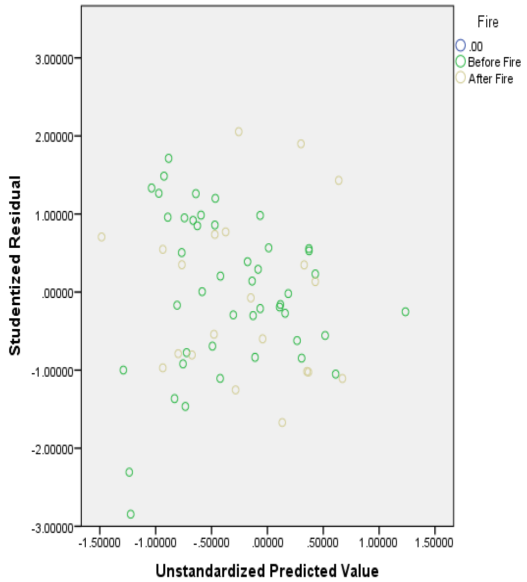


Figure C.3: Homoscedasticity test Lambrechtsbos B and Bosboukloof

Stellenbosch University https://scholar.sun.ac.za

If there is Homoscedasticity, the studentised residuals will be equally spread across the predicted values. Hence, the spread of points in the y-acis should be similar for both groups (i.e. before and a after fire) as you move across the x-axis. The studentized residuals in the scatterplot above does appear randomly scattered. On this basis, it would appear that the assumption of homoscedasticity has been met.

Testing for normality

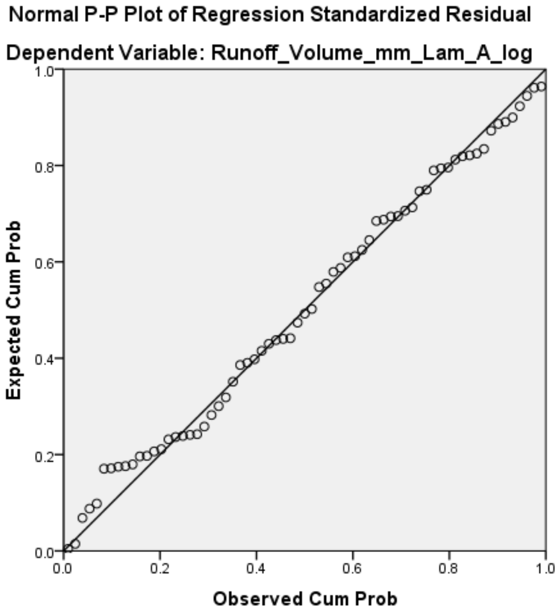


Figure C.4: Testing for normality Lambrechtsbos A

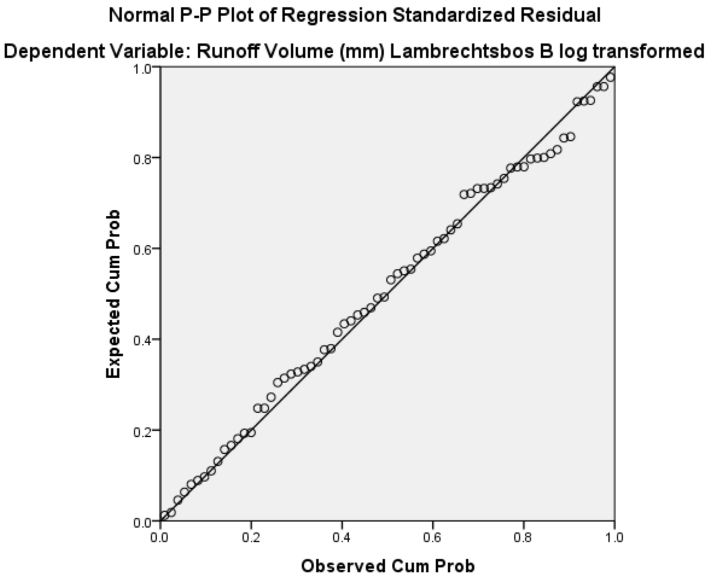


Figure C.5: Testing for normality

From the Normal P-P plot above can be seen that the data was approximately normally distributed.

Peak flows

Testing for linearity

After the variables had been log transformed, all independent variables were linearly related to the dependent variable, within each level of the moderator variable, as can be seen from the scatterplots in Figure C.6.

Stellenbosch University https://scholar.sun.ac.za

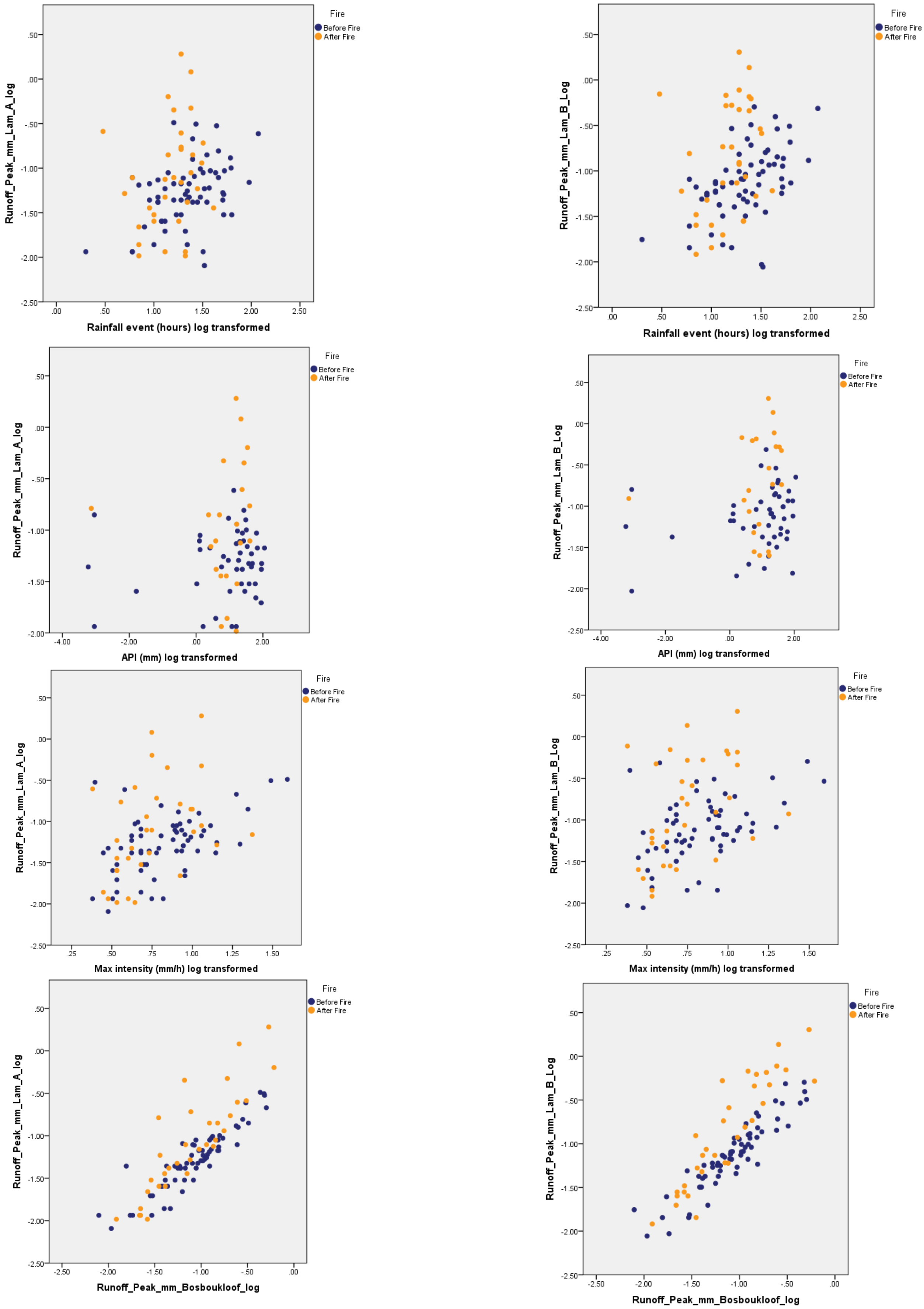


Figure C.6: Testing for Linearity

Stellenbosch University https://scholar.sun.ac.za

Testing for outliers

There was only one outlier in the data. This outlier was not classified as either a high leverage value or a highly influential point, and was therefore not deleted from the analysis.

Detecting leverage points

Leverage points were detected by calculating a cut-off value based on the following formula: 3p/n, where p = number of parameters plus the intercept and n = sample size. The cut-off value was 0.371. Thus, any values greater than 0.371 would be considered high leverage values. There were a number of high leverage points in the data. Notes were made of these to assess if they were outliers or highly influential values as well.

Detecting highly influential values

There was one highly influential case in the dataset, with Cook's Distance values greater than one. This value was also a high leverage value, and it was consequently decided to delete this data point (rainfall event 2015/07/11) from the dataset.

Testing for homoscedasticity

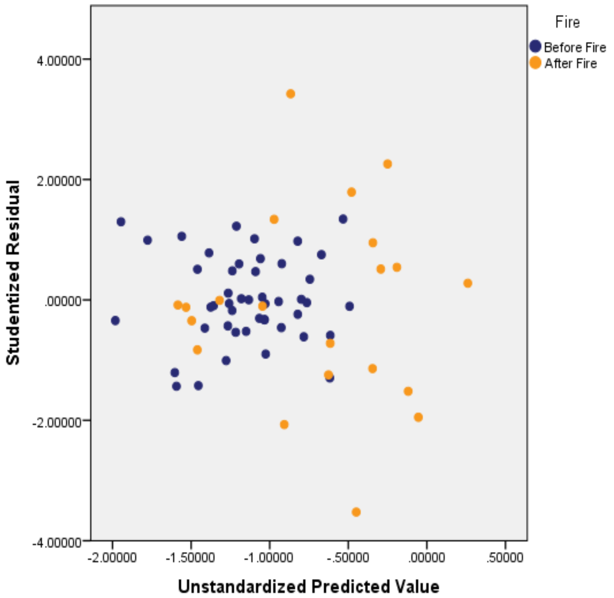


Figure C.7: Testing for homoscedasticity Lambrechtsbos A and Bosboukloof

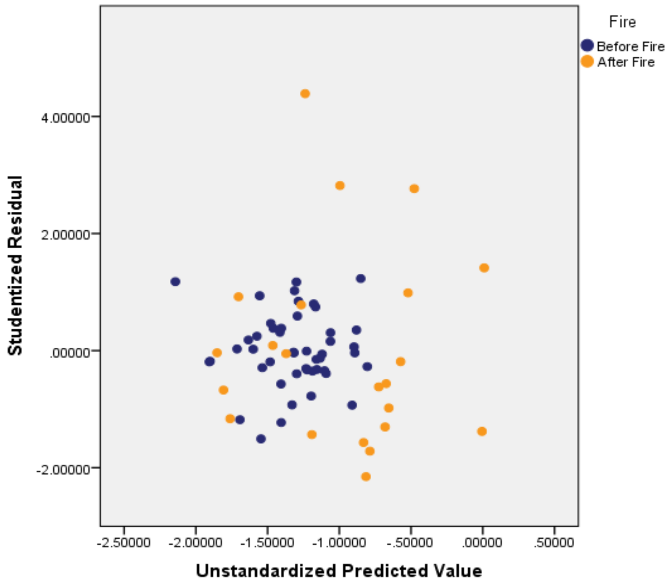


Figure C.8: Testing for homoscedasticity Lambrechtsbos B and Bosboukloof

Stellenbosch University https://scholar.sun.ac.za

If there is homoscedasticity, the studentised residuals will be equally spread across the predicted values. Therefore the spread of points should be similar on the y-axis for both groups (i.e. before and after the fire) as one moves across the x-axis. The studentised residuals in the scatterplot above do appear randomly scattered. On this basis, it would appear that the assumption of homoscedasticity has been met.

Testing for normality

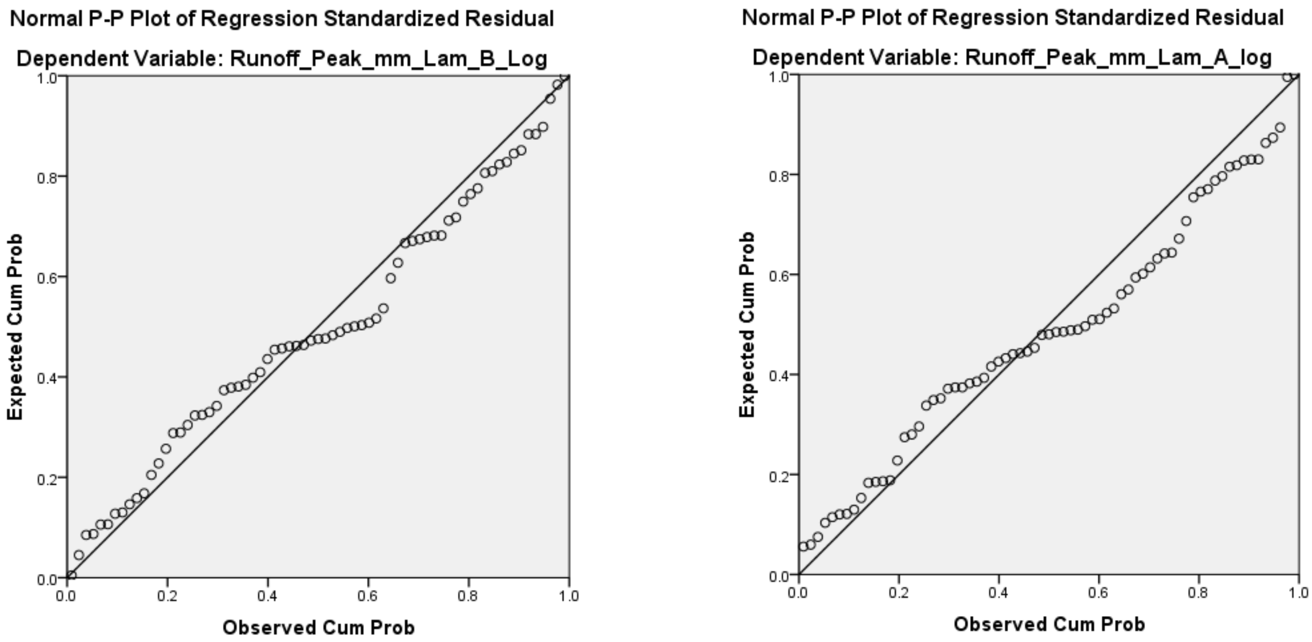


Figure C.9 Testing for normality

From the Normal P-P plot in Figure C.9 it can be seen that the data was approximately normally distribute

Stellenbosch University https://scholar.sun.ac.za

APPENDIX D: MIXED ANOVA ANALYSIS BETWEEN BOSBOUKLOOF AND LAMBRECHTSBOS A

Table D.1: Test of within subjects effects between Bosboukloof and Lambrechtsbos A

Test of Within-Subjects effects	
Type 3 Sum of Squares	2.721
df	1.000
Mean Square	2.721
F	76.565
Significant	0.0012
Partial Eta Squared	0.043

The Significant row in the Table D.1 represents the p-value for the two-way interaction effect in the two-way mixed ANOVA. It can be seen that the p-value for the two-way interaction effect is .00012 (i.e., $p < .01$). This is less than .01 (i.e., it satisfies $p < .01$), which means that there is a statistically significant two-way interaction effect on the runoff between the control and affected catchment. However, the effect size (measure of practical significance) shows only a small effect (Partial eta squared = 0.043). From this effect size, a deduction was made that the difference in runoff between the catchments was statistically significantly different before and after the fire, but that this effect had small practical significance. A run was also made for the simple main effects before and after the fire. Table D.2 displays the before fire effects.

Table D.2: Test of within subjects effects between Bosboukloof and Lambrechtsbos A before fire

Test of Within-Subjects effects	
Type 3 Sum of Squares	67.590
df	1.000
Mean Square	69.590
F	1832.684
Significant	0.0006
Partial Eta Squared	0.595

From the Significant row in Table D.2 it can be seen that there was a statistically significant difference in the runoff (mm) between Bosboukloof and Lambrechtsbos A catchments, before the fire ($p<0.01$). However, due to the large sample size, the statistical significance should be interpreted with caution, and that special attention should be paid to the effect size. From the descriptive statistics in Table D.3 it can be seen that before the fire the mean runoff (mm) for Bosboukloof (1.08 mm) differed from that of Lambrechtsbos A (1.135 mm). This difference is

Stellenbosch University https://scholar.sun.ac.za

confirmed by the effect size statistic in Table D.2 (Partial Eta Squared = 0.595, indicating a large effect).

Table D.3: Descriptive statistics of runoff before fire for the affected (Lambrechtsbos A) and control catchment

Descriptive Statistics					
	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Average volume run-off per day in mm for Bosboukloof	1249	0	7.629	1.079	1.022
Average volume run-off per day in mm for Lambrechtsbos A	1249	0	6.123	1.135	0.653

The same procedure was then completed after the fire (Table D.4).

Table D.4: Test of within subjects effects between Bosboukloof and Lambrechtsbos A after fire

Test of Within-Subjects effects	
Type 3 Sum of Squares	48.125
df	1.001
Mean Square	48.125
F	1519.274
Significant	0.0001
Partial Eta Squared	0.767

From the Significant row in Table D.4 above it can be seen that there was a significant difference in the runoff volume (mm) between the Bosboukloof and Lambrechtsbos A catchments after the fire ($p < 0.01$). The effect size of the difference in runoff volume between the catchments was greater than that shown before the fire (Partial eta squared = 0.767 after the fire compared to 0.595 before the fire). From the descriptive statistics Table D.5 below it can be seen that, after the fire, the mean volume runoff (mm) for Bosboukloof (0.598 mm) was considerably smaller than that of Lambrechtsbos A (0.941 mm), confirming the large effect size found.

Stellenbosch University https://scholar.sun.ac.za

Table D.5: Descriptive Statistics on Runoff after the fire

Descriptive Statistics					
	N	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Average volume run-off per day in mm for Bosboukloof	462	0	3.586	0.598	0.543
Average volume run-off per day in mm for Lambrechtsbos A	462	0	5.759	0.941	0.496

Stellenbosch University https://scholar.sun.ac.za

APPENDIX E: APPLICATION OF THE PAIRED CATCHMENT REGRESSION MODEL

Refer back to Equation 3.5 (Section 3.3.4) the multiple regression model for applying the paired catchment method. The introduction of the dummy variable F, together with the corresponding interaction terms between F and each of the independent variables, enables the evaluation of the Fire event as a moderator of the relationship between each of the independent variables and the dependent variable. A significant moderation effect on the dependent variable is indicated if the null hypothesis (H_0: $\beta_i = 0$) for any interaction term coefficient *i* is rejected. The null hypothesis H_0: $\beta_i = 0$ is tested through the t-test entry of the associated interaction term into the model.

With the dummy variable F coded as F = 0 (pre-fire), and F = 1 (post-fire), the α coefficients ($\alpha_0 - \alpha_5$) show the effects of each of the independent variables on the dependent variable in the pre-fire state. Thus, it represents the simple main effects for each of the independent variables on the dependent variable, before the fire. Any significant moderation effects for Fire on any of the predictor variables were further investigated through looking at the simple main effects for that variable on the dependent variable when F = 0 (pre-fire), and for F = 1 (post-fire).