MAPPING OF FLASH FLOOD POTENTIAL AREAS IN THE WESTERN CAPE (SOUTH AFRICA) USING REMOTE SENSING AND IN SITU DATA

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DISCLAIMER

This document describes work undertaken as part of a programme of study at the Faculty of Geo-Information Science and Earth Observation of the University of Twente. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the Faculty.

ABSTRACT

Flash floods are caused by large amounts of runoff from short duration and high intensity rainfall. Besides high rainfall intensity being the major cause for flash flood, this study considers flash flood as a hydro meteorological problem. Although high rainfall intensity was evaluated as the major cause of flash flooding in different literature, the run off generation as a result of causative rainfall event for flash floods is contributed by hydro geomorphic characteristics of catchments. High spatial and temporal resolution remote sensing rainfall products tested in this study are MPE, CMORPH and TRMM 3B42. The aim of the study was to evaluate flash flood potential areas in the western part of South Africa by integrating remote sensing products of high rainfall intensity, antecedent soil moisture and topographic wetness index based on assigning different weights to each layer. Rainfall has high spatial and temporal variability, thus needs to be quantified at an area scale in real time from remote sensing unlike from sparsely distributed, point gauge network measurements. Western part of South Africa was found to have high spatial variation in topography which results in major differences in received rainfall within areas not far from each other. Satellite rainfall products were statistically compared with local gauge measurements at 3 and 24 hourly time scales. TRMM 3B42 was found to overestimate whereas CMORPH and MPE underestimate extreme rainfall events at both time scales. At 3 hourly time step, bias for TRMM 3B42, MPE and CMORPH was found to be 0.19, -0.96 and -0.97 respectively. However, the accuracy of all satellite rainfall estimates in form of bias, correlation coefficient and RMSE was found to improve with increasing time step of analysis. Satellite products are susceptible to systematic errors; they have to be calibrated and validated with local in situ data before further applications. Cumulative satellite rainfall estimates for two flash flood events that occurred on 12 July 2009 and 11 August 2012 in Berg and Breede catchments respectively were calibrated for bias and systematic errors by using quadratic curve fitting method. Quadratic curve fitting method improves accuracy by lowering bias and RMSE and increasing the correlation coefficient for areal rainfall quantification. RMSE for TRMM 3B42 and MPE for 12 July 2009 in Berg catchment improve from 29.54 mm/3 hours to 8.15 mm/3 hours and 34 to 15.73 mm/3 hours respectively. Corrected satellite rainfall estimates were used to calculate rainfall anomaly using daily climatological satellite rainfall product RFE ARC2 data. Areas of high flash flood potential were found to be associated with high rainfall, antecedent precipitation and topographic wetness index. Although, TRMM 3B42 was found to have better accuracy, the product is not available in near real time but rather at a rolling archive of 3 months therefore, MPE rainfall estimates available in near real time are opted for flash flood events. ASCAT soil moisture observations were found to have low RMSE and MAE of 4.18 m³/m³ and 3.8 respectively when validated with in situ soil moisture measurements. Hydro geo-morphometric catchment properties associated with flash flood potential such as relief ratio, drainage density, basin shape, form factor and bifurcation ratio among others were discussed. Relief ratio was found to be 0.18 for Berg and 0.12 for Breede.

Key words: Topographic Wetness Index, satellite rainfall estimates, gauge comparison, antecedent soil moisture, hydro geomorphic, satellite rainfall estimates, flash flood, in situ and remote sensing.

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LIST OF ACRONYMS

AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observation System
AMSU-B	Advanced Microwave Sounding Unit-B
ASCAT	Advanced Scatterometer
CCD	Cold Cloud Duration
CMORPH	Climate Prediction Centre MORPHing Technique
CoSch	Combined Scheme
DEM	Digital Elevation Model
DMSP	Defence Meteorological Satellite Program
FEWSNET	Famine Early Warning Systems network
GIS	Geographic Information Science
GloVis	Global Visualisation Viewer
GPS	Global Positioning System
GTS	Global Telecommunication Systems
ILWIS	Integrated Land and Water Information System
ISOD	In-situ and Online Data Toolbox
LST	Local Standard Time
MPE	Multi – Sensor Precipitation Estimate
MSG	Meteosat Second Generation
MW	Microwave
NASA	National Aeronautics and Space Administration
NDWI	Normalised Difference Wetness Index
NOAA	National Oceanic and Atmospheric Administration
OI	Optimum Interpolation
PR	Precipitating Radar
RFE ARC2	Rainfall Estimate Africa Rainfall Climatology Version 2
SFD	Single Flow Direction
SRE	Satellite Rainfall Estimate
SRTM	Shuttle Radar Topographic Mission
SSM/I	Special Sensor Microwave Imager
SWI	Soil Wetness Index
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
TWI	Topographic Wetness Index
UTC	Coordinated Universal Time
VIS/IR	Visible Infrared

1. INTRODUCTION

1.1. Background and scene setting

Flash floods are natural disasters which cause significant socio-economic and environmental impacts such as loss of animal and human life, destruction of infrastructure and natural environment. Flash floods are caused by excessive amount of rain falling within a short period of time or massive amount of water suddenly released from rivers or dams (Murray & Ebi, 2012). Borga *et al.* (2011) narrated that flash floods are difficult to predict because they are characterised by quick and intense runoff generation that leads to rapid rise of water levels and discharges reaching to peak within less than one hour to few hours after the onset of the generating storm.

In the past years, there has been an increase in intense storms and difficult to predict weather events such as flash floods around the world due to global warming and climate change (Groisman *et al.*, 2005; Mason *et al.*, 1999). Despite climate change causing a decrease in annual precipitation in most regions of the world, it has triggered the occurrence of extreme rain events such as flash flood events (Mason et al., 1999). de Coning and Poolman (2011) observed that in South Africa, particularly in the Western Cape of the country, there is an alteration of the magnitude, timing and spatial distribution of storms that produce extreme events. Recently, in July 2012, South African Weather Services (SAWS) reported that Cape Town received 70 mm of rain in 2 hours, while Cape Agulhas received 153 mm in 3 hours and 115 mm at Struisbaai in 2 hours on 22 January 2009. These rainfall amounts have triggered devastating flash flood impacts which include damage to shelter and infrastructure in the mentioned areas.¹ Considering these tremendous impacts of flash floods an effective assessment of flash flood potential areas using remote sensing methods is critical in Western Cape of South Africa such as the one proposed in this study.

Accurate areal rainfall field is the starting point for flash flood potential areas mapping followed by hydro morphological processes within a catchment that influence the production of rapid runoff. In this study, the assessment of flash flood potential areas (only those induced by high rainfall intensity) is done using remote sensing products basing on the assumption that flash floods are a hydro meteorological problem in accordance with Adeyewa and Nakamura (2003) and Borga et al. (2011). Although Doswell *et al.* (1996), argued that rainfall intensity is the major triggering factor for flash floods; (Patton & Baker, 1976) argued that a given rainfall event's chances to produce a flash flood are dramatically affected by other factors such as antecedent precipitation, morphometric properties of the basin and the land cover. In simple words it means that for flash floods to occur they should be a combination of high rainfall rate and very efficient runoff production. Efficient runoff is influenced by topography, antecedent soil moisture, land cover and soil properties. Marchi *et al.* (2010) concluded that antecedent soil moisture should be considered also for flash flood potential since it enhances the forecast of a storm event to cause flash flooding. Remote sensing can observe almost all the hydro meteorological ingredients of flash flood frequently, consistently and significantly cheaper.

With the increase in multiple and better quality satellite rainfall products it is important to evaluate the precision and uncertainty of high temporal and spatial satellite rainfall products for the western part of South Africa before opting for a specific application such as flash flood prediction. Satellite rainfall estimates are susceptible to algorithm and regional errors thus they need to be calibrated with less biased gauge measurements for that specific area. Therefore, this study is testing whether the accuracy of areal

¹ http://article.wn.com/view/2012/07/11/Number_of_Cape_flood_victims_rises/

rainfall quantification for flash flood potential areas can be significantly improved by merging high spatial and temporal resolution satellite rainfall products with gauge measurements in the Western Cape of South Africa by using a quadratic regression fit (Crosson *et al.*, 1996). Crosson *et al.* (1996) has applied this method for the matching of the rain gauge and radar reflectivity.

High temporal and spatial resolution satellite rainfall estimates (SRE) algorithms namely Multi-sensor Precipitation Estimate (MPE) (Heinemann & Kerenyi, 2003), Climate Prediction Centre (CPC) morphing technique (CMORPH) (Joyce *et al.*, 2004) and Tropical Rainfall Measuring Mission (TRMM 3B42) (Huffman et al., 2007) are target satellite rainfall products utilised in this study. In spite of these products having been validated and applied in the field of flash floods in many parts of Africa (Adeyewa & Nakamura, 2003; El Bastawesy *et al.*, 2009), they have not been applied in the study area. This study is intending to test their ability as well as their accuracy to detect patterns of high rainfall intensity that may lead to flash floods in the Western Cape of South Africa for two flash flood events that occurred in two different catchments.

There are also other satellite rainfall products namely Tropical Applications of Meteorology using SATellite (TAMSAT) Rainfall Estimate (RFE) and Famine Early Warning Systems Network African Rainfall Estimate Climatology Version 2 (FEWSNET RFEARC2) of coarser temporal resolution (daily and dekadal) but have long term records which are tested in this study. They are going to show climatological occurrence anomaly of flash floods in the study area. The other remotely sensed hydrological parameters for catchments such as soil moisture and topography were computed from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and SRTM Digital Elevation Model (DEM) respectively. Normalised Difference Wetness Index (NDWI) product of VGT4Africa (Baret *et al.*, 2006), is also utilised to show the time series for temporal changes of wetter and drier areas. Furthermore, in order to understand the influence of geomorphological properties to flash flooding, morphometric properties of two catchments are studied in depth and related to their hydrology.

1.2. Research problem

Although flash flood accounts for highest proportion of disasters in the Western Cape of South Africa (Faling *et al.*, 2012) few studies focusing on reduction of the impacts over a river catchment have been done and documented. Knowledge of flash flood variability and distribution in the Western Cape of South Africa using high spatial and temporal resolution satellite data has not been done in the selected catchments. Real time study of extreme rain events, topography and physical characteristics of the catchments in this region using remote sensing is significantly important for the prediction of flash floods to minimise their impacts. Especially, the identification of the potential areas is really critical in the area.

Currently, in South Africa, there are efforts to forecast flash floods using satellites based on convective clouds (de Coning & Poolman, 2011), but not accounting for underlying hydro-meteorological conditions such as soil moisture and geomorphological properties of catchments. Moreover, so far the knowledge of flash flood potential areas using remote sensing in Western Cape of South Africa is still rudimentary. This limitation is attributed to limited or no ground soil moisture measuring stations currently in South Africa and sparse nature of in-situ rainfall data for validation of the satellites observation.

However, although gauges give relatively accurate point measurements of rainfall they are associated or characterised with sampling errors in representing the areal rainfall field for large areas. Moreover, operating gauges is costly, and in most cases are sparsely distributed and not available in remote areas. Borga et al. (2011), have recommended the use of remote sensing as an alternative means for estimating the rainfall field. The need for precise estimation of areal rainfall for flash flood estimation in Western Cape of South Africa is critical. The potential impact of antecedent soil moisture and the

geomorphological properties of catchments using remote sensing derived products form the basis for this research.

Motivated by the recent increasing availability of high temporal and spatial remote sensing data for estimating precipitation and estimating physical land surface characteristics such as soil moisture, this study attempts to obtain a flash flood index by incorporating satellite rainfall data, soil moisture and topography.

1.3. General objective

The main objective of this study is to evaluate the use of remote sensing and in situ data to map flash flood potential areas in selected catchments by integrating precipitation, topographic and soil wetness products

1.3.1. Specific objectives

- To find the relationship between gauge rainfall measurements with high spatial and temporal resolution satellite rainfall products.
- To find the spatial and temporal rainfall variability in the study area using gauges
- To combine gauge measurements with satellite rainfall products
- To use Normalised Difference Wetness Index (NDWI) and Topographic Wetness Index (TWI) to show the temporal and spatial occurrence of wet areas respectively
- To use in-situ soil moisture measurements to validate ASCAT satellite soil moisture derived observations

1.4. Research questions

- How good are the satellite remote sensing rainfall products in estimating rainfall field in flash flood potential areas of the Western Cape of South Africa?
- What is the temporal and spatial variability of extreme rain events in the Western Cape of South Africa?
- Can the merging of gauges and satellite rainfall products improve the accuracy of areal rainfall estimates?
- Can the NDWI product from VGT 4Africa be used to determine the temporal changes in surface wet areas in the Western Cape of South Africa?
- Can TWI, rainfall anomaly estimates and catchment antecedent moisture be integrated to derive flash flood potential areas?
- How accurate are soil moisture satellite derived products in relation to in situ soil moisture measurements in Western Cape of South Africa?
- What are the hydro geomorphic properties of the flash flood potential catchments based on remote sensing data?

1.5. Thesis structure

Chapter 1 gives a general comprehensive overview of the thesis. It consists of the introduction, problem statement, objectives and research questions.

Chapter 2 consists of the literature review relevant to the study such as flash flood, satellite rainfall products as well as the processes involved in the correction of satellite products by using gauge measurements.

Chapter 3 is a detailed outline of the study area as well as the materials and data sets used in the research to answer the research questions and achieve the objectives.

Chapter 4 encompasses all the steps for the research methods which include satellite and gauge data preprocessing and merging of satellite rainfall observations with the gauge measurements. Analysis of gauge measurements is done in chapter 5. Results along with discussions are presented in chapter 6. Finally chapter 7 has the conclusions and recommendations. This thesis structure is outlined in the thesis matrix in Figure 1- 1 below.



Figure 1-1: Thesis matrix for the thesis structure

2. LITERATURE REVIEW

2.1. Concept of flash floods

Jonkman (2005) defines flash floods as floods which are mostly associated with high intensity and shortduration local rainfall which leads to quick inundation. Marchi et al. (2010) distinguished flash floods from a regular flood by concluding that flash flood impacts basins of less than 1000 km² and are associated with short, high intensity rainfall, mainly of convective, frontal or orographic origin. Doswell et al. (1996) goes a step further by listing and explaining what he named 'ingredients' of flash flooding which includes and not limited to heavy precipitation, precipitation rate, storm type and geomorphology as well as the physical state of the catchments such as antecedent soil moisture. Though there are many contributing factors for flash flooding, Doswell et al. (1996) argued that rainfall intensity should be granted as the critical contributing factor. However, Marchi et al. (2010) argued that the study of flash flooding should be based on both hydrology, meteorology and topography and both should be given the same weight. His argument is based on the concept that high rainfall intensity will produce more runoff and the steep slopes will promote efficient and rapid overland flow to low lying areas. Contrastingly flash floods have occurred in low lying and normally dry areas such as urban areas.

Flash flooding has negatively impacted agriculture, environment, social and economic activities in many parts of the world and some regions have been recognised internationally as flash flood prone areas (Marchi et al., 2010). Occurrence and severity of flash flooding is increasing in many parts of the world due to global warming, climate change and degradation of the environment by human activities (Borga et al., 2011) .Due to rapid increase and impacts the study of flash flooding has gained popularity and has been introduced to new techniques and methods such as remote sensing which are going to be elaborated further in the following sub chapters.

2.1.1. Previous flash floods in South Africa

Disastrous flash floods have been occurring in many parts of South Africa such as the Western Cape, Eastern Cape, KwaZulu Natal and Gauteng provinces. Some of the well-known historical disastrous flash flood events in South Africa are:

Port Elizabeth	September 1968
East London	August 1970
Laingsburg (Western Cape)	January 1981
KwaZulu Natal	September 1987
Struisbaai (Western Cape)	January 2005

Flash floods in South Africa are caused by many weather systems such as thunderstorms, cut- off low pressure systems and tropical cyclones. However, in the Western Cape of South Africa flash floods are driven mainly by the cut off low and severe frontal rainfall weather systems that can trigger thunderstorms. Holloway *et al.* (2010) defined cut off low as a mid-latitude cyclone that becomes 'cut-off', or severed, from the main planetary circulation, and spins off independently. Cut-off low is associated with strong atmospheric instability and powerful convection updrafts. The other contributing factors for flash floods are geomorphic properties of the catchments and antecedent precipitation and both can be observed from remote sensing.

2.2. Satellite based rainfall estimation products

Satellite rainfall estimates (RFE) can be divided into two groups namely visible/infrared (VIS/IR) and microwave (MW) based on which portion of the electromagnetic spectrum is used. Satellite sensors estimate rainfall that reaches the ground based on interpretation of the solar radiation that is scattered or emitted from clouds, rainfall particles and earth surface. Levizzani *et al.* (2002) have described in depth remote sensing techniques for rainfall measurements as well as their pros and cons.

The IR (10.5μ m – 12.5μ m) and VIS ($0.4-0.7\mu$ m) techniques are based on the fact that cold cloud tops produce more rainfall as compared to those with warmer tops (Levizzani et al., 2002). IR assume that rain occurs when a certain cloud top temperature is below a selected threshold. On the other hand the visible is based on cloud optical thickness, water phases, particle size, and distribution. The visible has a drawback in that; visible imagery is only usable during the day when the sun is available. Despite the IR/VIS having high spatial and temporal resolution, many researchers have reported that they are biased on the cold cloud shield in a precipitating complex which may be several times larger than the areal coverage of the precipitating area and sometimes with no rainfall directly under the coldest section (Joyce et al., 2004; Levizzani et al., 2002; Vasiloff *et al.*, 2007). Conversely, some cold clouds such as cirrus are nonprecipitating and as well some warm low clouds during frontal processes can as well bring rain. Moreover, they also do not correlate well with rainfall that reaches the surface.

MW sensors suitable for precipitation cover the 1 to 300 GHz range of the electromagnetic spectrum. This range allows MW sensors to observe information about clouds and precipitation since these longer wavelengths are less likely to be scattered by small atmospheric constituents unlike the shorter wavelengths. MW sensors can be either passive or active. Passive sensors record energy emitted by the earth or atmosphere whereas active sensors record the backscatter from the signal that they send. MW sensors are installed on polar orbiting satellites which have smaller swath width and have low temporal resolution. The poor spatial resolution is mainly due to the need for large pixels because of low emissions from the earth's surface since passive microwaves detect natural microwave energy reflected and or emitted from the earth's surface.

MW rainfall algorithms based on high frequency microwave channels such as 85 GHz relate rainfall rates to the resulting brightness temperature depression created in the imagery when ice in clouds has scattered down warm terrestrial radiation (Ferraro, 1997). Whereas those based in the low frequency (Levizzani et al., 2002) "relate rainfall rates to the magnitude of resulting brightness temperature difference over cold areas when water in the clouds emits radiation." However, different radiative characteristics of land and sea such as emissivity make it difficult for MW to estimate rain on land surfaces since land surfaces have high emissivity of 0.7 - 0.9, close to that of precipitation. Nevertheless, Joyce et al. (2004), argued that MW rainfall estimates are much more physically accurate as compared to IR/VIS. MW estimates are based on the observations of raindrops and ice particles, which are the main source of scattering and absorption of upwelling radiation whereas IR/VIS are based on cloud and micro physical properties.

Summary of characteristics, strengths and weaknesses of rainfall measuring techniques have been studied at depth by Vasiloff et al. (2007) as shown in Table 2-1 below. In order to minimise the afore mentioned problems of MW and VIS/IR rainfall estimates and to improve satellite rainfall estimates researchers have ventured in new algorithms that blend or combine observations from TIR/VIS and MW spectral regions of the electromagnetic spectrum. The algorithms used to derive satellite rainfall estimates which are relevant to this study are explained in detail in the following sections.

Table 2-1:	Comparisons	between	rainfall	measurement	techniques,	their	strengths,	weaknesses	and	operational
application	s reproduced fr	om Vasil	off et al.	(2007)						

Sensor	Strengths	Weaknesses	Time- space scales	Applications
Weather radar	-High spatial and temporal resolution -Good areal coverage	-Range effects - Poor coverage in complex terrain -Z _e -R uncertainties -Non meteorological target contamination	-5-10 min -1 km	-Precipitation now casting -Flash flood forecasting -River forecasting (after bias correction) -Land surface modeling (after bias correction)
Geostationary satellites	-Continuous spatial coverage	 Indirect measurement of precipitation Difficulty with non-precipitation clouds 	-15 min - 3 km	-Now casting -Flash flood forecasting -River forecasting (after bias correction) -Land surface modeling (after bias correction)
Polar-orbiting satellite(Passive microwave satellites)	- Continuous spatial coverage	-Poor spatial/temporal resolution - Indirect measurement of precipitation - Difficulty with non-ice bearing clouds over land	-3-6h(6 +satellite constellation) -15 km	-Tropical Rainfall Potential (TraP) -Adjustment of GOES precipitation estimates
Precipitating gauge	-Direct measurement of precipitation	-Non uniform spatial distribution -Latency in real time data transfer -Quality measurement -frozen hydrometeors -Wind effects -Uncallibrated (tipping bucket type in high rain rate)	-10 min – 1 day	-Flash flood forecasting -River forecasting -Land surface modeling -Water supply forecasting Correction of radar and satellite quantitative precipitation estimate (QPE) -Hydro climatological studies -Verification

2.2.1. Tropical Rainfall Measuring Mission (TRMM 3B42)

TRMM is an initiative of the US Space Agency (NASA) and the Japanese Aerospace Exploration Agency (JAXA). The satellite swath cover only the tropical zone, from 50°N to 50° S and has on board VIS/TIR, passive microwave and active microwave sensors. Final TRMM 3B42 product is resampled to a spatial resolution of 0.25 degree. Huffman et al. (2007) described the algorithm for TRMM 3B42 known as TMPA rainfall retrieval in four steps namely: (i) the high quality (HQ) passive microwave (PM) estimates are corrected and merged, (ii) the HQ PM are used to calibrate and create the thermal infrared (TIR) precipitation estimates (iii) high quality PM and TIR estimates are merged and (iv) the data is rescaled to monthly totals and the gauge measurements are used indirectly to adjust the satellite product. The overall steps for the processes of the TRMM 3B42 product are summarised in Figure 2-1.

TRMM 3B42 monthly estimates have been validated over major climatic regions in Africa (Adeyewa & Nakamura, 2003). Adeyewa and Nakamura (2003) concluded that the product over estimates in most parts of Africa and has a large bias in the dry seasons whereas Huffman et al. (2007) observed that the product's accuracy improves at larger time steps. The products inter comparison with the gauges has both overestimated and underestimated summer rainfall diurnal variability over central eastern China (Yuan *et al.*, 2012).



Figure 2-1:Diagram for TMPA reproduced from Huffman *et al.* (2007). Slanted hatched background indicates calibration steps that are different in RT and research products. Square and cross hatched backgrounds indicate final RT and calibration steps, respectively

2.2.2. Multi-sensor Precipitation Estimate (MPE)

MPE is a rain rate product which is derived from the blending of high spatial and temporal resolution IR data of the geostationary satellites operated by EUMETSAT. Meteosat Second Generation (MSG) IR estimates are continuously recalibrated with more accurate rain rate data from polar orbiting microwave satellites (Heinemann & Kerenyi, 2003). IR-images based on IR 10.8 channel from MSG are co-located with passive microwave data from the Special Sensor Microwave/Imager (SSM/I) on Defence Meteorological Satellite Program (DMSP). MPE has high temporal and spatial resolution of 15 minutes and 3 km respectively. The MPE product is generated over regions bounded within 60°S and 60°N of the equator. The images are distributed freely to receiving stations around the world, for example, ITC receives in near real time MSG data and MPE product after every 15 minutes from the Euro bird 9° E satellite via GEONETCast.

MPE product has shown good agreement with ground data on daily time steps at a spatial resolution of 0.25 ° x 0.25 ° over Iberian Peninsula (Heinemann & Kerenyi, 2003) during convective weather systems. However, precipitation from non -convective weather systems such as frontal or orographic rainfall was missed.

2.2.3. Climate Prediction Centre (CPC) morphing method (CMORPH)

CMORPH is a technique that produces complete global precipitation estimates by combining different passive microwave (PM) rainfall estimates from a variety of algorithms (Kummerow *et al.*, 2001). CMORPH algorithm is computed based on propagation in space and time of precipitation estimates derived from low orbital microwave satellite sensors using motion vectors from half hourly thermal infrared (TIR) observations (Joyce et al., 2004). The CMORPH algorithm does not combine PM and IR rain estimates but rather uses IR to transport precipitation by assuming that fewer errors can be generated in precipitation rather than if IR is used to estimate precipitation. At present the CMORPH technique

incorporates precipitation estimates derived from the passive microwaves aboard the DMSP 13, 14 and 15 (SSM/I), the NOAA-15, 16, 17 and 18 (AMSU-B), and AMSR-E and TMI aboard NASA's Aqua and TRMM spacecraft respectively. The technique is not a precipitation algorithm but rather a means by which rainfall is estimated from a combination of existing microwave algorithms. CMORPH is flexible such that it can incorporate and combine any precipitation estimate from passive microwave satellite.

CMORPH provides the rainfall estimates at a higher temporal resolution of 30 minutes and 3 hours at a spatial resolution of 8 km and 0.25° x 0.25° respectively. The product has been validated over Europe (Stampoulis & Anagnostou, 2012), evaluated over Ethiopia for stream flow simulation in a hydrological model of a small mountainous watershed (Bitew *et al.*, 2012).

2.2.4. Other satellite rainfall products used in this study

a) Rainfall Estimator (RFE) Africa Climatology (ARC2)

The Climate Prediction Centre (CPC) of NOAA developed the Rainfall Estimator (RFE) to monitor hydrological trends in support of the humanitarian aid programs of Famine Early Warning Systems Network (FEWS-NET). RFEARC2 product blends local regional gauge with Special Sensor Microwave Imager (SSM/I) and AMSUB satellite rainfall estimates at a high spatial resolution of 0.1° on a near-real time basis to provide daily rainfall estimates over Africa (Novella & Thiaw, 2012). The product covers 40°N to 40° S and 20°W to 55°E. The product has proved to be of better accuracy when it was validated with independent gauges over Ethiopia and compared with CMORPH and TRMM 3B42 (Novella & Thiaw, 2012). The product has been reconstructed to Africa Climatology (ARC2) dataset from 1983-present; hence it is of significant value for the trend of extreme events in Africa at a higher spatial resolution over a longer term.

b) Tropical Applications of Meteorology using Satellite (TAMSAT) dekadal rainfall

TAMSAT dekadal rainfall produced by University of Reading, United Kingdom, estimate is based on the Cold Cloud Duration (CCD) algorithm which transforms linearly the duration of a given pixel temperature lower than the threshold temperature to a given rain rate of 3mm/hr. The product integrates thermal infrared imagery of Meteosat satellite data with local ground based observations over Africa at a ten day and 4 km temporal and spatial resolution. Although the product has been made available since 1983 it has not been widely used in the field of flood forecasting. However, it has been used for agricultural sectors and water resources management because of its coarse temporal resolution. Despite of its low temporal resolution it is going to be used in this study in collaboration with NDWI 10 day product for trend in surface wetness during rainy days.

2.3. Correction of satellite rainfall products using rain gauges

Satellite rainfall estima0tes are susceptible to algorithm, sampling and orbital errors (Chiang *et al.*, 2007). Therefore, they need to be corrected for such errors regionally or locally especially in areas where spatial variability of rainfall is mainly due to orographic effects. Although, there are many different methods that can be used to correct satellite rainfall estimates; Grimes *et al.* (1999) commented that the most effective way of removing quantitative satellite biases and errors is by bringing the satellite rainfall estimates values closer to rain gauge values. This method is based on the assumption that gauge measurements have insignificant errors. This reasoning has also been adopted in this study.

Grimes et al. (1999) blended and Chiang et al. (2007) bias corrected satellite rainfall estimates using gauge measurements in their studies. Moreover, Grimes et al. (1999) merged satellite observations with rain gauges by weighing them basing on the uncertainty given by their respective estimation variance. Chiang et al. (2007) use the Optimum Interpolation (OI) technique to merge satellites and gauge data over China.

The gauge observations were used to modify the first guess for CMORPH estimates. Vila *et al.* (2009) statistically evaluate combined daily gauge observations with TRMM 3B42 rainfall estimates over continental South America by using a procedure they named Combined scheme (CoSch) technique. They concluded that the CoSch procedure can correct satellite rainfall estimates such that when they are compared with gauges, their correlation improve. CoSch technique is an easy process based on reduction of satellite bias by using a combination of additive and multiplicative bias correction procedures based on gauge measurements (Vila et al., 2009).

2.4. Previous and ongoing studies on flash flood and satellite rainfall estimates

In order to compensate the problems of point rainfall estimation using rain gauges, mentioned in Table 2-1, researchers have shifted to the use of satellite rainfall products. Satellite rainfall estimates offer a complete rainfall field as compared to gauges. Even if gauge measurements are interpolated they offer a uniform rainfall field of which rainfall has a high spatial and temporal variability (de Coning & Poolman, 2011). Moreover, the use of satellite derived precipitation allows the identification of extreme rainfall events both in spatial extent and magnitude (Asante *et al.*, 2007). Nevertheless, Grimes et al. (1999) argued that satellite based precipitation estimates should not replace gauge measurements but rather as a compliment to the rainfall field.

Several studies used remotely sensed data as inputs in hydrologic models to estimate stream flow for flash flood events. Sanyal and Lu (2004) did a flash flood management over the Monsoon Asia by estimating flood depth using a digital elevation model (DEM). In the study of Sanyal and Lu (2004), they concluded that remote sensing and Geographic Information System (GIS) can be used as the best tool for flash flood management in developing countries. They derived Topographic Wetness Index according to Beven and Kirkby (1979) from a DEM to measure the depth of flash flooding.

Asante et al. (2007) developed a flood monitoring for the Limpopo river basin by parameterising the Geospatial Streamflow Model (GeoSFM) with remote sensed data and in situ data. In addition, satellite rainfall data was found to be of beneficial value to hydrologists and water managers in their decision processes for monitoring as well as forecasting extreme flood events (Asante et al., 2007).

South African Flash Flood Guidance (SAFFG) system is currently utilising hourly satellite rainfall accumulations from the Hydroestimator algorithm. de Coning and Poolman (2011) argued that the Hydroestimator does not represent accurately the areal rainfall field in Western Cape of South Africa. Furthermore, it overestimates on very short time scale and does not perform well for cool season and stratiform rainfall which occurs in the Western Cape of South Africa especially during the flash flood periods. Therefore, they suggested the improvement on the satellite rainfall estimates that can be input into the model.

There are also some on-going projects such as SERVIR (2009) that utilises remote sensing rainfall estimates for flood forecast mapping in different parts of the world. SERVIR project is utilising TRMM 3B42RT rainfall product to develop an expected flood depth map for Africa every 3 hours at 0.25 degree spatial resolution. There is also a web based system in Southern Africa namely the Southern African Regional Flash Flood Guidance (SARFFG) project, which highly depend on satellite rainfall estimates to forecast the catchments that have the possibility of flash flooding. This project is a collaboration of meteorologists, hydrologists and disaster managers of seven countries of Southern Africa.

2.5. Hydrogeomorphic controls for flash flooding

Hydro geomorphic properties of catchments has been known to influence flash flood potential in catchments due to combination of two main mechanisms; orographic effects increasing precipitation occurrence and relief promoting runoff (Marchi et al., 2010). The application of hydro geomorphic

properties of catchments to flash flood potential has been done in many parts of the world and documented well in literature (Beven & Kirkby, 1979; Horton, 1945; Marchi et al., 2010; Patton & Baker, 1976; Schumm, 1956). These have been achieved using traditional methods such as field observations, topographic maps and alternatively the new and improved approach of remote sensing and Digital Elevation Models (DEM).

The hydro geomorphic properties that influence flash flood potential include and are not limited to drainage density, topographic wetness index, drainage area, bifurcation ratio, and stream magnitude and relief ratio. Patton and Baker (1976) concluded that high potential areas for flash flooding potential tend to have higher values of relief ratio, drainage density, stream slope and ruggedness. The combination of high drainage density, relief ratio, stream slope and low bifurcation ratio might result in higher flood peaks for an equivalent rainfall input than for vice versa because these factors promote rapid generation of runoff. This is so because relief promotes flow concentration along drainage lines, resulting in high unit discharges over a short period of time. Though heavy convective rainfall can also occur in flat areas, the resultant effective rainfall lacks the kinematic component, which characterizes the propagation and hazard potential of flash floods (Marchi et al., 2010). Some of the morphometric properties that are relevant to this study as well as their definitions are presented in Table 2-2 below.

The morphometric properties have been used by Marchi et al. (2010) to explain the characteristics of catchments that have experienced flash floods in Europe. Their study was mainly focused on two specific morphological relationships namely catchment steepness to catchment size, and channel length to catchment size. The steepness of the catchment is evaluated in terms of relief ratio, which is the ratio of the catchment total relief to the length of the longest flow path catchment stream. Total relief is calculated as the difference between the highest points in the catchment to the lowest point in the catchment.

Drainage area as well as catchment size have significant impact to catchment's functions especially quantity of runoff generation (Gregory, 1973). However, Marchi et al. (2010) in their study found that drainage area correlated well with both frequent runoff events of low magnitude and infrequent events of high magnitude. The reasoning behind drainage area and flash flood is that runoff starting from upstream of a larger catchment takes longer travel time to reach the outlet whereas that one for the small drainage area reaches the outlet quickly. On another point of view, flash flood events are associated with convective rainfall which usually covers small catchments.

Horton (1945) added stream slope and drainage density to the morphometric properties that initiates flash flood. Stream slope increases the flow velocity whereas drainage density is a factor of relief, rainfall and infiltration capacity which promotes runoff generation. However, Patton and Baker (1976) describes drainage density as a measure of basin efficiency to remove excess precipitation inputs such as runoff.

Category	Morphometric	Formula	References
	Parameter		
	Catchment area (A)	A = Map scale x counted pixels (km ²)	Schumm (1956)
	Stream order	N _u = Hierarchical ordering	Strahler (1956)
	Bifurcation ratio (R _b)	$R_{b} = N_{i} / (N_{i} + 1)$	Horton (1945)
		N _i =Total no. of stream segments of order 'i'	
	Total streams	$\sum N_u$ where $N_u =$ Stream number	Horton (1945)
Area	Drainage density (D _d)	$D_d = L_i / A$	Horton (1945)
mea	Stream frequency (Fs)	$F_s = N / A$	Horton (1945)
	Circularity ratio (R _c)	$R_c = 4\pi A/P^2$	Miller (1953)
	Elongation ratio (Re)	Re = $(2/L_b)/(A/\pi)^{0.5}$	Schumm (1956)
	Form factor ratio(R _f)	$R_f = A/(L_b)^2$	Horton (1945)
	Stream frequency (S_f)	$S_f = \frac{N_i + N_{i+1} + N_{i+2} + N_{i+n}}{A}$	Horton (1945)
	Catchment length	The straight line from the catchment outlet to	Horton (1945)
	Total stream longth	Total length of all the streams in the catchment	Horton (1045)
	Average stream length	Total stream length	Strahler (1956)
Linear	(SL _w)	$SL_v = \frac{10tut stream tengen}{Number of streams}$	Strainer (1750)
			II. (1045)
	Length of longest path	The length of the major drainage line	Horton (1945)
Doliof	Relief ratio (R _r)	$R_r = \frac{(Highest elevation - Lowest elevation)}{(Highest elevation)}$	Schumm (1956)
Kellel		(Length of longest stream)	

Table 2-2: Morphometric parameters, formulas and their references

Where; A=Area of the catchment (km²), L_b=Length of the longest stream (m), N= number of streams,

 L_i = Length of streams of order 'i', P= Catchment perimeter and N_i = number of streams in order 1

2.6. Antecedent soil moisture and flash flood

Antecedent soil saturation conditions have contributed to flash flooding events in European catchments (Marchi et al., 2010). This is because the runoff coefficient has a positive correlation with initial soil moisture. This means that high antecedent soil moisture will result in high run off generation. In his conclusions Marchi et al. (2010) mentioned need for consideration of antecedent soil moisture in flash flood forecasting. Previously, antecedent soil moisture was determined using traditional methods which are time consuming and costly especially over large areas.

The advances in microwave remote sensing have resulted in the use of satellites such as ASCAT on board of METOP A/B to derive surface soil moisture. It derives surface soil moisture by measuring the backscatter pulse which is strongly influenced by soil moisture, since the soil moisture dielectric constant increases with increasing soil moisture content. ASCAT soil moisture is retrieved at a depth of less than 5 cm based on the TU-Wien algorithm for change detection corrected for the seasonal influence of vegetation at the incidence angle of 40° (Bartalis *et al.*, 2008). Time series of soil moisture are processed to relative units ranging from 0 (dry) to 100 (saturated). Satellite soil moisture products from ASCAT and AMSR-E have been found to have high correlations with in situ measurements (Brocca *et al.*, 2011).

The advances in remote sensing have resulted in the introduction of monitoring indices such as Normalised Difference Wetness Index (NDWI) to enhance features of interest and suppress other features (McFeeters, 1996). NDWI is based on the evaluation of the spectral signature in the near and mid infrared portions of the electromagnetic spectrum. In this range the water absorb almost all incident radiant flux while the land surface reflects significant amount. Thus wet surfaces can be easily recognised and dry surfaces suppressed. NDWI can be used to show the magnitude as well as temporal and spatial variability of wet (NDWI>0) and dry (NDWI<0) areas. In this study the SPOT-VEGETATION channels of near infrared and short wave infrared are used to derive the NDWI because of its near infrared band that is very sensitive to soil moisture. NDWI has proved to show seasonal pattern of rainfall and has shown positive correlation with rainfall. (Xiao *et al.*, 2002). It is calculated as follows;

NDWI = $\frac{Near InfraRed - Short Wave Infra Red}{Near Infra Red + Short Wave Infra Red}$

Where the near infrared and shortwave infrared refers to the range of 780 nm and 1580nm respectively.

Xiao et al. (2002) concluded that SPOT-VEGETATION NDWI can be used as a tool for detecting flooding based on their study over China in rice fields. Thus this product is also going to show the temporal and spatial trends in surface soil moisture over the Western Cape of South Africa but rather at a coarser temporal resolution (dekadal).

3. STUDY AREA AND DATA SETS

3.1. Geographic location of the study area

The study was done in the Western Cape of South Africa (Figure 3-1), with total catchment area coverage of about 14 000 km². In this study, focus is on the catchments namely Berg and Breede bounded by 32°50 ' - 34°10' S and 18° 30'- 20⁰ 30' E. Berg river flows south to north-west and Breede river flows from north west to south east. Western Cape of South Africa is a coastal area surrounded by Indian Ocean on the south east and South Atlantic Ocean on the west.



Figure 3-1: Study area, rainfall stations, stream gauges, and Berg and Breede catchments at outlet G1H075 and H7H006 respectively.

3.1.1. Climate and topography

The Western Cape of South Africa is characterised by steep gradients in both altitude (Figure 3-1) and precipitation (Figure 3-2). Mountainous areas have elevation of about 2000 metres above sea level and they can receive mean annual precipitation in excess of 3000 mm whereas low lying areas of about 40m receive mean annual precipitation of less than 200 mm (Bugan *et al.*, 2012). Spatial rainfall variability in Berg catchment is clearly seen in Figure 3-2. The upper part of the catchment, Somerset West area is bounded by Hottentots Holland Mountains receives annual average rainfall of greater than 1 500 mm whereas areas in less than 50 km from mountain ranges such as Kraaifontein receive half the annual average rainfall.

Furthermore, Western Cape of South Africa has diverse climatic conditions due to the meeting of the cold Atlantic Ocean and the warmer Indian Ocean along the coast of the Western Cape Province. The ocean waters contribute to the formation of "cut off lows" that brings convective rainfall in winter months as from mid-April to early September. Western Cape of South Africa has a Mediterranean climate with cold wet winters and hot dry summers. Bugan et al. (2012) described mean annual air temperature within the range of 3.5 °C and 31°C, with maximum in December and minimum in July. Western Cape of South Africa is well known for its all year south –easterly or north-westerly wind directions.



Figure 3-2: Annual average rainfall gradients over Berg catchment. Source, DWA²

3.1.2. Land use and land cover

The catchments in the study area are characterised by heterogeneous land use and land cover (Figure 3-2). Most of the areas surrounding the catchments especially the Breede catchment (Figure 3-2), are covered by crops, pasture, vineyards and sparse vegetation. The vegetation type ranges from steppe, bush-grass savannah to succulent Karoo shrub lands. The catchments are also surrounded by cities as well as the informal settlements.



Figure 3-3: Berg and Breede catchments a) Land use land cover and b) Soil type³.

² http://www.dwaf.gov.za/Documents/Other/CMA/Berg/BergCMAJul07.pdf

³ <u>http://www.fao.org/geonetwork</u>

3.1.3. Geology and soil properties

Geology of the Western Cape of South Africa shows minimal variation. It is dominated by Table Mountain Group sandstone in the high elevation areas and Malmesbury shale in the mid to low-elevation parts (Dingle, 1973). Meadows and Hoffman (2003), described the soil characteristics in the study area as poorly developed, relatively shallow, brownish sandy loam soils. Bugan et al. (2012) observed that the soil water-holding capacity ranges between 20 and 40 %, but can be up to 80 % in the lower areas of the catchments. Soil drainage is poor mainly due to the low hydraulic conductivity of the semi- weathered Malmesbury shale throughout the study area catchments, and decreases to the least in the lower reaches.

3.1.4. Economic activities

Intensive irrigation of grapes, wheat, deciduous citrus fruits, fisheries, forestry, financial, business services and extensive commercial grazing are the most important economic activities of the Western Cape of South Africa. These activities add a significant contribution of 34 % to the gross domestic product (GDP) of South Africa (Statistics South Africa, 2007).

3.2. Data sets and materials

The data sets used in the research are divided into three classes' namely secondary data (collected from relevant authorities), primary data (in-situ measurements and questionnaires) and relevant satellite products.

3.2.1. Secondary in-situ observation data

Ground based rainfall measurements were obtained from the South African Weather services (SAWS) and Agricultural Research Council of South Africa (ARC). SAWS and ARC measure rainfall depth using a tipping bucket and recordings are done automatically by use of Automatic Weather Services (AWS). Tipping bucket gauges can detect a minimum amount of 0.2 mm/hr. The operational principle of a tipping bucket is that falling water is collected into a fixed sized bucket that tips and drains when it is full. SAWS and ARC use tipping bucket rain gauge shown in Figure 3-3. The rain gauges are located away from obstacles such as trees and buildings to improve the accuracy of the rainfall measured at the gauges. The rain gauges are put firmly on the ground to reduce the shaking of gauges by strong winds.



Figure 3-4: Tipping bucket rain gauge used by SAWS and ARC

Department of Water Affairs of South Africa (DWAS) provided hourly stream flow data from 10 river gauges located on the main rivers of Berg and Breede. The stations have continuous data from as late as 1930 but only the data from 2008 to 2012 was considered in this research. The names and geographical

location of the stream gauge stations are shown in Table 3-1 below and their locations are plotted in Figure 3-1.

Gauge name	Latitude	Longitude	Gauge name	Latitude	Longitude
H1H003	33°22'50" S	19°18'06" E	G1H020	33°42'28"S	18°59'27"E
H1H006	33°25'18" S	19°16'01" E	G1H075	33°01'26"S	18°47'18"E
H4H017	33°49'05"S	19°41'35"E	G1H076	33°57'21"S	19°04 '22'' E
H5H004	33°53'52"S	20°00'42"E	G1H077	33°54'18"S	19°03'17"E
H7H006	34°04'03"S	20°24'20"E	G1H079	33°20'03"S	18°58'04''E

Table 3-1: Stream flow gauging stations in the study area

3.2.2. Field measured data

In situ data sets comprises of the volumetric and gravimetric soil moisture measurement were collected during the fieldwork in Western Cape Province, South Africa. Soil moisture measurements were done using a theta probe and soil measuring rings (Figure 3-5). Theta probes measure volumetric soil water content (m³m⁻³) based on the apparent water dielectric constant (Gaskin & Miller, 1996). Theta probe was chosen as the soil moisture measuring instrument in this study because it is "simple and quick or spot measurements can be obtained, has high accuracy of about 1 % when calibrated well, performs well in most soil types and it is handy and portable size" (Gaskin & Miller, 1996).

Sampling sites were chosen based on accessibility of the areas as well as the experience of flash floods in these areas. A desk study for the area was done to find the location of the sampling sites using the Google Earth imagery of 9 May 2012 together with maps for flash flood risk areas from City of Cape Town. Data were collected at grass, pasture, vineyards and shrub area. Geographical locations of sampling points were collected using the Global Positioning System (GPS) at 4 metres accuracy. After selecting sampling areas, the areas were subjectively divided into 200m by 200m transects. A total of 15 transects were sampled over four days and in each transect at most 20 points were sampled with a theta probe and concurrently samples were collected using soil rings.

Twenty sampling measurements from each transect were averaged using arithmetic mean and finally the average was considered as the value for that transect. The points were plotted on a scatter plot and outliers were removed from the sampling group for data consistency. Outliers were chosen as the points with very high values and very low errors when compared with other points. Thirty samples were collected from the core samples and put in zip lock plastics to prevent gain or loss of soil moisture. Samples were taken to the laboratory for gravimetric soil moisture measurement analysis. Gravimetric measurements were compared with theta probe measurements to assess accuracy of theta probe samples. Volumetric soil moisture was calculated using equation 3.2 below. The soil was oven dried at a temperature of 105 °C until there is no more change in weight. The drying and measurement of soil moisture was done at the University of the Western Cape.

$$Moisture \ content \ (\%) = \left(\frac{collected \ soil \ sample \ (gram) - oven \ dried \ soil \ (gram)}{dry \ soil \ weight}\right) \times 100$$
[3.2]



Figure 3-5: Fieldwork pictures showing how measurements were done in (a) and (b) and areas affected by flash floods (c) and (d)

3.2.3. Interviews of relevant authority and community

Residents who have witnessed flash floods in the selected residential areas of the Cape Flats such as Khayelitsha, Mitchell's Plain and Cross Roads were interviewed. The questionnaire provided as Appendix 1 was designed to get an overview of the areas that experience flash floods and if really flash floods occur in the area as well as the significance of the impacts to the local community. The City of Cape Town Department of Risk and Disaster Management was interviewed about information for the areas that are at risk of flash flooding and what they think are the major contributing factors for the flash floods in those areas.

3.3. Remote sensing data products

Satellite data products used in this research are shown in Table 3-2 below. In depth description of satellite rainfall products is presented in chapter 2. Three satellite rainfall products were selected regarding their high spatial and temporal resolution as well as their coverage as shown in (Table 3-2). Digital Elevation Model (DEM) used for this study was pre-processed for missing values and mosaicked to 5 ° by 5 ° tiles at a horizontal resolution of about 90m (3 arc second) at the equator by the product provider. The product has been compiled by Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI). It is an open access data depository and data was downloaded via the ILWIS In-Situ and Online Data (ISOD) toolbox. DEM was used for the extraction of catchments, morphometric properties of the catchments, drainage network and Topographic Wetness Index (TWI) as explained in following chapters.

Advanced Scatterometer (ASCAT) on board METOP-A satellite derived soil moisture estimates were validated with ground soil moisture measurements. ASCAT sensor estimates soil moisture based on C band at a spatial resolution of 25 km resampled to 12.5 km resolution. ASCAT soil moisture estimates product has been reported in literature to have a high correlation with in-situ measurements (Brocca et al., 2011). Unfortunately, the product could not be used to show time series of soil moisture before flash flood events because it has poor spatial coverage for the study area well. Instead, it was replaced with passive microwave Tropical Measuring Mission (TRMM) Microwave Imager (TMI) surface soil moisture

product. TMI retrieves volumetric soil moisture based on the X-band using the forward radiative transfer model namely Land Parameter Retrieval Model (LPRM) (Owe *et al.*, 2001). TMI has night and day over pass products at a spatial resolution of 0.25°.

Product	Properties	Details
Meteosat Second	Spatial resolution	3 Km (Global)
Generation (Derived	Temporal resolution	15 minutes
MPE)	Source (URL)	http://www.eumetsat.int/Home/Main/DataProducts/index.htm?l=en
Global CMORPH	Spatial resolution	0.25 X 0.25 degree (Global)
	Temporal resolution	3 hours (December 2002 to present)
	Source(URL)	<pre>ftp://ftp.cpc.ncep.noaa.gov/precip/global_CMORPH/3-</pre>
		hourly_025deg/
TRMM 3B42	Spatial resolution	0.25 X 0.25 degree (50°N-50°S)
	Temporal resolution	3 hours (January 1998 to present)
	Source (URL)	http://disc2.nascom.nasa.gov/opendap/TRMM_L3/TRMM_3B42/
SRTM (DEM)	Spatial resolution	90 m
	Source (URL)	http://srtm.csi.cgiar.org/
	-	
Soil moisture	Spatial resolution	12.5 Km
(ASCAT)	Temporal resolution	Approximately 1.5 days
	Source (URL)	http://www.eumetsat.int/Home/Main/DataProducts/index.htm?l=en
SPOT VGT4Africa	Spatial resolution	1 Km
NDWI	Temporal resolution	10 Days
	Source	http://www.agricab.info/Pages/home.aspx
TAMSAT Rainfall	Spatial resolution	4 Km
Estimate (RFE)	Temporal resolution	10 day (dekadal)
	Source (URL)	http://www.met.reading.ac.uk/~tamsat/data/rfe.html
Rainfall Estimator	Spatial resolution	0.1 degree
(RFE) Africa	Temporal resolution	Daily, dekadal and monthly
Climatology (ARC2	Source (URL)	<pre>ftp://ftp.cpc.ncep.noaa.gov/fews/AFR_CLIM/ARC2/CLIMATOLOGY_</pre>
		<u>DATA/</u>
Tropical Rainfall	Spatial resolution	25 km
Measuring Mission	Temporal resolution	Twice a day (Night and day overpass)
Microwave Imager	Source (URL)	ftp://hydro1.sci.gsfc.nasa.gov/data/s4pa/WAOB/LPRM_TMI_DY_SO
(TMI) soil moisture		<u>ILM3.001/</u>

Table 3-2: Summary of the satellite data products used in this study with sources, spatial and temporal resolution

4. PRE-PROCESSING AND METHODS

4.1. Preprocessing

Data pre-processing involved both satellite and ground data. These two data products are of different data type since gauge are point and satellite data are pixel based so special pre-processing steps were followed for data retrieval. Moreover satellite products are of different spatial and temporal resolutions so they have to be resampled and aggregated to same resolutions. Pre- processing steps which were done are shown in a flow chart, Figure 4-1 below.



Figure 4-1: Summary of pre-processing steps

4.1.1. Gauge data pre-processing

Gauge data sets were obtained from SAWS and ARC at 60 minutes temporal resolution for 147 unevenly distributed stations. The stations were screened to 90 for extreme events as well as mean annual precipitation analysis in the study area based on quality control. Gauge data quality control resulted in the discarding of data from stations that have redundancy; missing values, and showed some inconsistency

with stations in its proximity. Data was provided from 2007 but only the data from 2008 to 2012 was used because most of the stations were commissioned during 2007. However for satellite comparison all gauges in the vicinity of the sub catchments were averaged such that there will be one gauge at 8 km pixel for easy comparison with satellite products.

Hourly gauge data were summed to three hourly time steps as well as to daily for comparison with satellite rainfall at the same temporal resolution. The most important point which was put into consideration was the time difference between the South African LST and UCT. South African time is GMT +2 so as a result gauge data were compiled basing on two hours ahead. Thus three hourly rainfall for gauges is defined here as total for three consecutive hours beginning at 0000 UTC (0200 LST) for a given day. The 3 hourly time steps were chosen as proposed by Crosson et al. (1996) who said that hydro-meteorological applications such as flash floods require time steps of 1-12 hours since they are rapid events. No changes to gauge data were done but rather eliminating stations with significant errors. Only 9 stations for each sub catchment with good data quality in the vicinity of the two selected catchments were used for the merging of satellite and gauge measurements.

4.1.2. Satellite rainfall data pre-processing

Analysis was only done for the rainy months of May, June, July and August from 2008 to 2012. Fifteen minutes satellite precipitation estimates from MPE were aggregated to 3 hourly to match the temporal resolution of CMORPH and TRMM 3B42. Later all the products were aggregated to daily time step to get the idea on whether correlation improves at increased time step and also for calculation of rainfall using daily climatological RFE ARC 2 product. The next step was to resample the satellite products to the same spatial resolution of 8 km. Spatial resolution of 8 km was chosen such that we would compromise resampling errors almost equally for all satellite rainfall products and furthermore such that we have one gauge in each pixel.

CMORPH, MPE and TRMM-3B42 precipitation estimates for gauge locations were retrieved in two ways as elaborated by Crosson et al. (1996) namely; (a) Gauge locations were superimposed on SRE pixels, and the pixel value that coincides with the gauge location was considered (b) The mean rainfall over 3 x 3 pixel kernel (24 km x 24 km) regions centred at the gauge point of geo location. The later averaging method was done to minimise the errors associated with timing, image geo-location and wind driven rain shifts. The earlier method was chosen because a derived point value from the satellite has higher accuracy as compared to the pixel value from point interpolation method. Kernel size was chosen based on the assumption that 24 km is almost close to the original pixel size of the TRMM 3B42 and CMORPH before resampling. Pixel averaging method is illustrated below





4.2. Validation of satellite rainfall products with gaugemeasurements

Each 3 hourly satellite rainfall estimate product was paired with 3 hourly gauge measurements and also the daily gauge was also paired to daily satellite retrieved pixel values. To quantitatively assess the predictive power of satellite algorithms to estimate area rainfall, satellite estimates were statistically compared to nine gauge measurements in each catchment using a set of statistical error indices explained in sub sections below.

4.2.1. Root Mean Square Error (RMSE)

RMSE is one of the most widely used measurement of error between remote sensing observations and ground measurements. It is defined as the average error of predicted value to actual value, expressed as the square root of the mean sum of the square errors (Willmott & Matsuura, 2005). It was used for the validation of ASCAT satellite product with the in situ soil moisture measurements as well as the inter comparison between gauge and satellite measurements. RMSE was chosen for this study because it uses the unit of the dependent variable, does not increase with added values and validates well models that have the same dependent variable. RMSE was calculated as follows;

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (G_i - S_i)^2}$$

$$[4.2]$$

Where, G_i is the gauge measurement, S_i is the satellite observation and n is the number of observation in the data set.

4.2.2. Pearson product-moment correlation coefficient (r)

Pearson product of moment correlation coefficient (*r*) is a measure used to describe how well the data sets are correlated to each other. Values of *r* are in the range of -1 to 1 ($-1 \le r \le 1$). When *r* is close to 1 it indicates that the data sets have a high positive correlation whereas -1 indicates that the data sets have a high negative correlation. Advantages of *r* are that it explains strength of the variation in dependent variable and also the linear association between variables. The other major advantage is that it shows the direction of the correlation, whether it is negative or positive. Direction of correlation is very important when comparing two data samples because in some situations the increase in the variable can result in decrease in the dependent. It was calculated as follows;

$$r = \left(\frac{n(\Sigma GS) - (\Sigma G)(\Sigma S)}{\sqrt{\left(n\Sigma G^2 - (\Sigma G)^2\right)\left(n\Sigma S^2 - (\Sigma S)^2\right)}}\right)$$
[4.3]

Where S is the satellite rainfall estimate, G is the ground measurement and n is the number of pairs.

4.2.3. Mean Absolute Error (MAE)

Mean Absolute Error is a good measure of error in small datasets although it is less sensitive to errors as compared to RMSE. Moreover, it does not consider the direction of the errors. Willmott and Matsuura (2005) found out that MAE is a more natural measure of average error. In this study MAE was used to measure the average error between the gauge measurements and satellite rainfall estimates of TRMM 3B42, CMORPH and MPE. MAE is calculated as follows;

$$MAE = \frac{\sum_{i}^{n} Absolute(G_{i} - S_{i})}{n}$$
[4.4]

Where, n is the sample size, G_i is the ground measurements and S_i is the satellite observation.

4.2.4. Bias

Bias shows the tendency to underestimate (Bias<1) or to overestimate (Bias>1) for the satellite rainfall estimates (SRE). In this study bias was calculated as shown in equation 4.5 below.

$$Bias = \frac{\sum_{i=1}^{n} (S_i - G_i)}{\sum_{i=1}^{n} G_i}$$
[4.5]

Where G_i and S_i are the total cumulative rainfall from a gauge and satellite pixel over a rainfall duration period.

4.3. Combining gauge measurements with satellite estimates

Co-located 3 hourly matches of gauge and satellite rainfall estimates (CMORPH, MPE and TRMM 3B42) at 8km spatial resolution data were extracted for two extreme events that occurred in two different catchments. The extreme events considered were the 11-13 July 2009 and 11-13 August 2012 that occurred in Berg and Breede catchments. Curves were drawn through cumulative point measurements of the 3 hourly pairs. Resulting gauge and respective SRE plot suggested that a quadratic regression function was the most appropriate because of high correlation and low standard error as compared to the linear fitting. The quadratic equations show a high correlation and a low standard error of estimate as compared to the linear equations. Moreover, the size of the coefficients a, b and c were minimum. Especially the 'a' coefficient should not be large and has to be corrected for after the fitting because when there is no rainfall measured, the zeros are replaced with 'a' thus it has to be kept low. The curve expert software was used to calculate the coefficients of the regression fit as well as the standard error of estimate. Cumulative curves for the satellites were each fitted to the gauge cumulative curve. This was done basing on the assumption that gauge measurements are unbiased or have minimum errors as compared to satellite estimates. Xie and Arkin (1995) documented in their work that gauge-based analysis are less biased when there are at least 1 station over grid boxes of 0.25 °. In line to this argument there are at least two stations at 0.25 degrees as shown in Figure 3-1.

4.4. Validation of ASCAT surface soil moisture product

The overpass of 28 September during 2057 hours was used to validate the ASCAT soil moisture. The volumetric (m^3/m^3) in situ measurements were converted to percentage soil moisture for easy analysis with the ASCAT SWI. ASCAT has proved to be a good remote sensing product for soil moisture measurements in different parts of the world. Brocca et al. (2011) found correlation coefficients of greater than 0.92 and 0.74 between in-situ and ASCAT soil wetness index (SWI) in Italy and France respectively. Sinclair and Pegram (2010) got a good correspondence in the dynamic behaviour of ASCAT SWI using TOPKAPI land surface model for a significant proportion of South Africa.

ASCAT soil moisture product was validated with in situ soil moisture measurements collected during fieldwork at a depth of 0-10cm for 10 sites (Figure 3-2). The measurements which were done on 19, 20, 21 and 23 September 2012 were discarded because the satellite did not cover the study area on these days. However, the 28 September 2012 measurements sites (Figure 3-2) were used to validate the product. Root mean square error (RMSE) and Mean Absolute Error were used for validation. The pass was during the evening and fortunately there was no rain recorded by the nearby stations between the time of sampling and of overpass.

4.5. Extraction of catchments and hyro geomorphic properties

A catchment has been defined by Horton (1945) as a topographic area from which all water runoff finally reaches one single given outlet. From the highest point of land down to the stream bottom all the surface land is considered part of a stream or river basin. The processed two tiles of 5° by 5°, 90 m Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) were imported into Integrated Land and Water Information System (ILWIS) using In-situ and Online Data (ISOD) toolbox. A Geographic Information System (GIS) based algorithm called DEM hydro-processing in ILWIS, Maathuis and Wang (2006), was used to extract catchments and analyse their geomorphological characteristics of the catchments and river paths. The algorithm consists of several interconnected steps as shown in Figure 4-3 below. Two major catchments for the Berg and Breede rivers were extracted after running the Digital Elevation Model hydro-processing in ILWIS. From these main catchments, two sub catchments were chosen for further analysis in this study. Extracted catchments were further processed to derive compound parameters such as Topographic Wetness Index as well as Horton statistical parameters.



Figure 4-3: DEM processing for catchment extraction

4.5.1. Topographic wetness index (TWI)

TWI is calculated using representative points based on the assumption that the points in the catchment with the same range of topographic index will have same hydrologic responses (Beven & Kirkby, 1979). TWI is defined by the equation below;

$$TWI = \ln\left(\frac{a}{\tan\beta}\right)$$
[4.6]

Where, a is the source contributing area, and $\tan\beta$ is ground surface slope.

TWI can be derived from the DEM directly through the hydro-processing algorithm in ILWIS. Computation of a in ILWIS is based on the Single Flow Direction (SFD), D8 flow direction algorithm. The algorithm assumes that all water from the central pixel should flow into one of the surrounding neighbouring pixel which has lowest elevation or steepest slope. The flow is partitioned to all downslope neighbouring cells. The maximum downslope gradient is used to approximate tan β for TWI. Higher values of TWI indicate areas more likely to drain by saturated excess flow.

4.5.2. Morphometric properties of catchments

The morphometric analysis of extracted catchments was done based on the output from the DEM hydro processing tool in ILWIS. The morphometric properties were chosen based on the conclusions from previous studies which have found the relationships between catchment slope, area and linearity to be of high significance to peak discharge and runoff volume (Horton, 1945; Marchi et al., 2010; Patton & Baker, 1976). In this study morphometric properties were calculated according to three categories namely linear, relief and area as shown in Table 2-2 earlier.

4.6. Selection of rainfall events and sub catchments

Two flash flood events were selected for this study based upon the gauge measurements for the time period May to August of the years 2008 to 2012. Characteristics of flash flood events as narrated by Marchi et al. (2010) were used as a working principle for selecting two flash flood events. These include duration of the causative rainfall limited to 34 h, the response time of the catchment, peak discharge and the severity of the event. The two selected events are 12 July 2009 and 11 august 2012 which have occurred in catchments along the main rivers of Berg and Breede.

The second criterion used was based on observation of catchments where flash flood events had occurred as well as hydro geomorphic characteristics that can induce flash flooding. However, the later were not known a priori but were derived from DEM hydro processing later. Catchment size was a little bit relaxed to cater for the coarse resolution of the satellite products such as TMI for soil moisture which has 25 km spatial resolution. Differences between the spatial extents of the catchments and time of the season during which the flash floods has occurred were also put into consideration for the selection of the rainfall events. The selected catchments had also observed stream discharge data at selected points given in Table 3-1 and presented in Figure 3-1.

4.7. Determining flash flood potential areas by intergrating remote sensing products

Determination of flash flood potentials was based on the conceptual framework shown in Figure 4-4 below. All input product maps are from remote sensing data sources. Based on this framework, the flash flood index was developed to show potential areas for flash flooding by integrating high spatial and temporal resolution remote sensing rainfall, soil wetness and topographic data tested in two studied catchments. Soil moisture raster map from TMI was resampled to same spatial resolution with NDWI and later combined. After developing all raster gridded datasets that represent hydro physiographic characteristics that influence flash flood, these maps were resampled to a consistent resolution by using either bilinear or nearest neighbour resampling. The maps were classified into discrete dimensionless classes of 1, 2 and 3 based on class threshold values of neighbouring pixels. High values were assigned to high hierarchy classes. Considering two rainfall events and three satellite rainfall products six maps in total were produced at final stage.



Figure 4-4: Conceptual framework for flash flood potential areas

4.7.1. Combining rainfall anomaly, TWI and antecedent soil moisture

The static layer of slope in the form of TWI was combined to dynamic event layers of rainfall anomaly by the use of weights. Without first observing each map it was difficult to assign the weight values for combining the maps, therefore the maps were first qualitatively studied.

Three hourly gauge corrected satellite rainfall were accumulated and averaged to daily to match with the RFE daily climatological average. Since these events were considered for 36 hours, only the actual day of the event with high rainfall was chosen for this process. Thus only 12 July 2009 and 11 August 2012 were considered for Berg and Breede catchments respectively. Rainfall anomaly was calculated by finding the difference between the gauges corrected satellite rainfall and the climatological daily average rainfall. Positive anomaly shows the potential for flooding whereas negative reveal that lower than average rainfall was received. The anomaly maps were corrected for negative values and combined to TWI map. Rainfall was given much weight because it is the initiator for flash floods. They were combined using the calculations below;

Combined rainfall anomaly and TWI = 0.5(rainfall anomally) + 2(TWI) [4.7]

On the other hand TMI soil wetness was combined to the negative corrected NDWI. The NDWI was given much weight of 0.6 whereas TMI 0.4 because NDWI was subjectively determined as less bias regional product so it is less susceptible to local errors.

Finally, the maps were joined to one product with the soil wetness getting less weight. Rainfall and slope maps were much overweighed compared to soil wetness maps due to the fact that rainfall and topography are the major contributing factors for flash flooding (Marchi et al., 2010). This argument has been adopted from the study by Doswell et al. (1996) who concluded that even in dry soil conditions flash floods have been witnessed hence the hydrologic characteristics of the basin may be the most important considerations. The overall steps are summarised in the flowchart of Figure 4-5 below.



Figure 4-5 : Steps for derivation of flash flood potential areas based on two flash flood events.

5. ANALYSIS OF GAUGE MEASUREMENTS

5.1. Temporal trends in gauge measured rainfall

Temporal analysis for rainfall was done based on 90 unevenly distributed rainfall stations (Figure 3-1) for the period 2008 to 2012. Monthly average for each station was calculated using arithmetic mean and assumed to represent areal average surrounding the gauge. Figure 5-1 below shows that the study area receives rainfall almost throughout the year within the range of 25mm to 290 mm/ month. July is the wettest month with an average of 290 mm whereas January is the driest month with an average of 25mm. Western Cape of South Africa receives rainfall in winter months mainly due to "cold fronts and high pressure systems ridging along the coast ," (de Coning & Poolman, 2011). There is also another peak of rainfall in November as this has been documented by Midgley *et al.* (2005) that there is a slight more summer rainfall in the east of the Western Cape Province.

An extreme event is subjectively defined in this study as the rainfall depth in exceedance of a threshold of 30mm/hour per station. Therefore all the events with rainfall intensity greater than 30mm per hour were categorised as extreme events. Frequency of these extreme events for the period 2008 to 2012 for the 90 stations were analysed and the results obtained are shown in Figure 5-1 below. July has the highest frequency of rain events of greater than 30 mm per hour and December has the least. It is also interesting to note that November has also a number of extreme events even though its not a rainy season month.



Figure 5-1: Temporal trend analysis for rainfall based on 90 gauges from 2008 to 2012; a) monthly average and b) frequency of rain events above 30mm/hour.

5.2. Spatial distribution of rainfall

Spatial distribution of rainfall in the study area was analysed by the computation of Mean Annual Precipitation (MAP) using the 90 unevenly distributed gauges for the years 2008 to 2012. Inverse Distance Weighting (IDW) interpolation method was used to show spatial distribution of rainfall in the area. IDW gives more weight to areas which are close to the interpolated point. Although flash floods are caused by extreme events, mean annual spatial variability of rainfall gives information on the amount of rainfall the catchment is adapted to. For example, in Figure 5-2 the same amount of rainfall can have different impacts in Berg and Breede catchments. The Berg catchment is adapted to more rainfall whereas the Breede is adapted to less rainfall. Different responses of catchments to different rainfall depth shall also be seen in the following chapters.

There is a steep gradient from east to west and from south to north in spatial variability of rainfall in the study area as shown in Figure 5-2. This steep gradient has also been explained in chapter 3 by using a diagram from DWA. Midgley et al. (2005) explained that these gradients are mainly due to diverse topography especially by the Cape Fold Belt, Langeberg, Table mountain and Robertson ranges. The rain shadow side of these mountain ranges are much drier than the windward sides. Furthermore, de Coning and Poolman (2011) concluded that most of the areas in the Western Cape of South Africa are exposed to "cut-off low" weather systems which can result in high intensity of rainfall of short duration to coastal areas. Cut off low weather systems are the major contributing factor for the flash flooding in the study area especially for those areas which are close to the coast.



Figure 5-2: Spatial distribution of mean annual precipitation (MAP) for the period 2008 to 2012.

5.3. Rainfall intensities of extreme events

Vergelegenvrug station recorded the most intense rainfall event of 180.4 mm within one hour on 3 March 2009 at 1400 hours. Struissbai recorded the second and Cape Agulhas the third with 89.8 mm and 81.2 mm on 22 January 2009 respectively. All the three stations are close to the coast at low elevation. Therefore, the major cause for these rainfall events could have been due to 'cut off low" pressure systems. Stations which are close to the coast and on high elevation are on average those that receive large amount of rainfall as compared to those that are interior. Per year analysis of the extreme events, 2009 was found to have recorded the most intense extreme events. It was also observed that although, the winter months have the greatest frequency of extreme events, many of the events of greatest intensity occur outside winter months.

6. RESULTS AND DISCUSSIONS

6.1. Comparison between point and kernel pixel value retrieval

Rainfall estimates values were retrieved from satellite images based on two criteria as explained in Chapter 4.1.1. The two methods were tested over Berg catchment using total areal rainfall estimated by TRMM 3B42 based on 9 stations during the event of 12 July 2009. Table 6-1 shows the results that were obtained. There is no much difference between the obtained values from each of these procedures even though at some pairs the kernel values are greater than the gauge point values. In support to this observation, Crosson et al. (1996) found no difference between comparison of radar values using a kernel and gauge to pixel value in central Florida. The two methods show a negligible mean areal accumulated rainfall difference of 0.47 mm. In addition, the kernel method did not show much rainfall variability over the catchment because the satellites rainfall product pixel size was coarse in relative to the catchment size and gauge.

Station name	Latitude	Longitude	Pixel value (mm)	3 by 3 kernel average (mm)
Bien Donne PP	-33.84272	18.9842	42.34	41.08
Elsenburg	-33.58221	18.83048	35.58	34.25
Ashanti	-33.72356	19.04239	36.58	37.81
Bellevue	-33.74809	18.95857	39.15	40.26
Fairview	-33.77729	18.92297	37.02	35.18
Lamotte	-33.88132	19.07148	42.75	41.64
Le bonheur	-33.82939	18.86836	37.25	38.46
Merle	-33.8626	18.92847	37.65	36.42
Nietvoorbij	-33.91683	18.85988	39.47	38.14
Mean			38.6	38.13

Table 6-1: Comparison between point pixel measurements and 3 by 3 kernel averages in Berg catchment for 12 July 1500 hours.

Furthermore, gauge point observations were not interpolated but rather compared with satellite pixel values because rainfall fields are not homogeneous as shown on TRMM 3B42 satellite images in Figure 6-1 (left) unlike the homogeneous gauge interpolation Figure 6-1 (right). Taking into consideration drawbacks of point interpolation as well as unimproved results on kernel averaging, all the satellite values in this study were retrieved by using the location of gauge measurements that coincides with the pixel.



Figure 6-1: Gauge interpolation and TRMM 3B42 rainfall estimates in Berg catchment (12 July 2009 1500 hours)

6.2. Inter comparisons between gauges and satellite rainfall products

The first comparisons were done for two flash flood events that occurred on two respective days in the Berg and Breede catchments on 12 July 2009 and 11 August 2012 respectively. However, the duration of the events was a bit relaxed to a longer time period of 72 hours such that more pairs can be used in the analysis. The results for the inter comparison of satellite rainfall estimates with gauge stations within the vicinity of the two catchments are presented in Figure 6-2. The plots illustrates the tendency of MPE and CMORPH to underestimate rainfall by about 70 % and 40 % in Berg and Breede catchments respectively, whereas TRMM 3B42 over estimates by about 10 % in both catchments for both events. Furthermore, in some stations in the Berg catchments such as Ashanti, Merle and Elsenburg TRMM 3B42 underestimates. These stations generally are on high elevation and receive high rainfall due to orographic effects. Therefore, TRMM 3B42 can miss some of the orographic rainfall which can be measured by the gauges.

Even though MPE and CMORPH rainfall retrieval are based on different algorithms their rainfall estimates especially in the Berg catchment are close to each other. Moreover, the CMORPH and MPE estimates are analogues for all the stations regardless that the stations are more than 8 km apart. Although TRMM 3B42 overestimate, their estimates are close to the gauge measurements. This is so because the TRMM 3B42 has been bias corrected using the CPC gauge network over the study area unlike the other satellite rainfall products (Huffman et al., 2007). Nevertheless, all satellite rainfall products can show the spatial and temporal variability of rainfall. TRMM 3B42's strong positive bias has already been documented over Ethiopia as well as the CMORPH underestimation at a daily time step by the study of Romilly and Gebremichael (2011). MPE is found to have much lower differences with gauge measurements in the Breede catchment. This is explained based on the spatial location of stations, which are much further from the coast and also August the month in which this event occurred is much warmer than July. Both of these facts support the motive that the type of rainfall for this event could be of convective type which MPE is good at capturing.



Figure 6-2: Station based total accumulated gauge and satellite rainfall estimates for a) 11-12 July 2009 and b) 11-12 August 2012 events

Time series estimates were done using 9 gauges in each catchment for seasonal rainfall period (May to August) for 2009 and 2012 based on 3 hourly rainfall. The results show that MPE and CMORPH underestimate rainfall from gauges even at catchment area. This may be because the intense rain cells that are in gauge proximity are missed by the satellites snapshot and picked by gauges since the later measure rainfall continously (Crosson et al., 1996). Furthermore, the uncertainty related to the performance of

satellite data maybe due to different data types; satellite is area and gauge is point data and also satellite pre-processing such as resampling can add significant errors in the data.

Though the MPE and CMORPH underestimates the rainfall, they could measure high rainfall on the selected events as shown in Figure 6-3 and Figure6-4 for Berg and Breede catchments respectively. Comparing these four rainfall measuring techniques, all the three satellite-derived rainfall estimates capture the trend and pick the heavy rainfall events but slightly missed the onset of the events. In particular, MPE tends to miss low intensity rainfall and is good at capturing high intensity rain events.

Extreme events of 11-13 July 2009 and 11-13 August 2012 were also selected from these graphs by considering peak discharge and shape of storm hydrographs. As can be seen in the graphs both of the events' hydrograph shape have steep rising limbs with short duration, typical of flash flood events. Steep rising limbs of the storm hydrographs can also explain the characteristics of the catchments in terms of runoff generation and speed of its flow to low lying areas. Furthermore, the hydrographs reproduced the rainfall patterns shown by all satellite observations and gauge measurements.

Considering per catchment analysis in terms of stream hydrographs response curves, Breede catchments generate runoff even with minimum rainfall received as compared to Berg catchment. This clearly indicates different morphometric properties of these catchments. On another hand, it can be argued that Berg catchment is adapted to high rainfall intensities such that the same amount of rainfall in Berg catchment can cause large amounts of runoff in Breede catchment.



Figure 6-3: Measured discharge at G1H075 and rainfall trend from gauge and satellite estimates over Berg catchment for the rain season of 2009.

Impact of antecedent soil wetness in relation to runoff generation can also be seen in these graphs especially Breede graphs (Figure 6-4). When there was rain in some few days before intense rainfall the

peak of the resultant discharge graph is very high. This is so because the soils will only allow minimum amount of rainfall to infiltrate before they are saturated and the excess will be runoff. Overestimation of TRMM3B42 can also be explained by comparing its rainfall estimates with runoff generation. For example on the dates of around 20 July 2012 (Figure 6-4) it estimated high amounts of rainfall and the resultant run off was not much as compared to that one of around 26 June2012.



Figure 6-4: Measured discharge at H7H006 and rainfall trend from gauge and satellite estimates over Breede catchment for 2012 rain season

6.2.1. Results on statistical analysis at 3 hourly and daily time step

Gauge and satellite non-zero pairs for 3 hourly and daily time step were plotted on scatter plots in Figure 6-5 for detailed comparisons. The pairs did not have a zero value such that only rainy pairs are included in the comparisons. Each plot represents 3 hourly (top) and daily (bottom) accumulations at one rain gauge for the collocated pixel of the satellite rainfall estimate. Overestimation of rainfall at 3 hourly time step by TRMM 3B42 is revealed by a positive bias of 0.19 by TRMM 3B42 and underestimation by CMORPH and MPE with negative biases of -0.96 and -0.97 respectively. Bias was calculated using the equation 4.5 explained in Chapter 4. However, all the products show an improved correlation (*r*) at daily time step. Furthermore, even the RMSE and MAE decreases as the time step increases. This is so because the shorter the time step the more errors are incurred and whilst longer time steps normalises the errors. Daily TRMM 3B42, CMORPH and MPE when compared to daily gauge network show a RMSE reduction of 46 %, 25% and 43 % respectively.

All the products on the selected two extreme events showed good positive correlation with the lowest calculated r value of 0.61 from CMORPH at 3 hourly time step and the highest being 0.91 from TRMM 3B42 at a daily time step as shown in Figure 6-5. TRMM 3B42 has an improved r of about 15% from 3 hourly time step to daily. Furthermore, the correlation coefficients (r) of all the comparisons are positive,



meaning that the increase in the gauge measurements results also in the high values being estimated by the satellites.

Figure 6-5: Scatter diagrams of 3 hourly (top) and daily (bottom) satellite rainfall estimates paired with gauge measurements for the rain season of 2009.

Heinemann and Kerenyi (2003) concluded that MPE algorithm is only suitable for convective weather situations and also Liechti *et al.* (2012) found that CMORPH has strong negative bias when it was compared to gauges along the Zambezi basin. Frontal rainfall like the one that occur in Western Cape of South Africa is wrongly located and underestimated by MPE and CMORPH.

Further evaluation of the quantitative comparison of the 3 hourly rainfalls over the two catchments was carried out by calculating average accumulated areal rainfall for each rainfall season over the years 2008 to 2012 based on 9 stations. The results for these calculations are shown in Table 6-2 for Berg and Table 6-3 for Breede catchment. In both Breede and Berg areal rainfall; TRMM 3B42 was found to have the highest ratio of 0.89 and 0.84 respectively. CMORPH was found to have the lowest ratio with values of 0.24 in the Berg and 0.34 in the Breede. The higher the ratio the more close the satellite estimates are to the gauges.

	Mean seasonal areal rainfa	II (mm) , May to August o	obtained from	
Year	GAUGES	MPE	CMORPH	TRMM-3B42
2008	742.7	201.3	184.9	728.5
2009	681.6	183.8	176.4	706.2
2010	703.2	192.8	164.7	682.8
2011	928	263.4	248.7	867.3
2012	1146.8	276.6	262.1	1012.8
Ratio of mean satellite estimates to gauges for 5 years		0.27	0.24	0.84

Table 6-2: Mean seasonal rainfall for the period 2008 - 2012 as measured by satellites and gauges over Berg catchment based on 9 stations.

The results show that MPE and CMORPH have mean values which are almost close to each other in both catchments. TRMM 3B42 underestimates at long time scale. Nevertheless, TRMM 3B42 at longer time scale shows improved agreement to gauge measurements as compared to MPE and CMORPH products.

Table 6-3: Mean seasonal rainfall for period 2008-2012 as measured by satellites and gauges over Breede catchment based on 9 stations.

	Mean seasonal areal rainfall	(mm) , May to August	t obtained from	
Year	GAUGES	MPE	CMORPH	TRMM-3B42
2008	302.4	122.8	88.7	267.5
2009	367.9	152.4	128.8	347.1
2010	345.2	147.2	117.6	311.8
2011	371.8	141.3	122.7	345.6
2012	542	198.7	195.1	460.3
Ratio of m	ean satellite estimates	0.40	0.34	0.89
to gauges for 5 years				

6.3. calibration of satellite rainfall estimates using gauges

The quadratic equations as well as their correlation coefficient used for the curve fitting are listed in Table 6-4 below. Derivatives of these equations with respect to corrected satellite values give gradient of the curve. The gradient of the curve shows the rate in which the variable is changing with respect to the independent variable. A steeper gradient explains a quick difference in change between the gauge and the satellite estimates with time. Furthermore, a negative gradient shows that the dependent and independent have negative relationship. For example the gradient for TRMM3B42 for 11-13 August 2012 curve was found to be 0.62 - 0.02(T). This means that at higher intensities of greater than 31 mm, TRMM 3B42 starts to have a negative gradient in relationship with gauges.

Rain event	Satellite Rainfall	Satellite Me (mm)	ean rainfall	Mean Gauge	Quadratic equation	r
	product	Before correction	After correction			
11 –13 July 2009	TRMM 3B42	99.5	99.7	101.3	CorrectedT=0.94+1.26T - 0.02(T) ²	0.98
	MPE	31.5	101	101.3	CorrectedM=1.14+0.32M+ 0.32(M) ²	0.97
	CMORPH	23.3	96.3	101.3	CorrectedC=0.68+9.76C- 1.03(C) ²	0.94
11- 13 August 2012	TRMM 3B42	87.3	38.6	38.6	CorrectedT=0.37+0.62T- 0.01(T) ²	0.99
	MPE	6.3	37.8	38.6	CorrectedM=0.22+4.7M+0. 49(M) ²	0.96
	CMORPH	15.7	38.2	38.6	CorrectedC=0.47+1.03C + 0.24(C) ²	0.97

Table 6-4: Quadratic equations used to correct satellite rainfall estimates and the correlation coefficients for the fit based on 9 stations.

Where T= TRMM3B42, C=CMORPH and M=MPE satellite rainfall product.

Cumulative area rainfall for the two flash flood events based on satellite and gauge data after correcting with quadratic linear fitting are presented in Figure 6-6. These areal calculations are based on total cumulative rainfall for 9 stations in each catchment during 36 hours. The satellite images before and after correction for three satellite rainfall products are provided in list of appendices as Appendix 2 (12 July 2009) and Appendix 3 (11 August 2012).



Figure 6-6: Corrected cumulative rainfall data during a) 11-13 July 2009 and b) 11-13 August 2012.

6.4. Validation of quadratic curve fitting

The objective for curve fitting method is that bias of satellite rainfall estimates is lowered and accuracy is improved in relation to local gauge network. When the quadratic equation coefficients were used to

validate the satellite rainfall products, the accuracy of the rainfall estimates improved. The improvement in the gauge- based corrected satellite estimates is significantly noticeable in both extreme events, suggesting that the quadratic linear fitting has a great influence in reducing satellite bias and errors. Crosson et al. (1996) used the same method and managed to improve the accuracy of the relationship between radar and gauge reflectivity by lowering the bias, RMSE and increasing the correlation coefficient. The improvement in accuracy was measured by calculating bias, RMSE, r and RMSE for both the events and all satellite products. Scatter plot results are presented in in Figure 6-7 for 11-13 July 2009 and Figure 6-8 for 11-13 August 2012 events.

6.4.1. Validation in Berg catchment for 11-13 July 2009 event

Quadratic curve fitting improved the accuracy of the satellite rainfall fields in all satellite products based upon gauge measurements during the extreme rainfall event. Bias for CMOPH, MPE and TRMM 3B42 improved significantly after correction to 0.05, 0.02 and 0 respectively .Furthermore, correlation coefficient and RMSE improved by more than 50 % as shown in Figure 6-7. TRMM 3B42 was found to have high correlation coefficient of 0.97 and both MPE and CMORPH had 0.94. High correlation coefficient of 0.97 in TRMM 3B42 reveals that only 3 % of the variability in TRMM 3B42 remains unexplained by the gauges whereas 97 % can be explained by the gauges



Figure 6-7: Scatter plots before (top) and after (bottom) quadratic correction of for total accumulated rainfall during 11-13 July 2009 in Berg catchment.

6.4.2. Validation in Breede catchment for 11-13 August 2012 event

Quadratic curve fitting managed to reduce RMSE for all satellite rainfall estimates in Breede catchment as shown in Figure 6-8. However, bias was not well corrected using the quadratic curve fitting in Breede catchment. This could be because rainfall during the event was not normally distributed since the rainfall started with high intensities and quickly stops.



Figure 6-8: Scatter plots before (top) and after (bottom) quadratic correction for total accumulated rainfall during 11-13 August 2012 in Breede catchment

6.5. Climatological analysis of the extreme events

Climatological RFE daily mean from 1983 to 2012 was used to give a better representation of the trend of abnormal wetter and drier conditions in the Western Cape of South Africa. The difference between daily TRMM 3B42, MPE and CMORPH with RFE mean daily climatological was used to calculate the daily anomaly. Even though the anomaly is not an index, it can show the trend of wetter and drier than normal conditions as shown in figure 6-9. Negative anomaly shows drier conditions whereas on the other hand positive values indicate wetter conditions. Anomaly measurements were plotted together with discharge to get a more understanding on the peaks and shape of the discharge curves during wet conditions in the Berg and Breede catchments. The response of the catchments is very different as seen by the relationship between discharge and rainfall anomaly. Breede catchment produces much runoff with minimum amount of rainfall received. This could be because of different catchment morphometric properties which are going to be explained in sections to follow. Furthermore, discharge curves in both catchments are controlled by antecedent precipitation. Figure 6-9 shows that TRMM 3B42 and gauges can depict almost all the flash floods, but CMORPH and MPE can depict trend although they underestimate extreme rainfall events as shown in Figure 6-9. The highest anomaly was recorded in July for Berg catchment and for Breede catchment was recorded in August. Therefore, flash floods are more likely to occur during these months in the respective catchments.



Figure 6-9: Daily mean climatological RFE and anomaly over Berg (top) and Breede (bottom) catchments for the rainfall season of 2009 and 2012 at stream gauges G1H0075 and H7H006 respectively.

6.6. Comparison between SPOT NDWI and Climatological RFE ARC2

Dekadal SPOT NDWI was compared with dekadal climatological RFE ARC2 for dekads which include days of extreme events in the two respective sub catchments. The results of the comparison reveal that the two products show the same trend in terms of surface wetness as presented in Figure 6-10. The highest peak in the Berg catchment occurs in the dekad when the 12 July 2009 flash flood occurs whereas the one for the 11 August 2012 in the Breede has a slightly higher anomaly and NDWI. The RFE ARC2 also shows that Berg catchment receives much more rainfall as compared to Breede catchment as this is also shown by the results of spatial rainfall variability in the Western Cape of South Africa in Figure 5-2 as well as the seasonal amount of rainfall for the period 2008 to 2012. When rainfall is high NDWI is positive, therefore high rainfall intensity is likely to contribute to a flash flood occurrence on the areas with high NDWI.



Figure 6-10: Climatological dekadal RFE and NDWI in a) Berg (2009) and b) Breede (2012) catchments

6.7. Hydrogeomorphic properties of catchments of selected extreme flash flood events

Catchment steepness is evaluated by relief ratio which was found to be high for the Berg catchment with a value of 0.18 and for the Breede was found to be 0.12. Obtained values are within the range of values obtained in other studies (Marchi et al., 2010). High relief values are associated with catchments that have steep slopes and are more prone to flash flooding. Slope has capacity to promote rapid concentration of stream flow, which is one of the flash flood ingredients. Moreover, Midgley et al. (2005) found out that soils in Western Cape of South Africa are shallow and thin. Thin and shallow soils do not promote infiltration and vegetation growth which can reduce run off.

Relationship between catchment area and longest stream length was found to be high in the Breede with a value of 38 and low in Berg with a value of 25. Moreover, the Berg was found to have a circulatory ratio of 0.26 whereas the Breede has 0.31. The ratio of catchment area to longest stream length and circulatory ratio tell us the shape of the catchments as shown in Figure 6-11. Catchments with high ratio of catchment area to longest stream length are more circular and will tend to have steep stream hydrographs which are characteristics of flash floods. The elongation ratio is also another measure of catchment shape. The Berg was found to have an elongation value of 0.45 whereas Breede has 0.49. There is no much difference on the two catchments elongation ratio. Schumm (1956) described relatively high elongation values as those in the range of 0.6 to 1, therefore the two catchments have low elongation ratios. Low elongation ratios can mean that most of the streams in the catchment are close to the main stream thus resulting in steep rising limbs of stream hydrographs which are the characteristics of flash flood events.

According to the thresholds that have been used and validation Berg catchment was found to be a sixth order stream whereas Breede was found to be a fifth order stream. The number of streams in the Strahler class was found to decrease with increasing hierarchy of Strahler class as expected. For example the Berg catchment was found to have 50 streams of fifth order and 134 streams of fourth order. The catchment with streams of high order have a long flooding time since the water takes time to reach to the furthest point unlike a low order catchment. Conversely a high order catchment has a greater flash flood magnitude as compared to a lower stream order catchment since it has a large contributing area for flow volume. The Strahler stream ordering was further analysed by calculating the bifurcation ratio, length ratio and area ratio of these streams. Bifurcation ratio for this study was found to be 3.41 and 4.78 for Berg and Breede catchments respectively.



Figure 6-11: Strahler stream orders for a) Berg and b) Breede catchments for stream gauges G1H075 andH7H006.

Drainage density was found to be 153.16 km/km² for Berg and 196.2 km/km² for Breede. High drainage density in a catchment is associated with greater possibilities of maximum discharge from high order streams. Moreover, Patton and Baker (1976) stated in their study that drainage density has a high positive correlation with relief ratio, rainfall intensity and infiltration capacity. High rainfall intensity, topography and low infiltration capacity promotes the formation of streams in a catchment hence high drainage density. This has also been found in this study, Berg catchment has a higher drainage density as it receives more rainfall and has steep gradient. In this study result of catchment physiographic properties are shown in Table 6-5 below.

Morphometric parameter	Computed values	
	Berg sub catchment	Breede Sub catchment
Catchment area (km²)	3 973	9 864
Circulatory ratio	0.26	0.41
Bifurcation ratio	3.41	4.78
Length ratio	1.95	2.78
Area ratio	4.29	5.6
Drainage density (km/km ²)	153.16	196.2
Elongation ratio	0.45	0.49
Form factor	0.16	0.17
Length of longest stream (km)	158.922	251.764
Total stream length (km)	608.493	1 920
Relief ratio	0.18	0.12

Table 6-5 : Catchments morphometric calculations

6.7.1. Validation of catchment extraction

Catchment extraction is subjectively based on threshold selection so therefore these thresholds have to be qualitatively and quantitatively validated. Qualitative way of checking feasibility of the extracted catchments is to overlay the streams on the satellite image and or topographical maps of the area. Quantitative method involves plotting a curve of Horton statistics on the logarithmic scale known as Horton plot. Horton statistics as explained after Maathuis and Wang (2006) includes;

 $Cx_N = Number of streams; Cx_L=Average stream length (km); Cx_A=Average area of catchments (km²); Cx_N_LSq = expected values for Cx_N by means of a least squares fit through Cx_N; Cx_L_LSq = expected values for Cx_L by means of a least squares fit through Cx_L and Cx_A_LSq = expected values for Cx_A by means of a least squares fit through Cx_A$

The Horton plots for the Berg and Breede catchments are shown in Figure 6-12. Plots for stream length and area of catchments in relation to Strahler order have shown a positive correlation as expected whereas the number of streams has decreased with increasing stream order. The plots for the linear regressions are almost passing through the points as expected. Therefore, the thresholds used are correct in relation to the drainage network in the studied catchments. The result is the same as what has been explained after Maathuis and Wang (2006).



Figure 6-12: Horton plots for Berg and Breede catchments

6.8. Validation of ASCAT soil moisture

The interpolated point measurements resultant image for an overpass of 28 September at 2057 hours is shown below in Figure 6-13. The product shows a low MAE 0f 3.8, RMSE of 4.18 (m³/m³) and bias of -6%. The negative bias reveals that the ASCAT soil moisture product underestimates the actual soil moisture. The plot of the results as well as the image used for validation is shown in Figure 6-13 below. The results are supported by the outcomes of Sinclair and Pegram (2010), they found higher correlation between ASCAT product with in situ measurements in KwaZulu Natal of South Africa. Nevertheless, the product has both poor temporal and spatial coverage for the study area so the product has to be used when there is an overpass only. Fortunately, there is also now ASCAT instrument on board of Metop B.

Therefore, in this study ASCAT soil moisture was replaced with TMI. The products show almost the equal measurements though the TMI soil moisture product over estimates ASCAT measurements by about 37 %. The validation was only done using 3 pixels due to coarse spatial resolution of TMI in relation to geographical location of the sample points.



Figure 6-13: ASCAT inverse distance interpolated images of 28/09/201(2054 and 2057 hours) used for validation and b) validation results

6.9. Flash flood potential areas

6.9.1. Results on questionnaires and interviews

Out of the 27 residents interviewed, 70 % have been affected by flash floods in their homes and 30 % were new in the area but have heard in the media about the flash floods in these areas before. Residents reported that the water has entered in their shacks (informal house) and in some years they were evacuated from their houses.

The residents suspect that the major cause of the flash floods was due to heavy rainfall and also their areas are always wet throughout the year. Therefore, the same amount of rainfall in other areas cannot cause flash floods because other areas are not generally wet. The reasons provided by the residents for the major causes of flash floods were in accordance with City of Cape Town Department of Risk and Disaster Management (DRDM). The reports from DRDM were saying that the cities around the Cape flats area close to the Berg catchment and those close to the coast are more prone to flash floods due to high rainfall, low lying and shallow water table. The questionnaire and interview response were used to validate the results on the flash flood index.

6.9.2. Topographic Wetness Index output

Topographic Wetness Index (TWI) for the whole of the Western Cape of South Africa was computed in ILWIS and the resultant classified output is shown in Figure 6-14. The higher the pixel value the greater the potential for that area to be saturated with water based upon its contributing area and local slope characteristics. Furthermore, high TWI also reveals the potential for the pixel to be wet before other surrounding and contributing pixels. Therefore, areas with high TWI are more susceptible to flash flooding as compared to those with low TWI. In Figure 6-14 surface water bodies such as lakes also have high TWI. However, these areas are always flooded so they are not included as potential areas for flash flooding.



Figure 6-14: Topographic Wetness Index (TWI) for the study area and the sub catchments.

6.9.3. Combined antecedent soil moisture

Normalised dekadal NDWI combined with normalised SWI from TMI were classified into three classes and the results of this output are presented in Figure 6-15. Areas with high values of NDWI and SWI were given high weight of 3 and those with low SWI have a value of 1. Both results showed high SWI in lower areas of the catchments because these areas have alluvial soils which can keep moisture for a longer time.



Figure 6-15: Classified combined dekadal NDWI and dekadal TMI.

6.9.4. Combined TWI, rainfall anomaly and antecedent soil wetness

Results of daily rainfall anomaly maps for 12 July 2009 and 11 August 2012 which were generated from the difference between daily mean climatological RFE and satellite corrected daily mean are presented in Figure 6-16. Point to note is that each map was classified into 5 classes basing on its minimum and maximum anomaly. All the satellite products estimated high rainfall amounts close to the coast for the 12 July 2009 resulting in high anomalies also in these areas. However, for the 11 August 2012 event TRMM3B42 recorded highest rainfalls in the interior around the Breede catchment. The results of these rainfall anomaly maps are in accordance with interview results from the relevant agents about areas prone to flash flooding. Furthermore, there was also high rainfall in the catchments which were captured by all the satellite products respective of the day of the event and where the flash flood had occurred.



Figure 6-16: Satellite classified daily rainfall anomaly maps for 12 July 2009 (top) and 11 August 2012 (bottom)

The final product of flash flood potential areas is shown in Figure 6-17. Potential areas were classified into four classes based on their ability to generate high and efficient runoff, antecedent wetness soil moisture and high rainfall intensity. Areas which have an extreme potential to flash flooding have an index from 0.8 to 1 and the least have an index between 0 and 0.2. Most of these areas are those which are close to the coast as shown by the 12 July 2009 event. These results are in support to what Midgley et al. (2005) got in their study for assessment of climate change in the Western Cape Province. CMORPH and MPE estimates for the event of 12 July 2009 show almost the same areas which have high potential for flash flooding. On this day TRMM 3B42 misses some of the interior rainfall which was captured by CMORPH and MPE. During the 11 August 2012 event all the satellite products picked the rain estimates of this event. This could be because the event occurred almost at the end of the winter season and could have been of convection type and not of cut off low pressure systems.



Figure 6-17: Flash flood potential areas based on TWI, antecedent soil moisture and rainfall anomaly on 12 July 2009 and 11 August 2012 respective to satellite rainfall product.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

High rainfall intensity of short duration on saturated soils as well as on steep slopes favours flash flood potential. The integration of spatial layers of all the favourable characteristics for flash flooding results in the mapping of flash flood potential areas in the Western Cape of South Africa. The focus of this study was to improve the accuracy of satellite rainfall fields by correcting for their bias with local gauge measurements before they are further integrated with antecedent soil moisture and TWI for mapping of flash flood potential areas. Therefore, the impacts of flash floods can be reduced by using near real time satellite products such as MPE to predict their occurrence. However, based on the objectives and research questions of this study the following conclusions and findings were made;

7.1.1. Gauge measurements analysis

- July has the highest amount of extreme rainfall events greater than a threshold value of 30 mm per hour and also receives high rainfall. January has the least in both amount of rainfall and frequency of extreme events.
- Rainfall decreases from south to north and east to west mainly because of topography, warm and wet coastal winds that promote rain bringing clouds.
- There is a great difference in rainfall variability between stations which are in close proximity to each other. Berg catchment receives much rainfall as compared to Breede catchment.

7.1.2. Comparison between gauge and satellite rainfall products

- This study has shown that high temporal resolution satellite products namely TRMM 3B42, CMORPH and MPE are suitable for estimating extreme rainfall events. Generally speaking, the three satellite rainfall products studied here provide similar qualitative spatial distribution patterns of rainfall with different magnitudes of rainfall intensities. Higher correlation shows good timing as well as capturing of high rainfall intensities by both gauge and satellite data sources. TRMM 3B42 slightly overestimates at both 3 hourly and daily time scales compared to gauges but has a low bias.
- RMSE of these products are manageable for flash flood rain events capturing. Nevertheless, satellites and gauges are not expected to measure the same amount of rainfall because of different spatial and temporal resolutions and mechanisms for rainfall measurement. Gauges measure rainfall at a point scale continuously whereas satellites are based on MW and IR algorithms for rain rate estimation at an area average. There are a couple of issues that might have influenced the accuracy of the results. These could be the resampling of the satellite products, network of the rain gauges not adequately representing the pixels of the satellite products and mismatch in pixels due to parallax offsets resulting in satellite products having geo-location errors.
- However, the accuracy improved for all satellite products as the integration time step increases from 3 hourly to daily and seasonal. This improvement shows that even at higher temporal resolutions something can be done to improve satellite rainfall estimates for extreme rainfall prediction.

7.1.3. Calibration and validation of satellite rainfall products with gauges

- Satellite rainfall estimates need to be tested for accuracy and errors before their application in region of interest as well as extreme rain events evaluation. The correlation of satellite rainfall estimates with gauge observations varies from region to region as explained in the literature review of this study. The same satellite rainfall product can be found to overestimate in other region and underestimate in another region. Even in the same catchment TRMM 3B42 was found to both overestimate and underestimate the same event at different stations. The major cause of these differences was found to be variations in rainfall type namely convective, orographic, and frontal and or variations in climate regions across the globe.
- Accuracy of the quantification of areal rainfall field using satellite rainfall estimates was improved by calibrating and validating them with regional rain gauge network. Quadratic regression fitting procedure developed here has improved accuracy of multi-satellite rainfall estimates before combining them with gauge measurements for further analysis. The method proved to be successful in reducing satellite rainfall fields' bias.

7.1.4. Temporal and spatial occurrence of wet areas using NDWI and TWI

- NDWI from VGT 4 Africa can be used to show the temporal trends in wetness over the study area although the product has course temporal resolution (dekadal).
- TWI proves to be a very good topographic indicator for flash flood potential areas. The higher the TWI pixel value the greater the potential for that area to be saturated with water based upon its contributing area and local slope characteristics.

7.1.5. Validation of ASCAT soil moisture product

• ASCAT soil moisture product has low bias as compared to in situ measurements; hence it can be used for temporal and spatial monitoring of antecedent precipitation. However, long term continuous ground measurement and detailed analysis is needed to support these results.

7.1.6. Flash flood potential areas

Flash flood potential areas of the Western Cape of South Africa in the selected catchments can be demarcated by integrating remote sensing products. Areas with greatest potential for flash flooding where found to be those that have received high rainfall when the antecedent soil moisture was high and have steep slopes that increase the kinematic flow of run off to low contributing areas. Topography, antecedent moisture as well as high rainfall intensity promotes flash floods.

7.1.7. Hydro geomorphic properties of the catchments

- It is easy and accurate to analyse morphometric characteristics of catchments using remote sensing data and GIS software such as ILWIS for analysis of flash flood potential. Berg and Breede catchments have slightly different morphometric properties therefore the same amount of rainfall in one of these catchments has different impacts in the other. Berg catchment is a sixth order, long narrowed drainage catchment whereas Breede is a fifth order, circular-shaped basin.
- Higher relief ratio in Berg than in Breede shows that, Berg catchment has a large topographical gradient which is supported by large rainfall variation in the catchment due to orographic rainfall in high areas.

7.2. Recommendations

Basing on the findings and conclusions of this study the following recommendations can be drawn;

- As the extreme intensity of rainfall events in the Western Cape of South Africa can be depicted from remote sensing, it is advised to further studies on the application of remote sensing to predict these events. Although, the satellite rainfall estimates did not perfectly match with the ground measurements, they can still be used to estimate catchment area rainfall in hydrology modelling and catchment water resources management.
- Future researchers can increase gauge network by using gauge measurements from all authorities such as Department of Water Affairs, Agricultural Research Council, South African Weather services and from private farmers.
- Future researchers who propose hydrological modelling of flash floods using remote sensing in the Western Cape of South Africa should opt for MPE since it has high temporal and spatial resolution and provides images in near real time. Nevertheless, its accuracy for near real time monitoring of flash flood events can be improved used quadratic curve fitting tested in this study. Even though TRMM 3B42 has better accuracy as compared to MPE, its product is available at a rolling archive of 3 months before present. Therefore, it is not suitable for flash flood forecasting but rather water resources management.
- The effect of spatial rainfall variability in Western Cape of South Africa using remote sensing should be critically investigated as this study explores this influence in a more rudimentary approach. However, since the satellite data used in this study were not corrected for errors and bias before they were combined with gauges, therefore future studies are recommended to do some bias correction on the satellite data before it is merged with gauges.
- ASCAT on board of METOP A is scanning two 550 kilometres swath widths separated by a gap of 650 kilometres. The satellite's field of view does not cover the study area so the product has to be used in combination with other products such as AMSRE and TMI to improve the estimation of antecedent precipitation. Furthermore, there should be a number of in situ soil moisture stations that measure surface soil moisture continuously.
- Hydro geo-morphometric properties studied in this study can be further utilised in useful hydrological analysis for water resources management.
- Flash flood potential areas demarcated in this study can be validated by the use of aerial photographs taken during the period of the flash flood event. Furthermore, the flash flood index can be used to compute stream hydrographs for flash flood early warning in the studied catchments.

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APPENDICES

Appendix 1: Questionnaire for flash flood occurrence in Western Cape Province

Answer the questions. However, your answers should be guided by the definition of flash flood given as Flash floods are *"Flash floods are natural disasters which are caused by excessive amount of rain falling within a short period of time"*

Section 1: Personal experience of flash flooding 1 a) Do you leave in a flash flood prone area?
b) If yes, where?
State the name of the town. c) Have you experienced flash flooding? Yes If yes, how significant were the impacts? Low Mild 2 a) In which season do they occur? Summer Autumn Winter Spring b) In which period of the season do they occur? Onset Mid c) When was the last flash flood event?
Provide month and year What was the cause of the flooding?
3a) What were the impacts of flash flood in your area? List in the spaces below Answer:
b) Did the floods cause any loss of animal and human life? Yes
Section 2: Open questions In your opinion what are the major contributing factors for flash floods in the named cities? Provide your answer in the spaces below;

Section 3: Thank you

Thank you for taking your time to answer the questions. Return the completed form. For further enquiries, please contact;

Tsitsi Bangira, University of Twente, Faculty ITC, PO Box 217,7500 AE Enschede, The Netherlands



Appendix 2: Satellite rainfall fields for 12 July 1500 hours before (top) and after correction (bottom). Note that each satellite product after and before correction are corresponding.



Appendix 3: Satellite rainfall fields for 11August 2012 2100 hours before (top) and after correction (bottom). Note that each satellite product after an