

Effect of Topography on Rainy season Rainfall Variability over the Blue Nile
River Basin

The Effect of Topography on Rainy season Rainfall Variability
over Blue Nile River Basin

M.Sc Thesis

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Ethiopian Institute of Water Resources

ADDIS ABABA UNIVERSITY

Effect of Topography on Rainy season Rainfall Variability over the Blue Nile
River Basin

The Effect of topography on Summer Rainfall Variability

Blue Nile River Basin

By

Shambel Habte

A Thesis Submitted to the Ethiopian Institute of Water Resources

**In partial fulfillment of the requirements for the degree of
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Management (Surface Water Hydrology)**

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ADDIS ABABA UNIVERSITY

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Statement of the Author

This document describes work undertaken as part of a programme of study at Ethiopian Institute of Water Resource. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the Institute

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signature

Date

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Abstract

The effect of topography on rainfall variability in the East Africa highlands is less studied rainfall processes. 37 rain gauges and 5 complete weather sensors along four transects in the complex terrain region of the Blue Nile River Basin were deployed. The transects span along elevation ranges from about 677 m in lowland areas around the border between Sudan and Ethiopia to 4000 m in the central Ethiopia mountains. High quality summer monsoon rainfall data from the newly deployed rain gauges along each transects was used for this study. Based on the high temporal scale data obtained from the sensors, we presented the effect of topography on the spatial and temporal variability of rainfall across transects, and rain event properties using statistical techniques. Over the Blue Nile basin, the maximum % of hourly rainfall occurrence with a range of 18% to 24% at south west of choke mountain and western edge of the basin namely, Mendi, Nejo, Gimbi and the minimum % of hourly rainfall occurrences is 10.78% at south east of choke mountain .There is high spatial variability of total rainfall depth during the study period over the Blue Nile River Basin which is varied from 471.17mm south east of the choke mountain to 1569.97mm north west of choke mountain near Tana sub bain water divide. There was observed two rain reach zones over the basin, one is at south west of the basin and the other on south west of Choke Mountain. The terrain elevation greater than 2500 m along transects have the capacity to block the moist air movement over the basin. There is high variability of rainfall at relatively high elevation stations compared to low elevations at various temporal scales (15 min, 30 min, 1 hr, 3 hr and daily). Generally low total rainfall depth and frequency is observed from late morning to early after noon (10:00 to 14:00 LST) on each LST and high total rainfall depth and frequency from 4:00 to 7:00 after midnight and 15:00 LST to 19:00 LST during the afternoon while stations at Zanbit, chagni, Anjeni, Kuchit the low total rainfall depth and frequency for each hour during the day is from mid night to late morning and high total rainfall depth and frequency is only during afternoon which are located at the foot and mid elevation of mountain Unlike other station over the basin. The rain event properties, rain event depth, rain event duration, mean event intensity increase as elevation increase while Inter event time decrease as elevation increase. These results on the rainfall variability, effect of topography on rainfall rate and space time variability have significant importance for the understanding of rainfall processes, and its distribution, for evaluation of accuracy of satellite based rainfall estimates, for designing of ways of merging satellite rainfall estimates and ground based observations given sparsely distributed rain gauges.

Keywords: Topography, Transect, rainfall variability, rain event properties, rainy season, Blue Nile River Basin

Chapter One

1. Introduction

1.1. Background

Rainfall and its variability are important constituents of the global hydrological cycle; affect the development of all living organisms on earth. Two-third of the global rainfall falls is in the tropical regions of the earth between 30⁰N and 30⁰S(Kummerow *et al.*, 1998). As a result the tropics play an important role in the global hydrological cycle with high rainfall rates and depth(Fenta, 2010). The occurrence of precipitation in summer African monsoon is further increases with an evident westward streak frequency and a sharp diurnal signal linked to topographic features across all longitudes(Melani *et al.*, 2010). However, Rainfall in a region depends on the amount of moisture brought into the region, the amount of moisture recycled within the region, the extent to which the available moisture condensates to form rain.

Variability of rainfall plays an important role in hydrological processes like rainfall-runoff response, estimation of probable maximum rainfall and erosion processes. Hence, understanding rainfall variability at relevant space and time scales is vital for proper agricultural planning and optimal management of water resources. However, rainfall variability is influenced by non-linear interactions between several factors and its accurate estimation is one of the major challenges in hydrometeorology(Haile *et al.*, 2009b). This is particularly true in mountainous regions where the rainfall pattern may be influenced by orographic factors. For instance, (Buytaert *et al.*, 2006) reported that large variability in elevation, slope and aspect may increase rainfall variability by means of processes such as rain shading and strong winds; (Bitew and Gebremecheal, 2011) reported that the satellite-only Tropical rainfall measuring mission Muli-Satellite Precipitation Analysis Real Time version(TMPA3B42RT)products

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are found to be much better than the satellite-gauge Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis (TMPA3B42) products in terms of their ability in reproducing daily stream flow and suggested to the all algorithm developers to take a deeper look into their bias adjustments techniques especially in mountainous topography and rain gauge sparse region.

A strong relationship existed between elevation and the number of events, regardless of an event's rainfall duration; relatively long rainfall duration events were responsible for orographic rainfall, as measured in rainfall amount orographic rainfall characteristics can be attributed to the higher frequency of relatively weak rainfall intensity events at high elevations (Dairaku et al., 2004). For instance, Understanding of rain event properties at spatial scale have a great importance for hydrologic and climate studies, as rain event properties are affected by terrain elevation particularly the higher quantiles (Haile et al., 2009d); are shown to be significant in infiltration, generation of overland flow, and erosion process (Dunkerley, 2008).

Focusing more attention on rain events and their properties will be able to develop a fuller understanding of how rain events should be identified to yield the most explanatory power in studies of stream flow generation, soil erosion, and other process (Dunkerley, 2008). However, there has been less discipline-specific exploration of the definition and analysis of rain event properties, there geographical and temporal variability.

Rain gauges serve as main sources of rainfall data in many regions. They record rainfall data at discrete points in space and time while they are often sparse and unevenly distributed in space. For instance, (Haile *et al.*, 2009b) reported that the inter-station distance between the rain gauges is larger than the scales of the rainfall , as such the network does not satisfactorily capture the rainfall variability, that has a strong effect on the hydrology of the basin and the spatial

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variability of the rainfall is so large that a few rain gauges are not sufficient to simulate discharge adequately and Simulated discharges are found to be affected by not only network density but also network configuration.

For rainfall monitoring, World Metrological Organization (WMO) recommends an average non-recording rain gauge inter- station distance 25-30 km for flat and 18 km for mountainous areas; an average recording rain gauge inter- station distance 84 km for hilly and 54 km for mountainous areas (Awadallah, 2012) ,such requirement are rarely met in practice in developing country.

In practice, the density and configuration of a raingauge network is determined based on the availability of funds, accessibility of sites and the purpose of the network. Rain gauges in developing countries are commonly installed in towns that are located along main roads that provide accessibility. As a result,relatevily in accessible areas such as mountainous areas remains uncovered by obseravtional network.

In recent decades, rainfall has been extensively studied by using data from different satellite sources as an alternative. However, (Romilly and Gebremichael, 2011) stated that in the Blue Nile River Basin, elevation is one of the major driving factor of bias in satellite rainfall estimate, and to be able to interpolate precipitation there is a need to understand the spatial pattern and influence of topography (Johansson and Chen, 2003).

Topography plays an important role in the spatio-temporal variability of rainfall. As compared to valley areas, mountainous areas are characterized by closely clustered rainy hours, frequent yet small rainfall events(Gebremicheal *et al.*,2007; Dairaku *et al.*,2004). (Dunkerley, 2008) also

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stated that soil loss is less affected by lower rain rates than high rain rates events, this may be offset by relatively frequency of lower rain rates events, indicating that increased attention be paid to low rain rates events, especially where the climatic context suggests that these might be important hydrologically and geomorphologically. However, less has been done on the relation between terrain elevation and rainfall at fine scale (15-minutes, 30-minutes, 1-hourly) and rain event properties.

This has led to extensive research to characterize rainfall variability, rain event properties in relation to complex topography of the Blue Nile River Basin. However, the role of topography in affecting distribution of the rainfall, rain event properties in time and space of the Blue Nile River Basin is not clearly known due to the lack of fine temporal scale (15, 30 minutes, hourly, sub-daily) rainfall observations.

Hence, in this study in situ observation along various transects of the Blue Nile basin, transecting wide elevations ranges (from 600 m to maximal of 4000m a.m.s.l) were used for the analysis. Therefore, the purpose of this study is to assess the effect of topography on rain distribution at various temporal, spatial scales and rain event properties along transect over the basin.

1.2. Significance of the study

For so long, the lack of ground based rainfall data measured at fine spatial and temporal resolution has limited the extent of studies on rainfall variability in relation to topography in the Blue Nile River basin. This study focused on topographical based deployments of new automatic tipping bucket rain gauges along transect at a very fine temporal domain (15 minutes) have made possible study, effect of elevation on rainfall variability, rain event properties (rain event depth, rain duration, mean event intensity, inter event time) possible. This in turn will help

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in the study of rainfall-runoff modeling, runoff generation, soil erosion. In addition to this, in areas where there is sparse and uneven distribution of ground based meteorological stations, recent progress in satellite remote sensing techniques has made it possible to monitor rainfall from satellite data. However, satellite rainfall estimates are known to contain errors arising from several sources (Romilly and Gebremichael, 2011). Quantification and minimization of satellite errors is important to enhance the utility of satellite rainfall products. This requires comparison against independent, high-quality, rainfall data at the same resolution (Romilly and Gebremichael, 2011). Therefore, data collection of this kind will not only provide the possibility of improving satellite rainfall estimation mechanism in the region of study but also gives a clue of need to look forward to new paradigm of rainfall estimation in complex mountainous regions for the scientific communities around the world .

1.3. Study objectives

1.3.1 General Objective

General objective of the study is to detect the effect of topography on rainfall variability at various temporal, spatial scale and rain event properties along all transects over Blue Nile River Basin.

1.3.2. Specific Objectives:

- To detect the effect of topography on rainfall variability over the Basin.
- To evaluate the effect of terrain elevation on rain event properties over the basin

1.4. Research questions

- How does terrain elevation affect spatial and temporal variability of rainfall?
- What extent terrain elevation affects rain event properties?

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1.5. Structure of the Thesis

This thesis is structured in six chapters, in chapter1, the background, significance the study, research objectives are stated. In chapter 2, the relevant studies are stated. In chapter3, the study area which is the Blue Nile River basin of the study area is described and includes description of its geographic and climatic settings, In chapter 4 ,the data type and methodology used to analyzed spatial ,temporal variability and rain event properties related to terrain elevation. Chapter 5, the result and discussion, chapter 6, Conclusion from study and recommendation for future works are stated.

Chapter Two

2. Literature review

In summer (June July August September- JJAS) the Inter Tropical Convergence Zone (ITCZ) is located in northern Ethiopia and the region is under the influence of the southwesterly and southerly .The southwesterly and southerly flows bring moisture from three sources including, low level moisture which is pulled from the Congo vegetation basin, from the Atlantic Ocean and partly from the Equatorial Indian Ocean (Camberlin, 1997). In JJAS, convective activity typically develops over the Ethiopian highlands, while southern and southeastern Ethiopia receives little rain. The spatial distribution of mean total (June July August September) rainfall shows the greatest rainfall over the highlands of western/west-central Ethiopia, the northeast and southeast lowlands being relatively dry (Korecha and Barnston, 2007).

Over the South-western parts of the mountainous areas, an afternoon to midnight maximum rainfall occurrence is observed. However, over the North-eastern part, an afternoon maximum is observed but with relatively lower magnitude. This suggests the existence of orographic influences in the area that leads to rain shadow effect in the mountainous areas facing the Northeast (Fenta, 2010).

(Suzuki *et al.*, 2004) stated that the fluctuations of rainfall distribution depends on various factors concerning atmospheric conditions or topographic features ,i.e., moisture sources, wind speed, wind direction, topographic elevation, slope orientation, barrier characteristics , scale of mountains, and other factors; (Givone and Meignien, 1990) stated that stable air mass may be

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blocked by a barrier, and the collision may occur, during the fall when the lower layers are stable; the rainfall amount is maximal at upwind low lands and foot of hills; (Johansson and Chen, 2003) stated that mountain shading on the up wind side, precipitation was found to increase with increasing with increasing wind speed, confirming the assumption that wind speed is an indicator of the frontal system and thereby of precipitation amounts.

In recent decades, rainfall has been extensively studied by using data from different satellite sources as an alternative. However, (Romilly and Gebremichael, 2011) stated that in the Blue Nile River Basin elevation is one of the major driving factor of bias in satellite rainfall estimate, and to be able to interpolate precipitation there is a need to understand the spatial pattern and influence of topography (Johansson and Chen, 2003). (Fenta, 2010) reported on his satellite based study that high rainfall variability was observed related to variability in topography and two transects over Blue Nile River Basin transecting from north to south and east to west showed more rainfall where observed on wind ward side of high mountain ranges than leeward side over the Blue Nile Basin.

The main problem in validating satellite rainfall estimates in areas with sparse rain-gauge data is that "ground-truth" rainfall cannot be obtained for small spatial and temporal scales due to the extreme intermittence and variability in space-time rainfall over the Blue Nile River Basin (P.Georkakakos et al., 2001). Conway (2000) on his study of Climate and Hydrology of Blue Nile Basin stated that Mean annual rainfall generally decreases moving south-west to north-east and with decreasing elevation.

The average annual rainfall over the Blue Nile basin above Roseires is about 1600 mm. It increases from about 1000 mm near the Sudan border to about 1400-1800 mm over parts of the

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upper basin, in particular in the loop of the Blue Nile below Lake Tana, and above 1800 mm in the south within the Didessa basin. This revealed that the two main areas of high annual water surplus in Ethiopia are within the Nile basin in the Didessa and near Lake Tana(Sutcliffe and Park, 1999)

Climate in the highlands is strongly influenced by the effects of elevation which makes the basin ideal for estimating climatic variables based on empirical relationships with elevation (Conway, 2000)

Haile *et al.*,(2009b) reported that the median of Inter-event time (IET) (i.e. the dry period between two rain events) is 27 times the specified Minimum inter event time (MIT) which is 30 minutes for study over Gilgel Abbay watershed in the source of Blue Nile River. These shows that changing the MIT value to 1 hr will not largely change the statistics of the estimated event properties.

Chapter Three

3. Description of the Study area

The Blue Nile Basin is the source region of the Blue Nile River and drains a large area of the central and south-western Ethiopian Highlands. It is the largest river basin in Ethiopia in terms of volume of discharge and provides a vital source of freshwater to the downstream users, Sudan and Egypt (Conway, 2000). The basin is characterized by complex topography consisting of rolling ridges and flat grassland areas with twisting streams that waterfall over vertical sides of the gorge. The area is located between $7^{\circ}44'32''$ to $12^{\circ}45'19''$ North latitude and $34^{\circ}29'20''$ to $39^{\circ}48'17''$ East longitude. The total drainage area of the basin is about (176 000 Km²) as extracted from 90 m resolution Digital Elevation Model (DEM). The grades are steepest in the highland region and become flatter along the lowlands. The basin has elevations ranging from 435 m in low land between Sudan and Ethiopia boarder to 4235 m in the choke mountain. The livelihood of the people in the basin is heavily dependent on rain fed agriculture and small scale irrigation scheme. The Blue Nile River runs from its origin, Lake Tana, to the Sudanese border and meets the White Nile River at Khartoum, Sudan. The river has cut a deep and twisty route through the central Ethiopian Highlands and in some places its gorge is around 1 km deep. More than 85 % of the Nile River flows originate from the Ethiopian highlands and among the tributaries to the main stream of the Nile River, the Blue Nile River is the major tributary contributing about 60 % of the flow. The major tributaries of the Blue Nile River in Ethiopia are Gilgel Abay, Megech, Ribb, Gumera, Beshilo, Welaka, Jemma, Muger, Guder, Fincha, Didessa, Anger, Dabus and Belles see Fig. 2.

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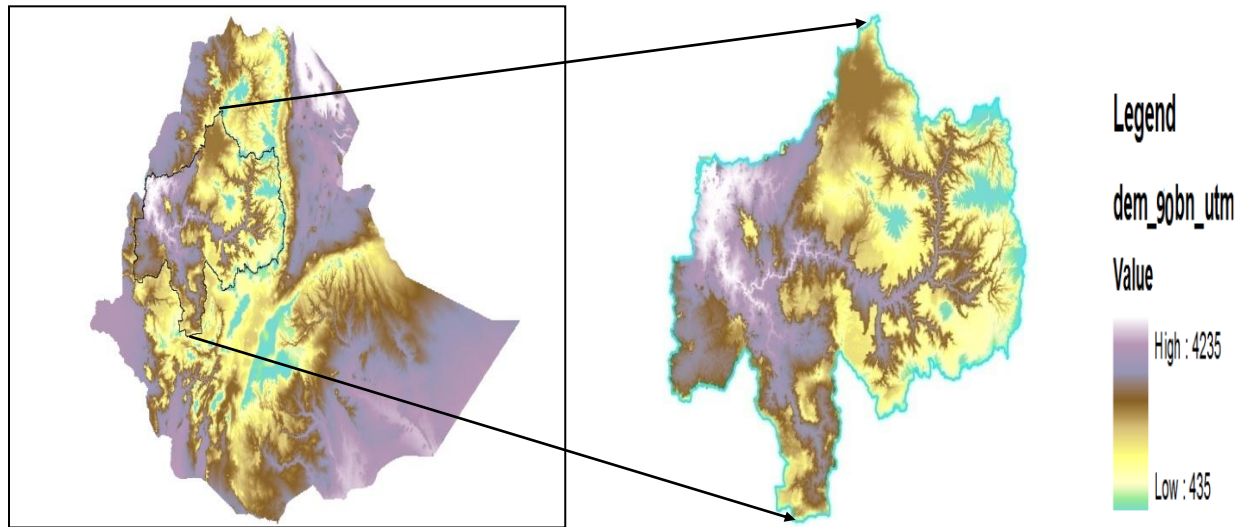


Figure 1: Location and DEM of Blue Nile Basin.

The Blue Nile River Basin is the largest river basin in terms of volume of discharge, second largest in terms of area in Ethiopia and contributes the greater part (about 60%) of the flow of main Nile (Sutcliffe and Park, 1999). The climate of the basin varies from humid to semi-arid. Because of widely varying topography of the basin, elevation strongly influences the climate and human activities of the basin (Conway, 2000). In the entire basin the wet season is from June through September with 70% of the annual rainfall and the dry season is from November through April while October and May are transitional months from the wet season to the dry season and from the dry season to the wet season respectively (Conway, 2000). The study area is an extension of the typical agro-climatic profile of Choke mountain, which is situated about center of the basin and extends from the cold and wet upper zones (Wurch, 4000 m) to the hot and moist/dry lower zones (Kolla, 600m) of the Blue Nile River Basin (Zelege and Hurni, 2001). The basin is characterized as a humid climate and strong inter tropical convergence zone (ITCZ) which is a rain producing feature and there is wide range of seasonal rainfall distribution in the basin (Conway, 2000).

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The Rivers in the south and south-western parts (e.g. Dabus, Anger and Didessa) have longer flow periods and larger dry season flows. These runoff patterns suggest the spatial variability of rainfall distribution in the basin with longer wet season in the south-west and shorter wet season in the north and northeast (Conway, 2000; Sutcliffe and Park, 1999).

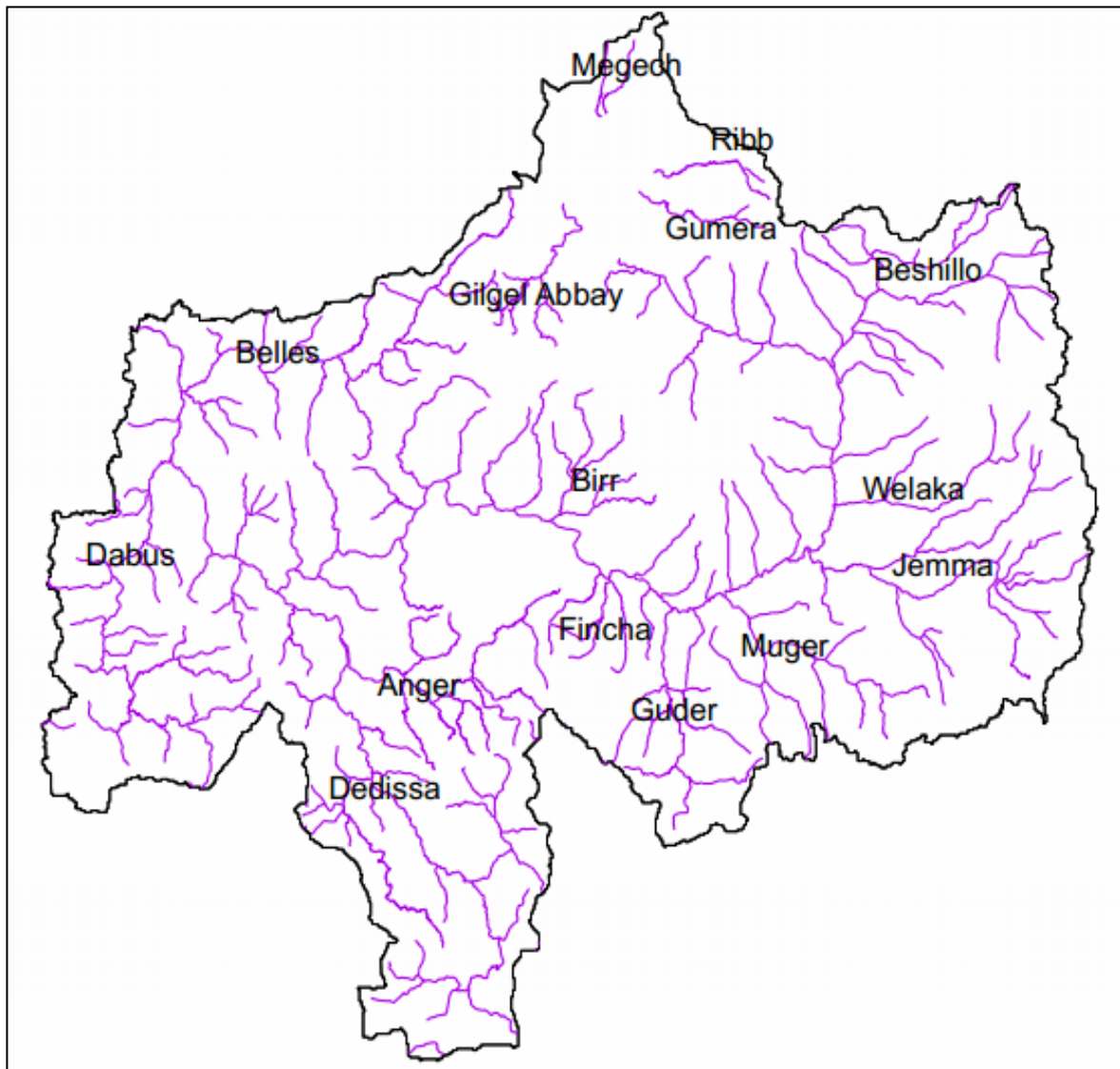


Figure 2: Major tributaries of the Blue Nile River

Chapter four

4. Data and Methodology

4.1. Data

The data for this particular study was collected in the summer of 2012 by the researcher himself through a Blue Nile basin data collection project led by the Ethiopian Institute of Water Resources (EIWR). The locations of the climate stations deployed by the institute shown in Fig. 3, laid over 90m Digital Elevation Model acquired from USGS.

a) Rainfall

In June 2012, the Blue Nile research team at EIWR installed 53 self recording rain gauges (Hobo RG3) in the valley and mountain area the Blue Nile River Basin, out of which 37 rain gauges are laid along four specific transect over the basin shown in Fig. 5& 6, their profile along transects are shown in Fig.7, 8, 9&10. The rests are within selected low land grid ($0.25^0*0.25^0$) and selected watershed over the basin. The rain gauges have a funnel diameter of 15.24 cm, work under tipping-bucket mechanism with a resolution of 0.254 mm, and a measurement range of 0–12.7 cm/hr. Out of the 37 rain gauges, 32 rain gauges provide complete observations during the study period. The rain gauges (namely, Abbay gorge, Yecherekatsion ,Finote selam, Haro hobora and Jiga), did not provide observations during the study periods from 10 July to 20 August ,15 August to 1 September, 13 August to 30 September, 15 June to 30 September 2012 respectively because of human interference. We exclude these stations from the analysis since the data cover a time period much smaller than the time period of our study, which extends from 8 July to 30 September 2012. One of the stations installed at Choke Mountain (4000 m a.m.s.l), which is considered to be the highest elevation of the Blue Nile basin. A typical rain gauge and weather

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station installed in the region are shown in Fig. 3&4 and the Characteristics of the location of the rain gauge stations shown in Tab.1 are based on Global Positioning System (GPS) reader.

Table 1: Characteristics of the location of the rain gauge stations.

Station ID	Location	Easting	Northing	Elevation	Transects	Remark
10	UKE	36.525650	9.374460	1390	1	
11	DORO HOBORA	36.649440	9.759750	2206	1	
12	Haro Hobora	36.869250	10.044190	2024	1	no full data
13	Abbay Brige	37.013750	10.292600	826	1	no full data
07	humusit	37.298650	10.545750	2002	1	
31	Dangber	37.321300	10.814700	2067	1	
27	Amestegna	37.300000	10.746000	2094	1	
26	Mekesegnt	37.331700	10.788100	2184	1	
38	Leba gedel	37.381000	10.953200	2027	1	
37	Zanbit	37.404100	11.056500	2778	1	
18	Mendi	35.100000	9.780000	1694	2	
19	Najo	35.450000	9.500000	1880	2	
20	Gimbi	35.834495	9.169046	1843	2	
21	Bako	37.053333	9.120333	1656	2	
22	Gedo	37.457500	9.021000	2523	2	
14	Sherkole	34.786100	10.594910	811	3	
15	Wenbera	35.665020	10.623440	2517	3	
16	Zigh	36.158470	10.673040	1351	3	
17	Ayehu	36.784600	10.665100	1759	3	
30	Mankusa	37.177400	10.699000	2000	3	
23	Finoteselam	37.278100	10.682500	1850	3	no full data
NO ID	Jiga	37.371031	10.672000	1818	3	no full data
35	Anjeni	37.530400	10.679200	2417	3	
52	Yecherekatsion	37.543700	10.610000	2267	3	no full data
50	Kuchit	37.712480	10.620230	2941	3	
53	Choke	37.839860	10.648880	4000	3	
49	Tebamet	38.144400	10.641670	2670	3	
51	Tenguma	38.213550	10.618760	2468	3	
01	Fiche	38.750000	9.765000	2775	4	
02	G/guracha	38.422900	9.806980	2558	4	
03	Gowha	38.255100	9.997800	2516	4	
04	Hidasse Brige	38.189711	10.078636	1153	4	Jica(Not Available)
05	Dejen	38.149360	10.172540	2452	4	
06	Fendika	37.611400	10.360500	2305	4	
07	Humusit	37.298650	10.545750	2002	4	
30	Mankusa	37.177400	10.699000	2000	4	
08	Chagn	36.498520	10.968340	1624	4	
09	Trakon	35.864900	11.169000	814	4	
44	Abraham	35.439600	11.200360	703	4	
43	Yabulu	35.372680	11.205320	677	4	

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Figure 3: Typical tipping bucket type automatic rain gauge

b) Wind direction.

In July 2012, we installed 5 weather sensor stations along T3, transecting choke mountain from west to east wards and measures wind direction, wind speed, temperature, solar radiation, relative humidity at 15 minute fine resolutions. For our analysis we used wind direction for detecting cloud movement.



Figure 4 : Typical Automatic Weather station

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4.2. Methodology

The study was conducted in two steps:

- 1) Deployment of Climate stations and data collection along four transects across the Blue Nile River Basin for rainy season of the year 2012.

To our knowledge, the rainfall in the area has never been monitored at fine temporal and spatial resolution. The sensor installation was topographical based rain gauge network and weather sensors across four transect; transect 1 (south to north), transect 2 (from west to south west), transect 3 (from west to east), and transect 4 (from northwest to south west). The weather sensors are placed along transect 3 which is pass choke mountain (the highest elevation with in the basin). There is high variation of elevation in the Blue Nile River Basin along transect 1, 2,3, 4 (see, Fig 4,5,6, 7). The distance along transects are measured starting from low elevation station along transect to higher elevation station Transect 1(T1) starting from Uke to Zanbit, Transect 2 (T2) from Mendi to Gedo, Transect3(T3) from Sherkole to Tenguma transecting choke mountain, Transect(T4) from Mankush to Fiche). The elevation along T1 ranging from around 1390 m to 2788 m, T2 from 1656 m to 2523 m, T3 from 811 m to 4000 m, T4 from 677 m to 2775 m. Figure 3 shows the layout of the sensors along transects and the sensors are designed to record the data at 15 minute resolutions and down loaded the data in one month interval for safety during the experimental period.

- 2) Data analysis using statistical tools along the four transects line in the Blue Nile River Basin.

The statistical analysis was conducted in three steps:

- a. Analysis of spatial variability of rainfall
- b. Analysis of temporal variability
- c. Understanding of rainfall event properties.

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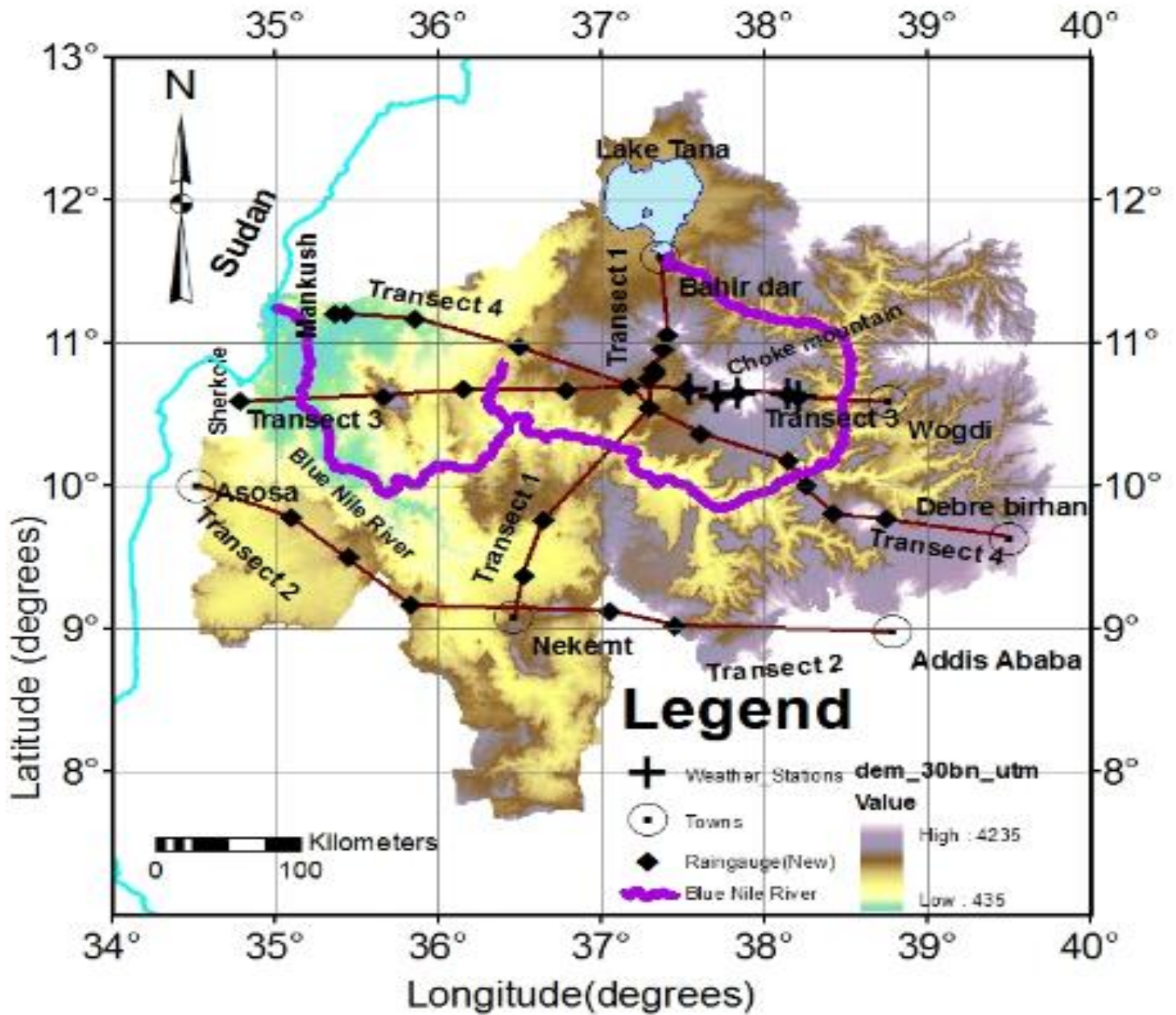


Figure 5: Experimental layouts of climate stations over the Blue Nile River Basin based on rectangular sign for rain gauge stations and plus sign for both weather station and rain gauge.

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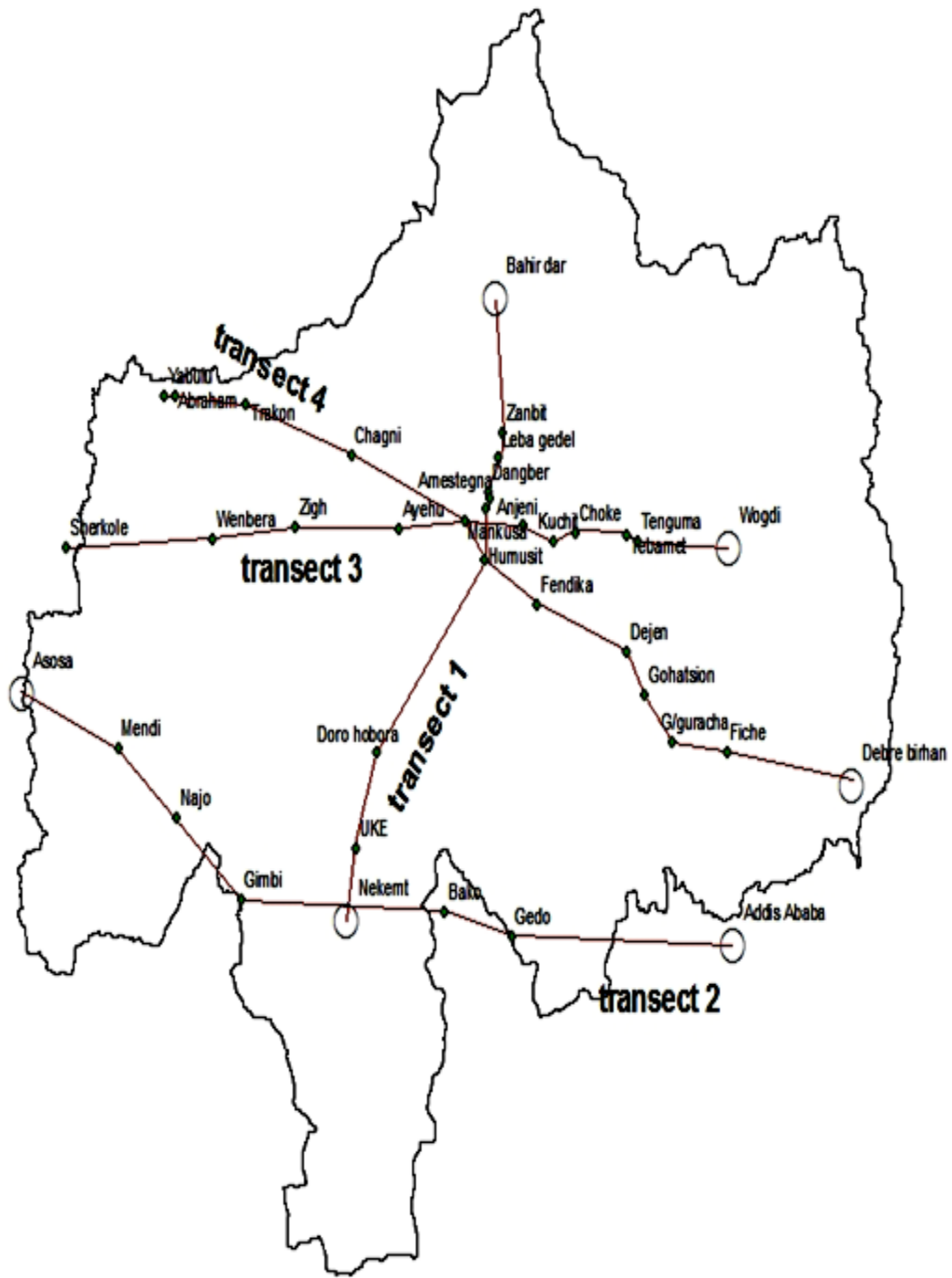


Figure 6: Experimental layouts of climate stations over the Blue Nile River Basin based on station name

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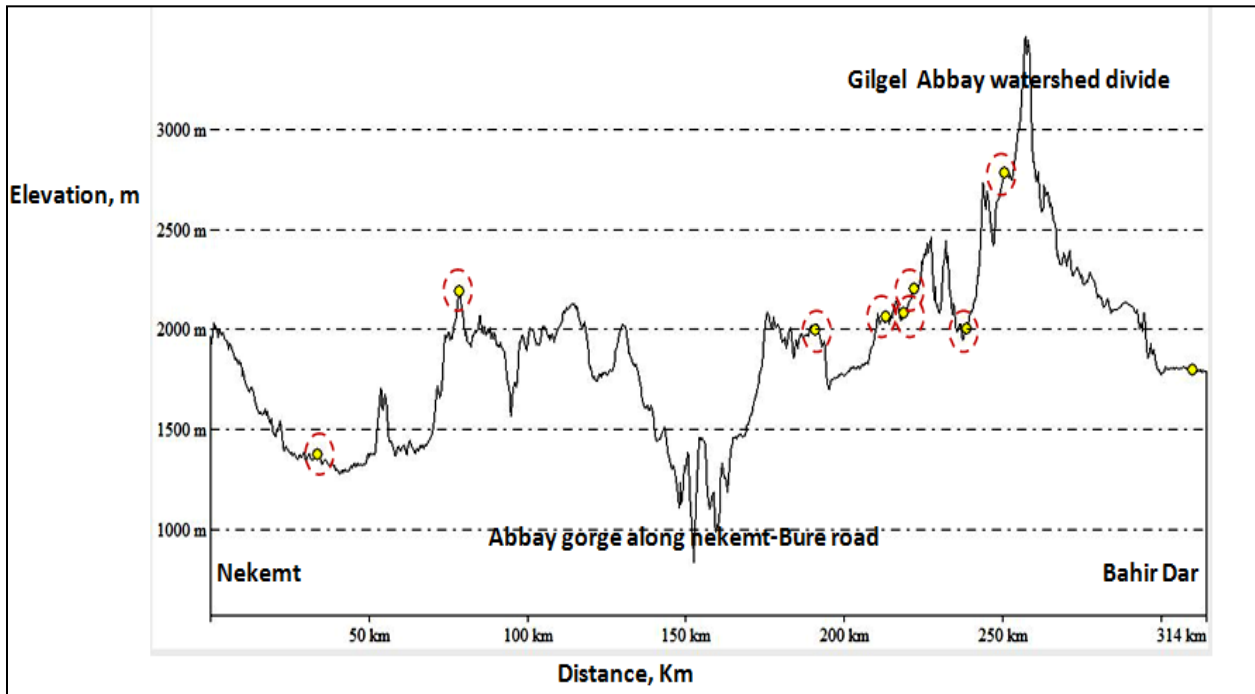


Figure 7: Profile along Transect 1

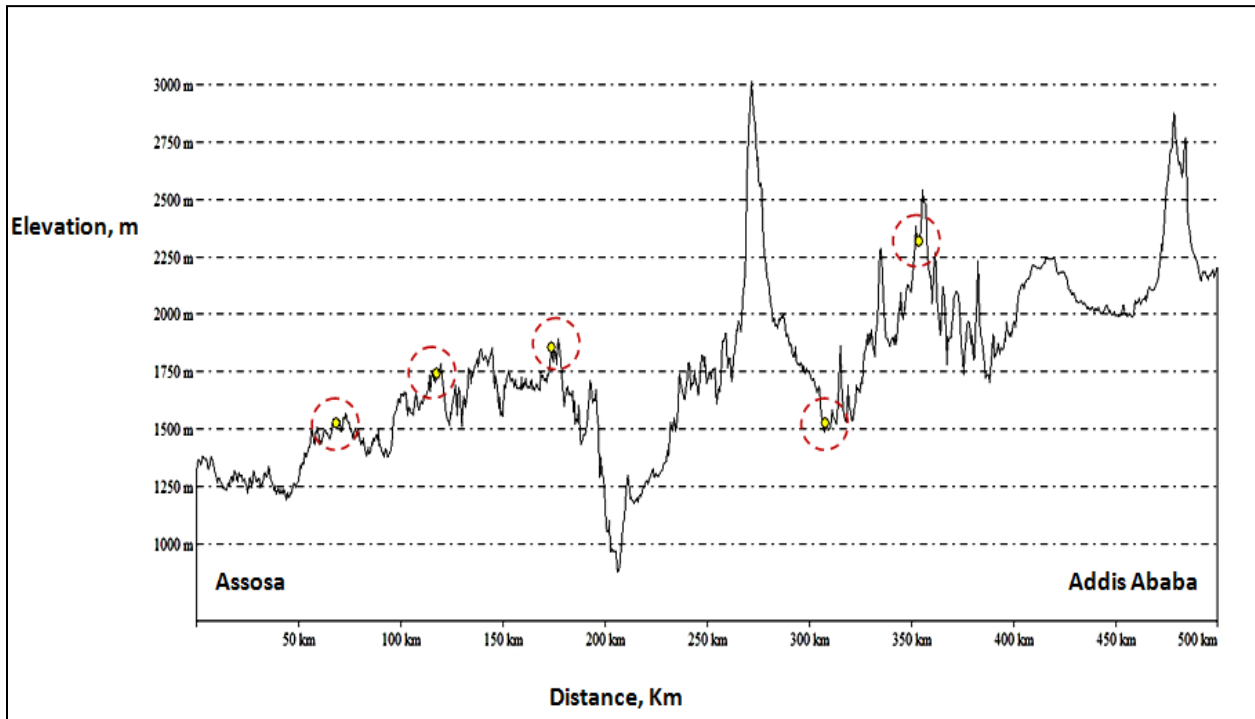


Figure 8: Profile along Transect 2

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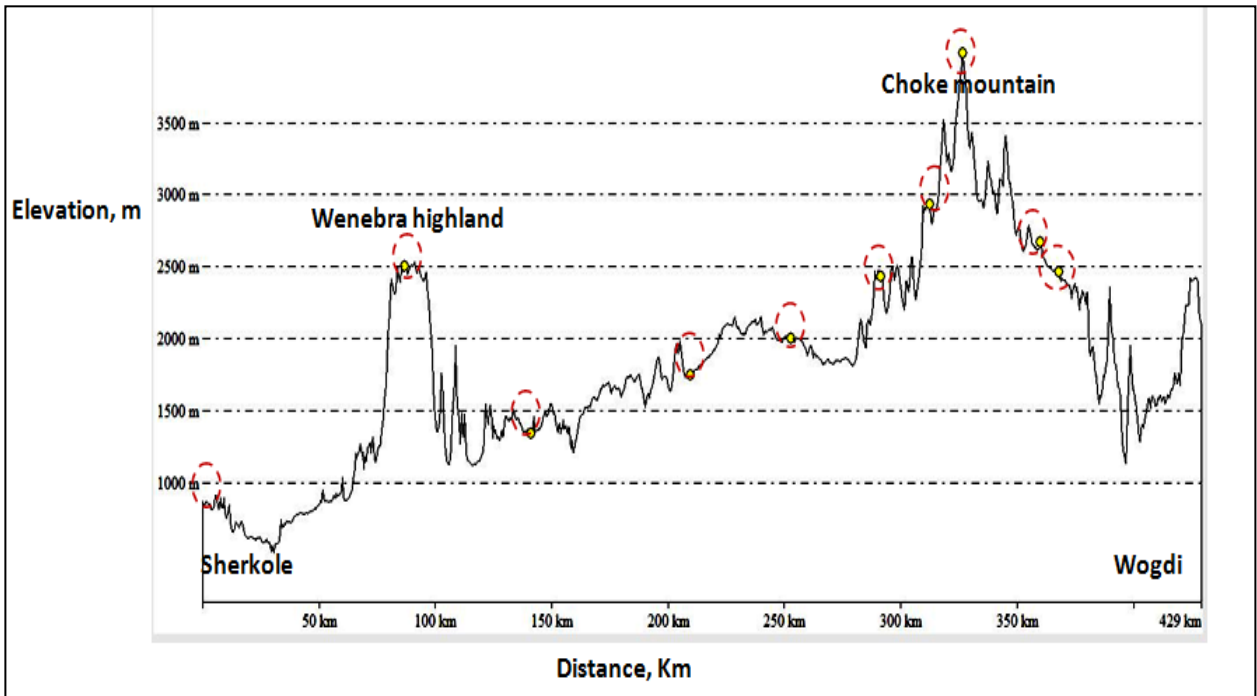


Figure 9: Profile along Transect 3

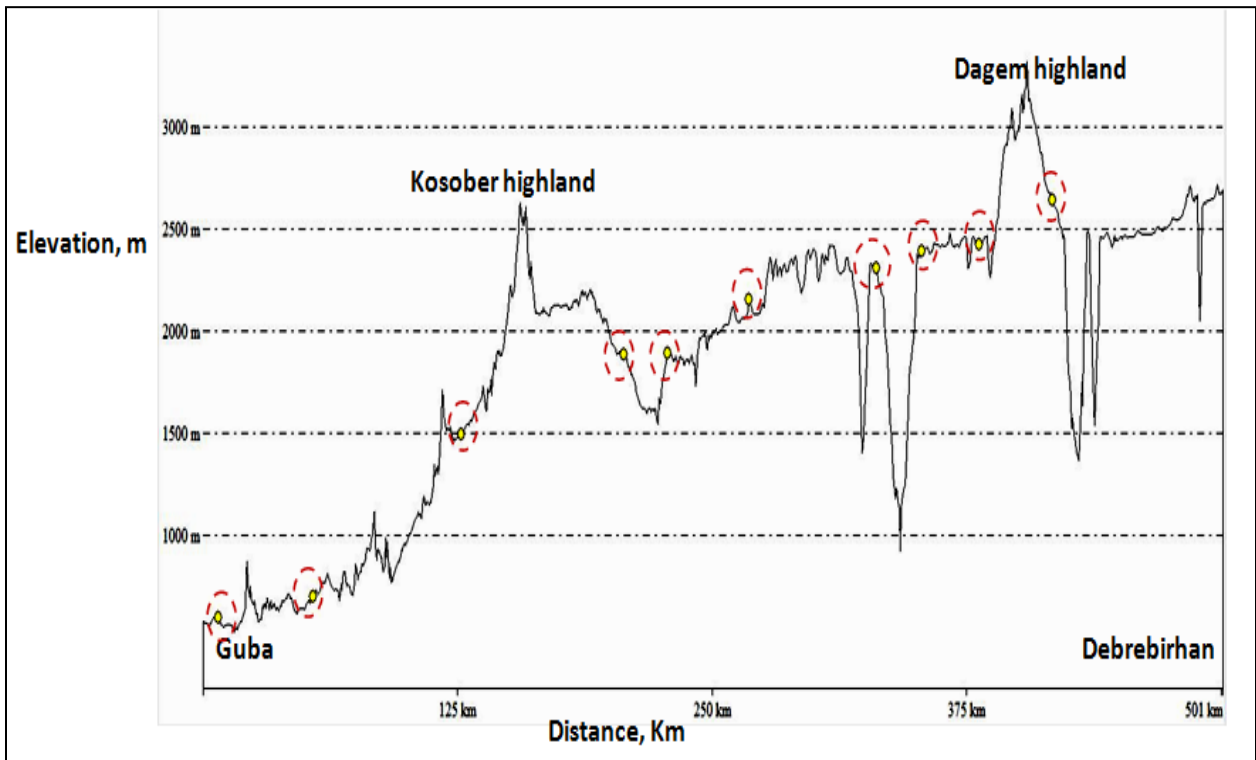


Figure 10: Profile along Transect 4

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4.2.1. Spatial Variability of rainfall

We have used statistical methods to analyze the different aspects of spatial patterns of rainfall. Statistical methods have been applied to the network data to assess the relation between terrain elevation and the effect of mountain orientation on rainfall distribution. For this purpose percentage of rainfall occurrence, Accumulated rainfall, conditional mean rate, coefficient of variation at different temporal scale, dominant wind direction at rainy event within experimental period during 15 minutes resolutions were used (e.g., Gebremichael *et al.*, 2007; Haile, *et al.*, 2009b).

$$\text{Accumulated rainfall (mm)} = \sum_{J=8}^{S=30} R, \text{ Where, } S=\text{September, } J=\text{July, } R=\text{Rainfall depth (mm)}$$

$$\text{Conditional mean rate (mm/hr)} = \frac{\text{Accumulated - rain(mm)}}{\text{number -of - rainy - hours}}$$

$$\text{Percentage of rain occurrence (\%)} = \frac{\text{Rainy - hours - during - study - period}}{\text{Total - available - hours - during - study - period}}$$

$$\text{Coefficient of variation(CV)} = \frac{Sd}{Rd}, \text{ where, } Sd \text{ stands for Standard deviation, } Rd \text{ stands for Mean}$$

for 15 minutes ,30 minutes,1-hour,3-hour,daily resolutions.

$$Rd = \frac{1}{n} \sum_{i=1}^{i=n} Ri, \text{ where } n \text{ stands for total number of data and } Ri \text{ is rainfall depth at 15 minutes, 30}$$

minutes,1-hour,3-hour,daily scale respectively.

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$$Sd = \sqrt{\frac{1}{n} \sum_{i=1}^{i=n} (R_i - R_d)^2}$$

Where n is total number of data, R_i is rainfall depth and R_d is the

Mean at 15 minutes ,30 minutes,1-hour,3-hour,daily resolutions respectively.

4.2.2. Temporal variability of rainfall

To understand the temporal variability of rainfall along transects over the Blue Nile River Basin rain gauge at 1 hour resolution data are analyzed. The accumulated rainfall at each hour of the day (the total rainfall during the study period starting from July 8 to September 30, 2012), frequency of rainfall occurrence (the frequent the rain occurrence) at each hour of the day and the effect of extreme events (maximum intensity) at each hour of the day on diurnal cycle is analyzed (see Haile *et al.*, 2009b).

4.2.3. Relation between rain event properties and terrain elevation

Selected criteria to identify rain events have influence on the properties of rain events; those are rain event depth, rain event duration, intensity of rain events, Inter event time and can change subject to the criteria to identify events (Dunkerley, 2008). Commonly, the minimum inter event time (MIT) and depth serves to identify rain events or classify a series of observations as a single event. Dunkerley(2008) reviewed number of criteria (minimum inter event time, event depth) and reported that the applied MIT varies from 3min to 24 hr while the event depth varies from the measurable amount that is the resolution of the rain gauge to 13.0 mm .Recently the issue of how rain events are delimited becomes critical. Currently there is a range of criteria in use for delimiting events(e.g., In work on canopy interception , events are often only separated if there

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is a dry intervening time (typically 6 hr) considered to be sufficient for canopy to dry completely before next rain event.

Haile *et al.*, (2009d) suggested on his study over Gilgel abbay watershed, changing the MIT value from 30 minutes to 1hr will not largely change the statistics of the estimated event properties. As a result the applied criterion in this study is a minimum inter-event time (MIT) of 6 hour.

The rain event properties that are analyzed in the present study include event depth, event duration, mean event intensity, IET (which is defined as the length of dry period between two consecutive events). These event properties are selected because they are considered to be related to terrain elevation (Haile *et al.*, 2009d) and the relation between rain event properties and terrain elevation are evaluated through coefficient of determination (R^2).

The event depth (d_e) defined as:

Event depth = $d_e = \sum_{i=1}^{Ed} I_i$, Where: Ed is event duration while I_i is the one -15 min rainfall depth at i^{th} 15 minute since the start time of the rain event.

Event intensity = $R_e = \frac{d_e}{Ed}$, where: d_e and Ed are the depth and duration of the rain event, respectively.

IET (Inter-event time) is defined as the length of dry period between two consecutive events).

Event Duration is defined as the time covered by a single event.

Chapter 5

5. Results and Discussion

5.1. Spatial variability

The coefficient of variation (CV) in each station along transect was analyzed and the result is shown in Fig. 11. It is inversely related with elevation consistently at various temporal scale (15 min, 30 min, 1 hour, 3 hour, daily) over all transects. It is due to the variable rain depth observed at low elevation station than high elevation station and suggests that there is high rainfall variability at lower elevation than higher elevation stations (e.g. Haile, *et al.*, 2009b; Gebremichael *et al.*, 2007 ; Romilly and Gebremichael, 2011).

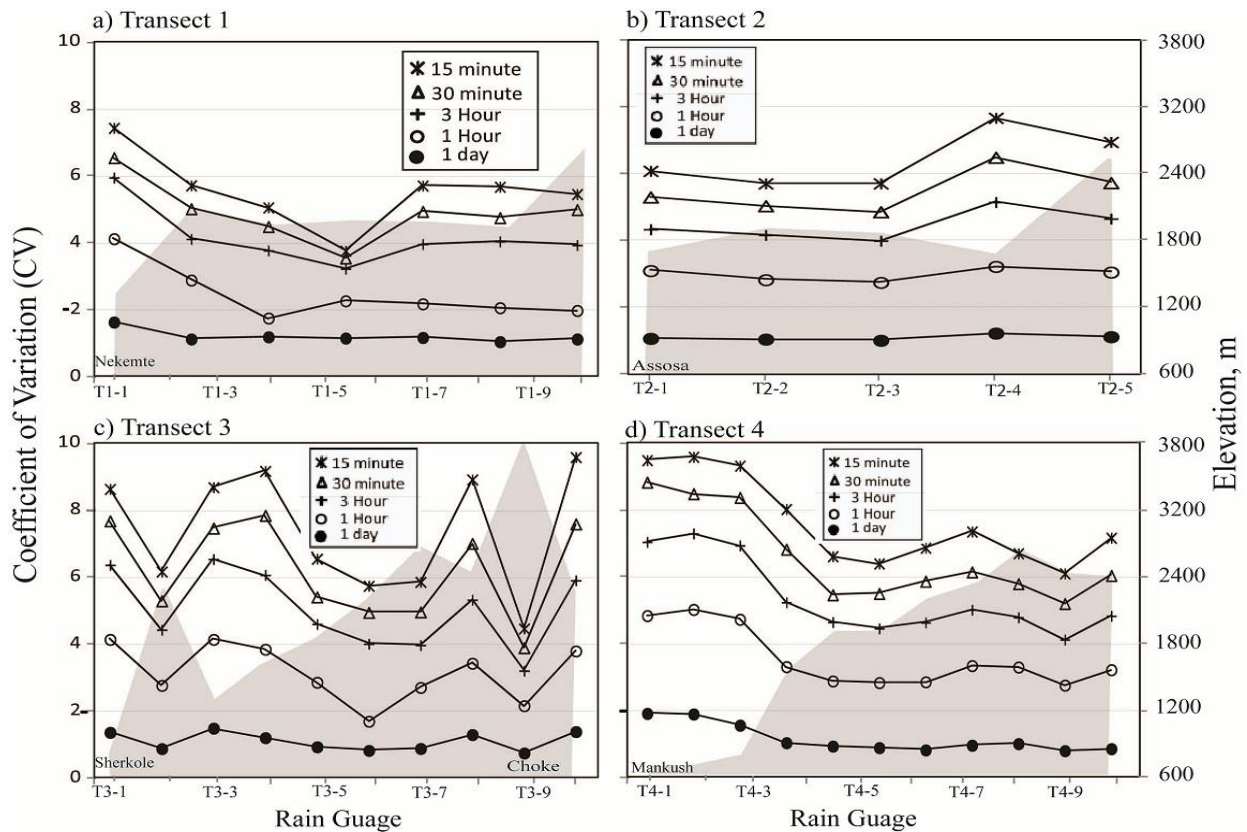


Figure 11: Coefficient of variation at stations along transects at various temporal scale.

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Frequent rain was observed at high elevation stations and at the foot of mountain on wind ward side, which is shown in Fig.12&13.

The accumulated rainfall along transect 1, 3 and 4 is directly related to terrain elevation, with frequent rainfall on the top and at foot of mountain especially because of the mountain acting as barrier. It is also observed that along all transect that local mountain average elevation greater than 2550 m a.m.s.l acting as barrier for the movement of moist air. As a result the stations at the foot of such elevation have got high accumulated rainfall even if the stations elevation is small compare to others along transects. For example, at stations Zanbit (2788 m) in T1, Anjeni (2417 m) in T3 and Chagni (1624 m) in T4 get high accumulated rainfall due to the barrier effect of the choke mountain extension to Gilgel abay watershed divide (3400 m),choke mountain(4000m) and Kosober high lands(2600 m) respectively see Fig. 7,9,10) for blocking effect and See Fig.12&13 for accumulated rainfall and frequency (e.g. Givone and Meignien, 1990; Fenta, 2010). Unlike other transects, transect 2 shows quite different trend in terms of accumulated rain rainfall, which is weekly related to terrain elevation. Even if the elevation is less than 1900 m, high accumulated rainfall was observed and higher elevation at the end of transect have got less accumulated rainfall. This might be attributed to the difference in rainfall process as the transect is at the south western tip of the basin and due to multiple type diurnal peak especially within a day see Fig.21 of stations (Mendi, Nejo,Gimbi).

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Table 2: Spatial rainfall characteristics over the Blue Nile River Basin

Station ID	Location	Easting	Northing	Elevation	Transects	Toatal rainfall(mm)	% of occurrences	Conditional mean	Remark
10	UKE	36.525650	9.374460	1390	1	671.576	14.17	2.32	
11	DORO HOBOR	36.649440	9.759750	2206	1	743.204	16.96	2.15	
12	Haro Hobora	36.869250	10.044190	2024	1				no full data
13	Abbay Brige	37.013750	10.292600	826	1				no full data
07	humusit	37.298650	10.545750	2002	1	471.17	16.72	1.38	
31	Dangber	37.321300	10.814700	2067	1	633.73	19.02	1.63	
27	Amestegna	37.300000	10.746000	2094	1	764.794	22.06	1.70	
26	Mekesegnt	37.331700	10.788100	2184	1	921.766	19.85	2.28	
38	Leba gedel	37.381000	10.953200	2027	1	798.83	19.61	2.00	
37	Zanbit	37.404100	11.056500	2778	1	986.79	18.68	2.59	
18	Mendi	35.100000	9.780000	1694	2	954.786	18.38	2.55	
19	Najo	35.450000	9.500000	1880	2	1051.56	20.15	2.56	
20	Gimbi	35.834495	9.169046	1843	2	907.288	19.90	2.23	
21	Bako	37.053333	9.120333	1656	2	535.432	12.75	2.06	
22	Gedo	37.457500	9.021000	2523	2	582.168	14.17	2.01	
14	Sherkole	34.786100	10.594910	811	3	554.99	12.60	2.16	
15	Wenbera	35.665020	10.623440	2517	3	889.254	20.59	2.12	
16	Zigh	36.158470	10.673040	1351	3	676.91	13.28	2.50	
17	Ayehu	36.784600	10.665100	1759	3	619.506	16.27	1.87	
30	Mankusa	37.177400	10.699000	2000	3	562.356	17.16	1.61	
23	Finoteselam	37.278100	10.682500	1850	3				no full data
no	Jiga	37.371031	10.672000	1818	3				no full data
35	Anjeni	37.530400	10.679200	2417	3	993.61752	24.17	2.02	
52	Yecherekatsid	37.543700	10.610000	2267	3				no full data
50	Kuchit	37.712480	10.620230	2941	3	777.24	20.34	1.87	
53	Choke	37.839860	10.648880	4000	3	711.962	22.94	1.52	
49	Tebamet	38.144400	10.641670	2670	3	509.524	11.32	2.21	
51	Tenguma	38.213550	10.618760	2468	3	484.124	10.78	2.20	
01	Fiche	38.750000	9.765000	2775	4	742.696	13.14	2.77	
02	G/guracha	38.422900	9.806980	2558	4	791.718	17.89	2.17	
03	Gowha	38.255100	9.997800	2516	4	786.13	15.20	2.54	
04	Hidasse Brige	38.189711	10.078636	1153	4				Jica(Not Available)
05	Dejen	38.149360	10.172540	2452	4	740.41	13.04	2.78	
06	Fendika	37.611400	10.360500	2305	4	527.812	18.68	1.39	
07	Humusit	37.298650	10.545750	2002	4	471.17	16.72	1.38	
30	Mankusa	37.177400	10.699000	2000	4	562.356	17.16	1.61	
08	Chagn	36.498520	10.968340	1624	4	949.706	21.91	2.12	
09	Trakon	35.864900	11.169000	814	4	614.934	13.77	2.19	
44	Abraham	35.439600	11.200360	703	4	837.692	13.09	3.14	
43	Yabulu	35.372680	11.205320	677	4	751.078	12.06	3.05	
24	Atiha	37.4144	10.7930	1924		1007.62	21.37	2.31	
25	Gentabo	37.4162	10.8209	1936		915.92	22.16	2.03	Jiga Watershade
28	Gundil	37.1016	10.9418	2584		1569.97	25.34	3.04	Jiga Watershade
29	Ajale	37.2498	11.0161	2613		1208.02	23.63	2.51	Jiga Watershade
33	Bahta	37.4326	10.9060	2047		1029.21	20.39	2.47	Jiga Watershade
34	Senbo	37.4153	10.8498	1985		879.09	19.90	2.17	Jiga Watershade
36	Fere bet	37.6048	10.8485	3001		1227.07	22.65	2.66	Jiga Watershade

Note:

- % of occurrences (percentage of hourly rainfall occurrences)
- Conditional mean (conditional mean rain rate (mm/hour))

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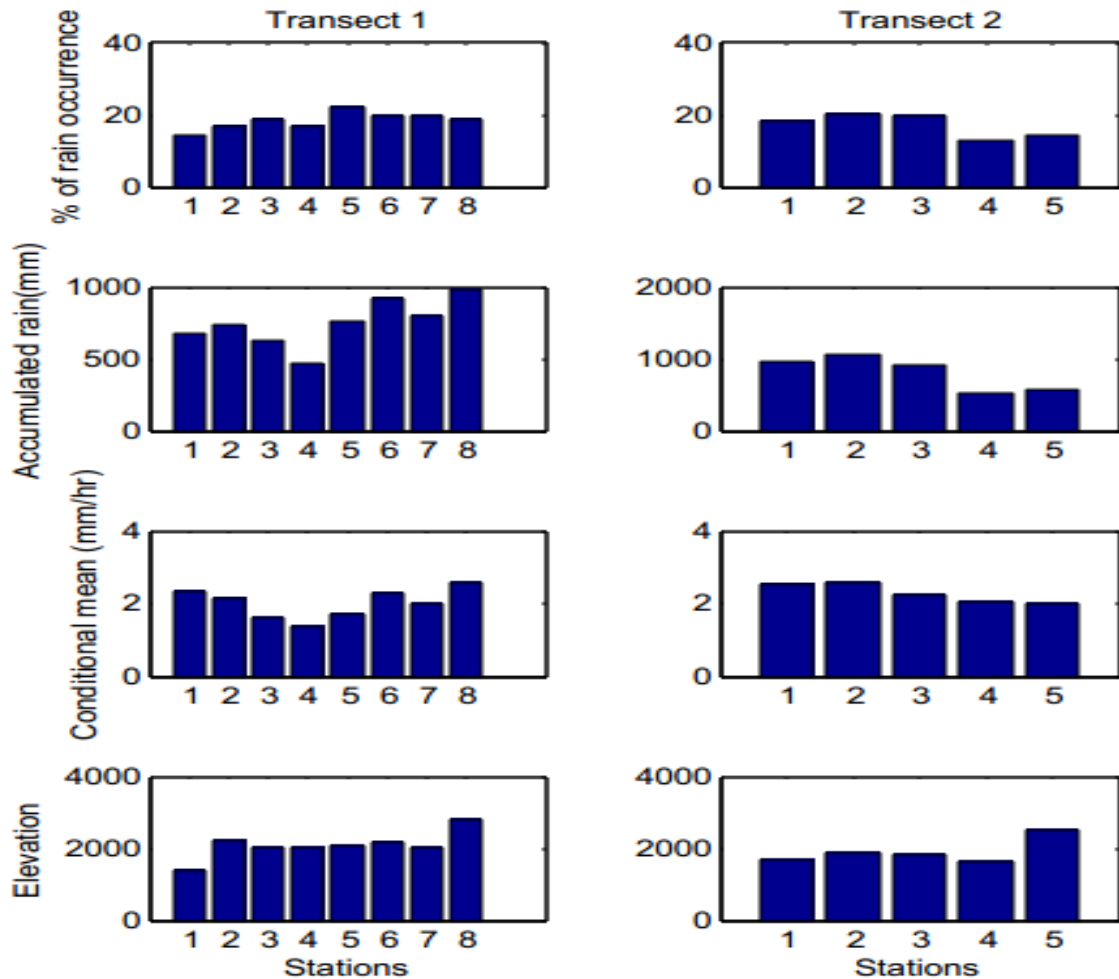


Figure 12: Bar plot of accumulated rainfall, % of hourly rainfall occurrences, Conditional mean rain rate(mm/hr) at each stations along T1 and T2 during period (July 8, 2012 to September 30, 2012) .

It is observed that the percentage of rainfall occurrences have strong relation to geographical location related to local highland orientation and point station elevation. Those with high elevation have got high accumulated rainfall than low elevation. Stations at the foot of mountain at wind ward side has got high accumulated rain due to both the frequent and high intense rainfall see(Fig.7,8,9,10) for transects profile and see (Fig.12&13) for frequency, accumulated rain, intensity (conditional mean rain rate). Low elevation stations obtained high rainfall due to

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intense rainfall for all transect but for transect 2 ,which is at south western edge of the basin have obtained high accumulated rainfall due both high intense and frequent rain even if the stations have low elevation.

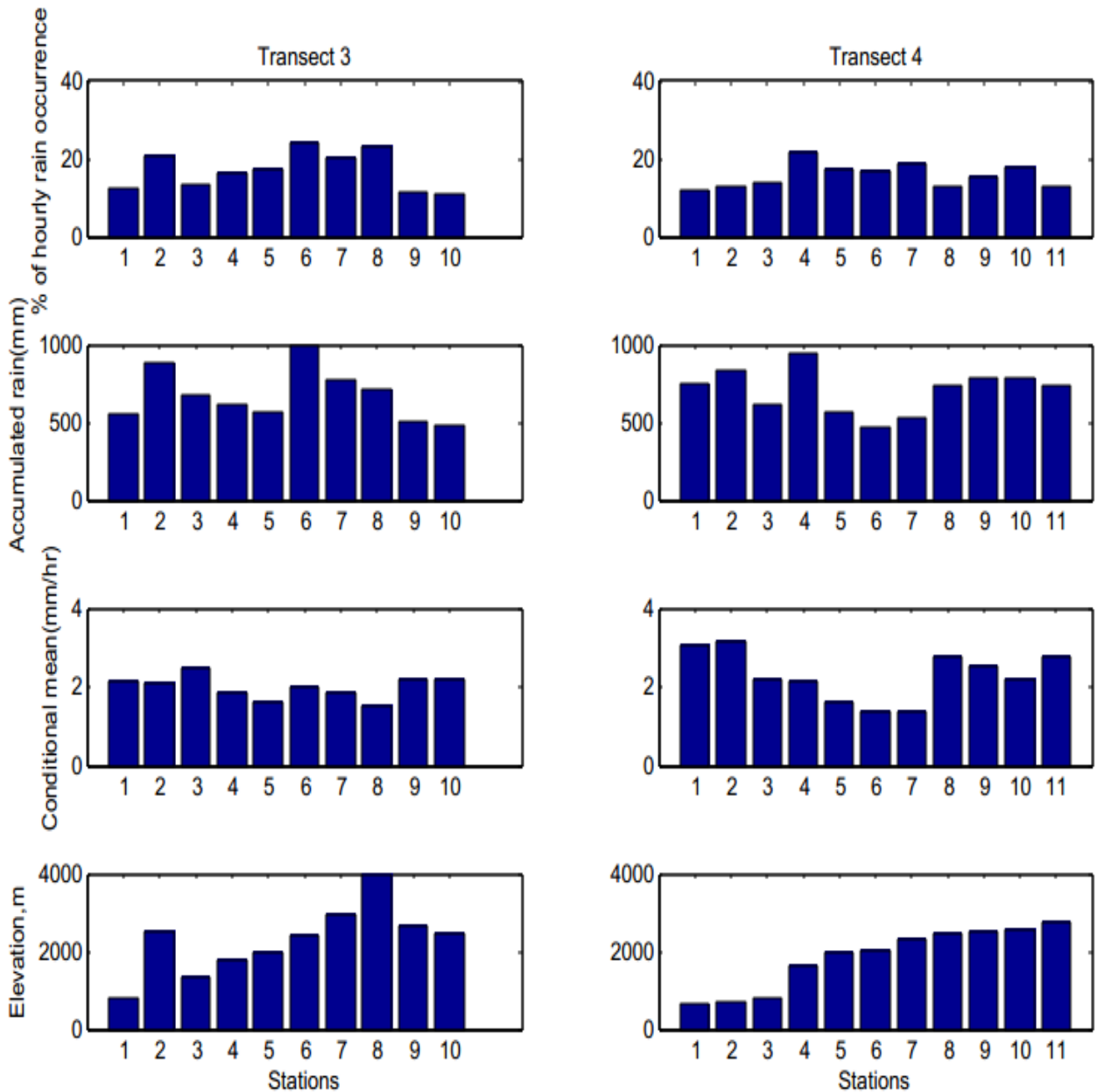


Figure 13: Bar plot of accumulated rainfall, % of hourly rainfall occurrences, Conditional mean rain rate(mm/hr) at each stations along T3 and T4 during period (July 8, 2012 to September 30, 2012) .

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5.1.1. Direction of cloud movement along Transect 3

The direction of cloud movement can be determined by the following approaches:

- a) Auto cross-correlation
- b) Direct wind direction measurement
- a) Auto cross correlation of rainfall.

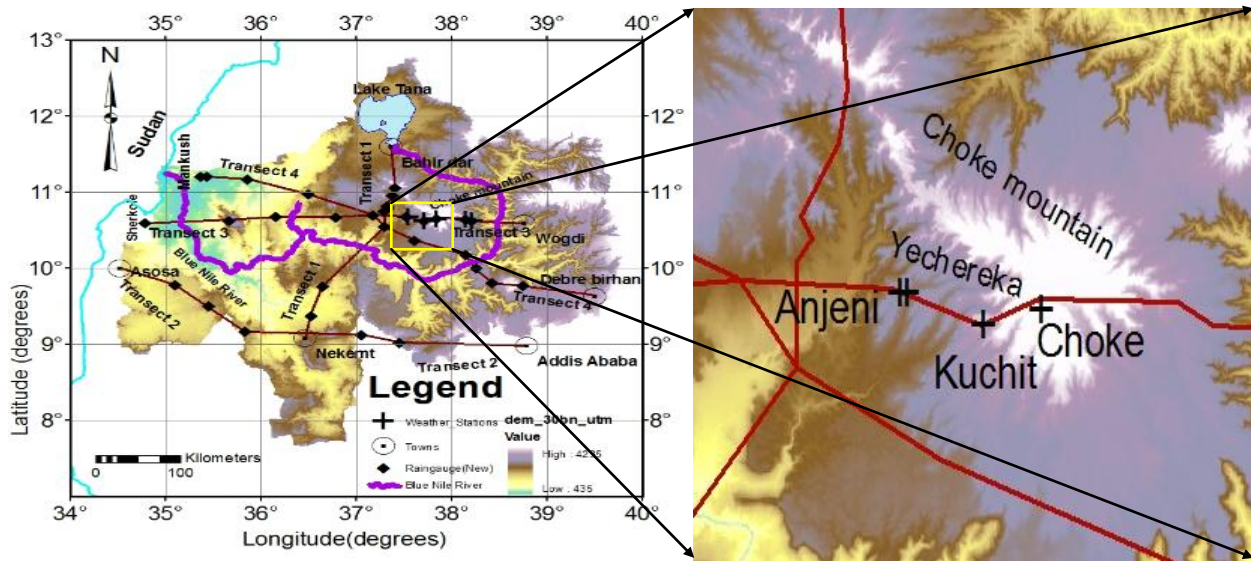


Figure 14: Experimental layout of weather sensors and rain gauges across Choke Mountain along transect 3.

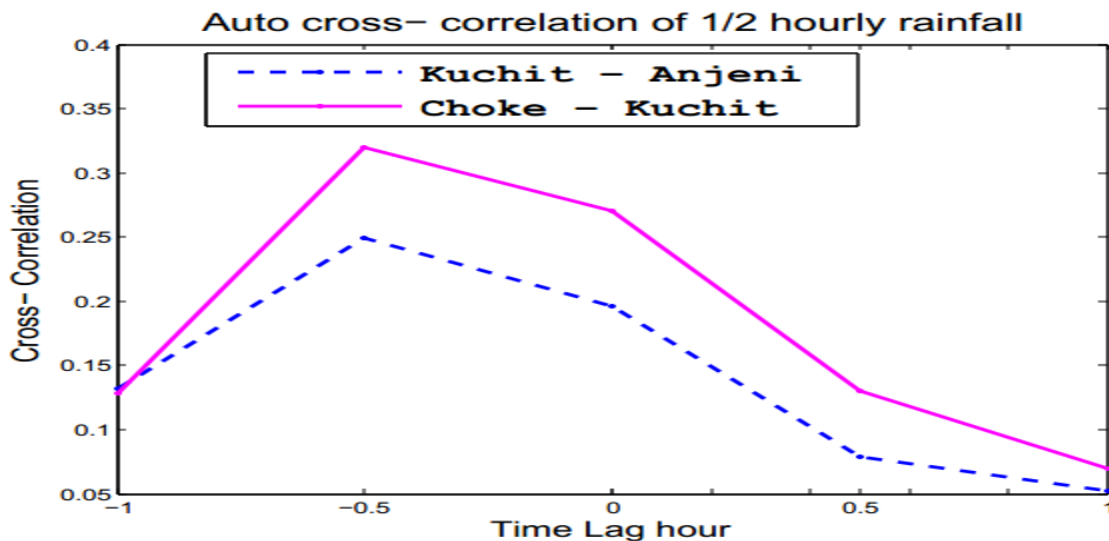


Figure 15: Auto correlation of 1/2 rainfalls

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The -1/2hr -lag cross correlation for Kuchit -Anjeni and Choke Kuchit is higher than the 0-h-lag cross correlation, suggesting movement of clouds from Anjeni to Kuchit and also Kuchit to choke.

b) Wind direction measurement

Wind direction measurement techniques of weather sensors are based on measured angle from true north at fine temporal resolution which is shown in Fig .16.

Histogram is used at selected bin width of 30^0 to get the dominant wind direction at two weather stations namely; Yecherekatsion and Kuchit which is located on the west of choke mountain at the foot and at the mid slope of the mountain respectively see (Fig. 16, 17 and 18).

Figure.14 shows the dominant wind direction at yecherekatsion station when the rain depth at 15 min temporal scale is:

1. $>5\text{mm}$ is 30^0 to 180^0 from true north (north east –south east)
2. $>2\text{mm}<$ rain depth $<5\text{mm}$ is 30^0 to 180^0 from true north (north east –south east)
3. $1\text{mm}<$ rain depth $<2\text{mm}$ is 30^0 to 60^0 and 180^0 to 240^0 from true north (north east and south-south west)
4. $0<$ rain depth $<1\text{mm}$ is 30^0 to 180^0 from true north (north east –south east)

Figure.15 shows the dominant wind direction at Kuchit station when the rain depth at 15 min temporal scale is:

1. $>5\text{mm}$ is 30^0 to 180^0 from true north (north east –south east).
2. $2\text{mm}<$ rain depth $<5\text{mm}$ is 30^0 to 180^0 from true north (north east –south east).

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3. $1\text{mm} < \text{rain depth} < 2\text{mm}$ is 30° to 60° and 180° to 240° from true north (north east and south west).
4. $0 < \text{rain depth} < 1\text{mm}$ is 30° to 180° from true north (north east –south east).

Based on the two approaches, result shows that the dominant wind direction at both stations, Yecherekatsion and Kuchit are (north easterly, south westerly, easterly) direction when rain depth $> 2\text{mm}$ which is the significant for total rainfall. As result the total rainfall during the study period is higher at the wind ward side, which is also agreed with (Fenta, 2010) of satellite based study over the basin.

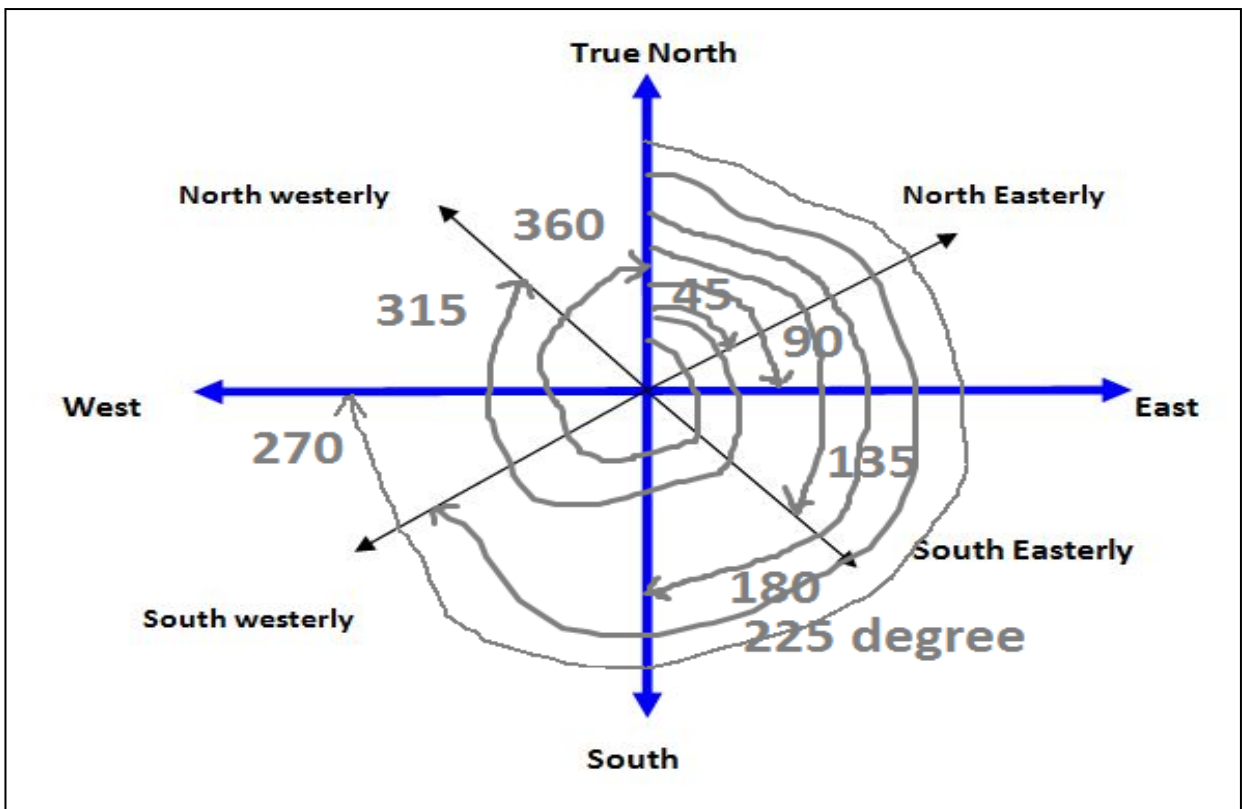


Figure 16: weather station wind direction measurement techniques (Angle from True north)

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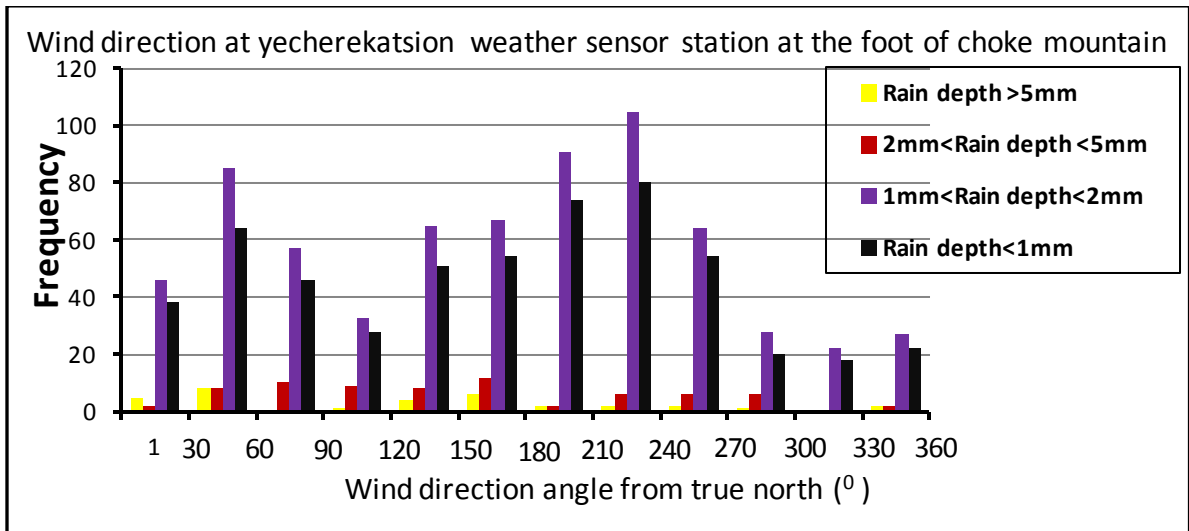


Figure 17: Histogram of wind direction angle at various rain depth scales at stations Yecherekatsion

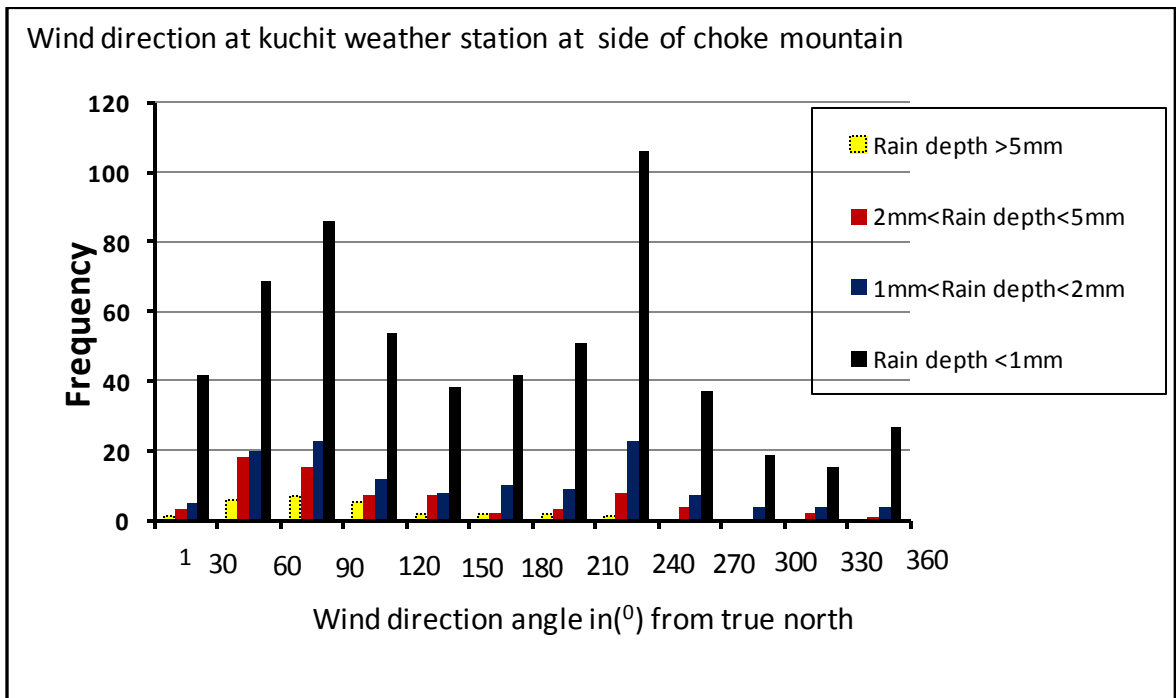


Figure 18: Histogram of wind direction angle at various rain depth scales at stations Kuchit

5.2. Temporal variability

5.2.1. Spatio-temporal variability

The spatio–temporal variability analysis at various temporal resolution between 15 minutes to daily scale along all transects is presented in this section, the terrain elevation along T1,T2,T3 have a direct relation to rainfall occurrence at various temporal scale (15 min, 30 min, 1hr, 3hr, daily) and rainfall occurrences at various temporal scale along T4 showed poor relation related to terrain elevation. The total seasonal rainfall amount at the foot of mountain is higher than stations at side slope and top of mountain, for stations along T1 and T3 is shown in Fig .19 and 20. The rainfall occurrence at (15 min,30 min, 1 hour, 3 hour, daily) scale is higher at foot along T1,T3, T4 and top of mountainous area along T3 as we have station on the top of mountain along T3. It might be the effect of wind direction and barrier effect of local highland. We observed exceptional behavior on T4 which is, relatively low elevation stations like Fendika, Hamusit Mankusa have the higher rainfall occurrence at(15 min, 30 min, 1 hour, 3 hour, daily) scale which might be is due to the location in the south west very close to choke mountain in which moist air movement pass through those stations for contribution for high accumulated rainfall in south west of choke mountain while higher elevation at the beginning of the T4 like Fiche, Gerbguracha, Gohatsion, Dejen fail to show such trends like other transects . But the frequency did not contributed to the accumulated rainfall to be higher within the study period. It might be the movement of cloud over pass through stations and less intense rain. The stations Fendika, Hamusit, Mankusa southwest of Choke Mountain but far from the foot of choke got rainfall of the same frequency as stations located at foot and top of Choke Mountain (Anjeni

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,Kuchit, Zanbit, Choke) but not in magnitude. It is due to the short duration rainfall at stations which have not barrier to block the cloud movement to increase the event duration.

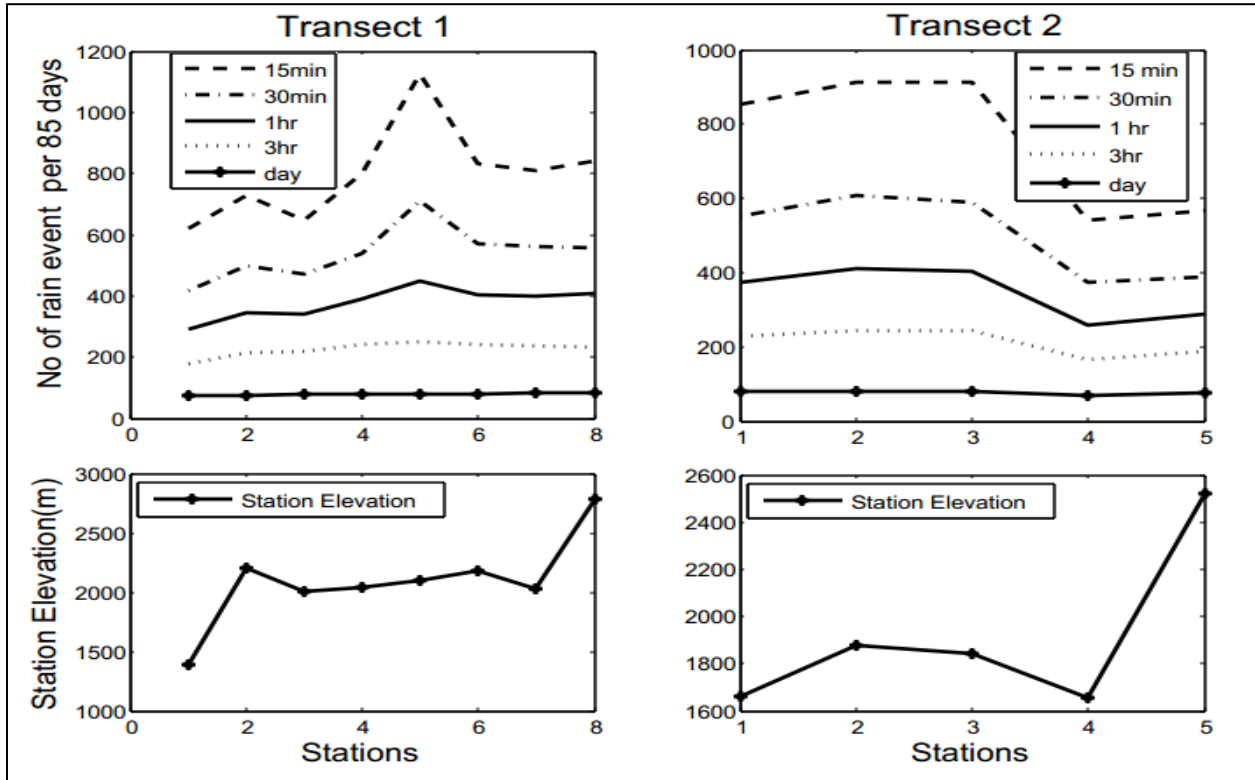


Figure 19: Topographical effects on rainfall occurrences at various temporal scales along T1 and T2.

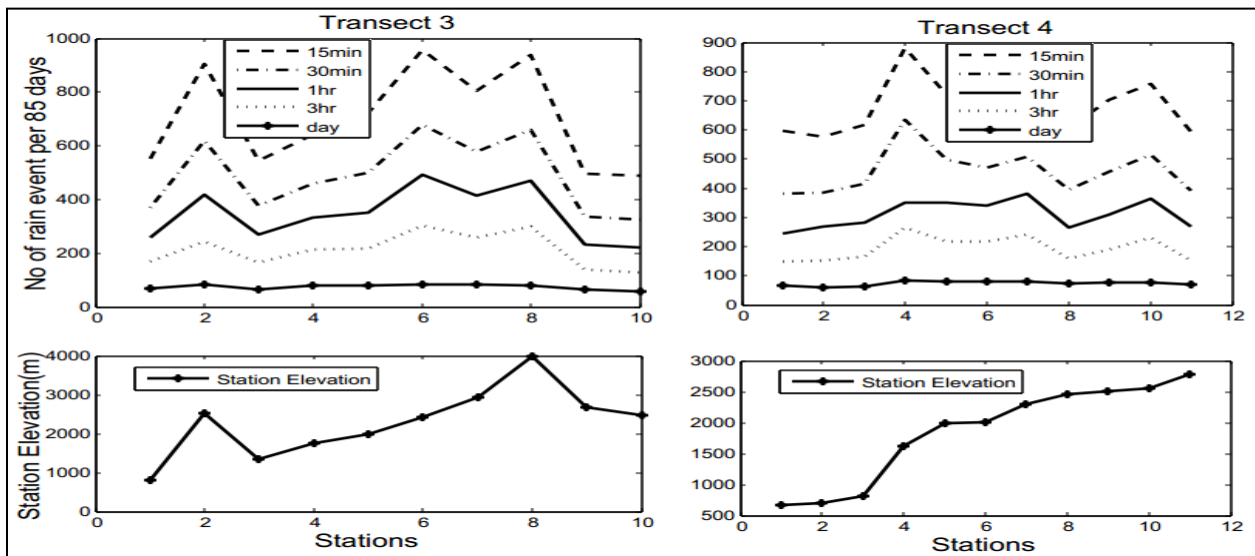


Figure 20: Topographical effects on rainfall occurrences at various temporal scales along T3 and T4

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5.2.2. Diurnal variability

In these section, Figure 21, 22, 23, 24 shows results of the analysis on the diurnal variability of the observed rainfall. The diurnal distribution of total rainfall, frequency and maximum rainfall for each hour of the day during the study period the from 8th July to september 30, 2012 at all stations along all transects are presented in this section. The threshold for rainfall occurrence is assumed to be the minimum resolution of the rain gauge(0.254mm). The frequency of rainfall occurrence is commonly used to assess rainfall diurnal variation and it shows the percentage of rainy hours at each one hour during the day. After analysing the data from 32 stations along T1, T2, T3 and T4 over the basin, the maximum rainfall frequency along T1 was observed between 3:00 and 6:00 LST at the very beginning of the transect on western edge of the basin and 19:00 and 23:00 LST near Tana sub basin water divide or the choke mountain extension. The maximum frequency of rainfall occurrence varied between 29.41% to 42.35%, with the mean of 35.14%. Maximum rainfall has higher contribution for total rainfall in each hour in low elevation station than higher elevation while the frequency of rainfall occurrence has higher effect on diurnal peak along T1. Unlike high elevation station at Zanbit (2788m) end tip of the T1, there was observed frequency less than (5%) and the total rainfall also less than 8 mm throughout the study period between 9:00 to 14:00 LST see Fig .18 while uke stations which is between 12:00 and 20:00 LST, Dorohobora less than(20mm) between 10:00 and 14:00 LST. In general higher elevation stations have small rainfall depth and frequencies for short period compared with low elevation station. In the south-western part of Choke Mountain extension to the Tana sub basin divide, an afternoon to mid night maximum total rainfall and frequent rainfall was observed which is similar to stations along T3 at south-west of Choke Mountain. This is due to blocking effect of

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the mountain to the general air circulation pattern in the Blue Nile basin which is characterized by south-westerly flow. Generally there was observed low total rain depth, frequency, maximum hourly rainfall during late morning to early afternoon while Station Zanbit at mid elevation of choke mountain extension to the Tana sub basin water divide have different behavior that is the maximum rain accumulated rain depth is observed during morning.

Note: (9:00) means the rain depth between 8:00 and 8:59:59 and 24:00 means the rain depth between 23:00 to 23:59:59 for all stations.

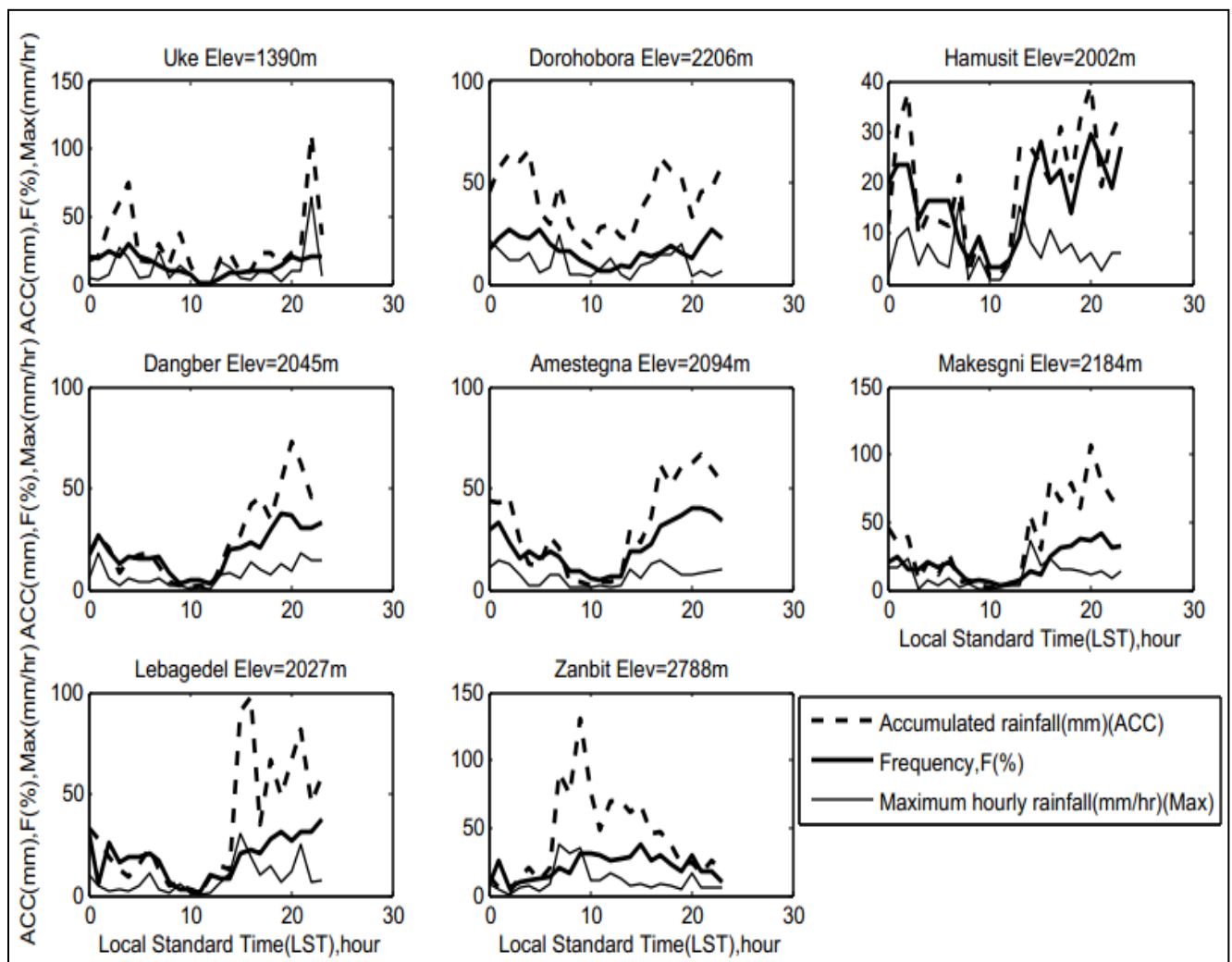


Figure 21 : Rainfall diurnal cycle at stations along T1

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The maximum rainfall frequency along T2 was observed at 5:00 LST at (MNG)stations, at 24:00 Lst (Bako)and at 21:00 LST Gedo stations. The maximum frequency of rainfall occurrence varied between 21.17% to 32.94% ,with the mean of 28.23%. Maximum rainfall and frequency has higher contribution for total rainfall in each hour at (MNG) stations while maximum rainfall only have significant contribution at Bako and Gedo station. (MNG) stations have got higher Accumulated rain like stations near Choke Mountain and have multiple diurnal peaks. The minimum rain observed throughout the study period was at 13:00 (Mendi) less than 10 mm at 10:00 (Nejo) less than 18 mm and at 10:00 and 12:00 (Gimbi) less than 5 mm rain depths see (Fig.22). The high accumulated rain in this (MNG) stations, it is due to frequent rainfall and high intensity, minimum rain duration within a day throughout the study period. Generally in station (MNG) there was observed no rain or minimum rain depth, frequency, maximum rainfall during late morning to early afternoon and accumulated rain depth is observed twice a day; from 4:00 to 7:00 at night and 15:00 to 19:00 LST. Station in T2 namely Bako and Gedo at south tip of transect behave different time of maximum rain depth which is between 22:00 to 24:00 but the minimum rain duration is longer, So that, the stations get small accumulated rain during the study period.

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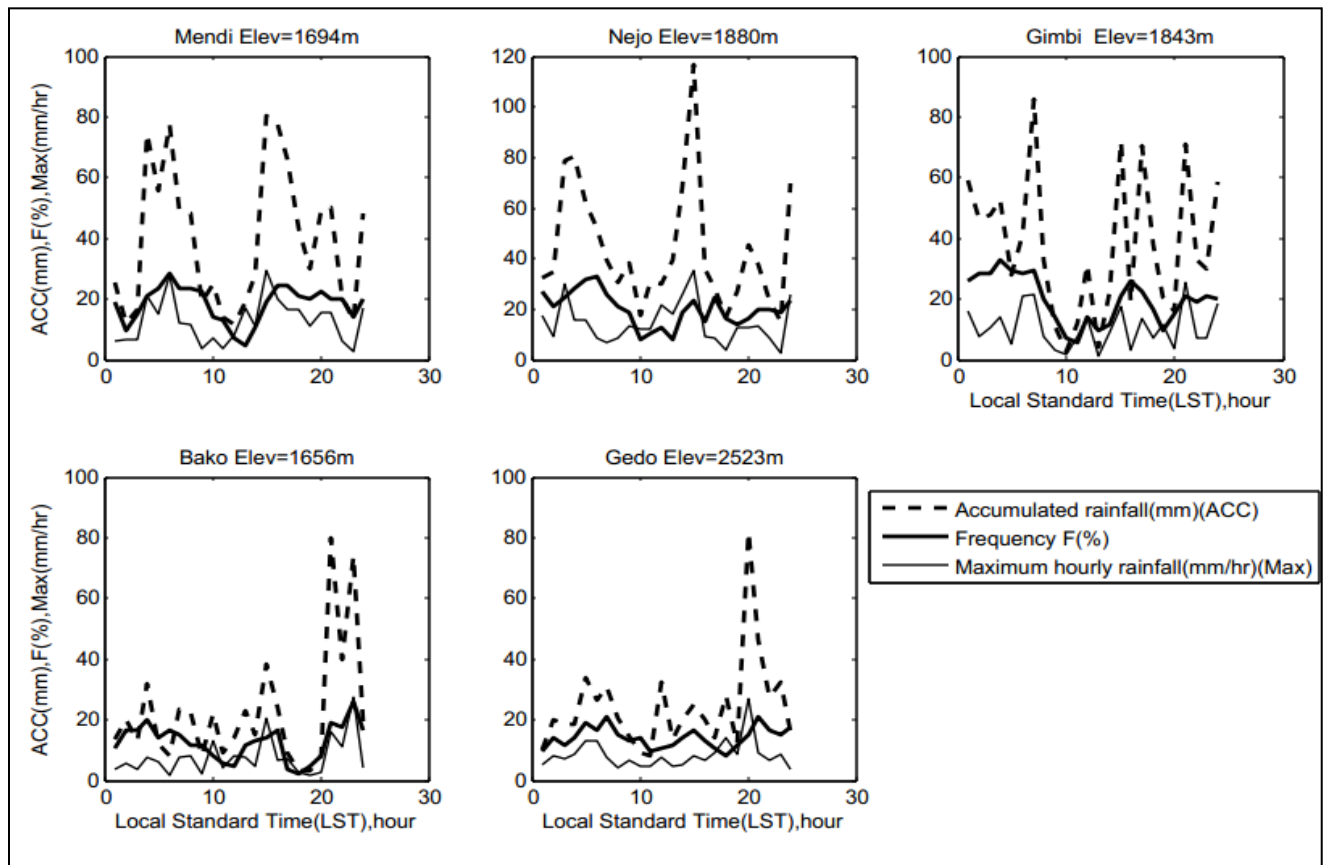


Figure 22: Rainfall diurnal cycle at stations along T2

The maximum frequency of rainfall occurrence along T3 varied between 21% to 47.05% ,with the mean of 31.41%. This large range of maximum rainfall frequency compared to other transects is due to the highest elevation range (811m to 4000 m) and it's blocking effect along T3. Maximum rainfall has higher contribution for Accumulated rain in each hour at relatively low elevation and east of choke mountain stations (higher elevation) while frequency has significant contribution for higher elevation station. Generally It was observed that minimum rain or no rain throughout the study period between 10:00 and 14:00 LST and maximum accumulated rain, frequency, maximum hourly rain at late night and afternoon while the stations south west of choke mountain namely, Anjeni, Kuchit have minimum or no rain from midnight to mid day and maximum rain from early afternoon to late afternoon. In the south-western part of

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Choke Mountain, an afternoon maximum accumulated rainfall, frequency is observed to midnight. Accumulated rainfall, frequency in the opposite side of the Choke Mountain (south-eastern part) is lower than the areas in the southwest of the mountain which can be attributed to the rain shadow effect. This is in agreement with (Fenta, 2010) as he found on his satellite based study stated that south western part of Choke Mountain an afternoon maximum mean rain rate was observed see Fig.23

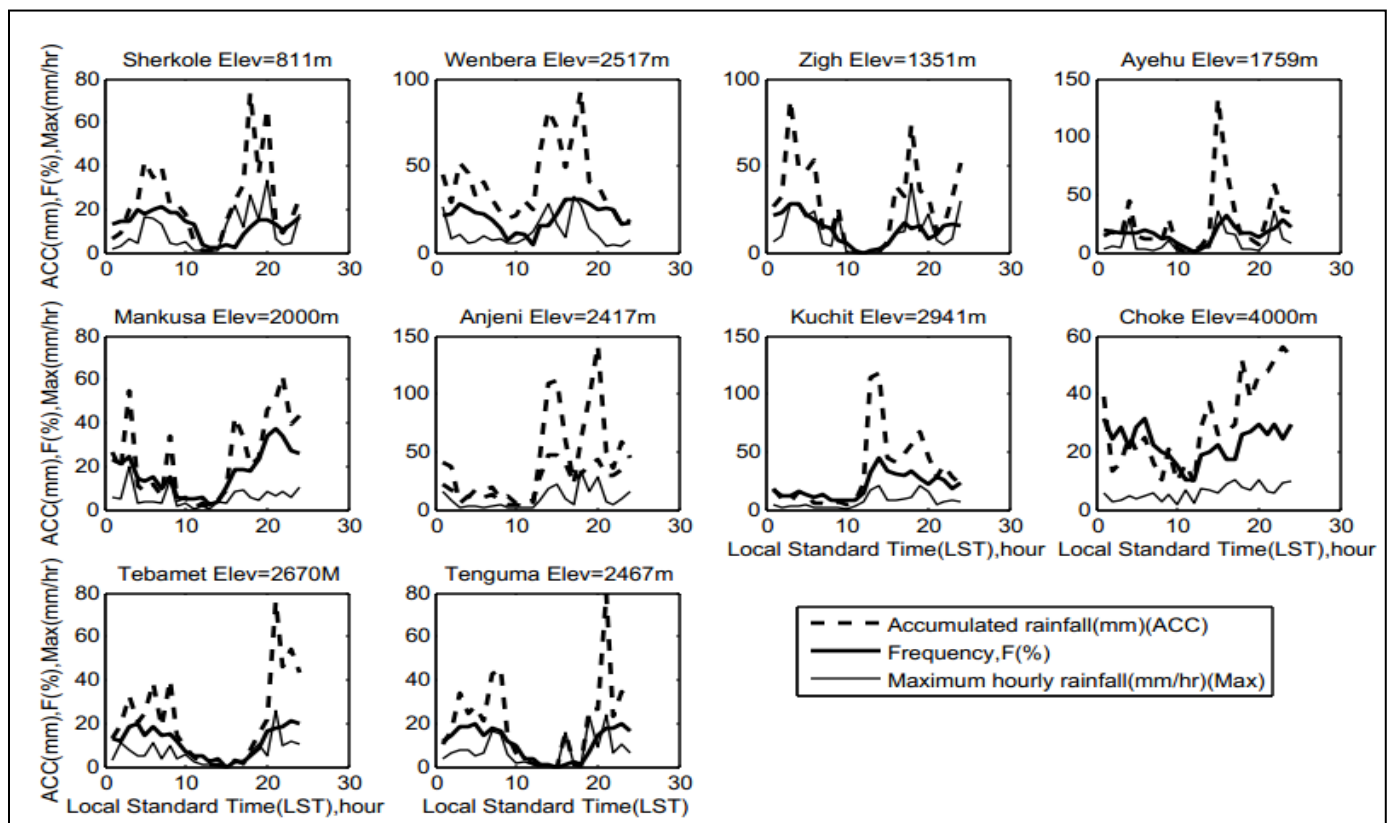


Figure 23: Rainfall diurnal cycle at stations along T3

The maximum frequency of rainfall occurrence along T4 varied between 25.9% to 41.17%, with the mean of 30.80%. Maximum rainfall has higher contribution for total rainfall in each hour at relatively low elevation stations while (higher elevation and geographically found central

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highlands of the basin) both frequency and maximum hourly rainfall has significant contribution for accumulated rain.

Generally it was observed that minimum rain depth (less than 10mm) or no rain throughout the study period between time range of 9:00LST and 14:00 LST and maximum accumulated, maximum hourly rainfall, frequency was observed at after midnight to late night and in the afternoon in most station along T4 while station Chagni and Fendika have got maximum accumulated rain, frequency, maximum hourly rainfall in afternoon only. At higher elevation and geographically found at the center of the basin the Minimum rain depth duration was too short compared to low elevation stations see (Fig. 24).

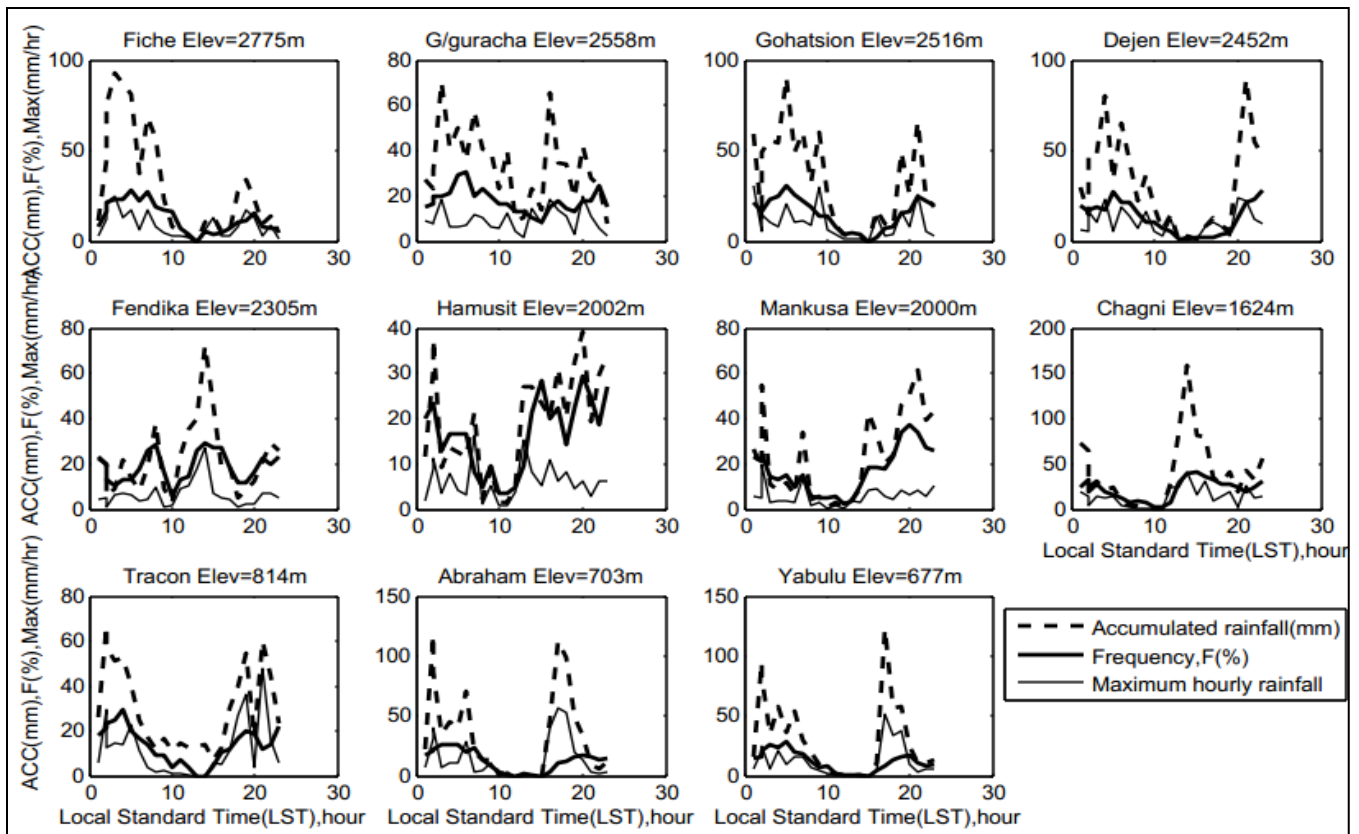


Figure 24: Rainfall diurnal cycle at stations along T4

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Generally most of the station in study region have shown minimum or no rain duration from late morning to early afternoon while stations namely; Zanbit, Chagni and Anjeni, Kuchit which are located at the foot and mid slope of mountain respectively along T1, T4, T3 have minimum or no rain duration observed in a day from midnight to late morning.

5.3. Relation between rain event properties and terrain elevation

5.3.1. Relation between number of rain events and terrain elevation

The spatial variation of rain event properties is analyzed based on rainfall records from 32 stations. The number of rain events along T1 transecting from south to north of the basin is 82, 83, 98, 91, 105, 97 and 94 for Uke, Dorohobora, Dangber, Amestegna, Makesegnt, Lebagedel, Zanbit respectively ; The number of rain events along T2 transecting from south western to south eastern part is 101, 95, 95, 83 and 97 for Mendi, Nejo, Gimbi, Bako, Gedo respectively; The number of rain events along T3 transecting from west to east part of the basin is 78, 96, 76, 97, 88, 107, 100, 95, 72 and 62 for Sherkole, Wenbera, Zigh, Ayehu, Mankusa, Anjine, Kuchit, Choke, Tebamet, Tenguma respectively; The number of rain events along T4 transecting from north west to south east part of the basin is 74, 67, 76, 100, 88, 93, 107, 77, 91, 97 and 74 for Yabulu, Abraham, Trackon trading, Chagni, Mankusa, Hamusit, Fendika, Dejen, Gohtsion, Gerbguracha, Fiche respectively. The station lay out is shown in Fig.3. The largest number of events are observed at Makesgnt, Mendi, Anjeni, Fendika for T1, T2, T3, T4 respectively. Makesgnt, Anjeni, Fendika which are located at the foot of the highlands elevation above 2400m. Mendi which is located south western part of the basin which have got also higher accumulated rainfall during study period which is not due to elevation effect like stations near choke mountain but due to geographic location while the smallest number of events are observed

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at Uke, Bako, Tenguma, Abraham respectively which are located leeward side of mountain and due to low elevation. The result showed that the rain event have strong relation to terrain elevation, mountain shading effect, geographical location. The importance of stations might be due to the large number of rain event compared with other stations for various purposes like soil erosion process, hydrological modeling, and flood monitoring see (Haile, *et al.*, 2009d).

The number of rain events shows general trend along transects: The number of rain event generally increase from south to north along T1, increase from west to east along T3, increase from south to west along T2 while T4 have not showed such trend it might be due to stations have lower elevation have got high number of rain event than highlands due to mountain shading effect.

Dairaku *et al.*, (2004) performed a linear regression to relate event properties and terrain elevation based on 50% quantile; Haile *et al.*, (2009d) performed non- linear regression to relate event properties and terrain elevation based on 50% quantile. Table 3, 4, 5, 6 shows the correlation result between event properties to terrain elevation for all transects. 50% quantile also selected in this study to consider event properties.

5.3.2. Relation between rain events properties and terrain elevation along T1

The coefficient of determination (R^2) value in Table.3, shows the terrain elevation weakly explains the variation in the 90% in event depth while 10%, 50% quantile strongly related to terrain elevation. The results suggest that the small and the normal event depths along T1 are largely affected by terrain elevation. In terms of event duration, the 90% is weekly related to terrain elevation while 10%, 50% quantile is relatively more affected by terrain elevation. The

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results suggest that small and normal event duration along T1 is relatively more affected by terrain elevation. In terms of mean event intensity 10% is weekly related to terrain elevation while 50%, 90% quantiles is more strongly related to terrain elevation. The result suggests normal and large event mean intensity is relatively more affected by terrain elevation. Although the 10 % quantile of IET is weekly related to terrain elevation; the 50% and 90% quantiles of IET have strong relation to terrain elevation. In general the high quantiles of IET, mean event intensity and small and normal quantiles of event depth and event duration are relatively more affected by terrain elevation along T1.

Table 3: The relation between rain event properties and terrain elevation along T1

Transect 1	Coefficient of Determination R^2			
Quartile	Depth	Duration	Mean event intensity	Inter event time
10% quartile	0.56	0.31	0.04	0.006
Median(50%) quartile	0.56	0.39	0.37	0.23
90% quartile	0.24	0.11	0.30	0.31

Figure 25 shows the relation between event properties and terrain elevation. The median of event properties is selected to evaluate the relation while the correlation result for small, normal, high quantiles are presented in table 3, 4, 5, 6. Figure 25 shows that rain event depth, rain event intensity and rain event duration increase as terrain elevation increase while the inter event time decrease with an increase terrain elevation along T1. In terms of (IET) which is agreed and result while other rain event properties (rain event depth, mean event intensity, event duration) contradicted with (Haile *et al.*, 2009d). It is due to criteria taken for event classification (IET=30

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minutes) by (Haile, *et al.*,2009d) and his suggestion on increasing IET to 1 hr could not change the statistics or rain event properties and in this study IET taken as 6hr that could change the statistics on rain event properties.

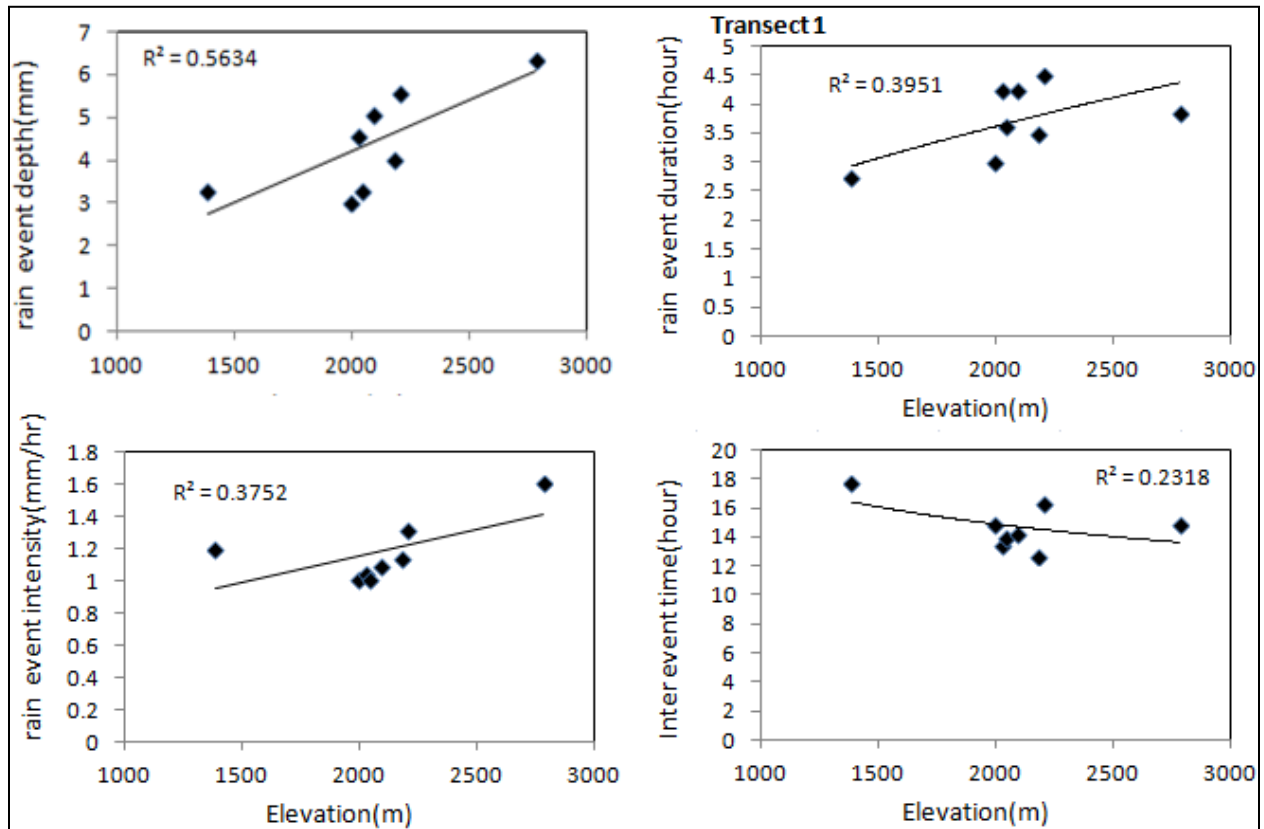


Figure 24: The relation between rain event properties and terrain elevation along T1

5.3.3. Relation between rain events properties and terrain elevation along T2

Excluding station (Gedo) at high elevation made strong the correlation. Unlike high elevation stations at Gedo have shown longer IET, shorter rain event duration, less rain event depth, which might be mountain shading effect as it is found at the east of basin divide b/n Omo Gibe basin and Blue Nile River Basin. The coefficient of determination (R^2) value in Table.4 shows the terrain elevation weakly explains the variation in the 10% in event depth while 50%, 90%

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quantile strongly related to terrain elevation. The results suggest that the normal and large event depths are largely affected by terrain elevation. In terms of event duration, the 10% is weekly related to terrain elevation while 50%, 90% quantile is relatively strong related to terrain elevation. The results suggest that normal and large event duration is largely affected by terrain elevation. In terms of mean event intensity 90% is weekly related to terrain elevation while 50%, 10% quantiles is strongly related to terrain elevation.

The result suggests small and normal event mean intensity is largely affected by terrain elevation. Although the 50%, 90 % quantile of IET is weekly related to terrain elevation; the 10% quantiles of IET have strong relation to terrain elevation. In general the high quantiles of event depth, event duration and lower quantiles of mean event intensity and IET are largely affected by topography along T2.

Table 4: The relation between rain event properties and terrain elevation along T 2

Transect 2	Coefficient of Determination R^2 when excluding station(Gedo) at the end of transect			
Quartile	Depth	Duration	Mean event intensity	Inter event time
10% quartile	0	0	0.4	0.28
Median(50%) quartile	0.95	0.92	0.54	0.52
90% quartile	0.56	0.82	0.001	0.96

Figure 26 shows that rain event depth and rain event duration increase as terrain elevation increase while the rain event intensity, inter event time decrease along T2. the rain event

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intensity and inter event time decrease as elevation increase is due to longer duration and frequent rain event at higher elevation respectively.

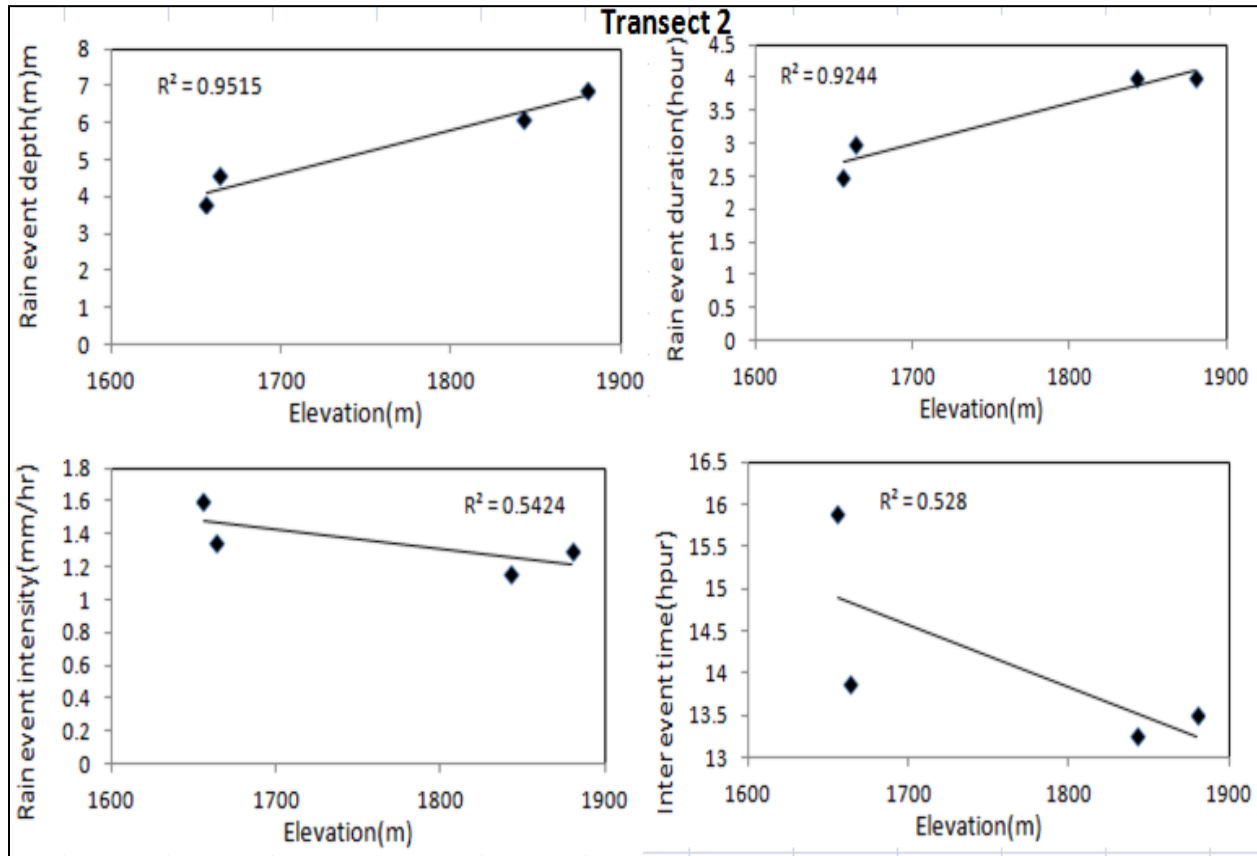


Figure 25: The relation between rain event properties and terrain elevation along T2

5.3.4. Relation between rain events properties and terrain elevation along T3

The coefficient of determination (R^2) value in Table.5 shows the terrain elevation weakly explains the variation in the 10% ,90% in event depth while 50% quantile strongly related to terrain elevation. The results suggest that the normal event depths are largely affected by terrain elevation. In terms of event duration, the 10% is weekly related to terrain elevation while 50%, 90% quantile is more strongly related to terrain elevation. The results suggest that normal and large event duration is largely affected by terrain elevation. In terms of mean event intensity and inter event time (IET) 10%, 50%, 90% is weekly

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related to terrain elevation and the result suggests the all quantiles poorly affected by terrain elevation. It is due the reason that stations at foot and windward side of choke mountain have lower elevation but have got high rain event depth, longer rain event duration and shorter Inter event time because of shading effect of the mountain compared with higher elevation stations and on the other hand station at leeward side of choke mountain have higher elevation but got less rain event depth ,shorter rain event duration, longer inter event time. In general the high quantiles of event depth, event duration are largely affected by topography along T3. The relation between event properties by excluding station at foot of windward side and the leeward side station of Choke Mountain showed improvement on the correlation coefficient. The 50% quantile of event depth, 50%, 90% quantile of event duration,90% quantile of mean intensity ,10%, 50%, 90% of Inter event time shows more strongly affected by terrain elevation. Over all the high quantile of event properties when excluding station at foot of windward side and the leeward side station of Choke Mountain are highly affected by topographical variation see Fig.28.

Table 5: The relation between rain event properties and terrain elevation along T3

Transect 3	Coefficient of Determination(R^2) (considering all rain gauges stations along the transect)				Coefficient of Determination (R^2) (Excluding rain gauge stations at foot of choke mountain, leeward side rain gauges).			
	Depth	Duration	Mean event intensity	Inter event time	Depth	Duration	Mean event intensity	Inter event time
10% quartile	0.06	0.06	0.04	0.04	0.14	0.09	0	0.4
Median(50%) quartile	0.61	0.41	0.06	0.01	0.79	0.75	0.15	0.8
90% quartile	0	0.49	0.1	0.05	0.09	0.94	0.3	0.61

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Figure 27 shows that rain event depth, and rain event duration increase as terrain elevation increase while the inter event time decrease with an increase terrain elevation along T3 while rain event intensity poorly correlated with elevation.

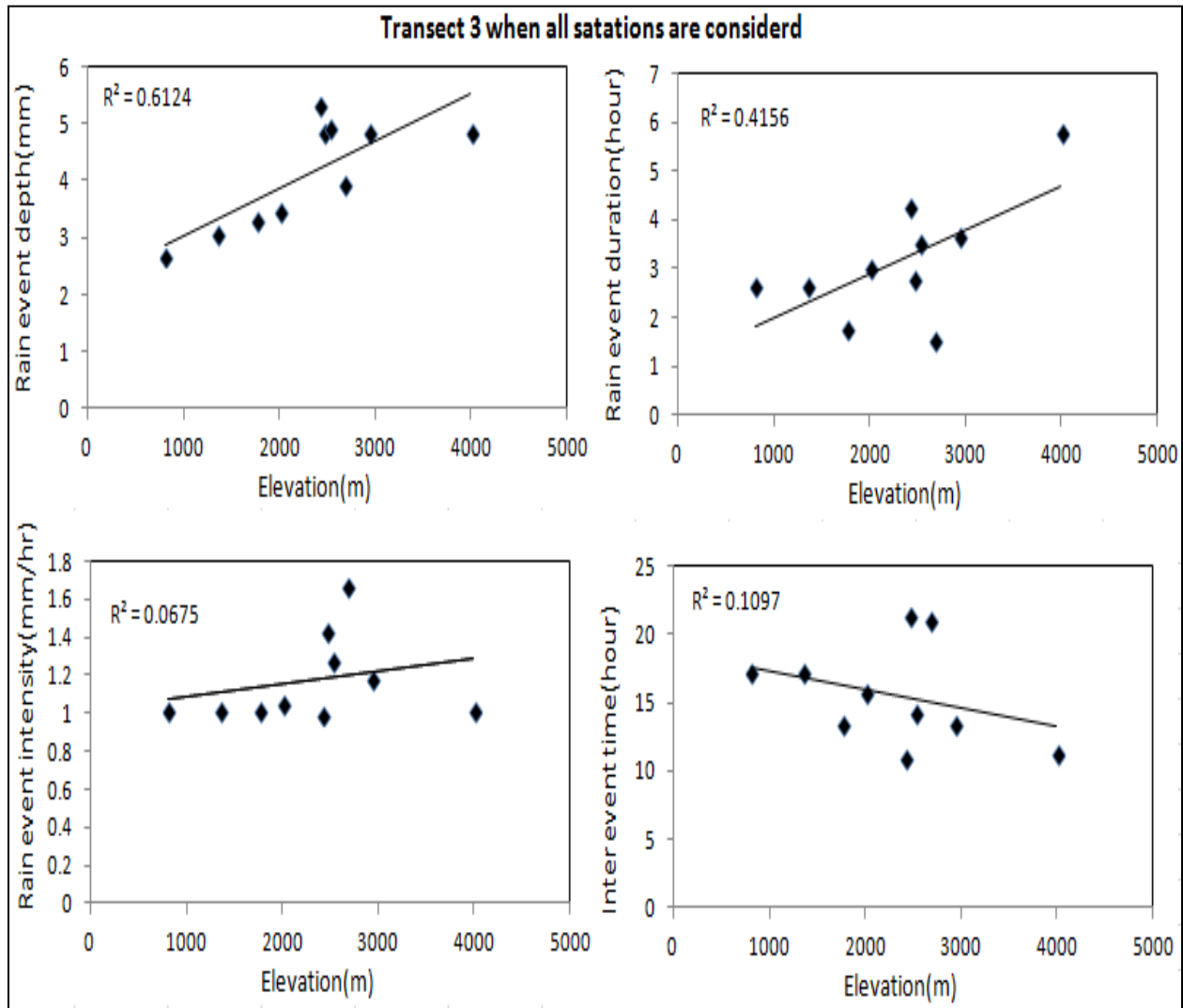


Figure 27: The relation between rain event properties and terrain elevation along T3

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Figure 28 shows that rain event depth and rain event duration increase as terrain elevation increase while the inter event time decrease with an increase in terrain elevation along T3 while rain event intensity still poorly correlated with station elevation.

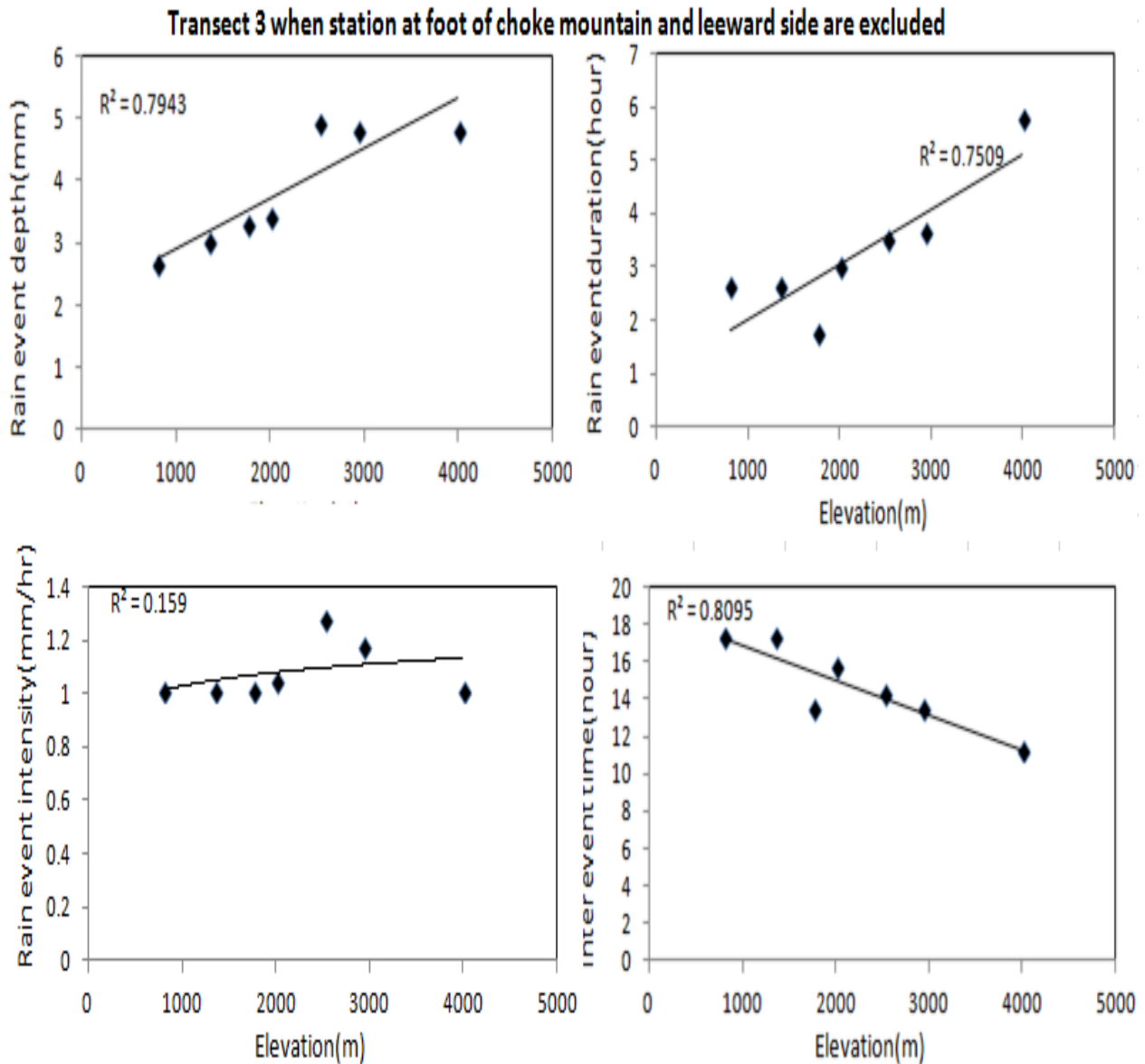


Figure 26: The relation between rain event properties and terrain elevation along T3 excluding station at the foot of Choke Mountain in wind ward side and leeward side stations.

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5.3.5. Relation between rain events properties and terrain elevation along T4

The coefficient of determination (R^2) value in Table.6 shows the terrain elevation weakly explains the variation in the 10%, 90% quartile event depth and 50% quartile strongly related to terrain elevation. The results suggest that the normal depths are largely affected by terrain elevation. In terms of event duration, the 10%, 50%, 90% is weakly related to terrain elevation. In terms of mean event intensity 10%, 50%, 90% is weakly related to terrain elevation. Although the 10%, 50% quartile of IET is weakly related to terrain elevation while the 90% quartiles of IET have strong relation to terrain elevation. In general the 50% of event depth and 90% quartiles of inter event time largely affected by topography along T4.

Table 6: The relation between rain event properties and terrain elevation along T4

Transect4	The coefficient of determination (R^2)			
Quartile	Depth	Duration	Mean event intensity	Inter event time
10% quartile	0.23	0.04	0.23	0
Median(50%) quartile	0.44	0.003	0.21	0.1
90% quartile	0.21	0	0	0.54

Figure 29 shows that rain event depth increase as terrain elevation increase and the inter event time decrease with an increase terrain elevation along T4. But the event duration and inter event time poorly correlated with elevation. It is due to low stations elevations which have got longer event duration, shorter inter event time unlike low elevation stations. It is because of mountain shading effect, geographical location (low lands and highlands along transect). For instance,

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station like chagni, Gerb guracha, fendika and hamusit have longer rain event duration and higher rain event depth but their station elevation ranging from 1624m to 2558 m. This made the whole correlation weak see Fig.29

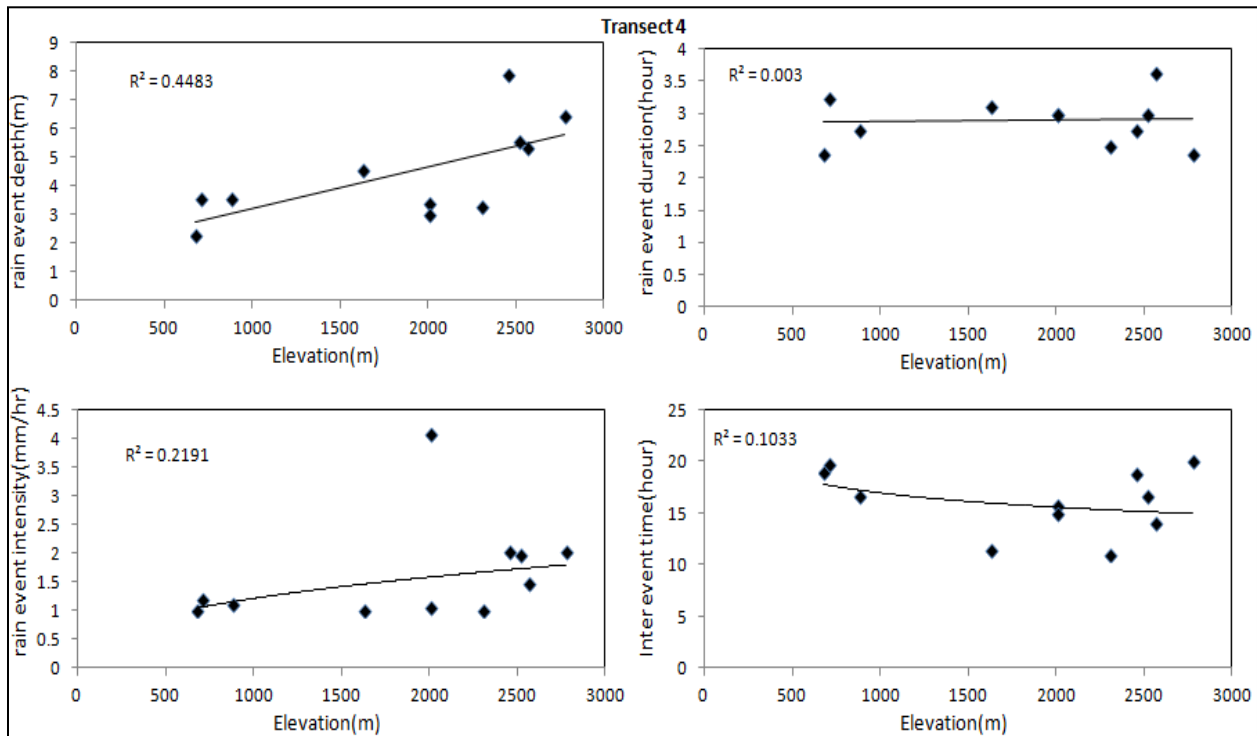


Figure 29: The relation between rain event properties and terrain elevation along T4.

The median of the IET along all transect is nearly 2 times the specified MIT which is 6 hour. In terms of median, the IET along all transect is about 13 hours that is about 4 times the median of the rain event duration indicating longer dry period than event duration. The median value of the IET also shows that the daily rainfall depth over the basin is mostly caused by one or two rain events. It is noted that the presences of multiple events in a day restricts the applicability of daily rainfall records for event based analysis. As such, the rainfall needs to be recorded at sub-daily scale time for such analysis.

Chapter 6

6. Conclusion and Recommendation

6.1 Conclusion

- Blue Nile River Basin is characterized by highly variable topography. Moreover, the orientation of the mountain ranges in relation to the general pattern of air circulation influences the rainfall distribution. Results of this study suggest that high variability of rainfall is related to the variability in topography. By use of four transects from north to south , east to west, south west to south east, north west to south east, it is revealed that more rainfall is observed on the windward side of the high mountain ranges than the leeward side and south western part of the basin(Upper Dedessa and Dabus basin). The areas in the southwest of the mountain ranges (windward side) are characterized by high rainfall occurrence and mean rain rate compared to the other sides of the mountains. This suggests the existence of orographic influences in the basin where the areas in the east of the mountains are affected by rain shadow effect.
- Rain event properties namely; Rain event depth, Rain event duration, Inter event time are affected by terrain elevation and wind direction (moist air movement) related to mountain orientation, geographical location over Blue Nile River. As elevation increase the rain event properties like rain event depth and rain event duration are increase and Inter event time decrease along all transect.

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- Variable rain depth observed at low elevation station than high elevation . These suggested that less rainfall variability and over high elevation stations than low elevation over the basin.
- Temporal variability of rainfall is highly related to terrain elevation, mountain shading, wind direction geographical location such as, longer dry hours within a day observed at low elevation stations than higher elevation stations in general and shorter dry hours within a day at southwestern part of the basin (Upper Dedesa and Dabus basin), an afternoon frequent rainfall was observed at the foot of Local Mountains, which suggested that low loss of water due to evaporation , Maximum hourly rainfall in each hour of the day has significant contribution for accumulated rain each hour of the day at low elevation stations and frequent rainfall for higher elevation.

We note that these results are for the rainy season over Blue Nile River Basin. It is important to recognize the limitations on drawing the above conclusion based on relatively short period of data starting from July 8,2012 to September 30 ,2012(85 days), indicating that further study using larger dataset is necessary.

6.2. Recommendation

- We recommend to study factors such as moist air availability within certain geographical location, wind speed, wind direction to assess further about rainfall process in addition to topographic effect.
- To study the blocking effect of minimum terrain elevation and cloud movement detection over the basin using wind direction measurement at fine temporal resolution is recommended.
- We recommend that future studies should evaluate effect of soil erosion in the watershed related to event properties since severe erosion has been found and mega hydropower dam is under construction.
- We recommended that the effect of wind direction, terrain elevation, wind speed and geographical location should be considered for satellite rainfall estimation algorithm over the basin.
- It is recommended to use Minimum inter event time (MIT) of 12 hour over the basin classify a series of observations as a single event.

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