ADDIS ABABA UNIVERSITY

ETHIOPIAN INSTITUTE OF WATER RESOURCES

MSc THESIS ON

UNDERSTANDING RUNOFF GENERATION PROCESSES AND RAINFALL RUNOFF MODELING IN MEJA WATERSHED

By:

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June 2013

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UNDERSTANDING RUNOFF GENERATION PROCESSES AND RAINFALL RUNOFF MODELING IN MEJA WATERSHED

Thesis Submitted to Ethiopian Institute of Water Resources in Partial Fulfillment of the Requirements for the Degree of Master of Science

In

Water Resources Engineering and Management (Specialization: Surface Water Engineering)

By

Solomon Berhane Gebreyohanes

APPROVED BY BOARD OF EXAMINERS

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Dedicated to my family, with love

BIOGRAPHICAL SKETCH

Solomon Berhane Gebreyohanes was born in Adwa, Tigray, Ethiopia, on December 24, 1980. He graduated with B.Sc degree of Water Resource Engineering from Bahirdar University Engineering Faculty in July 2010. He worked for Mekelle University as graduate assistant II after his B.Sc degree for nearly one year. Then, he joined Ethiopian Institute of Water Resources for Masters Program of Water Resource Engineering and Management (Surface Water Engineering and Management in June 2011.

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LIST OF ABBREVIATIONS

amsl	above mean sea level
DEM	Digital Elevation Model
GIS	Geographic Information System
GW	Ground Water
HBV	Hydrologiska Byråns Vattenbalansavdelning means Hydrological Bureau Water balance-section.
IWMI	International Water Management Institute
NMA	National Meteorological Agency, Ethiopia
RF	Rainfall
RRL SMAR	Rainfall Runoff Library Soil Moisture Accounting and Routing model
SM	Soil Moisture

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ABSTRACT

Understanding the basic relationships between rainfall, runoff, soil moisture and ground water level are vital for an effective and sustainable water resources planning and management activities. But so far there are no hydrological studies in Meja watershed that aims to understand the watershed characteristics and runoff generation processes. This study was conducted to understand runoff generation processes and model rainfall runoff relationship in Meja watershed having a drainage area of 96.6 km^2*.The watershed is one of the three research sites of International Water Management Institute (IWMI) developed in early 2010 in the upper Blue Nile Basin Ethiopia. In the study, primary data of soil moisture, shallow ground water level, rainfall and runoff were collected from the hydrological monitoring network in the watershed. Two nested sub- watersheds namely Galessa and Kolu were defined in the watershed for detail analysis of hydrologic variables. Galessa has drainage area of 1.6* km^2 *and Kolu has a drainage area of 2.5* km^2*. Hydrological models like HBV and RRL SMAR were configured to understand the relationship between rainfall and runoff in the watershed. Relationships between rainfall, soil moisture, shallow ground water level and runoff were developed to understand runoff generation processes in the watershed. Analysis of rainfall data indicated weak daily correlation (*$r^2<0.35$*) of areal rainfall between Galessa, Serity and Kolu and similar annual total and average rainfall of the three sites of Meja watershed. However monthly correlation of areal rainfall between the three sites was better than daily correlation (*$r^2>0.8$*). According to one year and three months data, there is no strong daily rainfall and runoff relationship (*$r^2<0.5$*) in Meja and Kolu which is nested sub - watershed; this may be due to abstractions such as irrigation and human interventions in the watershed. Ground water level and runoff has strong relationship (*$r^2>0.65$*) in monthly basis of Kolu nested sub watershed but there is moderate relationship of rainfall and ground water level. There is spatial variability of soil moisture content in Meja watershed, this variation occurs due to heterogeneity of the soil, which means the places are different in soil texture and also the variation is due to vegetation cover and change of slope. There is strong linear relationship of rainfall and monthly averaged volumetric soil moisture in most soil moisture layers of Meja and its nested sub-watersheds. The general relationship between runoff and monthly averaged soil moisture at different layers in Meja watershed and Kolu is strong. Analysis of rainfall runoff models indicated that relationships of rainfall with* *observed and simulated runoff was similar.HBV model performs better than RRL SMAR model in Meja and Kolu. RRL SMAR model couldn't capture low flow in Meja and Kolu. This inaccurate result of SMAR model in Kolu sub-watershed may be due to inability of the model to simulate runoff in very small catchments like Kolu.*

Key words: *Runoff generation processes; Rainfall Runoff Process; Meja watershed; HBV model; RRL SMAR model*

INTRODUCTION

1.1 Background

Runoff is one of the most important hydrological variables used in most water resources applications. Watershed based planning and management requires thorough understanding of the hydrological processes and accurate estimation of runoff. The determination of runoff is essential to address soil and water conservation practices in the watershed. The information pertaining to occurrence of runoff further helps in integrated soil and water management practices such as prioritizing watersheds, erosion control and selection of sites for conservation measures.

Design of effective soil and water conservation practices should take into account understanding of biophysical conditions in the area. Conversely, soil and water conservation practices affect the runoff processes of the watershed. Understanding runoff generation processes is therefore paramount importance for land and water resource management. (Zemadim *etal*., 2011)

Complete and reliable hydrological and meteorological data is important for an effective and sustainable water resources planning and management. To get such data there is a need to develop and maintain hydrometric stations in proper network and also these stations must work efficiently and continuously without any obstacles. Presently in Ethiopia most of the available gauging stations are located nearby access roads. Because of this situation, most of the rivers which are inaccessible to roads are not gauged. Gauged catchments also may not work properly due to several damages and human interference. Due to this there is missed data for many years, so it is difficult to design hydraulic structures and other water resource planning activities. (Woinishet, 2009)

This study utilized the already available hydrological and meteorological monitoring stations in Jeldu district. These monitoring stations were set up by the International Water Management Institute (IWMI) from May to August 2011.Primary data for the work was collected since the establishment of the monitoring networks. These data include rainfall, soil moisture, shallow ground water level and runoff. Detail description of the monitoring network establishment in three watersheds of the highland of Ethiopian Blue Nile basin is presented in the work of Zemadim *etal*. (2012).

The purpose of this research is to understand runoff generation processes and model rainfall runoff relationship and to get an alternative mechanism for estimating runoff, soil moisture and ground water level by using statistical analysis and rainfall runoff model. Finally to gain insight in to the rainfall-runoff hydrological processes two rainfall runoff models i.e. RRL SMAR and HBV were configured for the watershed.

1.2 Problem Statement

In the study area, i.e. Meja watershed there hasn’t been any hydrological monitoring stations until recently in 2011.To study the biophysical conditions of the catchment and improve rainwater management strategies; International Water Management Institute (IWMI) pioneered the establishments of hydro-meteorological stations. There are no hydrological studies in the catchment so far that aims to understand the catchment characteristics and runoff generation processes. In this study, therefore, runoff generation processes and rainfall runoff modeling of the catchment have been studied. Similarly relationships between hydrological variables like surface flow, ground water level and soil moisture were developed to help predict hydrological variables. It is envisaged that the work will be a first outcome for the watershed and planners use the output of the work for any water resource related development works.

1.3 Significance of the Study

- Derive relationship between rainfall, soil moisture, ground water and flow and hence predict hydrological variables and indicate the spatial variation of subsurface moisture status. Thus the relationship would inform decision makers and local communities in the farming system and water resource project implementation.
- To open an opportunity for further research in the area as it is the first of its kind in Meja watershed.

1.3 Research Question

- What is the pattern of rainfall in Meja watershed?
- What is the relationship of rainfall with runoff, soil moisture and groundwater table?
- What is the relationship between soil moisture and water table, soil moisture and runoff water table and runoff?
- Is a simulated variable well correlated with observed values of the watershed?

1.4 Objectives

1.5.1 General objective

- To understand runoff generation processes and model Rainfall Runoff relationship in the watershed.

1.5.2 Specific objectives

The specific objectives of this study are to

- To characterize the rainfall pattern in the watershed.
- To analyze the relationship of rainfall with runoff, soil moisture and ground water level
- To analyze the relationship of soil moisture with ground water level, soil moisture with runoff ,ground water level with runoff, and soilmoisture with Ground water level
- To model Rainfall-Runoff relationship of Meja watershed

2. LITERATURE REVIEW

The literature review consists different sections. The first section is about rainfall and its use in water resource management and also about spatial variability of rainfall. Second to fifth section reviewed about rainfall and runoff relationship, relationship of soil moisture and subsurface flow, relationship of ground water and flow and statistical techniques to study the relationships between hydrological variables. The last section of the literature review is about rainfall and runoff models applied in this study. These parts of hydrological studies were reviewed because the objective of this study is to understand runoff generation processes and rainfall runoff modeling.

2.1 Rainfall and its Role in Water Resource Management

Rainfall is the most important hydrologic parameter which used as an input for different water resource management activities and hydrological modeling. It can be used for different purposes such as washing, flushing, watering plants by harvesting water traditionally such as sandwich reservoirs especially in remote areas. In order to achieve good rural and urban water management strategies, occurrence, distribution, characteristics' and patterns of rainfall must be studied, because rainfall varies spatially and temporally. (Buytaert *etal.,* 2000)

Understanding the rainfall process is critical for the solution of several regional environmental problems of integrated water resources management at regional scales, with implications for agriculture, climate change, and natural hazards such as floods and droughts. (Manfreda *etal.,* 2003).

2.1.1 Spatial variability of rainfall

In mountain regions, in addition to the stochastic nature of rainfall, the precipitation pattern may be influenced by the irregular topography. The large variability in altitude, slope and aspect may increase variability by means of processes such as rain shading and strong winds. The best method to improve the quality of spatial rainfall estimation is to increase the density of the monitoring network. (Goovaerts, 2000)

Spatial variability of rainfall can be affected by different factors such as geographical and morphological factors, for example area exposure to the direction of wind and the characteristics of its surface (roughness, vegetative canopy). Elevation difference can also affect the spatial variability of rainfall. So that Quantification and a good knowledge of the characteristics of hydrological input data is essential for a correct interpretation of modeling results and water management activities. (Jake man and Hornberger, 1993)

2.2 Rainfall and Runoff Relationship

Rainfall falling in a given area will not be directly converted to runoff because before runoff is generated rainfall has to pass different steps. The rainfall-runoff process in a catchment is a complex and complicated phenomenon governed by large number of known and unknown physiographic factors that vary both in space and time. The rain falling on a catchment undergoes number of transformations and abstractions through various component processes such as interception, detention, evapotranspiration, overland flow, infiltration, interflow, percolation, sub-surface flow, base flow etc, and emerges as runoff at catchment outlet. (David, 2003).

There are different runoff generation mechanisms such as saturation overland flow and hortonian overland flow. Saturation overland flow differs from Hortonian overland flow in that in Hortonian overland flow the soil is saturated from above by infiltration, while in saturation overland flow it is saturated from below by subsurface flow. Saturation overland flow occurs most often at the bottom of hill slopes and near stream banks.

The following figure helps to visualize runoff generation processes.

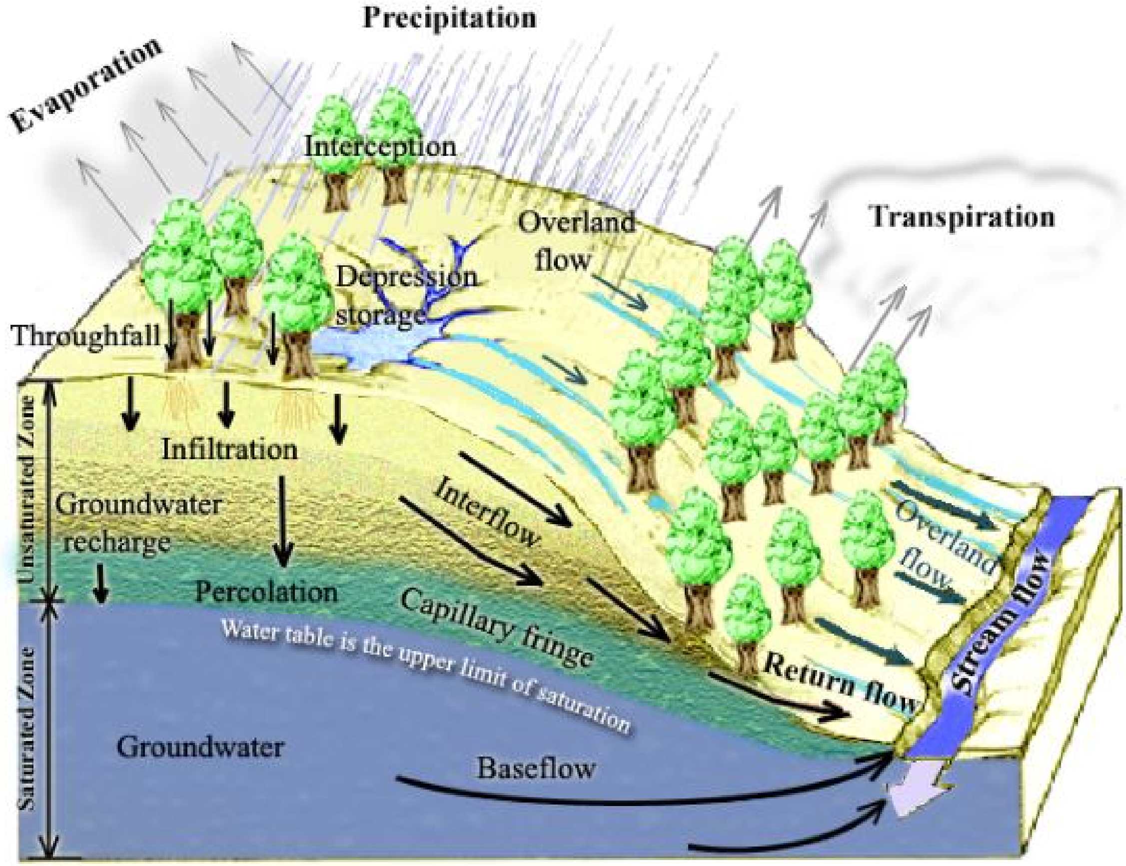

Figure 2.1 Physical processes involved in runoff generation (Source rainfall runoff process work book by David G. Tarboton

The relation between rainfall intensity and the discharge, strictly speaking, is not linear, which means that doubling the rainfall intensity does not produce a doubling of the hydrograph peak value. However in the catchment scale, due to the uncertainty of all the hydrological parameters, it might be assumed that the rainfall runoff relation follows a linear relationship. (Kharagpur, 2008).

In Meja watershed there was no research regarding runoff generation processes, but in other part of the world there are studies focusing on runoff generation processes. Latron and Gallart (2008) used limited and continuous data of rainfall, soil moisture, ground water and stream flow to analyze the runoff generation process in a small Mediterranean catchment, called can villa catchment. According to their study, the relationship between rainfall and runoff was characterized by high scattering, and even if a general increase of daily runoff with daily rainfall is appreciable there was no significant general relationship between daily totals of rainfall and runoff in the Can Vila catchment.

2.3 Relationship of Soil Moisture and Sub Surface Flow

Accurate understanding of the hydrological functioning of a catchment is not possible if only rainfall (input) and discharge (output) data are available, as many different processes or process combinations may lead to similar hydrographs (Hewlet etal., 1982). Indeed, rainfall and discharge do not generally provide sufficient information for a single determination of hydrological response through solution of the model inverse problem (Wheater etal., 1991). Therefore, the identification of runoff generation processes requires further observations or investigations of soil moisture status within the catchment to characterize dominant water flow pathways.

Soil moisture variation in time and space are controlled by many factors such as soil texture, vegetation and topography. Soil moisture affects the partitioning of incoming rainfall in to surface runoff and sub surface infiltration. Thus soil moisture is one of the key parameters governing interactions among atmosphere, land surface and groundwater. Identification of patterns of soil moisture response to rainfall and especially the vertical dynamics of soil moisture at the hill slope or plot scale can be useful for the investigation of runoff generation processes in a previously ungauged or data scarce catchment. Spatial patterns as well as temporal dynamics of soil moisture have a major influence on runoff generation. The investigation of these dynamics and patterns can thus yield valuable information on hydrological processes.

Blume etal. (2007) used soil moisture data to understand the dynamics of soil moisture and its influence on investigation of runoff generation processes. In their study data was collected with a data logger at high temporal resolution at three points and manually at irregular intervals at 11 additional points. Each measurement produces soil moisture data for 6 different depths along a vertical profile. Data was analyzed using different graphical methods allowing for data exploration at different spatio-temporal scales. They use dye experiment to analyze or visualize the soil profiles. Based on their study the combination of high temporal resolution but spatially scarce soil moisture data with episodic additional measurements proved to be useful for the investigation of runoff generation processes, especially with respect to preferential flow. According to their result soil moisture/flow patterns were shown to be persistent in time and highly variable in space. The most likely explanation for the observed flow patterns is a combination of hydrophobicity with strong gradients in unsaturated conductivities, were flow paths are caused either by the presence of roots or the highly heterogeneous distribution of through fall and thus water input. The flow patterns observed at the local scale are likely to be important for runoff response at the catchment scale. In that catchment there is accumulation or ponding of water at a certain depths that was assumed to be due to the effect of capillary barriers.

Field observations were conducted at Bukit Tarek Experimental Watershed in Peninsular Malaysia to investigate the relationship between rainfall-runoff responses and variation in soil moisture in a tropical rain forest. (Shaji Noguchi *etal.*, 2007).Storm flow depended strongly on the antecedent wetness as represented by the initial runoff rate. Though heavy rains fell in almost every month, the soil moisture decreased when fair weather was sustained. The soil moisture depleted and became dry at 160 cm depth during occasional dry spells. During dry conditions, stream flow responded quickly to rain events but declined rapidly after the rain stopped, and the soil moisture of surface soil (≤20 cm) increased but remained dry at lower depths (⩾80 cm). This suggests that the rain water was mostly retained in the soil and only small proportions appeared as storm flow. As soil moisture conditions became wetter, the recession limb of the storm hydrograph was more gradual. Storm flow volume increased with increasing soil moisture. During wet conditions, the soil profile was moist at all parts of the slope. The hydraulic gradient was around 1.0 and there was downward soil water flux, which followed the pressure gradient. This suggests that subsurface flow from the upper part of the slope might also be important for stream-flow production. Positive pressures were observed at 10 cm and 160 cm depths during large storms. The behavior of the subsurface flow might be an important determinant of storm flow. (Shaji Noguchi *etal.*, 2007).

2.4 Relationship of Ground Water and Flow

The amount of rainfall in excess of the infiltrated quantity flows over the ground surface following the land slope. This is the overland flow. The portion that infiltrates moves through an unsaturated portion of the soil in a vertical direction for some depth till it meets the water table, which is the free surface of a fully saturated region with water (the ground water reserve). Part of the water in the unsaturated zone of the soil (also called the vadose zone) moves in a lateral direction, especially if the unsaturated hydraulic conductivity in the horizontal direction is more than that in vertical direction and emerges at the soil surface at some location away from the point of entry into the soil. (David, 2003).

If the unsaturated zone of the soil is uniformly permeable, most of the infiltrated water percolates vertically. Infiltrated water that reaches the ground water reserve raises the water table. This creates a difference in potential and the inclination of the water table defines the variation of the piezometric head in horizontal direction. This difference in energy drives the ground water from the higher to the lower head and some of it ultimately reaches the stream flowing through the valley. This contribution of the stream flow is known as Base flow, which usually is the source of dry-weather flow in perennial streams. (David, 2003).

Water level fluctuation measurement in observation wells is an important aspect of ground water studies. Water level fluctuations are mostly influenced by hydrological, hydro meteorological and hydro geological phenomenon such as ground water recharge, artificial recharge, groundwater pumpage, and return flows from irrigation. In many cases there may be more than one phenomena/process operating simultaneously. (Sklash and Farvolden, 1979)

Under undisturbed natural conditions well hydrographs do not show any change in tendency with time because the recharge balances with the discharge. Aquifer response to recharge or discharge is reflected in water level fluctuations measured at different time periods. At any specific point the change in water level below ground surface depends not only on rates of pumping and recharge, but also on the intrinsic characteristics of the geological formations. Long and steady low rainfall on a loamy saturated soil with a highly permeable geological section and deep water table condition can result in a significant rise in the water table. Whereas, an intense rainfall event of shorter duration on a dry clayey soil with a shallow water table may not rise the water table a considerable amount. (Sklash and Farvolden, 1979)

Latron and Gallart (2008) used limited and continuous data of rainfall, soil moisture, ground water and stream flow to analyze the runoff generation process in a small Mediterranean catchment, called can villa catchment. According to their study, the relationship between runoff and the depth to water table showed much more scatter than is usually observed under more humid conditions. Likewise, water table variations (rise or fall) were on some occasions not in phase with runoff changes, suggesting somewhat more intricate hydrological behavior.

2.5 Statistical Techniques to Study Relationship between Parameters and Variables

Linear correlation coefficient is a statistical parameter, *r* used to define the strength and nature of the linear relationship between two variables or characteristics or attribute or quantity. Correlation is when two or more variables are related in some way. Correlation is measured on a scale of -1 to +1**,** where 0 indicates no correlation and either -1 or +1 suggests high correlation. Both -1 and +1 are equally high degree of correlation.

High Correlation - if one variable can consistently predict the value of the other variable, then a high degree of correlation exist between them. When two variables correlate and when the value of one increases as the value of the other decreases we say the relationship between both variables shows a negative correlation.

There is no absolute number guide for correlation coefficient that tell when a two variables have low to high degree of correlation; however, r closed to -1 or +1 suggest a high degree of correlation, values closed to 0 suggests no correlation or low correlation and values between 0.7 and 0.8 are moderate. (Richard, 1990) The correlation coefficient, r shows the degree of linear relationship between two variables. The coefficient of determination, *r2* is another way of looking at the correlation coefficient, *r,* it is the square of the correlation coefficient or better yet the correlation coefficient is the square root of the coefficient of determination. Since variations and deviations are easily interpreted quantities, the coefficient of determination attempts to look at strength of relationships in terms of deviations from some expected or defined set of values (the regression line or best-fit line).

2.6 Hydrological Models in Water Resource Management

Spatial and temporal variability and complexity of hydrological processes and limited availability of spatially and temporally distributed hydrologic, climatologic, geologic, and land use/land cover data challenge the ability to forecast hydrological data. Hydrological models are useful tools to solve such practical problems of forecasting hydrological data. From operational water resources management point of view hydrological models are developed to guide the formulation of water resource management strategies by understanding spatial and temporal distribution of water resources. (Lidén and Harlin, 2000)

In terms of spatial domains in catchment modeling, models can be classified as lumped, distributed and semi-distributed ones. The lumped model ignores spatial distribution of the catchment characteristics, represented by an average single value. In contrast, distributed model approaches capture the system by partitioning the catchment into a number of smaller units. Semi-distributed model is something in between the first two that means the catchment is partitioned but in a coarser unit as compared with distributed model. In another classification, based on deterministic rainfall–runoff models and mathematical solutions, models are classified into physical, conceptual, and empirical models. (Dingman, 2002)

Physically based models are based on physical laws that include a set of conservation equations of mass, momentum, energy and specific case entropy to describe the real world physics that governs nature. (Dingman, 2002)

Conceptually based models consider physical laws but in a simplified form that is able to explain the hydrologic behavior by empirical expression. Examples of this approach are HEC-HMS SMA, Tank, SMAR, Sacramento, TOPMODEL, and HBV

Empirically based models do not aid in physical understanding. However, they contain parameters that may have physical characteristics that allow the modeling of input-output patterns based on empiricism. Examples of this approach are unit hydrograph, rational method, etc. In this study two rainfall runoff models were used. Those are RRL SMAR and HBV models. These models are simple and needs small amount of data, and they are semi distributed and gave good performance in other watersheds of Blue Nile basin.

2.6.1 HBV

2.6.1.1HBV model description and structure

The HBV model is a rainfall-runoff model, which includes conceptual numerical descriptions of hydrological processes at the catchment scale. The general water balance can be described as:

$$P - E - Q = \frac{d}{dt}\left[SP + SM + UZ + LZ + lakes\right]$$

Where:
P=precipitation
E=evapotranspiration
Q=runoff
SP=snowpack
SM=soilmoisture
UZ=uppergroundwaterzone
LZ=lowergroundwaterzone
lakes = lake volume

Input data are observations of precipitation, air temperature and estimates of potential evapotranspiration. The time step is usually one day, but it is possible to use shorter time steps. The evaporation values used are normally monthly averages although it is possible to use daily values. Air temperature data are used for calculations of snow accumulation and melt. It can also be used to adjust potential evaporation when the temperature deviates from normal values, or to calculate potential evaporation. If none of these last options are used, temperature can be omitted in snow free areas.

The model consists of subroutines for meteorological interpolation, snow accumulation and melt, evapotranspiration estimation, soil moisture accounting procedure, routines for runoff generation and finally, a simple routing procedure between sub basins and in lakes. It is possible to run the model separately for several sub basins and then add the contributions from all sub basins.

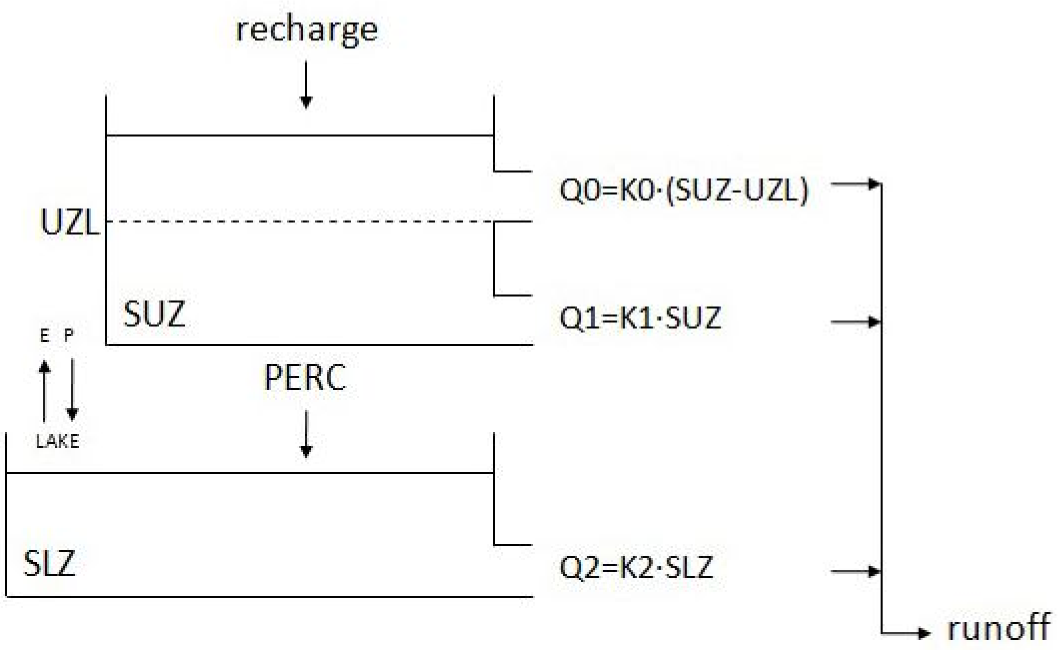

Figure 2.2 HBV standard model structure (Model version using UZL and K0 in SUZ-box) (Source HBV user guide, 2005)

Recharge = Input from soil routine [mm/d]

SUZ = Storage in soil upper zone [mm]

SLZ = Storage in soil lower zone [mm]

UZL = Threshold parameter [mm]

PERC = Maximum percolation to the soil lower zone [mm/d]

E = Evaporation from the lake

P = Precipitation into the lake

K*i* = Recession coefficient [1/d]

Q*i* = Runoff component [mm/d]

Runoff = Total amount of generated runoff [mm/d]

2.6.1.2 HBV model parameters and optimization techniques

The model simulates daily discharge using daily rainfall, temperature and potential evaporation as input. Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature, TT [°C]. All precipitation simulated to be snow, i.e. falling when the temperature is bellow TT, is multiplied by a snowfall correction factor, SFCF [-]. Snowmelt is calculated with the degree-day method (Equation 1). Melt water and rainfall is retained within the snowpack until it exceeds a certain fraction, CWH [-], of the water equivalent of the snow. Liquid water within the snowpack refreezes according to Equation 2. Rainfall and snowmelt (P) are divided into water filling the soil box and groundwater recharge depending on the relation between water content of the soil box (SM [mm]) and its largest value (FC [mm]) (Equation 3).

Actual evaporation from the soil box equals the potential evaporation if SM/FC is above LP [-] while a linear reduction is used when SM/FC is below LP (Equation 4). Ground water recharge is added to the upper ground water box (SUZ [mm]). PERC [mm d-1] defines the maximum percolation rate from the upper to the lower groundwater box (SLZ [mm]). Runoff from the groundwater boxes is computed as the sum of two or three linear outflow equations depending on whether SUZ is above a threshold value, UZL [mm], or not (Equation 5). This runoff is finally transformed by a triangular weighting function defined by the parameter MAXBAS (Equation 6) to give the simulated runoff [mm d-1].

If different elevation zones are used the changes precipitation and temperature with elevation are calculated using the two parameters PCALT [%/100 m] and TCALT [ºC / 100 m] (Equation 7 and 8). The long-term mean of the potential evaporation, *Epot*,M for a certain day of the year can be corrected to its value at day t , *Epot(t)*, by using the deviations of the temperature, *T(t)*, from its long-term mean, *TM* , and a correction factor, CET [°C-1] (Equation 9).

$$melt = CFMAX(T(t) - TT) \tag{1}$$

$$refreezing = CFR\ \ CFMAX(TT - T(t)) \tag{2}$$

$$\frac{recharge}{P(t)} = \left(\frac{SM(t)}{FC}\right)^{BETA} \tag{3}$$

$$E_{act} = E_{pot}\ \ \min\left(\frac{SM(t)}{FC \cdot LP},\ 1\right) \tag{4}$$

$$Q_{GW}(t) = K_2 SLZ + K_1 SUZ + K_0 \max\left(SUZ - UZL, 0\right) \tag{5}$$

$$\begin{gathered} Q_{sim}(t) = \sum_{i=1}^{MAXBAS} c(i)\ Q_{GW}(t - i + 1) \\ \text{where}\ \ c(i) = \int_{i-1}^{i} \frac{2}{MAXBAS} - \left|u - \frac{MAXBAS}{2}\right| \frac{4}{MAXBAS^2}\, du \end{gathered} \tag{6}$$

$$P(h) = P_0\left(1 + \frac{PCALT\left(h - h_0\right)}{10000}\right) \tag{7}$$

$$T(h) = T_0 - \frac{TCALT\left(h - h_0\right)}{100} \tag{8}$$

$$\begin{gathered} E_{pot}(t) = \left(1 + C_{ET}\left(T(t) - T_M\right)\right) E_{pot,M} \\ \text{but}\ \ 0 \le E_{pot}(t) \le 2\ E_{pot,M} \end{gathered} \tag{9}$$

The calibration of the model is usually made by manual try and error technique. Different criteria can be used to assess the fit of simulated runoff to observed runoff:

- visual inspection of plots with Qsim and Qobs
- accumulated difference
- statistical criteria

The coefficient of efficiency, R_{eff}, is normally used for assessment of simulations by the HBV model.

$$R_{eff} = 1 - \frac{\sum (Q_{Sim}(t) - Q_{Obs}(t))^2}{\sum (Q_{Obs}(t) - \overline{Q}_{Obs})^2}$$

R_{eff} compares the prediction by the model with the simplest possible prediction, a constant value of the observed mean value over the entire period.

$R_{eff} = 1$ Perfect fit, Q Sim(t)= Q Obs(t)

$R_{eff} = 0$ Simulation as good (or poor) as the constant-value prediction

$R_{eff} < 0$ Very poor fit

Note:

- the calibration period should include a variety of hydrological events
- normally 5 to 10 years sufficient to calibrate the model
- validation: test of model performance with calibrated parameters for an independent period

2.6.1.3 Previous application of HBV model

In different model versions HBV has been applied in more than 40 countries all over the world. It has been applied to countries with such different climatic conditions as for example Sweden, Zimbabwe, India and Colombia. Each sub basin is then divided into zones according to altitude, lake area and vegetation. The model is normally run on daily values of rainfall and air temperature, and daily or monthly estimates of potential evaporation. The model is used for flood forecasting in the Nordic countries, and many other purposes, such as spillway design floods simulation. Water resources evaluation nutrient load estimates.

In Ethiopia, Blue Nile Basin different studies were conducted using HBV model. Dr.Semu Ayalew (2007) studied Variations of Climate Change Impacts in Different Hydro-Climatologic regimes of the Nile Basin: A case study of Gilgel Abbay in the Blue Nile Sub-basin and Two Low land Reaches (Baro and Sudd**).** According to Dr.Semu result HBV model performs well with coefficient of determination during calibration and validation period 0.79 and 0.82 respectively.

Another study conducted in Blue Nile basin was rainfall runoff model comparison by Kumela tuffa (2011). According to his result HBV model performs well. Coefficient of determination during calibration and validation becomes 0.89 and 0.87 respectively.

2.6.2 SMAR

2.6.2.1 SMAR model description and structure

The Soil Moisture Accounting and Routing model (SMAR) is a lumped conceptual rainfall run-of water balance model with soil moisture as a central theme. The model provides daily estimates of surface run-off, ground water discharge, evapotranspiration and leakage from the soil profile for the catchment as a whole. The surface run-off component comprises overland flow, saturation excess run-off and saturated through-flow from perched groundwater conditions with a quick response time.

The SMAR model consists of two components in sequence, a water balance component and a routing component. The model utilizes time series of rainfall and pan evaporation data to simulate stream flow at the catchment outlet. The model is calibrated against observed daily stream flow.

The water balance component divides the soil column into horizontal layers, which contain a prescribed amount of water (usually 25 mm) at their field capacities. Evaporation from soil layers is treated in a way that reduces the soil moisture storage in an exponential manner from a given potential evapotranspiration demand. The routing component transforms the surface run-off generated from the water balance component to the catchment outlet by a gamma function model form, a parametric solution of the differential routing equation in a single input single output system. The generated ground water run-off is routed through a single linear reservoir and provides the ground water contribution to the stream at the catchment outlet.

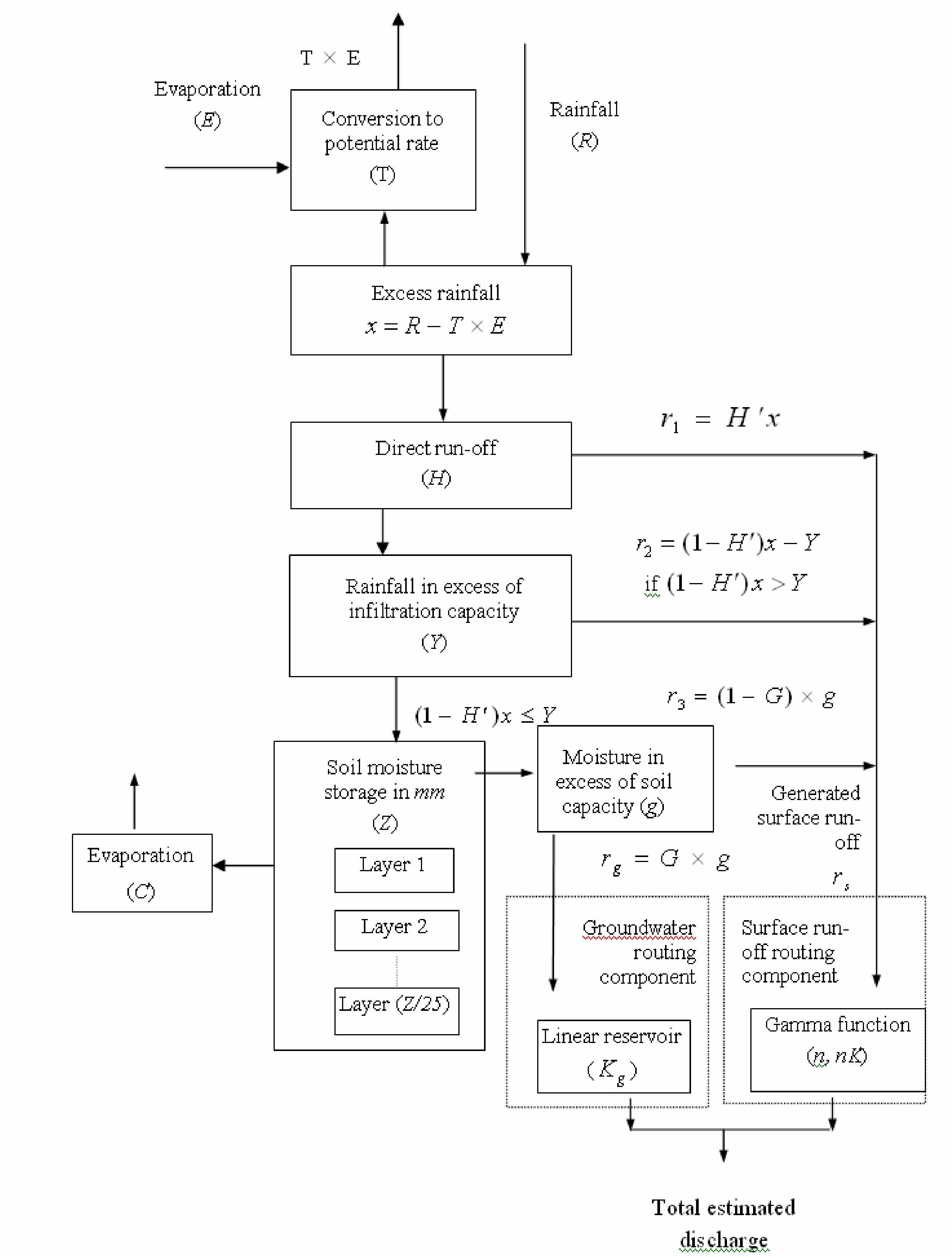

Figure 2.3 Structure of the SMAR rainfall-runoff model (Source: (RRL user guide)

2.6.2.2 SMAR model parameters and optimization techniques

The SMAR model contains five water balance parameters and four routing parameters.
The water balance component uses five parameters to describe the movement of water into and out of a generalized soil column under conditions of atmospheric forcing: C, Z, H, Y and T.

- The dimensionless parameter C regulates evaporation from the soil layers.
- The parameter Z (mm) represents the effective moisture storage capacity of the soil contributing to the run-off generation mechanisms. Each layer holds 25 mm at field capacity.
- The dimensionless parameter H is used to estimate the variable H', the proportion of rainfall excess contributing to the generated run-off as saturation excess run-off or the Dunne run-off. H' is obtained as a product of H, rainfall excess and soil saturation. Soil saturation is defined as the ratio of available soil moisture in mm at time t (days) and 125 mm, representing the maximum soil moisture content of the first five layers.
- The parameter Y (mm.d–1) represents the infiltration capacity of the soil and is used for estimating the infiltration excess run-off (Hortonian run-off).
- The dimensionless parameter T is used to calculate the potential evaporation from pan evaporation (E). Generated surface run-off is calculated from the excess rainfall (rainfall minus potential evaporation) as saturation excess run-off (shallow sub-surface flow) plus the Hortonian runoff and plus a proportion (1-G) of moisture in excess of the effective soil moisture storage capacity (g) (i.e. through flow). The remaining proportion (G) of the latter, i.e. the deep drainage component discharged from the ground water system to the stream, is routed through a linear reservoir and the total generated surface run-off is routed using a gamma function model form to obtain the daily total estimated discharge at the catchment outlet.

Ground water and surface run-off, generated from the water balance component, are routed to simulate the associated lags between rainfall events and flow out of the catchment. The Governing equations used in routing component of the SMAR model are presented as follows

The generated run-off (rs mm·d–1)) and the routed run-off (QT^{r} mm·d–1) can be time averaged, as in equations (2) and (3), to represent the daily values.

$$r_s(t)\Big| = \frac{1}{t}\int_{\tau-t}^{t} r_s(\tau)\,d\tau \tag{2}$$

$$Q_T^r(t) = \frac{1}{t}\int_{\tau-t}^{t} Q_T^r(\tau)\,d\tau \tag{3}$$

The linear model described by equation 4 is the simplest representation of a causal, time invariant, relationship between an input function of time (generated run-off) and the corresponding output function (routed run-off). It is used in conceptual modeling, as a component, representing the routing or diffusion, effects of the catchment on those components of the rainfall hyetograph contributing to the outflow.

$$Q_T^r(t) = \sum_{j=1}^{m} h(j)\, r_s(t-j+1) \tag{4}$$

Where, *m* = memory of the pulse response function (d).

The parameter pair n and nK are chosen for optimization, rather than n and K separately, because n is a ‘shape’ parameter and nK is the scale parameter. Expressed in this way, the two parameters are likely to be more independent than would be n and K separately, both of which contribute to the scale and to the shape, although in different ways.

The mass balance equation for the ground water system can be written as in equation 5.

$$Q_T^{rech}(\tau) - Q_T^{g}(\tau) = \frac{dS(\tau)}{dt} = D\,S(\tau) \tag{5}$$

Where,

$QT^{rech=}$ recharge to the ground water system ($mm.\ s$−1), =

$Q\ T^{g}$ = discharge from the groundwater system ($mm.\ s$−1), τ= time (s), S (τ) = storage of the ground water system (mm), and $D = d\,/\,d\tau$ is the differential operator (s−1).

There are three basic components of discharge from the ground water system:

- Discharge to the stream until a maximum threshold, after which discharge to land occurs following shallow water table development.
- Discharge to the land surface that is locked in the landscape and is eventually lost to the atmosphere.
- Inter-basin transport, from the local ground water system to the regional Ground water system.

Two assumptions are made in treating the ground water-routing components as a single linear reservoir:

- Discharge to the land that does not eventually reach the river is negligible.
- Inter-basin transport from the local flow system to a regional groundwater system is substantially less than the discharge to the stream (Bear, 1979)

Therefore,

$Q\ T^{g}(\tau)$ = is comprised mainly of the ground water discharge to the stream and to the land surface that eventually reaches the stream. The lag times between natural replenishment and groundwater discharge are substantial, and the groundwater system behaves like a highly damped system. This mechanism can be visualized as one of displacement whereby water from episodic drainage events is continually added at the bottom of the root zone and is removed from the ground water system at a very slow rate.

This process can be expressed by a single linear reservoir with a large storage coefficient Kg. The pulse-response function for the ground water component can be obtained in a manner analogous to equation 1 as in equation 6.

$$h^{g}(t) = \frac{1}{t}\int_{t-1}^{t} \frac{1}{K_g} \exp\left(\frac{-\tau}{K_g}\right) d\tau \qquad (6)$$

The recharge $Q_T^{rech}(t)$ and the discharge $Q_T^{g}(t)$ can be time averaged to mm·d–1 in an analogous manner, as in equations 2 and 3.

There are different optimization techniques which can be used in RRL SMAR model. Uniform random search is one of the optimization techniques applied in SMAR model. It is a very simple optimization method where by the parameter space for each parameter is divided up into a specified number of intervals between the minimum and maximum bound. The optimization proceeds by randomly selecting from the available options for each parameter then running the model and assessing the objective function. The pattern search is the simplest of all the search methods and has the advantage that it is quick but can suffer from finding local optimums rather than global optimums. This is particularly the case when models are strongly non-linear.

Multi start pattern search method works by dividing the parameter values into a specified number of increments between the specified bounds. For each of these possible starting points a pattern search is carried out. The best optimum of the pattern searches is taken as the global optimum.

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2.6.2.3 Previous application of SMAR model

Different studies were conducted in Blue Nile basin Ethiopia using RRL SMAR model. Kumela Tuffa (2011) studied rainfall runoff modeling using SMAR modeling Muger catchment. According to his study SMAR model performs well. Coefficient of determination during calibration and validation period was 0.89 and 0.88 respectively.

Woinishet Hailemariam (2009) conducted daily rainfall runoff modeling using RRL SMAR model. According to her study RRL SMAR model performs well in Blue Nile basin, Beles catchment. Coefficient of determination of RRL SMAR model during calibration and validation period becomes 0.55 and 0.2 respectively, the model didn’t capture high flow and low flow.

3.0 MATERIALS AND METHODOLOGY

In this chapter materials and approaches such as primary data collection, data analyses techniques are presented.

3.1 Description of the Study Area

The Jeldu area is located in the south of the Abay basin to the North-East of Ambo in geographical coordinates of 9° 1' 0" North, 37° 40' 0" East. With altitudes ranging from 1,328 to 3,200 masl. It is predominantly a highland area. Rainfall varies from 900 mm in the lower parts of the area to 1,350 mm at higher altitudes. Mean daily temperature ranges from 3^0c to 24 ^{0}c Mean Annual minimum temperatures is 8.5 ^{0}c and mean annual maximum temperature is 19 ^{0}c mean annual evapotranspiration is 4 mm. (Zemadim et al., 2011)

3.1.1 Drainage network

The major river draining approximately south-north is the Meja River, a tributary of the Melka River which joins the Gora River and then flows into the Guder River. The Meja River originates at high altitude just outside Jeldu Woreda in the Ginchi Woreda. The headwaters are in a flat wide valley, which is a wetland heavily utilized for livestock grazing. It then drops steeply and flows through a relatively narrow deeply incised valley. Numerous tributaries drain into the Meja from both the east and west. These are also deeply incised mountain streams with relatively small catchments (i.e. typically 3-4 km^2). (Zemadim et al., 2011)

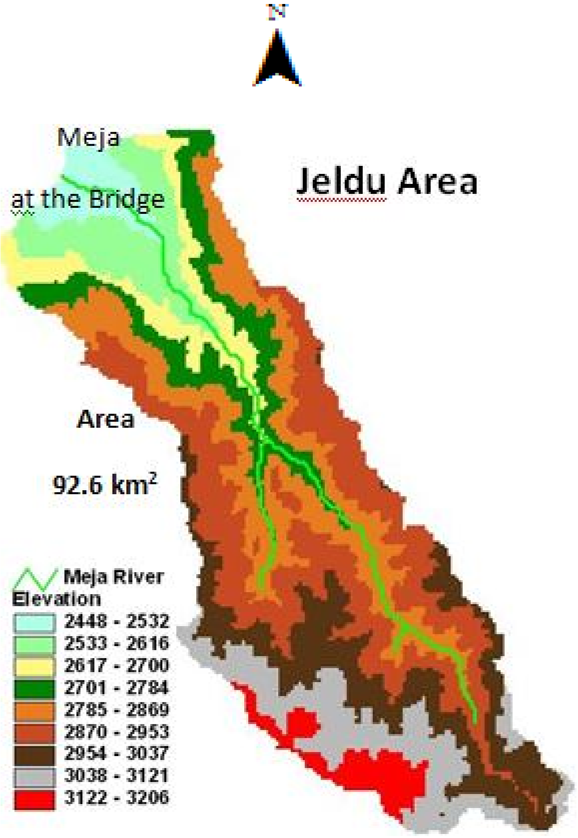


Figure 3.1 Meja watershed located in Jeldu Wereda (Source: Zemadim *etal*., 2011) CPWF Nile Project 2 field visit report)

3.1.2 Physiographic condition

The physiographic conditions near the Galessa water level recording site consists of cultivated hills, flat grazing areas which becomes swampy during the rainy season and eucalyptus plantations. The land use in the area consists of potato farms, eucalyptus plantations and flat grazing areas. The gauging station was established in a narrow gorge after identifying a stable river bank that consists of rock which is not susceptible for land sliding and bank erosion. The sides of the bank at the gauge location consist of slopes of greater than 60%, cultivated and are eroded.

The physiographic condition of Kolu consists of ploughed steep stony slopes. Eucalyptus plantation in open and gulley areas and potato and wheat farming on cultivated lands are common. There is not much grazing in this location. However homestead farming is common. The river draining in this area is called Laga Jaba river.

3.1.3 Soil type

The major soil group in Meja Catchment is Haplic Alisols (Figure 3.2).Haplic Alisols can form in wide variation of parent materials having high activity clay minerals such as vermiculite or smectate. The other soil types occurred in Meja catchment are Eutric Leptosols, Eutric Vertisols, Haplic Nitisols, Chromic Luvisols and Eutric Nitisols. Upper part of Meja watershed called Galessa is dominated by Eutric Nitisols and Haplic Alisols.

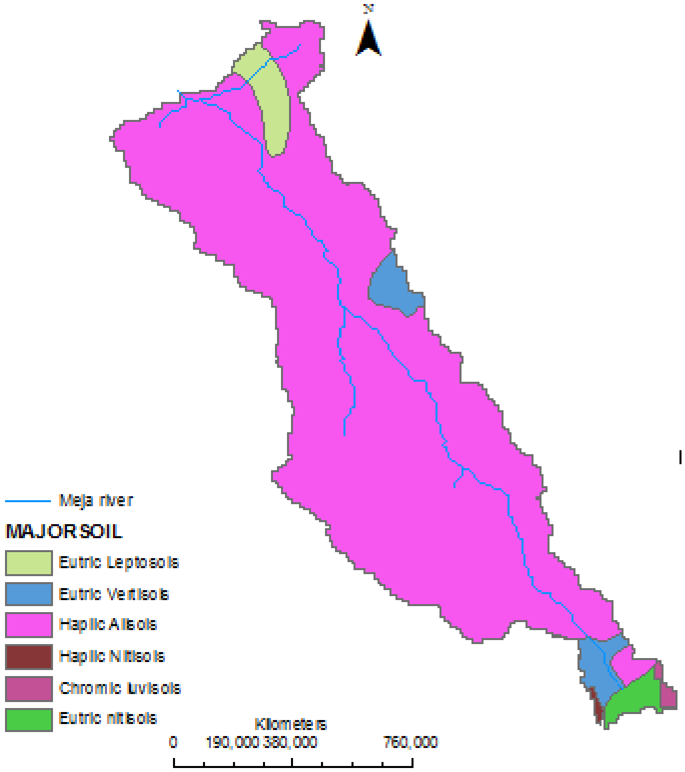


Figure 3.2 Major soil types of Meja watershed

3.1.4 Land use

The land use of the study area can be categorized mainly as agricultural and small part is agro pastoral (Figure 3.3). Eucalyptus globules are the main tree planted in the area for construction and income generation purposes.

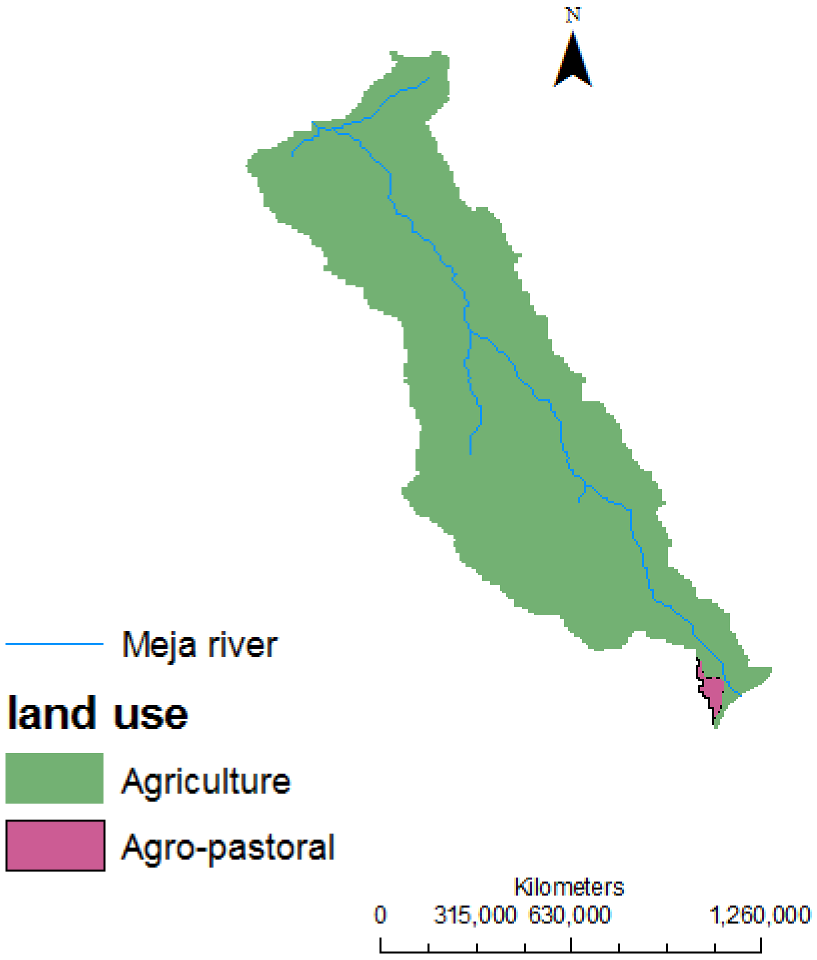


Figure 3.3 Land use types of Meja watershed

3.2 Data Collection

3.2.1 Primary data collection

3.2.1.1 Rainfall

Rainfall data was collected from the field using nine ordinary rain gauges and one automatic weather station. Data was collected from the automatic station by connecting to computer. After the data is logged in the data logger, a serial port is used to download the data to a computer. Rainfall data was collected from July 15, 2011 up to September 30, 2012

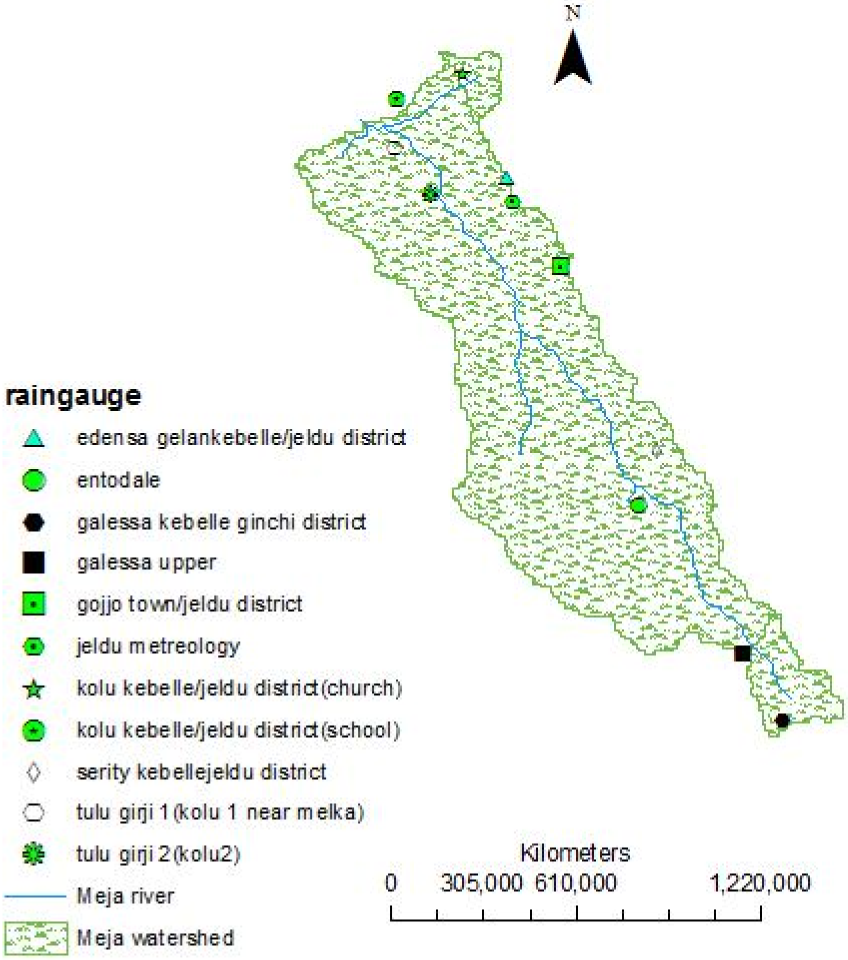


Figure 3.4 Raingauge locations of Meja watershed

3.2.1.2 Runoff

Runoff data was collected using current meter and water level recording instruments called stage boards. The data was collected from 15 July 2011 up to September 30 2012.

The current meter for discharge measurement consists of Models 001 and 002 flow meters. Both meters use the simple premise of converting speed of rotation of the helical impeller into speed of water. Available as a wading set for hand held use in shallow water or as a hand-suspension system for use from bridges, the Models 001 and 002 offer a quick, cost effective method of measuring flow in a variety of open channel applications.

The water level boards used in the current work are made of Glass Reinforced Plastic (GRP) which is a very well proven material for water level boards and has been proven both in practice and in laboratory tests to be tough, robust and easy to clean. The typical specification of the water level board used is the D64 type which is 100 mm wide and 1000 mm long. (Zemadim *etal.,* 2011).

There are four flow gauges in Meja watershed; those are Galessa flow gauge, Kolu flow gauge, Meja flow gauge at the bridge and Meja flow gauge at the upper confluence which is newly installed flow gauge. In this study runoff data was collected from Kolu and Meja at the bridge. There is no full data in the other flow gauges.

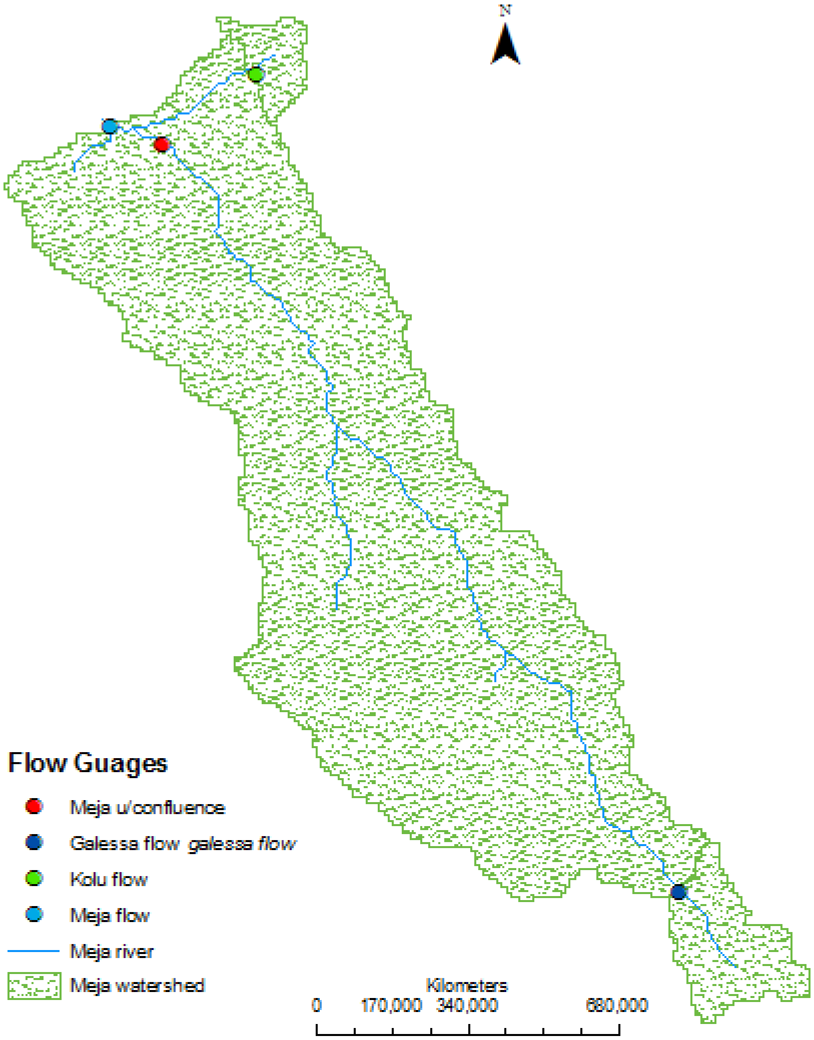


Figure 3.5 Flow gauge stations of Meja watershed

Galessa **Legajaba** **Meja at bridge**

Figure 3.6 Images of the water level measuring instruments located in Meja watershed (photo credit: Birhanu Zemadim (2011) and Simon Langan (2011))

3.2.1.3 Soil moisture

Soil moisture data was collected using profile probes PR2 with access tubes and moisture meter type HH2, ML2 theta probe. Soil moisture data was collected from 15 July 2011 up to 30 September 2012.The Profile Probe type PR2 measures the soil moisture content at different depths when inserted into an access tube that has been installed in the soil. Access tubes are fiberglass tubes inserted into pre-augured holes in the soil .Access tubes are exceptionally strong and durable in the soil. They require an installation hole only 27 mm in diameter, allowing easy installation and minimal soil disturbance.

Profile probe pr2 ML2

Figure 3.7 Soil moisture measuring instruments located in Meja watershed. (Source Zemadim *etal*. (2012))

The type of profile probe used in the current work is called PR2/6 that measures the soil moisture at 6 depths down to 100cm from the ground surface. The nominal sensing depths in cm are 10, 20, 30, 40, 60 and 100.

In Jeldu district/Meja watershed the first monitoring devices installed were the soil profile probes at a depth of 1m. In the watershed four transect lines were selected to represent a variety of slopes and physiographic conditions. The first transect is located at the head water of Meja watershed in Galesa kebele which is located in Ginchi district. The area is found just outside the boundary of the protected Chilimo forest at an average elevation of 2950 m above mean sea level. The top part of the watershed, i.e. the ridge area is steep, stony ploughed farmland, used mainly for potatoes. The first transect passes from the top part and crosses the lower grazing area and then passes through potato farmland and ends in eucalyptus plantation, after crossing the marshy area and the seasonal stream .In this transect five soil moisture profile probes were inserted .The second transect line is located in the middle of the Meja watershed in Serity kebele. This transect consists of five soil moisture monitoring stations positioned in a line from the ridge of the watershed to the stream. The third and fourth transects are located in the lowland part of Meja watershed close to the outlet in the Kolu kebele. Here a total of eight soil moisture profile probes were installed (three on the third transect and five on the fourth transect. (Zemadim *etal*, 2011).

3.2.1.4 Ground water level

Ground water data was collected using dip meter called SEBA Electric Contact Meter type KLL which is used to measure the water level in all tube wells manually. To measure water level in tube wells, the bob is lowered to the water level, when touching the level, a sensor effects the illumination of the signal lamp and creates a buzzer sound. The depth is shown on the cable in meters and centimeters. There are 18 perforated and wrapped PVC pipes .Ground water data was collected from July 15, 2011 up to August 30, 2012 from three tube wells Kolu 2(C45113), Kolu 5(C45171) and Serity 2(C45182).

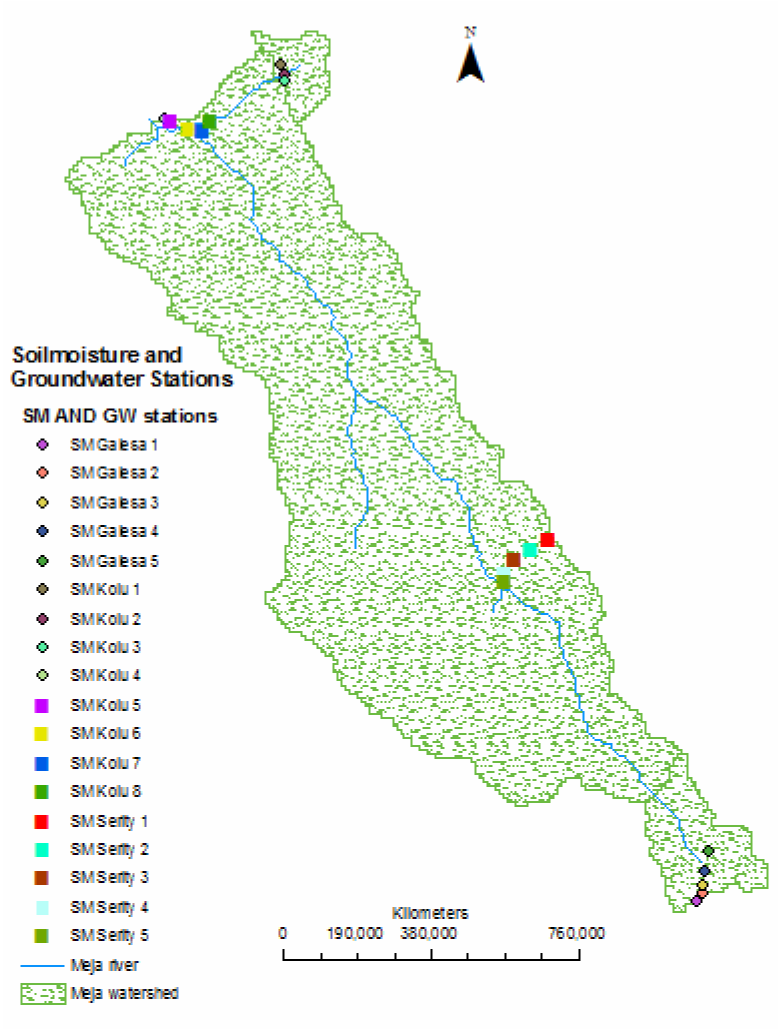


Figure 3.8 Soil moisture and ground water station locations of Meja watershed

3.2.1.5 Other meteorological data

Readings of weather conditions were recorded using Campbell scientific automatic weather station. These weather conditions are rainfall, average air temperature, maximum and minimum air temperature, relative humidity, net radiation, solar radiation, wind speed, wind direction, soil temperature and barometric pressure.

3.2.2 Secondary data

The National Meteorological Agency (NMA) is the responsible organization for the collection and issuing of meteorological data. One of the most important meteorological data for this study is the rainfall. The secondary data which is collected from NMA is rainfall. There is one third level meteorological station in Meja watershed which owned by NMA.The data length used in this study was from July 2011 to September 2012.

3.3 Data Analysis

3.3.1 Checking quality of data

The data are primary data of 1 year and 3 months. Quality was checked by visualization of the data using plots and arranged due to this visual inspection. Rough rainfall, runoff, soil moisture and ground water data screening of meteorological and hydrological stations in the study area was first done by visual inspection of daily data. To simply visualize the data, charts were done for the stations.

3.3.2 Filling missed data

Missed data is a common problem in hydrology. To perform hydrological analysis and simulation using data of time series, filling in missed data is very important. The missed data can be completed by using meteorological and hydrological stations located in the nearby stations, provided that the stations are located in a hydrologically homogenous region. In Meja watershed there are 11 rain gauges, 10 are ordinary, and one is automatic. From the ordinary rain gauges one is property of National Metreological Agency, while the others are property of International Water Management Institute (IWMI). From theses rain gauges four rain gauges have missed data. These rain gauges are Galessa 2; Kolu 1 near Melka, Kolu 2 and Entodale.In order to study runoff generation processes there is need of full data, so that these data were filled by using inverse distance weight method.

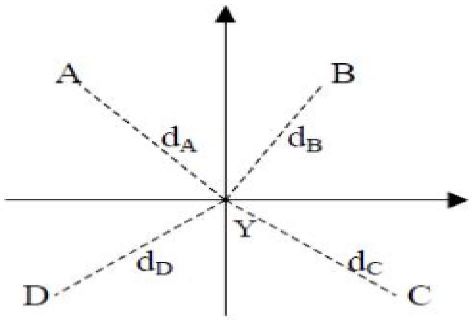


Figure 3.9 Inverse distance method of filling missed rainfall data

$$P_t(Y) = \frac{\left(\frac{1}{d_A}\right)^2 P_t(A) + \left(\frac{1}{d_B}\right)^2 P_t(B) + \left(\frac{1}{d_C}\right)^2 P_t(C) + \left(\frac{1}{d_D}\right)^2 P_t(D)}{\left(\frac{1}{d_A}\right)^2 + \left(\frac{1}{d_B}\right)^2 + \left(\frac{1}{d_C}\right)^2 + \left(\frac{1}{d_D}\right)^2}$$

---1

dZ = distance between gage *Y* and *Z*, where *Z* =*A*, *B*, etc.

Pt (*Z*) = precipitation at gage *Z* during time *t*, where *Z* =*A*, *B*, etc.

Pt(*Y*) = missing precipitation at gage *Y*

3.3.3 Areal rainfall

Areal rainfall was determined using thiessen polygons from the 11 rain gauges to account for the spatial variability. Thiessen polygon is graphical technique which calculates station weights based on the relative areas of each measurement station in these polygon networks. The Thiessen polygon method accounts for the variability in spatial distribution of gauges and the consequent variable area which each gauge represents. The areas representing each gauge are defined by drawing lines between adjacent stations on a map.

Stations outside the basin boundary should be included in the analysis as they may have Polygons which extend into the basin area. The area of a polygon for an individual station as a proportion of the total basin area represents the Thiessen weight for that station. Areal rainfall was thus estimated first by multiplying individual station totals by their Thiessen weights and then summing the weighted totals as follows:

$$P_{at} = \frac{A_1}{A}P_{1t} + \frac{A_2}{A}P_{2t} + \frac{A_3}{A}P_{3t} + \quad \cdots \quad + \frac{A_N}{A}P_{Nt} = \sum_{i=1}^{N}\left(\frac{A_i}{A}\right)P_{it}$$

where:
A_i = the area of Thiessen polygon for station i
A = total area under consideration

---2

The individual weights were multiplied by the station observation and the values were summed to obtain the areal average precipitation.

3.3.4 Rating curve development

A rating curve is established by making a number of concurrent observations of stage and discharge over a period of time covering the expected range of stages at the river gauging section. Rating curve in Meja Watershed was developed using the current meter data and gauge height measurement of two flow gauges. These flow gauges are Legajaba and Meja at the out let. The steps used to derive rating curve equation are

- Calculation of discharge using area and current meter reading
- Plotting stage and discharge
- Estimating coefficients of rating equation using least square method

3.3.5 Calculation of flow

Water level conversion to discharge values was obtained by use of the established stage discharge rating curve, calibrated by manual discharge measurements.

3.3.6 Soil moisture data analysis

Soil moisture data were analyzed by using spread sheet. Soil moisture data which were recorded in Meja catchment were very wide, so that average of soil moisture which occurred inside the watershed was used. There was no consecutive daily data, because of this reason rainfall versus soil moisture, soil moisture versus runoff relationship and soil moisture versus groundwater table was done by monthly average data for three sites, Galessa, Serity and Kolu, and also in the outlet of the watershed called Meja outlet. There are 6 layers of soil moisture readings for the 18 stations. There are 5 stations in Galessa, 5 in Serity and 8 in Kolu .the depths are 100, 200, 300, 400, 600 and 1000 in mm.

3.3.7 Ground water data analysis

Ground water level data was analyzed by plotting the time series of groundwater level with other hydrological variables like rainfall, soil moisture and surface flow using Microsoft spread sheet.

3.3.8 Potential evaporation estimation

Evapotranspiration is calculated using FAO Penman-Monteith equation .This equation is derived from the original Penman- Monteith equation and the equations of the aerodynamic and surface resistance. (Richard etal., 1998)

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

--------------3

ETO = Evapotranspiration [mm day-1]
Rn = Net radiation at the crop surface [MJ m-2 day-1]
G = Soil heat flux density [MJ m-2 day-1]
T = Mean daily air temperature at 2 m height [°C]
U2 = Wind speed at 2 m height [m s-1]

es = Saturation vapor pressure [kPa]
ea =Actual vapor pressure [kPa]
es - ea = Saturation vapor pressure deficit [kPa]
Δ =Slope vapor pressure curve [kPa °C-1]
Γ = Psychrometric constant [kPa °C-1]

3.3.9 Relationship of rainfall, soil moisture, ground water and flow

Relationship of rainfall with runoff, rainfall with soil moisture, rainfall with groundwater level, soil moisture with runoff ,groundwater level with runoff was conducted using excel sheet of statistical analysis techniques such as regression analysis, Linear correlation coefficient and coefficient of determination. Plot of each parameters are analyzed in order to understand runoff generation processes in the watershed.

3.3.10 Rainfall runoff modeling

For the part of the modelling, HBV and RRL SMAR models have been used. In Ethiopia HBV and SMAR model are applied in highlands of Blue Nile Basin and gives good result and the models are conceptual and needs small amount of data (Semu,2007). For this reason the two conceptual models were selected in this study. Rainfall, runoff and potential evapotranspiration data are required for simulation.

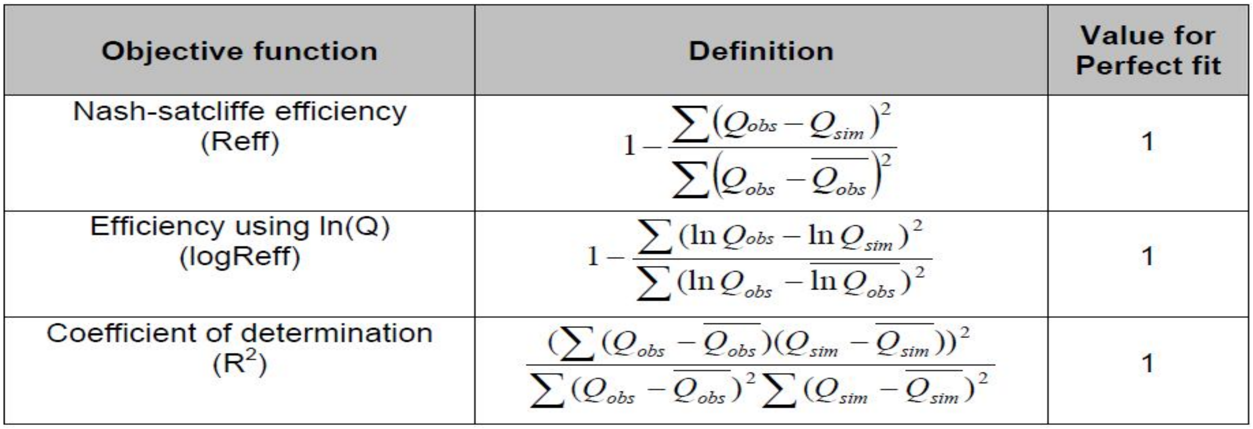
3.3.10.1 Calibration and validation of HBV and SMAR models

Calibration is a major aspect of hydrological modeling and is aimed at fitting simulated versus measured discharge best. Calibration of each model was done separately for the Meja watershed and Kolu which is a nested sub watershed of Meja watershed. Manual and Automatic calibration is used because it can be used to investigate how the different parameters change the shape of the simulated hydrograph and refine an optimized calibration. The available data set was split into two. The data range from 15 July 2011 to 5 may 2012 was used for calibration and the rest of the range between 6 May 2012 and 30 September2012 was used to validate the model without further fine tuning the model parameters.

3.3.10.2 Models evaluation criteria

The performance of a model must be evaluated on the extent of its accuracy, consistency and adaptability. Assessing performance of a hydrologic model requires subjective and/or objective estimates of the closeness of the simulated behavior of the model to observations. Performance of the model was determined using coefficient of determination and Nash Sutcliff efficiency criteria's. The evaluation criteria's are presented in table 3.1.

Table 3.1 Efficiency criteria for evaluating model performance



Objective function	Definition	Value for Perfect fit
Nash-satcliffe efficiency (Reff)	$1-\frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-\overline{Q_{obs}})^2}$	1
Efficiency using ln(Q) (logReff)	$1-\frac{\sum(\ln Q_{obs}-\ln Q_{sim})^2}{\sum(\ln Q_{obs}-\overline{\ln Q_{obs}})^2}$	1
Coefficient of determination (R^2)	$\frac{(\sum(Q_{obs}-\overline{Q_{obs}})(Q_{sim}-\overline{Q_{sim}}))^2}{\sum(Q_{obs}-\overline{Q_{obs}})^2\sum(Q_{sim}-\overline{Q_{sim}})^2}$	1

4. RESULTS AND DISCUSSION

This chapter includes results and discussion of the data analysis part. It consists rainfall pattern and its variability on the watershed, relationship of rainfall versus runoff, groundwater level versus runoff, rainfall versus groundwater level, rainfall versus volumetric soil moisture ,soil moisture versus runoff and soil moisture versus Ground water level using observed data in Meja and its nested sub watersheds. Results and discussion of rainfall runoff modeling using HBV and SMAR models are also presented in this chapter.

4.1 Results and Discussion using Observed Data

4.1.1 Rating curve development

Rating curves were developed by plotting stage and discharge. Discharge was calculated using the current meter data and gauge height measurement of two flow gauges. These flow gauges are Legajaba and Meja at the out let. The rating curve of Legajaba and Meja are Q=1.64(H+0.06) ^2.91 and Q=13(H+0.07) ^4.09 respectively. Figures of rating curve of Meja and Kolu are presented in Appendix 3.

4.1.2 Estimating areal rainfall

The output of thiessen polygon of Meja watershed is shown in figure 4.1.As shown in the figure there are 11 polygons representing each rain gauge stations. Rain gauge stations together with their elevation and mean annual rainfall in mm are presented in Table 4.1.

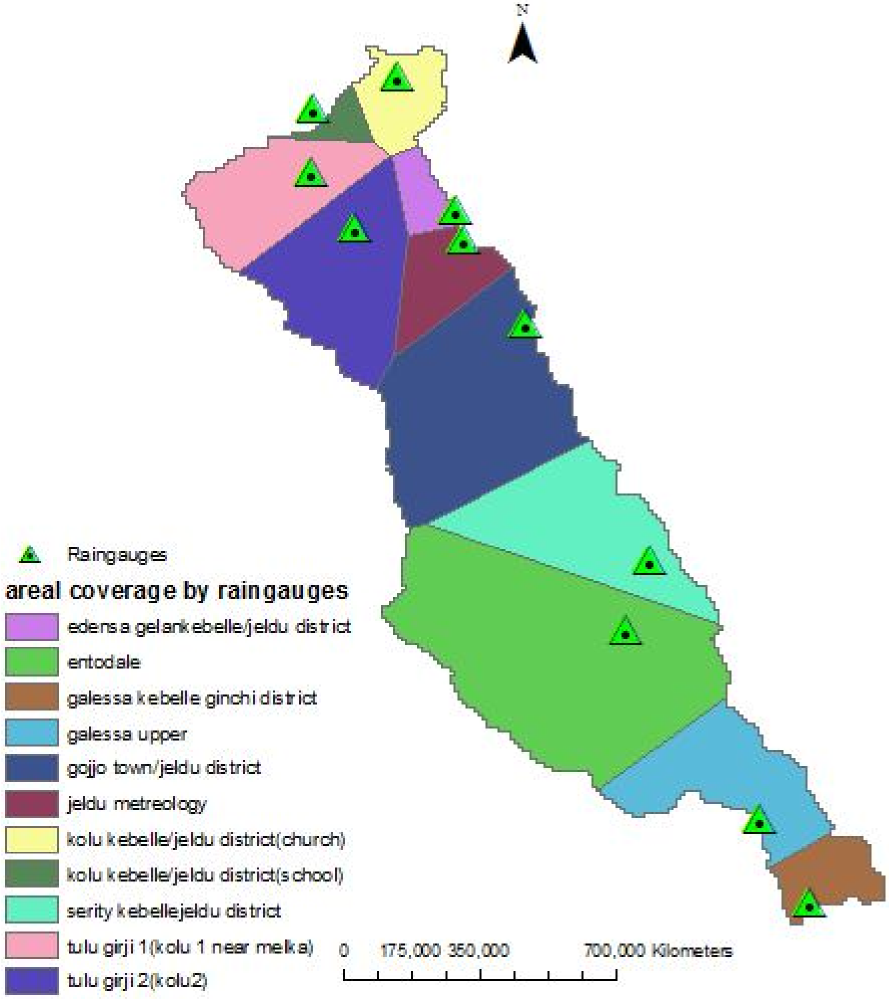


Figure 4.1 Areal coverage by raingauges located in Meja watershed

Table 4.1 Rain gauge stations with their annual sum rainfall

Station No.	Station Name	Elevation	Annual sum rainfall mm
1	Kolu 1near Melka	2522	1370
2	Kolu Elementary	2531	1400
3	Kolu 2	2578	1310
4	Kolu Church	2786	1417
5	Edensa Gelan	2862	1241
6	Jeldu Metreology	2867	1642
7	Hintodale	2903	1362
8	Aws	2942	1218
9	Serity	2946	1397
10	Galessa 1	2960	1460
11	Galessa2	3035	1464

Elevation is also analyzed with annual average rainfall. The pattern is presented in Figure 4.2. From the general concept, rainfall increases as elevation increases but here sometimes there is direct relationship but other times indirect relationship. This is because of the location of the rain gauges and shortage of long term data.

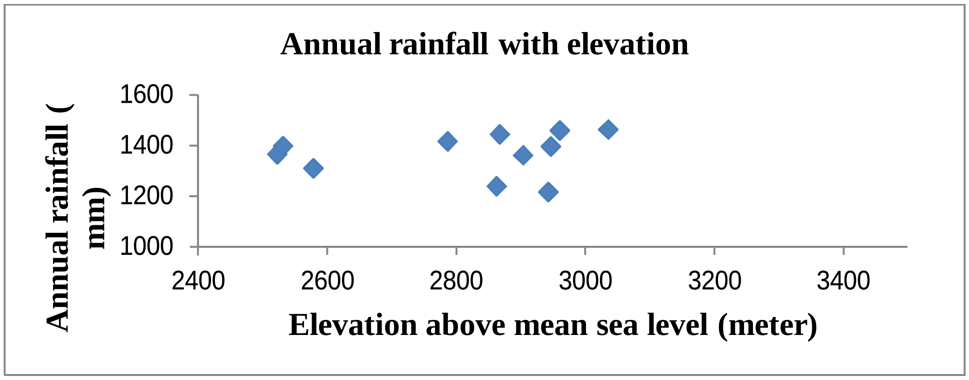


Figure 4.2 Relationships of annual rainfalls with elevation

4.1.3 Spatial variability of rainfall

The total annual rainfall from October 2011 to September 2012 in Galessa, Serity and Kolu is 1398 mm, 1364 mm and 1387 mm respectively. Galessa receives maximum annual rainfall followed by Kolu and Serity. The maximum amount of daily rainfall in Kolu is 31 mm in September 24, 2012, in Serity the maximum amount of daily rainfall is 39 mm during 8 June 2012, and in Galessa the maximum amount of daily rainfall is 35 mm during 17 July 2012. The result indicates that there is not much difference in the maximum records of daily rainfall from the three zones. However the occurrence period of the maximum rainfall in the three sub-watersheds is different. If the rainfall for each station is distributed over the whole year, the average daily rainfall is found to be 4 mm/day for Galessa, Kolu and Serity; this means average annual rainfall for all sites is almost similar. The pattern of rainfall in Galesa, Serity and Kolu is presented in the following figure.

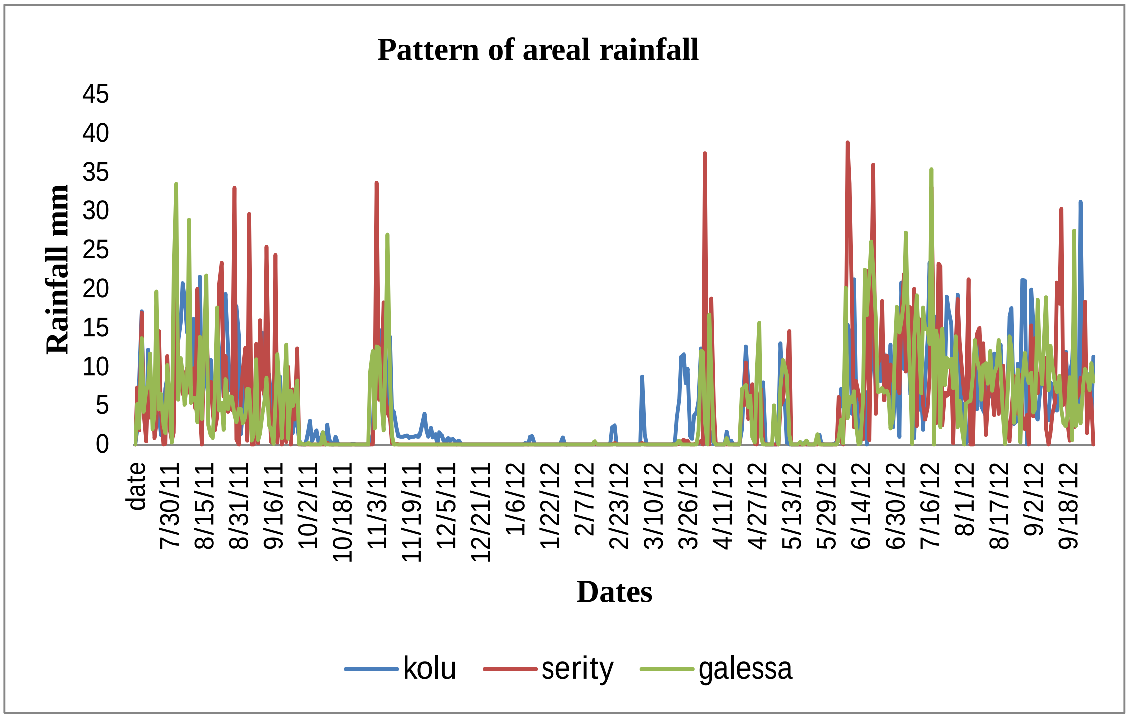


Figure 4.3 Daily patterns of areal rainfalls of Galessa, Serity and Kolu sites

There is no good relationship between the sites, coefficient of determination is less than 0.35 between each places. The coefficient of determination between Galessa and Kolu, Serity and

Kolu, Serity and Galessa is 0.35, 0.25, and 0.24 respectively (Appendix 4a). This variation comes due to their difference on topographical conditions, slopes and vegetation conditions and also on the rainfall pattern.

Figure 4.4 shows monthly patterns of areal rainfalls of Galessa, Serity and Kolu. The pattern in monthly case is almost similar for the three sites. Monthly average of rainfall of Kolu, Serity and Galessa is 107 mm, 117 mm and 115 mm respectively. In Kolu maximum total monthly rainfall was observed during August 2011, while in Serity and Galessa the maximum total monthly rainfall was observed during July 2012.As shown in Figure 4.3 the summer season rainfall is higher for Galesa, Kolu and Serity areas. This conforms to the known fact of higher storm occurrence in highland areas during the monsoon period.

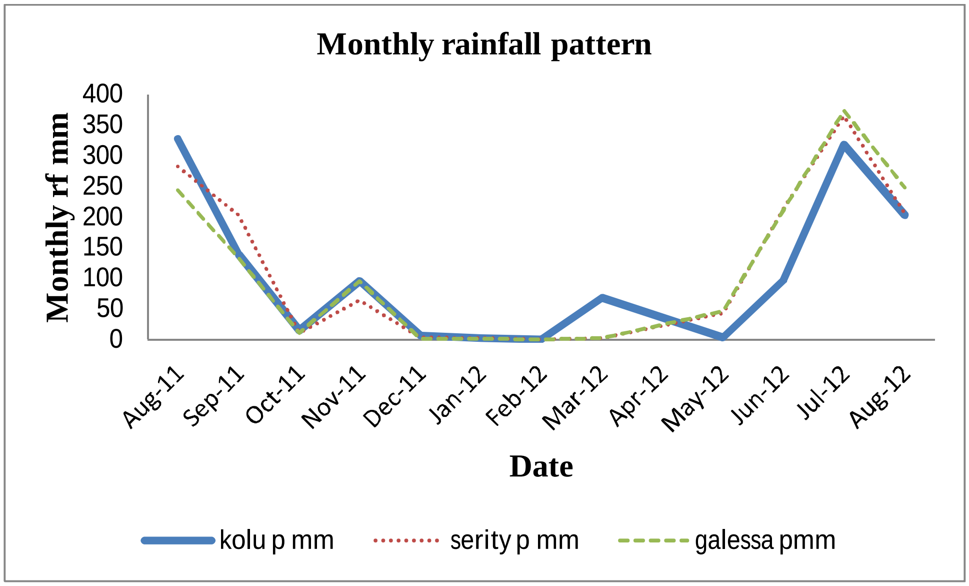


Figure 4.4 Monthly patterns of areal rainfalls of Galessa, Serity and Kolu sites

In monthly basis the relationship becomes strong. Coefficient of determination between Galessa and Kolu, Serity and Kolu, Serity and Galessa in Monthly basis is 0.83, 0.85 and 0.95 respectively (Appendix 4b). Monthly relationship is better than daily relationship.

When the individual rain gauges are assessed, there is good relationship between rain gauges located closely, but most rain gauges have poor relationship each other. Daily and monthly

Correlation coefficient and coefficient of determination for each rain gauge was also assessed. (Appendix 1a). Patterns of each rain gauge in daily and monthly basis is presented in Appendix 1b.

4.1.4 Rainfall runoff relationship of Kolu nested sub-watershed

Figure 4.5 shows pattern of rainfall and runoff in Kolu, Legajaba stream in daily basis. In September, October, November and December there is runoff in Legajeba stream, but there is no rainfall in these periods. This runoff comes from ground water table rising following the summer season, and the soil can remain saturated and can contribute a lot for the runoff and there is contribution of base flow. In early summer there is high amount of rainfall, but there is low amount of runoff compared with ending of summer season, but at the end of summer season which means in August there is high amount of runoff as rainfall amount decreases. This may be due to increase of soil moisture and ground water level in ending of summer season. There is high amount of runoff in wet season than dry season in Legajaba stream. (Table 4.2)

Table 4.2 Dry and wet season total runoff in mm at Lega Jaba stream

Station name	Catchment area Km ^{2}	Dry season flow in mm(October 2011 to May 2012)	Wet season flow in mm(June 2012 to September 2012)
Lega Jaba	2.5	124	543

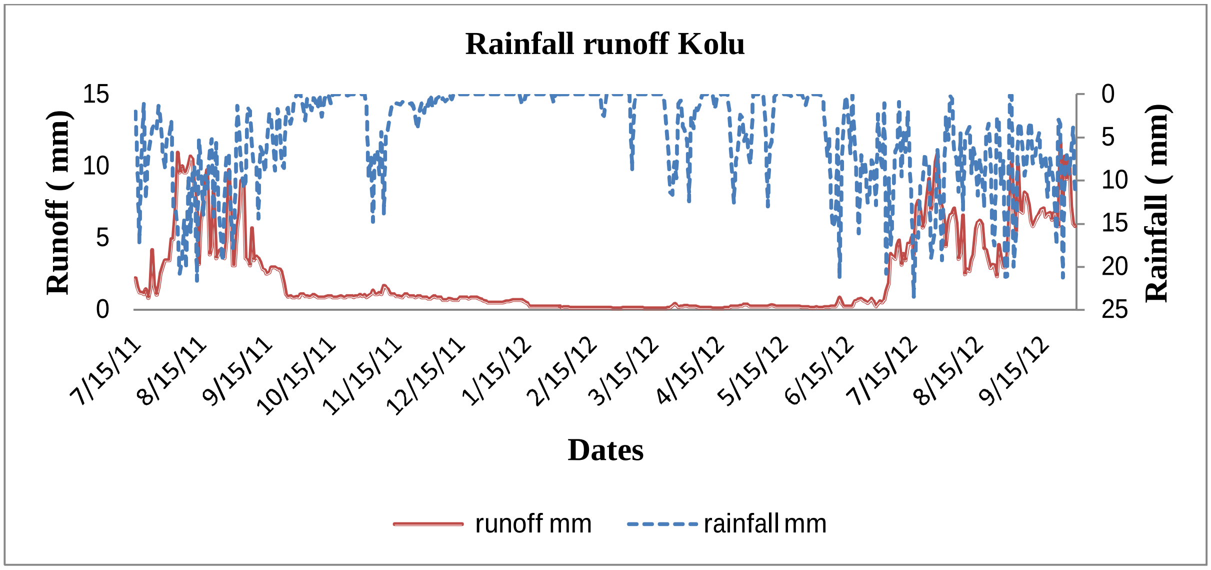


Figure 4.5 Daily rainfall runoff pattern of Kolu nested sub-watershed

There is no strong relationship between rainfall and runoff in daily basis. Coefficient of determination in daily basis is 0.32 and correlation coefficient is 0.55 which indicates low relationship of rainfall and runoff in Legajaba stream (Figure 4.6). This coefficient indicates that scatter of the relationship, and runoff is not much depends on the amount of rainfall, or there are other factors that influence runoff generation like abstractions such as irrigation requirements and infiltration or human interventions, and also runoff depends more on water table fluctuation than rainfall.

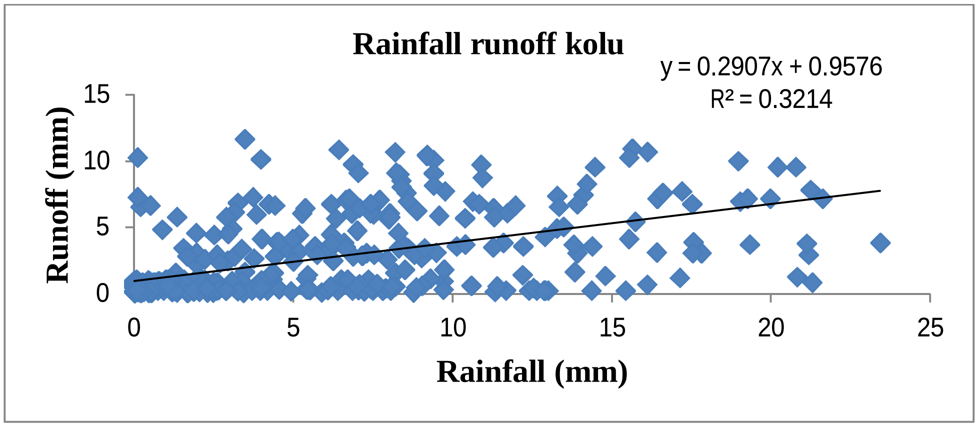


Figure 4.6 Daily rainfall and runoff relationship of Kolu nested sub-watershed

In monthly basis the relationship between rainfall and runoff is strong. According to figure 4.7 coefficient of determination between rainfall and runoff in monthly basis is 0.83 and correlation coefficient is 0.9 which indicates strong relationship. So that monthly rainfall runoff relationship is better than daily relationship.

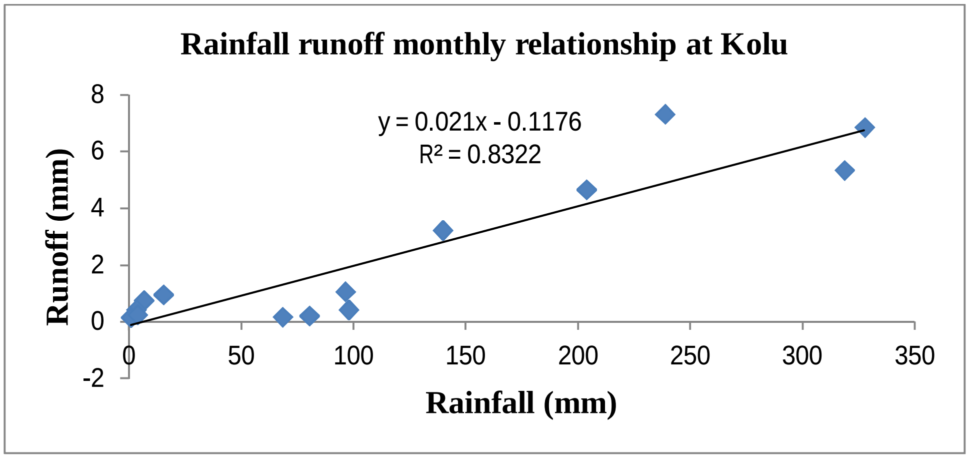


Figure 4.7 Monthly rainfall and runoff relationship of Kolu nested sub-watershed

65% of flow in Kolu is from base flow contribution. The method used for base flow separation from stream flow was Base flow program. Input data for this program is total stream flow data. The patterns of total flow, direct runoff and base flow is presented in Figure 4.8. As shown in this figure source of flow during winter season is base flow and during summer season also there is high amount of base flow contribution for the runoff.

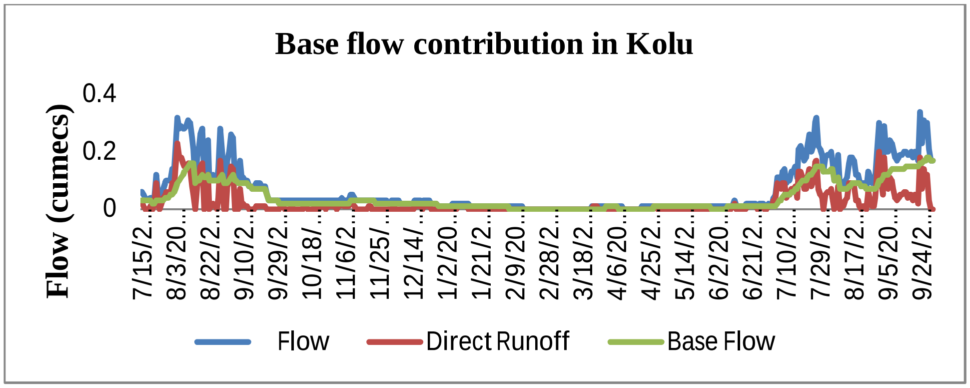


Figure 4.8 Patterns of total stream flow, direct runoff and base flow in Kolu nested sub-watershed

4.1.5 Rainfall runoff relationship of Meja watershed

Figure 4.9 indicated that if there is high rainfall there is high runoff, but occurrence of runoff doesn't mean there was high rainfall. When rainfall was 0 mm in October, November, December and February, runoff varies from 0.16 mm/day to 0.83 mm/day. There was runoff in the absence of rainfall during October, November, December, January, February, and March. During this time runoff was affected by other factors such as soil moisture and groundwater flow or base flow. Meja watershed requires only few storms at the beginning of wet season to satisfy the watershed and begun producing runoff but stream flow did not immediately return to dry season levels instead it steadily decreases.

There is moderate relationship between rainfall and runoff in daily analysis. According to table 4.3 there is high amount of runoff in summer season and low amount of runoff in winter season in Meja watershed.

Table 4.3 Dry and wet season total runoff in mm Meja at the outlet

Station name	Catchment area Km ^{2}	Dry season flow in mm (October 2011 to May 2012)	Wet season flow in mm (June 2012 to September 2012)
Meja at outlet	96.6	97	571

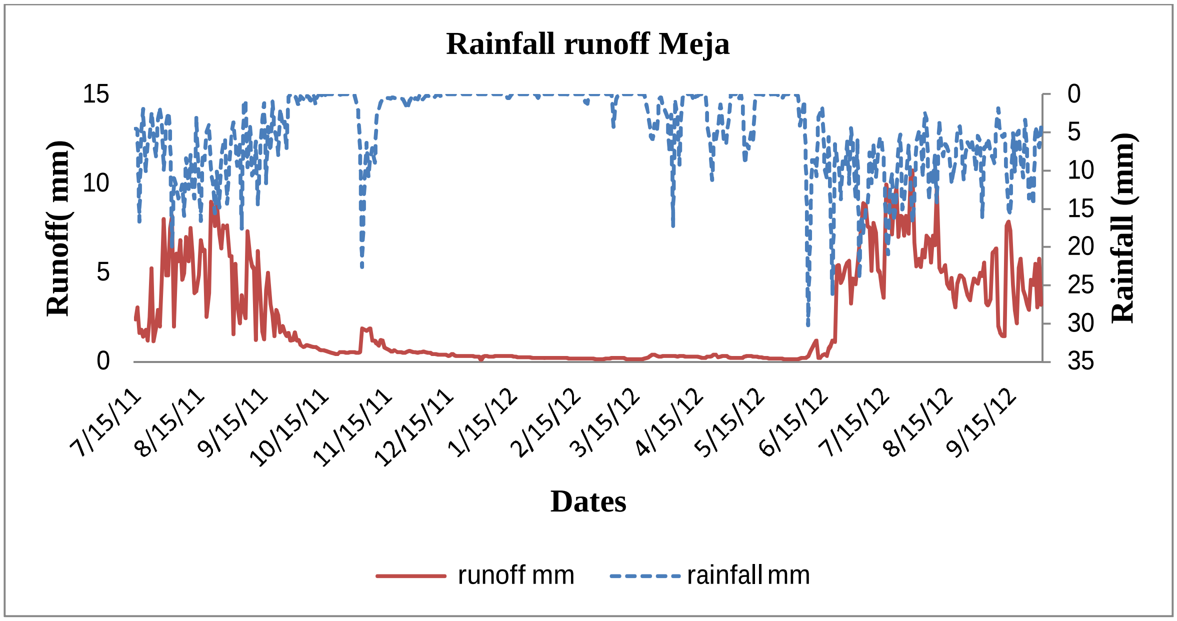


Figure 4.9 Daily rainfall runoff pattern of Meja watershed

Coefficient of determination of rainfall and runoff in Meja watershed in daily basis is 0.48 and correlation coefficient is 0.7, this indicates presence of moderate relationship. (Figure 4.10)

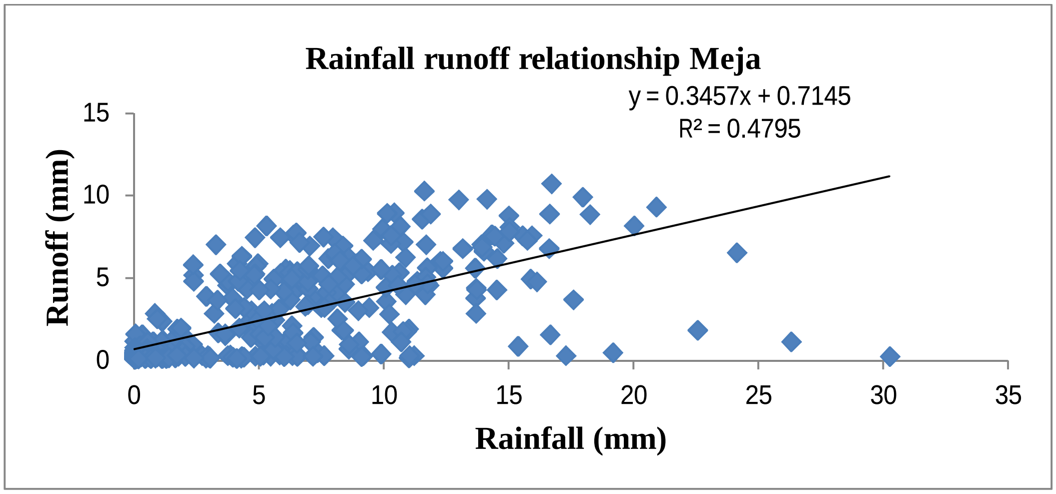


Figure 4.10 Daily rainfall runoff relationship of Meja watershed

In monthly basis the relationship between rainfall and runoff is strong. According to figure 4.11 coefficient of determination between rainfall and runoff in monthly basis is 0.94 and correlation coefficient is 0.97 which indicates strong relationship. So that monthly rainfall runoff relationship is better than daily relationship.

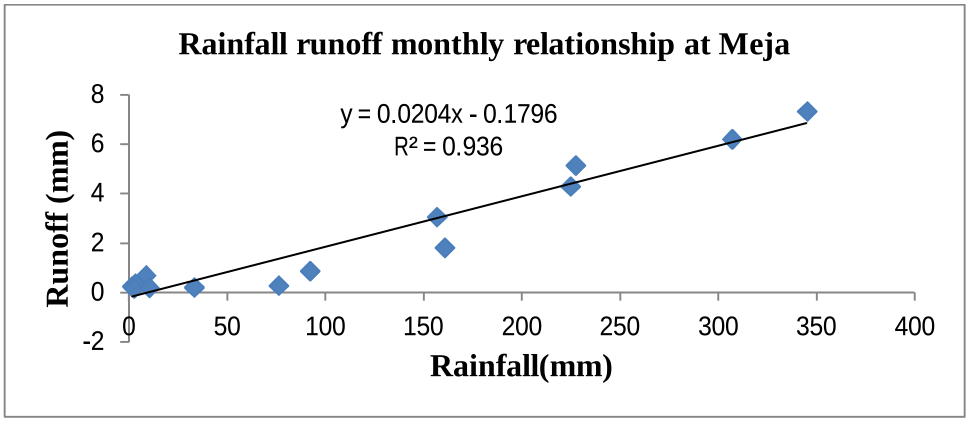


Figure 4.11 Monthly rainfall runoff relationship of Meja watershed

63% of the flow in Meja watershed is from base flow contribution. Input data for this program is total stream flow data. The daily patterns of total flow, direct runoff and base flow is presented in Figure 4.12. As shown in this figure source of flow during winter season is base flow and during summer season also there is high amount of base flow contribution for the runoff.

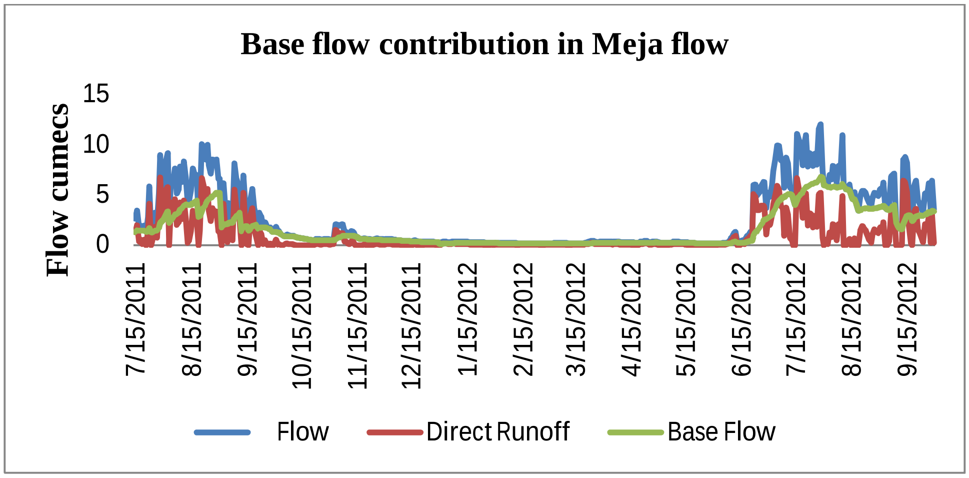


Figure 4.12 Patterns of total stream flow, direct runoff and base flow in Meja watershed

Meja River and Legajeba stream are perennial flow, which indicates a large proportion of the rainfall is infiltrated in to the basin and reaches the stream as subsurface flow, because for river with perennial flow most of the time the basin yield usually comes from base flow. Generally rainfall and runoff relationship in Meja and its nested sub-watershed, Kolu has no good relationship in daily basis this indicates the most factor that affect runoff generation is base flow and subsurface flow. And because of abstractions such as irrigations, rainfall and runoff relationship in daily basis was found to be poor.

4.1.6 Ground water level and runoff relationship, for Kolu nested sub-watershed

For purely hydrometric approach, using limited continuous data on soil moisture in addition to rainfall runoff data, this study describes general runoff generation processes of Kolu through the analysis of ground water level and runoff relationship.

In this analysis two water tube wells were used called Kolu 2 (C45113) and Kolu 5 (C45171). In Legajaba stream monthly runoff and Ground water level relationship is strong. Coefficient of determination between ground water level at Kolu 2 and flow at Lega jaba stream in monthly basis is 0.89 and correlation coefficient is 0.94 and the coefficient of determination between ground water level in Kolu 5 station and flow at Lega jaba stream is 0.65 and correlation coefficient is 0.81 which indicates strong relationship. (Appendix 5)

Even if ground water level and runoff has Strong relationship in monthly basis but there are some conditions that interrupted this general relationship, such as decrease of runoff when water level rises and increases of runoff when water table falls. This unusual behavior suggests that under these conditions runoff generation may be related to other factors other than the evolution of the water table position. Generally water table and runoff has good relationship in Kolu nested sub-watershed, this indicates that the most contributing factor to runoff at Kolu is subsurface and ground water flow.

Figure 4.13 and 4.14 shows daily pattern of ground water level at station of Kolu 2 and flow at Lega jaba stream and ground water level at station of Kolu 5 and flow at Lega jaba stream respectively. Accordingly in both stations most of the time flow increases as ground water rises and flow decreases as ground water falls. For example during July 2012, Ground water rises from 2738 m amsl up to 2739.04 and flow increases from 0.017 cumecs to 0.264 cumecs at station of Kolu 2.

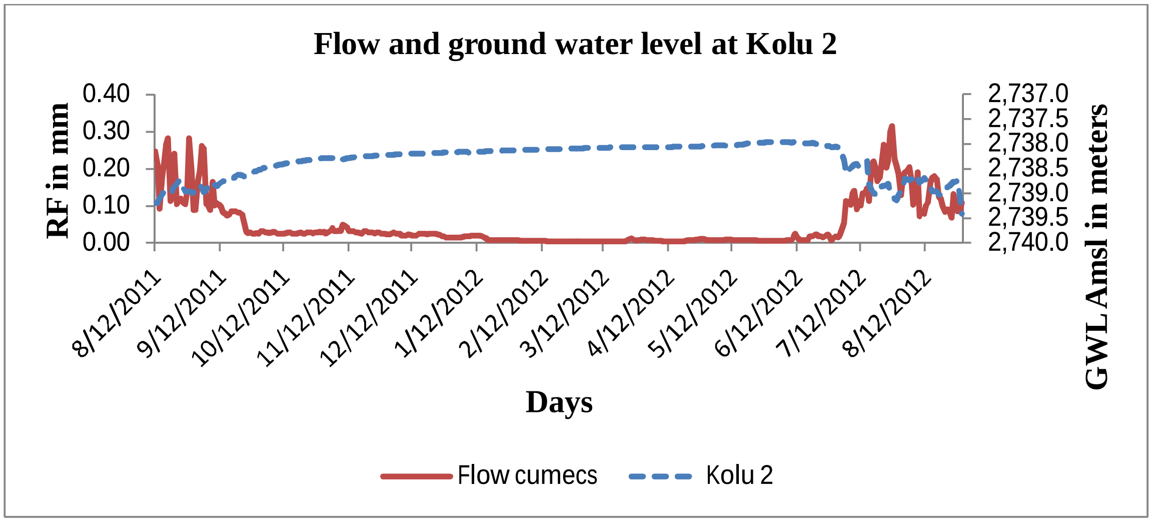


Figure 4.13 Daily ground water level and flow pattern at Kolu 2 nested sub-watershed

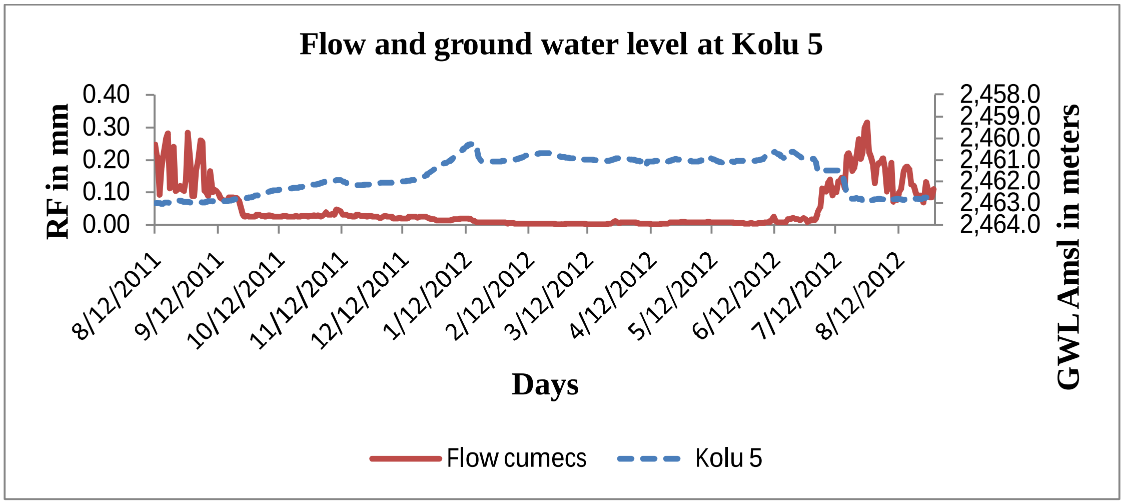


Figure 4.14 Daily ground water level and flow pattern at Kolu 5 nested sub-watershed

4.1. 7 Rainfall and ground water level relationship; for Serity

In this analysis one water tube well called Serity 2 (C45182) was used for the analysis. Figure 4.15 shows daily pattern of rainfall and ground water level at Serity 2.Accordingly in summer season rainfall and ground water level increases but in winter season there is small response of ground water as rainfall amount increases.

There is moderate relationship between rainfall and ground water level in Serity. Coefficient of determination between rainfall and ground water level in monthly basis is 0.56 and correlation coefficient is 0.75 which indicates moderate relationship (Appendix 6). Occurrence of rainfall doesn't indicate rising of water table or occurrence of high amount of rainfall doesn't indicate directly fast increase or rising of water table. There are also other factors that influence ground water fluctuation in Serity such as lateral flow from other local ground water medium.

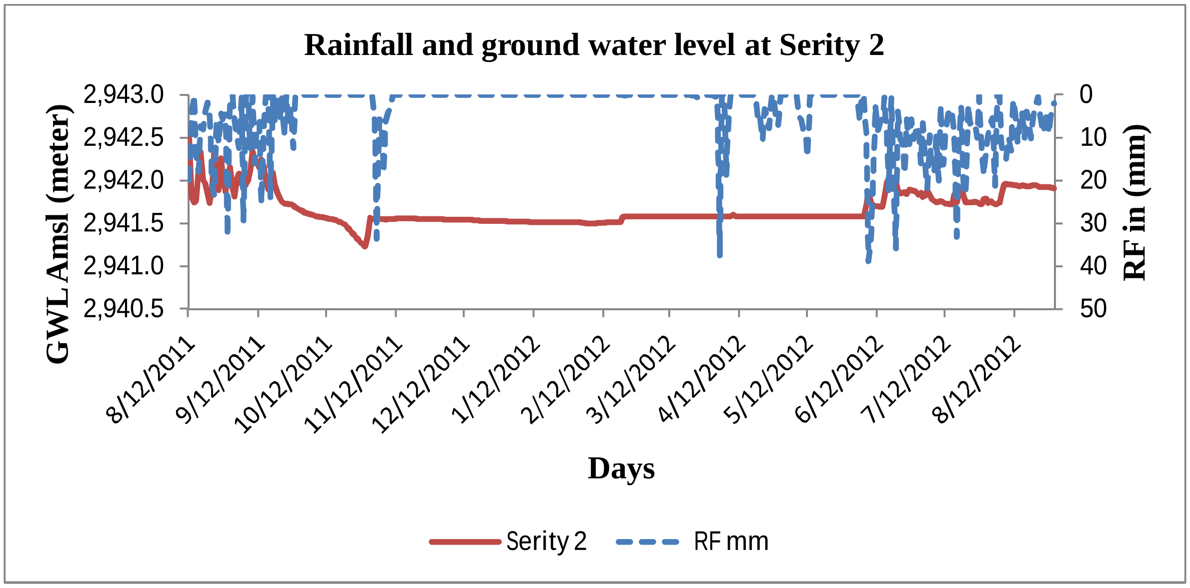


Figure 4.15 Daily rainfall and ground water level pattern of Serity

4.1.8 Rainfall and ground water level relationship; for Kolu sub watershed

Rainfall and ground water level relationship in Kolu nested sub watershed was analysed using two tube wells called Kolu 2 and Kolu 5. Coefficient of determination between ground water level at Kolu 2 and rainfall at Kolu site in monthly basis is 0.80 and correlation coefficient is 0.94 and the coefficient of determination between ground water level in Kolu 5 station and rainfall at Kolu site is 0.45 and correlation coefficient is 0.67 which indicates strong relationship. (Appendix 6).

In figure 4.16 and 4.17, it is presented that daily rainfall and ground water level pattern at Kolu 2 and Kolu 5.Accordingly in summer season rainfall and ground water level increases, but in winter season ground water level doesn’t change as rainfall increases. In kolu, nested sub watershed ground water level relates more to flow than to rainfall, so that there may be high horizontal hydraulic permeability than vertical hydraulic permeability. Peak ground water level doesn’t match with occurrence of peak rainfall; this indicates that there is delay of ground water response to rainfall.

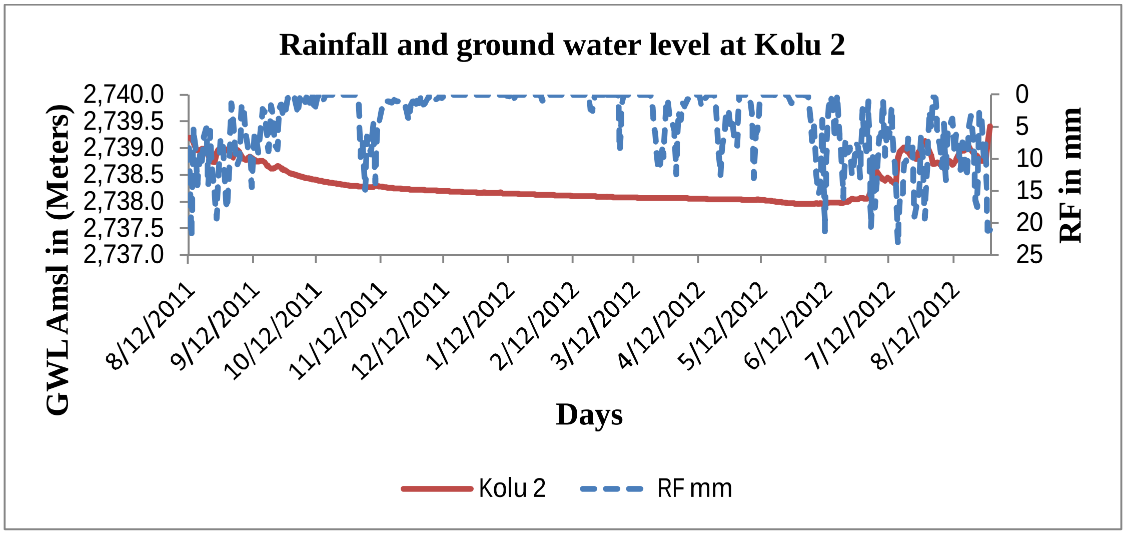


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Figure 4.16 Daily rainfall and ground water level pattern of Kolu 2

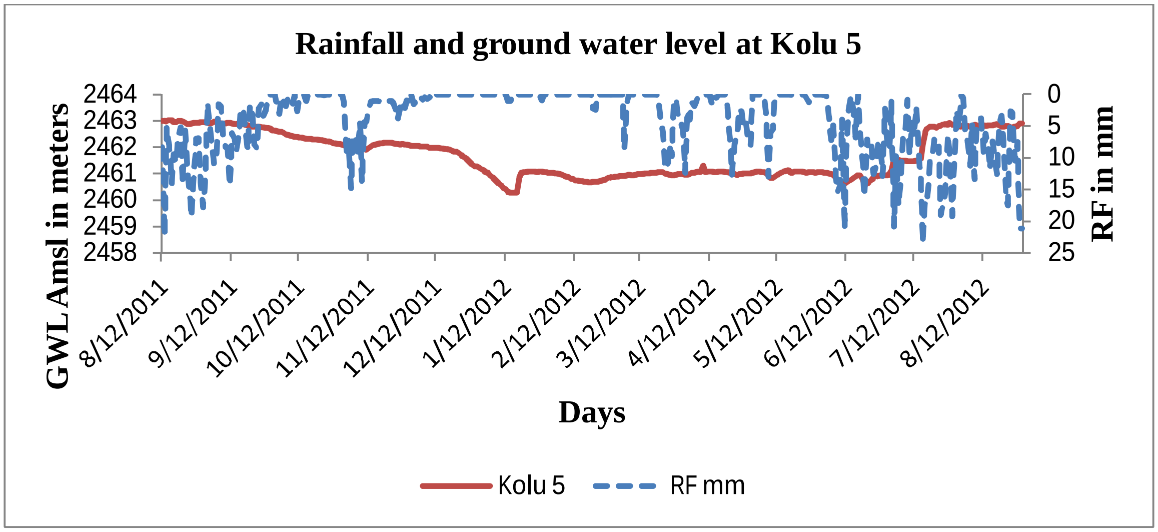

Figure 4.17 Daily rainfall and ground water level pattern of Kolu 5

4.1.10 Rainfall and soil moisture relationship of Galessa nested sub-watershed

Study of rainfall and soil moisture was conducted in monthly average basis because of lack of consistent and sufficient daily data. Soil moisture was measured in different layers 100 mm, 200 mm, 300 mm, 400 mm, 600 mm and 1000 mm.So that rainfall and volumetric soil moisture relationship was studied in each layer.

In 100 mm layer of volumetric soil moisture measurement there is strong relationship of rainfall and soil moisture. Coefficient of determination between rainfall and volumetric soil moisture at 100 mm is 0.74 and correlation coefficient is 0.86 (Appendix 7), which indicates the soil which is found in 100 mm is pervious, because water can infiltrate and moist the soil. In 300 mm layer of soil moisture measurement there is moderate relationship of rainfall and soil moisture. Coefficient of determination between rainfall and soil moisture at 300 mm is 0.58 and correlation coefficient is 0.76 which indicates moderate relationship, this means the relationship is not strong but there is a good relationship. As rainfall changes, soil moisture also changes but it is not as much as in 100 mm layer. This indicates there is a different soil horizon; the soil type here in 300 mm may be a little bit different from the upper soil type.

There is moderate relationship of rainfall and volumetric soil moisture content at 400 mm layer. Coefficient of determination between rainfall and soil moisture at 400 mm layer is 0.59 and correlation coefficient is 0.77 which indicates moderate relationship. This means the relationship is not strong but there is a good relationship. As rainfall changes, soil moisture also changes but it is not as much as in 100 mm layer. This indicates that there is a different soil horizon; the soil type here in 400 mm may be a little bit different from the upper soil type.

Coefficient of determination between rainfall and volumetric soil moisture in 600 mm layer is 0.59 and correlation coefficient is 0.77 which indicates moderate relationship. So that there is strong relationship of rainfall and volumetric soil moisture in the upper part of the soil. But here in the lower part there is moderate relationship.

Figure 4.18 helps to visualize each layer of soil moisture measurement with rainfall amount at Galessa site. Accordingly volumetric soil moisture increases when the depth from the ground surface increases. There is high amount of volumetric soil moisture in 600 mm layer than in 100 mm. The relationship of rainfall and volumetric soil moisture decreases when the depth from the ground surface increases, but the amount of soil moisture content increases. This shows that soil moisture at 100 mm layer is more affected by rainfall but at 300 mm, 400 mm and 600 mm, soil moisture influenced by other activities such as sub surface flow or interflow and capillary rise from the ground water.

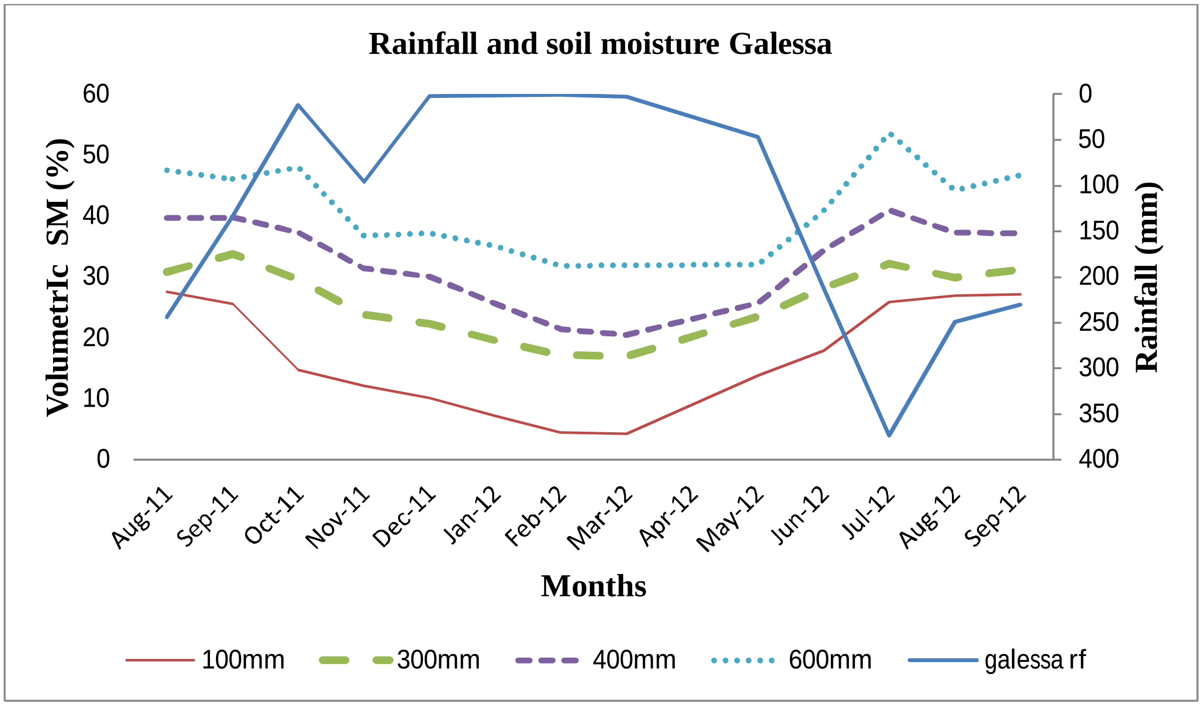

Figure 4.18 Rainfall and different layers of volumetric soil moisture pattern of Galessa nested sub-watershed

4.1.11 Rainfall and soil moisture relationship of Serity

There is weak relationship between rainfall and volumetric soil moisture in 100 mm layer of soil moisture measurement of Serity site. Coefficient of determination between rainfall and soil moisture at 100 mm layer is 0.34 and correlation coefficient is 0.59 which indicates low relationship. This means soil moisture in 100 mm layer doesn’t change with rainfall. This can be occurred in previously wet soil.

In 300 mm layer of soil moisture measurement there is moderate relationship of rainfall and volumetric soil moisture. Coefficient of determination between rainfall and soil moisture in 300 mm layer is 0.68, and correlation coefficient is 0.82 which indicates moderate relationship. Rainfall and volumetric soil moisture at 400 mm layer has strong relationship. Coefficient of determination between rainfall and soil moisture at 400 mm layer is 0.77 and correlation coefficient is 0.88 which indicates strong and linear.

In 600 mm the relationship between rainfall and soil moisture decreases as compared to other layers such as 300 mm and 400 mm.Coefficient of determination between rainfall and soil moisture in 600 mm is 0.44 and correlation coefficient is 0.66 which indicates low relationship of rainfall and soil moisture. In this layer soil moisture is most influenced by capillary rise than rainfall. The difference in relationship between rainfall and soil moisture in each layer in Galessa and Serity may be due to the soil type variability in each site.

Figure 4.19 helps to visualize each layer of soil moisture amount with rainfall amount at Serity site. Accordingly volumetric soil moisture increases when the depth from the ground surface increases. There is high amount of volumetric soil moisture in 600 mm layer than in 100 mm. And there is high amount of rainfall and volumetric monthly averaged soil moisture in summer season and low amount of rainfall and monthly averaged volumetric soil moisture in winter.

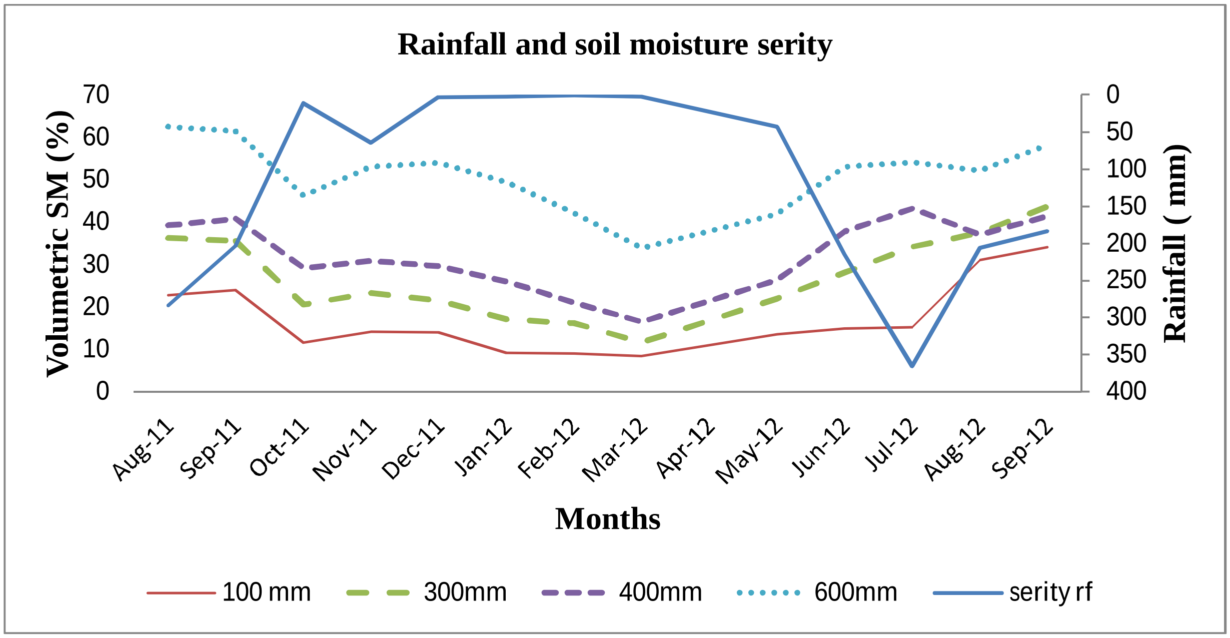

Figure 4.19 Rainfall and different layers of volumetric soil moisture pattern of Serity nested sub-watershed

4.1.12 Rainfall and soil moisture relationship of Kolu nested sub-watershed

There is strong relationship of rainfall and soil moisture at 100 mm layer. Coefficient of determination between rainfall and soil moisture at 100 mm layer is 0.87 and correlation coefficient is 0.93 which indicates strong and linear relationship. This shows soil in the upper horizon of Kolu site is pervious and previously dry.

There is strong relationship between rainfall and volumetric soil moisture at 200 mm layer. Coefficient of determination between rainfall and soil moisture at 200 mm layer is 0.8 and correlation coefficient is 0.9 which indicates strong and linear relationship. Soil moisture increases as rainfall increases and soil moisture decreases as rainfall decreases. There is also strong relationship of rainfall and soil moisture at 300 mm layer. Coefficient of determination between rainfall and soil moisture at 300 mm layer is 0.78 and correlation coefficient is 0.88 which indicates high, strong and linear relationship but this relationship is lower than of 100 mm and 200 mm.The relationship of soil moisture and rainfall decreases from layer to layer.

There is strong relationship of rainfall and soil moisture at 400 mm layer. Coefficient of determination between rainfall and soil moisture at 400 mm layer is 0.77 and correlation coefficient is 0.84 which indicates strong and linear relationship. In 600 mm layer coefficient of determination between rainfall and soil moisture is 0.3 and correlation coefficient is 0.55 which indicates low relationship. This weak relationship of rainfall and volumetric soil moisture at 600 mm layer indicates that, soil moisture at 600 mm layer is most influenced by capillary rise from the ground water than rainfall.

Figure 4.20 helps to visualize each layer of soil moisture measurement with rainfall amount at Kolu site. Accordingly volumetric soil moisture increases when the depth from the ground surface increases. There is high amount of volumetric soil moisture at 600 mm layer than 100 mm. And there is high amount of rainfall and volumetric monthly averaged soil moisture in summer season and low amount of rainfall and monthly averaged volumetric soil moisture in winter. In 600 mm layer there is high amount of volumetric soil moisture, but there is weak relationship of rainfall and soil moisture, this may be due to influence of ground water.

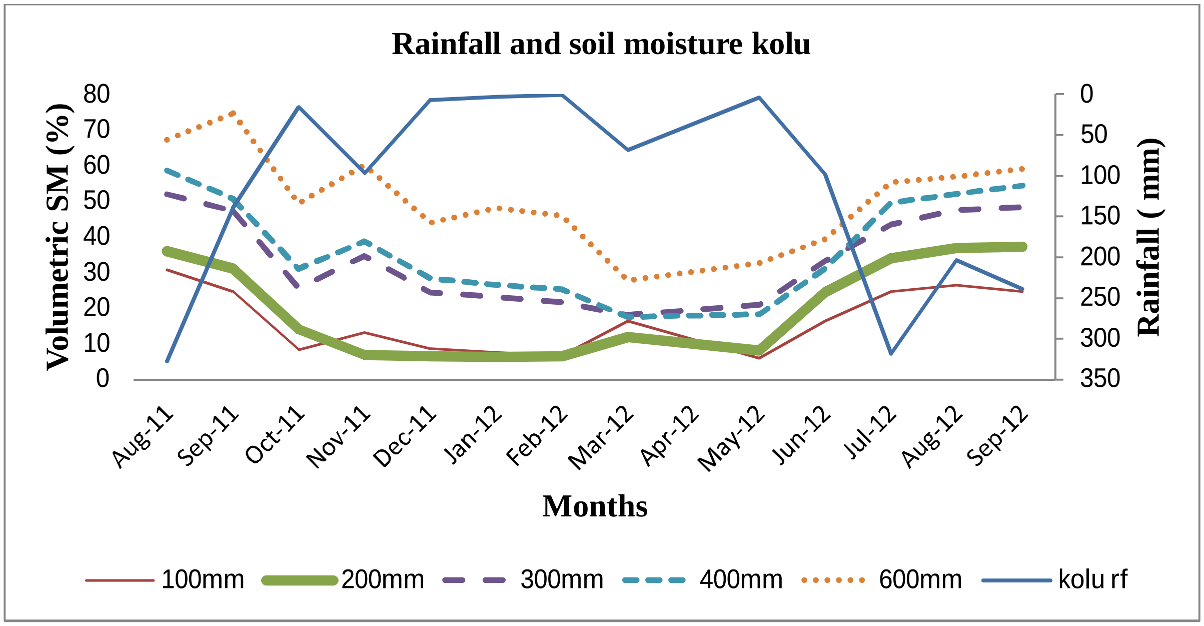

Figure 4.20 Rainfall and different layers of volumetric soil moisture pattern of Kolu nested sub-watershed

4.1.13 Rainfall and soil moisture relationship of Meja watershed

In 100 mm layer of soil moisture measurement there is strong relationship of rainfall and soil moisture. Coefficient of determination between rainfall and soil moisture at 100 mm layer is 0.76 and correlation coefficient is 0.87 which indicates strong relationship. This means soil in the upper horizon in Meja is pervious. There is strong relationship of rainfall and Soil moisture at 300 mm layer. Coefficient of determination between rainfall and soil moisture at 300 mm layer is 0.77 and correlation coefficient is 0.88 which indicates strong relationship. Soil type in upper horizon and in 300 mm layer is almost similar.

In 400 mm layer of soil moisture measurement strong relationship of rainfall and soil moisture content is observed. Coefficient of determination between rainfall and soil moisture at 400 mm layer is 0.76 and correlation coefficient is 0.87 which indicates strong relationship of rainfall and soil moisture. In 600 mm layer of soil moisture measurement coefficient of determination between rainfall and soil moisture is 0.52 and correlation coefficient is 0.7 which indicates moderate relationship. This moderate relationship indicates soil moisture in 600 mm layer in Meja watershed is influenced by groundwater than rainfall amount. In Galessa, Serity, Kolu and in the entire watershed soil moisture in 600 mm layer is influenced by capillary rise or ground water level.

In most layers soil moisture becomes higher in summer season and lowers in winter season. This is due to high rainfall amount and due to increase of ground water level in summer and decrease of ground water level and rainfall in winter.

There is spatial variability of soil moisture content in Meja watershed. This variation occurs due to heterogeneity of the soil, which means the places are different in soil texture and also due to vegetation cover and change of slope.

Figure 4.21 helps to visualize each layer of volumetric soil moisture measurement with rainfall amount at Meja watershed. Soil moisture increases along the layer profiles in Galessa, Serity and Kolu sites. Generally in Meja watershed, when the depth from the ground surface increases, volumetric monthly soil moisture also increases. In all sites soil moisture was measured at 100 mm, 200 mm, 300 mm, 400 mm and 600 mm layers. But there is no consistent data at 200 mm layer. So that rainfall and soil moisture analysis was not conducted at 200 mm layer. There was high amount of volumetric soil moisture in 600 mm layer than 100 mm layer. This may be because of capillary rise of ground water at 600 mm and there is more influence of rainfall at100 mm.

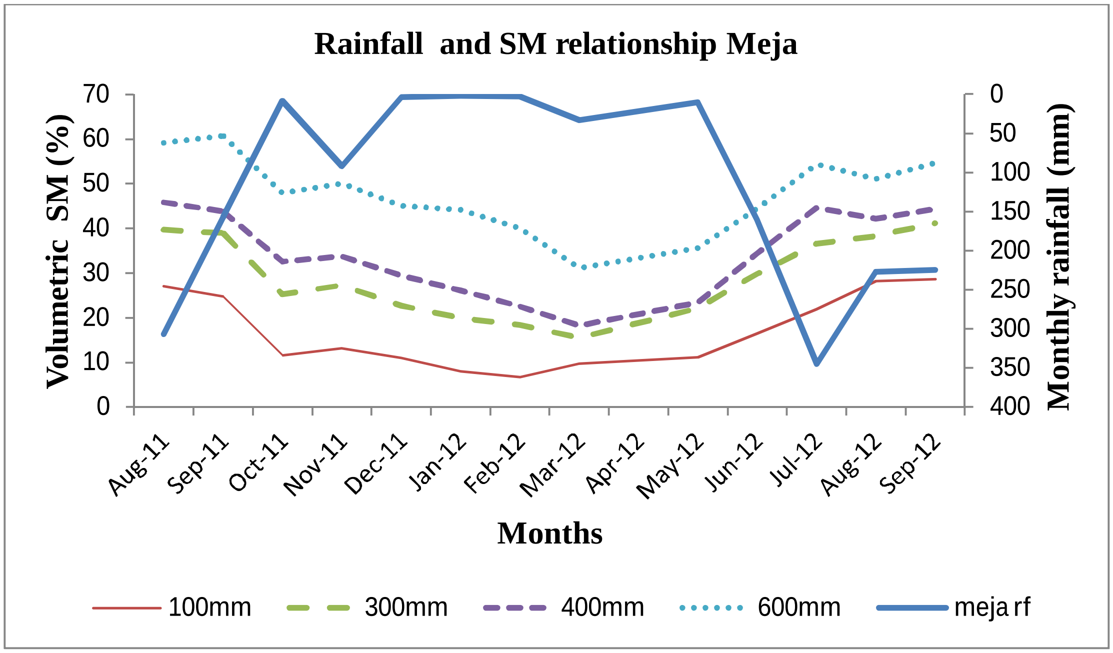

Figure 4.21 Rainfall and different layers of volumetric soil moisture pattern of Meja watershed

4.1.14 Relationship of flow and soil moisture of Kolu nested sub-watershed

In 100 mm layer there is strong relationship of runoff and soil moisture. Coefficient of determination between runoff and soil moisture at 100 mm layer is 0.77 and correlation coefficient is 0.88 which indicates strong relationship. Like 100 mm layer at 200 mm layer also there is strong relationship between runoff and volumetric soil moisture. Coefficient of determination between runoff and soil moisture at 200 mm layer is 0.8 and correlation coefficient is 0.88 which indicates strong relationship. This shows there is contribution of interflow from 100 mm and 200 mm layer.

The relationship of soil moisture and runoff increases from layer to layer up to 400 mm layer. So that there may be subsurface flow which initiates from theses layers. Coefficient of determination between runoff and soil moisture at 300 mm layer is 0.81 and correlation coefficient is 0.9 which indicates strong relationship. Coefficient of determination between runoff and soil moisture at 400 mm layer is 0.84 and correlation coefficient is 0.92 which indicates strong linear relationship. Coefficient of determination between runoff and soil moisture at 600 mm layer is 0.45 and correlation coefficient is 0.67 which indicates moderate relationship of runoff and soil moisture. Here in 600 mm the relationship of runoff and soil moisture decreases, this may be due to high contribution of ground water flow to the runoff. Figures of coefficient of determination between soil moisture and runoff are presented in Appendix 8.

Figure 4.22 shows pattern of soil moisture in each layer with runoff at Lega Jeba. In summer season runoff and soil moisture amount increases but in winter season runoff and soil moisture decreases. Accordingly runoff increases as soil moisture content increases in Kolu. The relationship between soil moisture and runoff in each layer increases from one layer to the next layer, this indicates as the depth from the ground surface increases contribution of sub surface flow to the stream increases. But below 600 mm layer contribution of ground water is more than subsurface flow.

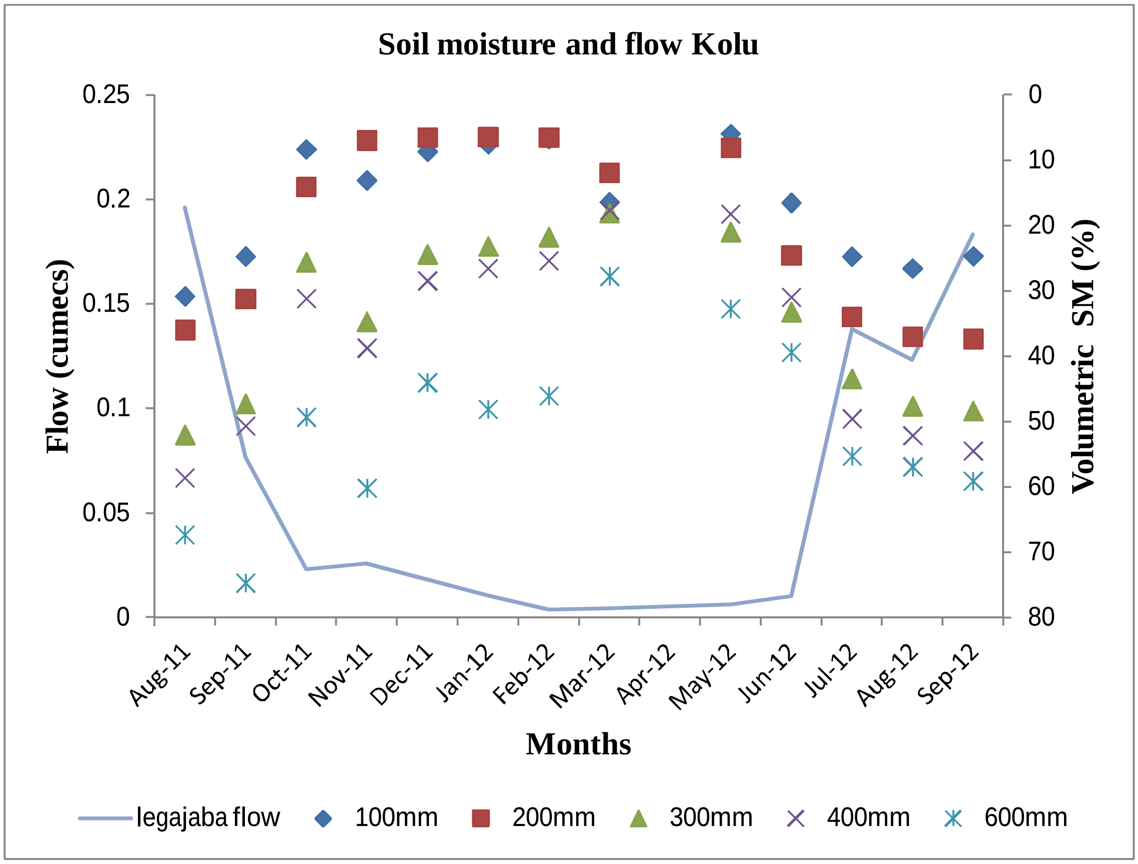

Figure 4.22 Runoff and different layers of soil moisture pattern of Kolu sub-watershed

4.1.15 Runoff and soil moisture relationship of Meja watershed

To look for other possible factors influencing runoff generation, the general relationship between runoff and soil moisture at 100,200,300,400 and 600 mm layer was investigated. Results given below shows that the relationship between soil moisture and runoff differed in little amount from layer to layer.

The relationship between runoff and soil moisture at 100 mm layer is strong. Coefficient of determination between runoff and soil moisture at 100 mm layer is 0.76 and correlation coefficient is 0.87 which indicates strong relationship. Coefficient of determination between runoff and soil moisture at 300 mm layer is 0.76 and correlation coefficient is 0.87 which indicates strong relationship.

In 400 mm layer of soil moisture, there is strong relationship of volumetric soil moisture and runoff. Coefficient of determination between runoff and soil moisture at 400 mm layer is 0.77 and correlation coefficient is 0.88 which indicates strong linear and direct relationship of runoff and soil moisture. In 600 mm layer there is moderate relationship of soil moisture and runoff. Coefficient of determination between soil moisture and runoff is 0.54 and correlation coefficient is 0.74 which indicates strong relationship. Figures of coefficient of determination between soil moisture and runoff are presented in Appendix 8.

In Figure 4.23, it is presented that the patterns of volumetric soil moisture with flow at Meja which is the outlet of the watershed. There is strong relationship between monthly averaged volumetric soil moisture and flow at each layer. But the relationship is moderate at 600 mm layer; this may be due to influence of ground water. Generally there is direct relationship between soil moisture and flow in Meja catchment.

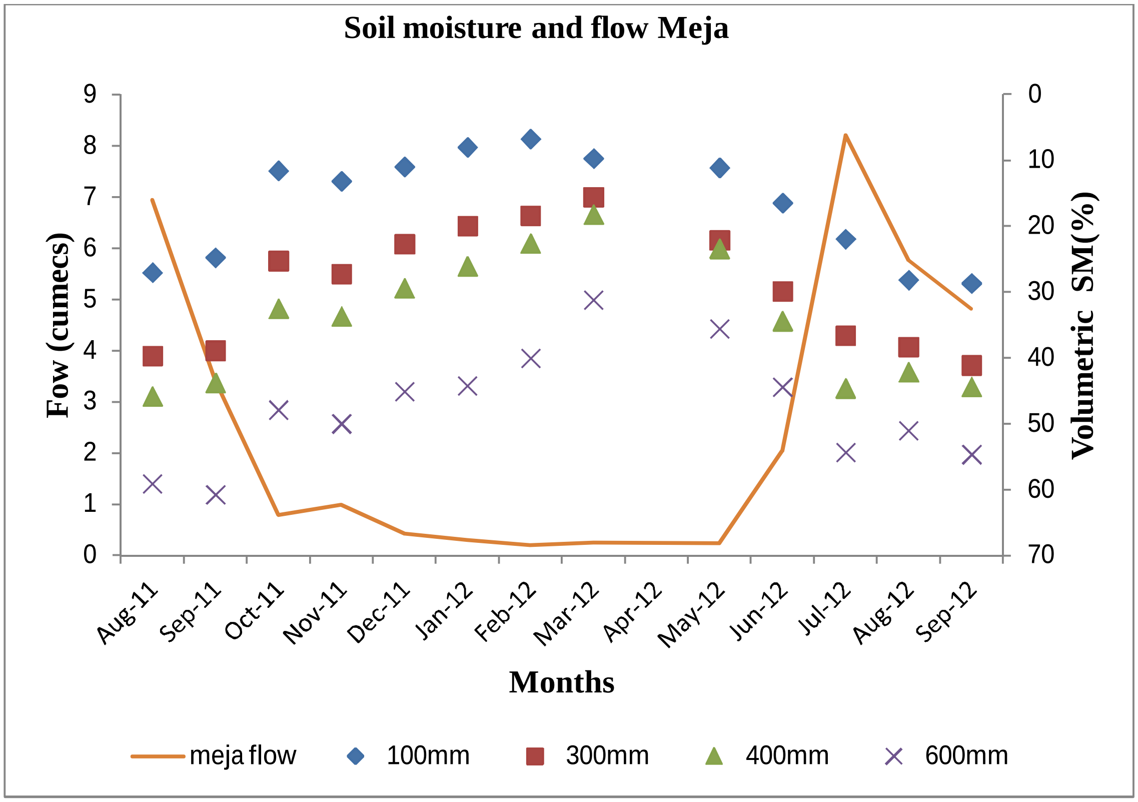

Figure 4.23 Flow and different layers of soil moisture pattern of Meja watershed

4.1.16 Soil moisture and ground water level relationship of Serity

In 100 mm layer of soil moisture measurement there is moderate relationship between soil moisture and ground water layer. Coefficient of determination between ground water level and soil moisture at 100 mm layer is 0.7 and correlation coefficient is 0.84 which indicates strong relationship. In 300 mm layer of soil moisture measurement coefficient of determination between ground water level and soil moisture is 0.8 and correlation coefficient is 0.9 which indicates strong relationship.

In 400 mm layer of soil moisture measurement coefficient of determination between ground water level and soil moisture is 0.6 and correlation coefficient is 0.77 which indicates low relationship. In 600 mm of soil moisture measurement coefficient of determination between groundwater and soil moisture is 0.48 and correlation coefficient is 0.7 which indicates moderate relationship. Figures of coefficient of determination between soil moisture and ground water level are presented in Appendix 9.

Figure 4.24 shows that volumetric soil moisture content increases as ground water level rises in Serity. There is strong relationship of soil moisture and ground water level in Serity at 100 mm and 300 mm layer and moderate relationship at 400 mm and 600 mm layer.

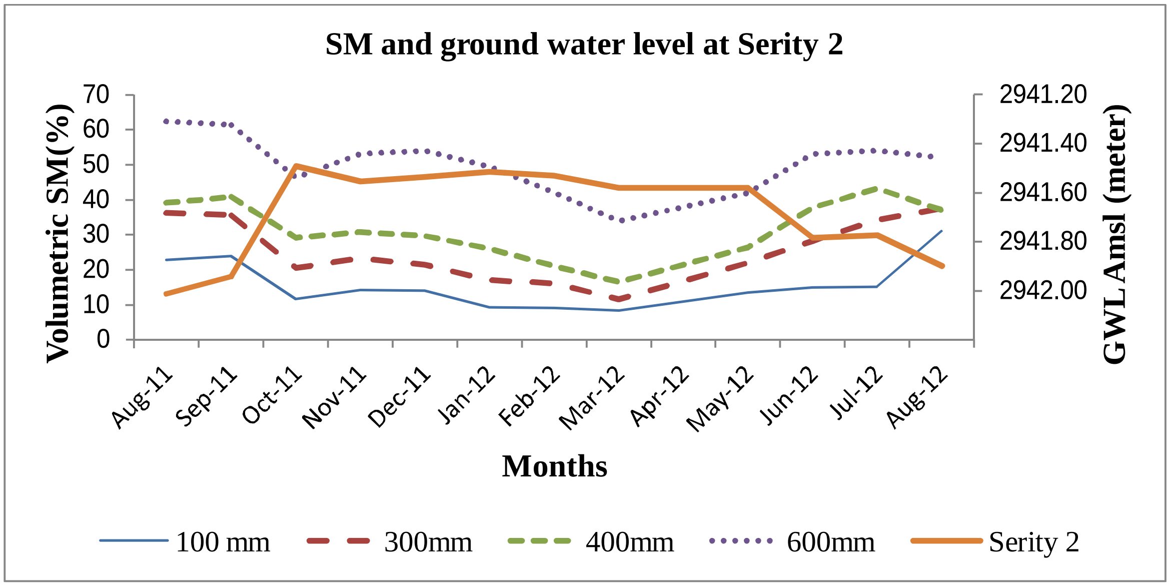

Figure 4.24 Patterns of Soil moisture at mean layer and ground water level of Serity

4.1.17 Soil moisture and ground water level relationship of kolu sub-watershed

Soil moisture and ground water level was analysed using two water tube wells called kolu 2 and kolu 5.In 100 mm layer of soil moisture measurement there is moderate relationship of soil moisture and groundwater. Coefficient of determination between soil moisture and groundwater at kolu 2 is 0.73 and correlation coefficient is 0.85 which indicates strong relationship. In 200 mm layer of soil moisture measurement there is moderate relationship of groundwater and soil moisture. Coefficient of determination between soil moisture and groundwater at 200 mm layer is 0.7 and correlation coefficient is 0.84 which indicates strong relationship. In 300 mm layer of soil moisture measurement there is strong relationship of soil moisture and ground water .Coefficient of determination between soil moisture and ground water level at 300 mm layer is 0.81 and correlation coefficient is 0.9 which indicates strong relationship.

In 400 mm layer of soil moisture measurement there is strong relationship of soil moisture and ground water. Coefficient of determination between soil moisture and groundwater at 400 mm layer is 0.85 and correlation coefficient is 0.92 which indicates strong relationship. In 600 mm layer of soil moisture the relationship of soil moisture and groundwater is strong. Coefficient of determination between soil moisture at 600 mm and ground water level is 0.71 and correlation coefficient is 0.84 which indicates strong relationship. This means soil moisture is influenced by ground water rising or capillary rise. Figures of coefficient of determination between soil moisture and ground water level are presented in Appendix 9.

In Figure 4.25 and 4.26, it is presented that soil moisture content increases as ground water level rises in Kolu. There is strong relationship of volumetric soil moisture and ground water level at each layer that means there is more influence of ground water level to soil moisture content.

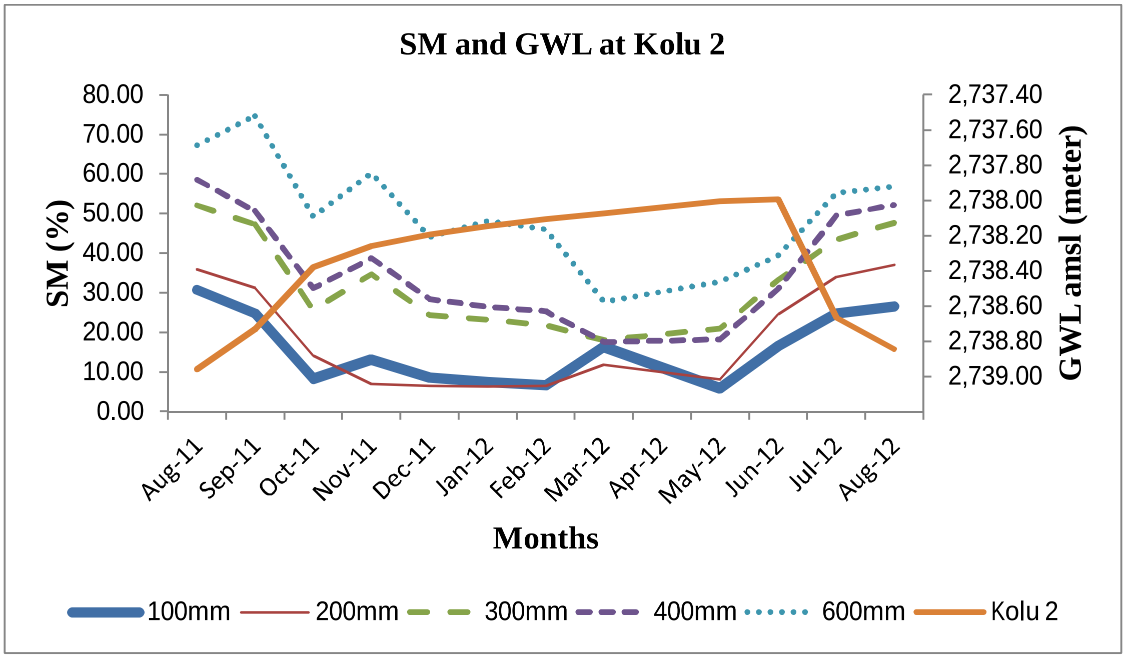

Figure 4.25 Patterns of soil moisture at each layer and ground water level of Kolu 2

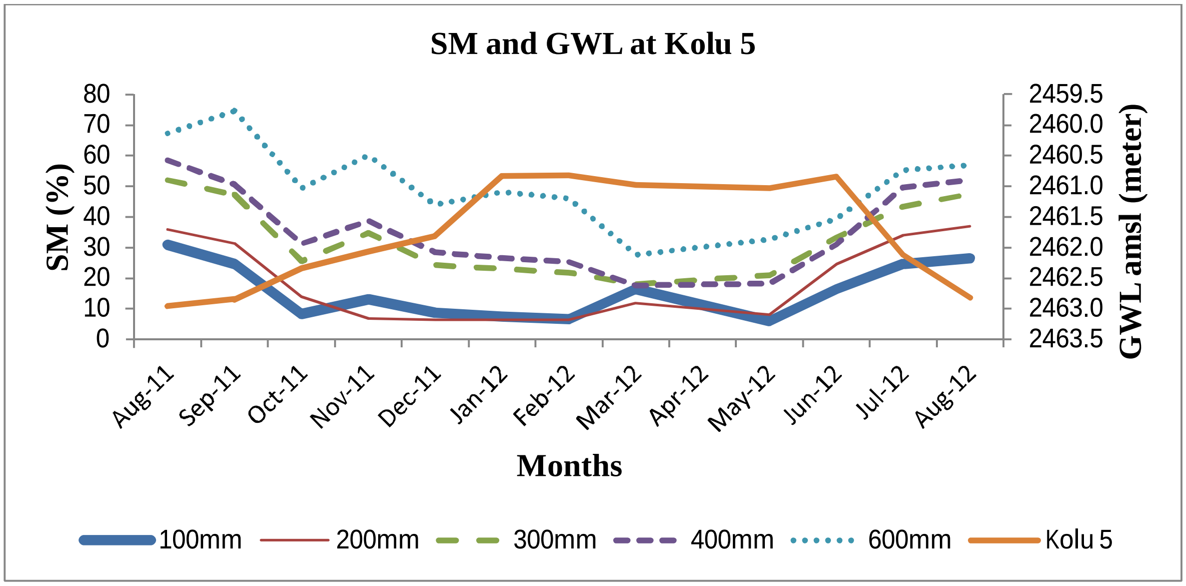

Figure 4.26 Patterns of soil moisture at each layer and ground water level of Kolu 5

4.1.18 Evapotranspiration, rainfall and runoff relationship

Evapotranspiration in Meja and its nested sub-watershed that means Galessa, Serity, and Kolu is analyzed with rainfall and runoff pattern.

Average daily evapotranspiration in Meja watershed and its nested sub watersheds is 3.9 mm/day. In all sites rainfall and evapotranspiration have high variability from day to day. Patterns of evapotranspiration, rainfall and runoff are presented in the following figures (4.27 _4.30). In Meja and in its entire nested sub watersheds evapotranspiration is maximum during winter season, because of increases of solar radiation, but in summer season evapotranspiration is low, because of decrease of sunshine hours and solar radiation.

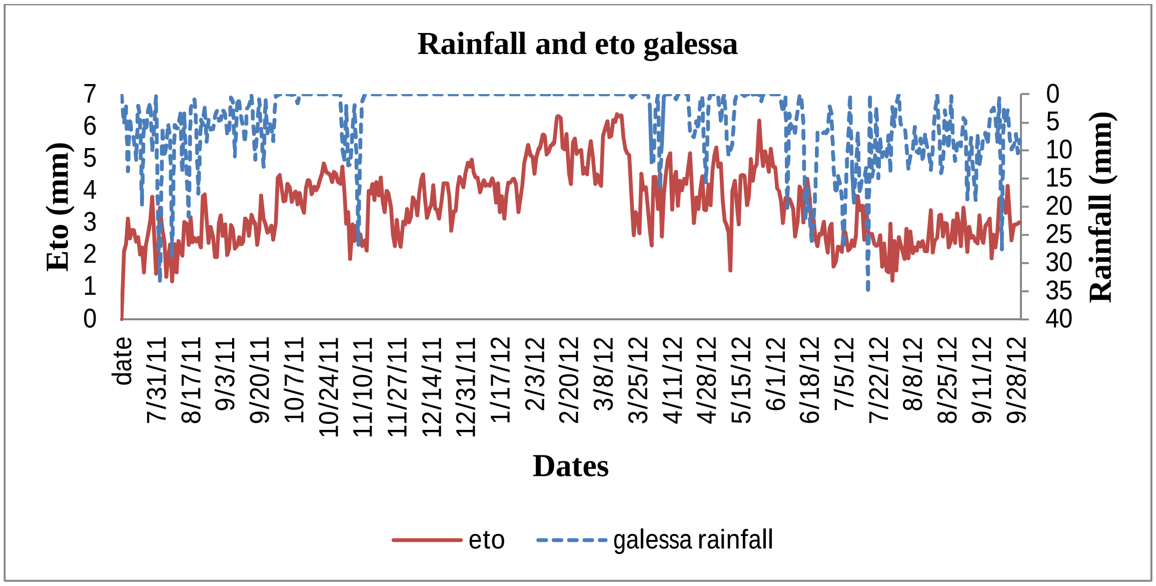

Figure 4.27 Relationship of evapotranspiration and rainfall of Galessa nested sub-watershed

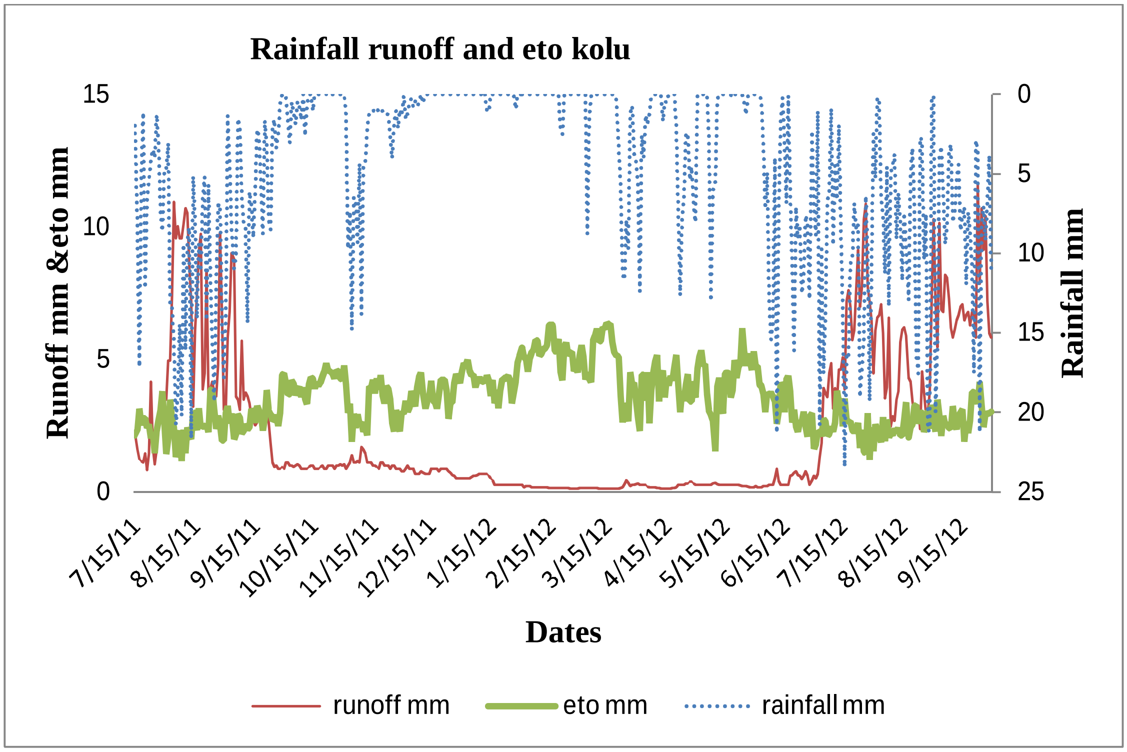

Figure 4.28 Relationships of evapotranspiration, rainfall and runoff of Kolu nested sub-watershed

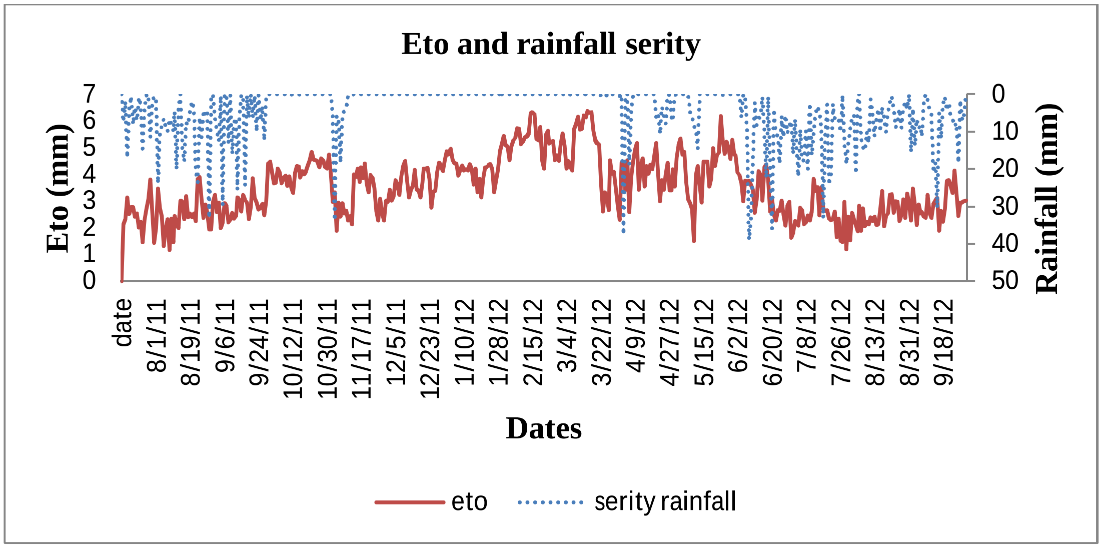

Figure 4.29 Relationship of evapotranspiration and rainfall of Serity

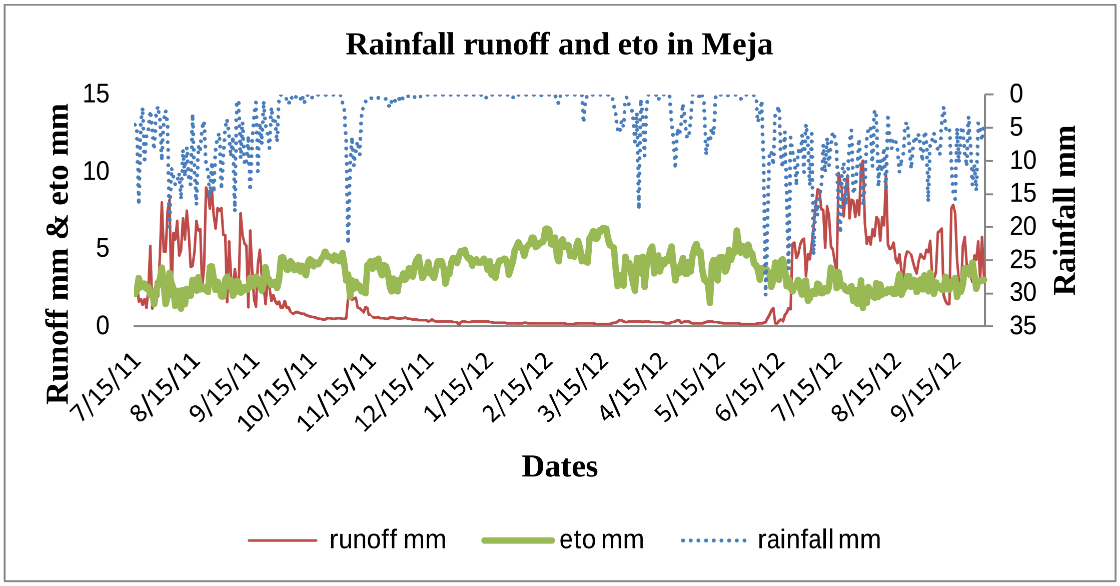

Figure 4.30 Relationships of evapotranspiration, rainfall and runoff of Meja sub-watershed

Maximum evapotranspiration was observed in February, March and April, but during this time rainfall and runoff decreases. In summer season evapotranspiration decreases but rainfall and runoff increases. Generally evapotranspiration has indirect relationship with rainfall and runoff.

4.1.19 Evapotranspiration and its variables

Annual average wind speed ,solar radiation ,relative humidity minimum ,relative humidity maximum, air temperature minimum, air temperature maximum and evapotranspiration was 1.74 m/sec,18.98 Mj/day,39.4%,79.99%,8.5oc,18.99^{o}c and 3.9 mm/day respectively. Patterns of evapotranspiration and its variables in daily case are presented in figure 4.31.

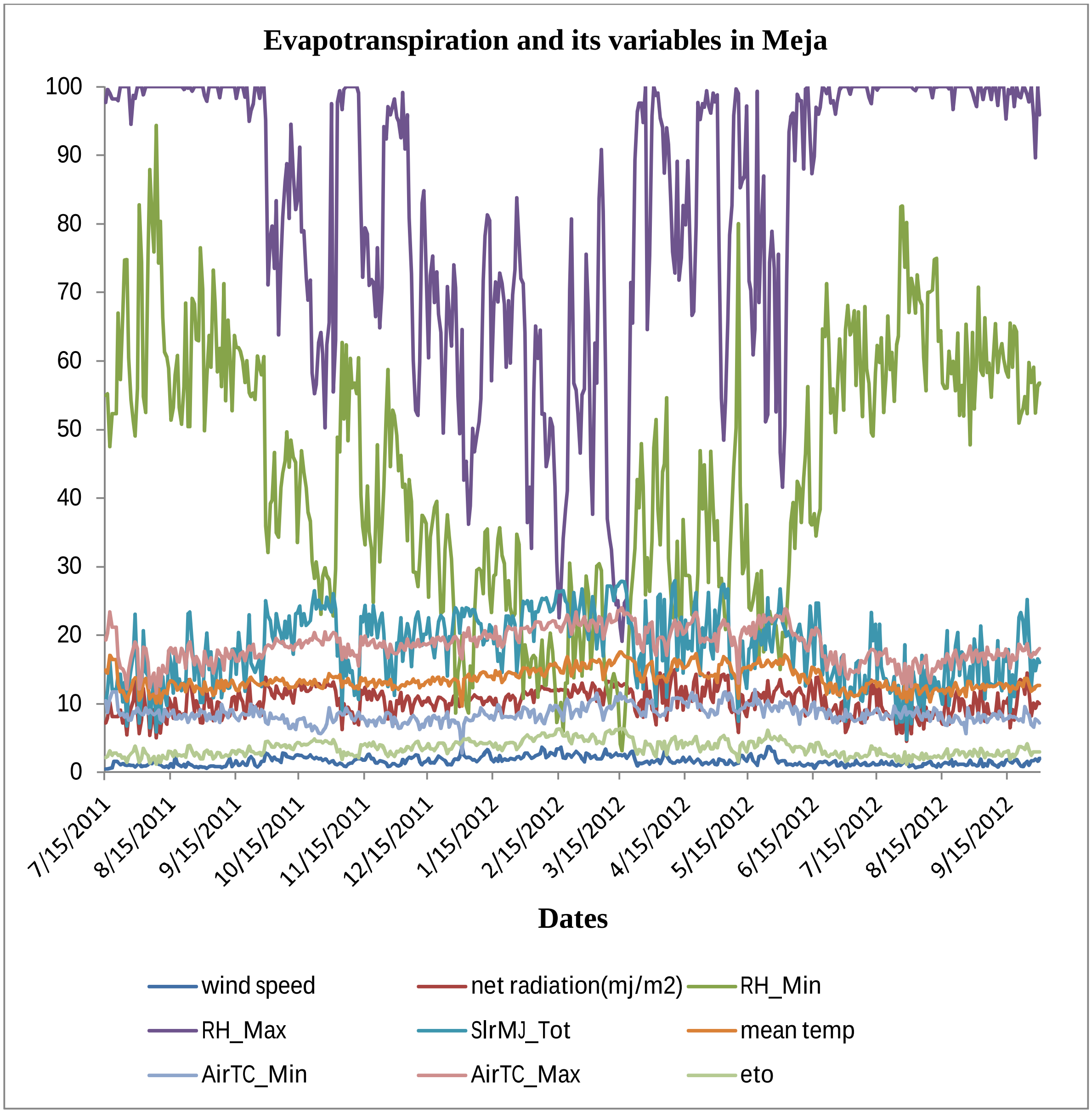

Figure 4.31 Relationship of evapotranspiration, and its variables of Meja watershed

4.2 Result and Discussion using Rainfall Runoff modeling

4.2.1 HBV model analysis

4.2.1.1 Calibration

The available data set was split into two. The data range from 15 July 2011 to 5 May 2012 was used for calibration and the rest of the range between 6 May 2012 and 30 September 2012 was used to validate the model without further fine tuning the model parameters. For visual evaluation, goodness of fit between the observed and simulated flows after calibration is shown on Figure 4.32 for Meja and figure 4.33 for Kolu. The calibrated parameters are shown in table 4.4 for catchment parameters and table 4.5 for vegetation zone parameters.

Table 4.4 Optimal model calibration for catchment parameters of HBV model for the Meja and Kolu.

Parameter	Lower limit	Upper limit	Calibrated value
PERC	0	4	1
UZL	0	70	45
Ko	0.1	0.5	0.3
K1	0.01	0.2	0.01
K2	0.00005	0.1	0.01
MAXBAS	1	2.5	1

Table 4.5 Optimal model calibration for vegetation parameters of HBV model for Meja and Kolu.

Parameter	Lower limit	Upper limit	Calibrated value
TT	-2	0.5	0
CFMAX	0.5	4	3
SFSC	0.5	0.9	1
CFR	0.05	0.05	0.1
CWH	0.1	0.1	0.1
FC	100	550	150
LP	0.3	1	0.5
BETA	1	5	1

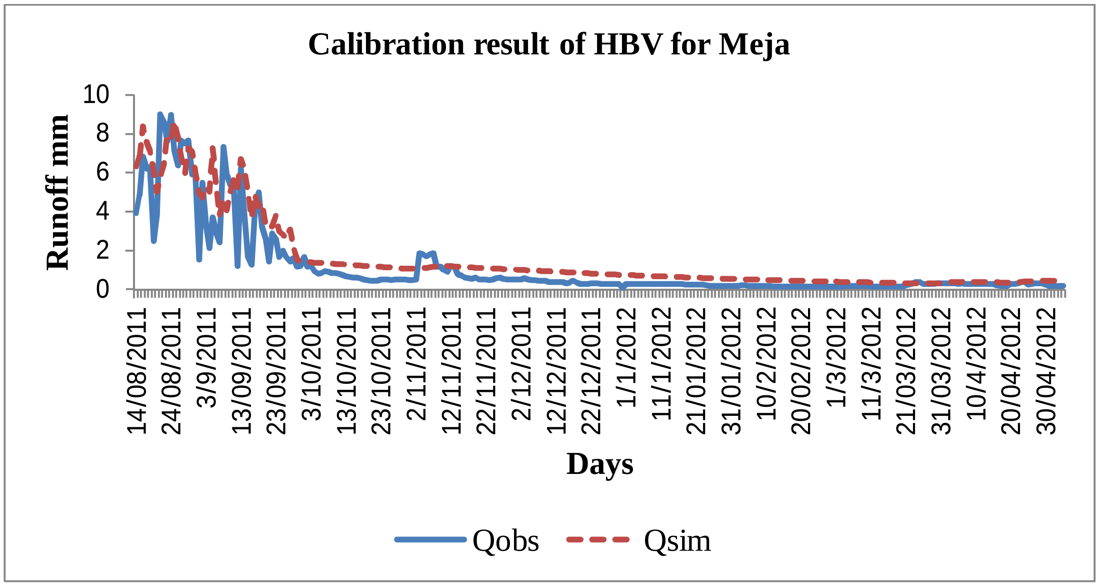

Figure 4.32 The HBV model after calibration for Meja watershed

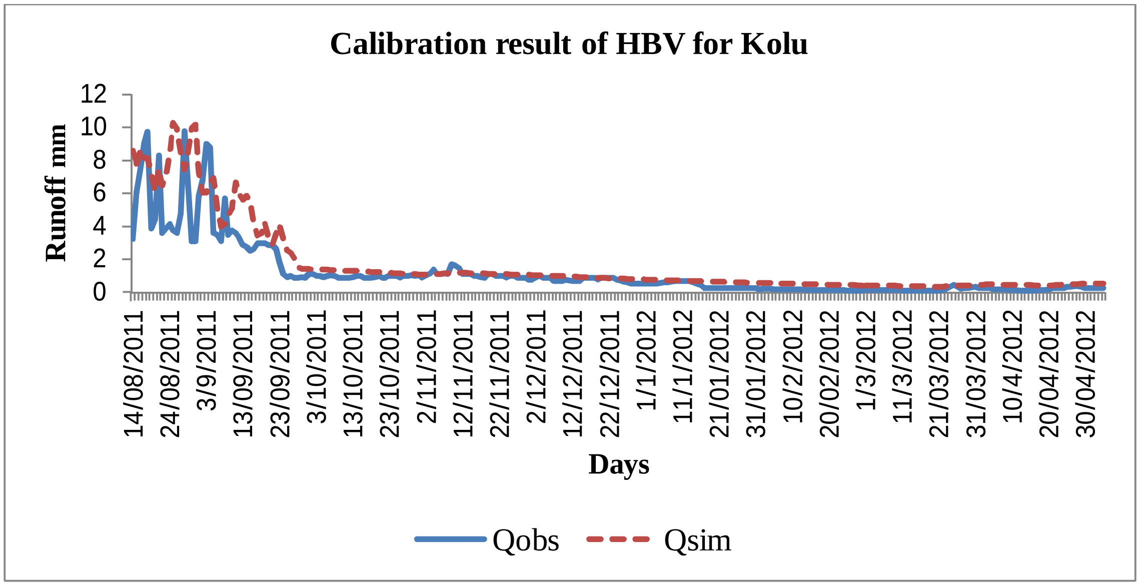

Figure 4.33 The HBV model after calibration for Kolu sub-watershed

4.2.1.2 Sensitivity analysis

Sensitivity analysis of Meja watershed and Kolu were conducted by varying the parameters and observing the simulation results. According to the result the most sensitive parameters that affect the simulation result in Meja and Kolu are PERC and K_2. The most sensitive parameters are the response routing (PERC) and K2 which govern sub surface and base flow contributions in Meja and Kolu.PERC defines the maximum percolation rate from the upper to the lower groundwater box (SLZ [mm]).K2 is recession coefficient.

4.2.1.3 Verification

For visual evaluation, goodness of fit between the observed and simulated flows after validation is shown on Figure 4.34 for Meja and Figure 4.35 for Kolu. Accordingly the pattern of daily simulated and observed runoff seems similar.

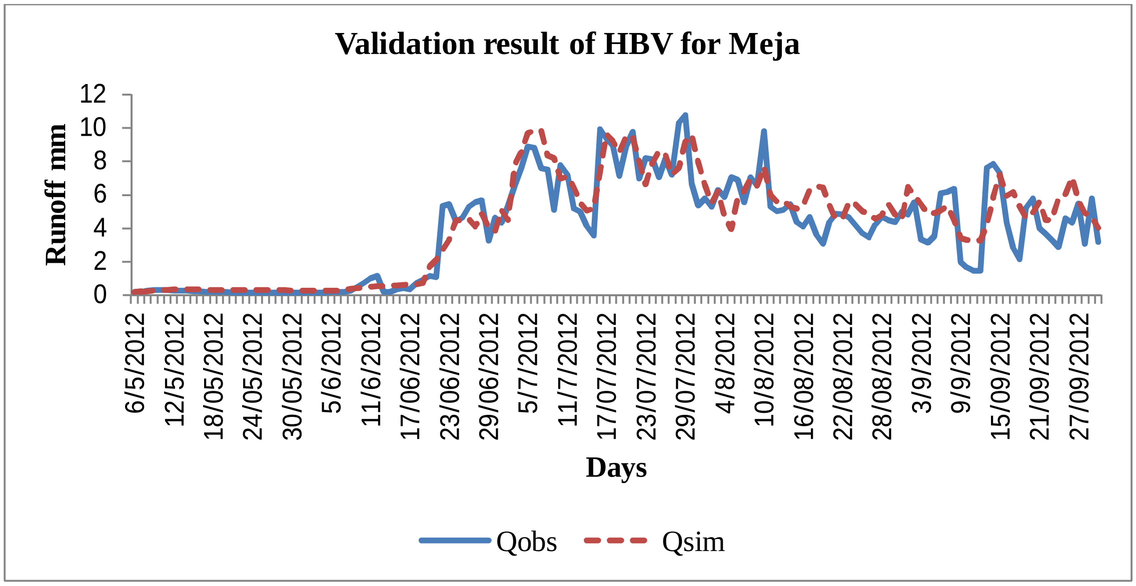

Figure 4.34 The HBV model after validation for Meja watershed

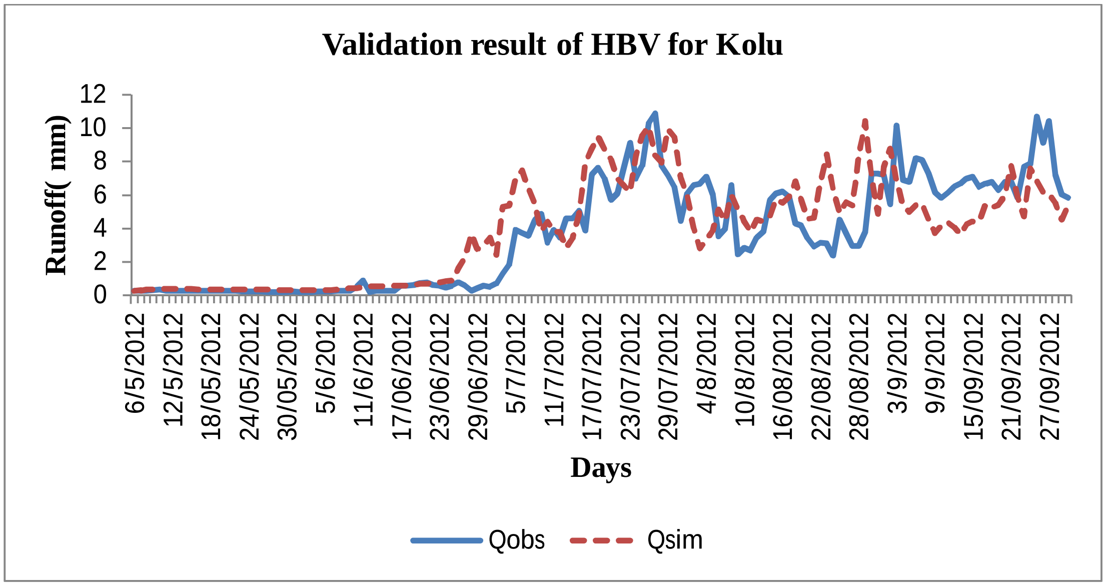

Figure 4.35 The HBV model after validation for Kolu sub-watershed

4.2.2 RRL SMAR model analysis

4.2.2.1 Calibration

The available data set was split into two. The data range from 15 July 2011 to 5 May 2012 was used for calibration and the rest of the range between 6 May 2012 and 30 September 2012 was used to validate the model without further fine tuning the model parameters. Automatic adjustment of the calibration parameters (listed in Table 4.6 and 4.7) resulted in a set of parameters that minimized the difference between observed and simulated discharge for the gauged catchment of Meja and its nested sub-watershed**.** For visual evaluation, goodness of fit between the observed and simulated flows after calibration is shown on Figure 4.36 for Meja and Figure 4.38 for Kolu. Figure 4.37 shows the scatter plot of Nash-Sutcliffe efficiency criterion for calibration and validation of Meja and Figure 4.39 for Kolu.

Table 4.6 Optimal model calibration parameters of RRL SMAR model for Meja

no	Parameters	Optimized	Min	Max
1	Groundwater evaporation rate C	0.95	0	1
2	Groundwater runoff coefficient G	0.05	0	1
3	Proportion direct runoff H	0.65	0	1
4	Storage loss coefficient Kg	0.19	0	1
5	U.H linear routing N	1.44	1	6
6	U.H linear routing N*K=NK	0.98	0.01	1
7	Evaporation conversion parameter T	0.59	0.52	1
8	Infiltration Rate Y	342	0	5000
9	Soil moisture total storage depth Z	547.84	0	5000

Table 4.7 Optimal model calibration parameters of RRL SMAR model for Kolu

no	Parameters	Optimized	Min	Max
1	Groundwater evaporation rate C	0.03	0	1
2	Groundwater runoff coefficient G	0.97	0	1
3	Proportion direct runoff H	0.03	0	1
4	Storage loss coefficient Kg	0.06	0	1
5	U.H linear routing N	2.49	1	6
6	U.H linear routing N*K=NK	0.34	0.01	1
7	Evaporation conversion parameter T	0.59	0.52	1
8	Infiltration Rate Y	685.6	0	5000
9	Soil moisture total storage depth Z	210.1	0	5000

As shown in Figure 4.36 the patterns of observed and simulated of runoff using SMAR model during calibration period in Meja is satisfactory.RRL SMAR model couldn't capture low flow and peak flow.

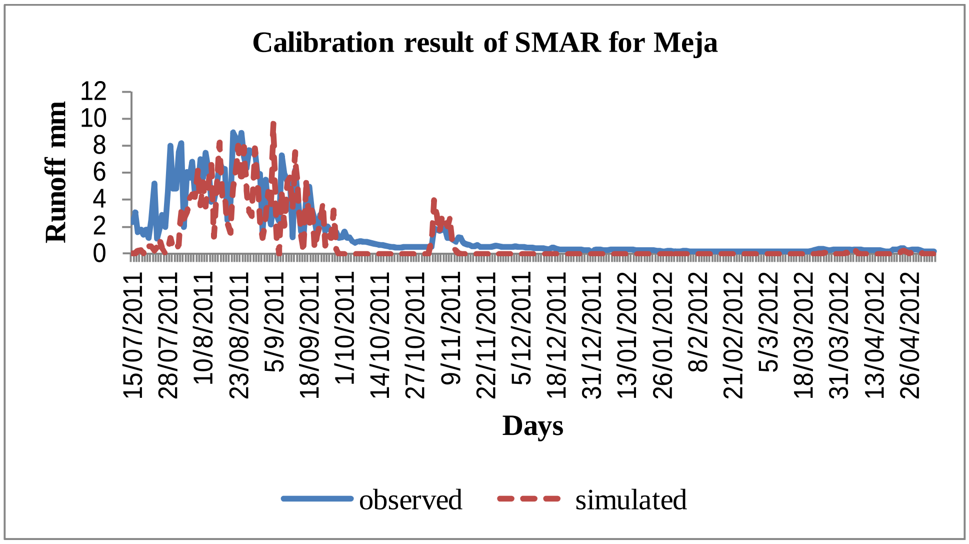

Figure 4.36 The SMAR model after calibration for Meja watershed

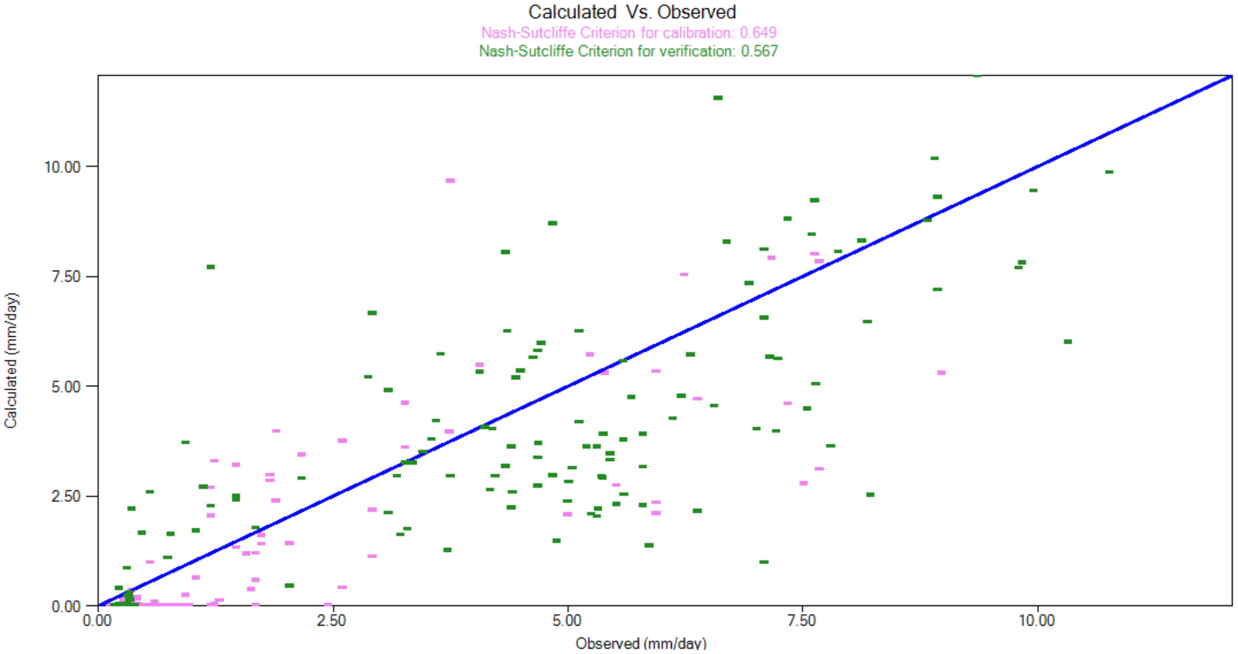

Figure 4.37 The SMAR model scatter plot of calibration and verification result for Meja watershed

As shown in Figure 4.38 SMAR model couldn't perform well for Kolu nested sub watershed, coefficient of determination and Nash Sutcliff criteria's were satisfactory, but the observed and simulated graph is bad. SMAR model in Meja and also in Kolu watersheds doesn't capture low flow. This may be drawback of the model.

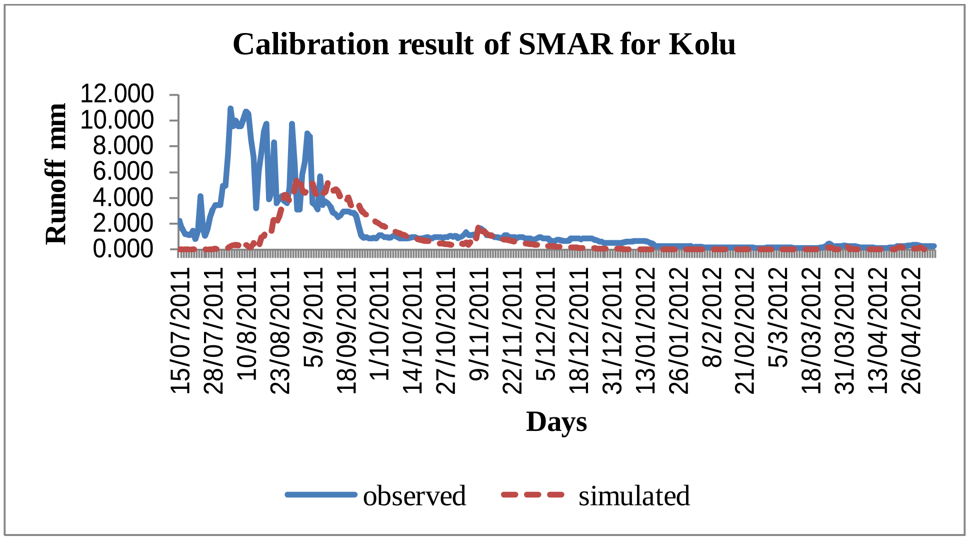

Figure 4.38 The SMAR model after calibration for Kolu sub-watershed

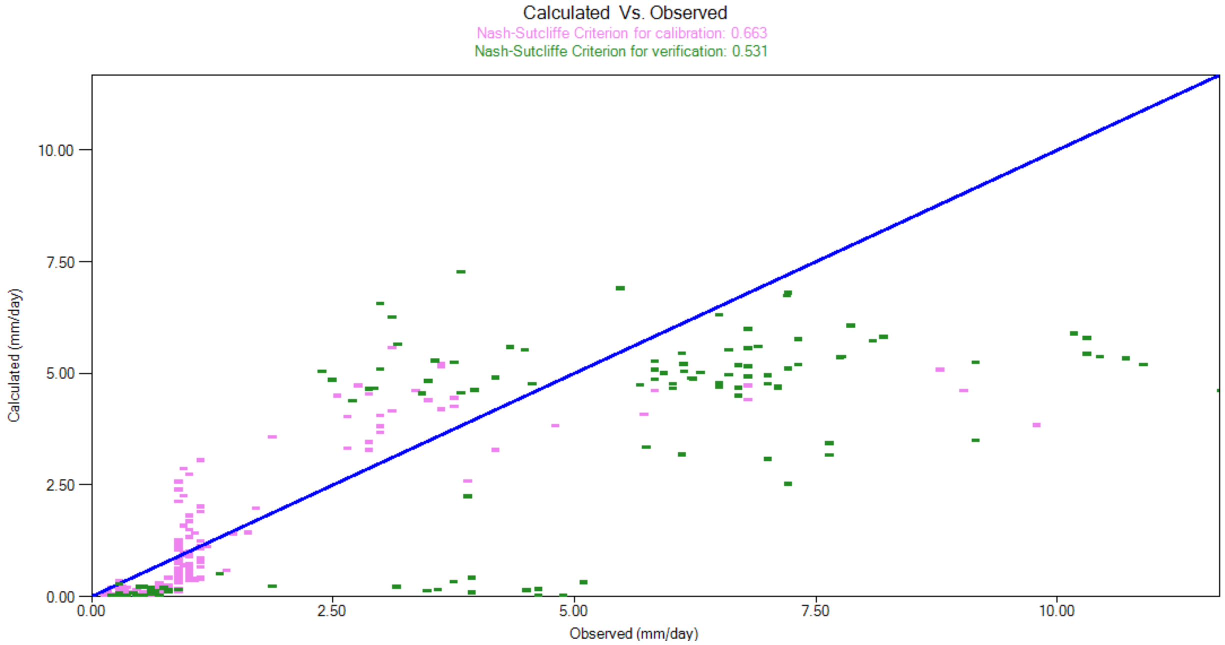

Figure 4.39 The SMAR model scatter plot of calibration and verification result for Kolu sub-watershed

4.2.2.2 Sensitivity analysis

Sensitivity analysis involves investigating the behavior of the performance of a model in respect of one or more parameters which might be highly sensitive or insensitive to changes in values. A sensitivity analysis of RRL SMAR was conducted by changing the parameters and observing the performance of the model. The result of the sensitivity analysis shows that groundwater evaporation rate, proportion direct runoff ,U.H linear routing N ,U.H linear routing component NK and Evaporation conversion parameter are the most sensitive parameters that can affect the simulation result in Meja watershed. And result from sensitivity analysis of Kolu nested catchment indicates that Ground water runoff coefficient, proportion direct runoff, storage loss coefficient, U.H linear routing component NK and evaporation conversion parameters are the most sensitive parameters that can affect the simulation result of Kolu sub-watershed.

4.2.2.3 Verification

For visual evaluation, goodness of fit between observed and simulated flows after validation is shown on Figure 4.40 for Meja and Figure 4.41 for Kolu nested catchment. As shown in Figure the simulated and observed flow in Meja during the validation period was good. But in Kolu it is not satisfactory this may be the model cannot use for small watersheds like Kolu. Time series of observed runoff, simulated runoff and base flow of the whole period using RRL SMAR is presented in Appendix 10b.

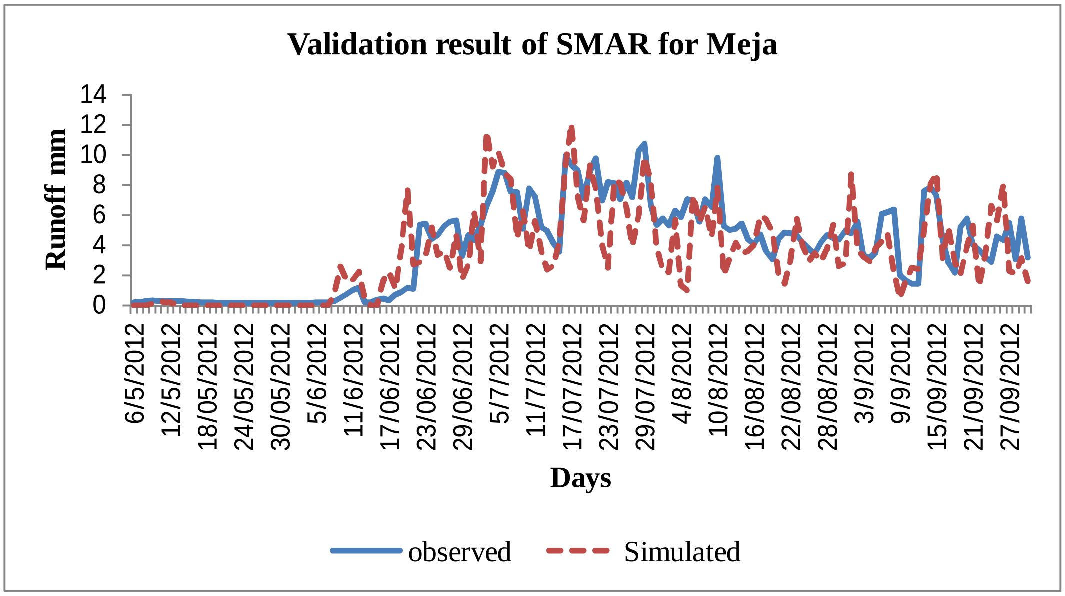

Figure 4.40 The SMAR model verification result for Meja watershed

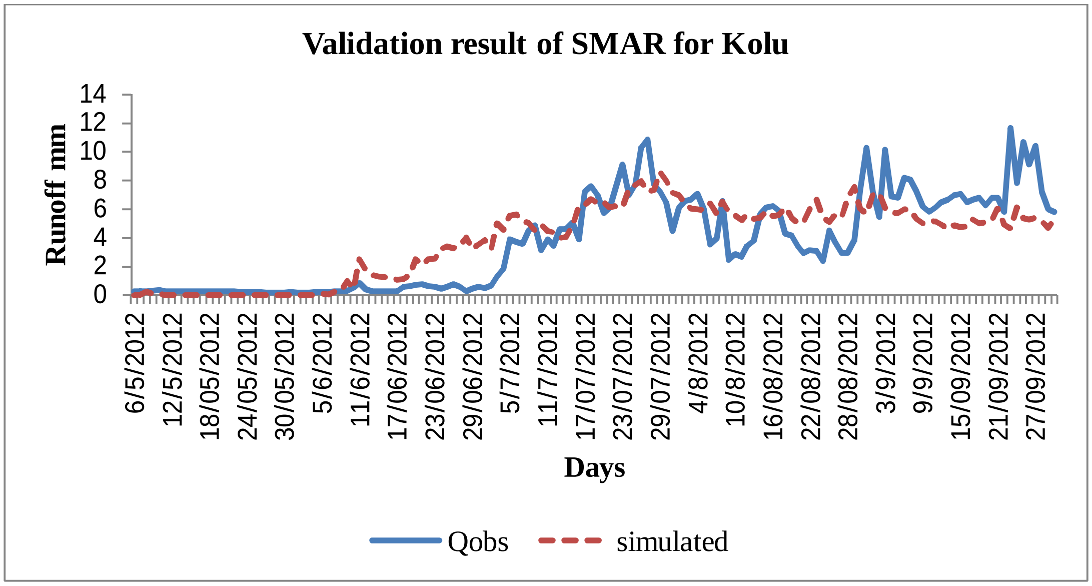

Figure 4.41 The SMAR model verification result for Kolu watershed

4.2.3 Estimating evaluation criteria

Performance of hydrological models can be assessed using Nash Sutcliff criteria. Classification of performance of hydrologic models can be done as follows if $0.75 < NSE < 1.00$ the model performs Very Good, if $0.65 < NSE < 0.75$ it is good, $0.50 < NSE < 0.65$ it is Satisfactory and if $NSE < 0.50$ the performance of the model becomes unsatisfactory (Moriasi etal., 2007) .In Table 4.8, it is presented that HBV model in Kolu during calibration and verification period was performed satisfactory and in Meja the model performed very Good during calibration and verification period. SMAR model in Kolu and in Meja indicates satisfactory performance during calibration and verification period. So that HBV model performed better than RRL SMAR in Meja and in Kolu.

Since Meja watershed is a representative area of highlands of Blue Nile basin, so that HBV model can use also for other parts of highlands of Blue Nile basin. And from this model results and correlation coefficients, data can be extended specially soil moisture data which is difficult and costly manual measurement. And also these models especially HBV model can use in filling missed data of the catchment and in study of climate change and other research studies in the watershed.

Table 4.8 Models performance evaluation result for Calibration and Validation of HBV and SMAR

Calibration	HBV		SMAR	
Efficiency criteria	Kolu	Meja	Kolu	Meja
Determination of correlation coefficient	0.75	0.85	0.71	0.72
Nash Sutcliff	0.5	0.78	0.66	0.65

Validation	HBV		SMAR	
Efficiency criteria	Kolu	Meja	Kolu	Meja
Determination of correlation coefficient	0.64	0.84	0.64	0.64
Nash Sutcliff	0.61	0.81	0.53	0.57

According table 4.8 HBV model is more acceptable than RRL SMAR.And from the above graphs of simulated and observed runoff; RRL SMAR is not accurate especially in Kolu, so that in Meja watershed especially in Kolu HBV model is recommended for hydrological researchers.

4.3 Relationship of rainfall and simulated runoff using HBV and SMAR model

Figure 4.42 and 4.43 shows coefficient of determination of observed rainfall and simulated runoff for Meja and Kolu using HBV model. Rainfall and runoff relationship of Meja and Kolu by using observed rainfall and simulated runoff of HBV model is almost similar with rainfall runoff relationship of observed rainfall and observed runoff in Meja and Kolu.

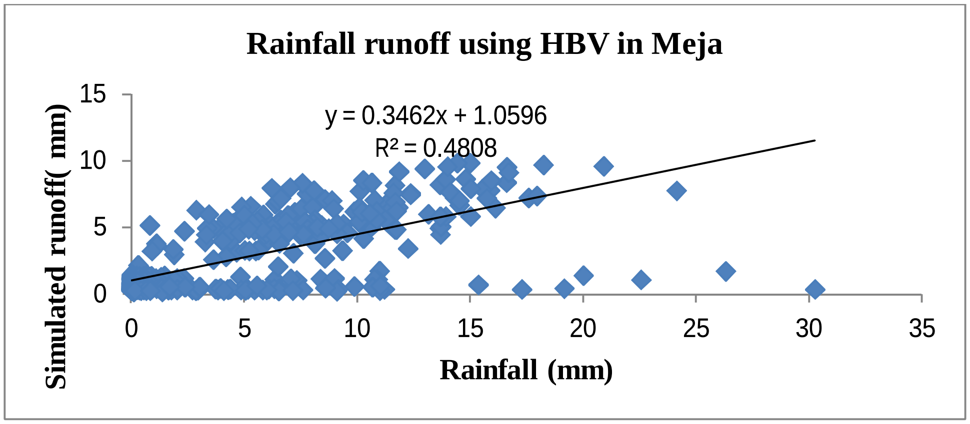

Figure 4.42 Rainfall runoff relationship of Meja watershed using HBV model

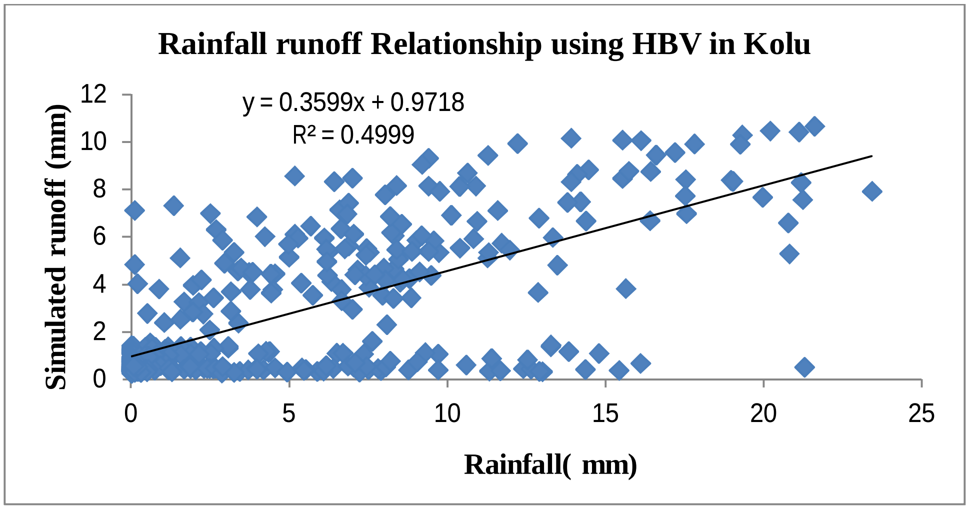

Figure 4.43 Rainfall runoff relationship of Kolu sub-watershed using HBV model

Figure 4.44 and 4.45 shows coefficient of determination of observed rainfall and simulated runoff for Meja and Kolu using RRL SMAR model. Rainfall and runoff relationship of Meja and Kolu by using observed rainfall and simulated runoff of SMAR model is almost similar with rainfall runoff relationship of observed rainfall and simulated runoff in Meja and Kolu In Kolu catchment the graph of observed and simulated runoff was not good during calibration and validation period, but the relationship of observed rainfall and simulated runoff was good as shown in figure 4.45.

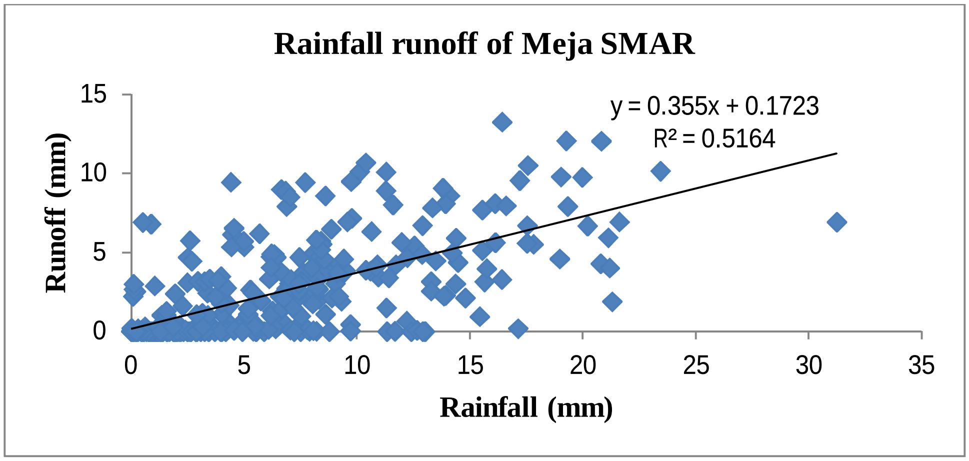

Figure 4.44 Rainfall runoff relationship of Meja watershed using SMAR model

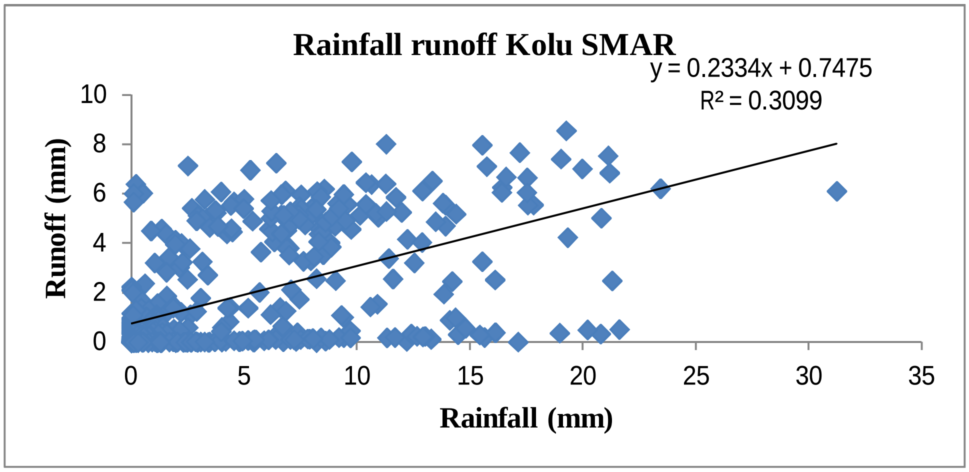

Figure 4.45 Rainfall runoff relationship of Kolu watershed using SMAR model

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Understanding the runoff generation processes in Meja and its nested sub-watersheds was conducted by using the data collected from the field and analyzing by drawing the relationships between rainfall and runoff, rainfall and soil moisture, rainfall and groundwater, soil moisture and runoff, ground water and runoff, soil moisture and ground water and by applying statistical techniques such as coefficient of determination and correlation coefficient. Spatial variability of rainfall in Meja watershed was also studied by using 11 rain gauge data distributed entirely in the watershed.

Analysis of rainfall data indicated weak daily correlation (r^2<0.35) of areal rainfall between Galessa, Serity and Kolu and similar annual total and average rainfall of the three sites of Meja watershed. However monthly correlation of areal rainfall between the three sites was better than daily correlation (r^2>0.8) because dry period compensates with the wettest period in the month. According to one year and three months data, there is no strong rainfall and runoff relationship (r^2<0.5) in daily basis of Meja and Kolu which is nested sub - watershed; this may be due to abstractions such as irrigation and human interventions in the watershed. But in monthly basis the relationship becomes strong (r^2>0.8).

Ground water level and runoff has strong relationship (r^2> 0.65*)* in monthly basis of Kolu nested sub watershed but there are some conditions that interrupted this general relationship, such as decrease of runoff when water table rises and increases of runoff when water table falls. In Kolu and Serity rainfall has moderate relationship with Ground water level. Occurrence of rainfall doesn’t indicate rising of water table level and absence of rainfall doesn’t indicate falling of water level; this indicates the most factors that affects water table fluctuations is lateral flow and there may be high lateral hydraulic permeability than vertical hydraulic permeability in Meja and its nested sub-watershed.

In Kolu site there is strong relationship of rainfall and soil moisture. Most of the time soil moisture increases as rainfall increases and soil moisture decreases as rainfall decreases. There is strong linear relationship of rainfall and monthly averaged volumetric soil moisture in Meja. In 600 mm layer soil moisture has strong relationship with ground water than rainfall but unlike this in 100 mm layer soil moisture has strong relationship with rainfall than groundwater level.

The general relationship between runoff and monthly average soil moisture at different layers in Meja watershed and Kolu is strong. There is direct relationship between runoff and soil moisture in all layers. There is strong relationship of soil moisture and ground water level in Kolu and Serity.

Further to the data analysis of understanding runoff generation processes, hydrological models like HBV and RRL SMAR were configured to understand the relationship between rainfall and runoff in the watershed. In both Models the same input data for the same period of time were used for model calibration and verification purpose. Calibration and validation of watershed parameters was done by manual and automatic procedures. Based on the efficiency criteria such as coefficient of determination and Nash Sutcliff criteria HBV model performs better than SMAR. SMAR model couldn’t capture low flow in Meja and Kolu. This in accurate result of SMAR model in Kolu nested sub-watershed may be due to inability of the model to simulate runoff in very small watersheds like Kolu. Rainfall and runoff relationship of Meja and Kolu by using observed rainfall and simulated runoff of HBV and SMAR model is almost similar with relationship of observed rainfall and observed runoff in Meja and Kolu. Since Meja watershed is a representative area of highlands of Blue Nile basin, so that HBV model can use also for other parts of highlands of Blue Nile basin. And from this model results and correlation coefficients data can be extended, especially soil moisture data and groundwater which are difficult and costly to measure manually. And also HBV model can use in filling missed data of the watershed and in study of climate change and other research studies which will conducted in the watershed.

5.2 Recommendation

- There is no enough current meters reading, but in order to develop accurate rating curve and rating equation there must be full measurement of flow during high flow and low flow period. Generally rating curve should be modified using full current meter reading.
- In order to know more on runoff generation processes study on the aquifer behavior and soil texture sample test is required.
- In order to know or confirm whether there is, blockage or capillary barriers dye tracer experiment must be done.
- There must be high temporal resolution of data, measurement specially soil moisture and groundwater in order to understand influence of soil moisture and groundwater on runoff generation processes and on the understanding of hydrological processes.
- In order to get accurate understanding of soil moisture dynamics interception and evapotranspiration conditions must be determined.
- In order to get accurate result on runoff generation mechanism or occurrence of surface runoff source areas it is good to conduct study using subsurface saturation and surface runoff sensors.
- Abstractions such as irrigation abstractions and other human activities must be included in the study of rainfall runoff relationship of the watershed
- SMAR and HBV model can be applied in Meja watershed but in the nested catchments such as Kolu HBV model is recommended.
- The models must be tested using long period of data.

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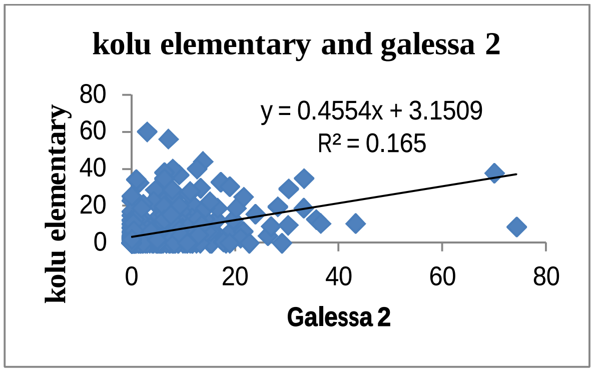
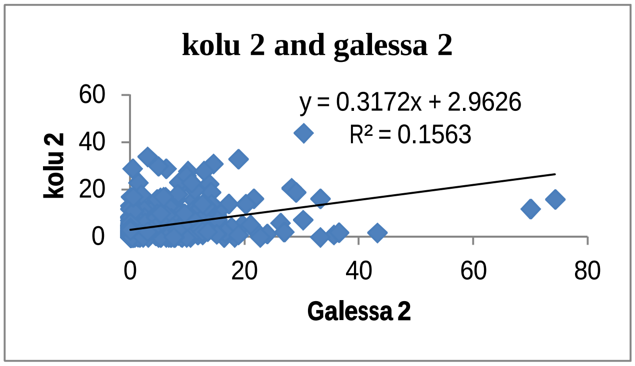
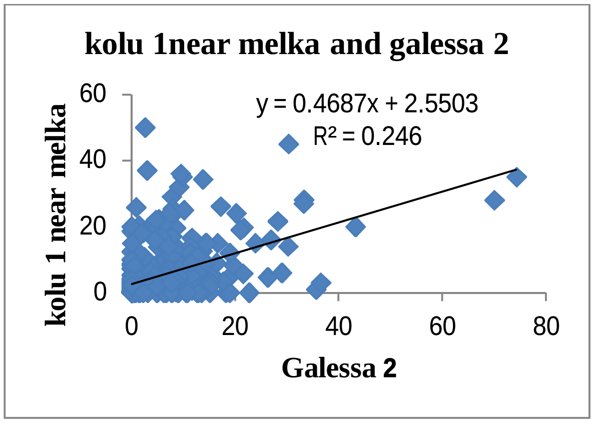
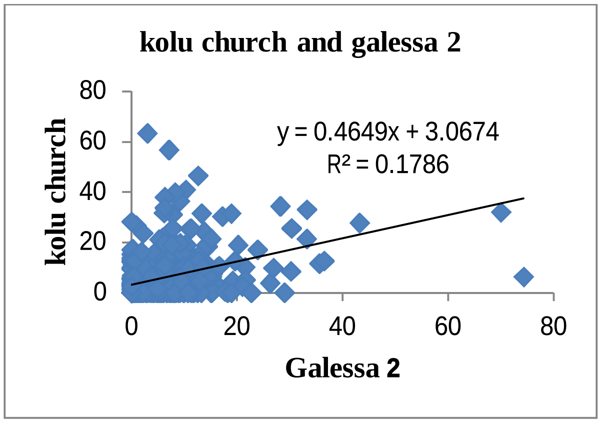
APPENDIXES

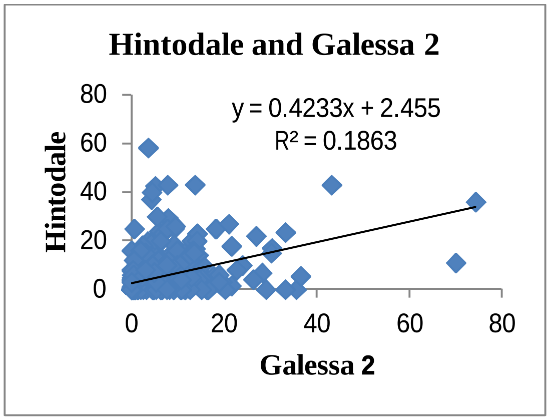
Appendix 1a. Relationship of each rain gauge stations in Meja watershed in daily case (mm)

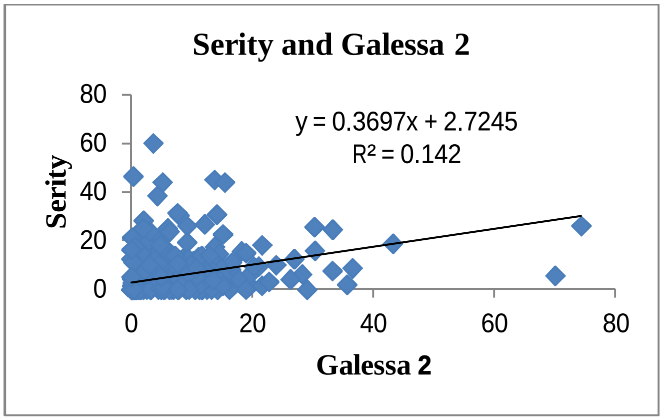


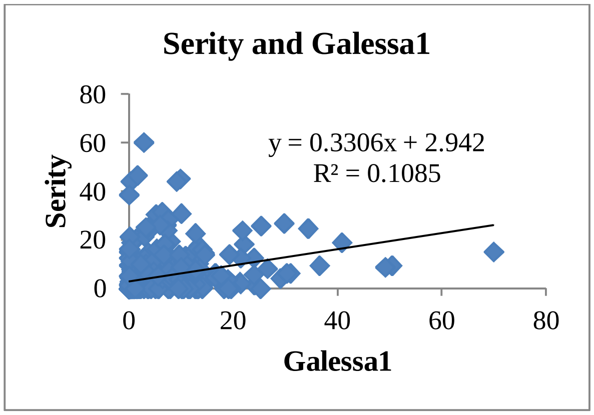


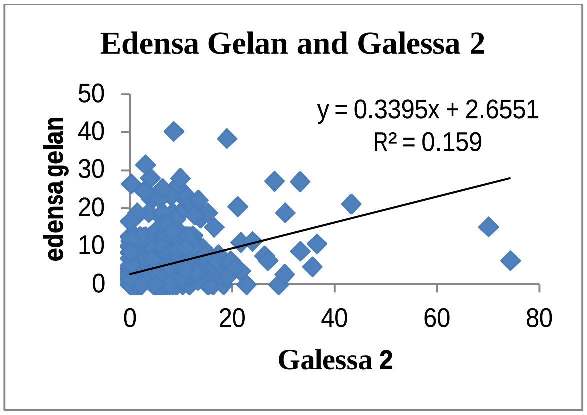


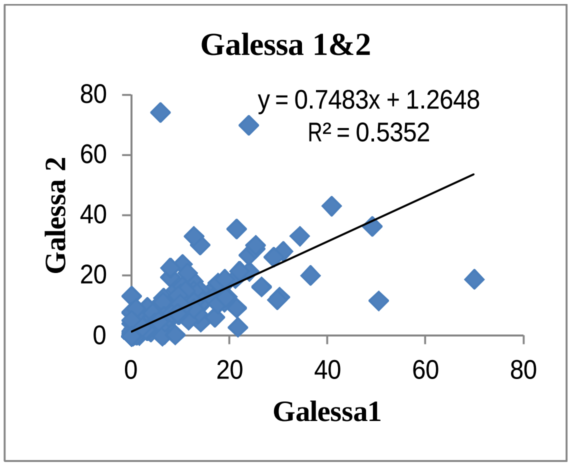


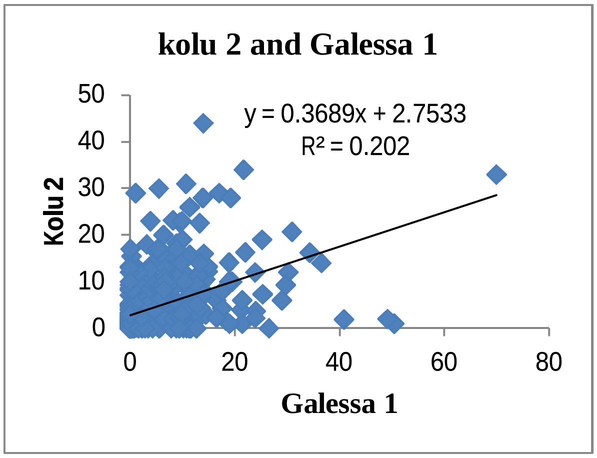


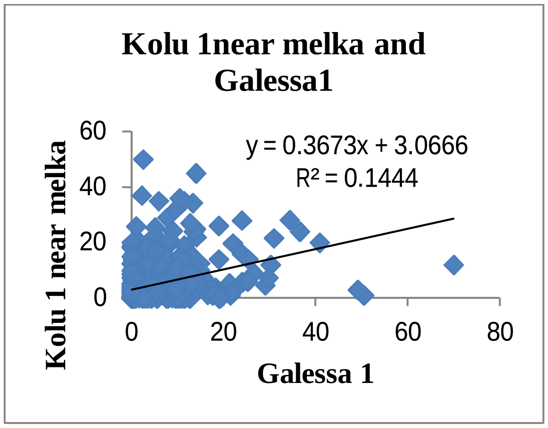


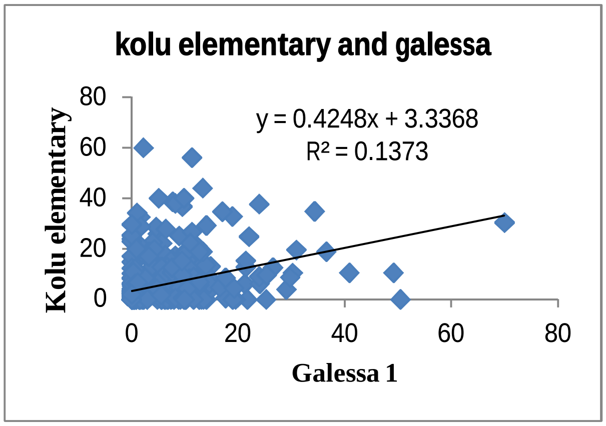

Serity and Galessa1
Serity
80
60
40
20
0
y = 0.3306x + 2.942
R² = 0.1085
0
20
40
60
80
Galessa1

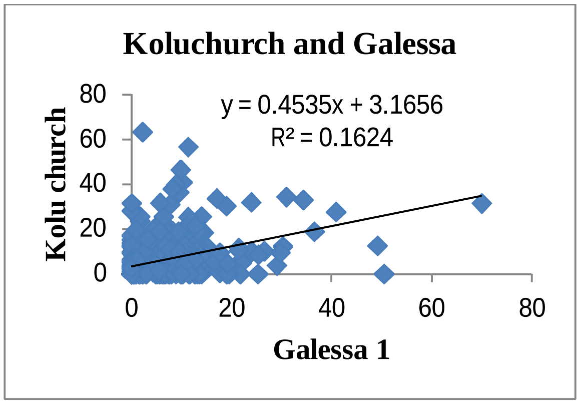

Edensa Gelan and Galessa 2
edensa gelan
50
40
30
20
10
0
y = 0.3395x + 2.6551
R² = 0.159
0
20
40
60
80
Galessa 2

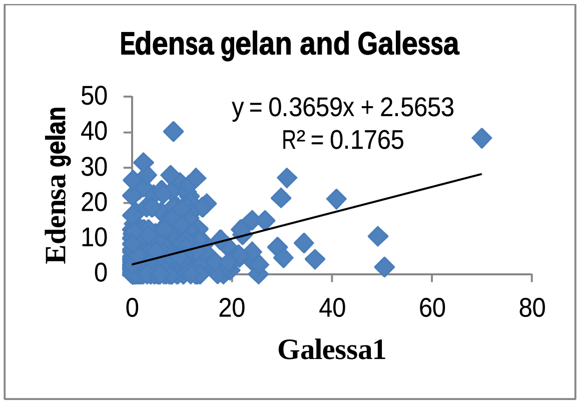

Galessa 1&2
Galessa 2
80
60
40
20
0
y = 0.7483x + 1.2648
R² = 0.5352
0
20
40
60
80
Galessa1

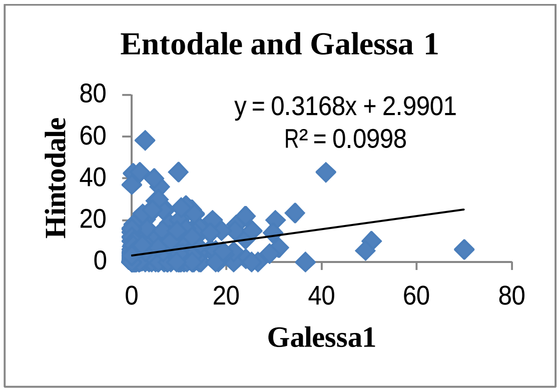

kolu 2 and Galessa 1
Kolu 2
50
40
30
20
10
0
y = 0.3689x + 2.7533
R² = 0.202
0
20
40
60
80
Galessa 1

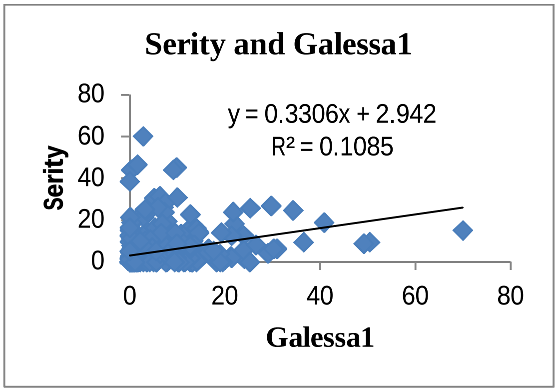

Kolu 1near melka and Galessa1
Kolu 1 near melka
60
40
20
0
y = 0.3673x + 3.0666
R² = 0.1444
0
20
40
60
80
Galessa 1

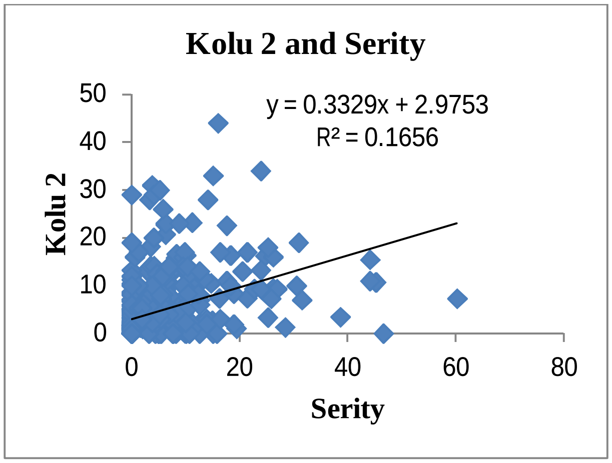

kolu elementary and galessa
Kolu elementary
80
60
40
20
0
y = 0.4248x + 3.3368
R² = 0.1373
0
20
40
60
80
Galessa 1

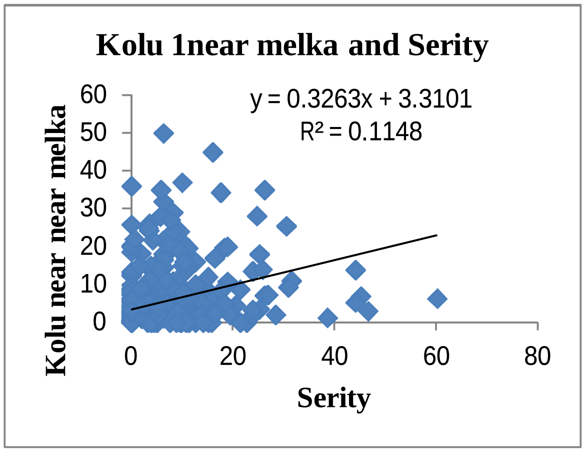

Koluchurch and Galessa
y = 0.4535x + 3.1656
R² = 0.1624
Kolu church
80
60
40
20
0
0
20
40
60
80
Galessa 1

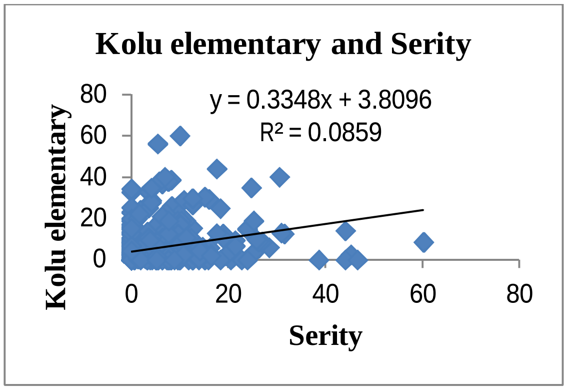

Edensa gelan and Galessa
y = 0.3659x + 2.5653
R² = 0.1765
Edensa gelan
50
40
30
20
10
0
0
20
40
60
80
Galessa1

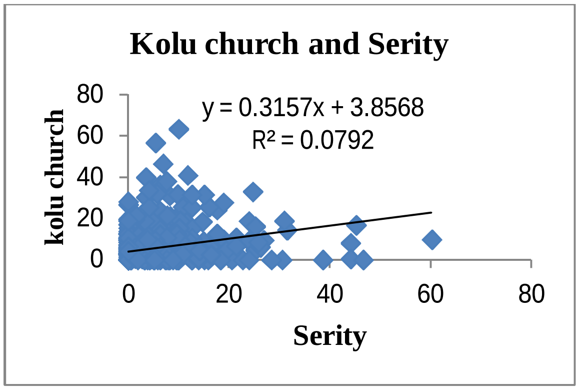

Entodale and Galessa 1
y = 0.3168x + 2.9901
R² = 0.0998
Hintodale
80
60
40
20
0
0
20
40
60
80
Galessa1

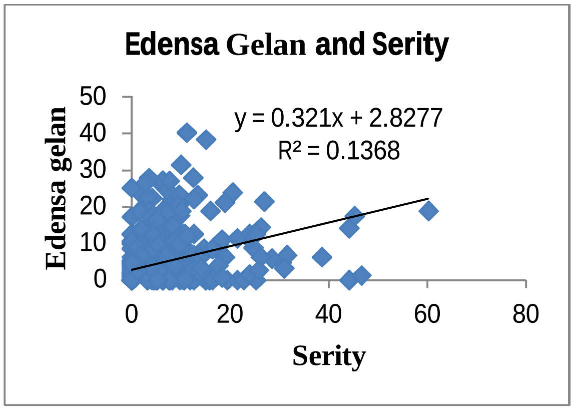

Serity and Galessa1
y = 0.3306x + 2.942
R² = 0.1085
Serity
80
60
40
20
0
0
20
40
60
80
Galessa1

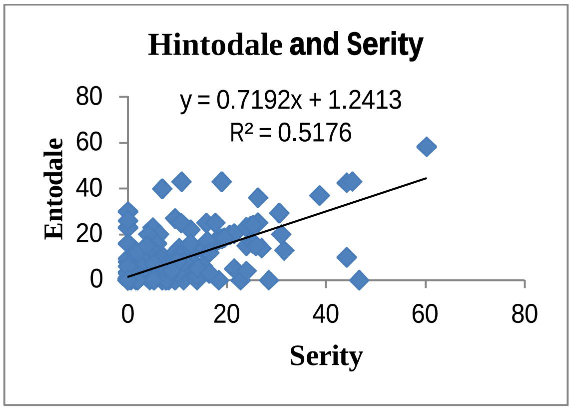

Kolu 2 and Serity
y = 0.3329x + 2.9753
R² = 0.1656
Kolu 2
50
40
30
20
10
0
0
20
40
60
80
Serity

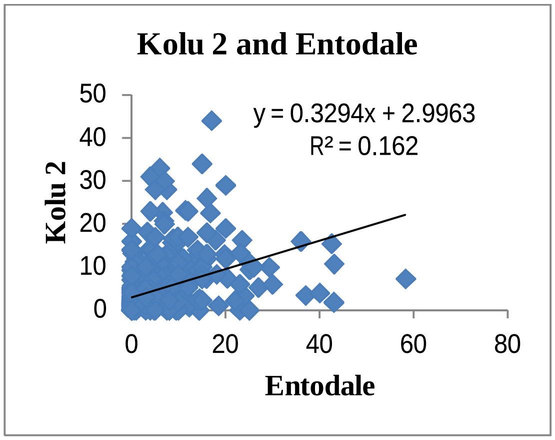

Kolu 1near melka and Serity
y = 0.3263x + 3.3101
R² = 0.1148
Kolu near near melka
60
50
40
30
20
10
0
0
20
40
60
80
Serity

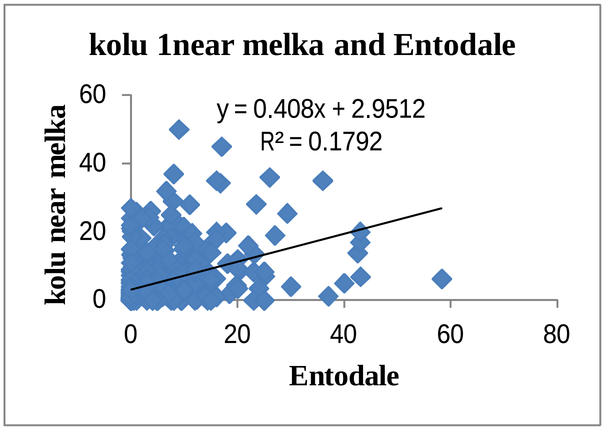

Kolu elementary and Serity
Kolu elementary
80
60
40
20
0
y = 0.3348x + 3.8096
R² = 0.0859
0
20
40
60
80
Serity

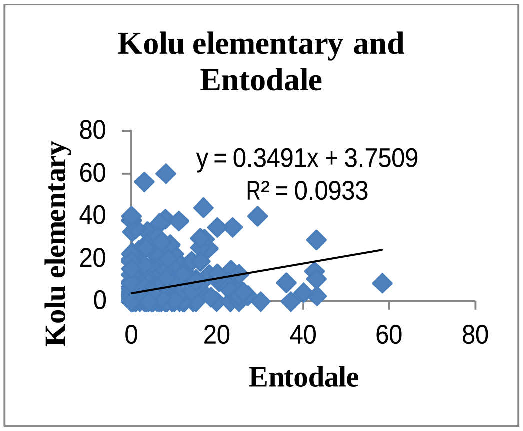

Kolu church and Serity
kolu church
80
60
40
20
0
y = 0.3157x + 3.8568
R² = 0.0792
0
20
40
60
80
Serity

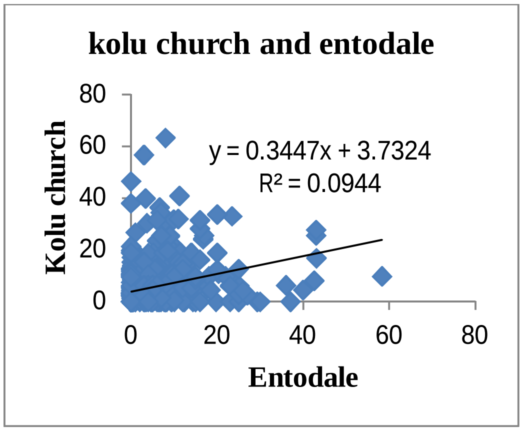

Edensa Gelan and Serity
Edensa gelan
50
40
30
20
10
0
y = 0.321x + 2.8277
R² = 0.1368
0
20
40
60
80
Serity

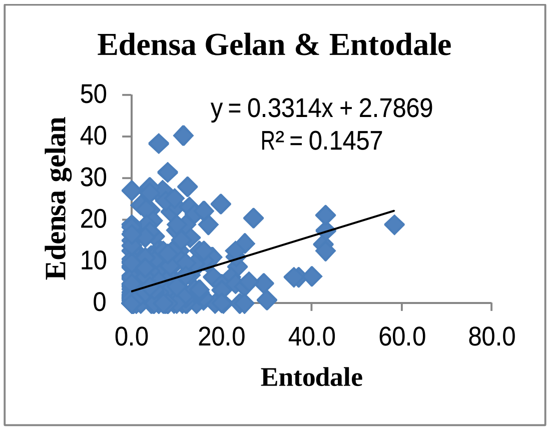

Hintodale and Serity
Entodale
80
60
40
20
0
y = 0.7192x + 1.2413
R² = 0.5176
0
20
40
60
80
Serity

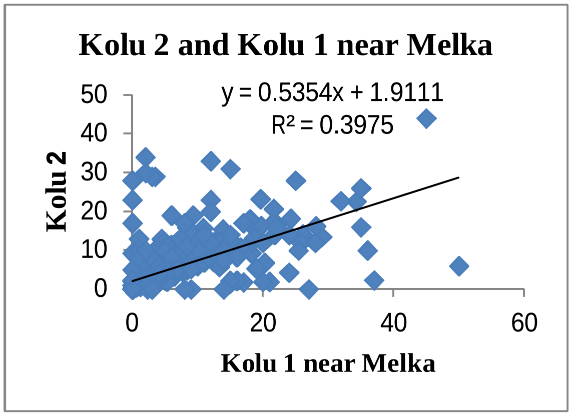

Kolu 2 and Entodale
Kolu 2
50
40
30
20
10
0
y = 0.3294x + 2.9963
R² = 0.162
0
20
40
60
80
Entodale

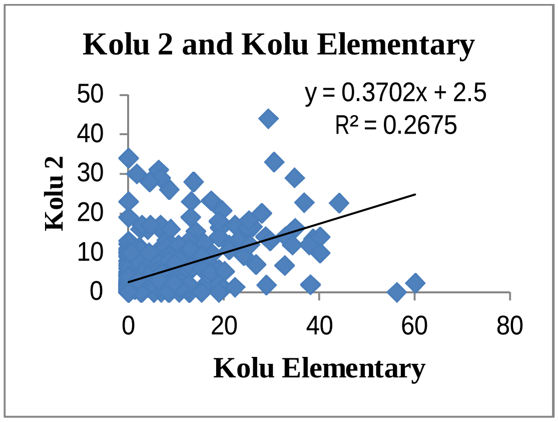

kolu 1near melka and Entodale
kolu near melka
60
40
20
0
y = 0.408x + 2.9512
R² = 0.1792
0
20
40
60
80
Entodale

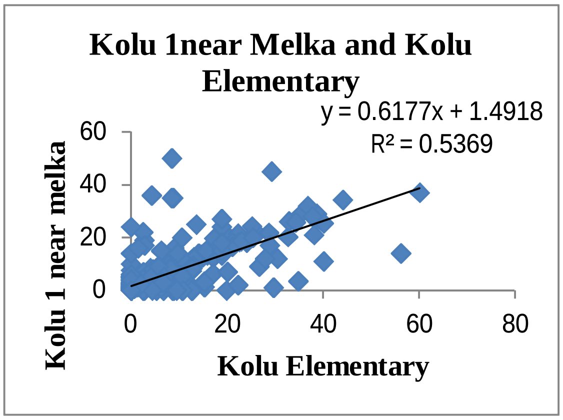

Kolu elementary and Entodale
y = 0.3491x + 3.7509
R² = 0.0933
Kolu elementary
0
20
40
60
80
0
20
40
60
80
Entodale

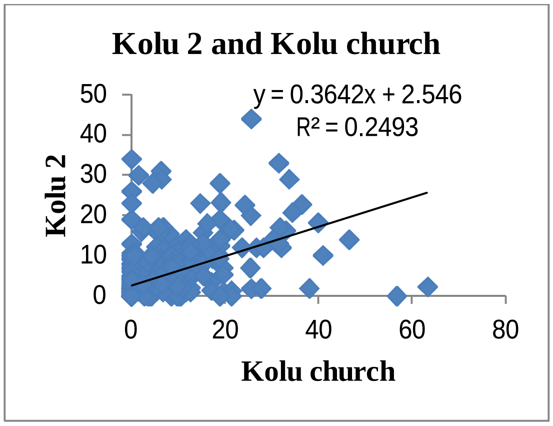

kolu church and entodale
y = 0.3447x + 3.7324
R² = 0.0944
Kolu church
0
20
40
60
80
0
20
40
60
80
Entodale

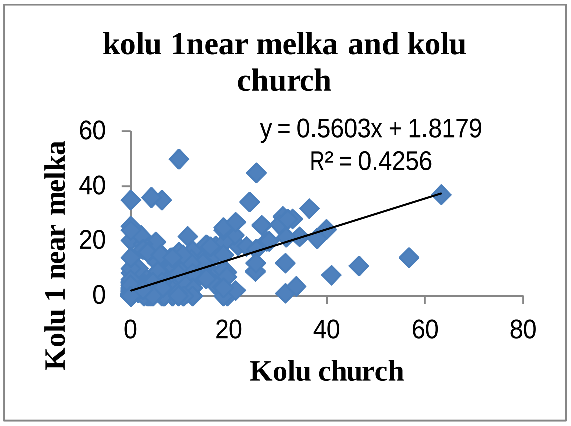

Edensa Gelan & Entodale
y = 0.3314x + 2.7869
R² = 0.1457
Edensa gelan
0
10
20
30
40
50
0.0
20.0
40.0
60.0
80.0
Entodale

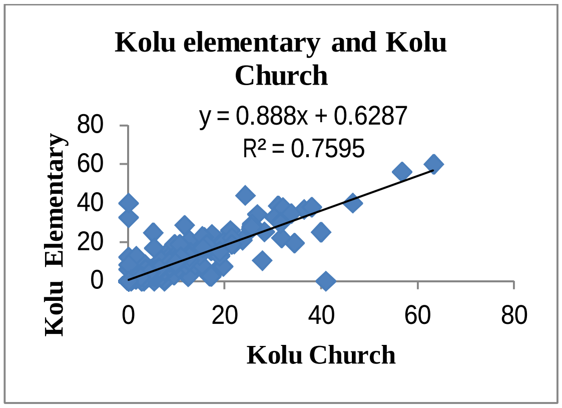

Kolu 2 and Kolu 1 near Melka
y = 0.5354x + 1.9111
R² = 0.3975
Kolu 2
0
10
20
30
40
50
0
20
40
60
Kolu 1 near Melka

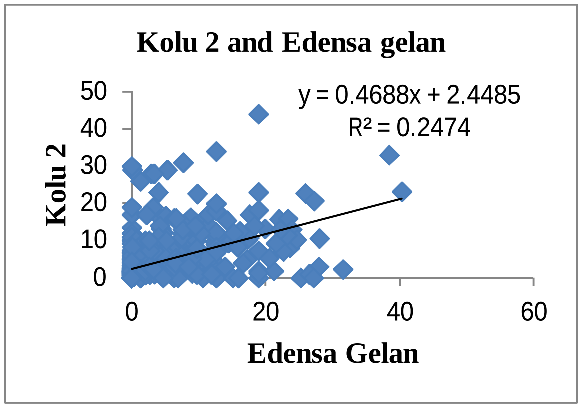

Kolu 2 and Kolu Elementary
y = 0.3702x + 2.5
R² = 0.2675
Kolu 2
0
10
20
30
40
50
0
20
40
60
80
Kolu Elementary

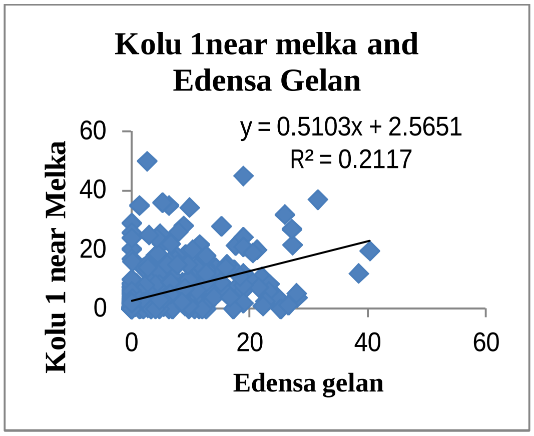

Kolu 1near Melka and Kolu Elementary
y = 0.6177x + 1.4918
R² = 0.5369
Kolu 1 near melka
0
20
40
60
0
20
40
60
80
Kolu Elementary

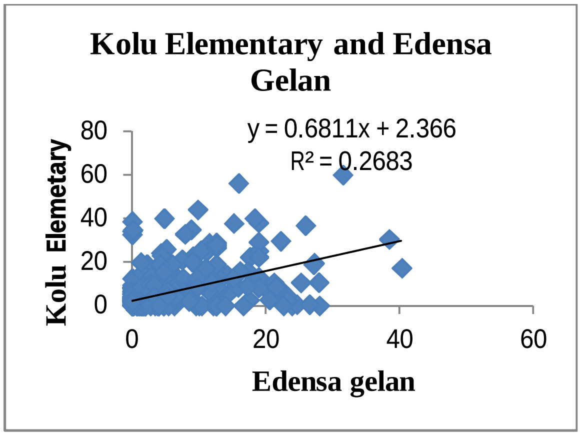

Kolu 2 and Kolu church
y = 0.3642x + 2.546
R² = 0.2493
Kolu 2
50
40
30
20
10
0
0
20
40
60
80
Kolu church

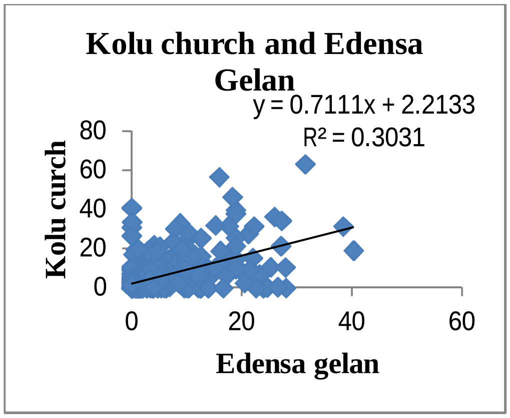

kolu 1near melka and kolu church
y = 0.5603x + 1.8179
R² = 0.4256
Kolu 1 near melka
60
40
20
0
0
20
40
60
80
Kolu church


Kolu elementary and Kolu Church
y = 0.888x + 0.6287
R² = 0.7595
Kolu Elementary
80
60
40
20
0
0
20
40
60
80
Kolu Church

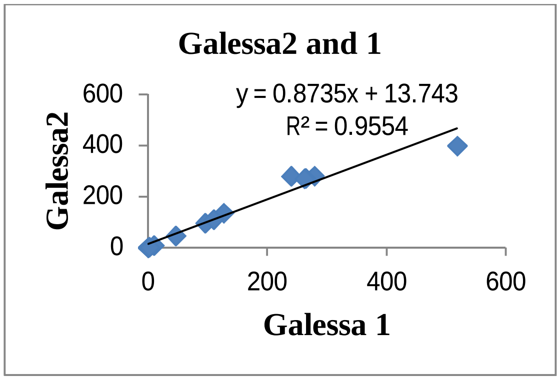

Kolu 2 and Edensa gelan
y = 0.4688x + 2.4485
R² = 0.2474
Kolu 2
50
40
30
20
10
0
0
20
40
60
Edensa Gelan

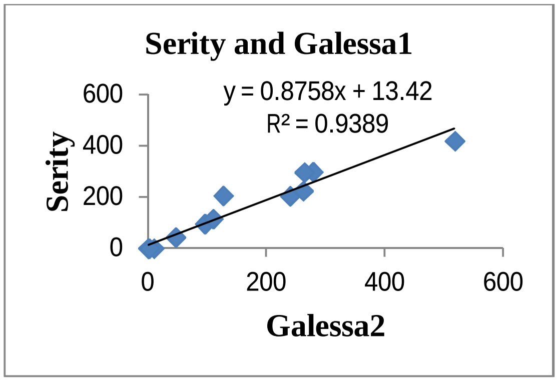

Kolu 1near melka and Edensa Gelan
y = 0.5103x + 2.5651
R² = 0.2117
Kolu 1 near Melka
60
40
20
0
0
20
40
60
Edensa gelan

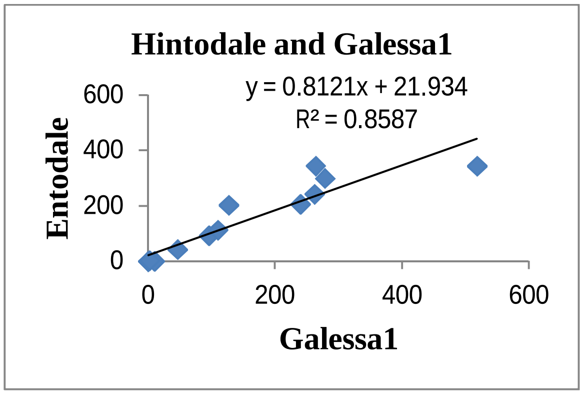

Kolu Elementary and Edensa Gelan
y = 0.6811x + 2.366
R² = 0.2683
Kolu Elemetary
80
60
40
20
0
0
20
40
60
Edensa gelan

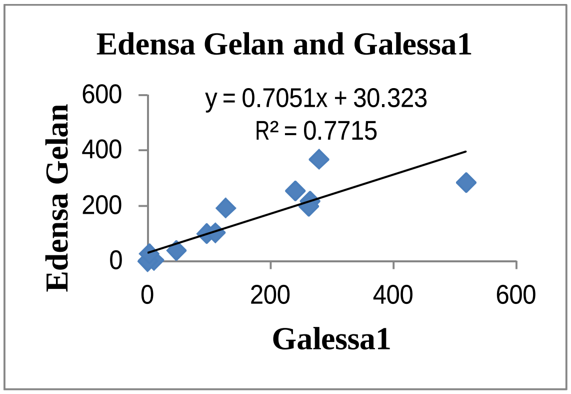


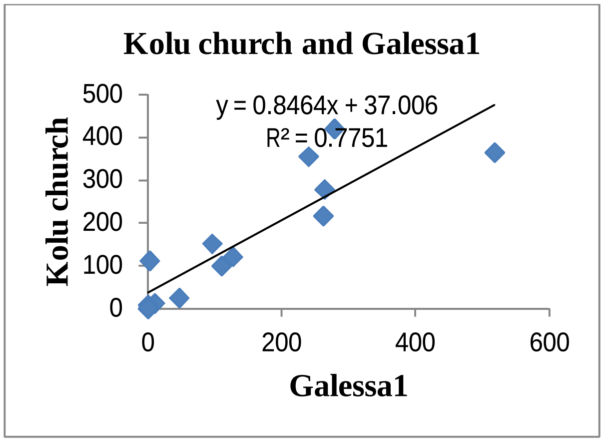
Appendex 1b. Relationship of each rain gauge stations in Meja watershed in monthly basis (mm)

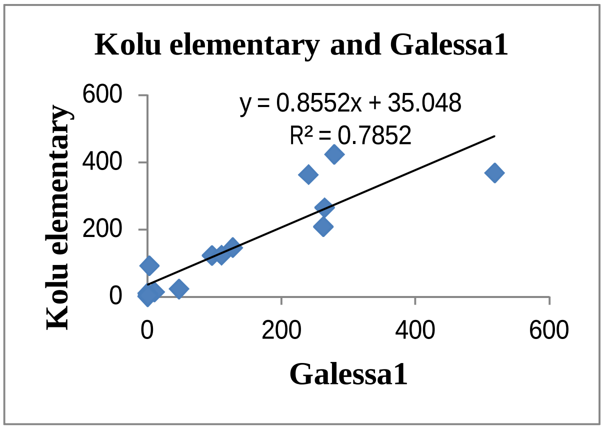


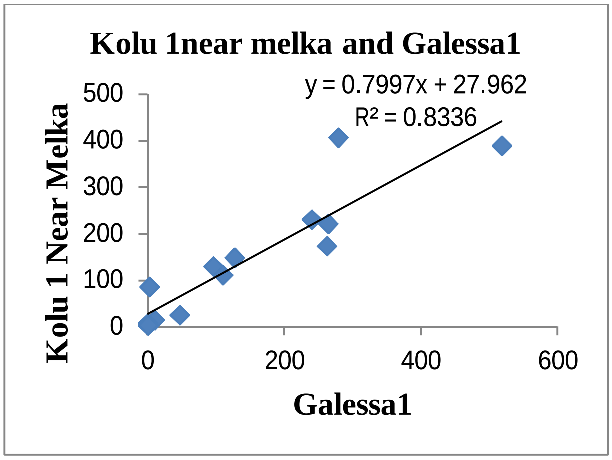


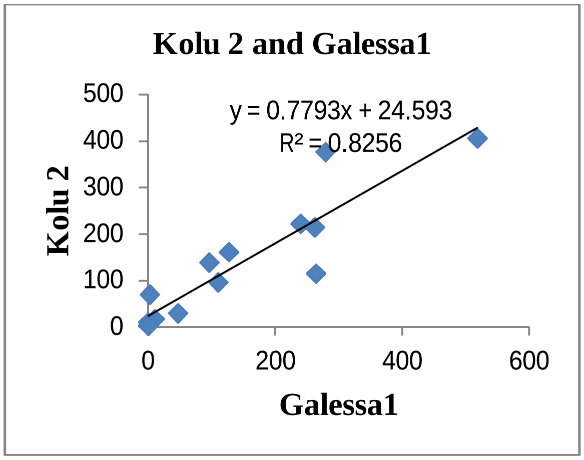


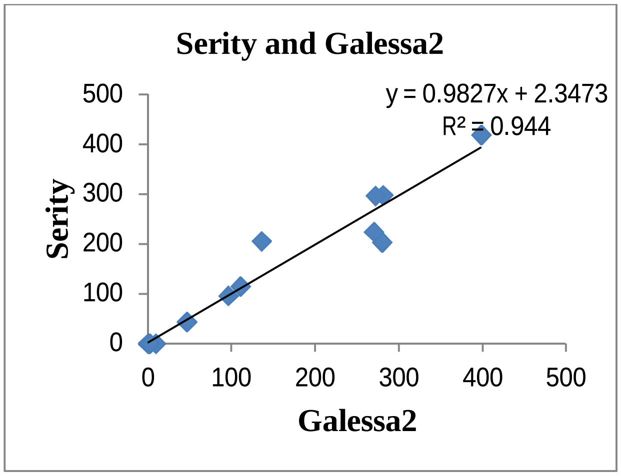


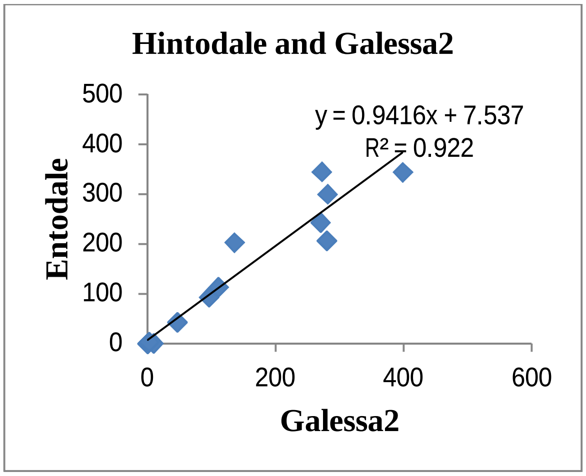

Kolu church and Galessa1
y = 0.8464x + 37.006
R² = 0.7751
Kolu church
500
400
300
200
100
0
0
200
400
600
Galessa1

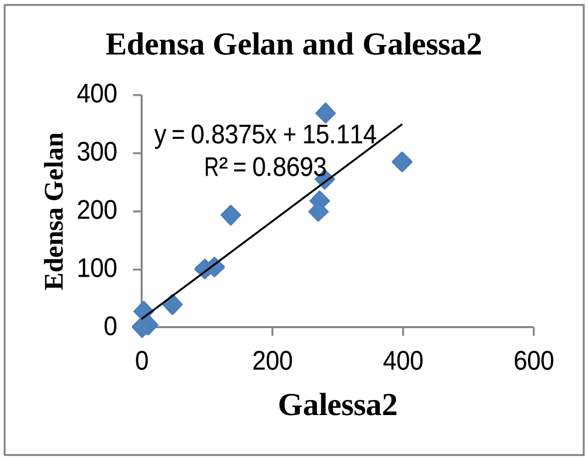

Kolu elementary and Galessa1
y = 0.8552x + 35.048
R² = 0.7852
Kolu elementary
600
400
200
0
0
200
400
600
Galessa1

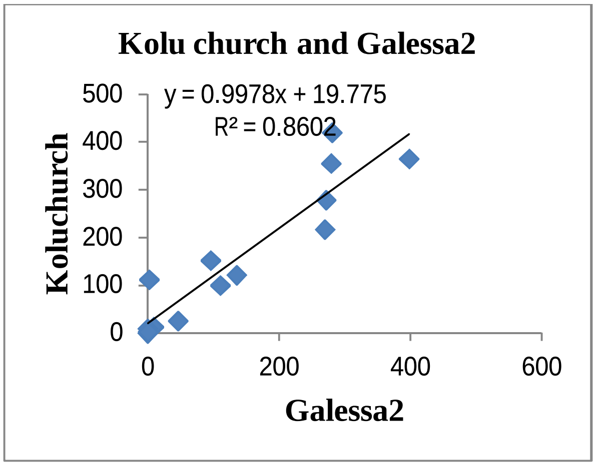

Kolu 1near melka and Galessa1
y = 0.7997x + 27.962
R² = 0.8336
Kolu 1 Near Melka
500
400
300
200
100
0
0
200
400
600
Galessa1

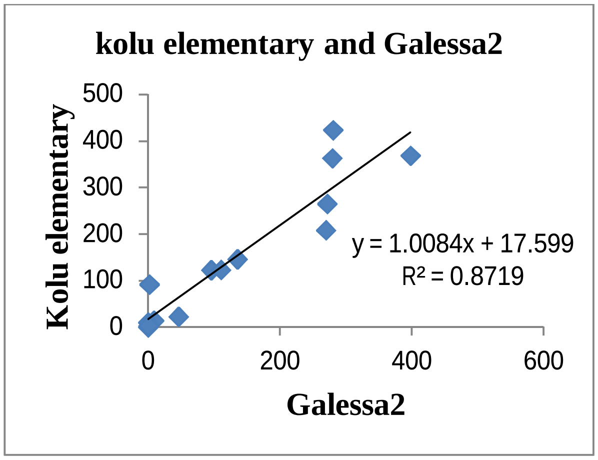

Kolu 2 and Galessa1
y = 0.7793x + 24.593
R² = 0.8256
Kolu 2
500
400
300
200
100
0
0
200
400
600
Galessa1

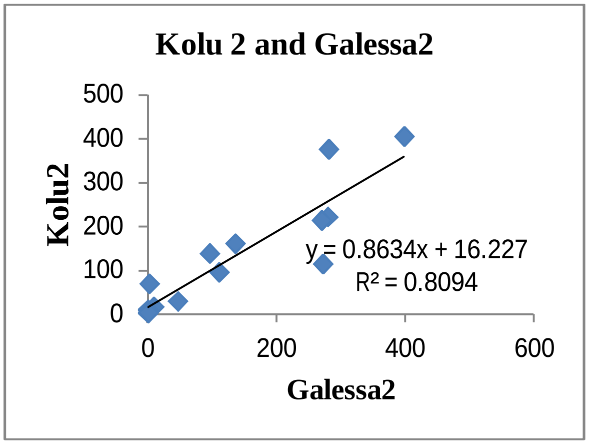

Serity and Galessa2
y = 0.9827x + 2.3473
R² = 0.944
Serity
500
400
300
200
100
0
0
100
200
300
400
500
Galessa2

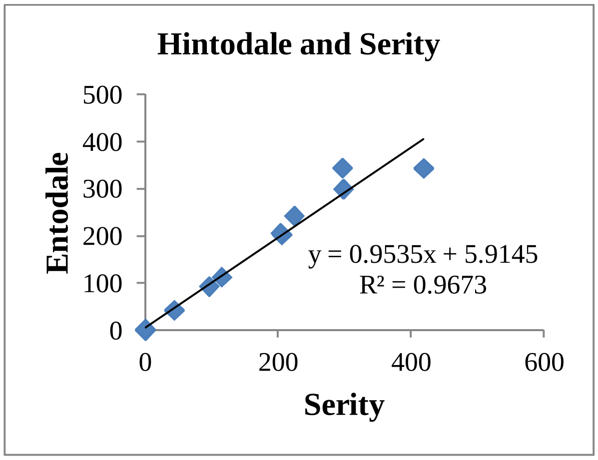

Hintodale and Galessa2
y = 0.9416x + 7.537
R² = 0.922
Entodale
500
400
300
200
100
0
0
200
400
600
Galessa2

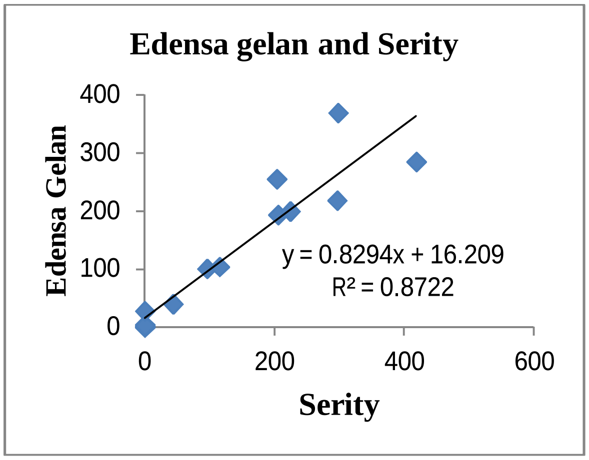

Edensa Gelan and Galessa2
400
300
200
100
0
Edensa Gelan
y = 0.8375x + 15.114
R² = 0.8693
0
200
400
600
Galessa2

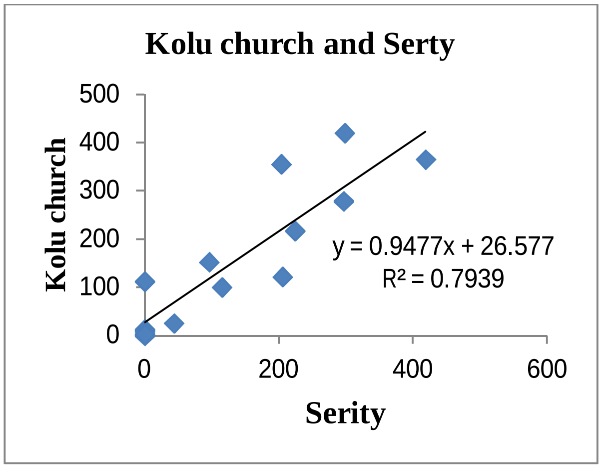

Kolu church and Galessa2
500
400
300
200
100
0
Koluchurch
y = 0.9978x + 19.775
R² = 0.8602
0
200
400
600
Galessa2

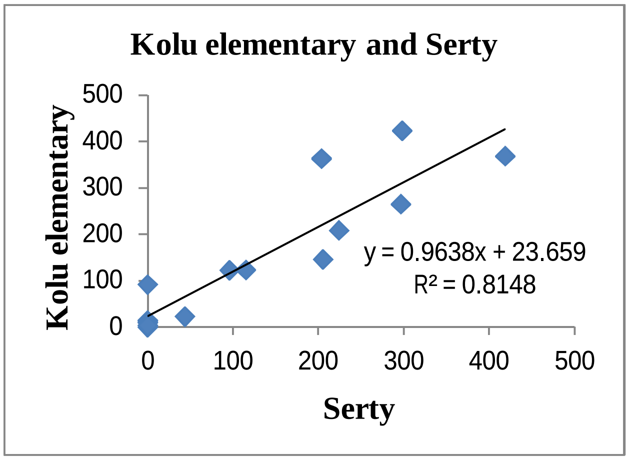

kolu elementary and Galessa2
500
400
300
200
100
0
Kolu elementary
y = 1.0084x + 17.599
R² = 0.8719
0
200
400
600
Galessa2

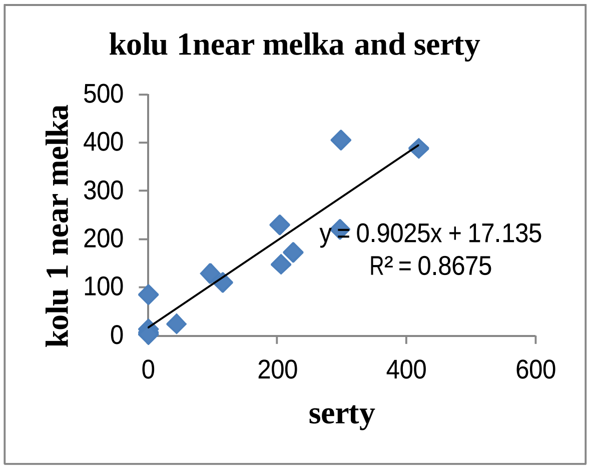

Kolu 2 and Galessa2
500
400
300
200
100
0
Kolu2
y = 0.8634x + 16.227
R² = 0.8094
0
200
400
600
Galessa2

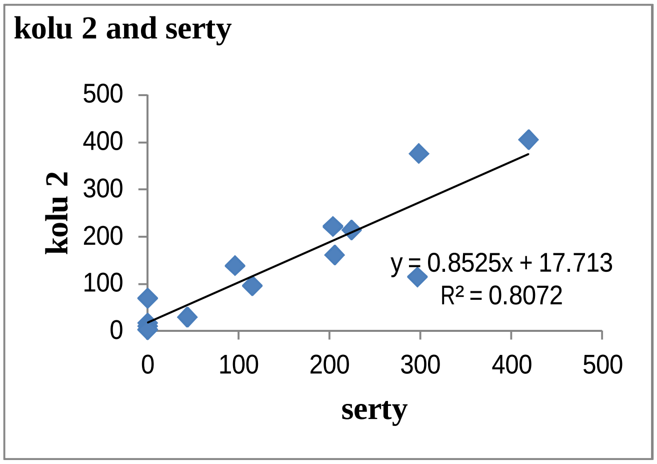

Hintodale and Serity
500
400
300
200
100
0
Entodale
y = 0.9535x + 5.9145
R² = 0.9673
0
200
400
600
Serity

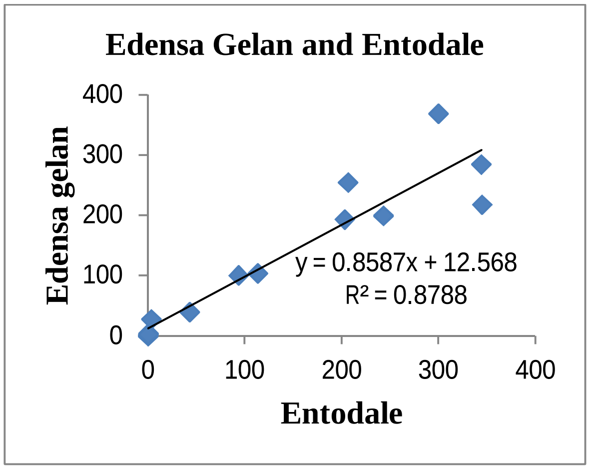

Edensa gelan and Serity
400
300
200
100
0
Edensa Gelan
y = 0.8294x + 16.209
R² = 0.8722
0
200
400
600
Serity

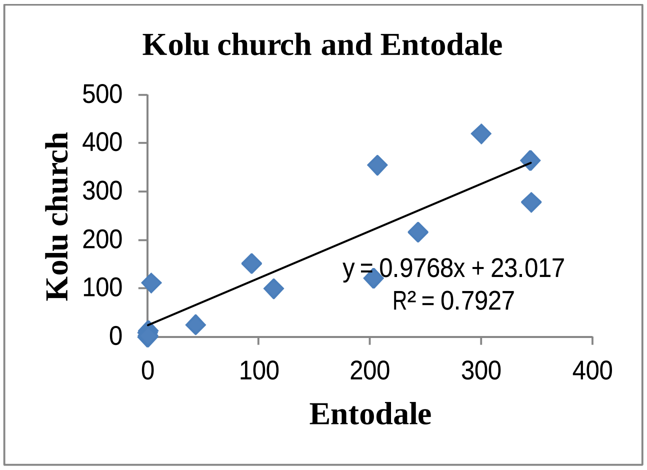

Kolu church and Serty
Kolu church
500
400
300
200
100
0
0
200
400
600
Serity
y = 0.9477x + 26.577
R² = 0.7939

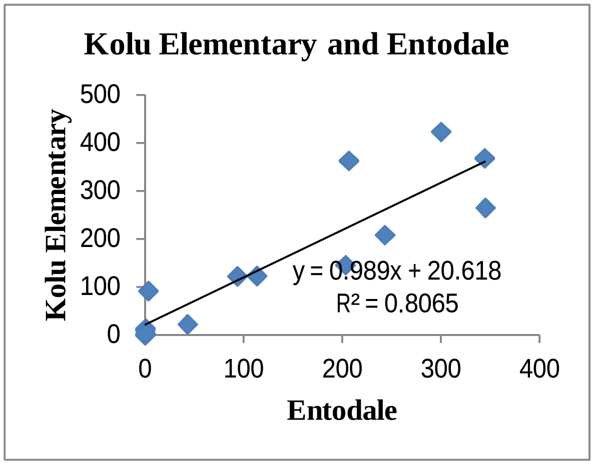

Kolu elementary and Serty
Kolu elementary
500
400
300
200
100
0
0
100
200
300
400
500
Serty
y = 0.9638x + 23.659
R² = 0.8148

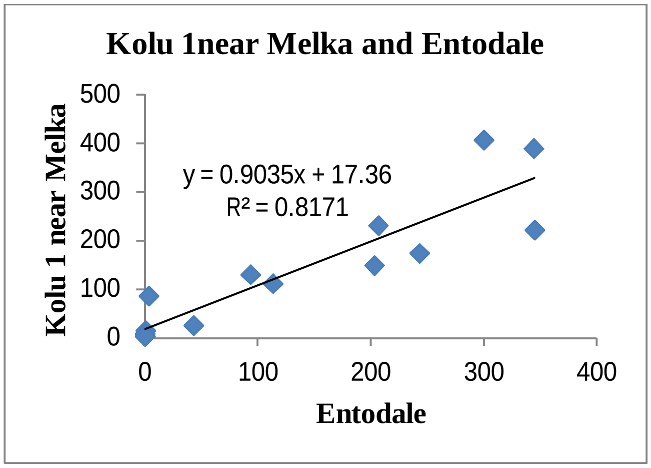

kolu 1near melka and serty
kolu 1 near melka
500
400
300
200
100
0
0
200
400
600
serty
y = 0.9025x + 17.135
R² = 0.8675

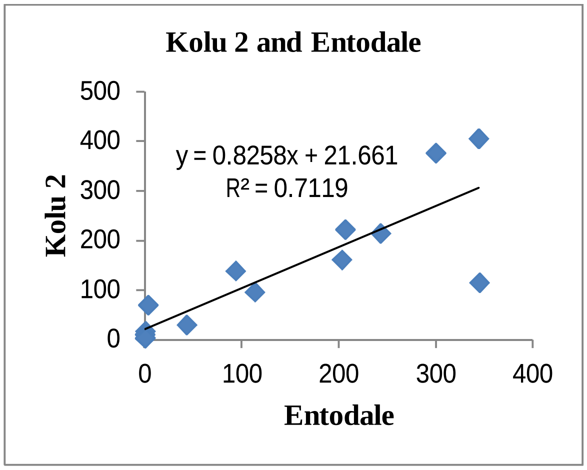

kolu 2 and serty
kolu 2
500
400
300
200
100
0
0
100
200
300
400
500
serty
y = 0.8525x + 17.713
R² = 0.8072

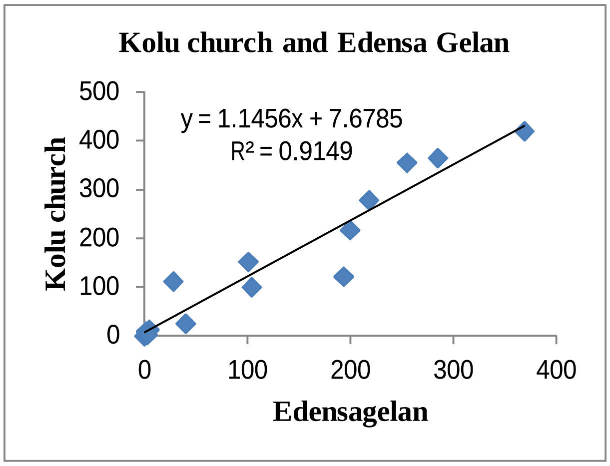

Edensa Gelan and Entodale
Edensa gelan
400
300
200
100
0
0
100
200
300
400
Entodale
y = 0.8587x + 12.568
R² = 0.8788

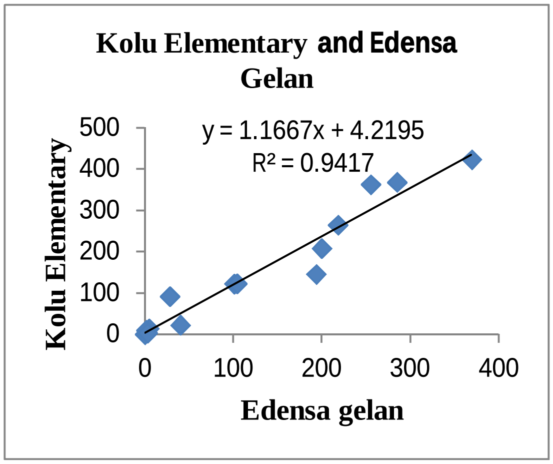

Kolu church and Entodale
Kolu church
500
400
300
200
100
0
0
100
200
300
400
Entodale
y = 0.9768x + 23.017
R² = 0.7927

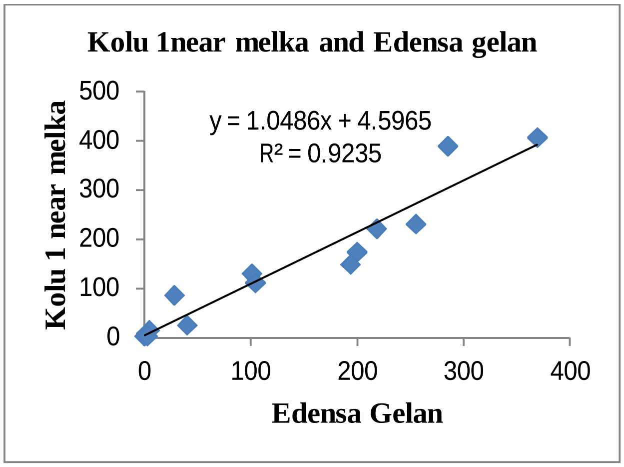

Kolu Elementary and Entodale
Kolu Elementary
500
400
300
200
100
0
0
100
200
300
400
y = 0.989x + 20.618
R² = 0.8065
Entodale

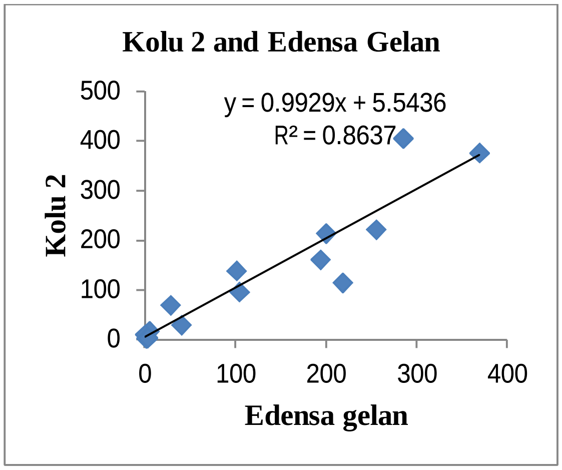

Kolu 1near Melka and Entodale
Kolu 1 near Melka
500
400
300
200
100
0
0
100
200
300
400
y = 0.9035x + 17.36
R² = 0.8171
Entodale

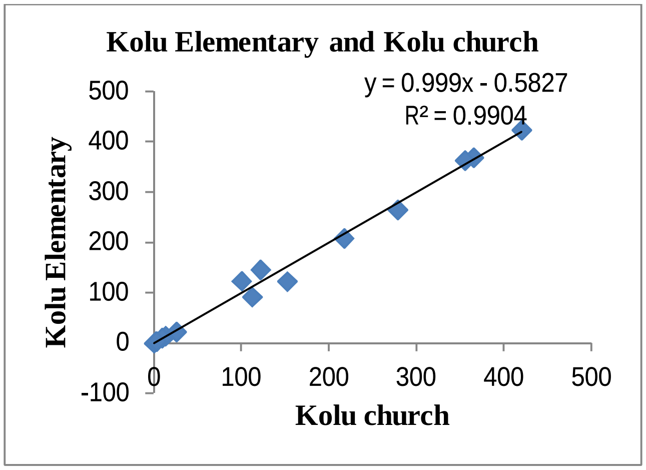

Kolu 2 and Entodale
Kolu 2
500
400
300
200
100
0
0
100
200
300
400
y = 0.8258x + 21.661
R² = 0.7119
Entodale

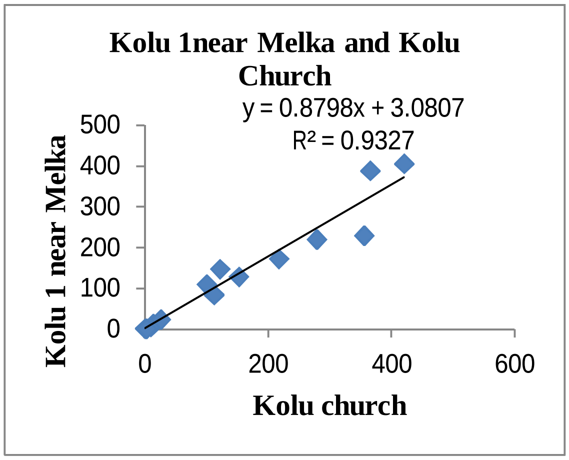

Kolu church and Edensa Gelan
Kolu church
500
400
300
200
100
0
0
100
200
300
400
y = 1.1456x + 7.6785
R² = 0.9149
Edensagelan

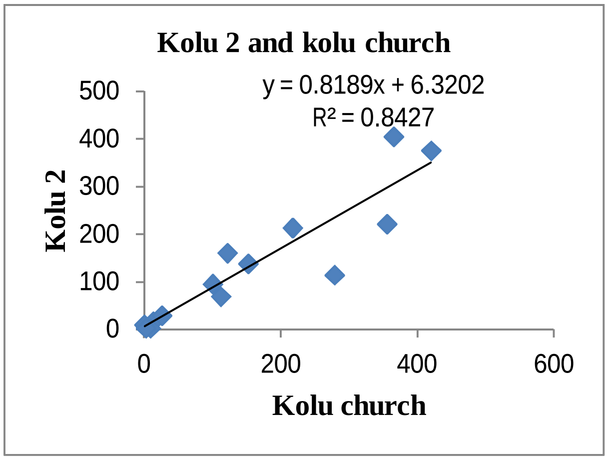

Kolu Elementary and Edensa Gelan
Kolu Elementary
500
400
300
200
100
0
0
100
200
300
400
y = 1.1667x + 4.2195
R² = 0.9417
Edensa gelan

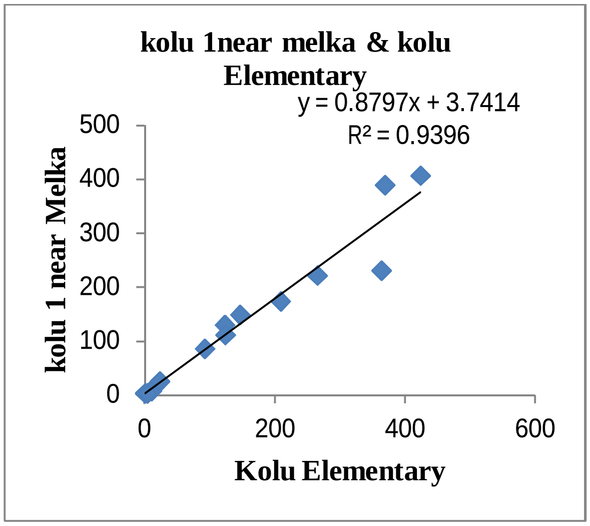

Kolu 1near melka and Edensa gelan
Kolu 1 near melka
500
400
300
200
100
0
0
100
200
300
400
y = 1.0486x + 4.5965
R² = 0.9235
Edensa Gelan

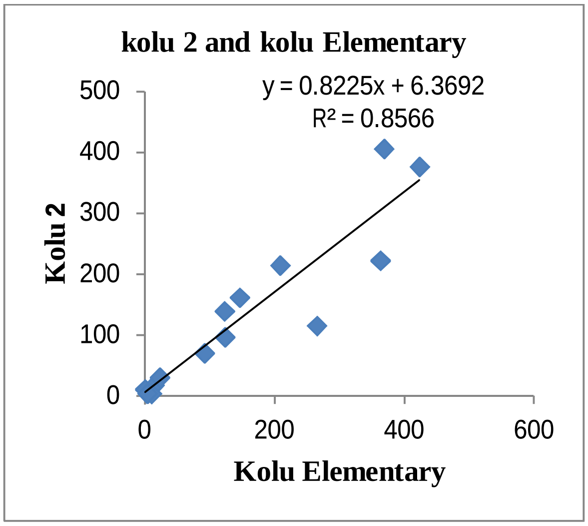

Kolu 2 and Edensa Gelan
y = 0.9929x + 5.5436
R² = 0.8637
Kolu 2
500
400
300
200
100
0
0
100
200
300
400
Edensa gelan

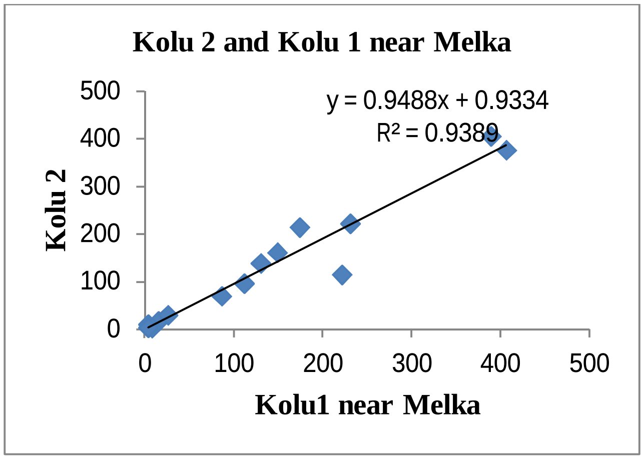

Kolu Elementary and Kolu church
y = 0.999x - 0.5827
R² = 0.9904
Kolu Elementary
500
400
300
200
100
0
-100
0
100
200
300
400
500
Kolu church


Kolu 1near Melka and Kolu Church
y = 0.8798x + 3.0807
R² = 0.9327
Kolu 1 near Melka
500
400
300
200
100
0
0
200
400
600
Kolu church

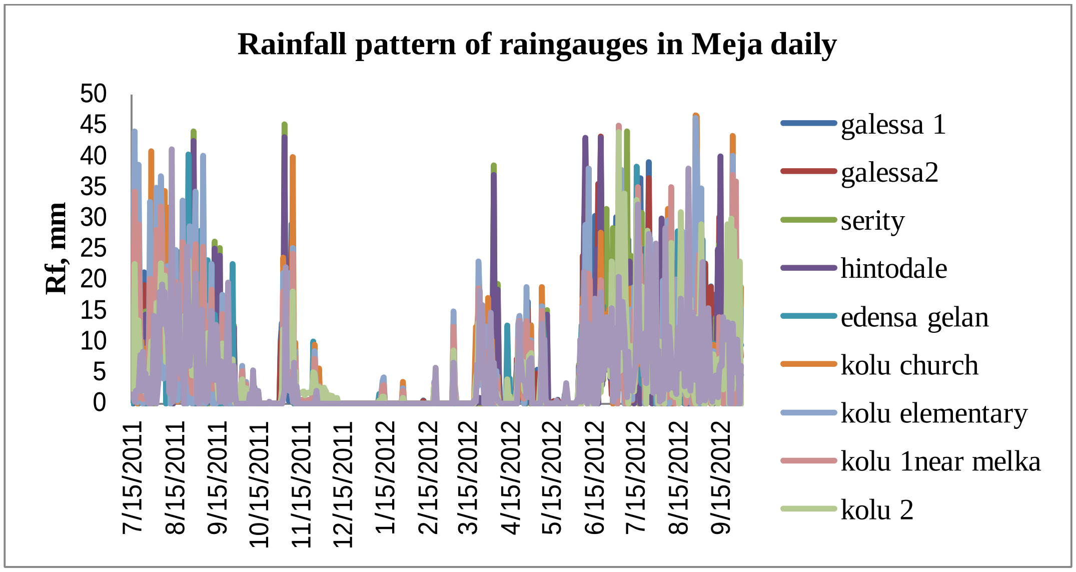

Kolu 2 and kolu church
y = 0.8189x + 6.3202
R² = 0.8427
Kolu 2
500
400
300
200
100
0
0
200
400
600
Kolu church

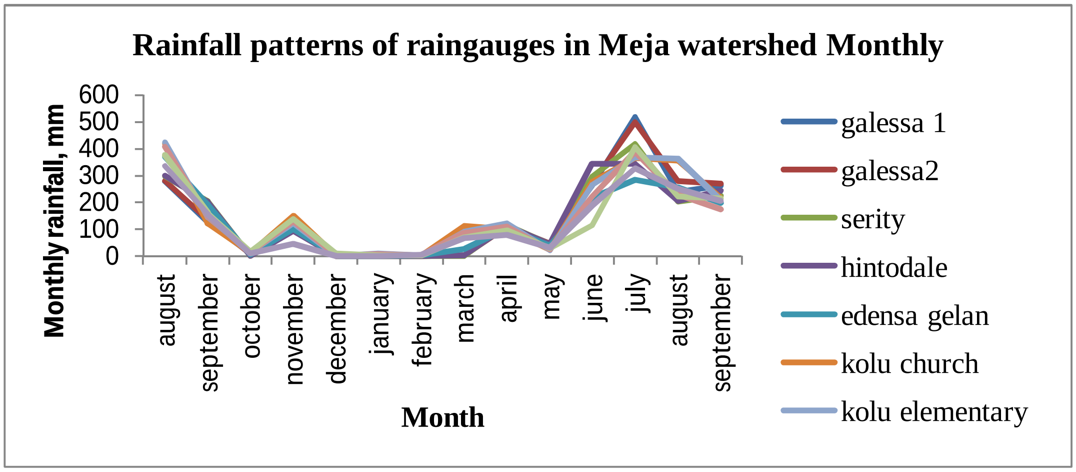

kolu 1near melka & kolu Elementary
y = 0.8797x + 3.7414
R² = 0.9396
kolu 1 near Melka
500
400
300
200
100
0
0
200
400
600
Kolu Elementary


kolu 2 and kolu Elementary
y = 0.8225x + 6.3692
R² = 0.8566
Kolu 2
500
400
300
200
100
0
0
200
400
600
Kolu Elementary

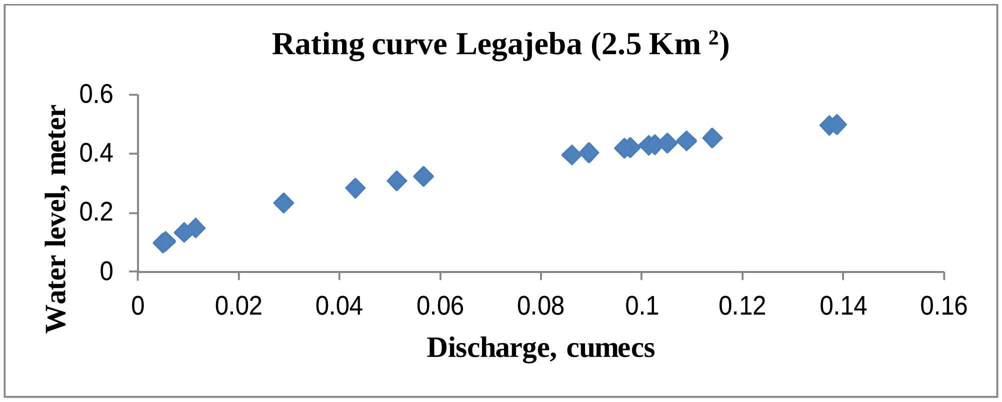


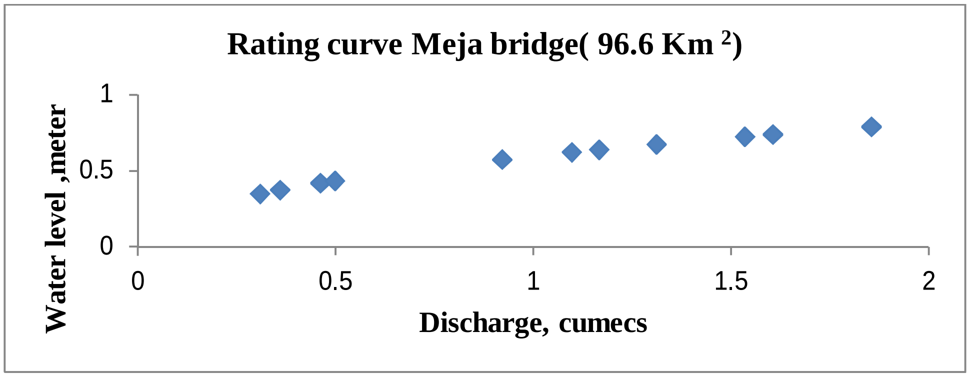
Appendex 2. Rainfall patterns of rain gauges located in Meja watershed daily and monthly



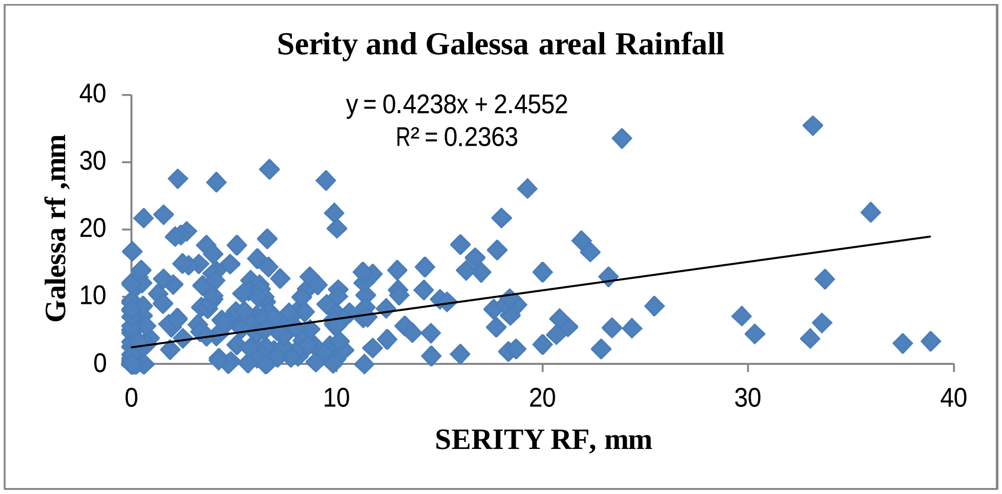


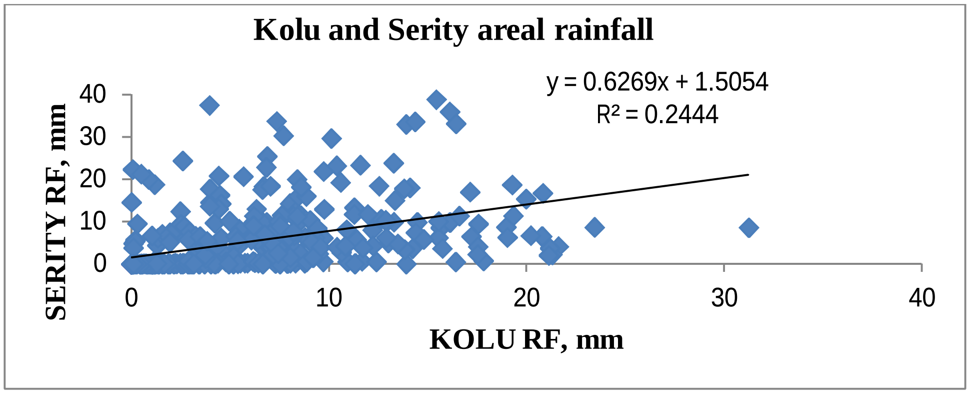
Appendex 3. Rating curves of Meja and Kolu

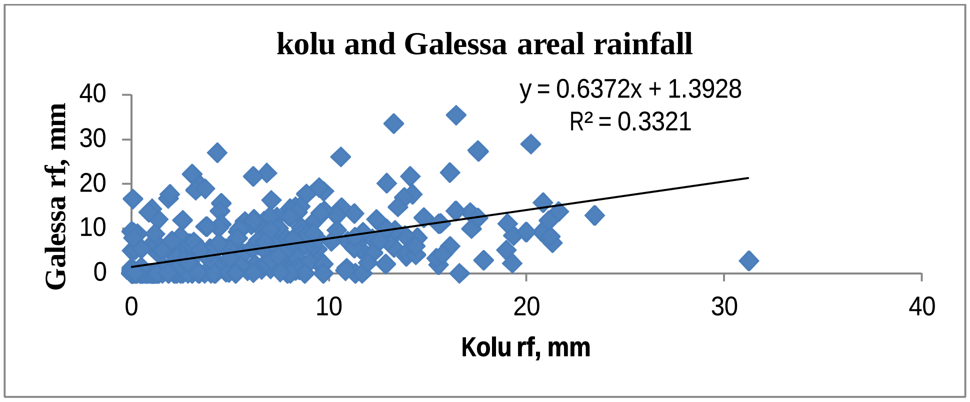




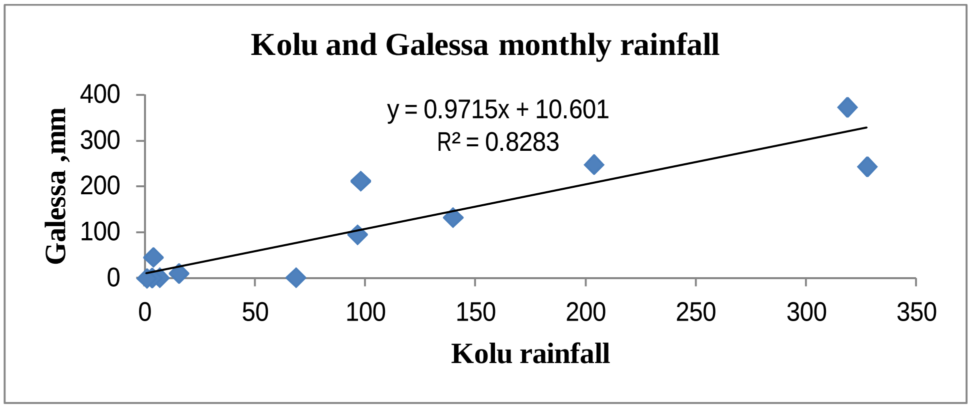
Appendex 4a.Daily areal rainfall relationship between Galessa, Serity and Kolu

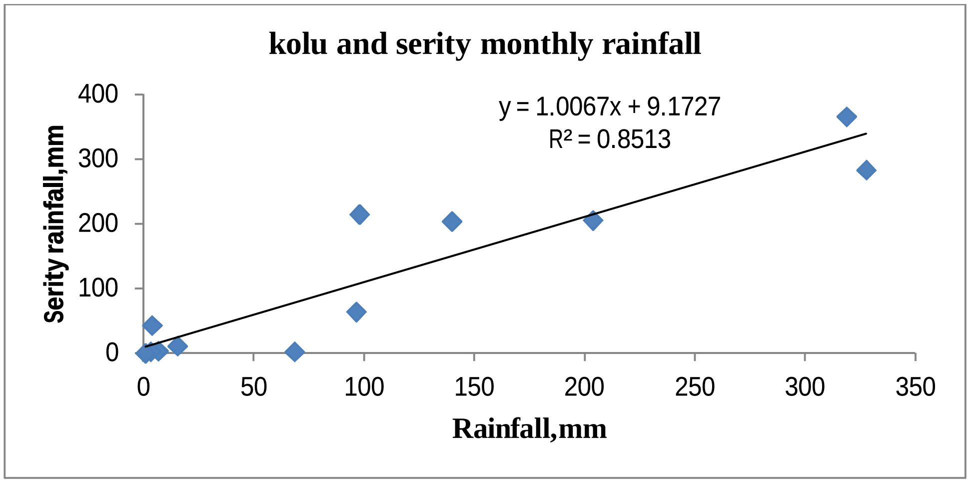


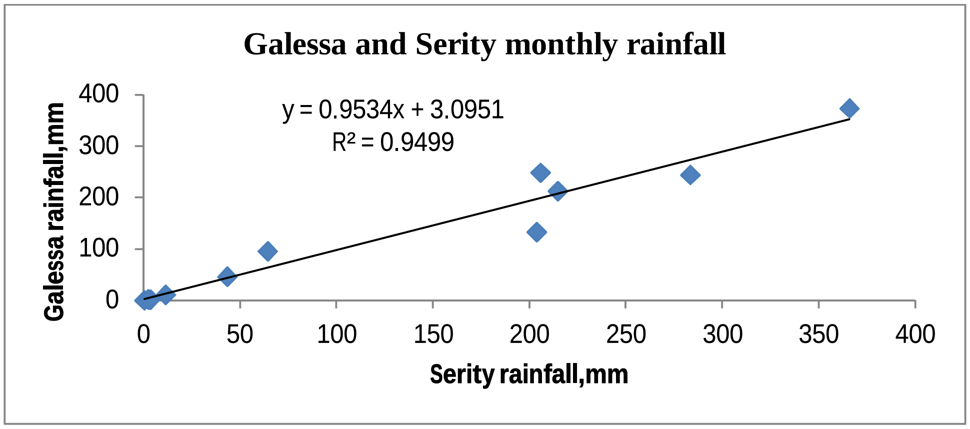




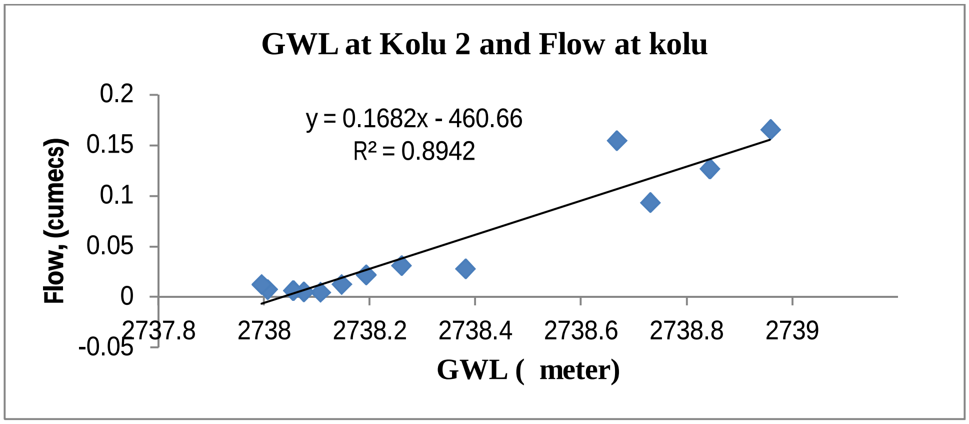
Appendex 4b.Monthly areal rainfall relationship between Galessa, Serity and Kolu

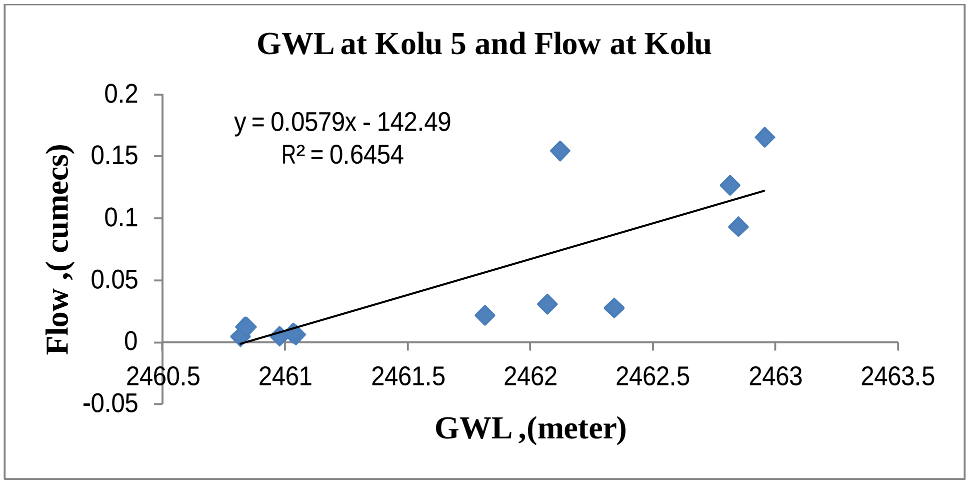




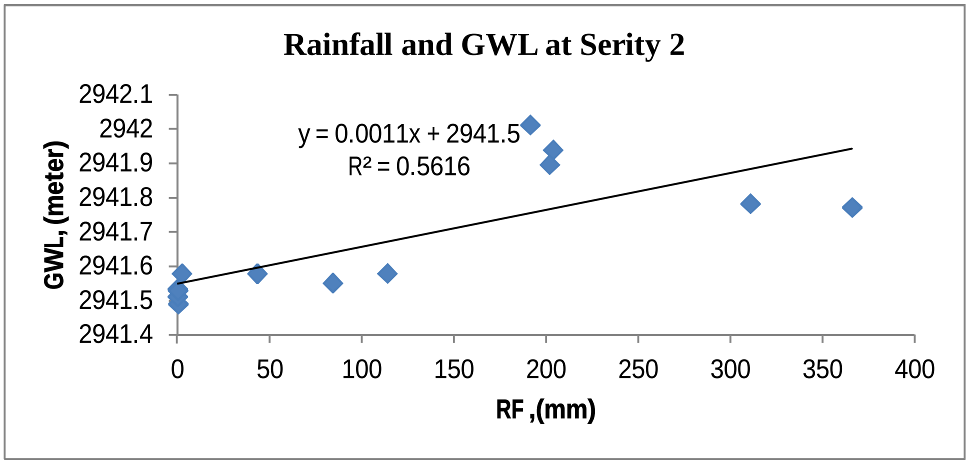


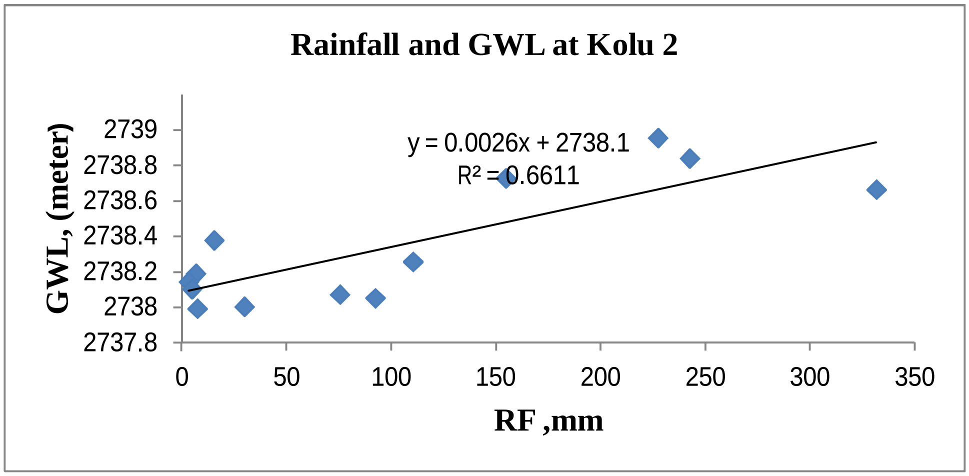
Appendex 5.Ground water level and runoff relationship

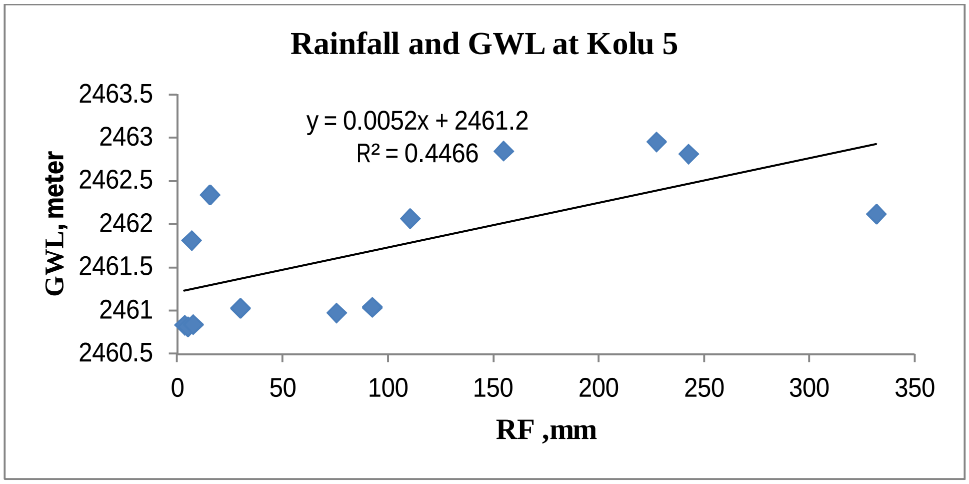




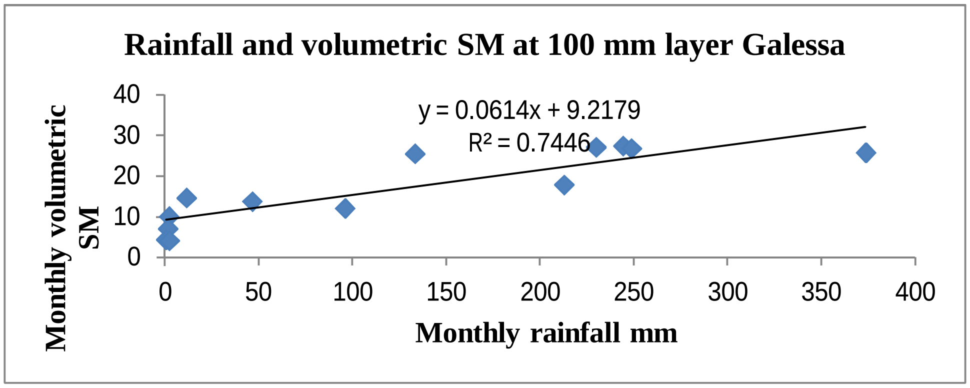
Appendex 6.Rainfall and Ground water level relationship

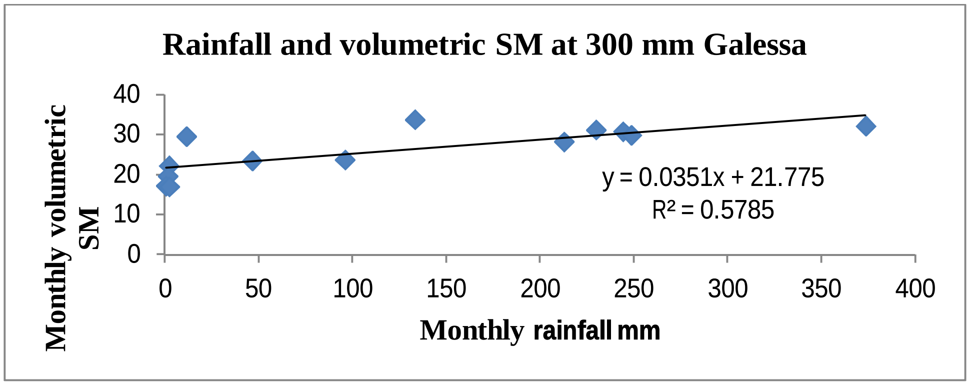


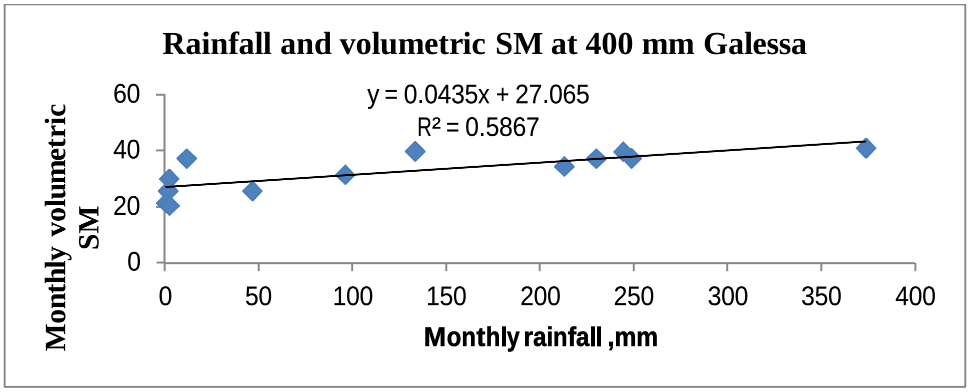


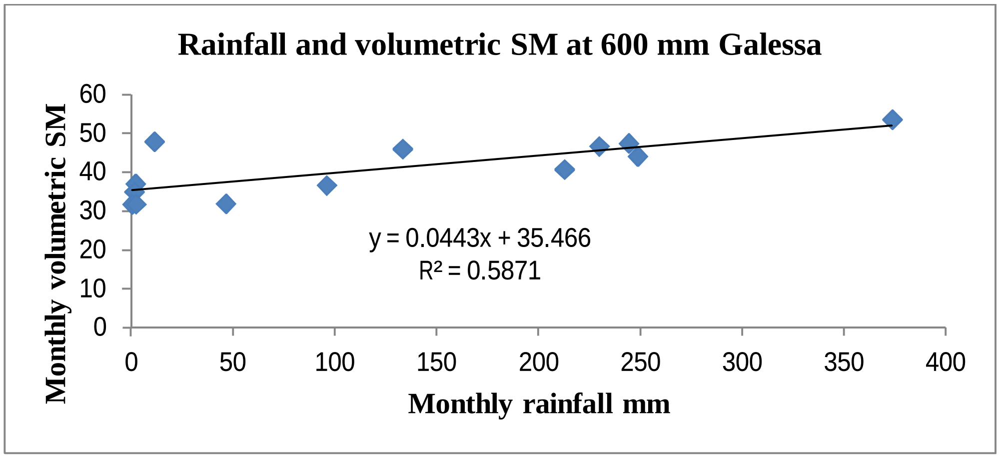


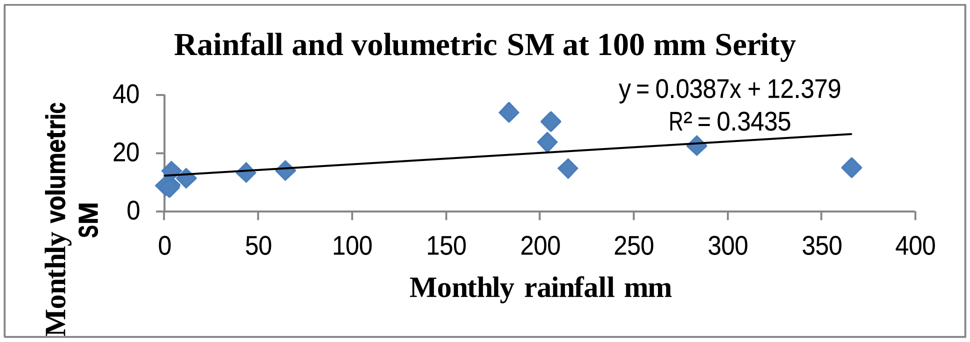
Appendex 7.Rainfall and volumetric soil moisture relationship

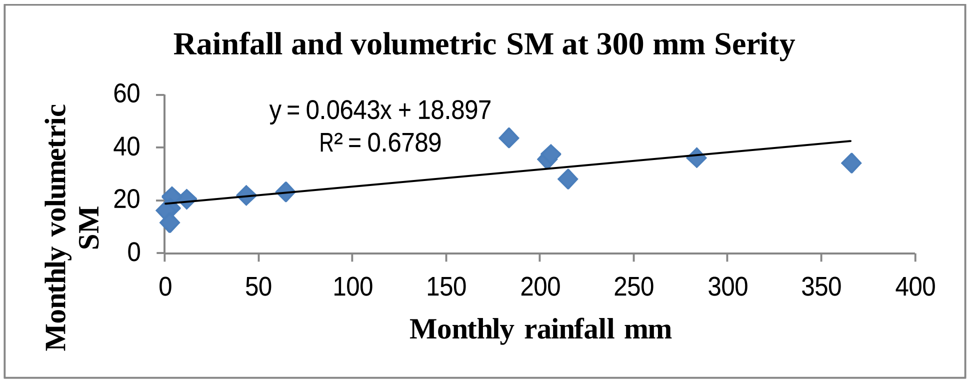


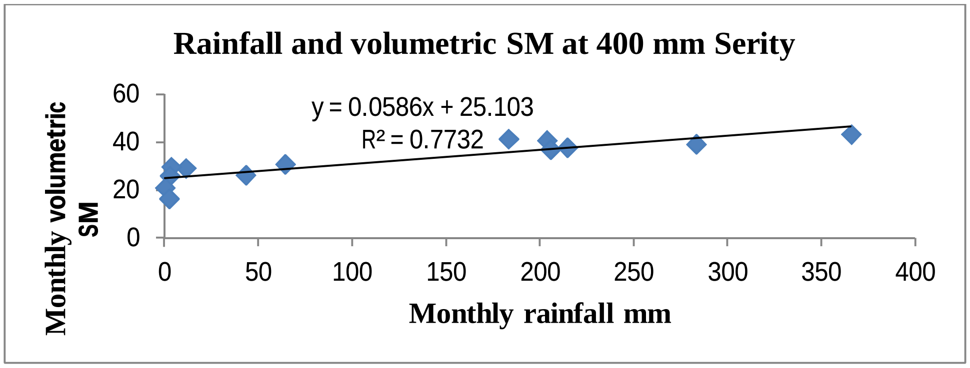


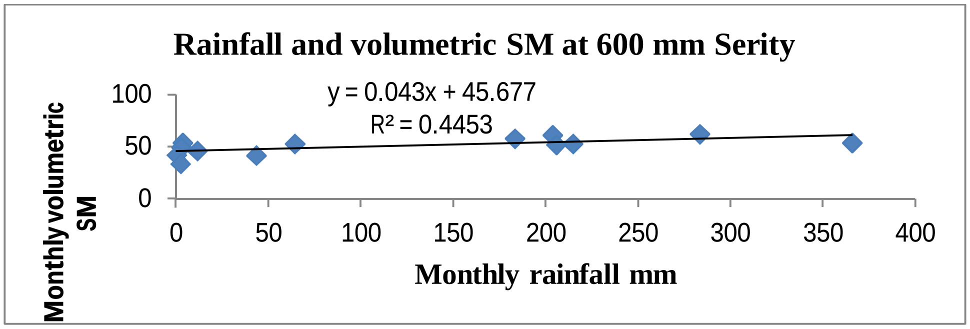

Rainfall and volumetric SM at 400 mm Galessa

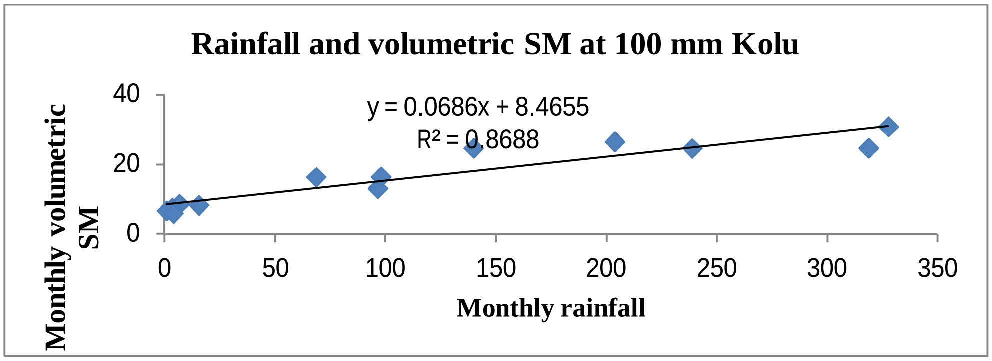

Rainfall and volumetric SM at 600 mm Galessa

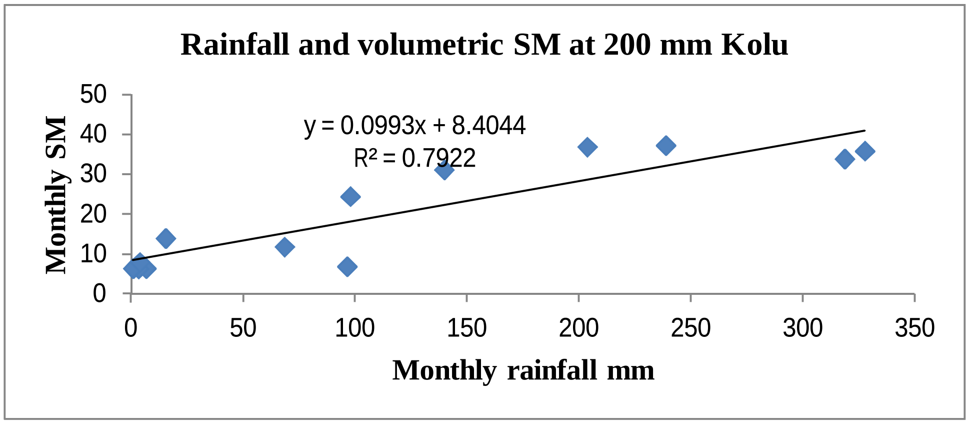

Rainfall and volumetric SM at 100 mm Serity

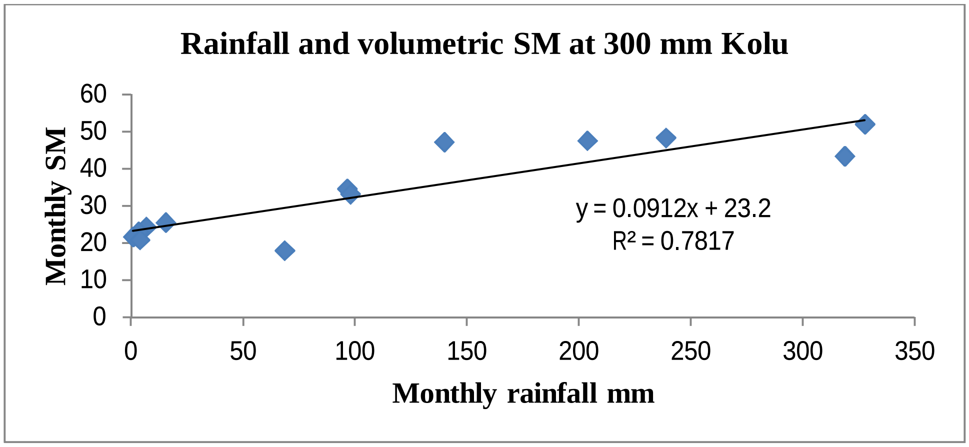

Rainfall and volumetric SM at 300 mm Serity

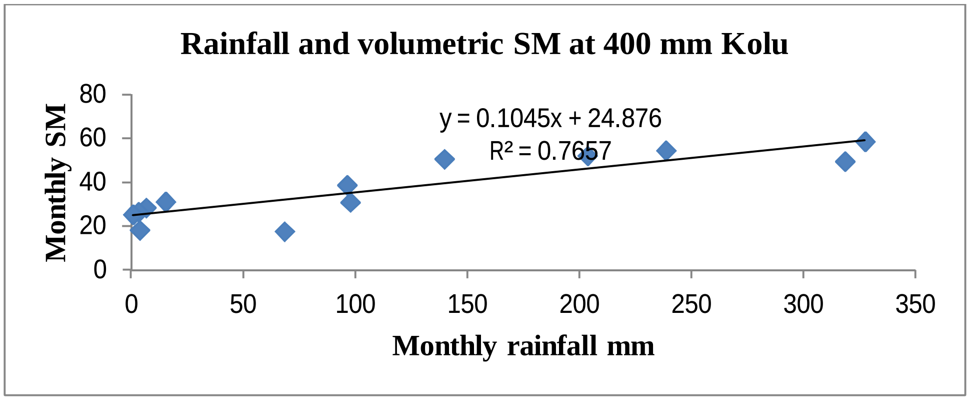

Rainfall and volumetric SM at 400 mm Serity

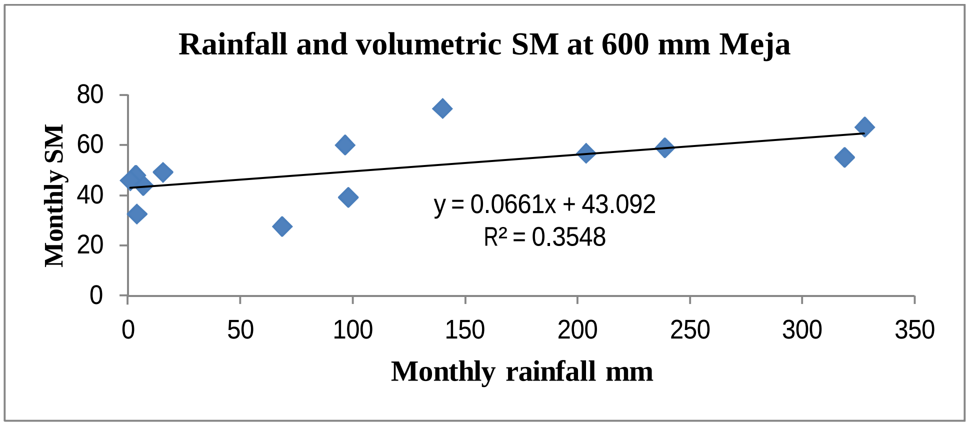

Rainfall and volumetric SM at 600 mm Serity

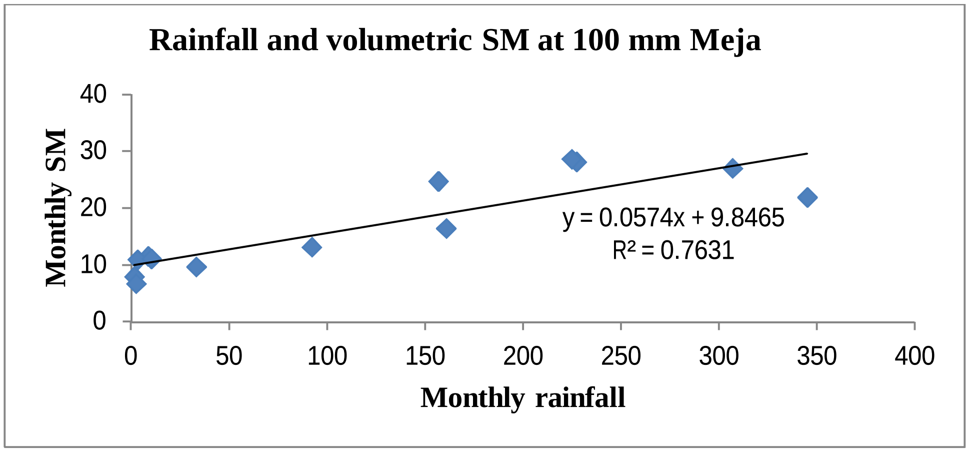

Rainfall and volumetric SM at 100 mm Kolu

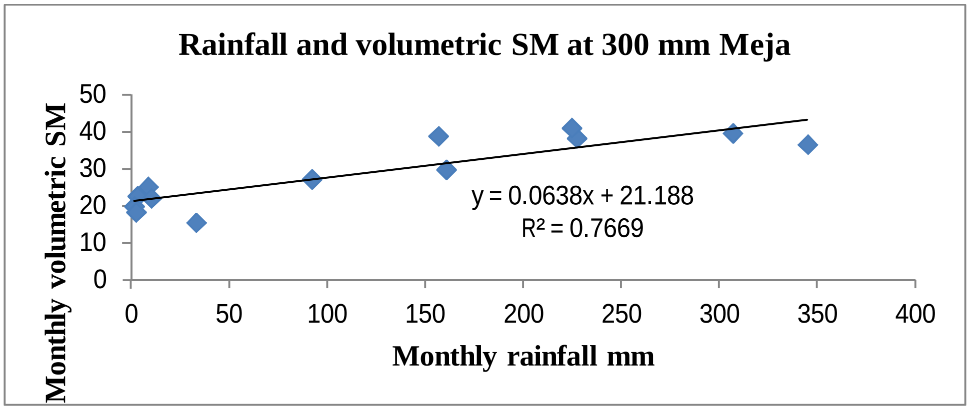

Rainfall and volumetric SM at 200 mm Kolu

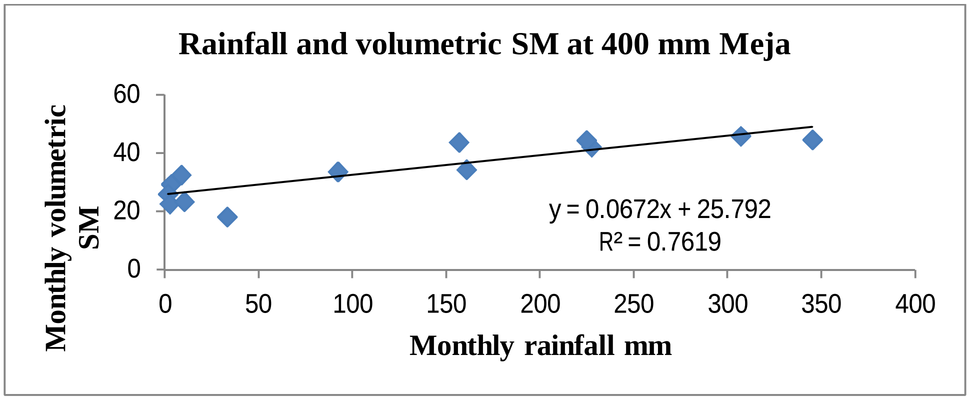

Rainfall and volumetric SM at 300 mm Kolu
Monthly SM
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
Monthly rainfall mm
y = 0.0912x + 23.2
R² = 0.7817

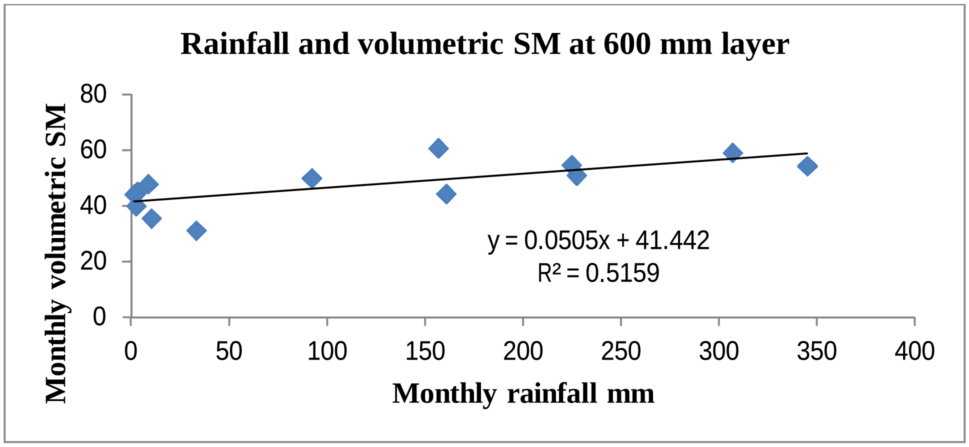

Rainfall and volumetric SM at 400 mm Kolu
Monthly SM
80
60
40
20
0
0
50
100
150
200
250
300
350
Monthly rainfall mm
y = 0.1045x + 24.876
R² = 0.7657


Rainfall and volumetric SM at 600 mm Meja
Monthly SM
80
60
40
20
0
0
50
100
150
200
250
300
350
Monthly rainfall mm
y = 0.0661x + 43.092
R² = 0.3548

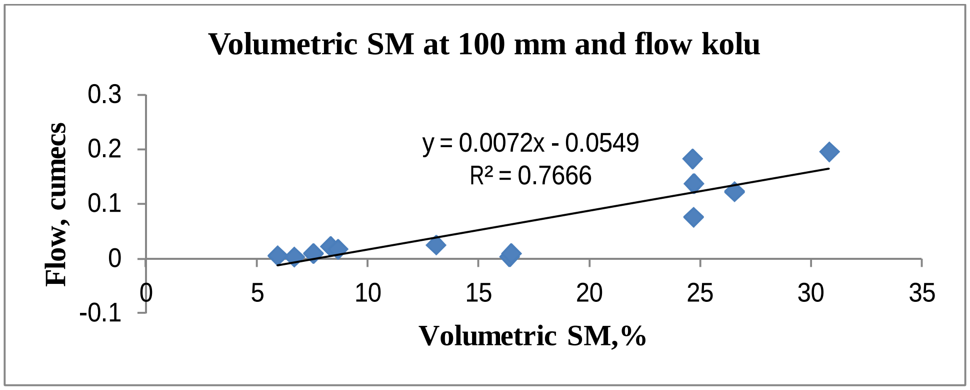

Rainfall and volumetric SM at 100 mm Meja
Monthly SM
40
30
20
10
0
0
50
100
150
200
250
300
350
400
Monthly rainfall
y = 0.0574x + 9.8465
R² = 0.7631

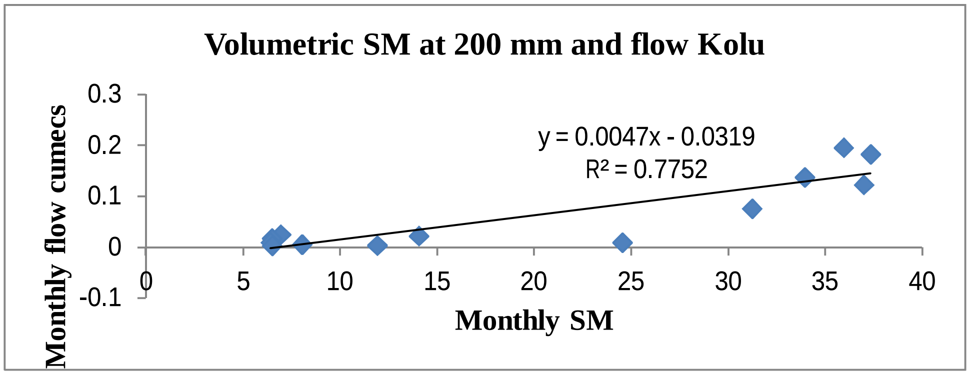

Rainfall and volumetric SM at 300 mm Meja
Monthly volumetric SM
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
Monthly rainfall mm
y = 0.0638x + 21.188
R² = 0.7669

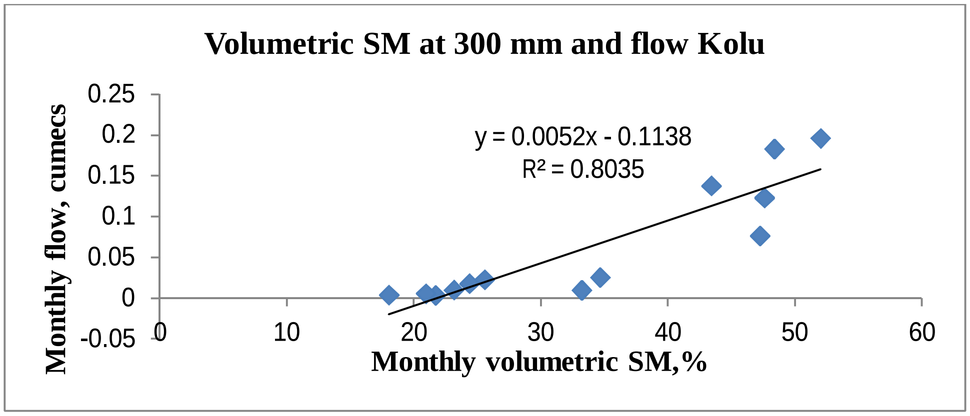

Rainfall and volumetric SM at 400 mm Meja
Monthly volumetric SM
60
40
20
0
0
50
100
150
200
250
300
350
400
Monthly rainfall mm
y = 0.0672x + 25.792
R² = 0.7619

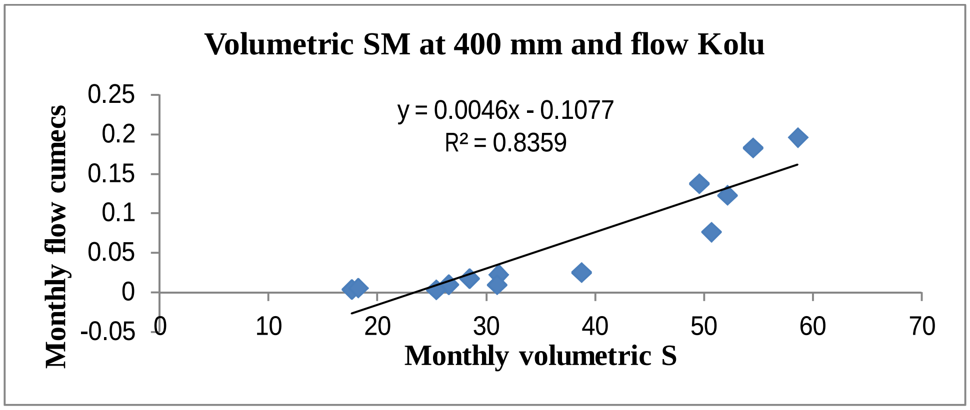


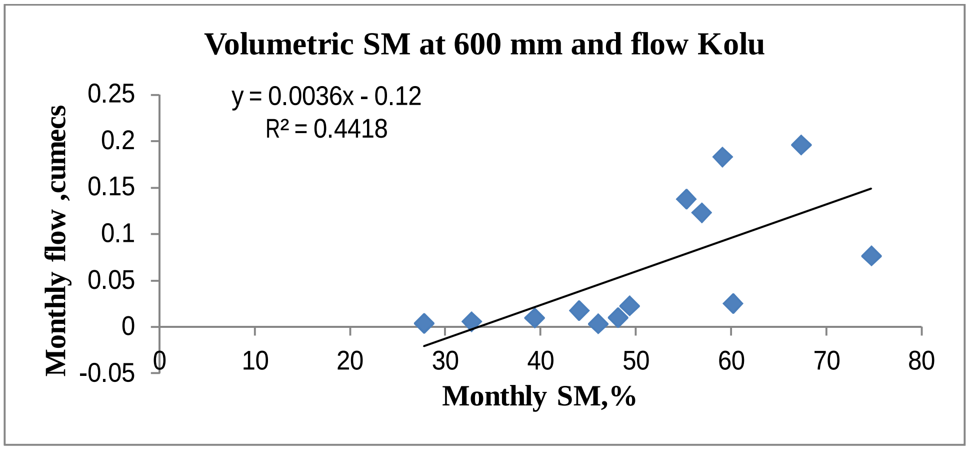
Appendex 8.Relationship of runoff and volumetric soil moisture

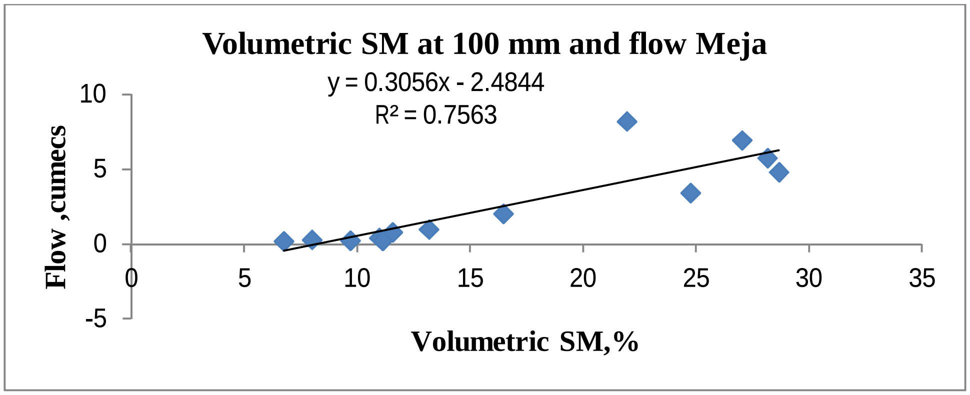


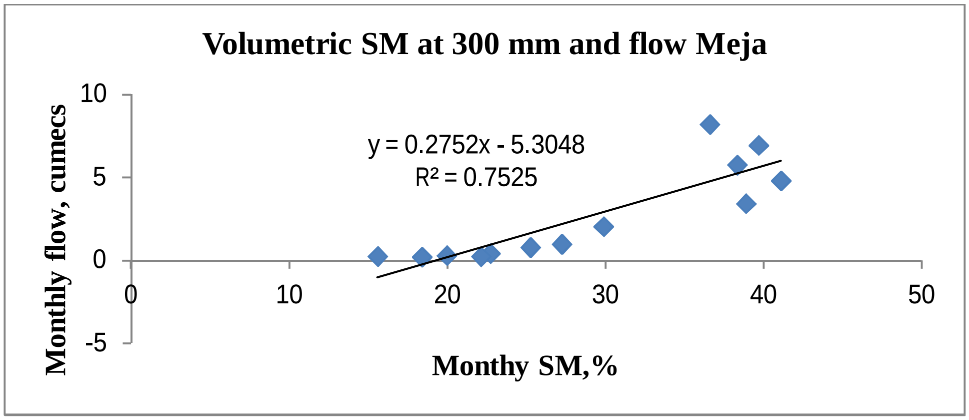


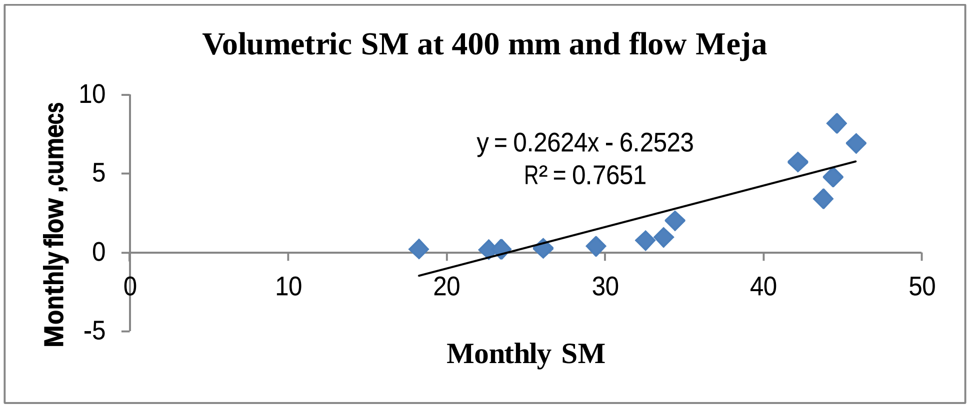

Volumetric SM at 300 mm and flow Kolu
y = 0.0052x - 0.1138
R² = 0.8035
Monthly flow, cumecs
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
10
20
30
40
50
60
Monthly volumetric SM,%

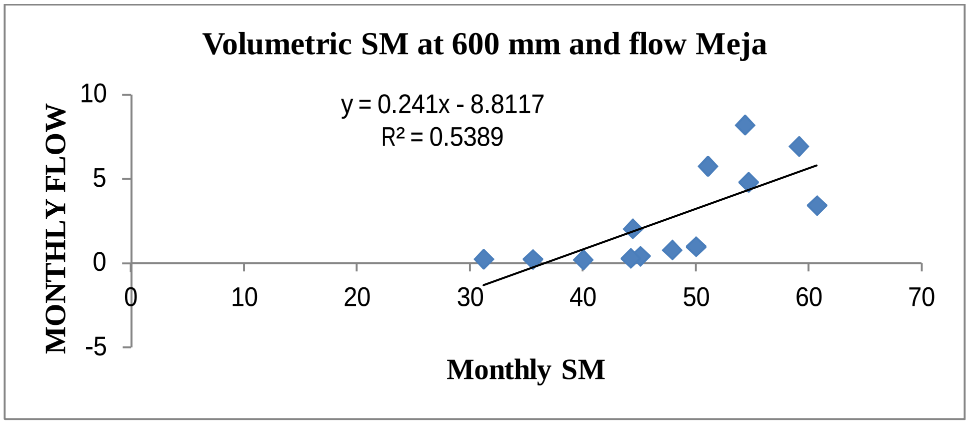

Volumetric SM at 400 mm and flow Kolu
y = 0.0046x - 0.1077
R² = 0.8359
Monthly flow cumecs
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
10
20
30
40
50
60
70
Monthly volumetric S


Volumetric SM at 600 mm and flow Kolu
y = 0.0036x - 0.12
R² = 0.4418
Monthly flow ,cumecs
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
10
20
30
40
50
60
70
80
Monthly SM,%

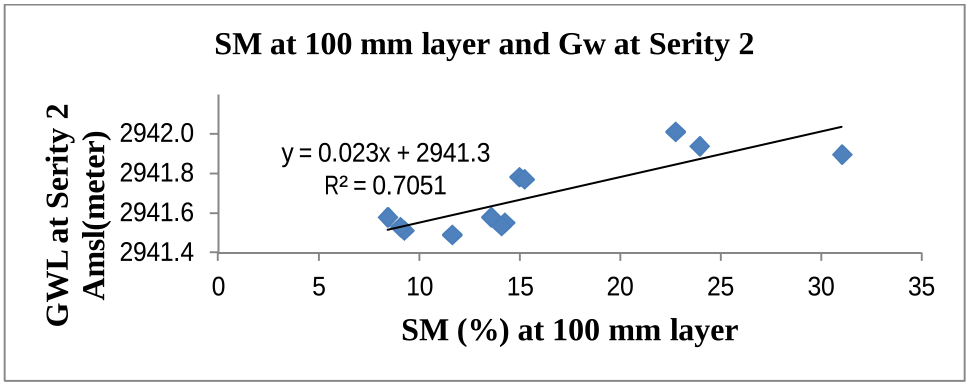

Volumetric SM at 100 mm and flow Meja
y = 0.3056x - 2.4844
R² = 0.7563
Flow ,cumecs
10
5
0
-5
0
5
10
15
20
25
30
35
Volumetric SM,%

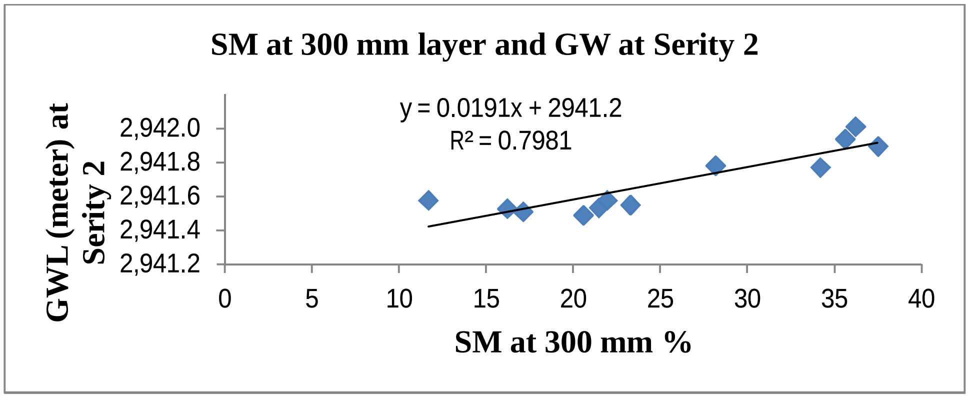

Volumetric SM at 300 mm and flow Meja
y = 0.2752x - 5.3048
R² = 0.7525
Monthly flow, cumecs
10
5
0
-5
0
10
20
30
40
50
Monthy SM,%

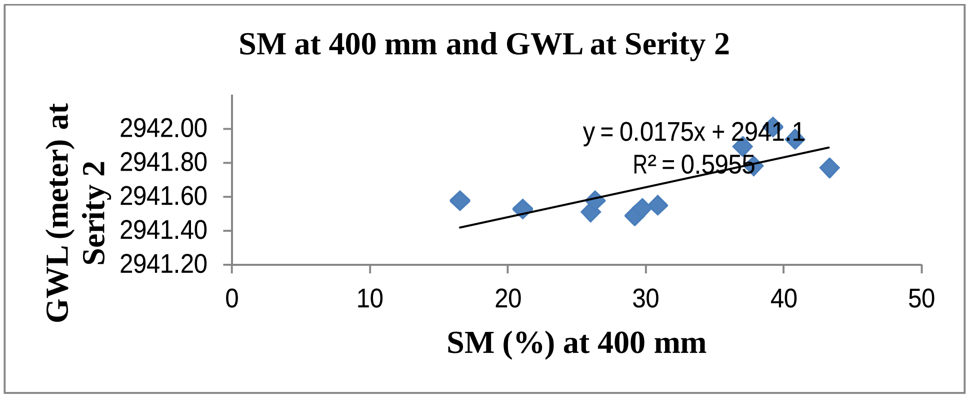

Volumetric SM at 400 mm and flow Meja
y = 0.2624x - 6.2523
R² = 0.7651
Monthly flow ,cumecs
10
5
0
-5
0
10
20
30
40
50
Monthly SM

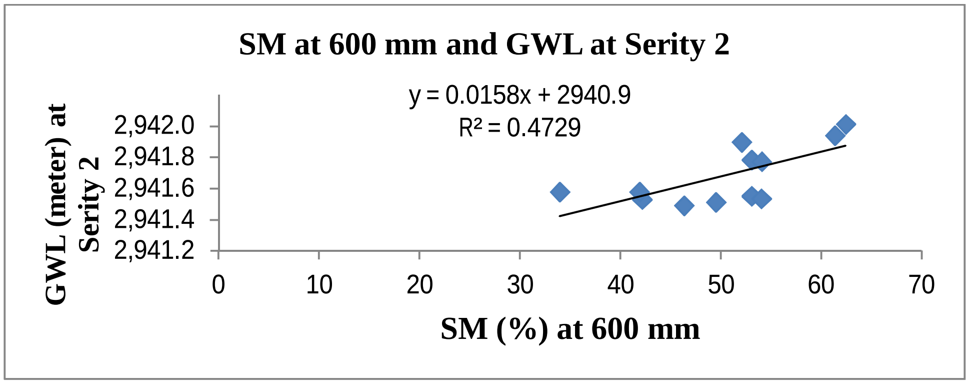

Volumetric SM at 600 mm and flow Meja
y = 0.241x - 8.8117
R² = 0.5389
MONTHLY FLOW
10
5
0
-5
0
10
20
30
40
50
60
70
Monthly SM

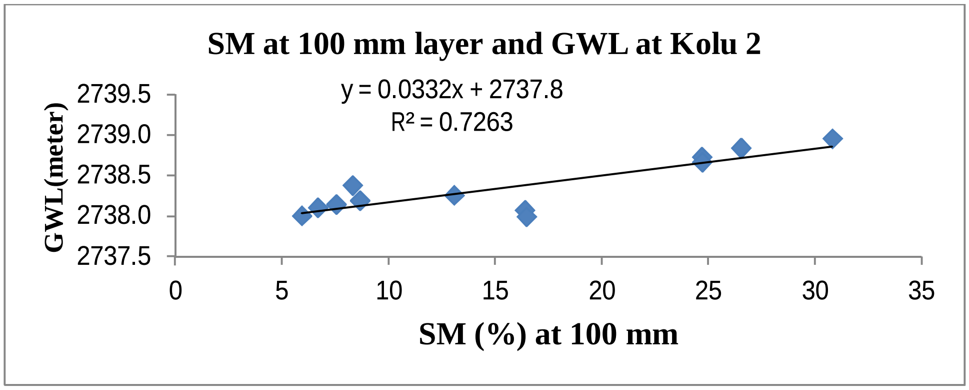
Appendex 9.Soil moisture and ground water level relationship

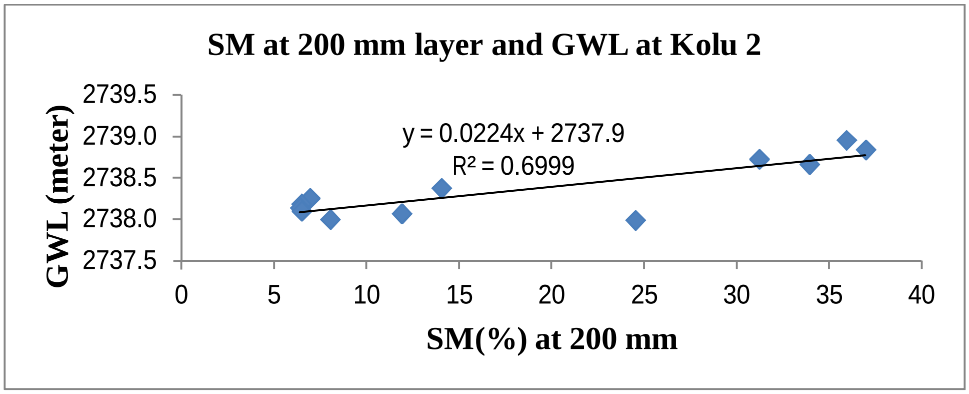


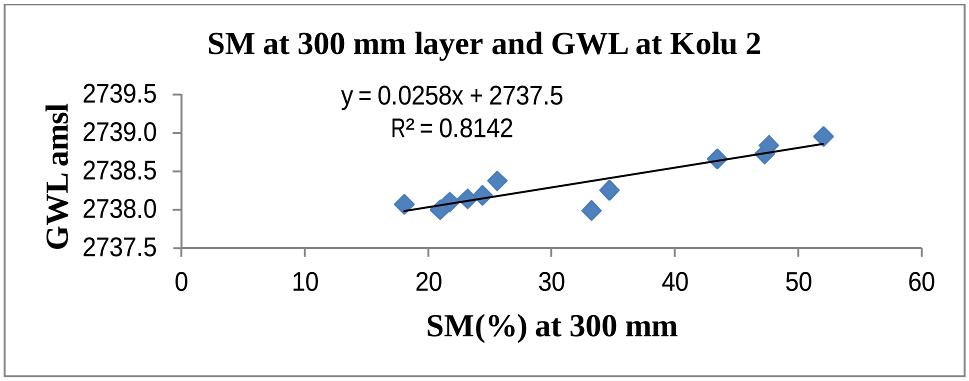


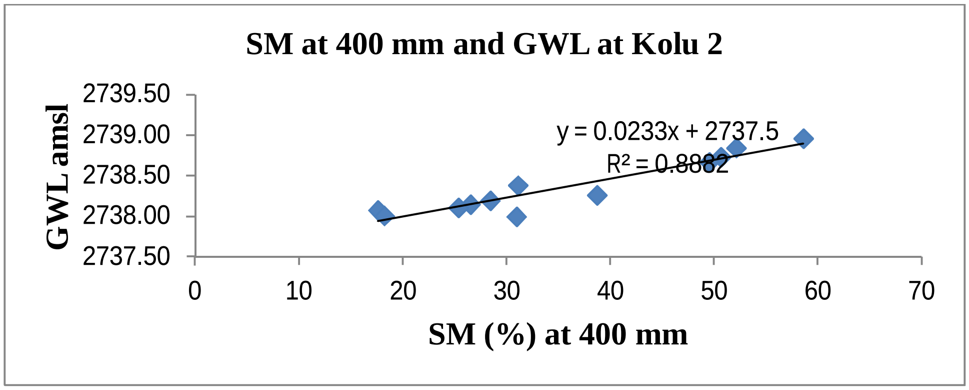


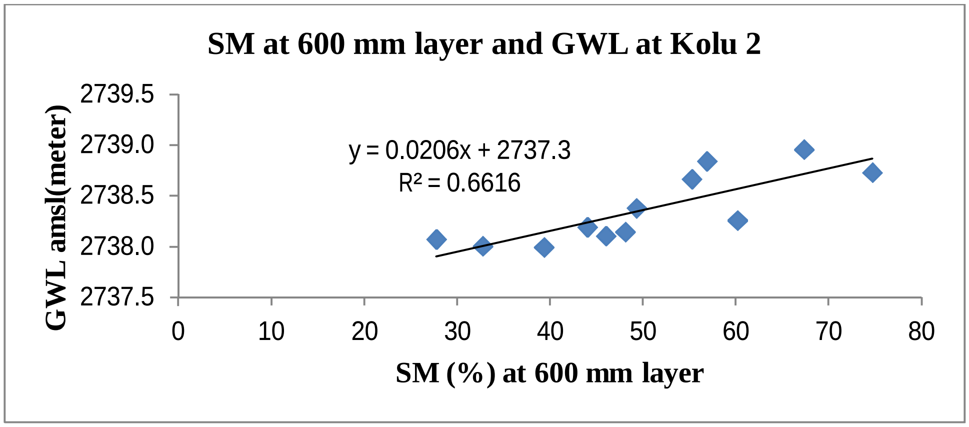


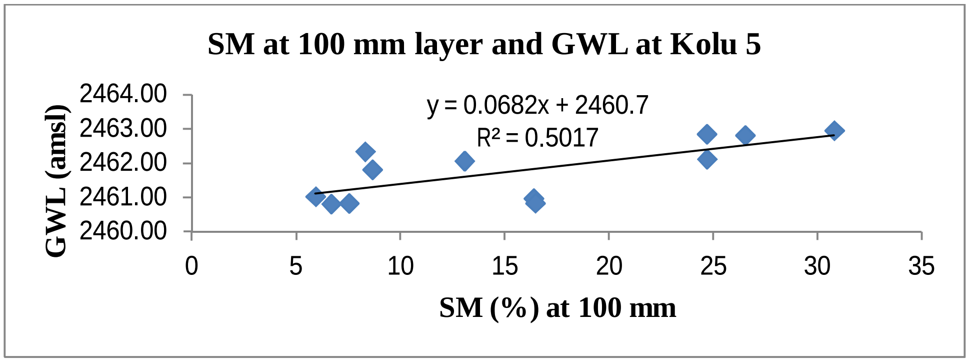

SM at 100 mm layer and GWL at Kolu 2
y = 0.0332x + 2737.8
R² = 0.7263
GWL(meter)
2739.5
2739.0
2738.5
2738.0
2737.5
0
5
10
15
20
25
30
35
SM (%) at 100 mm

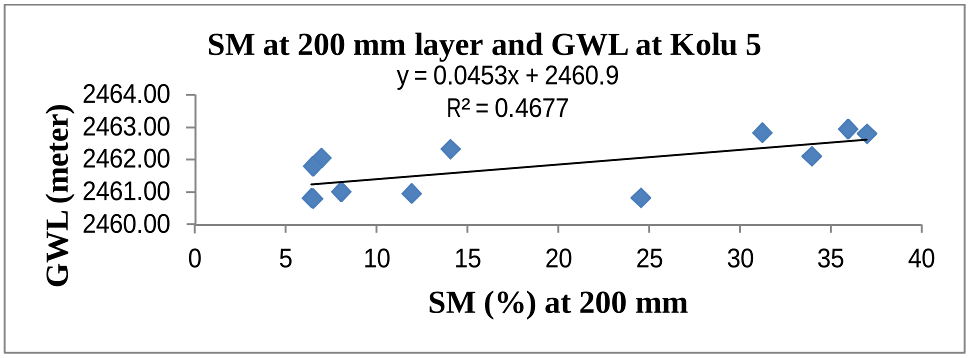

SM at 200 mm layer and GWL at Kolu 2
y = 0.0224x + 2737.9
R² = 0.6999
GWL (meter)
2739.5
2739.0
2738.5
2738.0
2737.5
0
5
10
15
20
25
30
35
40
SM(%) at 200 mm

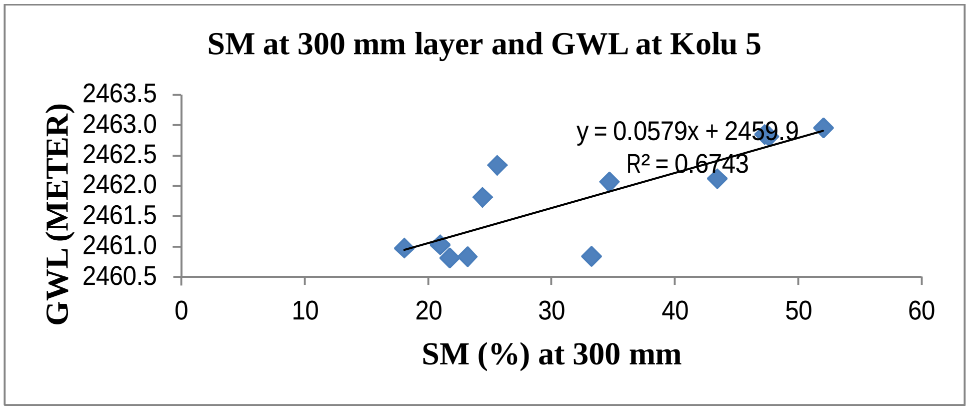

SM at 300 mm layer and GWL at Kolu 2
y = 0.0258x + 2737.5
R² = 0.8142
GWL amsl
2739.5
2739.0
2738.5
2738.0
2737.5
0
10
20
30
40
50
60
SM(%) at 300 mm

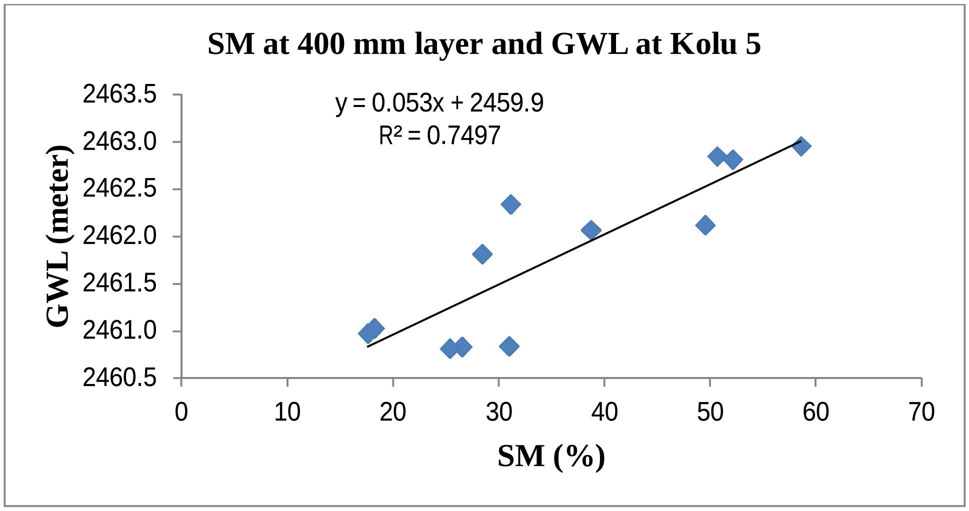

SM at 400 mm and GWL at Kolu 2
y = 0.0233x + 2737.5
R² = 0.8882
GWL amsl
2739.50
2739.00
2738.50
2738.00
2737.50
0
10
20
30
40
50
60
70
SM (%) at 400 mm

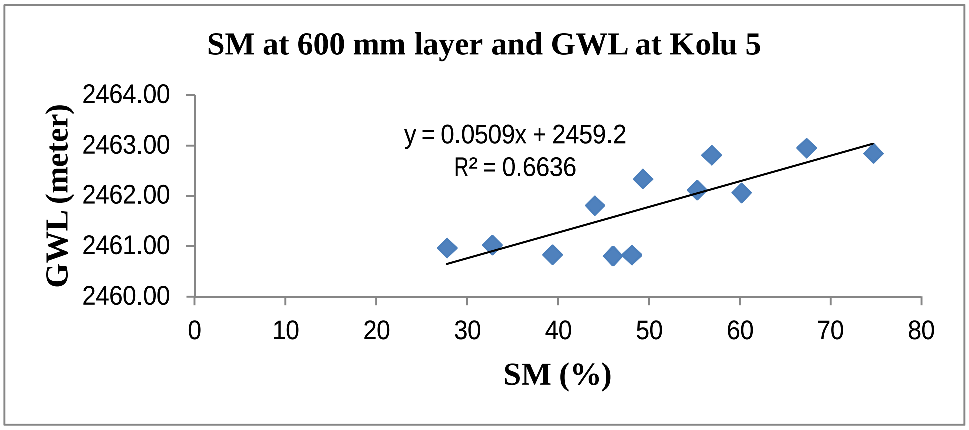

SM at 600 mm layer and GWL at Kolu 2
y = 0.0206x + 2737.3
R² = 0.6616
GWL amsl(meter)
2739.5
2739.0
2738.5
2738.0
2737.5
0
10
20
30
40
50
60
70
80
SM (%) at 600 mm layer


SM at 100 mm layer and GWL at Kolu 5
y = 0.0682x + 2460.7
R² = 0.5017
GWL (amsl)
2464.00
2463.00
2462.00
2461.00
2460.00
0
5
10
15
20
25
30
35
SM (%) at 100 mm

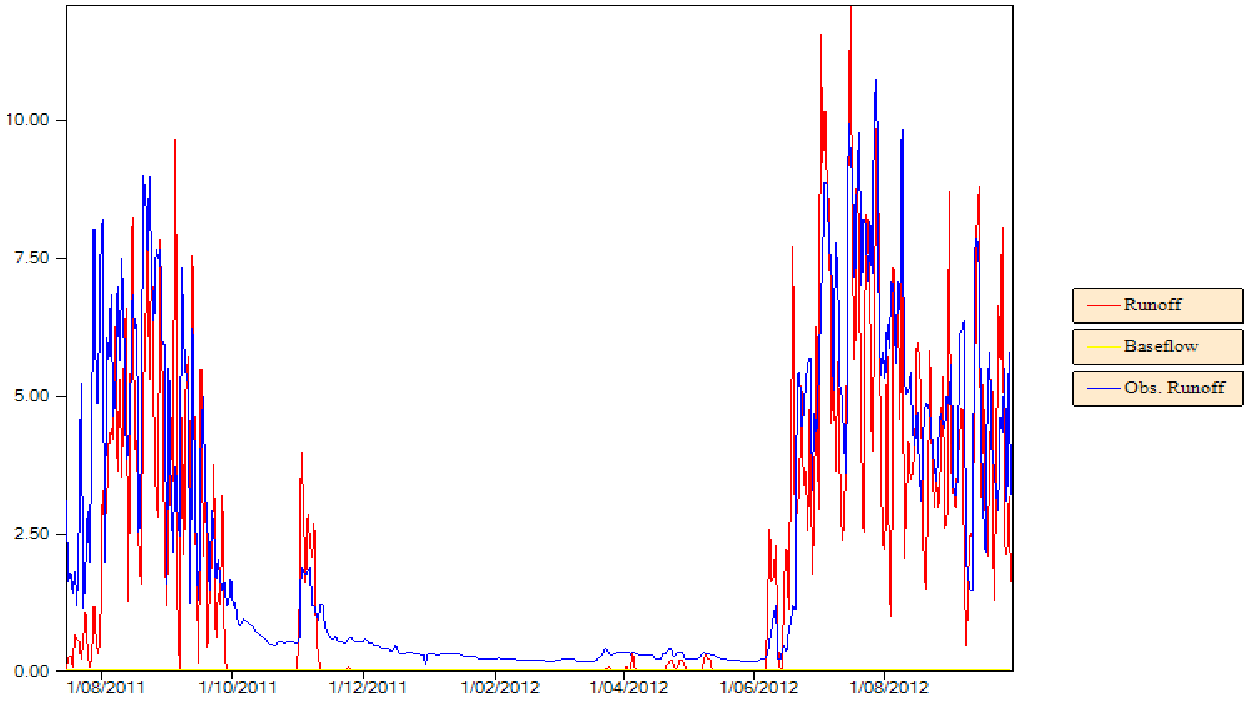

SM at 200 mm layer and GWL at Kolu 5
y = 0.0453x + 2460.9
R² = 0.4677
GWL (meter)
2464.00
2463.00
2462.00
2461.00
2460.00
0
5
10
15
20
25
30
35
40
SM (%) at 200 mm


SM at 300 mm layer and GWL at Kolu 5
y = 0.0579x + 2459.9
R² = 0.6743
GWL (METER)
2463.5
2463.0
2462.5
2462.0
2461.5
2461.0
2460.5
0
10
20
30
40
50
60
SM (%) at 300 mm

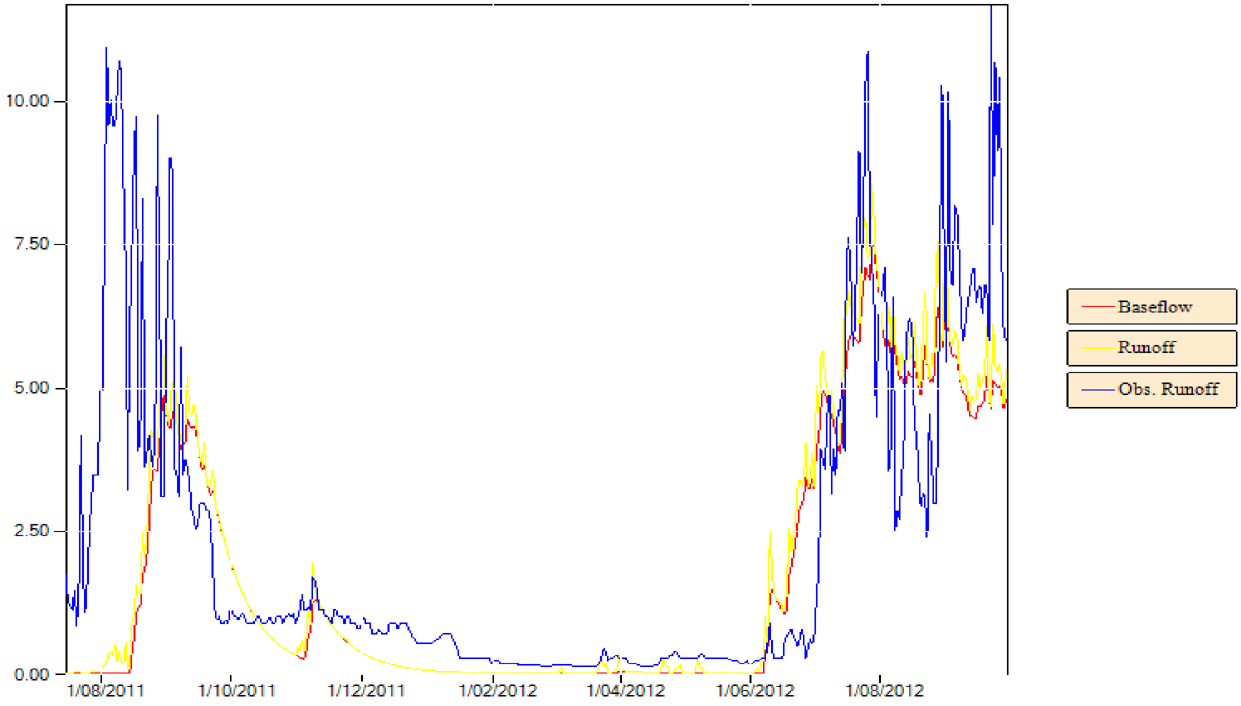

SM at 400 mm layer and GWL at Kolu 5
y = 0.053x + 2459.9
R² = 0.7497
GWL (meter)
2463.5
2463.0
2462.5
2462.0
2461.5
2461.0
2460.5
0
10
20
30
40
50
60
70
SM (%)


SM at 600 mm layer and GWL at Kolu 5
y = 0.0509x + 2459.2
R² = 0.6636
GWL (meter)
2464.00
2463.00
2462.00
2461.00
2460.00
0
10
20
30
40
50
60
70
80
SM (%)

Appendix 10a.Timeseries of observed runoff, simulated runoff and base flow using RRL SMAR model in Meja at the outlet



Appendex 10b.Timeseries of observed runoff, simulated runoff and base flow using RRL SMAR model in Kolu



STATEMENT OF AUTHOR

I declare that this thesis is my work and that all sources of materials used for this thesis have been duly acknowledged. Further I declare that when research paper is published from the thesis following sentence will appear at the bottom of the first page of the article or at the end of the article.

Name ----------------- Signature: ----------- Date------