Rainfall-Runoff Process and Groundwater Recharge in the Upper Blue Nile Basin: The Case of Dangishta Watershed

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Abstract. For planning, development and management of water resources, understanding runoff mechanism and groundwater recharge is useful especially to watershed management and groundwater use for domestic and irrigation water supply. During the period of the study, stream flow, groundwater levels, infiltration tests, rainfall and soil moisture measurements were conducted. The result from these measurement showed that saturation excess runoff were dominant in Dangishta watershed while infiltration excess runoff also contributes in some parts of the upslope area. This result was also corroborated by better correlation of (R^2 = 0.82) at the main outlet than upstream sub watershed outlet (R^2 = 0.56) using SCS runoff equation. The result from groundwater level measurement using water table fluctuations approach showed that the total annual groundwater recharge were found to be 400 mm (i.e. 24% of the total annual rainfall) which is a significant amount likely because of the interflow processes to each well.

Keywords: Dangishta watershed · Rainfall runoff mechanism · Groundwater recharge

1 Introduction

To simulate the transport mechanisms of sediment, nutrient and pollutants basic understanding of storm runoff and its mechanisms in the landscape is useful [24, 26, 27]. Important findings so far in the Ethiopian highlands are that saturation-excess surface runoff is generated in the periodically saturated bottom lands and from the degraded areas on the hill sides [14, 22]. Determination of the mechanism and runoff source areas are an important consideration in understanding where to implement watershed management [8]. The role of understanding runoff mechanism is not only useful to watershed management but also helps to identify areas of infiltration or recharge to groundwater. Any infiltrated water could lead to generation of runoff through subsurface flow either as interflow or groundwater flow to streams or as a return flow to the surface when the subsurface flow encounters a seepage face [5]. This groundwater from underground aquifers can be used for irrigation using deep and shallow wells. There is

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however little information about groundwater recharge and it's potential for irrigation in Ethiopia which is a challenge for its use for wide scale irrigation.

In order to promote an increase in agricultural production and sustainable use of groundwater, location of recharge areas, and quantification of groundwater recharge is needed which is a fundamental component in the water balance of any watershed [2].

Previous efforts to estimate ground water recharge were done in the northern semi-arid Ethiopian highlands by using MODFLOW and soil moisture balance (SMB) [31], and in the Blue Nile basin highlands using different methods such as base flow analysis, BASF model, Hydro chemical analysis (i.e. chloride mass balance) [2].

The recharge to groundwater depends on the infiltration area and overall runoff mechanism [7]. Spatial soil moisture and infiltration capacity measurement is a good indicator to understand the runoff mechanism in the watershed. The soil moisture content in the surface soil layer prior to a rainfall event strongly affects infiltration, and will thus affect the occurrence of runoff [15]. For a rainfall event of high intensity or where soils are less permeable, runoff generation might not depend on the antecedent soil moisture content of the surface soil layer. In this case, infiltration excess overland flow will be predominant. In this case more runoff is generated on the landscape and groundwater recharge is likely by infiltration of the surface runoff [13].

However, when rain storms are less intense and are falling on soils with high permeability, runoff is strongly controlled by the antecedent soil moisture of the surface soil layer [5]. In this case saturation excess overland flow will be the dominant runoff generating mechanism. On shallow depth soils located on hill slopes, rain water infiltrates and drains laterally following deep or short path to valley bottoms and rising the water level of shallow groundwater located on deep soils [22].

In order to strengthen the knowledge of runoff mechanism, runoff source areas, recharge areas and rate of recharge, Dangishta watershed in the Blue Nile Basin was selected since it is one of the location with good potential of shallow groundwater sources. This knowledge can improve identification of land management interventions to implement by locating runoff source areas. Groundwater recharge quantification would foster sustainable use of groundwater by balancing the recharge with the ground water use.

2 Study Area

Dangishta has a watershed size of 5700 ha and is found with in Dangila Woreda which is one of AGP and Feed the Future Woreda in the Amhara Regin (Fig. 1). Dangila Woreda is located in the North West highlands, in Awi zone in the Amhara region. It is located about 80 km south west from Bahir Dar, 36.83° N and 11.25° E and on average 2000 m above sea level. Brantie is located within Blue Nile Basin and drains to Gilgel Abay River that drains to Lake Tana. Brantie River is the river draining the watersheds. The climate of the region is moist subtropical with little annual temperature variation through high diurnal variation. The climate is sub-tropical with average annual rainfall of about 1600 mm but varies between 1180–2000 mm where the rain starts in the middle of June and stops at the beginning of October. The elevation of the watershed is within the range of 2036 to 2440 m a.s.l.

The geology of Dangishta watersheds are predominantly quaternary basalt and trachyte above ecocene oligocene basalts and trachyte including massive, fractured and vescular basalts, weathered basalt regolith overlain by red soils which is more litic and clayey with depth and other superficial materials underlying the flood plain which are often browner in color. The soils in Dangishta watersheds are Regosols accounts for 47%, Alisols for 16% and Nitosols and Vertisols for 13%.

Agricultural land is the main land use in the watershed covering 60% of the area. The main crops produced in the watershed are teff, millet, maize, chat and vegetables. Soil sample taken within the watershed show that the textural classification of soils in Dangishta to be clay and heavy clay. Most of the local people in Dangishta have wells use for irrigation, domestic use and livestock feeding.

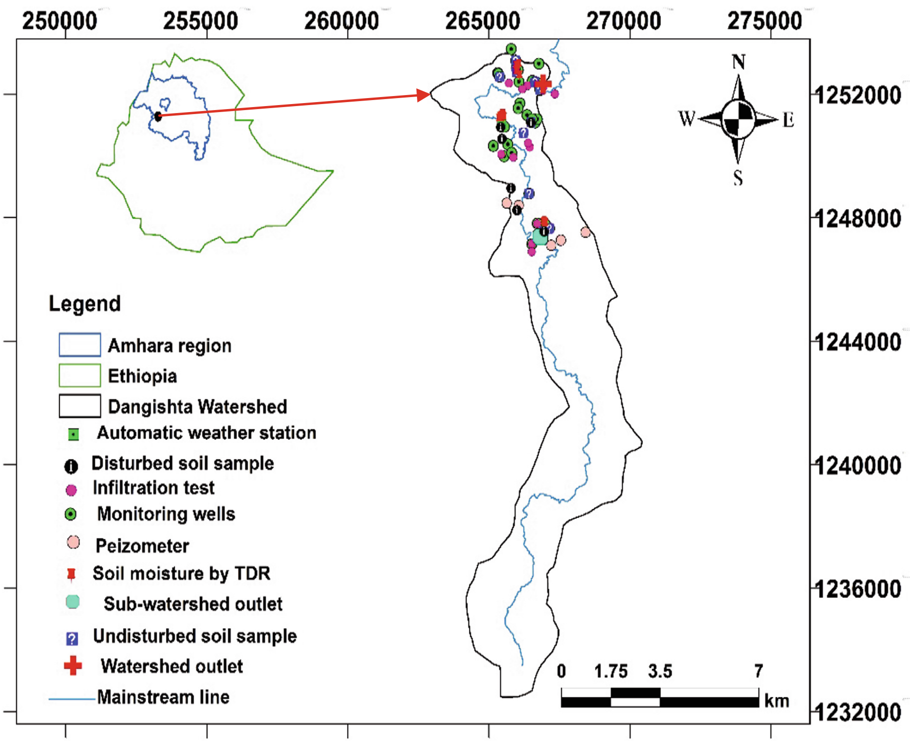

Fig. 1. Dangishta watershed

3 Materials and Methods

3.1 Data and Methodology

Field work as part of the Innovation Lab for Small Scale Irrigation funded by Feed the Future program of USAID was started during December 2014 after the rainy season in Dangishta Watershed. Rainfall, flow depth at sub watershed outlet and total watershed outlet, infiltration tests before and during rainy season, soil moisture by TDR and shallow ground water levels were monitored starting from December 2014 to end of October 2015.

Rainfall Measurement and Effective Rainfall Computation: An automatic weather station was installed in March 2015 to measure climatic parameters at 10 min interval. Effective rainfall was then be computed by subtracting the reference evapotranspiration from the total precipitation [6, 28]. The reference evapotranspiration for the entire watershed was estimated by the Penman- Monteith method [12, 32] using climatic data from the automatic weather station installed in the watershed.

Infiltration Measurement: Soil infiltration rates were measured at 19 different points throughout the watershed using 30 cm diameter single ring infiltrometer before and during rainy season of 2015 respectively. The steady state infiltration rates were then compared with the probability of exceedance of rainfall intensities to evaluate the runoff generation mechanism (Fig. 2).

Table 1. Number of repetition for each land use at different topography during infiltration measurement in the rainy season.

Land use	Upslope	Midslope	Downslope
Maize	3	2	1
millet	1	n.a	1
Teff	2	1	1
Eucalyptus	1	1	1
Vegetable	n.a	n.a	1
Grazing	1	1	1

Soil Moisture Measurement: To support determination of runoff generating mechanism in Dangishta watershed, soil moisture measurements were taken once every week using TDR at the dominant land uses (i.e. maize, millet, teff, eucalyptus and grazing land) at upslope, midslope and downslope topographic locations. For this study, moisture status of the surface soil layer was monitored using 20 cm long TDR roads. The TDR measurements was calibrated by gravimetric method. The soil field capacity is an indicator used in this study to determine how wet or dry the surface soil layer was prior to rainfall events and also throughout the study period.

Stream Flow Measurement and Base Flow Separation: Staff gauges were installed in May 2015 at the watershed outlet to be able to read the water level in the stream.

Stream flow discharge was measured from December 22, 2014 up to November 10, 2015 and the stage discharge relation was developed and finally Bflow base flow filter program (http://swat.tamu.edu/software/baseflow-filter-program/) [1] was used to separate the base flow from the stream flow. In this method, the interflow component is included in the surface runoff.

Runoff Depth and Determination of Runoff Coefficient: The runoff depth in the watershed was computed by dividing the runoff volume by the watershed area. To show the relation between rainfall and runoff for different months in the rainy period, runoff coefficient i.e. ratio of runoff (mm) to rainfall (mm) was determined. The result was compared for the different months in the rainy season.

SCS Runoff Equation: The watershed runoff response for the rainfall events was simulated using SCS runoff equation [20, 23, and 29] to support determination of runoff mechanism using Eq. 3-1.

$$Q = \frac{p_e^2}{P_e + S_e} \qquad (3-1)$$

Where, P_e is the effective rainfall in mm and S_e is the available watershed storage after runoff starts in mm. The simulated runoff from Eq. 3-1 using the developed Se value was plotted against the measured runoff and both R^2 and Nash Sutcliff Efficiency (NSE), [17] were used to indicate how well the plot of observed versus simulated data fits the 1:1 line.

Determination of Specific Yield: In this study, specific yield was determined by taking soil samples one from each topographic positions (i.e. Upslope, Midslope and Downslope) using two methods namely: by means of a pressure plate and by means of standing tubes of 10 cm in diameter and 50 cm height and finally average specific yield was taken. The standing tube approach determines the specific yield from the gravimetric moisture content difference of the soil at saturation and the moisture content retained by the soil sample in a standing tube after it was left to drain from saturation for two weeks without evaporation [10, 18]. In the pressure plate approach the moisture content difference between soil at saturation and soil after draining when a pressure of 0.33 bar was applied was taken to determine the specific yield.

Recharge Estimation: The amount of groundwater recharge in the watershed is a function of soil surface characteristics i.e. vegetation cover, soil type, soil surface condition and antecedent soil moisture content [9, 19, 21]. To determine the amount of annual recharge in the watershed groundwater level was monitored daily in the main rainy season of 2015. A total of 36 wells were monitored. Among the various methods used to estimate recharge [19], the water table fluctuation method was used for this study. Wells selected for water table monitoring in Dangishta are in unconfined aquifers. Recharge was calculated as:

$$R = S_y * \frac{dh}{dt} = S_y * \frac{\Delta h}{\Delta t} \qquad (3-2)$$

Where S_y is specific yield, h is water table height and t is time. For detail description of the method, [9] can be referred.

4 Results and Discussions

4.1 Runoff Generating Mechanisms Analysis

Infiltration Capacity and Rainfall Intensity: The median and average infiltration rate during dry period was 180 mm/h and 217 mm/h respectively but in the rainy season median and average infiltration rates were 72 mm/h and 86 mm/h respectively. In the valley bottoms where the soils get saturated, lowest infiltration rates of 6 mm/h was observed, which was consistent with similar studies conducted in the Ethiopian highlands where infiltration rates are limited in saturated soils [4, 25]. In general, infiltration rates were lowest in the grass lands. This is due to the compaction in these areas caused by free grazing of animals [16] and saturation from the shallow groundwater levels [26]. The rate of infiltration decreased in the rainy season when compared to the dry season measurements due to the increase in soil moisture in the soil profile that decreases infiltration of water into the soil. The difference in infiltration is similar with the studies conducted in Debre Mawi, Anjeni, Andit Tid, Maybar [6, 14, and 25]. From the rainfall recorded by automatic rain gauge at 10-min interval a total of 606 rainfall events were recorded during 2015 rainy period having a variation in rainfall intensities between 1.2 mm/h and 104 mm/h with an average of 6.8 mm/h. The probability of exceedance of each of the rainfall intensities was computed and plotted with the median infiltration capacity of the soil to compare the rainfall intensities with the infiltration capacity. The median is the most meaningful term to describe infiltration capacity of the watershed [3] (Table 2).

Table 2. Average steady state infiltration during the rainy season for different land use (mm/h).

Land use	Upslope	Midslope	Downslope
Maize	105	180	144
millet	60	Not taken	72
Teff	48	60	192
Eucalyptus	12	90	36
Vegetable	n.a	n.a	72
Grazing	24	6	n.a

As shown Fig. 2, during the rainy period the median infiltration rate was exceeded by the rainfall intensity almost 2.5% of the time. This shows that the most dominant runoff mechanism in the watershed during this period was saturation excess, but there were some portions of the watershed either in the upslope or downslope where the runoff contribution is due to infiltration excess as minimum infiltration rate during wet season was exceeded by rainfall intensity 25% of time.

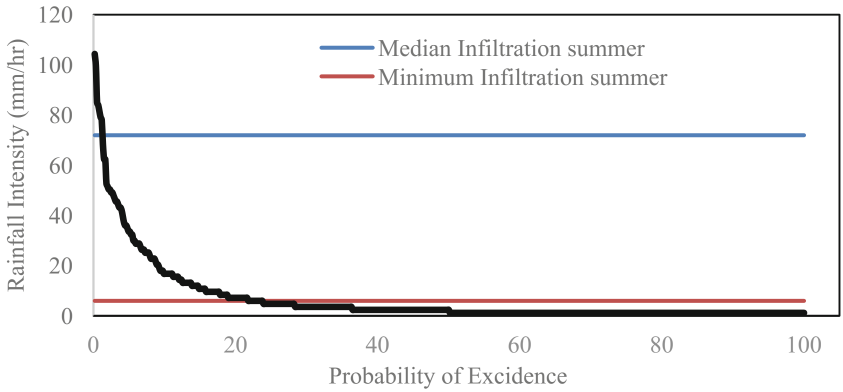

Fig. 2. Plot of the exceedance probability against ten minute rainfall intensity and steady state infiltration capacity

Soil Moisture: The moisture status of the upper 20 cm of soil was measured at different landscapes (upslope, midslope and downslope) portions of the watershed by considering maize, millet, eucalyptus, teff and grazing land as the dominant land uses. The measurement shows that the soil moisture status of the soil was dependent on the type of land use. As shown in Fig. 3, the soil moisture content was closer or below to the field capacity in various land uses in the upslope of the watershed. Rainfall raised the soil moisture content thus reducing space for water to infiltrate hence contributing to surface runoff (i.e. saturation excess flow). Any incoming precipitation on these areas produces runoff fast. In areas were soil moisture content was below field capacity but runoff was observed in the upslope areas, it suggests that infiltration excess was playing a role in runoff generation.

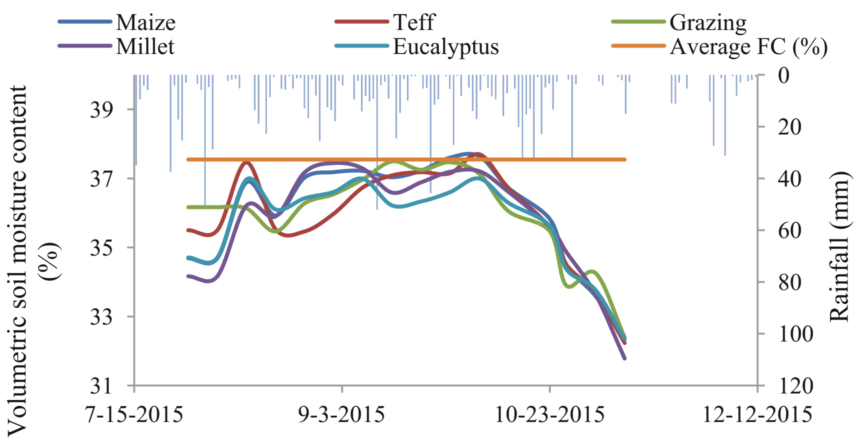

Fig. 3. Plot of soil moisture (vol %) for each of the land uses in the upslope area.

The minimum infiltration rate during rainy season in Fig. 2 showed that, 25% of the time the rainfall rate exceeds the infiltration rate which indicates there were places (for example in the upslope area as seen above) in the watershed which contributes infiltration excess runoff which support the above discussion on runoff generation mechanisms

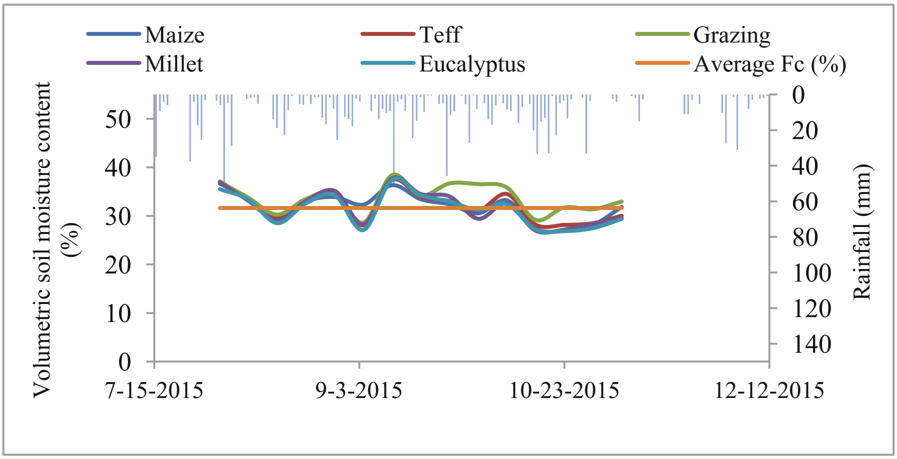

Fig. 4. Plot of soil moisture (vol %) for each of the land uses in the downslope areas.

The moisture status of the soil in the midslope and downslope areas shows similar trends during the rainy season (Fig. 4). The soil moisture content was greater than the field capacity for most of the time indicating that the soil was saturated and the main runoff mechanism for the measured runoff for these topographic positions was saturation excess.

Midslope and downslope areas receive water from both rainfall and both runoff and lateral subsurface flow from upper slopes [26]. As a result soil moisture content in upslope was below field capacity while in the mid and downslope areas, the soil moisture was above field capacity almost throughout the rainy season.

4.2 Base Flow Separation and Runoff Coefficient

During the rainy season both base flow and surface runoff contributes to stream flow which were determined from base flow separation techniques as shown in Fig. 5. Runoff coefficients at two outlets stations were then calculated for rainy period of 2015 for June, July, August and September (Fig. 6). An increase in runoff coefficient in Fig. 6 for the main rainfall season showed the dominance of saturation excess runoff mechanism because the soil surface gets saturated as the rains continues and any further rainfall became runoff as shown by the increasing runoff coefficients for the rest of the months. The result was similar with the findings of [28].

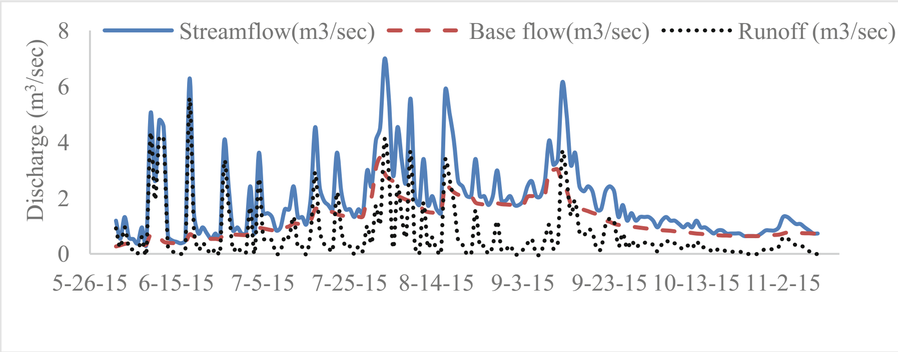

Fig. 5. Separation of stream flow from base flow at total watershed outlet of Dangishta

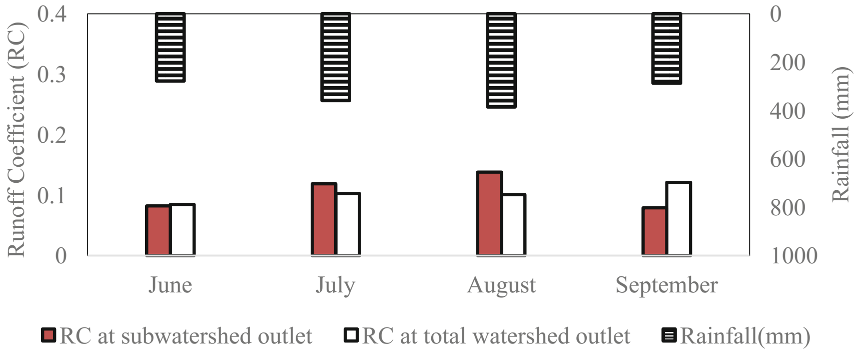

Fig. 6. Runoff coefficient at outlets of Dangishta watershed

4.3 SCS Runoff Equation

The measured runoff was used to calibrate the effective available storage, S_e, for Dangishta watershed. For the SCS runoff Eq. 3-1, weekly effective rainfall was computed as the difference between weekly rainfall and weekly reference evapotranspiration. The value of S_e was adjusted such that the simulated weekly runoff values from Eq. 3-1 have the closest fit to the measured weekly runoff. Better correlation was observed for the watershed at the outlet for effective available watershed, S_e, of 350 mm than upstream sub watershed outlet having effective available watershed, S_e, of 400 mm (Fig. 7).

The sub watershed at the upstream of the watershed loses water by lateral flow to the downstream. As a result the downstream remains saturated during the main rainy season which showed a high Se (i.e. 400 mm) value at sub watershed. Similar finding is reported at Debre Mawi watershed [29]. The better correlation at the total watershed outlet than upstream sub watershed outlet corroborates the fact that saturation excess runoff mechanism dominates while infiltration excess contributes in few cased for the upstream sub watershed.

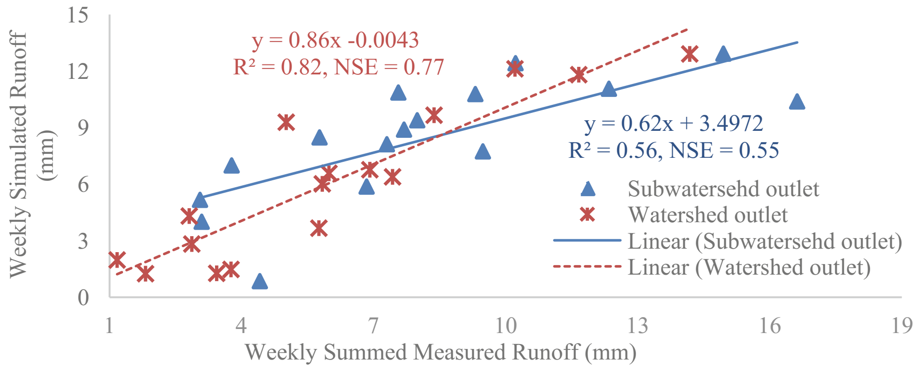

Fig. 7. Plot of measured cumulative runoff vs. cumulative runoff estimated by SCS at watershed outlets.

4.4 Groundwater Recharge

To use the water table fluctuation approach, an estimate of specific yield is important. Disturbed soil sample from three wells, one from each topographic location were taken to determine the average specific yield which is found to be approximately 0.089 which is equivalent with findings of [30] (Tables 3 and 4).

Table 3. Specific yield determination by pressure plate

Soil moisture at saturation (vol %)	Soil moisture at 0.33 bar pressure (vol %)	Specific yield (%)
50	37.5	12.5
51.1	48.6	2.4
56.8	44	12.7
Average		9.2

Table 4. Specific yield determination by standing tube

Soil moisture at saturation (vol %)	Soil moisture after draining (vol %)	Specific yield (%)
51.63	43.37	8.26
54.50	53.63	0.87
55.46	43.37	12.09
60.44	53.63	6.80
61.28	42.25	19.03
57.84	53.64	4.19
Average		8.54

Figure 8 showed a rise in shallow ground water level during the rainy season and that the water level starts to fall when rainfall declined. The amount of recharges for each of the wells were calculated by water table fluctuation method as discussed in the methodology section. The average total annual recharge was found to be 400 mm which is 24% of the annual rainfall. Spatially, there is a recharge of 380.6 mm in the upslope and 501.1 mm in the downslope. This estimate is within the range of 0 to 400 mm per year recharge reported by [11] for the Ethiopian high land.

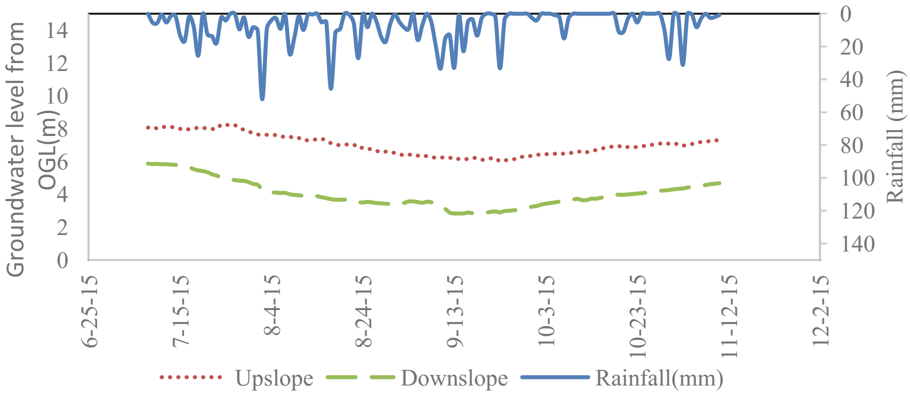

Fig. 8. Trend of average water level fluctuation for monitoring wells located upslope and downslope where the top line is the average of 5 wells and the bottom line is the average of 20 wells.

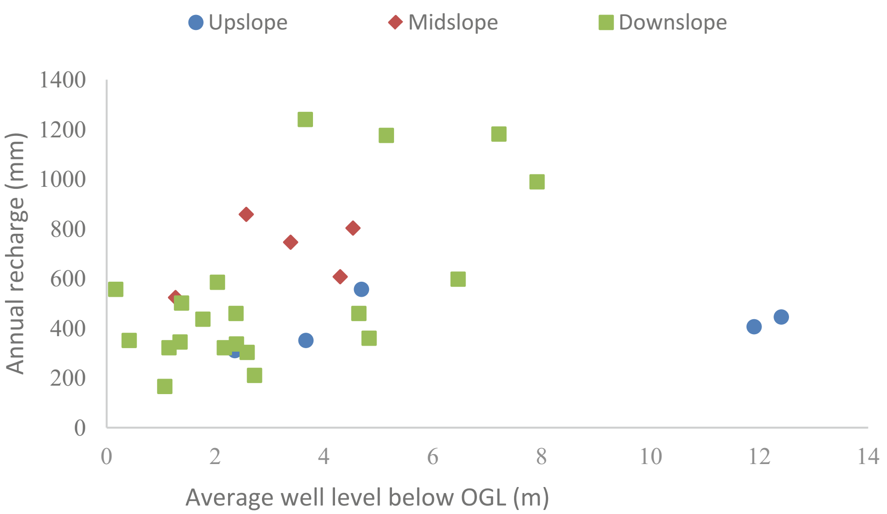

Fig. 9. Annual recharge of all monitoring wells in the watershed where OGL is original ground level

A study conducted by [30] reported a higher recharge amount in Dangishta using water table fluctuation method even if the sampling wells do not represent the spatial distribution in the watershed. This shows that a significant amount of groundwater exists which can be used for small scale farming activities using small scale irrigation technologies. The result also shows the downslope parts of the watershed is a potential area than the upslope part of the watershed to irrigate during dry period from shallow groundwater. As shown in Fig. 9 the maximum and minimum recharge is 1239 mm and 165 mm respectively.

5 Conclusions

Generally the dominant runoff mechanism in Dangishta watershed was found to be saturation excess but it does not mean infiltration excess runoff was not occurring. The minimum infiltration rate and the soil moisture content in the upstream part of the watershed shows that infiltration excess was also occurring in the upslope parts of the watershed. This was supported by the calculated runoff coefficient, SCS runoff equitation and soil moisture measurement. An increase in runoff coefficient and better correlation of measured runoff with SCS at the total watershed outlet supports the findings that saturation excess runoff was the dominating runoff generating mechanism in the watershed.

The total amount of recharge in the watershed was found to be 400 mm which was 24% of the annual rainfall, which is significant groundwater storage for irrigation and domestic water supply during the dry period.

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