Revisiting Storm Runoff Processes in the Upper Blue Nile Basin: The Debre Mawi Watershed

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Abstract

There is a scientific knowledge gap in locating runoff producing areas and their spatial variation in the landscape of the Ethiopian highlands and the Upper Blue Nile Basin. Identification of these spatial variations and runoff generation mechanisms is needed for optimum implementation of conservation measures. In many cases poor performance of soil and water conservation practices for erosion control can be traced back to non-optimum placement. A 95 ha watershed in the headwaters of the Blue Nile basin was used to investigate the runoff processes using the 2010 and 2011 monsoon, precipitation and runoff measurements made at sub-watersheds and watershed outlets. Perched water table heights and infiltration rates were also recorded. With the median infiltration rate exceeded by the rainfall intensity only 3% of the

time the dominant runoff generation mechanism is found to be a saturation excess runoff process. Using the saturation excess interpretation of the Natural Resources Conservation Service Curve Number method, the seven day cumulative runoff fits better to the input as 7-day cumulative effective rainfall amount than to the rainfall intensity. In a monsoon climate where the watershed is dry at the onset of the rainfall, the saturated areas and the runoff coefficients varied in the landscape (upslope locations vs downslope locations) as the rainy season progresses and available water storage adjusts.

Key word: saturation excess overland flow; perched groundwater table; Ethiopian highlands; SCS runoff equation

1. Introduction

Understanding the storm runoff producing mechanisms and identifying locations where runoff is generated in a watershed are fundamental in simulating the transport mechanisms of sediment, nutrients and pollutants. Proper simulation of these mechanisms are lacking partially because of the high data requirements for each model, while more importantly the complex interactions between the different processes at the watershed scale also pose limitations (de Vente and Poeson, 2005). The applicability of traditionally accepted and modeled concepts of runoff generation in humid conditions has been questioned over the past several decades (Dunne and Black, 1970). Previous efforts to predict runoff and erosion processes in the Ethiopian highlands (Zeleeke, 2000; Haregeweyn and Yohannes, 2003; Mohammed *et al.*, 2004; Setegn *et al.*, 2008; Setegn *et al.*, 2011) have been based on infiltration excess runoff mechanisms (Hortonian flow) without thoroughly investigating the possibility of other governing hydrologic processes (Steenhuis *et al.*, 2009). Indeed, absence of empirical evidence demonstrating sheet flow on

1 hillsides in the presence of high infiltration rates in soil can cast doubt on the usefulness of
2 Hortonian infiltration theory for analyzing the majority of storms under such conditions (Dunne
3 and Black, 1970). Over the past decades the soil and water conservation practices in these
4 highland watersheds have not been effective (Herweg and Ludi, 1999; Bewket and Sterk, 2002)
5 as the permissible values of soil loss are still being exceeded in the Blue Nile basin (Easton *et al.*,
6 2010) and average sediment concentrations have not decreased in streams (Tebebu *et al.*, 2015).

7
8 There is a large effort in the Ethiopian highlands to parameterize land use or vegetation cover to
9 improve modeling of the transport of sediment, nutrient, and pollutants (e.g., Setegn, 2008, 2010;
10 Yesuf *et al.*, 2015). These studies assume inherently that infiltration in the soil is limiting and
11 that by changing land use the consequent infiltration characteristics of the soil and thus runoff
12 will change (Bayabil *et al.*, 2010; Tebebu *et al.*, 2015). For example in an interesting paper,
13 Zenebe et al. (2013) attribute the increasing runoff coefficients to the vertic properties of some
14 soils allowing high infiltration at the beginning of the season when the cracks are open but then
15 very little infiltration after the cracks close. While these efforts contribute to understanding of the
16 rainfall-runoff relationships, more improvements may be found by refocusing on the other
17 fundamental governing hydrologic processes since several studies do not find a direct
18 relationship with vegetative cover (Balthazar *et al.*, 2013; Tebebu *et al.*, 2010). Recent analysis
19 on hydrological data from three experimental watersheds established by the Soil Conservation
20 Research Program (SCRIP) (Anjeni, Andit Tid and Maybar) showed that storm runoff is mainly
21 generated by saturation excess runoff (Liu *et al.*, 2008; Collick *et al.*, 2009; Steenhuis *et al.*,
22 2009; Bayabil *et al.*, 2010; Engda *et al.*, 2011; Tilahun *et al.*, 2013, 2014). Both Bayabil et al.
23 (2010) and Engda et al. (2011) found that infiltration rates in Maybar and Andit Tid watersheds

are rarely exceeded by rainfall intensities and most rain falling on the hillsides flowed downhill as lateral shallow subsurface flow over the hardpan. Runoff generation and flow patterns can have especially important implications for erosion and environmental management. Outside of the SCRP experimental network Tebebu et al. (2010) and Zegeye et al. (2010) investigated gully and upland erosion processes in the Debre Mawi watershed. They showed that erosion from the wet down slope areas were greater than from the drier upland fields.

Modeling of hydrology based on saturation excess runoff mechanisms in the Ethiopian highlands (Steenhuis *et al.*, 2009; Easton *et al.*, 2010; White *et al.*, 2011; Tilahun *et al.*, 2013b) performs better at a shorter time scale than the infiltration excess based models. In particular, while the customary SWAT approach in the Ethiopian highlands uses the Natural Resources Conservation Service Curve Number (CN) method (Betrie *et al.*, 2011, Van Griensven *et al.*, 2012) based on producing runoff that exceeds the infiltration capacity of the soil, Easton et al. (2010) instead employ SWAT-WB which is an approach that simulates the variable source area hydrological phenomenon resulting in a better performance with a greater Nash Sutcliffe Efficiency (NSE). The semi-distributed water balance model (Steenhuis *et al.*, 2009) that divides the watershed into three areas (i.e., saturated, degraded, and infiltration zones) representing the common landscape in the Ethiopian highlands was able to capture the hydrologic processes in the area (Tesemma *et al.*, 2010; Tilahun *et al.*, 2013a, 2013b, 2014). Since in the SCRP watersheds the discharge was only measured at the outlet, the distribution of runoff in the watershed was not known and the locations of the conceptualized runoff producing areas could not be verified accurately. Precise information concerning runoff depths and location of these runoff producing areas is important for designing effective soil and water structures. The objective of this study is, therefore, to

quantify the spatial variation of runoff and to specify the extent of the saturated areas based on the variable source interpretation of NRCS method (Steenhuis *et al.*, 1995).

The Debre Mawi watershed with its nested sub-watersheds was selected, because it was selected as a demonstration watershed by the Amhara Regional Agricultural Research Institute (ARARI). ARARI installed a weir at the outlet of this watershed and nested sub-watersheds were then established by installing more weirs for this study to monitor flow and sediment. In addition, ARARI characterized the soils and facilitated bus transportation from Bahir Dar to the site. Initial collaboration was motivated by the need to find out more about the deep gullies that were advancing uphill in the watershed and the conditions enabling this.

2. Material and Methods

The present study investigates the differences in runoff processes from the upland and lowland areas through field measurements of runoff from four nested locations and at the outlet of the watershed. Additionally, the perched water tables along six transects, rainfall amounts and intensities in the center, and infiltration rates throughout the watershed were measured. These data are then used to quantify the spatial variation of runoff and to specify the extent of the saturated areas.

2.1 Site Description

The Debre Mawi watershed research site, named after the Kebele Debre Mawi in Yilmana-Densa Woreda (district), covers a total area of 523 ha. It is situated 30 km south of Bahir Dar adjacent to the Bahir Dar-Adet road at 37°22' East and 11°18' North (Figure 1) in the western plateau of the Ethiopian highlands at the northern source region of the Blue Nile River. A sub-watershed of approximately 95 ha was selected for this study and is located in the upstream portion of the

whole watershed. Its slope ranges from 1 to 30% and topography ranges from 2,212 m above sea level (m.a.s.l.) near the outlet to 2,306 m.a.s.l. in the southeast.

[Figure 1]

The watershed is underlain by shallow, highly weathered and fractured basalt overlain by dark brown compacted clay, then by light brown wet and sticky clay soil and then finally by black clay and organic rich soil sequences (Abiy, 2009). The thickness of the clay varies from shallow and highly eroded in the upper sections to deep in the valley bottoms. The fractures are highly interconnected with limited clay infillings. Intrusive lava dykes are seen across the stream nearly perpendicular to the flow direction of the watershed (Figure 1) interrupting the connection in fissures and giving rise to several springs and periodically saturated areas. The dominant soil types in the watershed are Nitisols, Vertisols and Vertic Nitisols. Nitisols (locally, *Dewel*) are found in the upper part of the watershed. This is a very deep, volcanic derived well-drained permeable red clay loam soil which is very productive. The Vertisols (locally called *Walka*) are black and cover the lower slope positions. This soil forms deep wide cracks during the dry phase of the monsoon, and it swells and develops stickiness during the rainy period. Vertic Nitisols (locally known as *Silehana*) are located mid-slope between the Vertisols and Nitisols. It is a reddish-brown well-drained permeable soil with high moisture retention and forms cracks when dry. It is well suited for tef production.

Most of the upper (slope of 0 to 6%) and middle area (slope of 6 to 27%) of the watershed (Figure 2a) is used for cultivation. The lower watershed with slopes of 0 to 6% (Figure 2b) is usually saturated during the rainy season and covered with grass. These lower grassy areas of the watershed serve as grazing land. Sparse shrubs are located at the middle section where many of the dikes are located, and where it is relatively steeper and difficult to plow. Fields at the upper

1 and middle are continuously cropped. Cereal-plow cultivation is the dominant land use and most
2 of the cultivated fields are usually planted with tef, wheat, maize, and barley. Finger millet,
3 lupine (particularly, *Lupinus albus*) and grass pea are also the common crops grown in the area.

4 [Figure 2]

5 Different level rectangular weir notches were constructed from cinderblocks and steel bars at
6 four locations as shown in Figure 1 and a masonry weir at the outlet was constructed by the Adet
7 Research Center in 2007. Two weirs were constructed upstream of the watershed outlet to
8 monitor upland runoff and the other two were placed at the inlet and outlet of a tributary of a
9 stream that began as a gully. These weirs created four sub-watersheds. Sub-watersheds from
10 each weir were defined using GPS tracking in the field. The size of the sub-watershed areas are
11 8.8, 10, 6.4 and 10.3 ha at weir 1, 2, 3 and 4, respectively. The surface area of the sub-watersheds
12 was used to calculate runoff depth at the outlet of each of the watersheds.

13
14 The slopes of the sub-watersheds range from 0.6 to 16% with elevation ranging from 2,233 to
15 2,286 m.a.s.l. All sub-watersheds located at the upper parts of the slopes are flat or gently
16 sloping and dominated by agriculture. The wet bottom area of the sub-watershed at Weir-1 was
17 covered by deep Vertic Nitisol and grass during the two rainy seasons (2010 and 2011). It was
18 saturated during the last part of the rainy phase of the monsoon. This part was not cultivated and
19 used only as grassland because it was too wet for crops. The sub-watershed at Weir-2 was
20 draining storm runoff from part of the main road from Bahir Dar to Adet and developed a
21 relatively small gully upstream and a more substantial gully downstream. The sub-watershed at
22 Weir-4 drained mainly upland runoff from the sub-watershed at Weir-3 and it contained a

1 saturated area upstream of its outlet. The upland areas pertaining to Weir-1, Weir-2 and Weir-3
2 have lava intrusions at the mid-slope steepest part of the sub-watersheds.

3 ***2.2 Data and Methodology***

4 Fieldwork was carried out during the summer of 2010 and 2011 in Debre Mawi watershed.
5 Rainfall was measured during the two summers and runoff discharge was also monitored at five
6 weirs (one at the outlet and four at sub-watersheds) during the same period. Infiltration tests were
7 conducted and perched ground water levels were monitored in 2010.

8 ***2.2.1 Hydro-meteorological data***

9 Rainfall and flow measurements were carried out during the rainy seasons. Rainfall is measured
10 at five minute intervals from July 4 to October 11, 2010 and from June 14 to September 24,
11 2011. Over 2500 recordings of 5-minute interval rainfall intensities with a maximum intensity of
12 143 mm hr^{-1} were recorded. Additional meteorological data before and after the measurement
13 periods were obtained from a nearby weather station, 10 km south of the watershed.

14
15 Flow was measured at five locations using constructed weirs distributed over the watershed (one
16 at the outlet and four at sub-watersheds, Figure 1). Water depth and surface water velocity (V , m s^{-1})
17 were recorded at the weirs in 10-minute intervals during the storm period. The surface
18 velocity was determined by releasing a floating object in the river. The average velocity is two-
19 thirds of the surface velocity. The discharge is calculated by multiplying the average velocity
20 with the cross-sectional flow area. Baseflow in the watershed is minimal as the streams dry out
21 in November indicating minimal contribution. A best fit rating curve was developed for each
22 weir from 10-minute interval depths and mean discharge measurements. Flow depths larger than

20, 22 and 30 cm at Weir-1, Weir 2 -4 and Weir-5, respectively result in poor stage–discharge relationship with power fit. Hence a second order polynomial function was used.

Perched water depths were measured twice a day from July 17 to November 5, 2010 at 19 piezometers placed along 6 transects from the top of the hill slope down to the saturated area near the river (Figure 1). The sixth transect was installed across a gully. The T in Figure 1 denotes the transect (with subscript) for every group of three piezometers except for T₅ which has four piezometers in the transect.

Soil infiltration rates were measured at fourteen different locations throughout the watershed using a 25-cm diameter single-ring infiltrometer in August 2010 on the upslope, mid slope and down slope areas of the watershed with different land use (Figure 1). Initial infiltration tests on down slope saturated areas showed that the water did not infiltrate and these areas were omitted in any further measurements. After driving the ring to a depth of about 10 cm, an average total of 28 cm of water was added into the ring keeping the water level constant, and the infiltrated water depth was measured at varying time intervals. A ruler was used to read water depth fluctuations in the infiltrometer throughout the duration of the test. The constant infiltration rate at the end of the test was taken as the infiltration capacity of the test area.

2.2.2. Runoff predictions

The validity of the SCS was tested for predicting the runoff of the watersheds. The SCS runoff equation is

$$Q = \frac{P_e^2}{(P_e + S_e)} \quad 1$$

Where Q is the runoff (mm); P_e is the effective rainfall after the runoff starts. $P_e = P - I_a$ where I_a is the initial abstraction (rainfall retained by the watershed prior to the beginning of runoff

generation) and P is the total precipitation. S_e is the effective average available watershed storage after the first runoff until the watershed is completely saturated. Steenhuis et al. (1995) and Schneiderman et al. (2007) showed that the SCS equation represents in principle a saturation excess runoff processes where the fractional area of saturation, A_f , can be found by taking the derivative of the runoff, Q , with respect to the precipitation P , e.g.

$$A_f = 1 - \frac{S_e}{P_e + S_e} \quad 2$$

To find the effective storage of the watershed, daily effective rainfall and storm runoff data were summed over weekly periods for the 2010 and 2011 summer. Daily effective rainfall is defined as rainfall minus potential evaporation ($P - E$) (Liu *et al.*, 2008). Potential evaporation was obtained from the nearby Adet weather station, 10 km south of Debre Mawi. The initial abstraction in a monsoon climate is approximately equal to the water that is lost during the dry phase (Liu *et al.*, 2008). Thus, the first rains have a distinctly smaller amount of runoff for a given amount of rainfall than rains later in the rainy phase (Liu *et al.*, 2008). Hence the June and early July storms were not included in calibrating the S_e values and only weekly values after July 23 were used. A linear regression model was used to analyze the relationship between measured rainfall and runoff. Thus, the maximum 5-minute rainfall intensity and averaged rainfall intensities were regressed with observed runoff at the outlets. A better fit than the saturation excess SCS approach suggests a different dominant runoff process. The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), slope of line, and coefficient of determination (R^2) were used to determine the model fitness to observations (Griensven *et al.*, 2012). An F-test at 1% significance level (α) is also applied to verify the statistical significance of the relationship.

3. Results

3.1 Rainfall intensity and infiltration capacity

Large rainfall intensities greater than 15 mm hr^{-1} occur with low relative frequency (Figure 3). Intensities greater than 15 mm hr^{-1} occurred only 9% of the time in 2010 and 12% in 2011. The largest intensities occurred in July. For example in 2011, out of 55 events that were greater than 30 mm hr^{-1} , 49% of the events occurred in July while 31% occurred in August and 20% in September. The distribution of intensities in 2010 differed with only 39 events being greater than 30 mm hr^{-1} . Of these, 46% occurred in July, 21% in August and 33% in September. Table 1 shows the rainfall intensity distribution for events greater than 15 mm hr^{-1} following similar patterns as of that for the rate of 30 mm hr^{-1} . Table 2 shows the results of regressing the maximum 5-minute rainfall intensity and averaged rainfall intensities with observed runoff at the outlets.

[Figure 3]

[Table 1]

[Table 2]

In order to compare rainfall intensity with the infiltration capacity, the spatially averaged infiltration capacity of the watershed was compared to the exceedance probability of the rainfall intensity as shown in Figure 3. The steady state infiltration rates ranged from 6 to 360 mm hr^{-1} (Table 3) and were conducted in August 2010 when some of the soils had already decreased infiltration due to the saturation of the soil. In general, infiltration rates were smallest in the down slope areas where the nearly saturated Vertisols and Vertic Nitisol soils are found and greatest in the upslope positions of the landscape with the unsaturated Nitisol soils (Table 3). The

average infiltration rate from all 14 measurements was 70 mm hr⁻¹ and the median was 33 mm hr⁻¹.

[Table 3]

Since runoff water from low infiltration areas during a burst of high intensity rain can infiltrate downhill on its way to the stream in soils with good infiltration capacity, especially after the rainfall intensity has decreased (van de Giesen, 2000; Stomph *et al.*, 2002), the median infiltration is the most meaningful rate to compare with rainfall intensity (Bayabil *et al.*, 2010; Engda *et al.*, 2011). Figure 3 shows that the median infiltration is only exceeded by 1.5% of the 5-minute rainfall intensities in 2010 and 4.4% in 2011. Since the minimum rate was exceeded 30 percent of the time, surface runoff due to either saturation or infiltration excess can be expected to occur in the watershed. Saturation excess can be expected when the low infiltration rates are due to saturation of the soil (and there is no pore space available for water) in the bottom part of the watershed. Infiltration excess may be expected to occur in the unsaturated top of the watershed but as discussed later it often infiltrates further down slope in the more permeable soil, if not saturated (Van de Giesen *et al.*, 2000; Stomph *et al.*, 2002).

3.2 Storm Runoff from 5 weirs

A total of 38, 41, 39, 41, and 46 average storm runoff depths (mm) were measured at Weir-1, Weir-2, Weir-3, Weir-4, and Weir-5, respectively for which both rainfall and runoff amounts were available. Discharge is increasing for similar amounts of rainfall with the progression of the rainy monsoon phase. For example, a 2-hour rainfall event of 14 mm on July 5, 2010 and 17 mm on September 15, 2010 produced storm runoff depths of 0.8 mm in early July and 7.6 mm in September (Figure S1 in Supplementary Material).

In order to easily compare runoff among the sub-watersheds and watershed outlets, a runoff coefficient (defined as the quotient of runoff and rainfall volume) was calculated for each storm and averaged for each month that data was available (Figure 4). June 2011 has the lowest runoff coefficient indicating that most of the rain water infiltrated. No data were available for June 2010. The runoff coefficients at all weirs for the remaining months of 2010 were close to 0.45 likely because of the high monthly rainfall in June 2010 (Figure S2 in Supplementary Materials) which having filled up the water deficit after the prolonged dry phase produces a form of equilibrium in the watershed in which the runoff coefficient is nearly constant, consistent with the findings of Liu et al. (2008). Beginning in 2011 when June was not as wet, the runoff coefficients for Weir-5 at the outlet increased consistently over the next two periods of observation indicating that the area of saturation increased during this time in the bottom part of the watershed since the runoff coefficients for the sub-watersheds (Weirs 1 to 4) did not vary consistently for July, August and September. The increase in saturation is corroborated by the perched groundwater level measurements in the next section.

[Figure 4]

3.3 Perched groundwater water table

Perched water table depths (Table S1 in supplementary material) were monitored during the rainy phase in 2010 using piezometers to map saturated areas and the timing of saturation during the rainy period. Results from Transects 3 (P7, P8, and P9) and 5 (P13, P14, P15, and P16) as shown in Figure 1 are shown here because they represent the perched water table in the watershed. The water ponded above a lowly permeable basaltic layer is depicted as depth below the ground surface (0 cm) to reach the water table (Figure 5). P7 and P13 are located on the steep mid-slope part of the watershed where no perched water was observed, possibly due to the water

draining quickly during storms as subsurface flow. The water tables near P8 and P9 on the lower slopes of the watershed with grassland reached the surface in the first week of August and became saturated. Likewise within the same period, the water table depths for P14 and P15, which are located on the gentle mid-slopes in the cultivated land, were near the surface (Figure 5). Piezometer 16 at the lower slopes in the area that saturates during the first week of August was situated in close proximity to a deep gully drawing down the water table and hence the water table was deep, close to the gully bottom.

[Figure 5]

Following a rise in the water table depth during the heavy rainfall at the end of July and the beginning of August, Piezometer 14 declines faster than P15. P14 is located directly uphill from P15 and indicates that the water table drains as expected faster uphill than at downhill locations. A map of the saturated areas in August based on the piezometer readings and physical observation during the rainy period is shown in Figure 2c. This area is approximately 9 ha (10% of the total watershed area) and exists for approximately a month after the first week of August. The area of saturation decreases as the saturated area recedes in September and October.

3.4 Runoff predictions

SCS runoff equation: The storm runoff (without including June and early July runoff) correlated well with the cumulative effective rainfall (Figure S3 in Supplementary Materials). This correlation is statistically significant at the 1% significance level with P-value less than 0.01 at all weirs (number of data, $n = 17$). The correlation became poor when the June and early July data were included implying that early rains in the rainy monsoon phase infiltrate and fill up the soil storage similarly observed in other highland watersheds (Liu *et al.*, 2008).

By fitting the shortened dataset (i.e., removing the June and early July data) of rainfall and average storm runoff depth to the SCS runoff equation (equation 1), we found that the S_e varies from 4 to 18 cm (Figure 6a) with Nash-Sutcliffe efficiency (NSE) of 0.71 to 0.89 and coefficient of determination (R^2) ranges from 0.50 to 0.74 as shown in Figure 6b. This correlation is statistically significant ($\alpha = 1\%$) at all weirs using F-test (P-value <0.01 , $n = 17$). The corresponding saturated area fractions from equation 2 are shown in Figure 7.

[Figure 6]

[Figure 7]

The large range of S_e and A_f values represents the variability in available storage in the watershed. Since the bottom part of watershed becomes saturated, we expect that the available storage ($S_e = 7 \pm 2$ cm) for rainfall to be retained is smaller for the whole watershed (represented by Weir-5) than the average of the sub-watersheds with the exception of the watershed of weir 2 where the road contributes runoff to the weir. As Figure 7 shows, once the watershed reached equilibrium, the saturated area fraction during rainfall varies according to the prevailing amount of rainfall. The watershed of Weir-2, draining storm runoff from an intersecting road, has a smaller S_e (4 ± 1 cm) than Weir-5 and has saturated areas at the bottom with gullies (Figure 2c), resulting in larger runoff potential and runoff area fraction. The watershed of Weir-1 consists of relatively deep soils at the bottom without lava intrusions and consequently can store a large amount of water before the whole watershed would be saturated and therefore, a high S_e value (18 ± 3 cm) and lower area fraction for all prevailing excess rainfalls were obtained (Figure 7). The watershed of Weir-3 ($S_e = 17.5 \pm 3$ cm) has intermediate amounts of lava intrusions while Weir-4 has the same lava intrusions as in the watershed of Weir-3 and saturated area (Figure 2c), therefore a relatively small S_e (12 ± 2.5 cm) value and large runoff area fractions. The area

fractions at the end of the rainy period (Figure 7) are lower than the runoff coefficient measurement (Figure 4) which is likely due to the contribution of runoff from infiltration excess processes occurring during high rainfall intensities at the upslope sub-watersheds such as on September 16, 2010 in Table S2 in Supplementary Material.

In order to test if infiltration excess mechanisms could describe the overall watershed runoff behavior, daily runoff depth was regressed with the 5-minute maximum intensity and average rainfall intensity (data are shown in Figure S4 in Supplementary Materials). The coefficient of determination R^2 is 0.32 and less than that of the SCS equation that used total amount of storm rainfall as independent variable. The F-test (Table 2), however, showed that there is significant correlation between maximum rainfall intensity and storm runoff at 1% significance level for all watersheds except for the sub-watershed at Weir-1. The relation between storm runoff and average rainfall intensity was only significant for sub-watersheds at Weir-3 and -4. The significant correlation with maximum rainfall intensity disappeared when the few extreme events are removed as shown in Table 1. Since the infiltration rate is exceeded only a few times by rainfall intensity (Figure 3), rainfall intensity is only a good predictor for watershed outflow for extreme high intensity events. However, for rainfall intensity below the extreme value, rainfall is not a good predictor as the correlation is poor (Table 2).

4. Discussion

In temperate humid climates, subsurface storm runoff and saturation excess runoff principles are often found, in soils with sufficient organic matter, to describe the runoff processes better than the Hortonian infiltration excess overland flow mechanisms (Hewlett and Hibbert, 1963; Dunne and Black, 1970). Only recently has modeling runoff in the Ethiopian highlands with Hortonian

1 flow processes been questioned (Liu *et al.*, 2008) and questions raised as to whether saturated
2 excess runoff mechanisms could provide a better alternative.

3
4 As we will discuss below based on our observations, we demonstrate that subsurface flow and
5 saturation excess are prevailing in the landscape occurring for most of the time but that in
6 portions of the landscape, infiltration excess rainfall might be occurring.

7
8 The importance of saturation excess in producing runoff can be demonstrated by comparing
9 infiltration rates with rainfall intensity (Figure 3), where the median steady state infiltration rate
10 (33 mm hr^{-1}) was exceeded only 3% of the time. The lowest infiltration rate of 6 mm hr^{-1} was
11 exceeded 30% of the time. Runoff from the low infiltration areas can infiltrate further down
12 slope on soils with greater infiltration rates. When the rainfall intensity is equal to the median
13 steady state infiltration rate half of the watershed area produces runoff and on the other half,
14 where the infiltration is greater than the median of 33 mm hr^{-1} , the water will infiltrate. The
15 Andit Tid watershed behaved similarly (Engda *et al.*, 2011) with a median infiltration rate (48
16 mm hr^{-1}) that was only exceeded 3% of the time. This is different from the Maybar watershed
17 where median infiltration rate was greater than any measured rainfall intensity and the minimum
18 infiltration rate of 20 mm hr^{-1} was only lower than the rainfall intensity 9% of the time (Bayabil
19 *et al.*, 2010).

20
21 Calculated runoff coefficients corroborate the above findings (Figure 4). In all watersheds the
22 runoff coefficients were low early in the rainy monsoon phase and then increased. For the sub-
23 watersheds in Debre Mawi, the runoff coefficients were low in June and then were elevated in

1 the remaining months. In 2010 no data were collected in June. The increase in runoff coefficient
2 for the whole watershed occurred during the extent of the rainy phase when the watershed
3 became more and more saturated (black bars in Figure 4). The increase was faster in 2010 than in
4 2011, since there was more rain in June in 2010 (Figure S2 in Supplementary Materials). Thus in
5 all watersheds studied, the water infiltrated first before the runoff became significant. The soils
6 are deeper in the bottom part of the watershed so it took longer for the discharge to increase at
7 Weir-5 at the outlet of the whole watershed. July 2011 (Figure S1 in Supplementary Materials)
8 shows this most clearly where the runoff coefficient for the whole watershed is less than any of
9 the sub-watersheds meaning that the runoff from the sub-watersheds infiltrated in the lower parts
10 of the entire watershed. It is expected that the runoff coefficients remain constant once the
11 watershed is wetted up. This is not the case in 2011 and we expect that the variation is caused by
12 the most intense storms as the number of intense storm events is greater in 2011 than 2010
13 (Table 1). Runoff coefficient and storm runoff from the sub-watershed at Weir-2 is much greater
14 during some months because of the contributions of the road drainage (Figure S5 in
15 Supplementary Materials).

16
17 A direct comparison of perched water tables in piezometers and runoff coefficients is not
18 feasible, because the piezometers represent local conditions and are affected directly by nearby
19 abnormalities in elevation such as the case for P16 (Figures 5 and 7) that is in a generally
20 saturated area but because of the nearby gully, it has a deep water table. The general trend,
21 however, confirms that the upslope areas are generally unsaturated as shown by Piezometers P7
22 and P13, (Figures 2 and 5) where the horizontal line in the figure for these piezometers is
23 generally at the same depth of the slowly permeable layer and therefore there is no saturation in

1 the profile with the exception being during the period with heavy rain around July 20, 2010.
2 Although it is difficult to compare individual piezometers with the runoff coefficients, the
3 general trend is correct with low runoff coefficients in the beginning of the rainy phase when
4 perched water tables are deep and high runoff coefficients when the water tables are at shallow
5 depths (Figure 4 and 5).

6
7 The fact the SCS equation (based on total effective rainfall and effective storage) for storms after
8 the beginning of July fits the runoff data better than a model with precipitation intensity indicates
9 that saturation excess is more dominant than infiltration excess. Only for the three largest storms
10 with high intensities on July 13, 2010, July 20, 2010 and July 17, 2011 (see Table S2 in
11 Supplementary Materials) infiltration excess could have taken place, because if these storms are
12 included there is a significant correlation of maximum rainfall intensity with storm runoff depth
13 in Table 2, but if these storms are not included the relationship becomes weak and statistically
14 insignificant for maximum intensity at all areas. Moreover, under saturation excess conditions
15 short high intensity rainfall bursts are associated with high discharges from the runoff source
16 areas that are more likely to reach the outlet than the same amount of rain over a longer period.

17
18 Whether infiltration excess or saturation excess runoff occurs has important implications on
19 whether soil and water conservation practices are effective. Implicit in the concept of infiltration
20 excess is the assumption that land use affects the infiltration capacity of the soils and is the
21 determining factor for whether overland flow is generated or not (Rittenburg *et al.*, 2015). Thus,
22 in situations where infiltration is limited such as in Palouse in Eastern Washington State (Brooks
23 *et al.*, 2006) and in the Tigray region of Ethiopia improving plant cover and soil health will, in

1 general, reduce overland flow and increase infiltration and interflow. On the other hand,
2 saturation excess assumes that water cannot infiltrate because of the lack of space where it can be
3 stored (Hewlett and Hibbert, 1963). In this case, changing plant cover will have little effect on
4 runoff unless either the conductivity of the most restricting layer is increased in the case of a
5 perched water table, or the amount of lateral flow or interflow reaching the saturated areas is
6 reduced by upland practices. Additionally, artificial drainage will decrease surface runoff as
7 well. Finally, the underlying runoff mechanism should be taken into account when evaluating
8 modeling results (such as recently by Schmidt and Zemadim, 2015, Yesuf *et al.*, 2015, and
9 Haregeweyn *et al.*, 2015), specifying the effect of landscape interventions.

10 It is important to note that our study site the Debre Mawi watershed was located in the sub-
11 humid climate. Other watersheds where saturation excess runoff has been noted such as the
12 SCRP watersheds (Anjeni, Maybar and Andit Tid) are located in the humid monsoon zone. In
13 these watersheds the precipitation exceeds the potential evaporation of around 60 mm/month
14 several times during the rainy monsoon phase. For highland areas with a semi-arid monsoon
15 climate, such as most of Tigray, the evaporation and moisture deficit at the end of the dry phase
16 are of the same order as the precipitation. Saturation is thus much less likely in those instances as
17 shown for a study in Tigray where the ground water reached the surface only for a short time and
18 in a small number of areas (Walraevens *et al.*, 2009). Only for closed basins in the semi-arid
19 areas will wetlands form, as shown by McHugh *et al.* (2007).

20 **5. Conclusions**

21 In this investigation, we attempted to quantify the spatial variation of runoff and to specify the
22 extent of the saturated areas in the 95-ha Debre Mawi watershed by measuring infiltration rates,
23 rainfall intensities, rainfall amounts, perched water tables and discharge for the main watershed

1 and four nested sub-watersheds. In general, rainfall intensities were greater than the infiltration
2 capacity of the soil except in some locally degraded areas where the subsoil was close to the
3 surface. In addition, since total storm rainfall and total discharge were correlated after the
4 watershed was wetted up, we concluded that saturation excess was the dominant runoff
5 mechanism. Contributing runoff source areas ranged from 60% of the total watershed during the
6 high rainfall periods to less than 10% when rainfall amounts decreased. Since the SCS runoff
7 equation can be interpreted as being based on saturation excess runoff mechanisms, (e.g.,
8 discharge is a function of total rainfall), we found good Nash Sutcliffe efficiencies between
9 predicted and observed weekly discharges using this method. Finally our findings suggest that
10 runoff contributing areas are positioned in landscape specific locations and are likely not altered
11 by changing vegetation type. This is important knowledge useful for planning watershed
12 improvements.

13
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Table 1: Rainfall intensity distribution within three months in 2010 and 2011 rainy period.

Month	Number of 5-min measurements taken during storm events	Number of 5-min interval storm intensities >15mm hr ⁻¹	Percent of time >15mm hr ⁻¹
July 2010	528	44	8
Aug 2010	411	37	9
Sep 2010	349	35	10
July 2011	479	57	12
Aug 2011	501	56	11
Sep 2011	255	40	16
Total	2523	269	

Table 2: Statistical analysis of average storm runoff with maximum and average rainfall intensity in Debre Mawi watershed.

Variables			Average storm runoff (mm) at weir				
			1	2	3	4	5
Maximum rainfall intensity (mm/hr)	R^2		0.14	0.23	0.32	0.31	0.31
	n		36	40	38	40	46
	P-value (F-test)		0.022	0.001	0.0002	0.0002	<0.0001
Maximum rainfall intensity (mm/hr)*	R^2		0.07	0.08	0.1	0.08	0.14
	n		35	37	35	37	44
	P-value (F-test)		0.14	0.09	0.06	0.09	0.011
Average rainfall intensity (mm/hr)	R^2		0.12	0.13	0.22	0.18	0.12
	n		36	40	38	40	46
	P-value (F-test)		0.037	0.024	0.003	0.007	0.017

* excluding maximum rainfall intensity events of July 13, 2010, July 20, 2010 and July 17, 2011; bold numbers indicate the existence of statistical significance.

Table 3: *Infiltration capacity from infiltration test conducted in Debre Mawi Watershed August 2010.*

ID No	Landscape position	Infiltration Capacity (mmhr ⁻¹)	Land cover	Slope (%)	Soil type
I1	Up-slope	12	cultivated land (tef)	7	Nitisols
I2	Up-slope	30	cultivated land (tef&bean)	6	Nitisols
I11	Up-slope	216	cultivated land	8	Nitisols
I12	Up-slope	360	cultivated land	7.3	Nitisols
I13	Up-slope	18	cultivated land	7.4	Nitisols
I14	Up-slope	16	cultivated land	5.9	Nitisols
I3	Mid-slope	44	bush & grass land	10	Vertic Nitisols
I4	Mid-slope	102	bush land	8	Vertic Nitisols
I9	Mid-slope	42	grass land	11	Vertic Nitisols
I10	Mid-slope	78	grass land	13.8	Vertic Nitisols
I5	Down-slope	22.5	grass land close to saturation	14	Vertisols
I6	Down-slope	12	cultivated land	12.3	Vertisols
I7	Down-slope	6	cultivated land	14.2	Vertisols
I8	Down-slope	36	grass land close to saturation	9.8	Vertisols

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 1: Location, boundary and drainage map of Debre Mawi storm runoff monitoring sites (weirs), perched water table sampling and infiltration test sites within the watershed (piezometer is abbreviated as P, transect as T, and I stands for infiltration)

Figure 2: (a) Upper and middle part of the watershed with unsaturated hillsides (part of T1) in the background and in the foreground (part of T3) facing opposite, the steeper middle part of the watershed (b) Lower portion of the sub-watershed at Weir-2 with wet area located in the foreground (pictures taken on 18 Aug 2011). (c) Saturated areas mapped from water table reading of piezometers and physical observations for the end of July and beginning of August.

Figure 3: The exceedance probability of the average intensities of 2523 storm events and median infiltration rate for the Debre Mawi watershed in 2010 and 2011.

Figure 4: Runoff coefficients for four months at each weir for summer 2010 and 2011. (Runoff was not measured in June 2010).

Figure 5: (a) Transect 3 and (b) Transect 5 (from Figure 1) in the Debre Mawi watershed where the groundwater level is averaged from twice a day measurements during the 2010 main rainy season using the ground surface as a reference and rainfall was summed on a daily basis.

Figure 6: (a) Fitting an SCS runoff equation for the different weirs in the Debre Mawi watershed (June and early July data excluded). (b) Scatter plot for measured and simulated runoff with SCS runoff equation (equation 1) using data of cumulative weekly runoff (June and early July data are excluded).

Figure 7: Area fraction (A_f) from equation 2 for weekly cumulative effective rainfall.