Chapter 7 Watershed Hydrology of the (Semi) Humid Ethiopian Highlands

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Abstract Understanding the basic relationships between rainfall, runoff and soil loss is vital for effective management and utilization of water resources and soil conservation planning. A study was conducted in three small watersheds in or near the Blue Nile basin in Ethiopia, with long-term records of rainfall and discharge. To better understand the water movement within the watershed, piezometers were installed and infiltration rates were measured in the 2008 rainy season. We also reanalyzed the discharge from small plots within the watersheds. Infiltration rates were generally in excess of the rainfall rates. Based on this and plot discharge measurements, we concluded that most rainfall infiltrated into the soil, especially in the upper, steep and well-drained portions of the watershed. Direct runoff is generated either from saturated areas at the lower and less steep portions of the hill slopes or from areas of exposed bedrock. Using these principles, a simple distributed watershed hydrology model was developed. The models reproduce the daily discharge pattern reasonably well for the small watershed and the 10-day discharge values for the whole Blue Nile Basin in Ethiopia. The simplicity and scalability of the model hold promise for use in un-gauged catchments.

Keywords Variable source area · Perched water table · Saturation excess · Infiltration excess · Hillslope hydrology

Abbreviations

GPS Global Positioning System

SCRP Soil Conservation Research Program

SCS Soil Conservation Service

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7.1 Introduction

A better understanding of the hydrological characteristics of different watersheds in the headwaters of the Ethiopian highlands is of considerable importance because only 5% of Ethiopia's surface water (0.6% of the Nile Basin's water resource) is being currently utilized by Ethiopia while cyclical droughts cause food shortages and intermittent famine (Arseno and Tamrat, 2005). At the same time the Ethiopian highlands are the origin, or source, of much of the river flow reaching the Nile River, contributing greater than 60% of Nile flow (Ibrahim, 1984; Conway and Hulme, 1993) possibly increasing to 95% during the rainy season (Ibrahim, 1984). In addition, there is a growing anxiety about climate and human-induced changes of the river discharge (Sutcliffe and Parks, 1999), especially because there have been limited studies on basin characteristics, climate conditions, and hydrology of the Upper Nile Basin in Ethiopia (Arseno and Tamrat, 2005).

To predict future water availability three general model types have been used in the Blue Nile basin. Simple engineering approaches such as the Rational Method (Desta, 2003), pure water balance models, and semi distributed models. Pure water balance approaches have been made by Ayenew and Gebreegziabher (2006) for Lake Awassa, Conway (1997) and Kim and Kaluarachchi (2008) at the upper Blue Nile, and Kebede et al. (2006) at Lake Tana. These models provide only information on water quantity at the watershed outlet and perform best at a monthly time scale. Semi distributed models that have been applied in the Nile basin are SWAT (Setegn et al., 2008), Water Erosion Prediction Project (WEPP) (Zeleke, 2000), the Agricultural Non-Point Source model (AGNPS) (Haregeweyn and Yohannes, 2003; Mohammed et al., 2004), and for South Central Ethiopia PRMS (Legesse et al., 2003).

Most semi distributed models use the SCS runoff equation for determining surface runoff. The SCS curve number method is based on a statistical analysis of plot runoff data from the mid-west USA with a temperate climate. When applied to Ethiopia with a monsoon climate, it has been a bit problematic. While most of these models were run on a daily time step, the results are presented on a monthly time step, which indicates these models do not work well at the daily scale. By integrating the result over a monthly time step, errors in daily surface runoff are compensated for by opposite errors in interflow predictions. Thus, the monthly validation indicates that the monthly water balances are met but not necessarily that the daily rainfall-runoff relationship for landscape units in the watershed are correct. In order to understand why a statistically derived and widely used SCS curve number fails to predict the daily direct runoff in monsoonal climates, the effect of climate on the hydrology during the dormant and growing seasons must be considered. The similarity between temperate and monsoonal climate types is that both have a dormant period and a growing period. However, the similarity between the two climates stops there. In the temperate climates, the growth in the dormant season is limited by the temperature. There is usually sufficient precipitation and there is little evaporation with the result that the soils wet up and watershed outflow increases. In monsoonal climates, the limiting factor is insufficient rainfall with the consequence

that the soils dry out and therefore during the dormant season, discharge out of the watershed decreases. Understanding the effect of climate on the hydrology during the growing season is more complicated. We can simply make the observation that the landscape dries out in temperate climates and the opposite is true for monsoonal climate. These differences in how climate interacts with the hydrology, indicates that only physically sound models can be applied in both climates and statistical techniques will be less successfully transferred.

Thus, in order to refine the estimates of watershed outflow in the Ethiopian highlands with a monsoonal climate, a better understanding is needed of rainfall and runoff relationships of the various landscape units. In this chapter, we will use recently collected information by Engda (2009), Leggesse (2009) and Bayabil (2009) in three Soil Conservation Research Program (SCRP) watersheds in the Ethiopian highlands – Andit Tid, Anjeni, and Maybar – to derive how interflow, surface runoff, and baseflow are generated spatially. This information then will be used to develop a physically sound model that can be used in the Ethiopian highlands.

7.2 Watershed Descriptions

Soil Conservation Research Program (SCRP) watersheds have the longest and most accurate record of both rainfall and runoff data available for small watersheds in Ethiopia. Three of the watersheds are located in the Amhara region either in or close to the Nile Basin: Andit Tid, Anjeni, and Maybar (Fig. 7.1). All three sites are dominated by agriculture with soil erosion control structures built to assist the

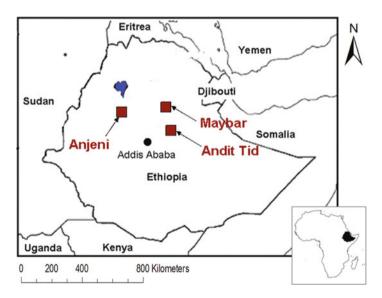


Fig. 7.1 Locations of the three SCRP watersheds in Amhara, Ethiopia

| Research site | Location (region) | Area (ha) | Elevation (masl) | Precipitation mm/year | Length of data |
|---------------|-----------------------------|--------------|------------------|--------------------------|--|
| Andit Tid | 39°43′E, 9°48′N (Shewa) | 477.3 | 3,040–3,548 | 1,467 | 1987–2004 (1993, 1995–1996 incomplete) |
| Anjeni | 37°31′E, 10°40′N (Gojam) | 113.4 | 2,407–2507 | 1,675 | 1988–1997 |
| Maybar | . 3 | 112.8 | 2,530–2,858 | 1,417 | 1988–2001 (1990–1993 incomplete) |

Table 7.1 Location, description, and data used in the model from the three SCRP research sites

rain-fed subsistence farming but the watersheds differ in size, topographic relief, and climate (Table 7.1).

The Andit Tid watershed unit covers a total area of 481 ha, with a hydrological surface area of 477 ha. It is situated 180 km northeast of Addis Ababa at 39°43' east and 9°48' north in the Blue Nile Basin. The topography of Andit Tid ranges from 3,000 m near the research station in the western reach of the research unit to 3,500 m in the southeast. Andit Tid, the largest watershed, is also the highest and least populated. It receives more than 1,500 mm/year and has a bimodal rainfall pattern, smaller/belg from March to May, and main/keremt from June to Octber. Hill slopes are very steep and degraded, resulting in 54% of the long-term precipitation becoming runoff. Despite its larger size, stream flow quickly returns to nearly zero during the typically dry months of November through March. Some of the contour bunds constructed at the start of the project were destroyed after installation because, according to farmers, they increased erosion (Engda, 2009). Terraces and small contour drainage ditches were installed by the farmers to carry off excess rainfall. From 1987 to 2004, rainfall was measured and discharge was recorded at the outlet and from four runoff plots. Evaporation was measured using the standard pan. During the 2008 main rainy season, soil infiltration rates were determined at 10 different locations throughout the watershed using a 30-cm diameter single-ring infiltrometer. In addition, piezometers were installed in transects to measure the water table depths. Finally, soil depth estimations were taken by field technicians throughout the watershed and registered using Global Positioning System (GPS) points. Further information can be found in Hurni (1984), Bosshart (1997), and Engda (2009).

The Anjeni watershed is located in the Blue Nile basin of Amhara Region in one of the country's more productive agricultural areas and is dominated by highlands. The watershed is oriented north-south and is flanked on three sides by plateau ridges. It is located at 37°31′E and 10°40′N and lies 370 km NW of Addis Ababa to the south of the Choke Mountains. Minchet, a perennial river, starts in the watershed and flows towards the Blue Nile Gorge. The Anjeni watershed covers a total area of 113 ha. It is the most densely populated among the three watersheds. The topography of Anjeni ranges from 3,000 m near the research station in the western reach of the research unit to 3,500 in the southeast. This site receives more rain than the other two watersheds and has only one rainy season, typically May through October.

This watershed has extensive soil and water conservation measures, mainly terraces and small contour drainage ditches, installed each year by the farmers to carry off excess rainfall. From 1987 to 2004, rainfall was measured at five different locations, discharge was recorded at the outlet and from four runoff plots. Forty-five percent of the rainfall becomes runoff. During the 2008 rainy season, soil infiltration rate was measured at 10 different locations throughout the watershed using a 30-cm diameter single-ring infiltrometer. In addition, piezometers were installed in transects to measure the water table depths. Finally, soil depth estimations were taken by field technicians throughout the watershed and registered using GPS points.

Finally, Maybar is located in the northeastern part of the central Ethiopian highlands situated in Southern Wollo Administrative Zone near Dessie Town. It is the first of the SCRP research sites. The gauging station lies at 39°39′E and 10°51′N. The area is characterized by highly rugged topography with steep slopes ranging between 2,530 and 2,860 m, a 330 m altitude difference within a 112.8 ha catchment area. From 1988 to 2004, rainfall data was available using an automatic rain gage and two manual rain gage at two different locations, one in the upper part of the catchment and the other near the office. Discharge was measured with a flume installed in the Kori River using two methods: float-actuated recorder and manual recording. During the main rainy season in 2008, 34% of the long-term precipitation in Maybar became discharge at the outlet. The ground water table levels were measured with 29 piezometers. The saturated area in the watershed was delineated and mapped using combined information collected using GPS instrument, field observation, and ground water level data (piezometer head readings).

7.3 Rainfall Runoff Characteristics for Monsoonal Climates

7.3.1 Analysis of Rainfall Discharge Data

In order to understand the rainfall/runoff relations in monsoonal climates, Liu et al. (2008) examined how the watershed outflow changed as a function of precipitation for the three SCRP sites. To find the most appropriate representation of watershed behavior, daily rainfall, evaporation, and discharge data were summed over biweekly periods; only with longer time periods could the total stream responses to a rainfall event be determined because interflow lasts several days.

To investigate runoff response patterns, the biweekly sums of discharge were plotted as a function of effective rainfall (i.e., precipitation-evapotranspiration) during the rainy season and dry season, respectively. In Fig. 7.2a, an example is given for the Anjeni watershed. As shown from Fig. 7.2a, the watershed response behavior changes as the wet season progresses, with precipitation later in the season generally producing a greater percentage of runoff. As rainfall continues to accumulate during the rainy season, the watershed eventually reaches a threshold point where runoff response can be predicted by a linear relationship with effective precipitation,

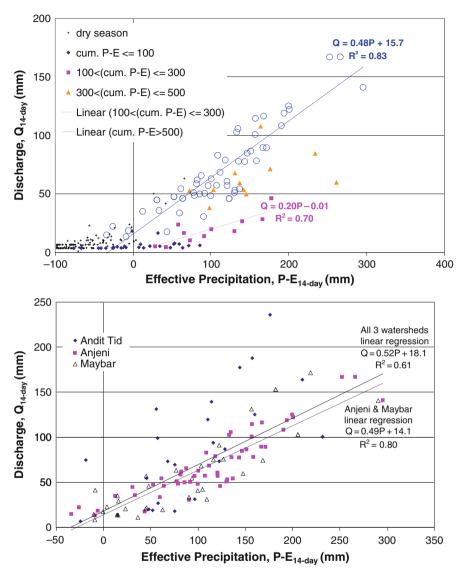


Fig. 7.2 Fourteen day discharge vs. effective precipitation in (1) the Anjeni watershed, and (2) all three SCRP watersheds with cumulative effective precipitation in excess of 500 mm since the beginning of the rainy season (Liu et al., 2008)

indicating that the proportion of the rainfall that became runoff was constant during the remainder of the rainy season. For the purpose of this study, an approximate threshold of 500 mm of effective cumulative rainfall, P-E, was selected after iteratively examining rainfall vs. runoff plots for each watershed. The proportion Q/(P-E) varies within a relative small range for the three SCRP watersheds despite their

differing characteristics. In Anjeni, approximately 48% of late season effective rainfall, P-E, became runoff, while ratios for Andit Tid and Maybar were 56 and 50%, respectively (Liu et al., 2008). There was no correlation between biweekly rainfall and discharge during the dry seasons at any of the sites.

Since each of the SCRP watersheds showed a similar linear response after the threshold cumulative rainfall was satisfied, the latter parts of the wet seasons were all plotted in the same graph (Fig. 7.2b). Despite the great distances between the watersheds and the different characteristics, the response was surprisingly similar. The Anjeni and Maybar watersheds had almost the same runoff characteristics, while Andit Tid had more variation in the runoff amounts but, on average, the same linear response was noted with a higher intercept (Fig. 7.2b). Linear regressions were generated for both the combined results of all three watersheds and for the Anjeni and Maybar watersheds in combination (Fig. 7.2b). The regression slope did not change significantly, but this is due to the more similar Anjeni and Maybar values dominating the fit (note that these regressions are only valid for the end of rainy seasons when the watersheds are wet).

Why these watersheds behave so similarly after the threshold rainfall has fallen is an interesting question to explore. It is imperative to look at various time scales, since focusing on just one type of visual analysis can lead to erroneous conclusions. For example, looking only at storm hydrographs of the rapid runoff responses prevalent in Ethiopian storms, one could conclude that infiltration excess is the primary runoff generating mechanism. However, looking at longer time scales in Fig. 7.2a, it can be seen that the ratio of Q/(P-E) is increasing with cumulative precipitation and consequently the watersheds behave differently depending on how much moisture is stored in the watershed. This suggests that saturation excess processes play an important role in the watershed runoff response. If infiltration excess was controlling runoff responses, discharge would only depend on the rate of rainfall, and there would be no clear relationship with antecedent cumulative precipitation, as is clearly the case in Fig. 7.2a.

7.3.2 Infiltration and Precipitation Intensity Measurements

To further investigate the likelihood of infiltration excess, the infiltration rates are compared with rainfall intensities in the Andit Tid watershed where infiltration rates were measured in 2008 by Engda (2009) and rainfall intensity records were available from the SCRP project for 1986–2004 on the pluviometric charts. These were transcribed to digital form by Engda (2009). The exceedance probability of the average intensities of 23,764 storm events is plotted in Fig. 7.3 (dotted black line). These intensities were calculated by dividing the rainfall amount on each day by the duration of the storm. In addition, the exceedance probability for actual intensities of short periods ranging from 5 to 10 min are plotted in Fig. 7.3 (red line). Since there were bursts of high intensity rainfall within each storm, the rainfall intensities for short periods exceeded that of the storm averaged intensities in Fig. 7.3.

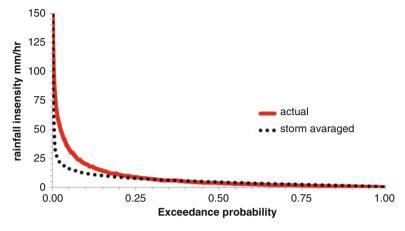


Fig. 7.3 Rainfall intensity exceedance probability for the Andit Tid watershed

Table 7.2 Average soil infiltration rate at different soil types, slope range and land use types

| Testing sites | Location in the watershed | Average IR (mm/h) | Location slope (°) | Soil type | Soil depth | Land use |
|---------------|---------------------------|-------------------|--------------------|--------------------|------------|-------------------------|
| 3 | Тор | 25 | 15 | Andosol | Medium | Fallow grass |
| 5 | Тор | 24 | 15 | Andosol | Medium | Fallow grass |
| 8 | Тор | 594 | 29 | Andososl | Shallow | Bush land |
| 1 | Middle | 226 | 30 | Regosol | Shallow | Terraced and cultivated |
| 2 | Middle | 26 | 21 | Regosol | Deep | Terraced and cultivated |
| 4 | Middle | 140 | 21 | Andosol | Medium | Fallow |
| 7 | Middle | 29 | 21 | Humic andososl | Shallow | Fallow |
| 6 | Bottom | 43 | 10 | Andosol | Deep | Fallow |
| 9 | Bottom | 53 | 2 | Eutric regosol | Medium | Cultivated |
| 10 | Bottom | 870 | 18 | Eutirc cambisol | Medium | Terraced and cultivated |

The infiltration rates for 10 locations measured with the 30-cm diameter single-ring infiltrometer (shown in Table 7.2) varied between a maximum of 87 cm/h on a terraced eutric cambisol in the bottom of the watershed to a low of 2.5 cm/h on a shallow soil near the top of the hill slope. This low infiltration rate was mainly caused by the compaction of free roaming grazing animals. Bush lands, which are dominant on the upper watershed, have significantly higher infiltration rates. Terraced and cultivated lands in general have also higher infiltration rates. The average infiltration rate of all 10 measurements indicates that the storm intensities were 20.3 cm/h and the medium 4.8 cm/h. The median infiltration rate of 4.8 cm/h is the most meaningful number to compare with the rainfall intensity since it represents

a spatial average. This median intensity has an exceedance probability of 0.03 for the actual storm intensities and 0.006 for the storm averaged intensities. Thus, the medium intensity was exceeded only 3% of the time and for less than 1% of the storms. Storms with greater intensities were all of short duration with amounts of less than 1 cm of total precipitation, except once, in which almost 4 cm of rain fell over a 40 min period. The runoff generated during short duration intense rainfall can infiltrate into the soil in the subsequent period down slope when the rainfall intensity is less or the rain has stopped. In the Maybar watershed, Derib (2005) performed 16 infiltration tests and observed even greater infiltration rates than in Andit Tid. The final steady state infiltration rates ranged from 1.9 to 60 cm/h with a median of 17.5 cm/hr.

Thus, the infiltration measurements confirmed that infiltration excess runoff is not a common feature in these watersheds. Consequently, most runoff that occurs in these watersheds is from degraded soils where the top soil is removed and by saturation excess in valley bottoms where the interflow accumulates. Since the degraded soils have little storage, the runoff can be classified as either infiltration excess or saturation excess.

The finding that saturation excess is occurring in watersheds with a monsoonal climate is not unique. For example, Hu et al. (2005), Lange et al. (2003), and Merz et al. (2006) found that saturation excess could describe the flow in a monsoonal climate in China, Spain, and Nepal. There are no previous observations published for Ethiopia on the suitability of these saturation excess models to predict runoff even though attempts to fit regular models based on infiltration excess principles were not always satisfactory (Haregeweyn and Yohannes, 2003; Zeleke, 2000).

7.3.3 Piezometers and Ground Water Table Measurements

Ground water table height measurements allow us to determine how the rain that falls on the upslope areas reaches the river. In all three watersheds, transects of piezometers were installed and ground water tables were observed in the 2008 main rainy season.

Both Andit Tid and Maybar have hill slopes with shallow to medium depth soils (0.5–2.0 m depth) above a sloping slowly permeable layer (either a hardpan or bedrock). Consequently, the water table height above the slowly permeable horizon (as indicated by the piezometers) behaved similarly for both watersheds. An example is given for the Maybar watershed where ground water table levels were measured with 29 piezometers across eight transects. The whole watershed was divided into three slope ranges: upper steep slope [25.1°–53.0°], mid slope [14.0°–25.0°], and relatively low-lying areas [0°–14.0°]. For each slope class, the daily perched ground water depths were averaged (i.e., the height of the saturated layer above the restricting layer, Fig. 7.4a). The depth of the perched ground water above the restricting layer in the steep and upper parts of the watershed is very small and disappears if there is no rain for a few days. The depth of the perched water table on

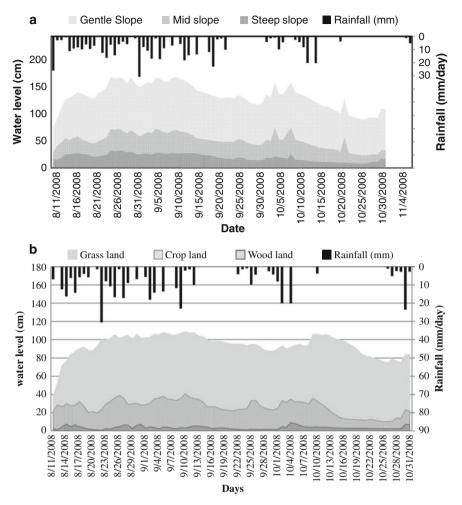


Fig. 7.4 Water table height measured in the Maybar watershed during the 2008 rainy season and start of dry season. **a** Effect of slope on water table heights; **b** land use effects on the water table heights

the mid slopes is greater than upslope areas. The perched ground water depths are, as expected, the greatest in relatively low-lying areas. Springs occur at the locations where the depth from the surface to the impermeable layer is the same as the depth of the perched water table and are the areas that the surface runoff is generated.

The water table behavior is consistent with what one would expect if interflow is the dominant conveyance mechanism. All else being equal, the greater the driving force (i.e., the slope of the impermeable layer), the smaller the perched ground water depth required to transport a given quantity of water downslope. Moreover, the drainage area and the discharge increase with down slope position. Consequently,

one expects that the perched groundwater table depth increases with down slope position as both slope decreases and drainage area increases.

These findings are different than those generally believed to be the case, i.e., that the vegetation determines the amount of runoff in the watershed. We therefore plotted the average daily depth of the perched water table under the different crop types (Fig. 7.4b). Unexpectedly, there was a strong correlation of perched water depth with crop type as well. The grassland had the greatest perched water table depth, followed by cropland and bush land with the lowest ground water level. However, some local knowledge was needed to interpret these data, as the grasslands are mainly located in the often saturated lower lying areas (too wet to grow a crop), the croplands are in the mid-slope (with a consistent water supply but not saturated) and the bush lands are in the upper steep slope areas (too droughty for good yield). Since land use is related to slope class, we expect the same relationship between crop type and soil water table height as slope class and water table height. Thus, there is an indirect relationship between land use and hydrology determined by the landscape features. The landscape determines the water availability and thus the land use.

In the Anjeni watershed, which had relatively deep soils and no flat bottom land, the only water table that was found was near the stream. The water table level was above the stream level indicating that the rainfall infiltrates the landscape first and then flows laterally to the stream. Although more measurements are needed, we speculate that there was a portion of the watershed that had a hard pan at a relative shallow depth causing saturation excess overland flow.

These findings are consistent with the measurements taken by McHugh (2006) in the Lenche Dima watershed near Woldea where the surface runoff of the flat bottom lands was much greater than the runoff (and erosion) from the hillsides. Thus, in summary, the generally held opinion that the hill slopes are the high surface runoff producing areas is not true, at least at a minimum, for the season of observation in the three watersheds. The only areas that are expected to produce surface runoff are the severely eroded areas where the bedrock or subsoil is exposed and other areas that saturate during the storms.

7.3.4 Conceptual Model for Predicting Watershed Discharge

In order to develop a realistic hydrological model, the interflow and saturation excess flow phenomena must be included. In our conceptual watershed model, the watershed is divided into three areas based on slope steepness, soil depth, and infiltration capacity of the soil. Surface runoff source areas include areas near the river and the degraded hillsides with little or no soil cover. The well-drained hillsides transmit water as interflow to the stream and are modeled as the third component. Both the degraded and the bottom lands produce surface runoff after they are saturated. For a better understanding of the processes, the three areas are schematically superimposed on a photograph of the upper part of the Andit Tid watershed (Fig. 7.5). In addition to the three surface areas modeled, we included a subsurface reservoir that generates baseflow.

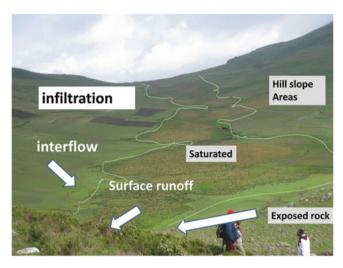


Fig. 7.5 Conceptual model for predicting watershed discharge superimposed on the upper Andit Tid watershed

For each of the three source areas, a water balance is kept in the model

$$S = S_{t-\Delta t} + (P - AET - R - Perc)\Delta t \tag{7.1}$$

where P is precipitation (mm/day); AET is the actual evapotranspiration (mm/day), $S_{t-\Delta t}$, previous time step storage (mm), R saturation excess runoff (mm/day), Perc is percolation to the subsoil (mm/day) and Δt is the time step.

Based on a linearly decreasing evaporation rate from the maximum moisture content at saturation or field capacity to wilting point, the surface soil layer moisture storage can be written as:

$$S_s = S_{t-\Delta t} \left[exp \frac{(P - PET\Delta t)}{S_{max}} \right] \quad when p < PET$$
 (7.2)

where S_{max} (mm) is the maximum available soil storage capacity and is defined as the difference between the amount of water stored in the topsoil layer at wilting point and the maximum moisture content, equal to either the field capacity for the hill slope soils or saturation (e.g., soil porosity) in runoff contributing areas. S_{max} varies according to soil characteristics (e.g., porosity, bulk density) and soil layer depth.

By assigning a maximum storage to each of the three source areas, a water balance is maintained for each of the watershed source areas. Surface runoff occurs from the degraded hillsides and the valley bottom when the water balance indicates that the soil is saturated. The flatter areas remain wet even during dry months of the year; only the top most soil layer will dry due to small amounts of water percolating downward from the hills. Hence, these areas need only a small amount of rainfall to

start generating surface runoff. There is even less rainfall needed at the beginning of the rainy season for the degraded hillsides to produce surface runoff

Interflow is generated by the excess rainfall when the hillside is at field capacity. Because these hillsides drain fully and are at or near the wilting point before the rainy season, a significant amount (on the order of 300–400 mm) of effective rainfall (defined as precipitation minus potential evapotranspiration) is needed before the interflow starts to contribute to the lower slope areas. The interflow can be modeled as a zero reservoir. This means that the same quantity of water drains from the hillside each day for each storm. The result is in a linear recession curve. The outflow from different storms is superimposed. Finally, the baseflow is modeled as a linear reservoir with a maximum storage. This base flow reservoir adds water to the stream during the dry period.

This model is similar to that developed by Steenhuis et al. (2009) for the whole Ethiopian Blue Nile Basin but slightly different from Collick et al. (2009) who tested a similar water balance model for the same three SCRP watersheds. Collick et al. (2009), using the semi distributed model, did not have particular landscape units in mind but fitted four areas that produced runoff and interflow based on specific ratios. Our current semi distributed model for the Ethiopian Highlands is more physical based and we do not need to specify a ratio between surface runoff and percolation of water.

7.4 Simulation Results

The mathematics for this conceptual model is presented in Steenhuis et al. (2009). The mathematical model was calibrated for each of the three watersheds by Legesse (2009) for Anjeni, by Bayabil (2009) for Maybar, by Engda (2009) for Andit Tid, and by Steenhuis et al. (2009) for the whole Blue Nile Basin. We will present in this chapter the results for two of the years between 1992 and 1995 depending on what quality data was available for each of the three SCRP watersheds. Parameters were slightly adjusted to represent the period after which the conservation practices were in place.

Parameters needed to simulate discharge include potential evaporation (PET), which varies little between years and between watersheds. On average, PET was 5 mm/day during the dry season and 3 mm/day during the rainy season. The precipitation values used were measured for the small SCRP watershed with rain gauges in the watershed itself and for the whole Blue Nile Basin, the average of 10 stations were used.

For calibration, the maximum storage values, S_{max} , for the contributing areas and hill slopes were based initially on the values of Steenhuis et al. (2009) for the whole Blue Nile Basin. S_{max} values for the three source areas were then varied around these values to obtain the best fit. Subsurface parameters were adjusted at the same time to fit the recession flows. The parameter set with the highest Nash Sutcliff efficiency was selected. The validation used the most optimum parameter set.

Table 7.3 Model input values for surface flow components for the three SCRP watersheds and the Nile upstream of the border with Sudan. The watershed is divided into regions with different characteristics: exposed bedrock and saturated areas that contribute surface runoff when the soil is saturated or hillsides that produce recharge when the soil is above field capacity. Maximum storage of water is the amount of water needed above wilting point to become either saturated (runoff contributing areas) or to reach field capacity (*hill slopes*). Model input values for the baseflow and interflow reservoirs are the maximum storage of the linear base flow reservoir; the time in days to reduce the volume of the baseflow reservoir to half under no recharge conditions, t* is the duration of the period after a single rainstorm until interflow ceases, Nash-Sutcliffe efficiency for simulated daily averaged discharge for the three SCRP watersheds and 10 day average values for the Blue Nile basin were calculated for the periods of calibration and validation

| | Maybar | Andit Tid | Anjeni | Nile in ¹ Ethiopia | Type of source area |
|-----------------------------------|--------|--------------|--------|----------------------------------|------------------------|
| Valley bottom portion of area | 0.23 | 0.1 | 0 | 0.1 | Surface runoff |
| Max storage (mm) | 110 | 90 | _ | 250 | |
| Degraded hill portion of area | 0.01 | 0.05 | 0.2 | 0.2 | Surface runoff |
| Max storage (mm) | 20 | 20 | 150 | 10 | |
| Hillside portion of area | 0.50 | 0.85 | 0.6 | 0.7 | Interflow and baseflow |
| Max storage (mm) | 150 | 150 | 250 | 500 | |
| Max storage linear reservoir (mm) | 80 | 90 | 70 | 20 | |
| Half life linear reservoir (days) | 60 | 70 | 70 | 140 | |
| Drainage time hillsides (days) | 3 | 10 | 20 | 35 | |
| Nash Sutcliff | 0.78 | 0.80 | 0.88 | 0.60 | |

¹Ten day intervals.

The optimum parameter set for each of the three basins and for the Ethiopian highlands are shown in Table 7.3 and the comparison of observed versus predicted values for the SCRP watersheds are shown in Fig. 7.6a, b, c. The model fit the observed data well for the SCRP watersheds with Nash Sutcliffe efficiencies for daily values in the range of 0.78–0.88 (Table 7.3) for the small watersheds. Due to difficulties with obtaining a true average rainfall for the whole Blue Nile Basin, Nash Sutcliffe efficiency for the Blue Nile Basin was lower.

The parameter values for all three SCRP watersheds fall in the same range: 0–23% for the saturated bottom lands with a maximum storage of 110 mm; 0–20% for the degraded lands with storage values less than 150 mm; and 50–75% for the hillsides with storages up to 250 mm. The degraded land in the Anjeni watersheds consists of agricultural soils on terraced land, which soil has a restricting layer at shallow depths. In Maybar and Andit Tid, the degraded soils consist of both exposed hardpan areas and slipping hillside areas. Maybar has less of the soils than Andit Tid. This is the reason that the maximum storage for Anjeni is greater than for the other two watersheds.

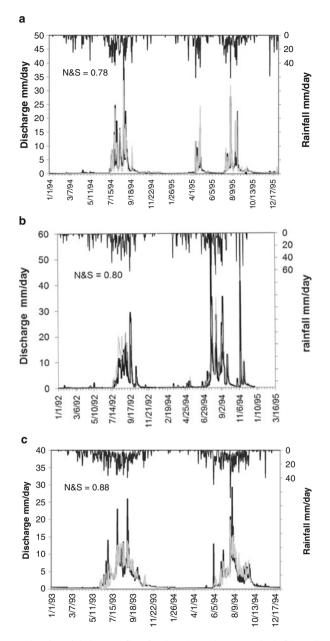


Fig. 7.6 Measured and modeled streamflow for the **(a)** Maybar watershed, **(b)** Andit Tid watershed and **(c)** Anjeni watershed. The *light grey line* is the simulated discharge values and the *thick black curve* is observed runoff. The *thin black line* is the surface runoff. N&S is the Nash Sutcliffe efficiency

Good fits were obtained between simulated and observed values for both the daily calibration and validation periods. However, the model underestimates most peak flow periods for Anjeni and Andit Tid (Fig. 7.6b, c). Water balance type models have difficulty handling intense convective storms or events of very short duration but high intensity rainfall. In addition, it is likely that a larger part of the hillside contributed to the flow than initialized in the model structure in which the watershed is divided in three regions. Seasonal variations in rainfall amount and distribution may affect the extent of saturated areas and thereby stream flow generation. Several researchers point out that the dynamic variation of stream zone saturated areas due to accumulation of lateral water flow from upslope and the ground water system is responsible for a highly non-linear catchment response during storm events (Todini, 1995; Bari and Smettem, 2004). Adding a fourth region that can saturate during large storm events may produce better estimates for these high runoff events.

The variation among the parameters was in agreement with the landscape characteristics. In Maybar, the model fitting indicated that there were almost no degraded hill slopes. For the Anjeni watershed that had a deep gully and ground water tables generally at least 2 m below the surface, the model fit the data best if there was no saturated area included. Note also that for the two smallest watersheds, Maybar and Anjeni, the portions of the three modeled areas (Table 7.3) of the total watershed area did not add up to one because of regional flows where water drained under the gage. But, for the whole Blue Nile Basin and Andit Tid, the water balance closed and the portions of the total area summed to one. Finally, the magnitude of the subsurface parameters increased with the size of the watershed as expected because as watershed size increases, more deep flow paths become activated in transport.

7.5 Conclusions

Direct runoff is generated either from saturated areas at the lower portions of the hill slopes or from areas of exposed bedrock while the upper hill slopes are infiltration zones. As a result, the watersheds were divided into variable saturated areas, exposed rock and hill slopes. This was verified by high measured infiltration rates on hill slope areas and shallow ground water depth at the bottom flat lands. Other findings showed that the lower slope areas produced high runoff compared to high slopes for a given rainfall event. The discharge in each of three watersheds was modeled by separately using a simple water balance type model for degraded hillsides, saturated areas, and non-degraded hillsides. The main input data for the model are rainfall, evaporation, the relative magnitude of the three areas, and soil water holding capacity for the three areas. In addition, interflow and baseflow constants are needed. The model results were encouraging, not only for the three small watersheds, but for the Blue Nile watershed at the Ethiopian-Sudan border as well. The model has the potential to predict runoff in ungauged basins using a small amount of field data.

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References

- Arseno Y, Tamrat I (2005) Ethiopia and the Eastern Nile basin. Aquat Sci 16:15-27
- Ayenew T, Gebreegziabher Y (2006) Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. Hydrol Sci 51(3):418–431
- Bari M, Smettem KRJ (2004) Modeling monthly runoff generation processes following land use changes: ground water-surface runoff interactions. Hydrol Earth Sys Sci 8(5):903–922
- Bayabil HK (2009) Modeling rainfall runoff relationships at Maybar watershed, Wollo, Ethiopia. Master Thesis, Integrated Watershed Management and Hydrology Program, Cornell University, Bahir Dar Ethiopia and Ithaca, NY
- Bosshart U (1997) Measurement of River discharge for the SCRP research Catchments: gauging station profiles. Soil conservation research project, Research reports 31 University of Bern, Bern
- Collick AS, Easton ZM, Engda TA, Ashagrie BB, Adgo E, Awulachew SB, Zeleke G, Steenhuis TS (2009) Application of physically based water balance model on four watersheds throughout the upper Nile basin in Ethiopia. Hydrol Process 23:3718–3727
- Conway D (1997) A water balance model of the upper Blue Nile in Ethiopia. Hydrol Sci 42: 265-282
- Conway D, Hulme M (1993) Recent fluctuations in precipitation and runoff over the Nile sub-basins and their impact on main Nile discharge. Clim Change 25:127–151
- Derib SD (2005) Rainfall-runoff processes at a hill-slope watershed: case of simple models evaluation at Kori-Sheleko Catchments of Wollo, Ethiopia. M.Sc. Thesis
- Desta G (2003) Estimation of runoff coefficient at different growth stages of crops in the highlands of Amhara Region. M.Sc. Thesis, Alemaya University, Ethiopia
- Engda TA (2009) Modeling rainfall-runoff-soil loss relationships of North-eastern Highlands of Ethiopia, Andit Tid watershed, Ethiopia. Master Thesis, Integrated Watershed Management and Hydrology Program, Cornell University, Bahir Dar Ethiopia and Ithaca, NY
- Haregeweyn N, Yohannes F (2003) Testing and evaluation of the agricultural non-point source pollution model (AGNPS) on Augucho catchment, western Hararghe, Ethiopia. Agric Ecosyst Environ 99:201–212
- Hu CH, Guo SL, Xiong LH, Peng DZ (2005) A modified Xinanjiang model and its application in northern China. Nordic Hydrol 3:175–192
- Hurni H (1984) The third progress report. Soil conservation research project, Vol.4. University of Bern and the United Nations University. Ministry of Agriculture, Addis Ababa, Ethiopia
- Ibrahim AM (1984) The Nile description, hydrology, control and utilization. Hydrobiologia 110:1-13
- Kebede S, Travi Y, Alemayehu T, Marc V (2006) Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. J Hydrol 316:233–247
- Kim U, Kaluarachchi JJ (2008) Application of parameter estimation and regionalization methodologies to ungauged basins of the Upper Blue Nile River Basin, Ethiopia. J Hydrol 362:39–52

Lange J, Greenbaum N, Husary S, Ghanem M, Leibundgut C, Schick AP (2003) Runoff generation from successive simulated rainfalls on a rocky, semi-arid, Mediterranean hillslope. Hydrol Process 17:279–296

- Legesse D, Vallet-Coulomb C, Gasse F (2003) Hydrological response of a catchment to climate and lane use changes in tropical Africa: case study south central Ethiopia. J Hydrol 275:67–85
- Leggesse ES (2009) Modeling rainfall-runoff relationships for the Anjeni watershed in the Blue Nile basin, Ethiopia. Master Thesis, Integrated Watershed Management and Hydrology Program, Cornell University, Bahir Dar Ethiopia and Ithaca, NY, USA
- Liu BM, Abebe Y, McHugh OV, Collick AS, Gebrekidan B, Steenhuis TS (2008) Overcoming limited information through participatory watershed management: case study in Amhara, Ethiopia. Phys Chem Earth 33:13–21
- McHugh OV (2006) Integrated water resources assessment and management in a droughtprone watershed in the Ethiopian highlands. PhD dissertation, Department of Biological and Environmental Engineering. Cornell University, Ithaca, NY
- Merz J, Dangol PM, Dhakal MP, Dongol BS, Nakarmi G, Weingartner R (2006) Rainfall-runoff events in a middle mountain catchment of Nepal. J Hydrol 331(3–4):446–458
- Mohammed A, Yohannes F, Zeleke G (2004) Validation of agricultural non-point source (AGNPS) pollution model in Kori watershed, South Wollo, Ethiopia. Int J Appl Earth Obs Geoinf 6: 97–109
- Setegn SG, Srinivasan R, Dargahi B (2008) Hydrological modeling in the Lake Tana Basin, Ethiopia using SWAT model. Open Hydrol J 2:49–62
- Steenhuis TS, Collick AS, Easton ZM, Leggesse ES, Bayabil HK, White ED, Awulachew SB, Adgo E, Ahmed AA (2009) Predicting discharge and erosion for the Abay (Blue Nile) with a simple model. Hydrol Process 23:3728–3737
- Sutcliffe JV, Parks YP (1999) The hydrology of the Nile. IAHS Special Publication 5, Wallingford, 180pp
- Todini E (1995) The ARNO rainfall-runoff model. J Hydrol 175:339–382
- Zeleke G (2000). Landscape dynamics and soil erosion process modeling in the North-western Ethiopian Highlands. African Studies Series A 16, Geographica Bernensia, Berne