Are Runoff Processes Ecologically or Topographically Driven in the (Sub) Humid Ethiopian Highlands? The Case of the Maybar Watershed

Haimanote K. Bayabil[1], Seifu A. Tilahun[2,3], Amy S. Collick[2,3] , Birru Yitaferu[4] and Tammo S. Steenhuis[2,3*]

[1] Master's Program in Integrated Watershed Management and Hydrology, Cornell University, Bahir Dar, Ethiopia
[2] Department of Biological and Environmental Engineering, Cornell University, Ithaca NY USA
[3] School of Civil and Water Resources Engineering, Bahir Dar University Bahir Dar Ethiopia
[4] Soil and Water Research Directorate, Amhara Region Agricultural. Research Institute, Bahir Dar Ethiopia

ABSTRACT

Understanding the basic runoff processes in the Ethiopian highlands is vital for effective management and utilization of water resources and soil conservation planning. An important question for judging effectiveness of conservation practices is whether runoff is affected by ecology (mainly type of crop) or topography (landscape). A study was conducted in the 113 ha watershed of Maybar, located in the highlands. This watershed has long-term records of rainfall and discharge. To study runoff processes, piezometers were installed in eight transects up and down the slope. In addition, infiltration rates (measured earlier) were compared with rainfall intensities. The results show that the amount of runoff at the test plots was greater for cropland located on mild to intermediate slopes than for grass and wood lands on the steeper slopes. Water tables were closer to the surface on cropland for the mild to intermediate slopes than on grass and in woods for the steeper slopes. Thus, although water table depths and plot runoff were inconclusive on the type of runoff mechanisms, infiltration rates that were generally in excess of the rainfall rates imply that any ecological effect on the amount of surface runoff is small. This is because water infiltration is independent of crop type. Only in cases where the soil was saturated does runoff occur. Piezometer readings show that saturation occurs at the foot of the steep slopes and therefore demonstrates that topographic processes are dominant. Ecology becomes important when infiltration rates are in the same order as the rainfall intensities.

Published as: Bayabil, Haimanote K., Seifu A. Tilahun, Amy .S. Collick and Tammo .S. Steenhuis. 2010. Are runoff processes ecologically or topographically driven in the Ethiopian Highlands?: the case of the Mayabar watershed2010 Ecohydrology 3 , pp. 457-466

INTRODUCTION

The Ethiopian highlands, which are the center of major agricultural and economic activities, are the source of much of the water flowing into the lowlands, which includes Sudan and Egypt. For example, the Blue Nile River (*Abbay*) basin contributes more than 60% of the Nile flow (Ibrahim 1984; Conway and Hulme 1993) and increases up to 95% during the rainy season (Ibrahim 1984). It has experienced soil loss of approximately 140 million tons per year, or approximately 7 tons per hectare per year, which is 60% of the total Nile sediment (Garzanti et al 2006).

In the Ethiopian highlands, all suitable agricultural areas, in addition to less suitable, marginal lands on erodible slopes, are intensely cultivated in order to meet the demands for food by an ever increasing population (Hurni 1988; Bewket and Sterk 2003). Many traditional soil and water conservation practices are in use. These include shallow furrows that carry any excess water down the slope without causing excessive erosion. With the inception of the Soil and Conservation Research Program (SCRP), formal soil and water conservation practices have been implemented since the 1980s. The SCRP was established in 1981 by the Swiss Agency for Development and Cooperation aiding the Ethiopian government in its efforts to improve the soil and water conservation activities employed to counteract land degradation (SCRP 2000).

Current soil and water conservation practices brought about a considerable reduction in soil loss and runoff (Herweg and Ludi 1999); however, the impacts of these efforts were far below expectations and soil erosion continued to be a serious problem. This is partly because of a lack of consideration for local conservation and farming practices (Amsalu and Graaff 2006) and lack of consideration for the different climatic zones and runoff source areas. Mitiku, et al. (2006) states that 36% of all erosion is caused by inappropriate soil and water conservation practices.

Climate zones are important in choosing the type and location of conservation measures. In semi -arid areas in Ethiopia (rainfall of less than 500 mm/year), water conservation is the most important function while in sub -humid (rainfall of between 500 and 1300 mm/year) and humid areas (over 1300 mm/year of rainfall), water conservation during low rainfall years and drainage of excess water during wet years should be used. In all cases, the landscape should be protected from erosion, especially during heavy storms (Mitiku et al 2006; Herweg and Ludi 1999).

The effectiveness of a soil and water conservation practice depends whether watershed runoff processes are ecologically or topographically based. Inherent in the assumption of ecological based runoff processes is the concept of infiltration excess overland flow in which runoff occurs when rainfall intensity exceeds the infiltration capacity of the soil. Thus, for ecological based models, improving plant cover and soil health will, in general, reduce overland flow and increase infiltration and interflow. On the other hand, topographical-based runoff processes are, in general, based on the principle that if the soil saturates either above a slowly permeable layer or a ground water table, runoff occurs. In this case, changing plant cover will have little effect on runoff unless either the conductivity of the most restricting layer or interception of rainfall by the plants is altered. These areas, which saturate easily, are called runoff source areas. They indicate where soil and water conservation practices preventing erosion would be most effective because the majority of erosion originates in these areas. For example, keeping these areas in permanent vegetation and out of agricultural production would reduce erosion.

Models are currently being used in many aspects of planning and in studying the effect of soil and water conservation practices. Most models, such as Soil and Water Assessment Tool (SWAT) (Setegn, et al. 2008), Water Erosion Prediction Project (WEPP) (Zeleke 2000), and the Agricultural Non-Point Source model (AGNPS) (Haregeweyn and Yohannes 2003; Mohammed, et al. 2004), applied in the Ethiopian highlands to indicate appropriate sites for soil and water conservation practices are mostly ecologically based. This is because they are based both on the US Soil Conservation Service (SCS) curve number approach and the universal soil loss equation (USLE). In the SCS equation plant cover, soil type and hydrological condition are part of the “eco” system. Only antecedent rainfall is a physical parameter. In the USLE, ecological factors (plant cover and soil type) are combined with topographical factors (slope and length) and a physical factor representing the kinetic energy of rainfall. These models can reasonably predict monthly values but fail to predict daily runoff and erosion values (Steenhuis, et al 2009). In addition, the values in both the SCS equation and the USLE are derived statistically from plot data in the US with a temperate climate. Models that can predict runoff in periods shorter than a month were written by Collick, et al. (2009) for four small watersheds in the Ethiopian highlands and by Steenhuis, et al. 2009 for the whole Blue Nile Basin in Ethiopia. Both models use a semi-distributed, topographically- derived water balance model which is based on saturation excess runoff mechanisms and identifying exposed hardpan (bed rock) and valley bottom as runoff producing areas. This topographical concept, although providing reasonable runoff predictions, has not been experimentally validated.

The objective of this paper is to identify whether ecological and/or topographical factors determine the runoff processes in the sub -humid Ethiopian highlands. Since only the Maybar watershed, with annual rainfall amounts averaging 1325 mm per year, is studied, we cannot apply our findings to all of the Ethiopian highlands, especially those in the semi -arid areas. But our results will be valid at least for a portion of Ethiopia where the rainfall exceeds the potential evaporation during the majority of the rainfall season. More studies are needed to determine how widely our results will be applicable.

MATERIAL AND METHODS

Site Description

Maybar (Figure 1) is located in the sub -humid northeastern part of the central Ethiopian highlands situated in Southern Wollo Administrative Zone near Dessie Town. Maybar watershed consists of two different parts (Figure 2) connected by a channel through a rock area. It is the first of the SCRP research sites and is located at the Kori River, the main river in the Kori Sheleko catchment, which is the main inflow to Lake Maybar. The whole of the Maybar Watershed drains into to the Borkena River, ultimately flowing to the Awash River basin. The gauging station is located at 39°39’ E and 10°51’ N and is approximately a distance of 0.5 km uphill of Lake Maybar.

The area is characterized by highly rugged topography with steep slopes ranging between 2530 and 2860 m, a 330 m altitude difference within a 113 ha catchment area. Slopes range from over 64 % to less than 6%. The soil types in Maybar watershed are sandy clay loam covering 80% of the watershed, and the rest is clay loam (see auxiliary material A1). The soils are developed from the alkali-olive basalts and tuffs of the Ashangi group, which are part of the tertiary volcanic trap series (Weigel, 1986). The sandy clay loam, located on steep slopes, is shallow Phaeozems, associated with Lithosols (soil depth 0-50 cm, with an average of about 15 cm), and is mostly excessively drained and well structured (Mitiku et al, 2006). The clay loam, located on gently flat slopes, is moderately deep to deep Haplic Phaeozems.

According to Hurni, et al. (2005), approximately 60% of the total catchment area is cultivated whereas 20% is woodland and 20% is grassland. The grassland is mainly located on the lower and flatter slopes. The croplands are generally at mid-slope and the grass and woodlands are near the divide of the watershed and on the shallowest soils. The people of the Maybar catchment exercise a rain fed, subsistence -oriented mixed crop-livestock production farming system with ox -drawn farm implements. The major crops are tef, wheat, barley, pulses and maize on an average land holding of 0.5 to 1 ha per household.

The Maybar research watershed receives an average annual rainfall of 1325 mm/y, which was calculated from 11 years of available data, and has an average runoff coefficient of 0.30. Soil losses on plots is estimated to be 32 to 36 t/ha·y and sediment yield from the catchment is 12 t/ha·y (Mitiku et al. 2006).

DATA AND METHODOLOGY

Infiltration rate and precipitation intensity: In order to understand whether runoff processes in the Ethiopian highlands are topographically or ecologically driven, information from plot runoff, rainfall intensity, and soil infiltration capacity in Maybar watershed were collected.

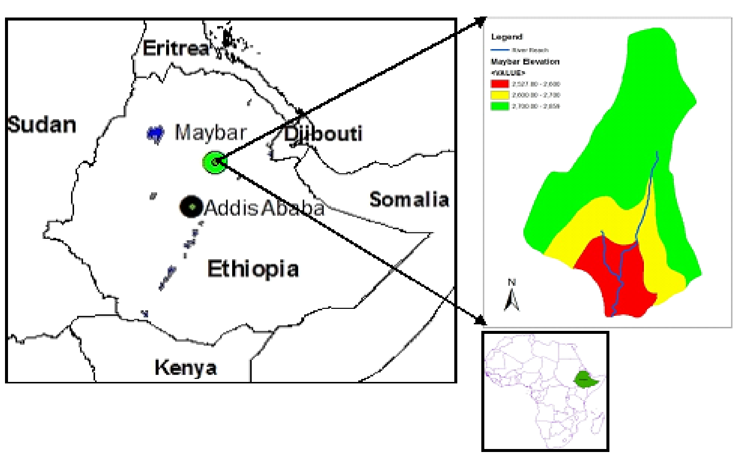

Figure 1: Location, watershed boundary and drainage map of Maybar Watershed

Figure 2 Photo (a): Lower portion of the watershed with wet area located in the foreground, the trees mark the river going to the upper portion of the watershed (not visible); Photo (b): Upper part of the watershed with unsaturated hillsides and bottom l

Infiltration measurements were carried out with a double ring infiltrometer in a previous study by Derib (2005) in 2004 in the Maybar watershed and the results were applied in this study. Rainfall intensity (1996-2004, except data for 2002 and 2003) was obtained from calculation of continuous pluviograph recordings by dividing the amount of storm rainfall by its duration.

Runoff: Discharges were collected from four test plots from 1988 to 1994. Each test plot covered a 2 m x 15 m area and represented different land use areas and different slope gradients. Test plots 1 and 4 were located on cultivated land with slopes of 16% and 37%while Test plots 2 and 3 were located on grassland and woodland with slopes of 64% and 43%. Surface runoff water was collected in a tank. Water was removed within 24 hours when the rainfall was in excess of 12.5 mm in less than six

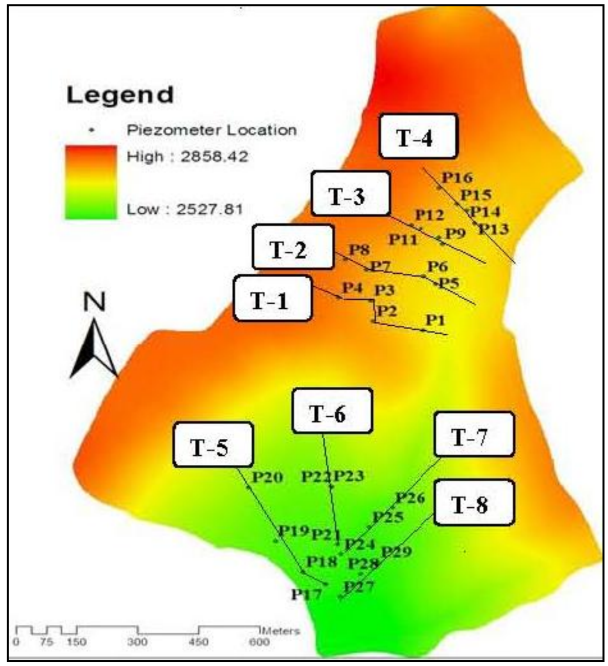

Figure 3: Location of piezometer transects superimposed on the topographic map. T stands for transects and P stands for piezometers

hours or if the water depth in the collection tank was more than 25.5 cm. The discharge at the watershed outlet was determined continuously with a flume for the period 1988–1989, 1992-2000, 2002, 2004 and 2008 using a chart recorder for measuring water heights. Manual measurements were made during runoff events in case the chart recorder failed.

Perched ground water levels: Perched water tables were measured with 29 piezometers twice a day during the 2008 main rainy season. Since there was no prior knowledge on the water table heights in the Ethiopian Highlands, the piezometers were installed from the top of the hill slope down to the saturated area near the river in eight transects throughout the watershed at approximate equal distances for each transect between the river and the watershed boundary. This resulted in 4 transects with 16 piezometers in the upper watershed and 13 piezometers in 4 transects in the lower watershed (near the gauging station, Figure 3). In case the distance between the river and watershed boundary was relatively short only 3 piezometers were used per transect. An “Idle Man Auger” was used to drill the holes for installing the piezometers. On the hillsides, drilling was stopped when it became more difficult, indicating that the impermeable layer had been reached. In the deep valley bottom soils, piezometers were installed to just below the water table. The piezometers consisted of 5 cm diameter PVC pipes and were installed to the top of the restricting layer ranging from 0.65 to 2.0 m. The bottom 30 cm of the piezometers were perforated and covered with cloth allowing water inflow towards the tubes but preventing inflow of sediment. The bottom end (opening) of the pipe was closed with a plastic cap and sealed with a plastic bandage to block inflow and outflow of water. The above ground opening of the piezometers was capped to protect against the entrance of rainfall. Water level response was measured twice a day using a stick.

Mapping: The saturated area in the watershed during the wettest part of the year (in August) was delineated and mapped by combining information collected using a Global Positioning System (GPS) instrument, field observation, and ground water level data (piezometer head readings).

Topographic index maps: Finally to examine whether the location of the saturated areas were in accordance with the concept of the topographically derived runoff processes, topographic index maps based on 10 by 10 m grid cells were derived from the digital elevation model (DEM).

From the several topographic indices that have been employed to find the runoff source areas within a watershed, the topographic index developed by Beven and Kirkby, (1979) is used and modified by Walter et al (2002) for shallow hill slope soils. It is represented by the following equation.

where λ is the topographic index, A is the upslope area per unit length of contour line, R is the average recharge rate, Ks is the saturated hydraulic conductivity, D is depth to the slowly permeable layer and α is slope of the hillside. Because detailed values of in situ hydraulic conductivities were not available. A simplified topographic index (Eq. 1) for each 10 by 10 m grid cell was calculated as the quotient of upslope contributing area per unit length of contour and divided by the slope of the cell. This gives valid results since the slopes of watershed changed by nearly two orders of magnitude while the transmissivity (defined as the product of saturated conductivity and soil depth above the restricting layer) varied one order. Moreover, the steep and moderate slopes consisted of sandy loam soils with relatively greater conductivities than the flat slopes with the clay loam soils. Either soil or groundwater depth was less than 1 m Since transmissivity and slope are both in the denumerator of Eq. 1, they enforce each other (i.e., making the small Topographic Index (TI) values lower and high TI values greater in the case transmissivity values were included in the topographic index calculations).

RESULTS AND DISCUSSION

Rainfall Intensity and Soil Infiltration Rate: One of the main considerations in understanding whether the runoff processes are ecologically or topographically driven is by comparing the infiltration rate of soil to the prevailing rainfall intensities. The steady state infiltration rates at the end of the experiment measured by Derib (2005) for the Maybar watershed ranged from 19 to 600 mm/hr. The average steady state infiltration rate of all 16 measurements was 4 mm/min and the median was 3 mm/min. or approximately 180 mm/hr.

The average daily rainfall intensity for seven years (1996-2004, except data from 2002 and 2003) was 8.5 mm/h. The rainfall intensity is defined as the amount of rainfall divided by the duration of the storm. Comparing means of precipitation intensities and steady infiltration rates is not meaningful. A more meaningful assessment consists of equating the geometric mean infiltration rate with the probability that a rainfall intensity of the same or greater magnitude occurs. The geometric mean is the spatially averaged infiltration rate, and the exceedance probability of average rainfall intensities of 869 storm events is plotted in Figure 4. From the figure, the median steady state infiltration rate is not exceeded while the minimum infiltration rate is exceeded only 9% of the time. Thus, only during the most intense storms overland flow is produced

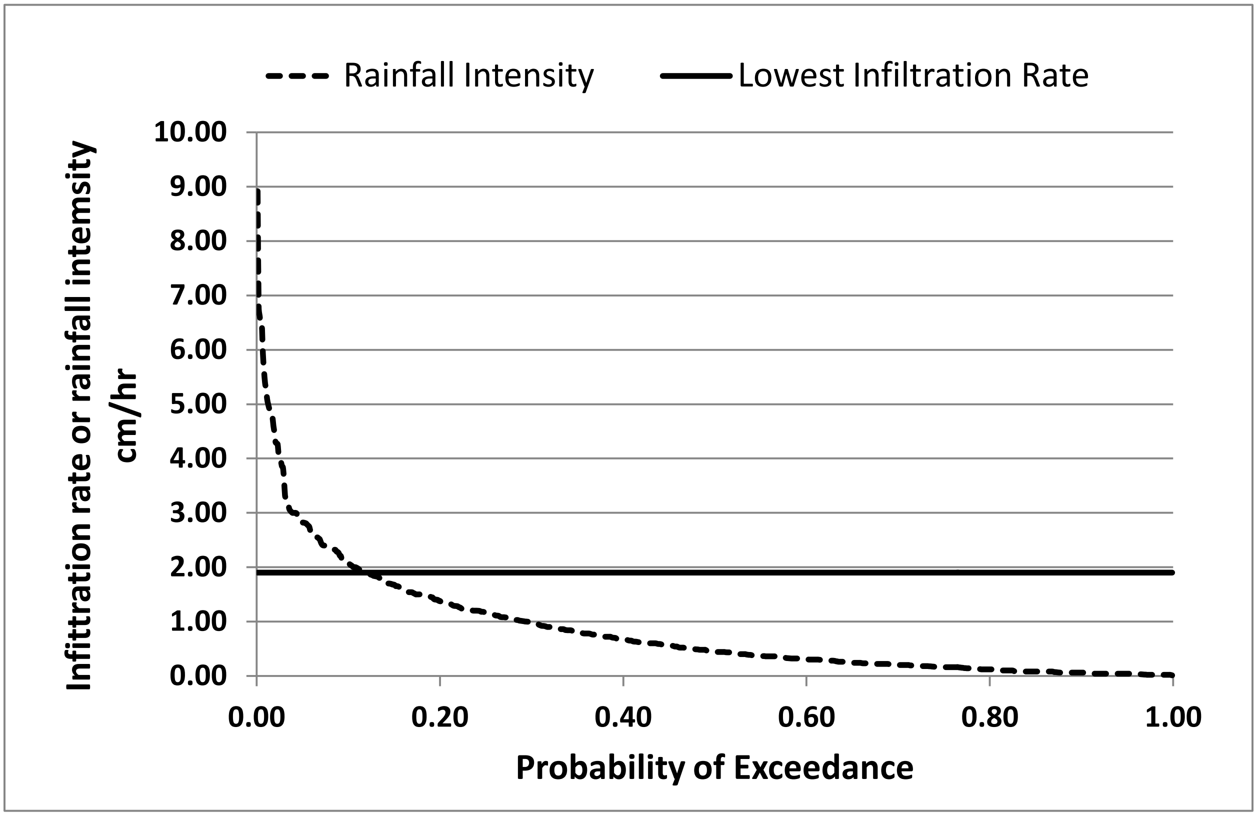

Figure 4: The exceedance probability of the average intensities of 869 storm events and lowest infiltration rate

on the soils with the minimum infiltration rates. Hence, improving infiltration rates by ecological measures would reduce overland flow on these soils, but on the majority of watershed ecological measures would have no effect since in almost all other times, the surface runoff observed in the watershed originates from saturated areas where despite the high infiltration rates, the water cannot infiltrate because the pores are filled with water. Areas saturate at locations in the landscape where the flow uphill is greater than the flow downhill. This can occur at locations where the slope decreases, in concave areas and where the permeable soil over the restricting layer becomes shallower. In addition if the impermeable layer is very shallow, the rain by itself can saturate the soil. Thus the overland flow is topographically driven, because it is dependent on the position where it is located in the landscape and independent of the plant cover as long as the infiltration capacity is greater than the rainfall intensity. Locally, there can be exceptions. For example, when the large pores are destroyed by trampling of cattle, the infiltration is reduced. Removing the cattle will increase the infiltration rate and decrease runoff (Nyssen et al. 2010).

The concept of topographic induced runoff is also confirmed by the data in Figure 5 where the average monthly rainfall and runoff over a 13-year period is plotted together with the runoff coefficients. In this case, the runoff is both surface and subsurface flow (i.e., interflow and baseflow). The runoff coefficients generally increase during the main rainy season starting in July and then decrease after September, indicating that the wetness of the watershed and the extent of the saturated areas (caused by topographical factors) are likely a better estimator for total runoff than rainfall intensity (related to ecological driven factors).

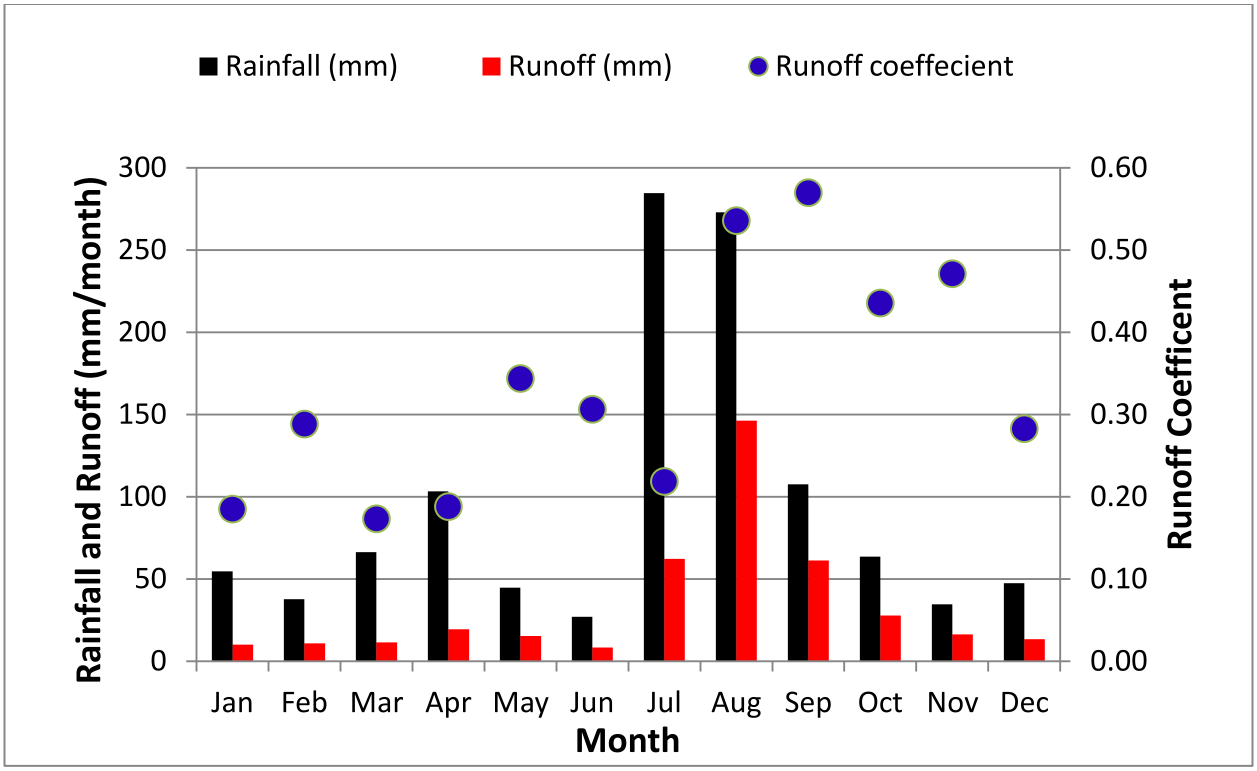

Figure 5: Long-term average monthly rainfall and runoff of Maybar Watershed with the computed runoff coefficient. In this case, runoff is both surface and subsurface flow.

Runoff from Test Plots: The rainfall-runoff data collected from runoff plots for the years 1988, 1989, 1992 and 1994 allow us to further clarify the nature of runoff processes in the watershed. The average annual runoff from the four runoff plots showed that the runoff from the cultivated land with maize on plot 1 and plot 4, having slopes of 16% and 37%, respectively, was greater than the woodland and grassland of plot 2 and plot 3 which were both on steeper land with slopes of 43% and 64%, respectively. Dividing the total plot discharge (surface runoff) over the total precipitation, the runoff coefficients were obtained. The runoff coefficients ranged from 0.06 to 0.15 (Figure 6). Nyssen, et al. (2010) compiled the data of many small runoff plots in Ethiopia and showed an even larger range of runoff coefficients. In addition to the factors (e.g. infiltration rate) mentioned by Descheemaeker et al. (2006); and Nyssen et al. (2010), this study finds that landscape position might play an important role in the magnitude of the runoff coefficients as well.

Piezometric Data Analysis: To this point, we have mostly been concerned with surface runoff at the downstream end. Piezometric data allows us to look at the runoff processes within the watershed. Transect 1 (Figure 3) represents the watershed behavior because it is located on an even slope. This and other transects have a slowly permeable layer (either a hardpan or bedrock) and the water is ponded above this layer.

At the beginning of August 2008 (the middle of the rainy season) the water table at the most down slope location, P1, increased and reached the surface of the soil on August 17 (Figure 7). On a few dates, it was located even above the surface indicating surface runoff at the time. The water table started declining at the end of September when precipitation ceased. The water level in P2, located upslope of P1, reached its maximum on August 29 and the level remained below the surface. It decreased around the beginning of September when rainfall storms were less frequent (Figure 7). The water table in P3 responded quickly and decreased rapidly. Thus, unlike P1 and P2 the water did not accumulate there and flowed rapidly as interflow down slope. Finally, the response time in the most upstream piezometer P4, was likely on the order of the duration of the rainstorm and was not recorded by our manual measurements.

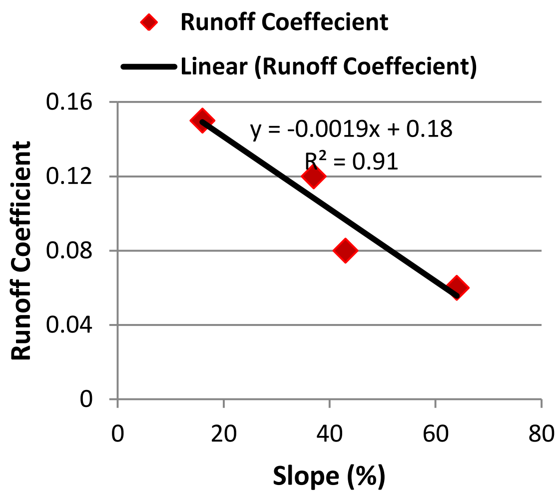

Figure 6: Plot runoff coefficient computed from daily 1988,1989, 1992, and 1994 rainfall and runoff data for different slopes

Thus the piezometric data in this and other transects indicate that the rainfall infiltrates on the hillsides and flows as interflow down slope. At the downstream end of the hillside where the slope decreases the water is accumulating and the water table increases and when it intersects with the soil surface, a saturated area is created. Rainfall on this saturated area will become overland flow. In addition rainfall on location where the water table remains steady such as for P2 will become runoff too since otherwise would have risen till the surface. Pipes that have been seen in many places in this watershed (Figure 8) might be responsible.

In order to examine further both the effect of slope and plant cover on ground water level, and to include the data of the other transects, the whole watershed was divided in to three slope ranges; upper steep slope [25°– 53°], mid slope [14°– 25°], and relatively low-lying areas [0°-14°]. For each slope class the daily heights of the perched ground water were averaged (i.e., the height of the saturated layer above the restricting layer, Figure 9a). 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 few days. The depth of the perched water table on the mid slopes is greater than upslope areas. The perched ground water depths are, as expected, the greatest in relatively low-lying areas.

The average ground water table is similar to transect 1 where the depth of the ground water was shown (so saturation could be shown). The water table behavior is consistent with what would one expect if interflow is the dominating conveyance mechanism. All else being equal, the greater the driving force (i.e., the slope of the impermeable layer) the perched ground water depth needed to transport the same water is smaller. 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 would indicate that topographic factors would dominate any ecological factors. However, when we plotted the average daily depth of the perched water table under the different crop types (Figure 9b) we find that there is a strong correlation of perched water depth with crop type as well. The grassland at the bottom of the slope had the greatest perched water table depth, followed by cropland and wood land with the lowest ground water level. Thus it seems that similarly to the plot data both ecological factors and topographically factors play a role in determining the perched water table height.

Local knowledge can be used to untangle whether topographic or ecological factors are deceive for the hydrology. It is generally accepted that the grasslands used for grazing are often saturated lower lying areas (too wet to grow a crop), while the cropland are in the mid-slope (with a consistent water supply but not saturated) and wood land 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. The landscape determines the water availability and thus the land use

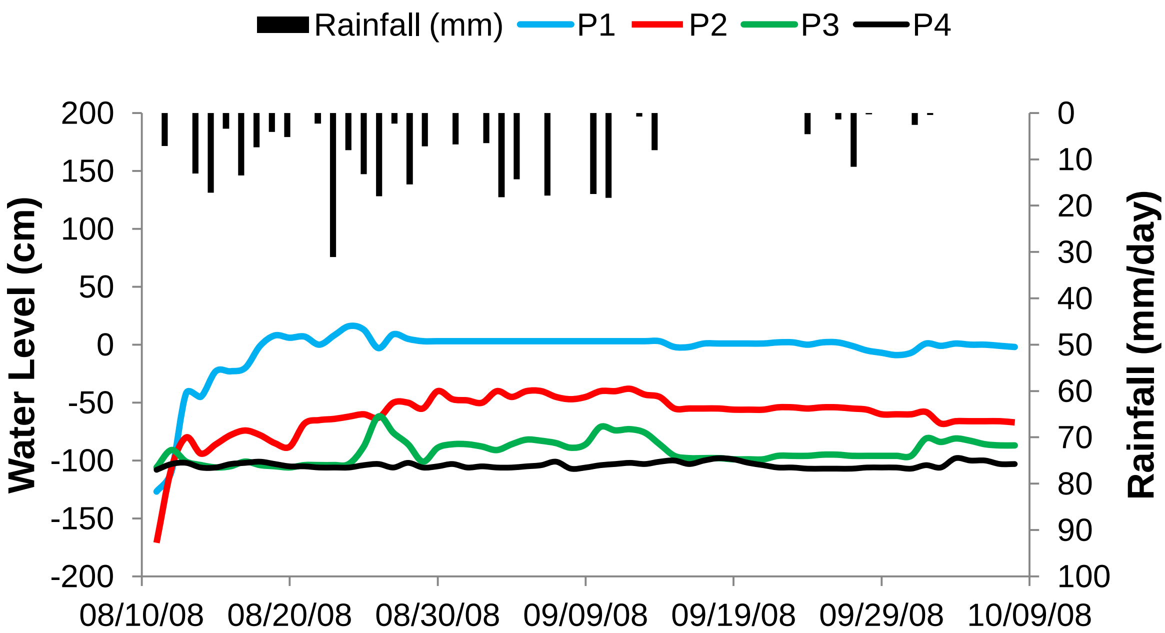

Figure 7: Piezometric water level data transect 1 (T1 in Figure 2) in the upper part of the watershed where slope is even. Water level was measured twice a day during the 2008 main rainy season using the ground surface as a reference and rainfall in upper gage is a daily measurement.

Figure 8: Pipe in the upper watershed down slope position near to piezometers installed at transect 1(T1) which drains subsurface water from the nearby saturated area. The diameter of the pipe is around 4 – 5 cm.

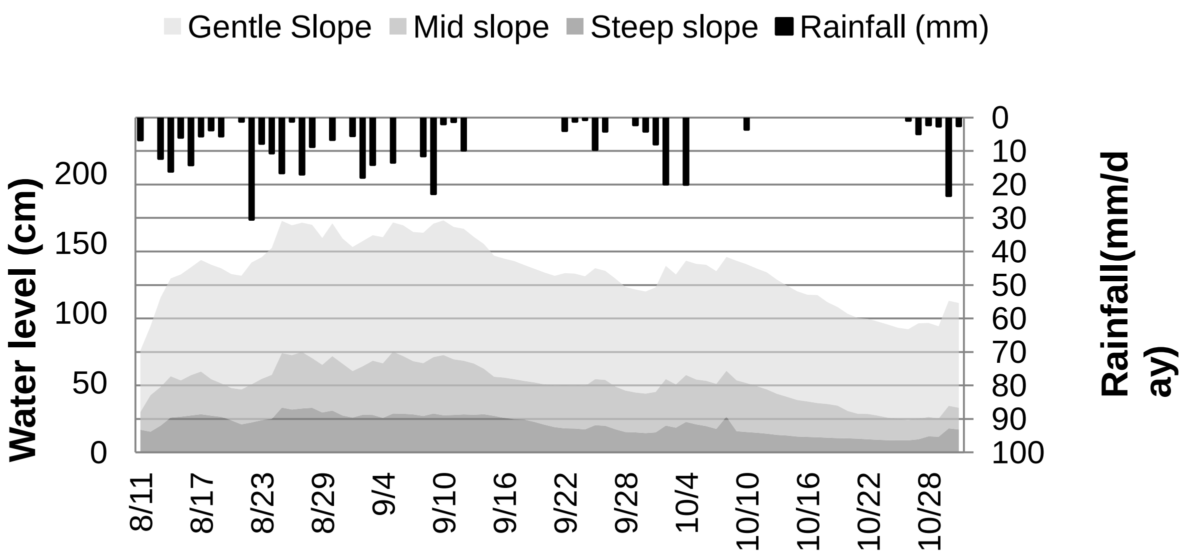

Figure 9a: Average daily water level above restrictive layer for three slope ranges i.e., upper steep slope [25°–53°], mid slope [14°– 25°], and relatively low-lying areas [0°-14°] calculated above the impermeable layer superimposed with daily rainfall

As a

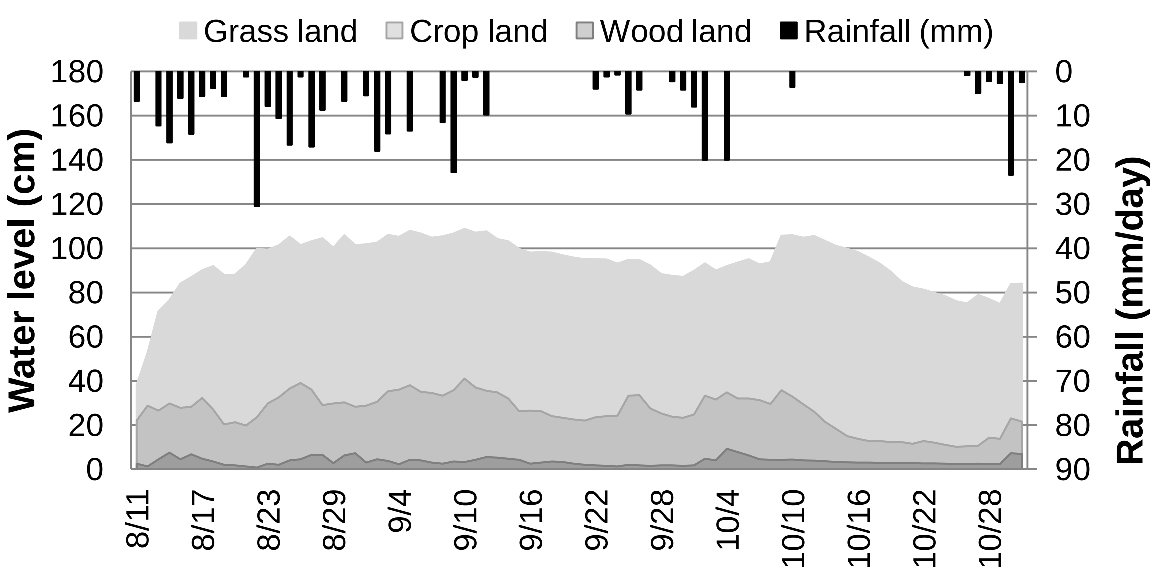

Figure 9b: Average daily water level above restrictive layer for three land uses i.e., grass land, crop land and wood land calculated above the impermeable layer superimposed with daily rainfall averaged over two rainfall stations.

To test of the relative importance of ecological and topographical factors, we plotted the map of topographic indices and superimposed the saturated areas (Figure 10). For the top area (Atarimesk), the saturated area indicated by the solid lines was located within the area with the greatest topographic indexes and is indicated by the purple color. For the bottom part of the watershed, the location of the saturated area is just above of area with the greatest topographic indices. Not being able to predict the exact location could be caused by the soil depth and conductivity values in the topographic index not being including. Also the topographic map might not have been precise. However, in general, there is a good agreement indicating that topographically controls are most important.

The results of this study are similar to the May Zeg Zeg watershed, which is in a much dryer area in Tigrai which has an average annual rainfall of around 600 mm/y (Nyssen et al . 2010). In this study, the water table in the valley bottom was measured with a single piezometer. Nyssen and colleagues observed that increasing infiltration on the hillside resulted in a faster increase in water tables in the valley bottom. Thus, also in this region, with a rainfall approximately half of that in Maybar, water moved via the subsurface which increased the water levels where the slope decreased.

Thus, in addition to the study of Nyssen et al. (2010), both local knowledge and the topographic index map confirmed that topographic factors were the main driving factors. Moreover, we found that land use was directly related to the water availability. Thus, although there is a relationship between runoff potential and crop type, the relationship is indirect. The saturated areas are too wet for a cereal crop to survive and so grass is grown. The middle slopes have sufficient moisture (and do not saturate) to survive the dry spells in the rainy season. The steep slopes, without any water table, are likely too droughty for a crop to survive during dry years and are therefore covered by trees or shrubs.

Finally, the indirect relationship between the crop type and landscape position as shown in Figure 9b, can also be observed in the Catskills, NY, USA where one can find forests on the steep uplands, agricultural on the lower mid-slopes and grassland in the wet patches near the stream (unpublished data). This indirect relationship is likely the reason that the models that use ecological factors as input parameters such as by Setegn et al. (2008); Zeleke (2000); Haregeweyn and Yohannes (2003); and Mohammed et al. (2004) can reasonably predict the runoff potential under Ethiopian conditions.

CONCLUSIONS

In this paper, we looked at whether ecological factors or topographic factors affected the hydrology. Several of the indicators showed that the topographic factors were more important than ecological factors. Soil infiltration rates were greater than observed rainfall intensities meaning that rainwater would infiltrate into the soil except in areas where the soil was saturated and surface runoff was occurring. In addition, both test plot data and piezometric data indicated that most surface runoff was generated from saturated areas at the lower portions of the hill slopes, while the upper hill slopes were mainly infiltration zones. Infiltrated water on the hill slopes became interflow and flowed downhill to gently sloping areas which were then saturated and produced surface runoff.

What this means in practical terms is that improving infiltration capacity with ecological methods, such as better plant cover, will not alter the hydrology. This does not mean that ecological factors are not important because as soon as the infiltration capacity decreases to below the prevailing rainfall intensities, surface runoff will be produced by infiltration excess before the soil saturates. Under this condition of limited infiltration capacity, ecological based practices that will increase infiltration rates are effective. Moreover, deep rooted plants could possibly break up the hardpan and improve water storages.

ACKNOWLEDGEMENTS

Funding of the assistantship for the senior author was made available by the CGIAR Challenge Program on Water and Food (CPWF) and carried out under the auspices of the International Water Management Institute (IWMI), managed project PN19, “Improved Water and Land Management in the Ethiopian Highlands and its Impact on Downstream Stakeholders Dependent on the Blue Nile.” The runoff data was graciously made available by Amhara Regional Agricultural Research Institute.

The help and cooperation of the field technicians and farmers in the Maybar watershed is greatly appreciated. Without their help, this research would have been impossible to carry out.

Finally, we would like to thank Professor Hurni for his foresight in establishing the Maybar watershed for the runoff data collection.

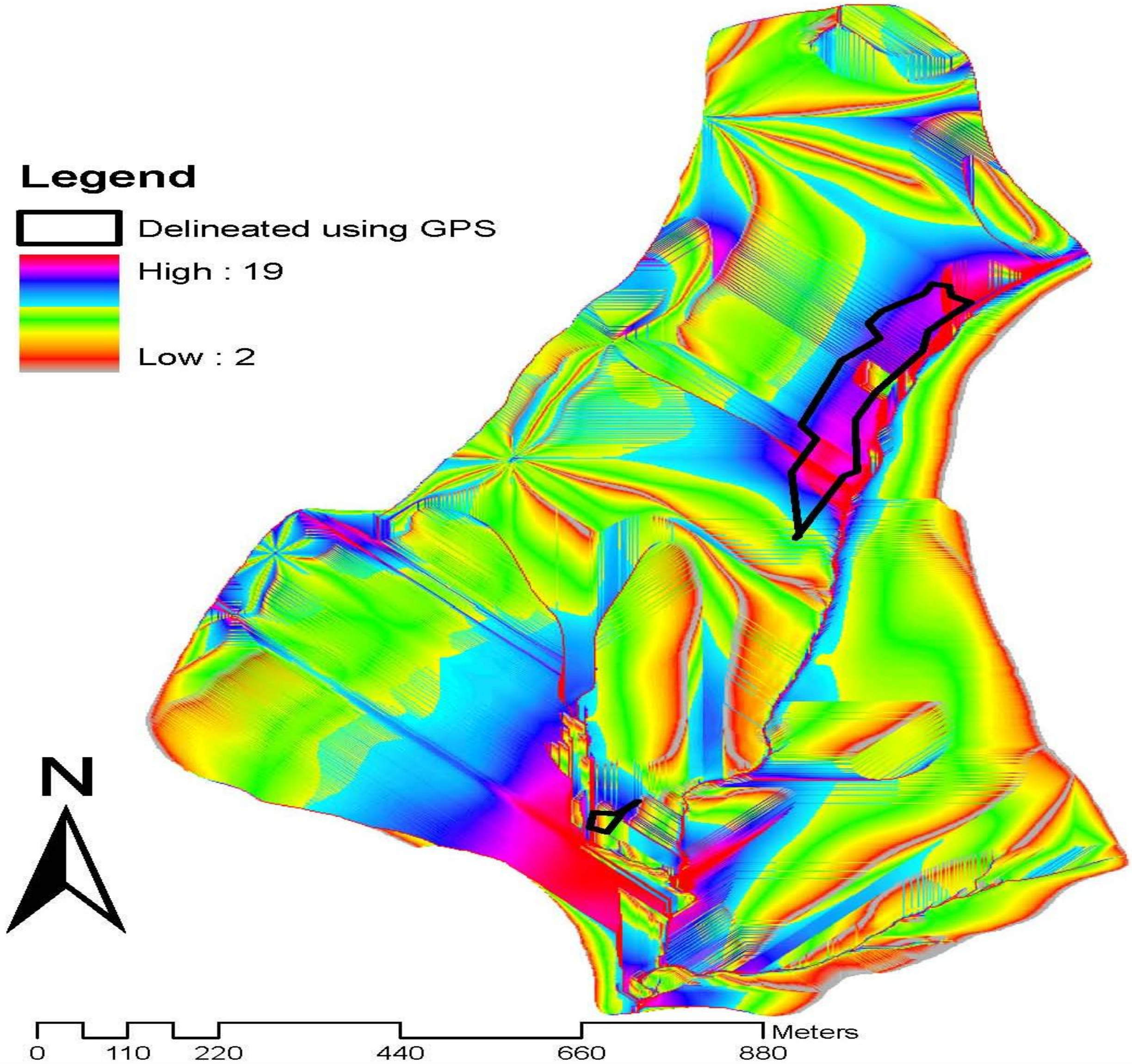

Figure 10: Map of runoff source area delineated using GPS (Solid black line) superimposed on topographic index which is developed from 10m by 10m DEM provided by University of Bern, Switzerland. Purple followed by blue on the map represents the greatest

REFERENCES

1. Amsalu ,A. and Graaff, J. 2006. Farmers' views of soil erosion problems and their conservation knowledge at Beressa watershed, central highlands of Ethiopia. *Agriculture and Human Values* 23: 99–108 (DOI 10.1007/s10460-005-5872-4).
2. Beven, K.J., Kirkby, M.J., 1979. A physically-based, variable contributing area model of basin hydrology. Hydrol. Sci. Bull. 24, 43–69.
3. Bewket, W and Sterk, G. 2003. Assessment of soil erosion in cultivated fields using a survey methodology for rills in Chemoga watershed, Ethiopia. Agriculture, Ecosystem and Environment 97,81-93.
4. Collick, AS, Easton, ZM, Ashagrie, T, Biruk, B, Tilahun, S, Adgo, E, Awulachew, SB, Zeleke, G, Steenhuis, TS. 2009. A simple semidistributed water balance model for the Ethiopian highlands. Hydrological Processes 23: 3718–3727.
5. Conway, D, and Hulme, M. 1993. Recent fluctuations in precipitation and runoff over the Nile sub-basins and their impact on main Nile discharge. Climatic Change 25: 127-151.
6. Derib, S.D. 2005. Rainfall Runoff Processes at a Hill slope Watershed: Case of Simple Models Evaluation at *Kori Sheleko* Catchment of Wollo, Ethiopia. Hydrology and Quantitative Water Management Group, M.Sc. thesis, Wageningen University, Wageningen, the Netherlands.
7. Descheemaeker, K, Nyssen, J, Poesen, J, Raes, D, Haile, M, Muys, B,Deckers, S. 2006. Runoff on slopes with restoring vegetation: a case study from the Tigray highlands, Ethiopia. Journal of Hydrology 331: 219–241.
8. Garzanti ,E, Ando S, Vezzoli, G, Ali Abdel Megid, A, El Kammar, A. 2006. Petrology of Nile River sands (Ethiopia and Sudan): Sediment budgets and erosion patterns. *Earth and Planetary Science Letters*, 252 (3-4), pp. 327-341.
9. Haregeweyn, N and Yohannes, F. 2003. Testing and evaluation of the agricultural non-point source pollution model (AGNPS) on Augucho catchment, western Hararghe, Ethiopia. Agriculture Ecosystems & Environment 99: 201-212.
10. Herweg, K.and Ludi, E. 1999. The performance of selected soil and water conservation measures. Case studies from Ethiopia and Eritrea. Catena 36: 99-114.
11. Hurni, H. 1988. Degradation and Conservation of the Resources in the Ethiopian highlands. Mountain Research and Development 8(2/3): 123-130.
12. Hurni, H, Tato, K, Zeleke, G.2005. The Implications of Changes in Population, Land Use, and Land Management for Surface Runoff in the Upper Nile Basin Area of Ethiopia. Mountain Research and Development. 25(2)147-154.
13. Ibrahim, AM. 1984. The Nile—description, hydrology, control and utilization. Hydrobiologia 110: 1–13.
14. Mitiku , H, Herweg, K, Stillhardt, B. 2006. Sustaiable land management –A new approach to soil and water conservation in Ethiopia. Mekelle, Ethiopia: Land Resource Management and Environmental Protection Department, Mekelle university ; Bern, Switzerland: Center for Development and Environment (CDE), University of Bern and Swiss National Center of Competence in Research (NCCR) North-South, 269 pp.
15. Mohammed, A, Yohannes, F, Zeleke, G. 2004. Validation of agricultural non-point source (AGNPS) pollution model in Kori watershed, South Wollo, Ethiopia. International Journal of Applied Earth Observation and Geoinformation 6: 97–109.
16. Nyssen, J, Clymans, W, Descheemaeker, K, Poesen, J, Vandecasteele, I, Vanmaercke, M, Zenebe, A, Camp, M. V, Mitiku, H, Nigussie, H, Moeyersons, J, Martens, K, Tesfamichael, G, Deckers, J, and Walraevens K. 2010. Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia. *Hydrol. Process. DOI: 10.1002/hyp.7628*.
17. SCRP. 2000. Area of Maybar, Wello, Ethiopia: Long-term Monitoring of the Agricultural Environment 1981-1994. Soil Conservation Research Programme, University of Berne: Switzerland.
18. Setegn, S G, Ragahavan, S, Bijan, D. 2008. Hydrological Modelling in the LakeTana Basin, Ethiopia using SWAT model. The Open Hydrology Journal 2: 49-62.
19. Steenhuis, TS, AS Collick, ZM Easton, ES Leggesse, HK Bayabil, ED White, SB Awulachew, E Adgo, AA Ahmed. 2009. Predicting Discharge and Erosion for the Abay (Blue Nile) with a Simple Model. Hydrological Processes 23: 3728–3737.
20. Walter, MT, TS Steenhuis, VK Mehta, D Thongs, M Zion, and E Schneiderman. 2002. Refined Conceptualization of TOPMODEL for Shallow Subsurface Flows. Hydrol. Proc. 16:2041-2046.
21. Weigel,G. 1986. The Soils of Maybar Area. Soil Conservation Research Program (SCRP), Report no 7. Berne, Switzerland: University of Berne. Zeleke, G. 2000. Landscape Dynamics and Soil Erosion Process Modeling in the North-western Ethiopian Highlands. African Studies Series A 16, Geographica Bernensia, Berne.
22. Zeleke G. 2000. Landscape Dynamics and Soil Erosion Process Modeling in the North-western Ethiopian Highlands. African Studies Series A 16, Geographica Bernensia, Berne.