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Hans Hurni, Kebede Tato, and Gete Zeleke

The Implications of Changes in Population, Land Use, and Land Management for Surface Runoff in the Upper Nile Basin Area of Ethiopia

Much concern has been raised about population increase in the highlands of Ethiopia and its potential to decrease runoff from the upper Nile Basin to the lowland countries of Sudan and Egypt. The present article examines long-term data on population, land use, land management, rainfall, and surface runoff rates from small test plots (30 m^2) and micro-catchments (73–673 ha) in the highlands of Ethiopia and Eritrea. Although the data were generated only on small areas, the results of the analyses can nevertheless be used to draw some conclusions relevant to the highland–lowland water controversies that have persisted in this particular region for many decades. The data indicate that there have been no significant trends over the long term in total annual rainfall in the highlands over the past 30–50 years. Nevertheless, test plot surface runoff rates are clearly influenced by land use and soil degradation, and hence by population density and duration of agriculture. In effect there is 5–30 times more surface runoff from cultivated or degraded test plots than from forested test plots. Analysis and interpretation of data support the hypothesis that surface runoff and sediment yield from the Ethiopian and Eritrean highlands into the upper Nile Basin have most probably increased in the long term due to intensified land use and land degradation induced by population increase, when seen in a historical perspective. Rates of base flow, in turn, must have decreased during the same period, but to a much lesser extent, although conclusive empirical evidence cannot be gained from this experimental setting. One can assume that soil and water conservation measures aiming to ensure long-term livelihoods in the humid to sub-humid highlands will, on the one hand, barely affect overall catchment runoff to the downstream areas, though they will considerably reduce surface runoff and soil loss on slopes as well as river sedimentation rates. On the other hand, in a semiarid catchment where intensive soil and water conservation was carried out, reduction in runoff rates was more pronounced. It can be concluded that population increase in the Ethiopian highlands increased overall runoff rates to lowland areas in earlier times, while recent efforts to conserve watersheds might affect total runoff rates in catchments only in semiarid parts, and much less in humid parts of the Ethiopian highlands.

Keywords: *Surface runoff change; population change; land use change; soil and water conservation; Nile Basin; Ethiopian highlands.*

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FIGURE 1 Field research sites of the Soil Conservation Research Program (SCRP) in different agroclimatic zones of the Ethiopian and Eritrean highlands. The gray line shows the limits of the Nile Basin. (Source: ETHIO–GIS 2004; map by Kaspar Hurni)

Introduction

Seventy-two percent of the runoff flowing into Lake Nasser, estimated at 68 billion m^3 per year, originates from 2 rivers in the Ethiopian highlands: the Atbarah River, from which a net 8 billion m^3 per year flow into the main Nile, and the Blue Nile River, from which a net 38 billion m^3 flow at its confluence with the White Nile at Khartoum (Rizzolio Karyabwite 2000: 27; Figure 1). While the runoff totals for these 2 rivers are considerably higher and subject to inter-annual fluctuations (Conway and Hulme 1993), part of the Blue Nile is retained in the Roseires Dam on the Ethiopian–Sudanese border, and both rivers have considerable water losses due to evaporation, irrigation, and infiltration. The water from these 2 rivers is used primarily for irrigation in the 2 semiarid-to-arid countries of Egypt and Sudan. About 85 million people in these lowland countries are directly dependent on highland waters.

Much international attention is thus being given to potential changes in runoff in the upper Nile Basin area, where another 90 million people live in an additional 11 riparian countries. Most of the latter highland populations practice rainfed agriculture, as rainfall is adequate in these regions, although at the expense of dramatic soil erosion rates and century-old soil and

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land degradation (Hurni 1993). The present paper focuses on Ethiopia, because of its overwhelming contribution to overall runoff, and because actual and potential changes there could considerably alter both patterns and amounts of runoff, with possible consequences for neighboring countries downstream. Of central concern to downstream inhabitants are upstream dam construction projects on any one of the rivers originating in the Ethiopian highlands. These could reduce the total amount of runoff to the lowlands or change the patterns of seasonal distribution. Another concern is the effect of global climate change, particularly relating to patterns and amounts of rainfall in the upper catchment areas, which directly affect runoff patterns (Conway 2000).

In addition to the threats of climate change and the larger dam projects planned on the major tributaries of the Nile, scientists have more recently raised questions about the possible implications of land management changes on highland–lowland runoff coefficients (personal communication from Dr Mahmoud El Zain Hamid, Khartoum, 30 April 2004). Although the effects of land management change might be more subtle and more difficult to detect, they could also have significant downstream effects, particularly if such management measures were to be widely applied in the Nile tributary areas of Ethiopia. One of the issues raised has been land use change induced by population increase in the upper Nile catchments, due to natural growth or migration policy, based on projections that increased population in the headwaters might result in reduced runoff to the lowland areas.

The present article therefore addresses the following questions:

- Can long-term rainfall trends be observed in the Ethiopian highlands in recent decades?
- What implications do demographic change and changes in population density in the highlands have for land use and runoff?
- What implications does land use change have for soil degradation and runoff?
- What are the effects of soil and water conservation on runoff in agricultural catchments in the highlands?
- What are the possible implications of the above factors for runoff coefficients in the tributary areas of the upper Nile Basin in Ethiopia?

Due to the lack of a well-organized long-term data series from large basins, the present article cannot produce conclusive statements about the effects of the above factors on amounts and patterns of runoff in the major tributaries of the Nile River. Instead, it provides an overall assessment within orders of magnitude. Analysis is based on field data from small runoff plots and small catchments in the Ethiopian and Eritrean highlands, as well as analysis of historical information on population and land use change. Several controversial conclusions can be drawn, for instance, that increases in population density in historic times may have actually increased runoff rates and intra-annual variability in the catchment areas of the upper Nile Basin. Measures that are currently being introduced by governments to conserve water and soil on agricultural land, on the other hand, may have reduced runoff rates and variability, particularly in the drier areas of Northern Ethiopia and Eritrea where the overall contribution to the Nile waters is much less than in the humid southwestern parts of Ethiopia. Discussion here will not address the issues of soil erosion and sedimentation. These have been introduced elsewhere, as transboundary effects of soil erosion and conservation in the Nile Basin (El-Swaify and Hurni 1996).

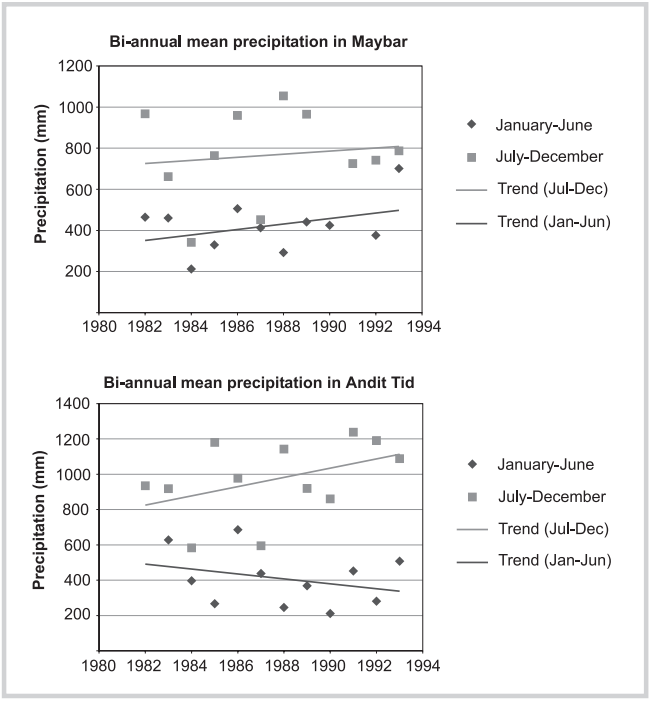
This paper is part of a broader study on mitigating syndromes of land degradation in the Ethiopian highlands. The overall aim is to contribute to the development of an integrated, sustainable land management strategy, particularly in areas of land degradation, in order to promote greater ecosystem resilience, enhance food security, and improve rural livelihoods in the Ethiopian highlands. The Ethiopian mitigation study is a component of the highland–lowland syndrome context approach in the global program known as Research Partnerships for Mitigating Syndromes of Global Change (SARPI 2000). The highland–lowland context approach includes a comparative synthesis of mountain systems in Asia, Africa, and Latin America (Hurni et al 2004).

Materials and methods

Empirical data are based on a long-term study of biophysical and socioeconomic parameters assessed at selected field sites in the Ethiopian and Eritrean highlands. In 1981 the Ethiopian and Swiss Governments agreed to implement the Soil Conservation Research Program (SCRP 1982). Between 1981 and 1987, 7 research units were selected in different agro-ecological zones of Ethiopia (Figure 1), 3 of which are situated within the Nile Basin. At these field sites, the program introduced a system of long-term monitoring of climatic parameters, single storm-based runoff from small catchments and multi-scale plots, and measurements of plot soil loss and catchment sediment loss. This was complemented by observations and samplings of seasonal land use and crop production, as well as specific studies of soils, land degradation, land cover change, and social and demographic factors. Of particular

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FIGURE 2 Rainfall data for 2 SCRP research sites with a 'small' and a 'big' rainy season. A trend line is given for the data. (Source: SCRP database)



importance was the monitoring of soil conservation measures implemented in the catchments and other areas by government agencies and NGOs, and the effects of these measures on natural resources, farmers' attitudes, land productivity, and agricultural production. Finally, the program interacted closely with government agencies, extension services and NGOs that concurrently implemented a series of soil and water conservation projects and programs throughout the country, by advising them on technologies and approaches in soil and water conservation. A comprehensive database was developed from the long-term monitoring activities and published by the SCRP (2000) for all research units.

In the present article, we selected certain SCRP data, including long-term annual rainfall and long-term runoff coefficients from 27 test plots (2 m wide and 15 m long), long-term runoff coefficients from the 7 research catchments (between 73 and 673 ha) in different agro-ecological zones of the Ethiopian and Eritrean highlands, regular mapping and observations of land use and land cover change on test plots and in these catchments, and information from secondary sources related to research in the SCRP framework. With reference to the effects of soil and water conservation on runoff, long-term rainfall–runoff coefficients were taken from experimental plots (6 m wide and 30 m long) in these research catchments, as well as annual rainfall–runoff coefficients for 3 research catchments. The first of these was in Anjeni, Gojam Region, Central Ethiopia, which was conserved in 1986 after 2 years without soil and water conservation (1984–1985); the second in Gununo, Southwestern Ethiopia, where 1 out of 2 twin catchments was conserved in 1980; and the third in Afdeyu, Eritrea, where soil and water conservation was first introduced in 1985, and intensified in 1997.

Results and discussion

Changes in rainfall in the Ethiopian highlands in recent decades

Seleshi and Zanke (2004) analyzed changes in annual, June–September, and March–May rainfall, based on 11 key stations located in different climatic zones of the Ethiopian highlands for the period 1965–2002. They demonstrated that there were no trends in total annual rainfall, seasonal rainfall, or the number of rainy days per year in central, northern and northwestern Ethiopia for the period 1965–2002. By contrast, both the annual and the June–September rainfall totals for the eastern (Jijiga), southern (Negele) and southwestern (Gore) stations showed significant declines from about 1982 onwards. According to these authors, below-average June–September rainfall in part of the Ethiopian highlands appears to be associated with warm El Niño–southern oscillation episodes.

Meze-Hausken (2004) analyzed long-term rainfall data up to 2002 for 4 stations in northern Ethiopia (Mekelle from 1960, Gonder from 1953, Bahr Dar from 1962, and Combolcha from 1953). No trends were detected in these data during this extended period. Farmers' perceptions, however, indicate progressively unfavorable conditions in the past 20–30 years.

Data from the 7 SCRP field research sites (Table 1; Figure 1) broadly confirm the above conclusion of no significant trends in annual rainfall, although the observation period was much shorter (about 10–15 years between about 1981 and 2002). Nevertheless, two of the stations, Maybar and Andit Tid along the Eastern Escarpment, where a small rainy season (*belg*) is common in the first half of the year, followed by the *kremt* season in the second half, showed slight to pronounced trends (Figure 2). In Maybar, both the *belg* and *kremt* seasons showed a tendency towards increased total rainfall, and in Andit Tid *kremt* showed a distinct increase, while *belg* totals decreased over the same period. Although Maybar Station is close to Combolcha, it is located about 800 m higher, at 2400 m; Andit Tid is at 3200 m.

We can conclude that during the decades observed in the second half of the 20th century, total annual rainfall in the Ethiopian highlands was quite variable, but that no significant long-term trends can be demonstrated. The 2 stations higher up (Maybar and Andit Tid) proved to be exceptions in that some

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TABLE 1 Main characteristics of SCRP research sites, annual rainfall, and total catchment runoff for multi-annual observation periods between 1981 and 1996. (Source: SCRP 2000; ETHIO–GIS 2004 for population analysis)

SCRP research unit	Catchment area (ha)	Population density (per km^2)	Woodland (%)	Grassland (%)	Cultivated land (%)	Annual rainfall (mm)	Catchment runoff (in % of rainfall)
Andit Tid (Shewa)	477	45	15	70	15	1417	**55**
Anjeni (Gojam)	110	80	5	15	80	1690	**43**
Maybar (Wello)	113	80	20	20	60	1211	**27**
Gununo (Sidamo)	94 and 73	180	10	50	40	1340	**19 and 11**
Hunde Lafto (Harerge)	236	70	15	25	60	860	**9**
Afdeyu (Eritrea)	177	80	1	29	70	382	**6**
Dizi (Illubabor)	673	45	65	10	25	1536	**5**

trends were discerned for the relatively short observation periods of 13 years. Rainfall–runoff relationships, therefore, cannot be expected to change noticeably, although inter-annual variation may be considerable (Conway 2000).

Implications of population change for land use and runoff

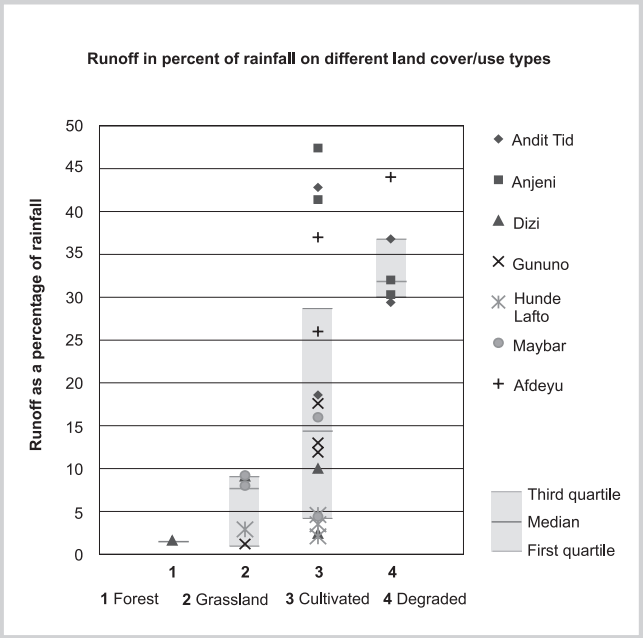
In the period between about 1950 and 2000, the population in the Ethiopian highlands is estimated to have increased by a factor of 4, from about 16 million to about 65 million. Of this latter number, about 26.2 million currently live in the Nile Basin area within Ethiopia (362,000 km^2), and an additional 1.4 million in the Eritrean part of the basin (25,000 km^2; Krauer 2004). Apart from some population movement due to resettlement of people from Tigray and Northern Wello in 1985, and their return home in early 1990, the main migration policy of the government between 1975 and 2003 was to keep populations in place; that is, no migration was allowed in principle. This led to intensification of land use in the rainfed highlands, resulting in shortening and eventual abandonment of fallow periods, expansion of cultivation land into grazing land, and wherever forests existed, continued deforestation, particularly in the western parts of the highlands. Simultaneously, soil and water conservation measures were introduced in many parts of the highlands, as was some expansion of irrigated agriculture and some intensification of home gardening.

Gete (2000) observed a reduction of forest cover in central Gojam (Anjeni research site, Figure 1) from 27% in 1957 to 0.3% in 1995. Solomon (1994) in western Ethiopia (Dizi research site, Figure 1) observed a similar trend from relatively extensive forest cover in the 1960s. With the exception of these 2 stations, extensive areas around all other stations had relatively little forest cover by the late 1950s (based on the earliest available air photography), and little deforestation has been observed since then. On the contrary, reforestation has occurred in many places, with a positive balance since the early 1980s, ie around Maybar (Wello), Andit Tid (Shewa), Hunde Lafto (Harerge), and Afdeyu (Eritrea) stations. The area around Gununo, finally, already had a relatively dense stand of trees in 1981, with few changes since then, but only few forested areas (Table 1). These trees were mainly on private agricultural land and hence constituted an integral part of the farming system. The changes in population densities during the second half of the 20th century thus clearly had an effect on land use and land cover, resulting in shrinking forests and grassland, expansion of cultivated areas, and intensified use resulting from reduction and almost complete abandonment of fallow systems. As a consequence, soil degradation and sediment loss were also heavily intensified (Hurni 1993).

A pertinent question is whether these changes in land use, land cover, and land degradation have had a significant impact on rainfall–runoff coefficients at the catchment level. The assumption would be that more intensive land use would result in higher runoff rates, unless water conservation measures were introduced on

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FIGURE 3 Long-term surface runoff coefficients measured from test plot experiments (2 m × 15 m) under natural rainfall and field conditions in 7 research sites in the Ethiopian and Eritrean highlands, 1981 to 1996. (Source: SCRP database; analysis by authors)



cultivated land. In order to test this hypothesis, two types of analysis were considered appropriate:

a) A comparative assessment of the different research catchments for a given period, as these catchments would represent different population densities and types of land use, and
b) An analysis of changes in rainfall–runoff coefficients over time in a given research setting.

In relation to a), Table 1 presents a comparative overview and multi-annual rainfall–runoff coefficients for the 7 SCRP research units in Ethiopia and Eritrea. Given the size of catchments—less than 10 km^2—coefficients above 30% would be expected for Ethiopian conditions (Nyssen et al 2003). Nevertheless, 5 of the 7 catchments have coefficients below 30%, which would be "normal" only for much larger catchments.

In an initial overview of the table, no clear relationship can be discerned between multi-annual runoff coefficients and population density, forest cover, grassland cover, or cultivated area. It must be assumed that physical characteristics such as geomorphology, soil type, annual rainfall, and geology are as important as population density or land use and land cover. For example, the low runoff percentage in the Afdeyu Research Catchment in Eritrea is assumed to be a result of very low rainfall, coupled with intensive water retention through agricultural terracing in the catchment since 1984. The equally and also surprisingly low rate in Hunde Lafto may be explained by geological features, as this catchment lies at the basement of the basalt series, just slightly above the gypsum and limestone sediments, and infiltration rates into geologic fissures are extremely high throughout the catchment. In conclusion, a comparative assessment of the different research catchments does not support the hypothesis that increased population density and intensified land use lead to higher runoff. This is because the biophysical and socioeconomic parameters of these widely separated catchments are not sufficiently comparable.

Implications of land use changes for land degradation and surface runoff

In order to carry out analysis type b) above, 27 runoff plots (2 m wide and 15 m long) were used in the 7 SCRP research units to measure runoff, soil loss, and productivity for different land uses and land covers; they were monitored for periods of 6–14 years. This included measurement of all storms in this period, ie 20–50 erosive storms per plot and year. For the analysis in Figure 3, the long-term runoff totals were divided by the long-term rainfall totals for each test plot, resulting in a long-term runoff coefficient. Land cover and land use were broadly classified for each plot into 4 categories: forest, grazed perennial grassland, cultivated or fallow land, and degraded land (ie degraded soils that are cultivated or grazed badlands), and plotted against the average runoff coefficients from each plot.

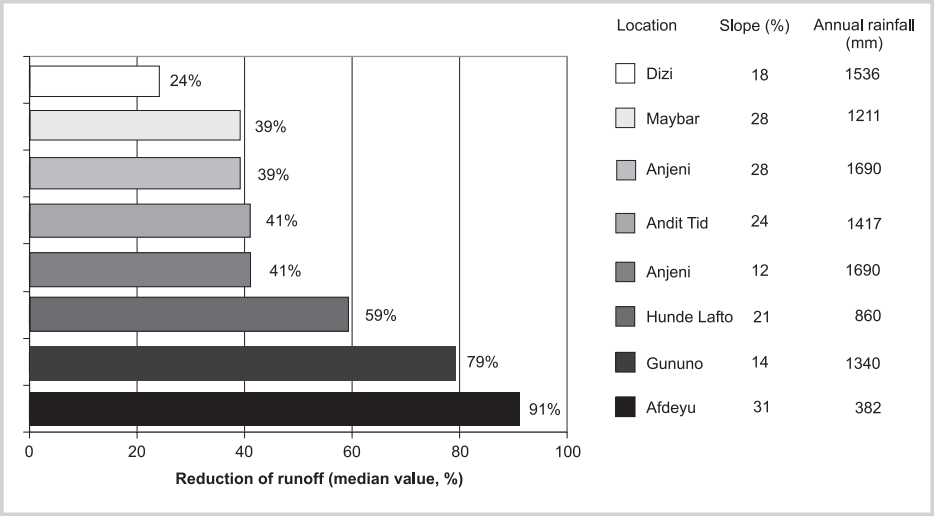
Although the database for forested land cover consists of storm assessments on only 1 test plot in Dizi from 1988 to 1993, the presentation in Figure 3 is of considerable interest. Test plot categories 1 (1.6%) and 2 (8%) clearly show very low average runoff percentages, while degraded plots (category 4, 32%) mostly had very high percentages. The cultivated plots (category 3, 14.5%), which were sometimes left fallow and sometimes continuously hoed artificially in experiments, but were mostly cultivated with different crops, show high variability in their runoff coefficients. These cultivated test plots are thus highly unpredictable. It is worth observing that the Anjeni, Afdeyu and Andit Tid research sites had the highest coefficients for cultivated plots. Surface runoff in the Ethiopian and Eritrean highlands can thus be considered to increase with population growth, land use expansion, and intensification without soil and water conservation, as well as with accelerated land degradation. On field plots of limited size, this can be a factor 5 to 30 for annual averages compared to a forested plot.

Effects of soil and water conservation on runoff in a highland situation

The impact of soil and water conservation on surface runoff was tested on a series of experimental plots

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FIGURE 4 Long-term average reduction of surface runoff due to soil and water conservation measures on cultivated land on different experimental plots (6 m × 30 m) on SCRP research sites in the Ethiopian and Eritrean highlands, calculated by comparing with runoff on non-conserved cultivated land (control plot). (Data source: SCRP 2000; analysis by authors)



(each 6 m by 30 m), with several measures being tested against a non-conserved control plot at all SCRP research sites—over several years and under local farming and natural rainfall conditions. Figure 4 presents the results of this analysis. Strongly decreased surface runoff coefficients were observed in these long-term measurements; on average, 40 to 50% less surface runoff was observed on the conserved plots as opposed to non-conserved conditions, the latter still being predominant for cultivated land almost everywhere in the highlands.

In order to repeat this observation at the level of a whole catchment, the Anjeni research site was used as an example. Anjeni is situated in central Gojam at an elevation of 2400–2600 m. This 110-ha catchment was intensively cultivated (80%) and had hardly any soil conservation measures in 1984 and 1985, but was fully conserved in 1986, with graded *fanya juu* soil bunds and a drainage system to allow surplus runoff to drain into the river. Outside the cultivation areas, part of the catchment was closed for natural regeneration, and reforestation was carried out at several field sites. From a 17-year database (1984–2000), an almost complete data set of rainfall and runoff from the catchment was used to do a long-term analysis (except for the years 1994, 1997–1999, where data were incomplete). Again, all storms were recorded, and suspended sediment samples taken for sediment loss analysis; but these are not discussed here. In Figure 5, the annual rainfall–runoff coefficients were calculated by taking the total annual catchment runoff, and dividing this by the total annual rainfall values, plotted against time.

The result (Figure 5) shows that despite intensive soil and water conservation activity throughout the catchment in 1986, the rainfall–runoff coefficients in this humid environment did not substantially decrease during the 17-year period, while rainfall was constant and soil substantially conserved. Does this contradict the results in Figure 4, where conservation experiments showed an average reduction of nearly 50% surface runoff for cultivated land? It should be borne in mind that about 50% of the catchment runoff is base flow, ie benefiting from subsurface water (Schum 2004), while the effect on experimental plots is based purely on observations of surface runoff. Hence the water conservation effect on cultivated land can be explained as resulting in an enhanced groundwater portion of catchment runoff. The effects of soil and water conservation on total runoff in a humid highland catchment can thus be considered almost negligible for the conditions at Anjeni. In contrast, a reduction in sediment loss can clearly be observed (Bosshart 1997).

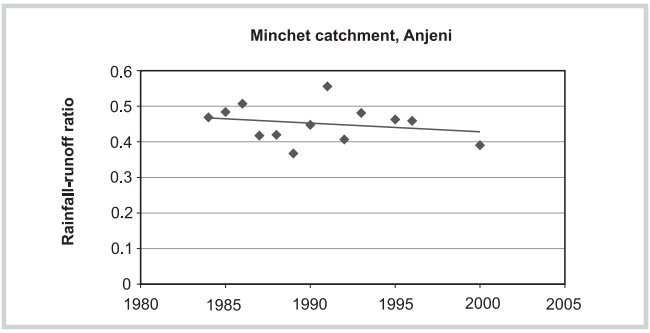


FIGURE 5 Annual rainfall–runoff coefficients measured at an experimental long-term catchment site (110 ha) under natural rainfall and cultivated field conditions in Anjeni, 1984–2000. Soil and water conservation was introduced in the whole catchment in 1986. (Source: SCRP database; analysis by Cornelia Schum [2004]; compiled by authors)

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Another research set-up in Gununo allowed direct comparison of a conserved catchment with a non-conserved catchment for an observation period of 12 years (1982–1993). Here the long-term runoff percentage was 19% for the non-conserved catchment, versus 11% for the conserved catchment (SCRP 2000). Although this considerable difference may be explained in part by the great effect of the soil and water conservation measures on surface runoff (see also Figure 4), part of the difference must be attributed to different characteristics between the twin catchments, as this difference already existed at the beginning of the experiment in 1981, before one catchment was conserved.

Finally, long-term monitoring of a research catchment of 177 ha established by SCRP in Eritrea in 1984 showed that through intensified soil and water conservation in the whole catchment in 1997, with almost level stone terraces on all cultivated land (80% of the catchment), the total runoff coefficient changed from 12.6% in 1996 (552 mm rainfall) to 6.6% in 1999 (598 mm rainfall) after conservation activities had been carried out (Burtscher 2003). It should be noted that the latter figure corresponds to the long-term average runoff coefficient of the catchment measured from 1984 to 1990, when average rainfall was much lower (Table 1).

Conclusions

Analysis of multi-annual series of runoff data from small test plots (30 m^2, 180 m^2) and micro-catchments (73–673 ha) shows that runoff rates under natural rainfall conditions and traditional land management practices in the Ethiopian highlands are clearly influenced by population density, land use change, and soil and water conservation, as follows:

1. In general, no major changes in annual rainfall patterns were identified in the Ethiopian highlands in the past decades, although some important observations were made after differentiating between rainfall data in the small and big rainy seasons along the Eastern Escarpment of the highlands, between Shewa and Wello. Here the small rainy seasons (*belg*) tended to decrease, while the big rainy seasons (*kremt*) increased in the 1980s and early 1990s. Comparison with long-term studies, however, only confirms the first statement made in this paragraph.
2. Population increase was substantial in the highlands during the 20th century: from an assumed 16 million around 1950, to about 65 million at the turn of the 20th century. The implications for land use were: increased deforestation and intensified cultivation, as well as increased and accelerating soil and land degradation throughout the highlands. This presumably had consequences on surface runoff, which must have increased with intensifying land use and degradation during the same period.
3. Although the effects of such increases on surface runoff due to land use intensification and accelerated land degradation cannot be exactly determined, one may assume that the spread of agriculture in the Ethiopian and Eritrean highlands had a considerable impact on surface runoff rates, which may be 5–30 times higher than on originally forested land. Because this observation would be valid for cultivated land—which covers less than an estimated 20% of the highlands at present—the total downstream runoff effect would be much lower. This interpretation, however, must be regarded with great caution, as the data are based on measurements from small test plots under natural rainfall and local land use conditions. Catchment values would be more conclusive, but the great variability between catchments does not allow such interpretation, and a chronological data set in a single catchment does not exist for land cover change from forest to agricultural land.
4. The effects of soil and water conservation on runoff were considerably reduced surface runoff rates on conserved cultivation plots compared to non-conserved plots. At the catchment level, however, there were mixed results. In the humid parts of the highlands, the total runoff coefficient in one agricultural catchment was not altered despite the introduction of soil and water conservation measures. In another humid catchment, the runoff-reducing effect was more pronounced, but not clearly attributable to soil and water conservation. In a semiarid catchment, finally, the rates were considerably reduced after the introduction of thorough soil and water conservation measures.
5. Finally, the data analysis and interpretation presented here support the conclusion that, from a historical perspective, runoff from the Ethiopian and Eritrean highlands into the upper Nile Basin most probably increased due to population increase and subsequent land use intensification and land degradation. This was particularly important in the 20th century, when such increases were substantial. In contrast, farmers' soil and water conservation activities on their own agricultural land—conducted at a considerable scale and partly sustainable since the late 1970s—generally did not have a diminishing effect on total catchment runoff rates, except in the semiarid Eritrean highlands.

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