# Hydrology and Forests in the Blue Nile Basin

## What can be Learned from Half a Century of Observations and Community Perception for Water Management?

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Cover photo: Forest and other land uses in the Megetch watershed and gauge station at Andasa River, Ethiopia; photo by Kevin Bishop

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# Hydrology and forests in the Blue Nile Basin: what can be learned from half a century of observations and community perception for water management?

## Abstract

Forest cover change is considered a major cause of water scarcity during the dry season in the Blue Nile River Basin of Ethiopia, which is part of the Nile River system. However, this is an over-simplification of the complex reality of forest and flow relationships, especially in the tropics. The objectives of this study were to explore the spatial relationship of land use and flow regime, detect temporal changes in the hydrological regime, determine changes in the forest cover, and summarize the results to define the relationship between forest cover and hydrological regime. Two broad approaches were used to address these aims: observational data analysis and community perception. Thirty-two watersheds were covered in the spatial study, and 45 years of data for a dozen of these watersheds were analyzed in the temporal study. Statistical methods were used to explore the spatial relationship of land use and flow, and both statistical and modeling methods were used to detect hydrological change over time. Remote sensing analysis was used to document forest cover changes.

Natural grassland and woodland had a positive, while grazing land and open bush land had a negative correlation with low flow regimes at the spatial scale. There were no major temporal changes in the flow regime, or clear results to attribute land degradation or land use change to hydrological changes and specific changes within each watershed. The change related to forest cover were watershed specific, although there were general differences between southern and northern watersheds regarding the time of deforestation. The community perception indicated the relationship of forest cover change and flow regime was more complex than just deforestation causing loss of dry season flow. According to the elders, forest and flow relationships were watershed specific, even sub-watershed specific. The lack of a clear relationship between forest cover change and flow regime in the temporal dimension could be attributed to the scale of watersheds, uncertainty about the measurement of flow extremes, and the impact of variability in rainfall within the region.

The watershed-specific nature of the relationship between forest and flow within the Basin, confirmed by the community perception, indicates forest hydrology studies should be tailored to watershed scale, or even sub-watershed scale i. e. hill-slope scale, and address the relevance of water availability at farm and river scale.

*Keywords:* Community perception, Ethiopia, forest hydrology, low flow

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# Dedication

To the late Nigatua Kefale and Gebreyohannis Gebrehiwot

# Contents

# List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Gebrehiwot, S. G., U. Ilstedt, Gärdenäs, A. I. and Bishop, K (2011). Hydrological characterization of watersheds in the Blue Nile Basin, Ethiopia. *Hydrological Earth Systems Science* 15, 11-20.

II Gebrehiwot, S. G., Gärdenäs, A. I, Bewket, W., Seibert, J., Ilstedt, U. and Bishop, K. Hydrological change detection in the rivers of the Blue Nile Basin in 1960–2004: A statistical analysis (Submitted: *Hydrological Science Journal*).

III Gebrehiwot, S. G. Seibert, J., Gärdenäs, A. I., Mellander, P.-E. and Bishop, K. Hydrological change detection using modelling: Half a century of runoff from four rivers in the Blue Nile Basin (manuscript).

IV Gebrehiwot, S. G., Bewket, W., Gärdenäs, A. I and Bishop, K. Forest cover change over four decades in the Blue Nile Basin, Ethiopia: comparison of three watersheds (manuscript).

V Gebrehiwot, S. G., and Bewket, W. and Bishop, K. Community perception of forest-water relationships in the Blue Nile Basin of Ethiopia (manuscript).

Papers I and II are reproduced with the permission of the publishers.

The contribution of Solomon Gebreyohannis Gebrehiwot to the papers included in this thesis was:

I The respondent compiled data from the USBR document, analysed and wrote the manuscript.

II The respondent collected, organized and analysed the data provided by the Ministry of Water and Energy, Ethiopia, and wrote the manuscript.

III The respondent ran the model, organized and interpreted the results.

IV The respondent did the land classification analysis of one of the watersheds, the remote sensing and data compilation of all watersheds, and wrote the manuscript.

V Data gathering from the community, compiling and summarizing, and writing were the main duty of the respondent.

# Abbreviations

| | |
|---|---|
| BNB | Blue Nile Basin |
| FAO | UN Food and Agriculture Organization |
| IPCC | Inter-governmental Panel for Climate Change |
| NAMSA | National Meteorological Service Agency of Ethiopia |
| PCA | Principal Component Analysis |
| PLS | Partial Least Square |
| PLS-DA | Partial Least Square-Discriminant Analysis |
| PRA | Participatory Rural Appraisal |
| USBR | US Bureau of Reclamation |
| WWF | World Wildlife Fund |

# 1 Introduction

## 1.1 Blue Nile Basin

The $2 \times 10^5$ km$^2$ Blue Nile Basin (BNB) is located in the eastern part of the Nile Basin that flows from the Ethiopian highlands to the border between Ethiopia and Sudan (Figure 1). The BNB comprises 7% of the Nile Basin area, but contributes 62% of the Nile water at Aswan, Egypt. In absolute terms, this is 51 G m$^3$ yr$^{-1}$ at the outlet to Sudan (Ministry of Water Resources, 1999) that results from an annual rainfall ranging from 800 to 2200 mm within the BNB. Despite this contribution to the Nile and the abundant rainfall, there is a prolonged dry period at the headwaters of the BNB from October to May. Due to this long dry season and higher evapotranspiration rates than in other regions, water availability with the BNB has become an important issue (Mohamed et al., 2005).

The BNB has been the focus of transboundary negotiation, and the basin is the main source of livelihood for 80% of the population; which was *ca* 20 million people during 2007 (Population Census Commission, 2008). The water flow during the dry season flow is a critical constraint for both water supply and subsistence agriculture for the fast growing population. During the rainy period (June-September, *kiremt* in the local language), soil erosion is a problem due to of the steep slopes and high intensity of rainfall (Gete, 2000). Annual soil loss in the highlands of the country is estimated as *ca* 32 tonnes ha$^{-1}$ yr$^{-1}$ (Berry, 2003). Deforestation is popularly believed to have contributed to soil erosion and diminishing dry season flows (low flows). Even though the impact of deforestation on soil erosion is well documented, there is no scientific consensus about the influence of forests on low flow during the dry season. However, the popular view in the country is that deforestation exacerbates the reduction of low flow and water scarcity in the dry season. In some cases, popular views are the basis of the region's integrated water resource management plan (Ministry of Water Resources, 2001).

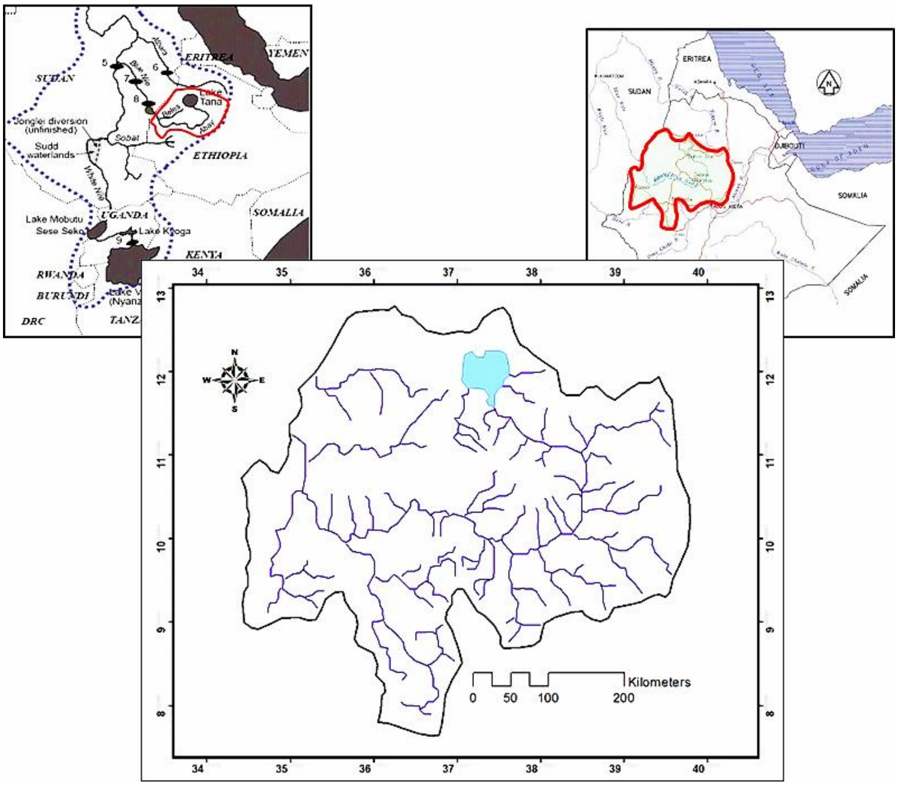


*Figure 1.* Location of the Blue Nile Basin (BNB: middle) indicated in the Nile Basin (top left) and in Ethiopia (top right).

## 1.2 River flow, forest and community perception

The interaction between forests and the hydrological cycle is a topic of lively debate, not least in tropical areas (Andreassian, 2004). The scale of watersheds, variable rainfall, differences in geology, soil and vegetation types are the main factors contributing to the complexity of this interaction. In addition to natural phenomena, the difference in forest management and land use history adds a dimension to the unresolved equation of the complexities of tropical forest hydrology.

There are many studies and reviews attempting to understand the relationship between forest and hydrological changes including, Bosch and Hewlett (1982), Bruijnzeel (1993), McCulloch and Robinson (1993), Andreassian (2004), and Bruijnzeel (2004). A common conclusion is that in most cases (both in temperate and tropical areas), there is a short period of increased water yield after forest harvest, and the impact becomes variable with time after forest harvest. The increment in water yield may not occur when forest change is different to clear cutting (forest harvest). The attempt to relate a change in forest cover to total flow and high flow is not valid for the low flow part of the hydrological regime (Calder, 2003), as an increased high flow does not necessarily result in a decreased low flow (Bruijnzeel, 2004). The influence of forest on the low flow hydrology is not as well understood as the influence of forest on high flow (Smahktin, 2001; Sikka et al., 2003). Forests and associated hydrological changes are one of the main issues in low flow hydrological research and low flow is a key topic of forest hydrology research due to existing and predicted climate change, livestock and human population growth, as well as the development of water resources investments. In addition, the impact of climate and land use becomes mixed in meso-scale watersheds, and climate impact could outweigh land use impact in larger (> 10 000 km$^2$) basins (Blöschl et al., 2007; Wei and Zhang, 2010; Ellison et al., 2011).

There are discrepancies between popular and scientific views about the influence of forests on hydrology. The popular view idealizes forests as always being positive for the flow regime, as forests increase precipitation, regulate extreme flows, increase low flow, decrease flooding, and reduce erosion. However, scientific studies present contradictory results concerning the relation between hydrology and forests (Hibbert, 1967; Calder, 2002). Although the optimistic popular view is considered a *myth* rather than a reality by some scholars (Calder, 2002), local community perception, obtained from people living in or close to an area of concern, could be a valuable complement to scientific findings (Gebrehiwot et al. 2010). Community perception is qualitative data that requires qualitative analytical methods. Local community perception provides firsthand information from the community's experience and knowledge that could 'fill gaps' in understanding the relationship between forests and water, especially in data poor areas such as the Blue Nile. It should be noted that some scientific results support the optimistic popular views, in some cases (Bruijnzeel, 2004).

# 2 Objectives

The main objective of this study was to assess and analyze changes in the hydrological regimes and forest cover in the Blue Nile Basin over half a century and to examine any relationships between the changes. The specific objectives were:

- To analyze the spatial relationship between watershed characteristics (including land use) and hydrological regime
- To detect and quantify any hydrological changes in the last half a century in the BNB
- To quantify land cover and especially forest changes during 1957-–2001 in the BNB
- To document the perception of local communities regarding the relationships between forest cover and flows, and
- To provide empirical evidence of the relationships between forests and hydrological regimes, with a special focus on the low flow regime, in the BNB.

# 3 Background

## 3.1 The influence of watershed characteristics on the runoff regime (Paper I)

Watershed characteristics can contribute to differences in hydrological response. Specific characteristics such as soil properties, geology, watershed size, local climate, topography, anthropogenic activity and vegetation cover are some characteristics affecting the hydrological regime (Black, 1997; Uhlenbrook, 2003; Sivapalan, 2005). The characterization of watersheds, based on the most important characteristics provides a basis for land management planning and for developing and securing water resources (Saxena et al., 2000; McDonnell et al., 2007). Moreover, the identification of watershed characteristics and their influence on the hydrological regime helps to define whether the type of land use, especially forest cover, is positively or negatively related to a specific hydrological variable, such as total flow, high flow, low flow or runoff coefficients.

The characterization of the hydrological response of watersheds is crucial in areas such as the Blue Nile where the impact of land use on different flow regimes are unclear. However, the spatial differences of land use and other characteristics of watersheds related to water scarcity are not well characterized in the BNB. The spatial difference in specific watershed characteristics influencing the hydrological regime of the Basin were investigated through four years (1960–1963) of data from 32 gauged stations (Paper I).

## 3.2 Half a century of river flow in the BNB (Papers II and III)

The historical dynamics of river flow are valuable for water resource planning. The potential for irrigation and water supply, design of water engineering structures and watershed development programs are based on past patterns of hydrological and meteorological parameters (Kundzewicz, 2004). The knowledge about historical flow regimes is increasingly critical due to increasing watershed changes associated with land use, soil and climate (Hamed, 2008). The Blue Nile Basin is characterized by severe soil degradation over many decades, and this degradation has a major impact on the water resources of the region (Gete and Hurni, 2001). The livelihood of the people in the region is dependent on rain-fed agriculture, which is sensitive to changes. Therefore, historical hydrological records and the detection of possible changes further help for understanding of how the livelihood of the population could be affected by increased water scarcity. The extent of the change in different parts of the hydrological regime (total annual flow, high flow, low flow and low flow index) over the last half a century was investigated through a statistical approach (Paper II).

Any impact on water resources is crucial in a region where the livelihood of the people is vulnerable to water availability. Thus, the extent of change within the hydrological regime that can be attributed to the changes in the characteristics of watersheds is of relevance for sustainable land management and adaptation to climatic change within the BNB. Models are appropriate tools for learning how changes in watershed characteristics are related to variability in the hydrological regime. Through a modelling approach, model parameters, model residuals and runoff simulations that could imply changes in a hydrological regime and watershed characteristics were used to identify hydrological change within the BNB (Paper III).

## 3.3 Forest cover change in the BNB between 1957 and 2001 (Paper IV)

A change in forest cover is the focus of land cover changes in the tropics (Giambelluca, 2002). Tropical deforestation contributes to loss of biodiversity, carbon emission, climate change, soil degradation, cultural shifts and disturbances of water resources (Laurance, 1999). Deforestation associated with changes in soil resources influences the relationship between forest change and the water regime (Bruijnzeel, 2004); thus, forest change studies are an important basis for the assessment of natural resources, including water, in tropical areas.

Deforestation is assumed the main cause of the soil and water degradation in Ethiopia, including the Blue Nile Basin. Historically, the general trend of deforestation was that forests in the northern part of the country/Basin were deforested earlier than in the southern part. Even though deforestation is a common phenomenon, the gains and losses to specific areas vary (Bewket, 2002; FAO, 2010; Gebrehiwot et al., 2010). Therefore, it is difficult to generalize the trend of deforestation or forest cover change in the Blue Nile Basin without compiling specific studies. As little quantitative information about the history of forest cover changes for specific landscapes and watersheds are available, the history of forest cover change during the last half century in the BNB was investigated (Paper IV).

## 3.4 Community perception of forest and water interaction in the BNB (Paper V)

Community perception relates to the knowledge of people who live in the immediate surroundings of a certain natural phenomenon. Local community perception can provide information from community experience that fills gaps in the knowledge obtained from measurements and modeling, such as the monitoring of rain and water flow. Community perception is different from what is termed popular belief as the local community is the direct recipient of the impact of changes in natural resources, such as changes in forests and waters. The World Wildlife Fund (WWF) documents the accounts of local residents, from around the world, on the effects of different aspects of climate change and related impacts on their local environment (WWF, 2007). The witnesses account contains statements about climate change that sometimes agree or disagree with the IPCC report on the climate change.

Information from community perception may be particularly useful if there is an unclear, scientific picture of the impact of forest cover change on the hydrological regime, as is likely in the case of the complex tropical forest hydrology, and it encompasses the human dimension, in addition to climate and land use issues (Bonnel, 1998). For example, based on community perception, a wetland was found to mask the effect of upland deforestation in the 260 km$^2$ Koga watershed in the BNB (Gebrehiwot et al., 2010). In Koga, a change from 26 to 2%

forest cover in the upland area rendered almost no change on the hydrological regime, as measured at a gauge downstream of the wetland. However, the community living upstream of the wetland reported hydrological changes associated with the deforestation, whereas, the downstream community did not. Community perception of four different watersheds in the BNB was investigated to increase the knowledge of the relationship between forest and river flow (Paper V).

# 4 Methodology

## 4.1 Paper I

Hydrology, soil, land use, geology, climate and topography data from 1960 to 1963 for 32 rivers (watersheds) were used for the spatial study in Paper I. The data were extracted from the US Bureau of Reclamation (USBR) study of land and water resources in the BNB that was conducted by water engineers from US and Ethiopia during 1958-1963 (US Department of Interior, 1964). Five hydrological variables were used: annual flow (Qt [mm $yr^{-1}$]); minimum monthly flow (Ql [mm $yr^{-1}$]); maximum monthly flow (Qh [mm $yr^{-1}$]); low flow index (LFI), the ratio of minimum flow to the total flow for the year; and, runoff coefficient (C), the ratio of total flow to rainfall. Rainfall (P [mm $yr^{-1}$]), temperature (T [°C $day^{-1}$], potential evaporation (ET [mm $day^{-1}$]), latitude (Lat [degree-decimal]), longitude (Long [degree-decimal]), area of the watersheds (Area [$km^2$]), average elevation (El [m]) and average slope class (Slope [%]) were also used. In addition, nine different soil types, four different geological classes, and nine different land use classes were extracted from map and descriptive information of the USBR document (Paper I).

Multivariate analysis, Principal Component Analysis (PCA) and Partial Least Square (PLS) were performed on the observations from the 32 watersheds using SIMCA 12.0.1 (Paper I) to identify watershed characteristics, including land use, which best described the variability of the hydrology.

## 4.2 Papers II and III

Climate and hydrological data from 1960 to 2004 were used for the studies in Papers II and III. Rainfall data were obtained from the National Meteorological Agency of Ethiopia (NAMSA) for 18 different stations (Figure 2 and Table 1). From these, areal weighted average rainfall data were generated for 12 rivers (watersheds). Monthly data from the 12 rivers were used for Paper II; daily data from four rivers (from the original 12) were used in Paper III (Table 1). Hydrological data were collected and processed by the Ministry of Water and Energy, Ethiopia (earlier called the Ministry of Water Resources). Daily rainfall, daily air temperature, mean monthly value of daily potential evapotranspiration (PET) and daily stream flow data were used for the modeling. The annual water balance was plotted with both monthly and daily data to control data quality (Dahmen and Hall, 1990). The hydrological variables included in the statistical analyses were annual flow (Qt [mm yr$^{-1}$]), annual rainfall (P [mm yr$^{-1}$]), runoff coefficient (C, the ratio of Qt to P), maximum monthly flow (Qh [mm]), minimum monthly flow (Ql [mm]) and low flow index (LFI, the ratio of Ql to Qt): the LFI normalized the low flow to annual flow.

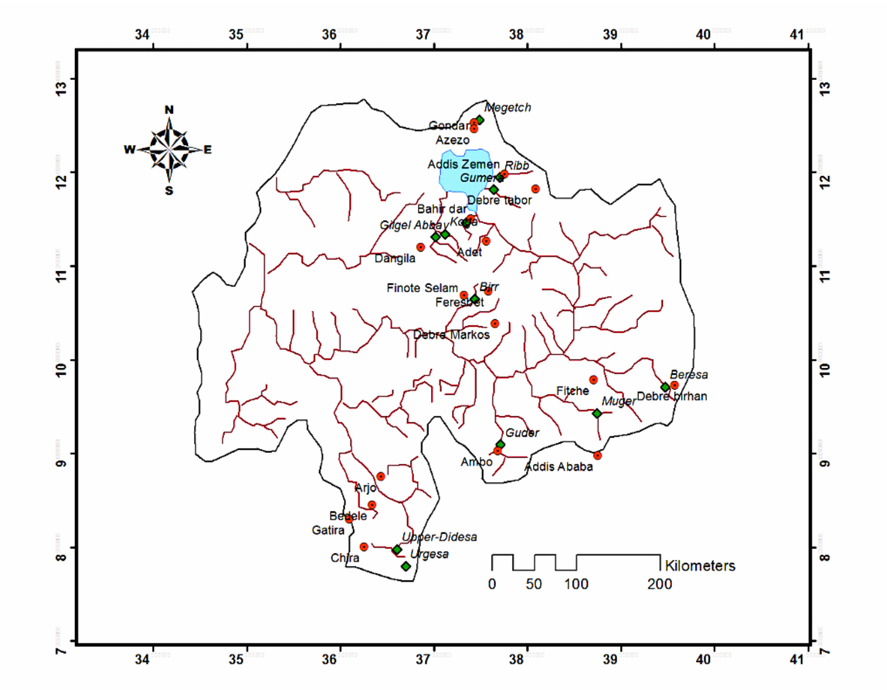


*Figure 2.* Hydrological gauge and meteorological stations in the Blue Nile Basin used for statistical analysis and modeling. Gauge stations are italicized diamond marks (green), and meteorological stations regular font with circle marks (red). All stations are used in the statistical analysis, and Gilgel Abbay, Koga, Birr and Upper-Didesa are used in the modeling.

Table 1. *The study watersheds/rivers used in the different papers included in this thesis*[a].

| Watersheds /Rivers | Data period | Area (km$^2$) | Mean annual rainfall (mm) | Mean total flow (mm) | Papers |
|---|---|---|---|---|---|
| Megetch | 1964-04 | 462 | 1150 | 387 | Papers II and V[b] |
| Ribb | 1961-04 | 1592 | 1440 | 291 | Paper II |
| Gumera | 1959-04 | 1394 | 1450 | 679 | Paper II |
| Andasa | 1960-05 | 573 | 1410 | 469 | Paper II |
| Koga | 1960-04 | 260 | 1560 | 565 | Papers II, and III |
| Gilgel Abbay | 1960-04 | 1664 | 1560 | 970 | Papers II, III, IV and V |
| Birr | 1960-04 | 978 | 1730 | 490 | Papers II, III, IV and V |
| Beresa | 1962-03 | 211 | 890 | 457 | Paper II |
| Muger | 1971-04 | 489 | 1650 | 513 | Paper II |
| Guder | 1959-04 | 524 | 1800 | 757 | Paper II |
| Upper-Didesa | 1985-05 | 1806 | 2010 | 670 | Papers II, III, IV and V |
| Urgesa | 1979-03 | 19 | 1975 | 468 | Paper II |

[a]The 32 watersheds/rivers included in Paper I are not included here.
[b]Angereb, a watershed included in Paper V is a sub-watershed of Megetch.

The trends over the whole time series, multivariate classification of the time series, and step-wise changes between classified periods were tested. Trends were tested with Spearman's *rho*, a non-parametric rank correlation test. Step-wise changes between the medians of the periods were tested with Wilcoxon signed-rank sum test. Three periods were postulated based on political and policy changes before and after 1975 and 1991, as these influenced the land management systems of the country (Rahmato, 2009; Gebrehiwot et al., 2010: Table 1). After transforming the non-linear data series, Partial Least Square-Discriminant Analysis (PLS-DA), a multivariate analysis technique, was used to test a classification of the whole time series: this classification divided the study period into three periods of *ca* 15 years each.

A model-based change detection approach was applied (Paper III). The conceptual rainfall-runoff HBV model (Lindström et al., 1997) was used to generate parameters, residuals and simulations for comparison among the different periods. The HBV model has nine parameters (FC, LP, BETA, PERC, UZL, K0, K1, K2 and MAXBAS, all of which are defined in Paper III). Instead of a single best set of parameter values, a collection of 50 best parameter sets was used, and the output of these sets was used for further analysis. To test the significance of differences in the runoff simulations, the T-test with $\rho \leq 0.05$ was used. Potential differences in parameter distribution and residuals were tested by Wilcoxon signed-rank test with a significance of $\rho \leq 0.05$.

## 4.3 Paper IV

Three watersheds from the Blue Nile Basin, Gilgel Abbay (1664 km$^2$), Birr (980 km$^2$) and Upper-Didesa (1980 km$^2$) were used to study land cover change since 1957/58 (Paper IV). Gilgel Abbay and Birr are located in the north-central part of the Blue Nile Basin, and Upper-Didesa is located in the southern part of the Basin. Land cover was classified with a focus on forest cover classes.

Aerial photos from 1957/1958 and Landsat satellite images from 1975, 1986, and from 2000/2001 were used. Topographic maps with a scale of 1:50 000 were also used for georeferencing. ArcGIS version 9.3 was used for all image-processing steps (ESRI, 2009), which were enhanced and filtered to correct for radiometric and atmospheric interference.

A manual digitization of the aerial photos was used for classifying land cover. This was further digitized on-screen to coordinate it with the digital classification used for the satellite images. A hybrid method was employed for land cover classification from satellite images; i.e. both supervised and unsupervised classification techniques were used. The supervised classification was based on the classes primarily generated through unsupervised classification and then refined with ground truth points collected by GPS. The ERDAS IMAGINE analysis tool embedded in ArcGIS 10 (ERDAS, 2010; ESRI, 2010) was used for the classification. After the supervised classification, finer classes were dissolved to match the resolution of the digitally classified shapes from the manually digitized classes in the 1957 aerial photos.

## 4.4 Paper V

Four watersheds (Angereb, Gilgel Abbay, Birr and Upper-Didesa) were selected for the community perception study, and communities from both upstream and downstream regions of each watershed were included. Forest, land use, soil and water resources, as well as their respective changes, were the main descriptors for gathering community perception data, and general perspectives on the relationship between forest and water were also investigated.

Participatory Rural Appraisal (PRA), a method of collecting social-qualitative data, was used to gather community perception. Group discussion, individual interviews and historical matrix analysis were conducted with 5–10 key informants from each community (often both an upstream and a downstream community in each watershed); this method is used for analyzing the extent or status of natural resource descriptors in respect to different periods. The information gathered through historical matrix and group discussion was cross-checked. Finally, information from different PRA tools was summarized by numerical grading from 0 to 7: this was generated in one of the study areas and was used as the base for presenting results from the different methods (Paper V).

# 5 Results and Discussion

## 5.1 Paper I

The total variation in the hydrological regime of 32 rivers explained by PCA and with watershed variables in the first two components was $R^2$=0.4 (Figure 2). The total variation explained by the first four components was $R^2$=0.6. In the PLS, for the first two components had $R^2$=0.5, and the four components had $R^2$=0.6. In general, dry season flows were positively correlated with wetland, savannah grassland and woodland, but negatively correlated with grazing land, bush land and extent of tuff/basalts in the basin. An increase in low flows due to increase in grasslands is hypothesized for tropical areas by Bruijnzeel (2004) and Malmer et al. (2009). In tropical areas, these types of land use increase water retention of soils, and land use such as grazing and bush land indicate degradation of land resources (forests and soils) (Gete, 2000; Demel and Tesfaye, 2002). Water resource management plans need to be based on an understanding of the full range of factors controlling watershed response to rainfall, in addition to the factors that management can influence.

## 5.2 Papers II and III

High flow comprised 18 to 67% of the total flow and low flow 0.2 to 2.4% of the total flow. Test results for trends over the entire period, the classification of the time series into three different periods and step-wise changes from one period to the next are reported. Over 45 years, there were 12 significant trends among 72 test cases (12 rivers x 6 hydrological variables). The PLS-DA analysis revealed a difference among the hydrological parameters in the three periods (P1, P2 and P3).

There were 36 significant step-wise changes among 192 test cases (36 period classes x 6 hydrological variables [minus 2 change cases from 2 rivers]) (Table 2). Although the variables differed among the three periods, there were few and inconsistent changes in individual hydrological parameters among the three periods, especially when the statistical 5% *false positive* and the influence of precipitation on hydrology were considered.

The hydrological regime of the 12 rivers appeared robust during the last half century, as only 17% of the trends tested and 19% of the step-wise changes were significant. The trends and step-wise changes were river specific, and at the scale of the Blue Nile Basin, there was no clear indication that soil degradation or land use change induced loss of low flow. However, more changes appeared during the latter part of the study period, possibly indicating an increasing rate of change.

Both model parameters and residuals changed from period to period (Paper III). Soil, evapotranspiration and subsurface response function parameters (FC, LP, BETA, K1, K2 and MAXBAS) changed most among the periods. In all watersheds, except Gilgel Abbay, model residuals changed significantly from period to period; however, there was no change in actual runoff with the parameter sets from different periods, except for a 15% daily mean runoff increment in P3 of Upper-Didesa and Gilgel Abbay. The changes in parameters and model residuals suggested a change in the characteristics of the watersheds since the 1960s; although, this had little impact on the overall function of the watersheds in generating runoff. However, before model parameters can be used as reliable indicators for the purpose of detecting change, there is a need for further investigation of how these parameters reflect differences in the characteristics of watersheds, especially for soil and land use resource planning. The lack of general trends in the hydrology of the BNB means that differentiated management plans for water resources are needed for specific watersheds.

## 5.3 Paper IV

Nine land cover classes were identified in the three watersheds (Table 2). Gilgel Abbay was covered by 10% forests in 1957 and 22% in 2000. Birr was covered by 30% forest during 1957 and by 20% forest during 2000. Upper-Didesa was 90% covered by forests in 1958 and 45% in 2001. Natural forest cover decreased in all watersheds over the 40-

year study period. The main changes in land cover type were an increment in Eucalyptus plantation, decrease in wetland and riverine forest, and an increase in cultivated land. Among the forest cover classes, riverine forest had the highest rate of loss, and in all three watersheds, almost 100% of the riverine forest was lost before the 1980s. Wet mixed forest, woodland and dry mixed forest had high deforestation rates: wet mixed forest lost 30% of a 68% forest cover in 40 years (from 1226 to 706 km$^2$). The actual amount of woodland lost during the 40-year period represented a decrease from 20% (360 km$^2$) to 6% (100 km$^2$) of the original cover.

Population density and population growth differ between the northern and southern parts of the Basin. Although the population density has been higher for Gilgel Abbay and Birr over the past years, the growth rate around Upper-Didesa has been much higher. The higher incremental rate around Upper-Didesa could be a result of the resettlement program in and around the watershed.

Table 2. *Land cover types and description in the study watersheds.*

| Land cover | Description |
|---|---|
| Cultivated land | Land under seasonal cultivation |
| Grazing land | Land under grass cover but highly managed by grazing and browsing of domestic animals |
| Open bush land | Land covered with open herbaceous plants (grass, bush) with shallow soil depth and degraded land (not referred to as forest cover) |
| Dry mixed forest | Evergreen and deciduous forest in areas where annual rainfall is < 1200 mm |
| Wet mixed forest | Evergreen and deciduous moist montane and afromontane forest in areas where annual rainfall is >1200 mm |
| Wooded grassland | Openly distributed trees including afromontane woodland, with wet savannah grassland |
| Riverine forest | A specific type of forest found along riverbanks and on flood plains, or a riparian vegetation dominated with trees. |
| Wetland | Land dominantly inundated with water, including marsh, peatlands, ponds |
| Eucalyptus plantation | Plantations of Eucalyptus species |

## 5.4 Paper V

Since 1991, soil conservation measures on the Angereb have developed, and this was perceived as a reason for reduction in peak flow and increment of baseflow by the community. During the 1990s, baseflow and groundwater availability also increased in the downstream areas of Birr, and the community attributed this to removal of riverine forest and the existence of wetland surrounding the main river. According to the community, *Rist*, a land allocation campaign by the Emperor during the 1940s and 1950s, was the main reason for the absence of large forest areas (only 10%) in Gilgel Abbay by the time the first aerial photos were taken in 1957: this might explain why Eucalyptus plantations were established in Gilgel Abbay earlier than in other watersheds. The difference in the date of deforestation between upstream and downstream areas in Gilgel Abbay was a similar to the pattern of deforestation in Koga, an adjacent watershed (Gebrehiwot et al., 2010). In the northern areas of the BNB, forest cover was already under 10% in many watersheds by 1960, whereas, in the southern part of the BNB, major deforestation occurred more recently since the 1980s. Woodland cover particularly diminished due to resettlement and new plantations. According to the community, rainfall variability was a key issue influencing the flow regime. Climate variability is a problem within the region (Haile et al. 2011), and the impacts of forest change on rainfall, as well as the population increase of both cattle and humans were cited as the most important factors affecting forests and the flow regime. Although there was a perception that forests were related to the flow regime, the communities, in all watersheds, did not consider this relationship to be simple or direct.

# 6 Summary and Synthesis

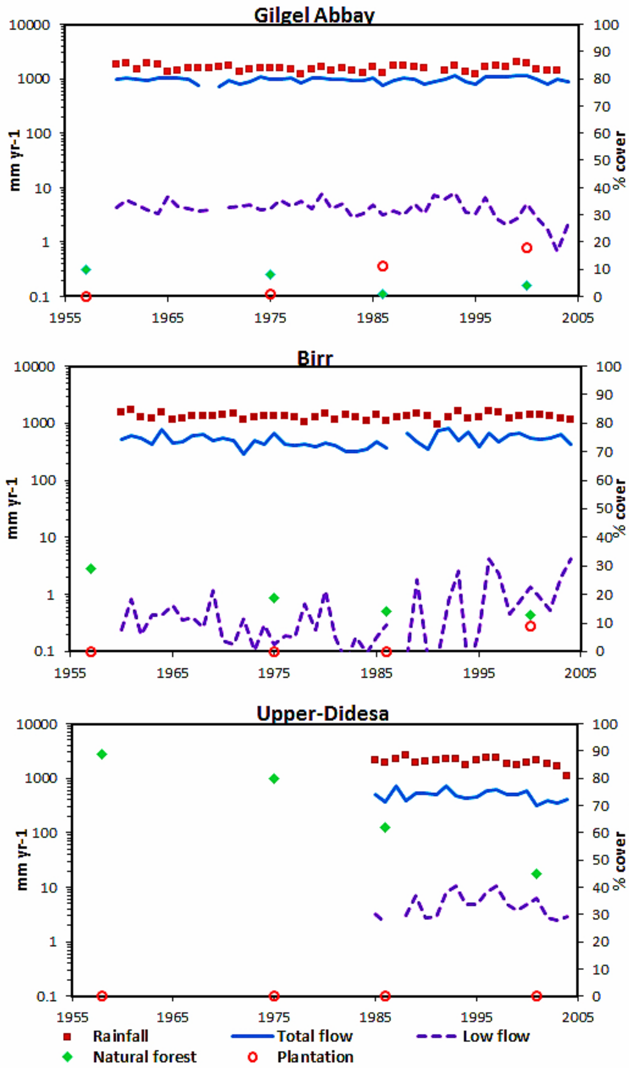
## 6.1 Flows and forest change in the BNB

The influence of tropical forests on hydrological regimes is of both scientific and societal concern. The relationship between forest change and the hydrological regime is both site and time specific (Andreassian, 2004; Bruijnzeel, 2004). Differences in watershed characteristics, forest function, hydrological processes and climate contribute to unresolved questions in forest hydrology. In addition to spatial differences, temporal changes in climate, soils, forest communities and societal pressures contribute to the differences in hydrology. Climate, topography and land cover systems are more complex in the tropics than elsewhere in the world (Malmer et al., 2009). Scale is a confounding factor that has a considerable influence. For example, the negative effect of forest evapotranspiration on runoff is directly measurable at the local scale (tens of square kilometers), whereas, the positive effect of forest evapotranspiration on precipitation is on a much larger scale (hundreds and thousands of square kilometers: Ellison et al., 2011). Thus, the influence of forests on hydrology in tropical areas is far from transparent, as there are different aspects influencing different parts of the hydrological regime. In regions where the livelihood of people depends entirely on the availability of water, any impact on low and high flows is important, particularly as these flow extremes (both high and low) are the most difficult to gauge accurately (McMillan et al., 2010; Westerberg et al., 2010).

In this work, the relationship between forest change and hydrological regime in the BNB of Ethiopia was assessed at the river/watershed scale of hundreds and thousands of square kilometers. Different analytical approaches (statistical analysis, hydrological modeling, remote sensing and community perception) were applied to assess half a century of changes in the hydrological regime and land cover of the BNB. A statistical approach applied to 12 rivers (19 –1800 km$^2$ sized watersheds) tested for possible hydrological changes over 45 years. Of these 12 rivers, four rivers were further analyzed through modeling to detect hydrological changes. The spatial relationships of the hydrological regime to watershed characteristics, including land cover/forest cover types, were also characterized with statistical approaches. Changes in land cover were analyzed through remote sensing with an emphasis on forest cover types. Finally, community perception, a source of information that can complement the instrumental observations was compiled through interviewing community elders in four of the 12 watersheds. The spatial, temporal and methodological breadth of this study was advantageous for attempting to clarify any relationships between forest cover and the flow regime in the Blue Nile Basin.

In the Blue Nile Basin, drought is the main problem facing the livelihood of the people and there is a popular belief that low flows are accentuated by deforestation in the highlands of the Basin. Despite this widespread belief, the general impact of highland deforestation on low flow was not readily identifiable in the instrumental records, at least for these specific watersheds. In most cases there were no major changes in the low or total flow regime, even though there has been ongoing deforestation for the past three to six decades. However, much of the absolute loss of forest occurred before the study period (Figure 3), and the impact of deforestation eluded simple generalization, as there were specific dates and rates of deforestation and types of forests involved. The spatial relationship between forest cover and low flows was more distinct than the temporal relationship between forest cover and low flows. Woodlands, grasslands had stronger positive relationships with low flow (Paper I). Riverine forest had a negative impact, according to the community perception, which may be due to the riverine forests utilizing much water in and around the riverbank and transpiring during the dry season (Winter, 2007).

The statistical analyses revealed specific hydrological changes in some watersheds of the BNB over 45 years. Although fluctuation in rainfall could explain some of those changes, further information is needed to increase understanding of the complex and unclear relationship between forest and flow in the temporal dimension. Factors that could contribute to the complexity of the relationship between forests and flow include possible errors in observational data of extreme flows, the different types of forest cover change, the specific timing of forest impacts on flow, the different factors affecting forest and flow relations, and the scale of forest impacts. As the relation between forest and flow is complex, community perception could be a complementary tool for addressing the areas in forest hydrology where there is a lack of knowledge.



*Much of the deforestation happened before 1960. The extent of Eucalyptus plantation has expanded since 1975. In the last two decades there were increment in grazing land, erosion, as well as wells and springs going dry. The community from the upstream perceived that clearance of the natural forest had reduced rainfall, which in turn changed the flow regime.*

*Much of the natural forest gone in 1960s and 1970s, and Eucalyptus has appeared in 1980s. There were no major changes in the flows in the upstream. The downstream community perceived a clear relationship between deforestation and water availability; increased water consumption by cattle and humans has a greater role to the problem of water availability than deforestation.*

*Enhanced deforestation has started after 1980s. Not so much happening in the flow regime. Much of water shortage is related with flash flooding as consequence of high intensity rainfall during recent years. Resettlement and expansion of cultivation are the main causes of deforestation.*

*Figure 3.* Relationship of rainfall, total flow and low flow to change of natural forest and

plantation in three watersheds in the Blue Nile Basin. The text for each watershed summarizes community perception for that watershed.

## 6.2 Community perception as a complement to observational analysis

In this study, community perception provided an alternative perspective for identifying the relationship between forestry, land use and flow regime. The community cited cattle and human populations as one of the factors for the impact of forest on flow being complex and non-direct. The impact of deforestation on rainfall was considered an additonal factor that rendered the causality of forest hydrology difficult to identify in the temporal dimension. The impact of deforestation on rainfall is one of the most complex issues in tropical hydrology (Ellison et al., 2011), as deforestation could affect albedo and wind direction, which in turn, affects the local rainfall pattern (Dickinson and Henderson-Sellers, 2006) that ultimately could affect the flow regime.

According to community perception and the spatial analysis of watershed characterization, forest change could directly affect low flow, for example the afforestation of Eucalyptus reduced low flow and the deforestation of riverine forest increased low flow. The increment of baseflow after deforestation of riverine forest was confirmed in measurments but the impact of Eucalyptus could be not confirmed. The suggestion that Eucalyptus reduces low flow regimes needs to be treated cautiously, as these impacts can be site specific (Wullschleger et al., 1998). In Angereb, the community mentioned that after the implementation of soil conservation practices low flow increased.

In the observational analysis, changes in the hydrological regime were watershed specific and the community perception amplified the specificity at the sub-watershed level. The relation of forest and flow in different parts of a single watershed could not be proved statistically over time with recorded observational data from the entire watershed, however, community perception provided information that was more specific to the sub-watershed level. Scale is a recognized issue in tropical forest hydrology (Blöschl et al., 2007), which was confirmed by the results presented in Paper II.

## 6.3 Future perspectives

The general conclusion was that forest impacts on hydrology over time could not be generalized at basin or regional scales. Community perception did not yield univocal results regarding forest influences. The large scale at which the instrumental observations were taken might be one reason for the lack of a clear forest-water relationship. The variability in rainfall patterns and topography of the watersheds (Haimanote et al., 2010) as well as the differences in vegetation types (Demel, 2002) further reduced the likelihood of finding clear relationships between forest and flow regimes. Future studies on forest hydrology need to address both sub-watershed scales and differences in watershed characteristics, including vegetation, and address the hydrological processes attributed to different forest types.

As forest change will continue in response to a range of drivers, from economic drivers at the local level to environmental and climatic drivers on a global scale, both short-term financial growth and long-term environmental impacts need to be addressed (Bonnel, 1998). The effect of changes in forest and other land use patterns on the flow regime needs monitoring, especially in areas such as the BNB where water availability during the dry season is an important factor for food security and the development potential of the region.

Apart from the issue of scale in detecting land use influences, it should be recognized that water availability at river scale and farm level could be different, with the latter being more important role for the livelihoods of the people in the basin. The residents of the basin are mainly subsistence farmers and any influence on farm-scale water availability can affect their way of life. Land use change could induce larger hydrological changes at the farm level than at the river scale. Farm level studies could be equated with hydrological studies at the hillslope scale. The issue of farm level (hillslope) versus river/watershed level water availability needs to be thoroughly elucidated. Another factor confounding the detection of land use influence on the flow regime is uncertainty in the hydrological data. This could be managed through data quality control, as many data quality problems arise from measurement and human-induced error. Data problems are manifested especially in the peak and low flow parts of the hydrograph (Westerberg et al., 2010), and it is these that are important extremes for characterizing changes in flow regime. During the modeling work in this study, simulated discharge was better fitted with the rising and falling limbs than peak and base flows (Paper III).

Therefore, in future hydrological analysis, there is a need to treat the peak and low flow parts of the hydrograph with particular care.

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# 7 Summary (Amharic)

## የደንና የወንዝ ፍሰት ቁርኝነት በዓባይ ተፋሰስ፤

### ለወደፊቱ የውሃ ልማት ሥራዎች መሠረት የሚሆን ከግማሽ ምዕተ ዓመት የተመዘገበ ልኬት ትንታኔንና የህብረተሰብ መረጃ የተገኘ ግንዛቤ

### ማጠቃለያ

ይህ ማጠቃለያ ከጠቅላላው የዚህ የዶክተሬት ድግሪ መጽሃፍ ይዘት የተውጣጣ ቅንጫቢ በመሆኑ ለዝርዝር ጭብጡ ሙሉ መጽሃፉን ማንበብ ይመከራል።

በዓባይ ተፋሰስና በሌሎች የሃገሪቷ ክፍሎች የወንዞች መድረቅ ከደን መጨፍጨፍ ጋር ተያይዞ ይነሳል። ይህ ተያያዥነት ከሳይንሳዊ ዳራ አንጻር እንደተጠቀሰው ቀላል ሆኖ አይታይም። ይህ ጥናት በዓባይ ተፋሰስ የወንዞች ፍሰት እና የደን ቁርኝነት ምን እንደሚመስል ይዳስሳል። ዝርዝር ዓላማዎቹ፤ የደንና የውሃ ፍሰት ከቦታ ስርጭት አኳያ፣ የወንዞች ፍሰት ለውጥ ላለፉት ግማሽ ምዕተ ዓመት እና የደን ሽፋን ለውጥ ላለፉት ግማሽ ምዕተ ዓመት ናቸው። ጥናቱ የተከናወነው የልኬት ትንተና፣ ሞዴሊንግ፣ የሪሞት ሴንሲንግና የህብረተሰብ መረጃን መሠረት በማድረግ ነው። ለጥናቱ ከአሥር ያላነሱ ስፋታቸው ከ አሥራ ዘጠኝ እስከ አንድ ሺ ስምንት መቶ ኪሎ ሜትር ስኩዌር ተፋሰሶች ተካተዋል።

በተለያዩ የዓባይ ተፋሰስ ቦታዎች ያለውን የደንና የወንዝ ቁርኝነት ለማየት በተጠናው ጥናት መሰረት የተፈጥሮ ሳር በቀልና እንጨታማ ደኖች ለበጋው የወንዝ ፍሰት አዎንታዊ ጥቅም ሲኖራቸው፤ የግጦሽ መሬትና ገለጣማ ቦታዎች አሉታዊ ተጽእኖ አላቸው። የግማሽ ምዕተ ዓመቱ ልኬት ትንተና ግን ብዙ የወንዝ ፍሰት ለውጦች እንደሌሉና የታዩትም ጥቂት ለውጦች ከተፋሰስ ተፋሰስ እንደሚለያዩ አሳይቷል። የደን ሽፋን ለውጥን በተመለከተ እንደ አጠቃላይ የሚነገረው በሰሜኑ የሃገሪቱ ወይም የዓባይ ተፋሰስ ክፍል ከደቡቡ ክፍል ቀደም ብሎ ደን መመናመኑ በዚህ ጥናትም የታየ ሲሆን፤ የደን ለውጦች ሂደት ከተፋሰስ ተፋሰስ እንደሚለያዩ ታይቷል። ስለዚህም

ከረዥም የጊዜ ልኬት አኳያ የወንዝ ፍሰትና ደን የጎላ ቁርኝነት አይታይባቸውም። ከአካባቢ ህብረተሰብ የተሰበሰበው መረጃም ደን ጠፋ፣ ወንዝ ደረቀ አይነት ቀላል አገላለጽ አያሳይም።

ከላይ የተጠቀሱት ወጤቶች የሚያመላክቱት የደንና የወንዝ ፍሰት ቁርኝነት ውስብስብ እንደሆነ ነው። በተለይ ግማሽ ምዕተ ዓመቱን የሚመለከተው ጥናት የደንና የወንዝ ፍሰት ቁርኝነት ውስብስብ እንደሆነ ያመላከተው ተፋሰሶቹ ትልቅ በመሆናቸውና በተለያዩ ጊዜያት የሚታየው የተዛባ የዝናብ ስርጭት አስተዋጽኦ ለኖራቸው እንደሚችል ይገመታል። በግማሽ ምዕተ ዓመቱ ጥናት የታዩት ጥቂት የወንዝ ፍሰት ለውጦችም ከተፋሰስ ተፋሰስ ሰለሚለያዩ፤ ወደፊት የውሃ ልማትን መሰረት ያደረጉ የተፈጥሮ ልማት ስራዎች ከተፋሰስ ተፋሰስ ሊለያዩ እንደሚገባ ይህ ጥናት ያስረዳል። እንደውም ከአካባቢ ህብረተሰብ መረጃ እንደሚያመለክተው፤ በአንድ ተፋሰስ ውስጥ እንኳን ልዩነት እንዳለ ነው። ስለዚህም የልማት ሥራዎቹ ከተፋሰስ ተፋሰስ መለያየት ብቻ ሳይሆን አንዱን ተፋሰስ ከፋፍሎ ማየት እንደሚያስፈልግም ያመላክታል፤ በተለይ ስፋታቸው አንድ ሺ ኪሎ ሜትር ስኩዌር አካባቢ ለሆኑት። ከዚህ በተጨማሪ ለወደፊቱ የወንዝ ፍሰት መድረቅ ከግብርና ሥራ ውሃ እጥረት ጋር ያለውን ትስስር ማየት ያስፈልጋል።

## ምሥጋና፦

ምንም እንኳን የዚህ መጽሃፍ ዝግጅት የአንድ ሰው ሥራ አለመሆኑና ለሥራው ሁሉ የበለጠ አስተዋጽኦ ያደረጉ በእንግሊዘኛው የምሥጋና ዝርዝር የተገለጹ ቢሆንም ለአማርኛ ተናጋሪዎች ይህንን ብያለሁ። በቅድሚያ ለዚህ የመጨረሻ ድግሪ ሥራ ያበቃኝን እግዚአብሔርን አመሰግናለሁ።

ለልጆቼና ለባለቤቴ፤ ለሐረገወይን፣ ለናሆም፣ ለአክሊለና ለሠናይት፤ በተለያየ ጊዜ ከነሱ መለየቴ ሳያስከፋቸው ፍቅራቸውን በመለገስ እዚህ እንድደርስ ስለረዱኝ በምላሹ ፍቅሬ ሁሉ ለነሱ እንደሆነ ልገልጽላቸው እወዳለሁ። እንዲሁም ለባለቤቴ አባት ለአቶ ተስፋዬ አበበ ሁሌጊዜ አይዞህ በማለት ስላበረታቱኝ ከልብ የመነጨ ምስጋናዬን አቀርባለሁ። በህይወት ለሌሉት ያሰደጉኝና ያስተማሩኝ ቤተሰቦቼ ለወ/ሮ ንጋቷ ከፋለና ለአቶ ገብረዮሐንስ ገብረህይወት ምሥጋናዬ የላቀ ነው። ይህ ሁሉ የነሱ አስተዳደግ ውጤት ነውና። ይህችን ሥራ መታሰቢያነቷንም ለነሱ አድርጌአለሁ።

ሰለሞን ገብረዮሐንስ ገብረህይወት

# 8 Sammanfattning

## Hydrologi och skog i Blå Nilens avrinningsområde: Vilka lärdomar kan dras om vattenförsörjning efter ett sekel av observationer och intervjuer med boende?

Förändring i skogstäckning har föreslagits vara en huvudsaklig anledning till brist på vatten under torrperioden i det 2 × 105 km$^2$ stora avrinningsområdet till Blå Nilen i Etiopien, en del av Nilens flodsystem. Detta är dock en förenkling av komplexa skogs- och flödes-förhållandensärskilt i tropikerna. Målen med denna studie var att studera det rumsliga förhållandet mellan markanvändning och flödesregimer, bestämma förändringen i skogstäckning, och summera resultaten för att kunna definiera relationen mellan skogstäckning och den hydrologiska regimen. Två huvudsakliga tillvägagångssätt användes: analys av observationsdata och intervjuer med boende. Trettitvå avrinningsområden ingick i den rumsliga studien och 45 års data för ett dussintal avrinningsområden analyserades i den temporala studien. Statistiska metoder användes för att studera det rumsliga förhållandet mellan markanvändning och flöde, och både statistiska- och modelleringsmetoder användes för att detektera hydrologiska förändringar över tid. Fjärranalyser tillämpades för att detektera förändringen i skogstäckning.

Naturlig gräsmark och skogsmark var positivt korrelerade medan betesmark och öppen buskmark var negativt korrelerade till lågflödes regimer i den rumsliga studien. Det fanns inga större förändringar i flödesregim över tid, eller tydliga, generella resultat som kunde koppla försämring av markens tillstånd eller förändringar i markanvändning med hydrologiska förändringar. Den förändring som kunde relateras till skogstäckning var avrinningsområdesspecifik, även om det generellt var skillnad mellan de södra och norra avrinningsområdena med avseende på tidsramen för avskogning. Intervjuerna med de boende indikerade att relationen mellan skogstäckning och flödesregim var mer komplex än att enbart avskogningen orsakade bortfall av flöde under torrperioden. Enligt de äldre invånarna var skog och flödesförhållandet avrinningsområdesspecifikt, förhållandet var även specifikt mellan delavrinningsområden. Avsaknaden av ett tydligt förhållande mellan förändringar i skogstäckning och flödesregim i en temporal dimension kan bero på skalan på ytan av avrinningsområden, osäkerhet i flödesmätningar när det kommer till flödesextremer och påverkan från variationen i nederbörd i regionen.

Den avrinningsområdesspecifika relationen mellan skog och flöde i avrinningsområdet, vilket bekräftades genom intervjuer med boende, indikerar att skogshydrologiska studier måste skräddarsys till avrinningsområdesskala, eller till och med delavrinningsskala som en specifik sluttning. Resultatet underströk också betydelsen av att kunna modellera eller mäta vattentillgång i skalor som passar enskilda jordbruk eller floder.

Nyckelord: Intervjuer, Etiopien, Skogshydrologi, Lågflöde, Observations analyser

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