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Changes in land cover and stream flows in Gilgel Abbay catchment, Upper Blue Nile basin – Ethiopia

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Abstract

We evaluated the land cover change in the Upper Gilgel Abbay catchment in the Upper Blue Nile basin through classification analysis of remote sensing based land cover data and through assessing the changes in the hydrological regime by statistical analysis of stream flow observations. Results of the land cover classification analysis indicated that 50.9% and 16.7% of the catchment area was covered by forest in 1973 and 2001, respectively. This significant decrease in forest cover is mainly due to expansion of agricultural land. A comparison of stream flow time series of the Upper Gilgel Abbay catchment to stream flow time series from two neighbouring catchments shows a different trend and a statistically significant change over time. In 1986–2001, the annual and the high flows of the catchment increased by 13% and 46%, respectively while the low flows decreased by 35%. Generally, the results indicate significant changes in land cover and the hydrological regimes of the Upper Gilgel Abbay catchment over the past 30 years.

1 Introduction

Evaluating the effects of land cover change on hydrological regimes has been a subject of ongoing research (see Cosandey et al., 2005; Andréassian, 2004; Bosch and Hewlett, 1982). Understanding these effects is of key importance since in many regions a rapid increase in population density generally results cultivation and conversion of forests and wetlands to agricultural land. Studies by Bewket and Sterk (2005) and Lørup et al. (1998) showed that such land cover changes cause changes in hydrological regimes that affect the stream flow volume but also the pattern of stream flow and peak flows.

Many studies that address the effect of land cover on hydrological regimes were undertaken in experimental watersheds of small scales (<1 km^2), e.g., Blösch and Hewlett (1982); Troendle and King (1987); Lavabre et al. (1993); Iroumé et al. (2005);

Guillemette (2005). However, water resources management often requires information how changes in land cover affect the hydrology of medium to large scale catchments (>1000 km^2). Land cover typically is a local phenomenon so the impact of any disturbance is likely to strongly decrease with catchment size (Blöschl et al., 2007). Some studies on medium to large-scale catchments showed that the expansion of agricultural land by deforestation resulted in an increase in annual stream flows (e.g., Bewket and Sterk, 2005; Costa et al., 2003; Siriwardena et al., 2006), an increase in high flows (e.g., Mati et al., 2008; Costa et al., 2003) and an increase in base flows (e.g., Zhang and Schilling, 2006). However, Kashaigili (2008) reported a decrease in base flows while Wilk et al. (2001) were unable to detect any change in hydrological regimes despite a significant change in land cover by deforestation. This indicates that the results of past studies are inconsistent but clear reasoning why results are inconsistent is difficult. We note that inconsistencies could result from differences in hydrological behaviour of catchments by differences in climatic setting, in topographic settings in terms of watershed geometry (i.e. size, shape and elevation), in soil properties and differences in land cover types.

In this study, we analysed the changes in the land cover and the hydrological regimes of the Upper Gilgel Abbay catchment with size of approximately 1656 km^2. The catchment is part of the Lake Tana basin that is the source basin of the Upper Blue Nile River. Gilgel Abbay is a densely populated catchment with an annual population growth of 2.31% according to the Central Statistical Authority (CSA) of Ethiopia. This has led to increased and intensified human activities that resulted in deforestation, overgrazing and expansion of agricultural land. During field visits to the catchment, we observed that there is significant water erosion with deeply incised gullies (>25 m) in the area where forests were cleared. We also observed that deforestation is a day-to-day activity of the people that use the wood for heating and cooking. The catchment is characterized by a rainfall regime with very high rainfall intensities (>20 mm/h) and high variability in space and time dimension (see Haile et al., 2009, 2010). We observed that particularly the high rainfall intensity aggravates the effect of deforestation

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by increasing water erosion problems. Abdo et al. (2009) showed that climate change may affect the hydrological regime of Gilgel Abbay. However, land cover changes and their effect on the hydrological regime of the catchment have not received much attention. An exception is the work by Solomon et al. (2010) that focused on hydrologic impacts of deforestation in the Koga catchment that neighbours the Gilgel Abbay catchment. We note that our work differs since we apply supervised satellite based land cover classification for the Gilgel Abbay catchment that is of much larger scale. Also, we use daily observations of the hydro-meteorological time series for our analysis instead of the monthly maximum and minimum in Solomon et al. (2010). Recent studies that exclusively focus on the hydrology of the Gilgel Abbay catchment are reported by Setegn et al. (2010) and Grange et al. (2008). In the first much attention is on uncertainty analysis of hydrological modelling by the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) ignoring issues of land cover changes. Also in Grange et al. (2008) much attention is on hydrologic modelling for the Koga catchment and the Gilgel Abbay that was partitioned in the Upper Gilgel Abbay that is gauged and the lower part that is ungauged. Modelling was by the "HBV light" approach (see Seibert, 2002) and focussed on issues of model complexity in selecting spatial model domains and simulating high flows and low flows. Model transferability was also addressed to allow for applications in ungauged catchments. Grange et al. (2008) paid much attention to correct hydrometeorological time series.

Objectives of this study are to evaluate how land cover of the Gilgel Abbay has changed over the past 3 decades (1973–2001) and to evaluate how changes may have affected the hydrological regime. The work focuses on seasonal and annual time scales to evaluate possible long-term impacts but also focuses on high flow and low flow indices to evaluate if extremes in discharges are affected. The present study has large societal and economic relevance since the catchment is situated in the source basin of the Upper Nile basin and since it has a very dense population that largely depends on agricultural production.

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2 Study area and data sources

Gilgel Abbay is the largest contributor to the inflow of Lake Tana (see Wale et al., 2009) which is considered the source lake of the Upper Blue Nile River. The study area covers the part of Gilgel Abbay that is situated upstream of the gauging station at Wotet Abbay as shown in Fig. 1 and commonly is referred to as the Upper Gilgel Abbay catchment.

The Upper Gilgel Abbay is located between 10°56′ to 11°22′ N latitude and 36°44′ to 37°03′ E longitudes. The surface area of the catchment is approximately 1656 km^2 while the longest flow path of the river is 84 km. The Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) shows that the elevation of the Upper Gilgel Abbay catchment varies from 1934 to 2917 m a.m.s.l. Generally, the main wet season covers the period June to September while the main dry season covers the period October to May. Haile et al. (2009) show that the spatial distribution of rainfall amount has a decreasing trend from south to north.

The analysis of the land cover is based on three remote sensing images that were acquired in 1973, 1986 and 2001. Details of the image characteristics and the remote sensing sensors are presented in Sect. 3.1. Stream flow data is available on daily base and covers the period 1973–2005. Time series data from 3 rain gauges are analysed to evaluate if annual and seasonal rainfall has changed. Locations of the rain gauges in and around Gilgel Abbay and its two neighbouring watersheds Gumara and Megech are indicated in Fig. 1. The figure shows that Dangila and Gondar stations are located in Gilgel Abbay and Megech watersheds, respectively. Bahir Dar station is the only nearby station to Gumara with time series of rainfall records (>15 year). For this study, the hydrometeorological time series are screened and corrected for missing and unrealistic values. We note that, for instance, discharges as high as to 750 m^3/day were recorded. Further, differences of rainfall depths over consecutive days are compared to differences in stream flow and served to identify and to correct erroneous runoff data. We note that after correction, runoff time series are used in hydrological modelling in the Gilgel Abay in Wale et al. (2009) and resulted in a Nash

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Sutcliffe efficiency of 0.85 when manually calibrating the HBV-96 model (see Lindström et al., 1997) at daily base.

3 Methods

3.1 Image processing

Three orthorectified images of the Upper Gilgel Abbay were available by the National Aeronautics and Space Administration (NASA) and the Global Land cover Facility center (GLCF) (see http://glcf.umiacs.umd.edu/index.shtml). Table 1 shows the acquisition dates, sensor, path/row, resolution and the provider's of the images. The acquisition dates of the 1973, 1986 and 2001 images correspond to the dry season of the study area while the images have resolutions of 57 m for 1973 and 30 m for 1986 and for 2001. The Landsat multispectral scanner (MSS) bands 1, 2, 3, and 4 cover the spectral range between 0.45–1.10 µm. Both the Landsat thematic mapper (TM) and enhanced thematic mapper (ETM+) bands 1, 2, 3, 4, 5, and 7 cover the spectral ranges between 0.45–2.5 µm. Observations by bands 1–3 represent visible electromagnetic (EM) radiances at wavelengths 0.45–0.52, 0.52–0.60, and 0.63–0.69 µm, respectively. Band 4 corresponds to the near infrared wavelengths at 0.76–0.90 µm while bands 5 and 7 correspond to the mid-infrared wavelengths at 1.55–1.75 and 2.08–2.35 µm, respectively. The land cover images were created using the band combination of 7, 4, 2 (Landsat TM and ETM+ images of 1986 and 2001) and 4, 2, 1 (Landsat MSS image of 1973) to allow visual interpretation of the images in their true color.

For this study the image in 2001 is georeferenced using ground control points collected using a Global Positioning System (GPS) during a field visit, and a 1:50 000 scale topographic map of the study area. The root mean square error (RMSE) of the first order polynomial function (affine transformation) was found to be 0.20 pixel (or 6 m on the ground). The images in 1973 and 1986 are geo-rectified by image to image registration method. By image registration, the same coordinates are assigned for the

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same object which is shown in different images and involves georeferencing if the reference image is already rectified to a particular map projection. This allows to compare and to combine images that are acquired at different instants in time to represent different periods. For this study, the 1973 and 1986 images are registered to the 2001 image by image to image registration with an RMSE of 0.34 pixel (19.38 m on the ground) for the 1973 image and 0.22 pixel (6.6 m on the ground) for the 1986 image. The RMSE of the registered images is acceptable since they are much less than the resolution of the images.

Since images are observed at different moments in time, different conditions can prevail in the atmosphere which affects the measured radiances. As such, the satellite images have been corrected for atmospheric effects by applying the ATCOR package (see http://www.erdas.com/tabid/84/currentid/1072/default.aspx) which is embedded in the ERDAS Imagine software (see http://www.erdas.com/).

During our field campaign in 2008, 498 ground control points (GCP) were collected for image based land cover classification where 80% of the data points were used for training, i.e. for classification, and 20% were used for validation purposes. We selected locations of the GCP data by interviewing local elderly people and using a topographic map to identify locations for which land cover has not changed between 2001 and 2008. Based on the collected field data, 5 land cover classes have been identified for the Upper Gilgel Abbay catchment. The description of these land cover classes is as follows:

- Forest Land (F): Area with high density of trees which include eucalyptus and coniferous trees.

- Agricultural land (AG): Areas used for crop cultivation, and the scattered rural settlements.

- Shrubs land (SL): Areas covered with shrubs, bushes and small trees with little wood mixed with some grasses.

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– Grass land (GL): Area covered with grass that is used for grazing and that remains covered by grass for a considerable period of the year.

– Water and marshy land (WM): Area which remains water logged and swampy throughout the year, and rivers.

3.2 Image classification

For supervised classification, the ground control points collected in the field are used as a training sample set. Information on land cover conditions in the field is obtained through interviewing local elder people and a topographic map of the study area. The sample set for the classification is created using the combination of bands 7, 4, 2 (for images of 1986 and 2001) and bands 4, 2, 1 (for images of 1973) since these band combinations allow visualization of the images in their true colour. The maximum likelihood classifier is selected since unlike other classifiers it considers the spectral variation within each category and the overlap covering the different classes.

3.3 Land cover change detection

In this study, post classification comparison is used to quantify the magnitude of land cover changes over the 30 years period. The advantage of post classification comparison is that it bypasses the difficulties associated with the analysis of the images that are acquired at different times of the year, or by different sensors and results in high change detection accuracy (Alphan, 2003). The output of the post classification comparison is best described with a matrix diagram in which the land cover classes in the respective periods are shown across the rows and columns of the matrix. The output classes are assigned according to the coincidence of any two input classes in the respective periods. If there is no change in the land cover in the respective time period, then values appear only in the diagonal of the matrix. Under such circumstances, the sum of the columns and rows are similar indicating no change in land cover.

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3.4 Trends in stream flows

Trend analysis of stream flow records is important to evaluate whether changes in climatic factors and/or human interference may have affected the hydrological regime of a catchment. Several approaches are proposed in literature to test the presence of a trend in stream flow records. In the present study, the commonly used Mann-Kendall (MK) test (see Burn and Hag Elnur, 2002; Zheng et al., 2007) is applied to test the presence of a trend in the stream flow records of Upper Gilgel Abbay and two neighbouring catchments which are Gumara and Megech.

The test statistic (S) for the MK test reads:

$$S = \frac{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}\left(Y_j - Y_i\right)}{\sigma_s} \quad (1)$$

With standard deviation:

$$\sigma_s = \sqrt{\frac{N(N-1)(2N+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18}} \quad (2)$$

where N is the number of data; Y_j and Y_i are the data values in two consecutive periods; t_i is the number of ties, i.e., equal values, of extent i and n is the number of tied groups. The function $\operatorname{sgn}(Y_j - Y_i) = 1$ if $Y_j - Y_i > 0$; $\operatorname{sgn}(Y_j - Y_i) = 0$ if $Y = 0$ and $\operatorname{sgn}(Y_j - Y_i) = -1$ if $Y_j - Y_i < 0$.

The test statistic (S) follows the standard normal distribution and therefore if the p-value is greater than the significance level α then there is a statistically significant trend. The p-value is the probability, under the null hypothesis, of observing a value as extreme or more extreme as the test statistic S.

3.5 Stream flow change detection

Following Zheng et al. (2007), the moving average t-test is applied to identify the year at which changes in stream flows occurred. In this procedure, a time window of length $2n$ years is centered on the year which is considered to be the potential change point. Next, the presence of a change in the mean of the stream flows is evaluated by applying the t-test for the mean values of the annual flows in the two periods of length n years before and after the potential change year. The window is sequentially moved over the entire time period of the flow records by positioning the center of the window at the potential change year.

The test statistic of the t-test reads:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s\sqrt{\frac{1}{n_1} - \frac{1}{n_2}}} \quad (3)$$

and

$$s = \sqrt{\frac{n_1 s_1^2 + n_s s_2^2}{n_1 + n_2 - 2}} \quad (4)$$

where $\overline{x_1}$ and $\overline{x_2}$ are the mean annual stream flow of the n years before the potential change point and the n years after the potential change point, respectively; s_1 and s_2, and n_1 and n_2 are the standard deviation and the number of years in the first and second period, respectively; s is the pooled standard deviation. In this study n_1 and n_2 will be equal.

After identifying the time periods that have a statistically significant difference in mean annual flows, some indexes of the flow in each period are estimated. These statistics include a low flow index (Q_{95}/Q_{50}) and a high flow index (Q_5/Q_{50}), where Q_k is the flow that is probably exceeded k% of the time. The exceedance probabilities are estimated applying the Weibull plotting position formula (the selection of the Weibull formula is arbitrary).

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4 Results

4.1 Land cover classification

Accuracy assessment

Results of image classifications are validated by creating an error (confusion) matrix from which different accuracy measures are derived. The confusion matrix is used to compare spatially coincident ground control points and pixels of the classified image. Table 2 shows a confusion matrix that is established using 100 ground control points (GCP) which are not used in the classification of the 2001 image. From the confusion matrix four measures of accuracy are estimated that are the overall accuracy, user's accuracy, producer's accuracy, and the kappa statistic. The overall accuracy is the number of correctly classified pixels (i.e., the sum of the diagonal cells in Table 2) divided by the total number of GCP (i.e., reference data) used for validation. The overall accuracy in the present study is 83%. The user accuracy in Table 2 is the probability that a certain class in the GCP is labelled the same class in the classification and refers to the columns of the table. The producer accuracy is the probability that a sampled pixel in an image falls in that particular class in the GCP and refers to the rows. Producer's accuracy values for all classes except WM ranged from 83–86%. The kappa coefficient (k) of 0.78 of the maximum likelihood classification represents a probable 78% better accuracy than if the classification would be based on random unsupervised classification. Monserud (1990) suggested a kappa value of <40% as poor, 40–55% fair, 55–70% good, 70–85% very good and >85% as excellent. According to these ranges, the classification in this study has very good to excellent agreement with the validation data set.

Land cover classification maps of the study area are produced for three reference years 1973, 1986 and 2001, see Fig. 1. The land cover classes in the respective years are summarized in Table 3 which shows that most parts of the Upper Gilgel Abbay were covered by forest in 1973 and by agricultural land in 1986 and 2001.

4.2 Change detection of the land cover

Tables 4 and 5 show the land cover changes that occurred in the period 1973 to 1986 and the period 1986 to 2001, respectively. In both tables, the areas of the land cover classes that did not change in the respective periods appear along the diagonal of the matrix.

The change detection analysis indicates that a significant change in land cover occurred in the period 1973 and 2001. The first row of Table 4 shows that the total area covered by grass land (GL) is 65.7 km^2 in 1973. It is shown that 6 km^2, 5 km^2, 5 km^2 and 10 km^2 of the GL has changed to shrubs, water and marshy, forest and agricultural lands respectively during the period 1973–1986. Table 4 shows that 267 km^2 of forest land was converted into agricultural land during the period 1973–1986. In this period, the agricultural land was expanded almost by 200 km^2 while 267 km^2, 68 km^2 and 95 km^2 forest land was converted into agricultural land, shrub land and grass land, respectively. On the other hand, 5 km^2 of grass land, 60 km^2 shrubs land and 66 km^2 of agriculture land were reforested.

Results in Table 5 indicate that 30 km^2, 23 km^2, 2 km^2 and 299 km^2 of forest land was converted to grass land, shrubs land, water and marshy land, and agricultural land, respectively in the period 1986–2001. In contrast, 27 km^2 grass land, 16 km^2 shrubs land, and 43 km^2 agricultural land was converted to forest land in this time period. Results show larger conversion of grass land and forest to agricultural land in 1986–2001 as compared to 1973–1986 suggesting acceleration of land cover changes.

4.3 Trends in stream flows

The stream flow records for the time period 1973–2001 are used to estimate the test statistic (S) for the MK test and results are shown in Table 6. Results show that the annual stream flow of the Upper Gilgel Abbay has a decreasing trend that is statistically significant. The monthly flows do not have a significant trend in the period January–April. However, the monthly flows in May, July and November have decreased significantly over time but the June flow has increased significantly. The analysis is repeated for Gumara and Megech catchments that bound the Gilgel Abbay catchment to test if similar trends can be observed. Both catchments have topographic and land use settings comparable to those of the Gilgel Abbay catchment and also are know for their still increasing population density. Some difference is that Gumara catchment has a large floodplain area that is not present in the Upper Gilgel Abbay catchment. Table 6 shows that the annual flow of Gumara does not show a significant trend over time but its monthly flows in August, September, October and December have an increasing trend while the November flow has a decreasing trend. The annual flow and the monthly flows of Megech watershed in July and September have a significantly increasing trend but its August flow has decreased over the years. In Sect. 4.4, the changes in rainfall in these catchments are analysed.

4.4 Change detection of stream flow

Figure 3 shows the estimated t-values for a window size of $2n$=10. In the present study, a significance level of α=0.05 is applied for which the absolute value of the critical t-value is t_α=2.3. As such, a change is considered to occur in a particular year when the absolute value of the estimated t-value in Eq. (3) exceeds 2.3.

Figure 3a shows the estimated t-values and the critical t-values for the stream flow of the Gilgel Abbay watershed which is represented by the solid line and the broken lines, respectively. The figure shows that for the years 1982 and 2001 the estimated t-values are higher than the critical t-values which indicate that the mean of the annual stream flows has changed.

Figure 3b shows the estimated t-values for the stream flow of Gumara watershed which is located in the eastern part of the Lake Tana basin. In the figure, critical t-values are not exceeded and this suggests that there is no statistically significant change in the mean annual flow of Gumara watershed.

Figure 3c shows the t-values for the stream flow of Megech watershed which is situated in the northern part of the Lake Tana basin. The figure shows that estimated

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t-values for the years 1982 and 1994 are higher than the critical t-values. The first change year is the same as that of Gilgel Abbay but the second one is different from that of Gilgel Abbay.

The results suggest that among the three watersheds, only Gumara watershed did not experience significant changes in its annual stream flow pattern. This suggests that the annual flow of Gumara has different characteristics as compared to annual flows of the two neighboring catchments that experienced changes in annual flow over time. The Upper Gilgel Abbay and Megech watersheds experienced two change years. The first change year is the same for the two watersheds. The second change year is different with the annual flows changing after 12 and 19 years of the first change year, respectively. Further analysis is required to assess the magnitude and directions of the changes as well as similarities in the factors that caused the changes in the respective years. We note that the change detection analysis in this Section provides input for the analysis of the changes in stream flow, see Sect. 4.4. The results indicate that for the change detection analysis, the annual stream flow of Upper Gilgel Abbay can be analyzed by dividing the flow records into three periods that are 1973–1981, 1982–2000, 2001–2005 while the records of Megech has to be divided into 1973–1981, 1982–1984, 1984–2005. The rainfall records in the respective catchments are divided to match the time periods of stream flows.

4.5 Changes in stream flow

Table 7 shows some features of the annual stream flow of three major catchments of the Lake Tana basin. The three time periods in the table are identified based on the results of the moving average t-test. In the analysis, results from the second period are compared to results from the first period while results from the third period are subsequently compared to results from the second period. Overall, the mean annual flow of Gilgel Abbay has significantly decreased over the period 1973–2005. The annual flow decreased by 5.3% during the second period and further decreased by 12.7% in the third period. This resembles the results of the MK test that indicated a significant

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decreasing trend in the annual flow. The high flow index of Gilgel Abbay increased by 7.6% during the second period and 46.6% during the third period and indicates a large increase of high flows over the years. The low flow index decreased by 18.1% and 66.6% in the second period and the third period respectively, which indicates that the low flow of Gilgel Abbay largely decreased.

The results of the moving window *t*-test indicated that there is no significant change in the mean of the annual stream flow of Gumara watershed. For further analysis on the magnitude and changes in stream flows, the time series of flow records is divided arbitrarily in three periods that match the periods of the Gilgel Abay catchment. Table 7 shows that the annual flow of Gumara increased by 8.1% and 8.7% during the second and the third period, respectively. The value of the high flow index decreased by 5.0% and 8.8% during the second and the third period which indicates that high flow of Gumara decreased over the years. However, the value of the low flow index increased by 25% and 260% during the second and third period which shows that the low flow has significantly increased over the years. In terms of mean annual flow, high flow and low flow, the direction of change in the stream flow of Gumara is contrary to that of Upper Gilgel Abbay. We speculate that such is caused by the differences in the changes of factors that affect stream flow. One such factor is land cover change and this study showed that the land cover of Upper Gilgel Abbay has largely changed over time with a significant expansion of agricultural land by deforestation. By its topographic settings with a large floodplain area and less high mountain ranges, we assume that land use in Gumera has not changed to the extent as observed in the Gilgel Abbay catchment. The results in Sect. 4.3 also endorse this assumption. To become more conclusive, however, land cover changes in Gumara catchment must be assessed in detail.

The flow record of Megech is divided into three periods based on the results of the moving window *t*-test results. These time periods do not correspond to the time periods that are identified for Gilgel Abbay except for the first period. Table 7 shows that the annual flow of Megech decreased by 55.5% during the second period but it increased by 97.4% during the third period. The high flow index increased by 7.9% during the second period but it decreased by 48.2% during the third period. However, the low flow index decreased by 40.0% in the second period but it increased by 116.6% in the third period.

Table 8 shows the rainfall amounts at three stations during the last two time periods for which changes in stream flows are detected. Each of the stations is situated close to or in one of the three catchments: Dangila and Gondar are situated in the Upper Gilgel Abbay and Megech watersheds, respectively while Bahir Dar is at relatively close distance (i.e. 30 km) to Gumara watershed. The table shows that not only the annual and the wet season rainfall in June, July and August (JJA) of Bahir Dar slightly increased but also the ratio of its JJA to its annual rainfall increased. These slight increases in rainfall are consistent to the increases in annual and dry season flows in the Gumara catchments. This strengthens our perception on the land cover of Gumara that has not significantly changed. The annual rainfall of Dangila, which is situated in Gilgel Abbay watershed, decreased over the two time periods suggesting that the decrease in the flow of Gilgel Abbay watershed can be partly explained by a decrease in rainfall amount. However, the JJA rainfall and the ratio of JJA to annual rainfall of Dangila slightly increased over the time periods. This is in agreement with the increase in the high flow index which shows that high flows of Gilgel Abbay increased.

Table 8 also shows that the annual rainfall of Gondar, which is located in Megech watershed, increased which also may affect the increase of the annual flow of Megech. The JJA rainfall of Gondar increased over time but as discussed previously, the high flow index of Megech showed a decrease in high flows.

5 Conclusions

In the present study, the changes in the land cover of the Upper Gilgel Abbay catchment and its effect on the catchment's hydrological regimes were analysed. The land cover was classified for three remote sensing images that are acquired to cover the period 1973–2001. Accuracy assessment of the supervised land cover classification indicates that the classification results are reliable.

We quantified the land cover changes in the study area using post classification comparison. Results showed that in the early nineteen-seventies most parts of the Upper Gilgel Abbay were covered by forest. However, a significant decrease in forest land was observed by the expansion of agricultural land in the following three decades. The post classification comparison showed that forest land decreased from 50.9% in 1973 to 32.9% in 1986. Agricultural land increased from 28.2% in 1973 to 40.2% in 1986. In the time period 1986–2001 forest land decreased from 32.9% to 16.7% while agricultural land increased from 40.2% to 62.7%. The results indicate that the rate of deforestation is slightly smaller in the second time period as compared to the first period due to reforestation activities. However, the extent of deforestation is still much larger than the extent of reforestation. The expansion of agricultural land is largest in the 1986–2001 period and also is larger than in the previous time period suggesting the increased demand for agricultural lands probably is a result of increasing population density. This suggests that the land cover change is still ongoing and as such we recommend that future work must evaluate effectiveness of measures that mitigate effects of land cover changes.

We showed that the annual stream flow of the Upper Gilgel Abbay experienced a decreasing trend over the 32 years time period. Results suggest that while there is a significant expansion of agricultural land on the expense of forest land in the watershed, the annual flows of the watershed has significantly declined over time. A change in annual flow is an aggregated effect of the changes in wet and dry season flows which are likely to be affected by land cover in different ways. Our analysis shows that the

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monthly flows in May, July and November have decreased significantly over time but the flow in June has increased significantly. May and June, November and July are at the beginning, the end and in the middle of the rainy season. Interpreting this result with respect to the detected land cover changes is not straightforward since flows are aggregated over a monthly time scale and changes in rainfall presumably contribute to the changes in stream flow.

Overall, the stream flow of Upper Gilgel Abbay shows a different direction in trend as compared to the flows of its neighbouring catchments which are Gumara and Megech. Such difference, for instance, could be caused by differences in human interferences as well as differences in catchment characteristics.

Through a change detection analysis we showed that the annual stream flow of Gilgel Abbay can be divided into three periods that are 1973–1981, 1982–2000, 2001–2005. These time periods correspond to the time periods over which we observed a significant change in land cover in the study area. Overall, the mean annual flow of Upper Gilgel Abbay has significantly decreased over these three time periods. The annual flow decreased by 5.3% and 12.7% during the second and the third period while the high flow index indicates that high flows largely increased over the years. Over the past 32 years the annual rainfall in the watershed decreased over the two time periods suggesting that the decrease in the flow of the Upper Gilgel Abbay watershed is not only the result of the expansion of agricultural land but also is due to a decrease in rainfall amount. The increase in high flows is as expected in areas where agricultural land has largely increased by deforestation (e.g., Mati et al., 2008; Costa et al., 2003). We showed that the wet season rainfall in Upper Gilgel Abbay increased significantly that as such could have contributed to the increase in the high flows. To become more conclusive on the specific causes, however, we recommend further assessment by use of rainfall-runoff modelling. We note that such is scheduled for future work.

The low flow index indicates that the low flow of Upper Gilgel Abbay largely decreased over the 32 years. Since a low flow index may be associated with dry season flows this suggest that changes in low flow are due to land cover changes. The decrease of low flows is similar to Kashaigili (2008) but is in contrast to Zhang and Schilling (2006). In both studies, an expansion of agricultural land is reported but its effect on the hydrologic regimes is shown to be inconsistent. We note that different climatic and catchment characteristics do not allow direct comparison of our results to results from other regions and therefore our results do not allow generalisation.

The time periods over which the stream flow characteristics changed are 1973–1981, 1982–2000, 2001–2005 and resemble the periods for the land cover changes. The analysis indicates an increasing trend in the changes in both land cover and the hydrologic regime of the watershed. To summarize, results for the Upper Gilgel Abbay watershed showed that deforestation caused a decrease in annual and base flows and an increase in high flows. Most of the deforested area is converted in agricultural land and largest changes in both the land cover and stream flow occurred in recent years. Annual rainfall and wet season rainfall in the watershed decreased and increased over the past three decades, respectively. We recommend that future work must apply distributed hydrologic models with a physical basis to allow better evaluation of effects of land cover changes and rainfall distributions on the hydrologic regime.

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Table 1. The data sources for the analysis of land cover change.

Path/Row	Sensor	Acquisition date	Resolution (m)	Provider
183/52	MSS	1 Feb 1973	57	GLCF
170/52	TM	3 Jan 1986	30	GLCF
170/53	ETM+	5 Feb 2001	30	GLCF
170/54	ETM+	12 Sep 1999	30	GLCF
	SRTM	2000	90	USGS/GLCF

Note: MSS multi-spectral scanner; TM Thematic mapper; ETM Enhanced thematic mapper; SRTM Shuttle radar topographic mission; GLCF Global Land cover Facility; USGS United States geological Survey

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Table 2. Confusion matrixes for validation of land cover map 2001.

Reference data	Classified data WM	AG	GL	F	WM	Producer's accuracy (%)
WM	12	0	2	0	0	85.71
AG	0	22	2	2	0	84.62
GL	1	2	17	0	0	85.00
F	0	1	1	19	2	82.61
WM	0	2	0	2	13	76.47
User's accuracy (%)	92.31	81.48	77.27	82.61	86.67	
Overall classification accuracy = 83%						
Kappa statistic = 0.78						

Note: WM = water and marshy land; AG = agricultural land; GL = grass land; F = forest; SL = shrubs

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Table 3. Summary of land cover type in Upper Gilgel Abbay catchment for 1973, 1986 and 2001.

Land cover types	1973		1986		2001	
	km^2	%	km^2	%	km^2	%
GL	65.7	4.0	215.9	13.0	146.5	8.8
SL	279.4	16.9	209.9	12.7	147.5	8.9
WM	0.1	0.0	20.5	1.2	45.8	2.8
F	843.8	50.9	544.2	32.9	277.4	16.7
AG	467.2	28.2	665.6	40.2	1038.9	62.7

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Table 4. Land cover (LC) conversion matrix (km^2) for the period 1973 and 1986.

Land cover types	GL	SL	WM	F	AG	1973
GL	41	6	5	5	10	67
SL	13	83	5	60	118	279
WM	0	0.1	0	0	0	0.1
F	95	68	0	414	267	844
AG	67	54	10	66	271	468
1986	216	210	20	545	665	1656

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Table 5. Land cover (LC) conversion matrix (km^2) for the period 1986 and 2001.

Land cover types	GL	SL	WM	F	AG	1986
GL	61	6	23	27	99	216
SL	18	76	0	16	100	210
WM	10	0	9	0	1	20
F	30	23	2	192	299	546
AG	29	43	11	43	538	664
2001	148	148	45	278	1037	1656

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Table 6. The Mann-Kendall test statistic (S) for trend analysis for annual and monthly flows in three watersheds of the Lake Tana basin. Note the p-values are shown between brackets while statistically significant trends are highlighted in gray.

Period	Upper Gilgel Abbay	Gumara	Megech
Annual	−0.99 (0.321)	+2.26 (0.0238)	+1.6235 (0.105)
Jan	−5.18 (0.000)	+3.62 (0.0000)	+2.3625 (0.018)
Feb	−5.52 (0.000)	+4.06 (0.0000)	+2.2945 (0.022
Mar	−5.14 (0.000)	+3.48 (0.0000)	+2.7704 (0.006)
Apr	−2.67 (0.008)	+3.86 (0.0000)	+3.1783 (0.002
May	−0.28 (0.780)	+3.28 (0.0010)	+2.8384 (0.005)
Jun	1.64 (0.101)	+3.01 (0.0026)	+2.1925 (0.028)
Jul	−0.50 (0.620)	+2.09 (0.036)	+1.1728 (0.241)
Aug	−2.42 (0.016)	+1.85 (0.064)	−0.2549 (0.799)
Sep	−2.73 (0.006)	+0.83 (0.405)	+0.0850 (0.932)
Oct	0.000 (−0.988)	+0.66 (0.507)	+2.9744 (0.003)
Nov	−1.53 (0.125)	−0.39 (0.696)	+2.6684 (0.008)
Dec	−3.38 (0.011)	+1.24 (0.215)	+2.4305 (0.015)

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Table 7. Stream flow characteristics of three major watersheds in the Lake Tana basin.

Gilgel Abbay			
Time period	1973–1981	1982–2000	2001–2005
Annual flow (mm/year)	1085	1027	896
High flow index, Q_5/Q_{50}, (–)	18.58	20.00	29.27
Low flow index, Q_{95}/Q_{50}, (–)	0.22	0.18	0.12
Gumara			
Time period (Similar to Gilgel Abbay)	1973–1981	1982–2000	2001–2005
Annual flow (mm/year)	743	803	873
High flow index, Q_5/Q_{50}, (–)	35.00	33.24	30.30
Low flow index, Q_{95}/Q_{50}, (–)	0.08	0.10	0.36
Megech			
Time period	1977–1981	1982–1993	1994–2006
Annual flow (mm/year)	528	235	464
High flow index, Q_5/Q_{50}, (–)	53.30	57.52	29.77
Low flow index, Q_{95}/Q_{50}, (–)	0.20	0.12	0.26

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Table 8. Rainfall depths of three stations for the period the changes in stream flow are observed. JJA is June, July, August.

Bahir Dar		
Period	1982–2000	2001–2005
Annual rainfall (mm)	1329	1490
JJA rainfall (mm)	950	1142
Ratio JJA to Annual rainfall (%)	71.5	76.6
Dangila		
Period	1988–2000	2001–2005
Annual rainfall (mm)	1625	1512
JJA rainfall (mm)	964	1006
Ratio JJA over Annual rainfall (%)	59.3	66.5
Gondar		
Period	1987–1993	1994–2006
Annual rainfall (mm)	1032	1146
JJA rainfall (mm)	680	750
JJA over Annual rainfall (%)	65.9	65.4

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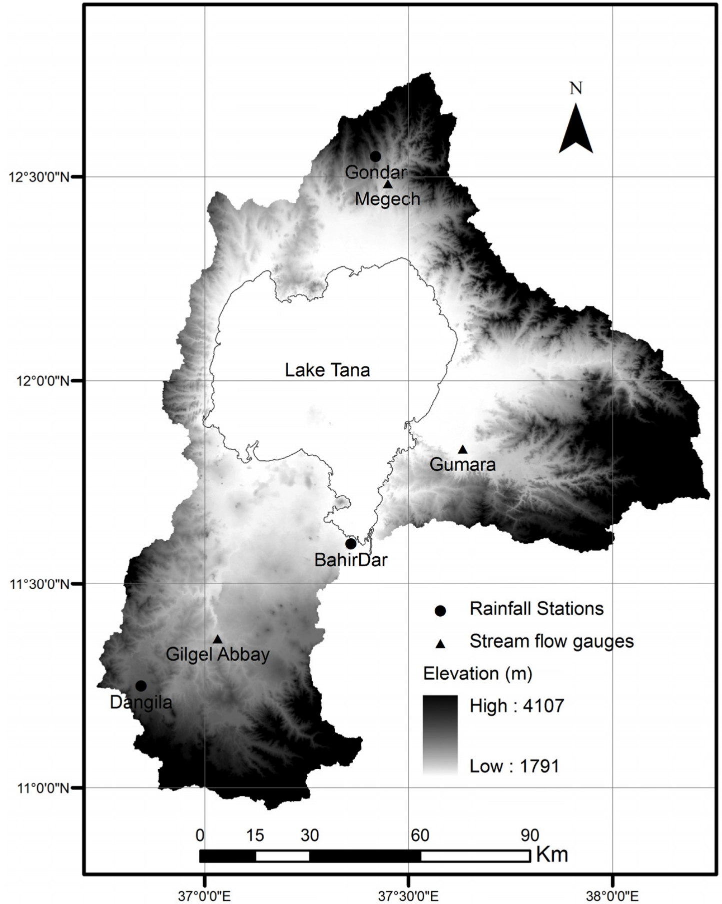
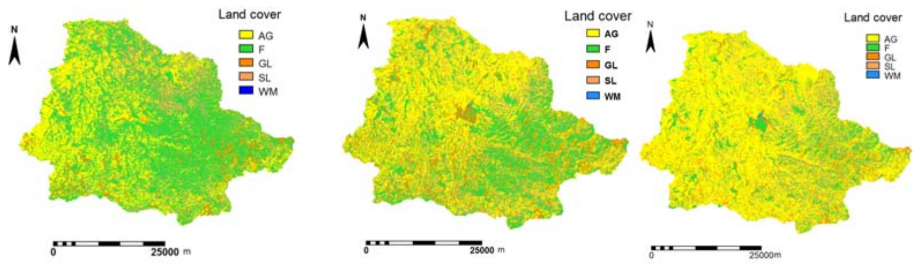


Fig. 1. Lake Tana catchment.



(a) (b) (c)

Fig. 2. Land cover map of Upper Gilgel Abbay catchment in 1973 **(a)**, 1986 **(b)**, 2001 **(c)** by Landsat satellites. AG stands for agriculture, F for forest, GL for grassland, SL for shrub land, WM for water and marshy land.

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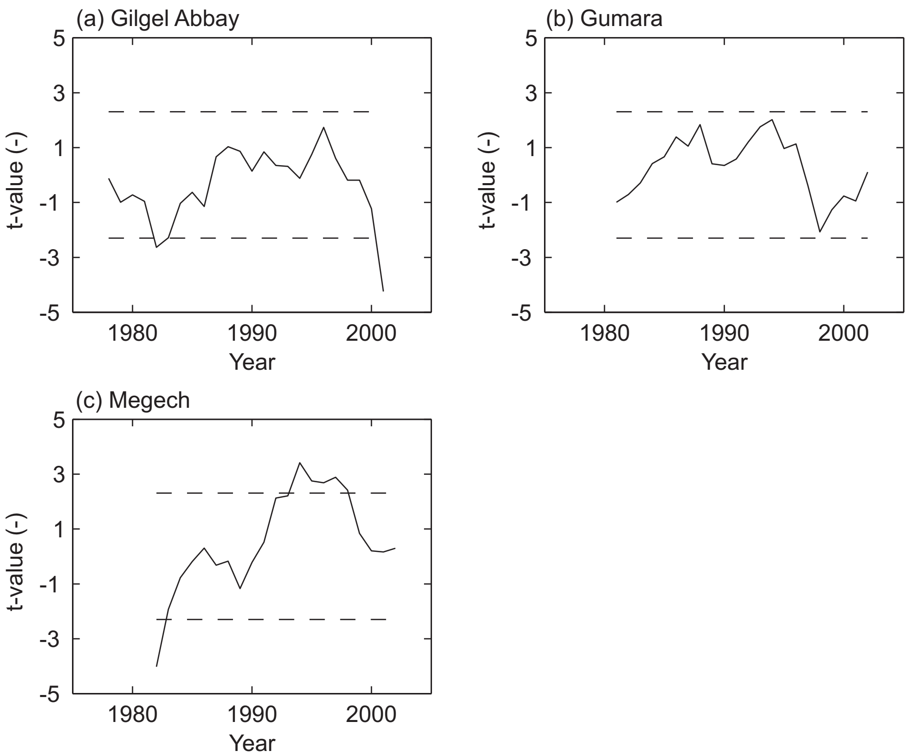

Fig. 3. Change-point detection for the annual flow of 3 watersheds in the Lake Tana basin using the moving t-test method. Note: the solid line represents the estimated t-values while the broken lines indicate the critical t-value for $\alpha = 0.05$.

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