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Biohydrology of low flows in the humid Ethiopian highlands: The Gilgel Abay catchment

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Abstract: In Ethiopia the population is rapidly expanding. As a consequence the landscape is rapidly changing. Eucalyptus plantations are increasing and irrigation projects are implemented. The hydrological effects of the changing landscape on river (low) flows have not been well documented and therefore the amount of water available in the future might be over optimistic. The objective of this paper is to establish how low flows have been impacted by new developments in irrigation and by landscape change. For this paper, we choose the Gilgel Abay in the headwaters of the upper Blue Nile basin, since it has both good quality discharge data and it is located in the Tana Beles growth corridor. Numerical and statistical means were used to analyze the 25 years of available low flow data. We found a statistically significant decreasing trend ($P < 0.00001$) of low flow in the Gilgel Abay. From 1980's to 1990's the low flow decreased by 25% and from 1990's to 2000's the low flow was reduced by 46%. The deterministic analysis with the Parameter Efficient Distributed (PED) model supported the statistical findings and indicated that in the middle of the nineteen nineties, after irrigation projects and eucalyptus plantations increased greatly, the low flows decreased more rapidly.

Key words: *Eucalyptus*; Blue Nile; Gilgel Abay; low flow; irrigation potential; PED model; watershed

Introduction

Population growth and associated expansion in domestic, industrial and agricultural use of water has put increasing pressure on the available water resource throughout the world. This growth has been accompanied by rapid change of landscapes in the case of Ethiopia: the increasing areas of irrigated crops and eucalyptus trees. These changes will affect the water resources availability. Managing the water resources with increasing population pressure has become more critical especially at the end of the dry monsoon phase, when meeting the water demand of irrigation, water supply, industrial, ecological and recreational purposes is most acute. Additional factor in managing water is the increasing emphasis on ecological, recreational and esthetical values of the river corridor.

Despite the importance little information is available how the low flow is changing in time as a function of climate, anthropogenic and biological factors in the landscape (Baveye 2013; Lichner 2013). This information is specifically needed in the Lake Tana Beles growth corridor in the northern Ethiopia highlands where water use has been rapidly expanding in the last twenty years. Predicting change of low flows require understanding and consideration of change in climate and land use, as well as various man-induced effects. In the Tana Beles growth corridor the anthropogenic factors affecting low flow consists of increased irrigation especially after 1995 and enlarged acreage of eucalyptus trees. This affects the low flow through its biological impact of increasing actively evaporating crops especially during the dry monsoon phase (Chanie et al. 2013) and climate changes.

A challenge in low flow estimation (prediction) comes from the inaccuracy of flow measurements. Many stations in the Lake Tana-Beles growth corridor are affected by this uncertainty with exception of the Gilgel Abay that has a stable cross section at the gauge site. The Gilgel Abay was chosen therefore for this study. Studies on low flow in the Tana Beles growth corridor, are: Gebrehiwot et al. (2010) studied the hydrologic impacts of deforestation in the Koga watershed that share boundary with Gilgel Abay catchment and concluded that deforestation has no measurable impact on low flow; Tesemma et al. (2010) considered the trends in rainfall and runoff for selected watersheds and found that while there were no trends in the annual rainfall pattern, the runoff during the wet monsoon phase increased. Rientjes et al. (2011) examined the effect of

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land cover change on stream flow in the same watershed using HBV model, and concluded the change in land cover in the watershed is directly related to the low flows. Several studies in the basin (Wale et al. 2009; Rientjes et al. 2011) reported that after the construction of the Chara Chara weir in 1996 at the outlet of the Lake Tana and more recently the tunnel from the Lake Tana to the Beles the flow in the Blue Nile during low flow periods has decreased. Consequently, the objectives of this study are: (1) to assess the long term trend in low flow of Gilgel Abay and (2) to relate this to biological and physical changes in the landscape. We will employ statistical methods and simulate the low flows with a physical model by calibrating the model to the early part of the low flow record and then looking at the deviation at the last part of the record.

Material and methods

Study area

Gilgel Abay located south of the Lake Tana is the largest contributor of Lake Tana inflow (Rientjes et al. 2011). The study area covers the upper part of the Gilgel Abay catchment; upstream of the gauging station at the Bikolo Abay shown in Fig. 1. The area of the watershed is about 1656 km^2, while the longest flow path of the river is about 84 km (Rientjes et al. 2011). The watershed is densely populated and is part of the Amhara region with annual population growth rate of 2.7% (ANRS, 2009). This growth has led to increased and intensified human activities that resulted in deforestation, overgrazing, land degradation and expansion of agricultural land. For the last 20 years, eucalyptus plantations have been increasing, some on the most degraded lands The annual rainfall in the Gilgel Abay catchment is about 1700 mm with standard deviation of about 180 mm (Haile et al. 2009, 2010, 2011). Generally, the main wet season covers the period from the beginning of June to the middle of September. There is a decreasing trend in rainfall from South to North (Haile et al. 2009). The upper Gilgel Abay watershed elevation varies from 1934 m at the gauging station to 3528 m.

Statistical methods

The index series of Mann-Kendall and Sens's t-test and linear regression methods were used for the long time series (1980–2005) fourteen day's low flow analysis in the watershed. The Mann-Kendall (MK) test, Mann (1945) and Kendall (1975) is applied and used to test the presence of a trend in the hydro-meteorological time series data. Linear regression was also used which fits a regression line to the data series, the method assumed a normal distribution of the residuals.

Mann-Kendall index test: Mann-Kendall (MK) is a non-parametric rank-based method that is widely used to test the randomness against trend in climatologically time series data (e.g., Kahya & Kalaycı 2004). The test does not require assumptions about the statistical distribution of the data. Since the method is rank based, extreme data points in the hydro-meteorological time series data will not largely affect the results of the trend analysis. The MK test is applied and used to test the presence of a trend for the fourteen days average observed low flow time series data in the Gilgel Abay catchment. The test statistic, 'S' follows the standard normal distribution. A positive value of 'S' indicates an increasing trend and a negative value indicates a decreasing trend (Partal & Kahya 2006).

Sen's t-test: The Sen's t-statistic 'T' is computed under the null hypothesis of no trend, and the distribution of T tends towards normality with mean zero and unit variance (Sen 1968a, b). The detailed computational procedure of the test statistic is given in (Belle & Hughes 1984). Positive values of T indicate an increasing trend, whereas negative values indicate a decreasing trend. The trend of the data set can be estimated using the Sen's slope estimator.

Physical methods: PED model

In the upper Blue Nile basin, a limited number of hydrological models have been used. A review by Awulachew et al. (2008) shows that the number of model simulating the discharge from the watershed in the Blue Nile and other river basin in Ethiopia and Africa has increased exponentially in recent years. Most of the models used for watershed modelling in the Blue Nile basin are developed for temperate regions where the rainfall characteristic is different from the monsoon climate. These models are providing mixed results when applied in the monsoon climate (Awulachew et al. 2008). To model the hydrology realistically the conceptual frame work for the model should be correct. According to Liu et al. (2008) saturation excess runoff from saturated areas dominates the runoff process in several watersheds in the Ethiopian highlands. Runoff from these almost impermeable areas can be modelled with either saturation excess models with a very small amount of retention before runoff occurs or infiltration excess models with a minimal infiltration capacity. Water balance models are consistent with the above-mentioned type of runoff processes, since the runoff can be related to the available watershed storage capacity and the amount of precipitation but not generally to the precipitation intensity. Moreover, as described above models developed and intended for use in temperate regions where rainfall is generally well distributed throughout the year do not perform well in regions with monsoonal rainfall distributions (Liu et al. 2008). Therefore, water balance models, that track soil moisture levels and the degree of saturation, often perform better than more complicated models in Ethiopian type landscape (Johnson & Curtis 1994; Conway 1997; Kebede et al. 2006; Liu et al. 2008). So, there is a need to test a model that is developed in the upper Blue Nile basin. Steenhuis et al. (2009) developed and validated a Parameter Efficient distributed (PED) model for runoff and erosion model at different watershed scales in the upper Blue Nile. It has been applied in Ethiopia (Tilahun et al. 2013) and other countries with a monsoonal climate (Caballero et al. 2013). In the PED model various portion of watershed become hydrologically active when moisture content treshold is exceeded. The three region distinguished in the model are the bottom lands that potentially can saturate, degraded hill slopes and permeable hill slopes. Each of the regions is the lumped average of all such areas in the watershed (Tesemma et al. 2010; Caballero et al. 2013). In the model the permeable hill slope contribute to rapid subsurface flow (called interflow) and base flow. For each of the three regions, a Thornthwaite and Mather (Thornthwaite & Mather 1955; Steenhuis & van der Molen 1986) type water balance is calculated. Surface runoff and erosion are generated when the soil is saturated and assumed to be at the outlet within the time step. The percolation is calculated as any excess rainfall above field capacity on the permeable hill side slope.

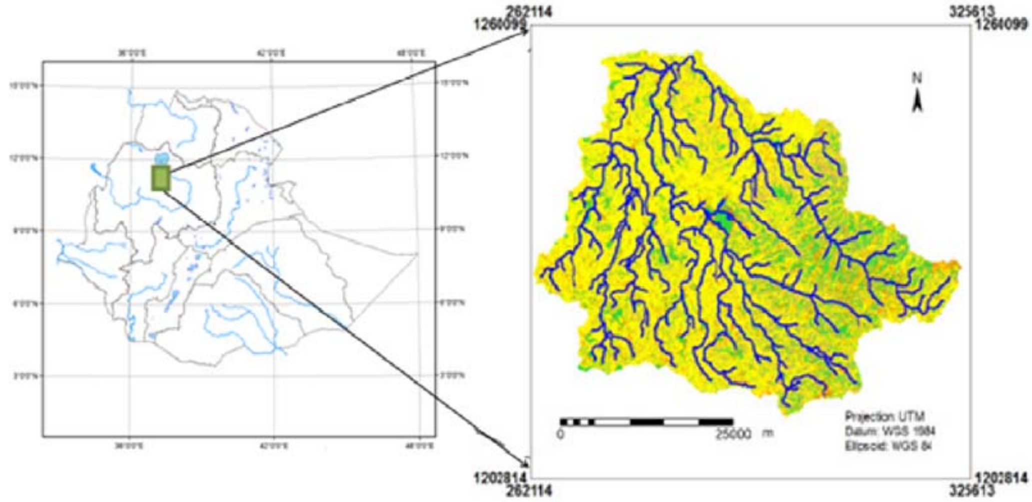

Fig. 1. Location map of the Gilgel Abay watershed.

The PED model is used for the analysis of the low flow. The meteorological (rainfall and temperature) input data for the study area collected from CFSR data were checked for its consistency and arithmetically averaged over the area. The temperature data were consistent whereas the rainfall data were found biased; the long term mean annual rainfall of Dangila and Sekela stations were used to correct these biases. These stations were found within the study watershed. Parameter Efficient Distributed (PED) model was used for the simulation of the daily and decadal flow rates. The model performance was evaluated through Nash Sutcliff Efficiency (NSE), coefficient of determination (R^2), Root Mean Square Error (RMSE), and Absolute Mean Error (AME). The detailed model description is found in Steenhuis et al. (2009), Tesemma et al. (2010), and Collick et al. (2009).

Data

Historical (1980–2005) meteorological data (precipitation and temperature) were collected from the Climate Forecast System Reanalysis (CFSR) grids of the watershed with grid numbers of GP113212 and GP114212, and recent rainfall data were also collected from the Meteorological Agency of Ethiopia. The stream flow data were collected from the Ministry of Water and Energy of Ethiopia.

Statistical input data: A series of fourteen days average observed low flow were computed in each year, for low flow trend analysis in the long term. This data is being analyzed in Mann-Kendall (MK) non-parametric test, and Sen's t-test, and regressed linearly.

Physical model input data: The model requires meteorological and hydrological data of daily precipitation, evapotranspiration, and stream flow data. We found that the CFSR rainfall was similar but overestimated the observed rainfall and the CFSR rainfall was multiplied by of 0.8 as a correction. Daily evapotranspiration (ET) was estimated from daily maximum temperature data using the temperature method developed by Enku & Melesse (2014). The long time series daily maximum temperature was collected from the CFSR dataset. The two grids that fall within the watershed were averaged and used to estimate daily ET for the whole time period (1980–2004). The daily stream flow record for the specified period was used in the model for the calibration and evaluation the performance of the model.

The landscape parameters (the relative areas of the watershed), the amount of water available for evaporation in the root zone for the three areas (between the field capacity and wilting point) were also the input to the model. For the areas that produce runoff, the threshold value is set to the saturated moisture content. Any rainfall in excess of saturation becomes runoff. For the permeable hillside the threshold value is field capacity and excess rainfall becomes recharge filling up the ground water reservoir and when that is full, the interflow reservoir. In addition to the six surface parameters, there are three base flow parameters. These are the first order reservoir constant, a zero order inflow rate constant that indicates the duration of the linearly decreasing interflow and the maximum water content of the base flow reservoir. The landscape parameters values cannot be determined a prior and need to be calibrated. The model parameters in this study for discharge simulation were refined and calibrated with the observed discharge.

Table 1. Fourteen-days averaged low flow for the Gilgel Abay at the Bikolo Abay gauging station.

Observed flow	14-day average low flow mm day^{-1}		
	1980–1989	1990–1999	2000–2005
Maximum	0.17	0.14	0.07
Third quartile	0.12	0.09	0.04
Median	0.10	0.07	0.03
First quartile	0.09	0.06	0.03
Minimum	0.08	0.04	0.03

Results and discussion

Statistical analysis

The observed low flow data were analyzed dividing the data in to three decades. The statistics of the 14-days averaged low flow observed data is shown in Table 1 in decades. The minimum flow decreased from the earlier decades to the recent times.

In order to show the trend in the observed low flow, the study period was divided into three decades and the lowest 14 days continuous observed low flow in a decade was determined in each of the three periods (Table 2).

Table 2. Observed 14-day low flow for each of three decadal periods.

Decade year	Mean low flow (m^3 s^{-1}/day)	Percentage change
1980–1989	2.03	
1990–1999	1.53	–25%
2000–2005	0.82	–46%

In the first decade (1980–1989) the 10-years mean of 14 days average low flow was 2.03 m^3 s^{-1}. This was reduced to 1.53 m^3 s^{-1} in the second decade (1990–1999). This reduction of low flow rate was about 25%. In the third period (2000–2005) the 6 years mean of 14-day average low flow was again reduced to 0.82 m^3 s^{-1}. The percentage reduction between the second period and the third period was around 46% in only 6 years (Table 2). Linear regression of annual two-week low flow (Fig. 2) shows that the low flow varies from year to year but there is overall decreasing trend ($R^2 = 0.65$). In the next section we use two statistical methods to determine of the observed trend in the Gilgel Abay is statistical significant. Since statistical methods cannot link the trend to any physical factors, we use the PED model to determine whether the trend can be determined by climatic factors such as a decreasing trend in precipitation.

Long time series (1980–2005) daily low flows were analyzed. Average of two weeks continuous minimum flows of dry periods in each year were calculated and then analyzed for its trend. The Mann Kendall statistical test show $S = -4.5$ with ($P < 0.00001$) for the annual 14 day-low flow data. The negative sign for test statistics means that the trend of low flows is decreasing with time and $P < 0.00001$ show the trend is highly significant. The Sen's statistical t-test again indicates similarly that there is a negative trend of annual low flows; with a slope of –0.06 (or a six percent decrease in annual low flows per year).

Physical analysis

The watershed flow was simulated with PED model. The nine parameters of the model (not counting the initial values) were fitted such that there was an overall good fit of discharge values but specifically that there was a good fit with the 14-day low flow values during 1980–1990. The best fit parameters for the area proportions were 2% for the saturated area, 10% of the degraded area and 82% for the hillside and saturated areas (Table 3). The proportions are similar as used for other larger watersheds. The interflow duration is directly related to the flow path of the water (Sabzevari et al. 2013) and has been found to last between the 4 days for simulations of the small watersheds and the 70 days for the Blue Nile Basin at the Sudanese border (Tilahun et al. 2013). Our value for the Gilgel Abay of 30 days is therefore reasonable. The remaining parameters are related to the maximum water storage in the root zone (Table 3). From the statistical calibration of the parameters the maximum soil water storage depth in the saturated areas was 100 mm, for hillslope the max storage depth was 200 mm, and for degraded areas it was 50 mm (Table 3). Although these storage depths are similar to other watersheds, the model output is not very sensitive to this set of parameters, since during the rainy phase in a humid monsoon climate, the soil evaporation is always at the potential rate.

After the model parameters were calibrated for the period of 1980 to 1992 (Table 3), the model performance was evaluated within three periods: One the total study period (1980–2005) and dividing the study period into two: i.e., the years (1980–1992) and (1993–2005). In these three periods, the performance of the PED model was evaluated through Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2), Root Mean Square Error (RMSE) and Absolute Mean Error

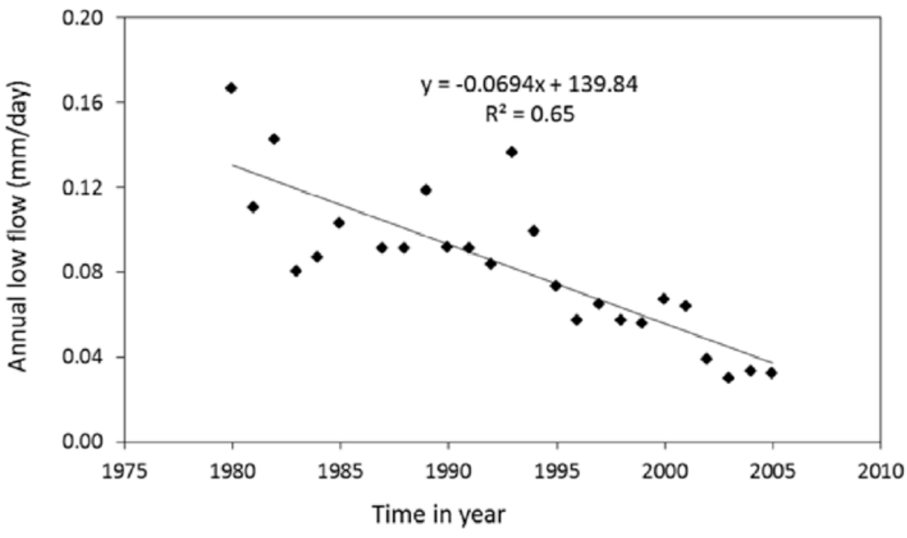

Fig. 2. Observed annual low flows for the Gilgel Abay from 1980 to 2005.

Table 3. Calibrated input values for PED model for surface flow parameters and subsurface flow parameters and the multiplication factor for precipitation obtained from the Climate Forecast System Reanalysis (CFSR). GW stands for groundwater.

Surface flow parameter	Area proportion	Max. storage (AWC) (mm)	Initial moisture (mm)
Saturated area	0.02	100	35
Degraded area	0.1	50	5
Hillside	0.8	200	100

Sub-surface flow parameter	Value	Unit
Max. Storage of GW	90	mm
Initial storage of GW	80	mm
Base flow half life ($t_{1/2}$)	80	days
Interflow duration (τ^*)	30	days
Rainfall factor CFSR	0.8	–

Table 4. Statistical results of the model performance for daily and decadal discharge predictions for three time periods. The statistical measures were Nash Sutcliff Efficiency (NSE), coefficient of determination (R^2), Root Mean Square Error (RMSE), and Absolute Mean Error (AME).

Periods	Daily performance				Decadal performance			
	NSE	R^2	RMSE	AME	NSE	R^2	RMSE	AME
1980–2004	0.61	0.72	3.4	1.3	0.75	0.82	20.2	10.9
1980–1992	0.65	0.76	2.3	1.2	0.78	0.83	10.1	19.9
1993–2004	0.58	0.68	3.6	1.4	0.7	0.80	11.9	20.4

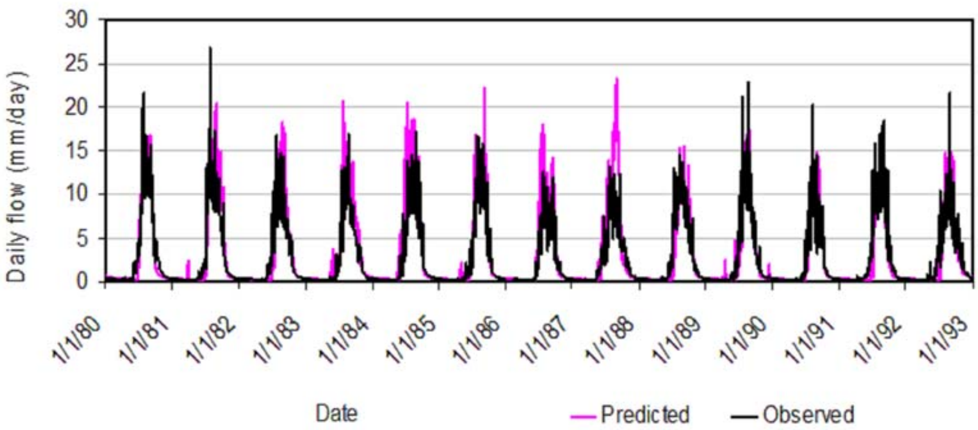

Fig. 3. Daily time series of observed and PED simulated discharge for Gilgel Abay in the period from 1980 to 1992.

(AME) on daily and decadal time steps. On daily simulations of the first half period NSE, R^2, RMSE, and AME were 0.65, 0.76, 2.3, and 1.2, respectively. In the same way, in the second half period NSE, R^2, RMSE, and AME were 0.58, 0.68, 3.5, and 1.4, respectively. On decadal simulations of the first half period NSE and R^2 were improved to 0.78 and 0.85 and in the second half period NSE and R^2 were 0.7 and 0.8 (Table 4). The model performed better in decadal time step simulation than the daily simulation as expected (Table 4) because errors in runoff predictions due to inaccuracies in daily rainfall amounts are averaged out over a longer period. Daily and decadal simulations are shown in Figs 3 and 4 for the period of 1980 and 1992.

The PED model could simulate the 14 day low flow relatively well up to around the year 1995 (Fig. 5). However, after this period the model was unable to simulate the low flows in the watershed (Fig. 5). This indicates that the relationship between model input (i.e., precipitation) and output (i.e., river discharge) had changed due to external factors. These external factors likely are due to the increasing population that affects landscape properties such as the extent of the degraded areas and changes in land use (Bewket and Sterk 2005; Hurni et al. 2005; Gebrehiwot et al. 2010; Rientjes et al. 2011). In the next section we will discuss the causes for the decreasing low flows after 1995.

Causes for decreasing low flows

There are various reasons given in the literature for the decrease in low flow. Rientjes et al. (2011) found that despite an increasing trend in annual rainfall, the low flow index based on the 5% exceedance decreased by 18% for the periods 1982–2000 and 67% for the period

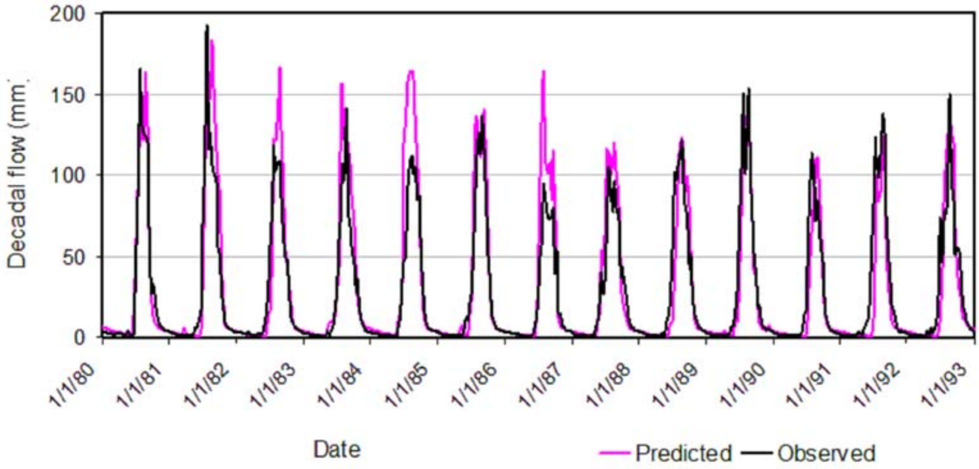

Fig. 4. Decadal time series of observed and PED simulated discharge for Gilgel Abay in the period from 1980 to 1992.

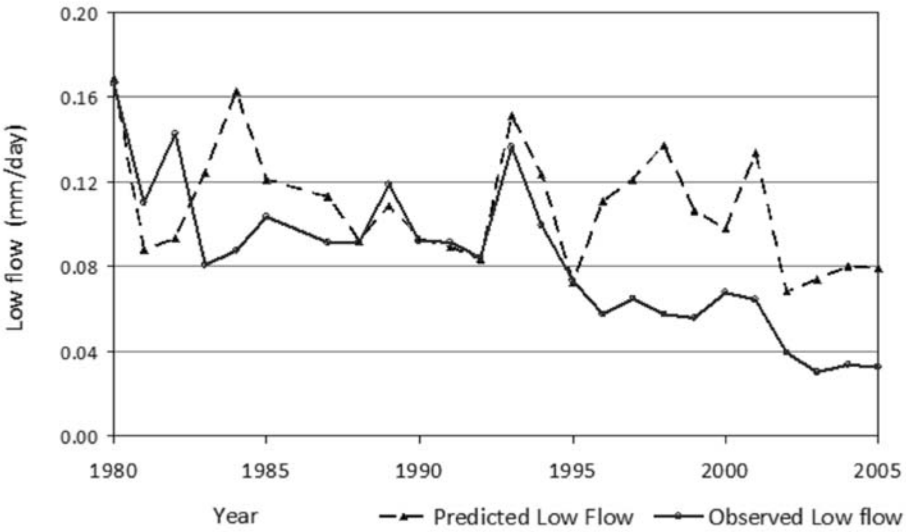

Fig. 5. Time series of simulated and observed 14-day low flow in Gilgel Abay.

from 2001–2005 and related this to biological factors consisting of a decrease in forest cover from 51% in 1973 and to 17% of the catchment in 2001. Most of the deforestation was likely completed before 1986 as since Bishop et al (2010) found for the Koga watershed which is part of the greater Gilgel Abay basin and enters the Gilgel Abay just below the gaging station, only 1% forest was left in 1986. However the hypothesis of Rientjes et al. (2011) that biological causes (i.e., land use change) had caused a significant change of runoff (both high and low flow) during the last four decades is consistent with the findings of Gebremicael et al (2013) for the upper Blue Nile basin using the combined results of the statistical tests, the SWAT model, and land use change detection. Finally Tesemma et al (2010) was of the opinion that the change in flow was related to an increase in degraded areas that would change the land use from cropped to grassland.

Although the statistical results of an initial small decrease in low flows followed by a rapid decrease in low flows are comparable to that of Rienjes et al (2011), our physical modeling effort shows that decrease in low flow especially occurs after 1995 indicating that the deforestation that was complete around 1986 was not the reason for the accelerated decrease in low flows. To find a more probable reason for the rapid decrease in low flow, we note that the Ethiopian government established in 1994 the Commission for Sustainable Agricultural and Environmental Rehabilitation in Amhara Region (Co_SAERAR) to aid small scale irrigation development to improve the traditional irrigation system. They were successful and a survey of eight counties (or woredas) within which the Gilgel Abay watershed is located, showed that in 2005, 106 km^2 were irrigated (Table 5). If we take the relative portion of each of these watersheds in the Gilgel Abay basin we found that there were a total of 18.6 km^2 improved or constructed traditional irrigation schemes in 2005 in this basin (BoWR_ANRS 2005).

In order to understand if the extension of irrigated area could explain the decrease in low flow we note that the daily amount of water on per unit depth basis

Table 5. Data to determine the irrigated acreage in the Gilgel Abay basin (GAb). Column 1 are the eight counties (called Woreta's in Ethiopia) with land in the GAb. Column 2 is the irrigated acreage in the county; Column 3 is the percent area of the county in the Gab and fourth column is the acreage if irrigated land in the GAb calculated as product of the data in columns 2 and 3. The last line is the total and irrigated acreage in the GAb.

County	Irrigated land in the county (ha)	% of area in GAb	Irrigated area in the GAb (ha)
Achefer	276	4.7	13
Dangila	1353	10.5	142
Fagita lakoma	6376	19.2	1224
Merawi	342	37.4	128
Sekela	1699	19.9	338
Banja	107	7.3	8
Adet	303	0.3	1
Quarit	71	0.8	1
Total	10527		1854

used by these schemes would be equivalent to the ratio of the irrigated area to the total area. Since the irrigated area makes up just over 1% of the total area, 1% of the potential evaporation would be roughly equivalent to 0.05–0.06 mm/day over the whole basin. The observed decline in Fig. 5 is an equivalent amount of 0.04 mm/day over the whole watershed. Since many of the irrigated areas are in chat (the local high value narcotic crop) which is irrigated once a week, meaning that the crop would evaporate at less than the potential rate. Moreover a portion of the current irrigated area was only improved and thus would not contribute to and additional decrease in low flow. In addition to irrigation activities the area of eucalyptus tree stands have largely expanded since 1995 due to the demand of the construction boom in the last 15–20 years. Susiluoto & Berninger (2007) showed that the expansion of Eucalyptus trees in head waters reduces the base flow of the watersheds because the roots of *Eucalyptus* trees are usually well developed in the dry areas and enable them to use the water stored deep in the soil during the dry season.

Thus, in summary, the introduction of irrigation projects and growth of eucalyptus trees in vast areas in the catchment after the middle of the nineteen nineties can easily explain the decrease in low flow of 0.04 mm/day (averaged over the whole watershed). Deforestation and the decreasing amounts of rainfall during this period (according to Rientjes et al. 2011) can explain the reported slight decline in low flow in the period before 1995.

Conclusions

The longtime series (1980–2005) annual low flow was analyzed in Gilgel Abay watershed. The statistical Mann-Kendall test, Sen's t-test and the linear regression; show that the low flow in Gilgel Abay watershed is significantly decreasing ($P < 0.00001$) trend with 6% annually. The volumetric low flow reduction from 1980–1989 to 1990–1999 was around 25% and from the 1990–1999 to 2000–2005 the reduction was about 46%. The PED simulation model results indicated that the reduction in low flow started in the middle of nineteen nineties when the introduction of irrigation projects and large coverage of eucalyptus trees in the watershed, that began after around that date decreased the low flow more rapidly than before.

Future planning of runoff of the river irrigation projects in the Gilgel Abay and Lake Tana basin need to be designed carefully with considerations of current irrigation demands and with environmental and ecological low flow requirements that likely will become more prominent in the future.

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